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Unconventional Gas Exploration and Extraction (UGEE) Joint Research Programme

Final Report 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems

Authors: Henning Moe, Oriol Ciurana, Pat Barrett, Laura Foley, Lorraine Gaston and Roger Olsen

Example of a drilling rig used for the installation of groundwater monitoring wells

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The Environmental Protection Agency (EPA) is an independent statutory body, established under the Environmental Protection Agency Act with a wide range of responsibilities including regulation of large scale industrial and waste facilities, monitoring and reporting on the state of the environment, overseeing local authorities' environmental responsibilities, coordinating environmental research in Ireland, promoting resource efficiency and regulating Ireland's greenhouse gas emissions. Through the Department of Communications, Climate Action and Environment (DCCAE) (and formerly through the Department of Environment, Community and Local Government - DECLG), the EPA has provided funding for environmental research since 1994. The current EPA Research Programme 2014-2020 is designed to identify pressures, inform policy and develop solutions to environmental challenges through the provision of strong evidence-based scientific knowledge.

On the 23rd of July 2016, the Department of Communications, Energy and Natural Resources (DCENR) became the DCCAE. Along with a name change, the new Department incorporates functions that were formerly held within the Environment Division of the DECLG. The Department retains responsibility for the Telecommunications, Broadcasting and Energy sectors. It regulates, protects, develops and advises on the Natural Resources of Ireland. Of particular relevance is the role of the Petroleum Affairs Division (PAD) to maximise the benefits to the State from exploration for and production of indigenous oil and gas resources, while ensuring that activities are conducted safely and with due regard to their impact on the environment and other land/sea users. The Geological Survey of Ireland (GSI) is also within DCCAE and provides advice and guidance in all areas of geology including geohazards and groundwater and maintains strong connections to geoscience expertise in Ireland.

The Department of Agriculture, Environment and Rural Affairs (DAERA) in Northern Ireland has responsibility for food, farming, environmental, fisheries, forestry and sustainability policy and the development of the rural sector in Northern Ireland. As an executive agency of DAERA, the Northern Ireland Environment Agency (NIEA) seeks to safeguard the quality of the environment as a whole through effective regulation of activities that have the potential to impact on the environment.

Administration of the Research Programme and Steering Committee

This Research Programme is being administered by the EPA and steered by a committee with representatives from DCCAE (formerly DCENR and the Environment Division of the DECLG), the Commission for Energy Regulation (CER), An Bord Pleanála (ABP), the GSI, NIEA, the Geological Survey of Northern Ireland (GSNI), as well as a Health representative nominated by the Health Service Executive (HSE).

UGEE Joint Research Programme

Environmental Impacts of Unconventional Gas Exploration and Extraction (UGEE)

(2014-W-UGEE-1)

Final Report 1:

Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems

by

CDM Smith Ireland Ltd

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References to government departments (DCENR and DCELG) throughout the report use the names of these departments prior to July 2016. References to the Department for the Economy (DfE) throughout the report use the name of its predecessor, the Department of Enterprise Trade and Investment (DETI), the department responsible for petroleum licensing in Northern Ireland until May 2016.

UGEE Joint Research Programme

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Project A1 Internal Review Panel[1]

British Geological Survey, Queen’s University Belfast, Independent reviewer (Irish University)

1 More details available at: http://www.epa.ie/pubs/reports/research/ugeejointresearchprogramme/ugeejrptasksorganisations.html

Contents

List of Figures

List of Tables

Executive Summary

Unconventional Gas Exploration & Extraction (UGEE) involves hydraulic fracturing (fracking) of low permeability rock to permit the extraction of natural gas on a commercial scale from unconventional sources, such as shale gas deposits, coal seams and tight sandstone. The Environmental Protection Agency (EPA), the Department of Communications, Energy and Natural Resources (DCENR) and the Northern Ireland Environment Agency (NIEA) awarded a contract in August 2014 to a consortium led by CDM Smith Ireland Limited to carry out a 24-month research programme looking at the potential impacts on the environment and human health from UGEE projects and operations (including construction, operation and after-care).

The UGEE Joint Research Programme (JRP)[2] is composed of five interlinked projects which address the key topics of water, air and seismicity. The research work has involved extensive desk-based literature reviews of UGEE practices and regulations worldwide as well as field surveys in two case study areas.

The UGEE JRP has been designed to produce the scientific basis, which will assist regulators – both North and South – in making an informed decision about whether it is environmentally safe to allow fracking. As well as research in Ireland, the UGEE JRP is looking at and collating evidence from other countries.

Requirements for baseline monitoring are embodied in the European Parliament resolution on the "Environmental impacts of shale gas and shale oil extraction activities" (2011/2308(INI)). Thus, baseline monitoring would be required should UGEE-related activity plans become known or proceed in the future. For this reason, the TOR and scope of work for the UGEE JRP included the design and specification of potential baseline monitoring programmes for water, as well as air and the analysis of seismic activity.

The original timeline for the research envisaged that the entire programme, including water, air and seismic baseline acquisition, would conclude by 2016. Following a comprehensive assessment of the two case study areas, the Steering Committee has considered that were the baseline acquisition to commence, the estimated timeline for the overall research programme to report would now be in 2018 at the earliest. Consequently, baseline monitoring programmes would result in the overall findings of the research being delivered after the project deadline of 2016. The decision was therefore taken to prepare a synthesis report drawing together the conclusions of the research to date in order that these findings could be reviewed and policy decisions formulated with regard to the use of this technology in Ireland.

It is noted that the baseline monitoring programmes proposed by the JRP remain valid and such programmes should be implemented in advance of any application for a UGEE licence. It should be noted that such baseline monitoring programmes should provide independent information on water, air and seismic activity and is therefore different from any baseline characterisation and monitoring that would be required of UGEE operators as part of a licensing process, which would be case- and site-specific, and would be designed to monitor specific receptors.

Project A1 of the UGEE JRP, which is the subject of this report, addresses the baseline characterisation and potential future baseline monitoring of groundwater, surface water and associated ecosystems in the two case study areas: the Northwest Carboniferous Basin and the Clare Basin. The research conducted is guided by the source-pathway-receptor (S-P-R) model of

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2 www.ugeeresearch.ie

environmental risk assessment which has served as the basis for most other water resources and environmental protection programmes on the island of Ireland. This model examines environmental risk factors and linkages between potential sources of contamination, pathways of contaminant migration, and associated receptors of contamination.

Northwest Carboniferous Basin

The Northwest Carboniferous Basin (NCB) is a geologically complex sedimentary basin in the border region of Counties Sligo, Cavan and Fermanagh. The rock formations are extensively faulted and are in certain parts intruded by volcanic dykes. The stratigraphy comprises a range of shale, sandstone and limestone formations which are well correlated across the basin. Regional NE-SW trending strike-slip faults extend through the entire stratigraphic sequence. These are accompanied by smaller conjugate sets of normal and reverse faults that trend mainly NW-SE. As a result of rock displacements along faults, different geological formations are juxtaposed against one another at numerous locations.

Prospective unconventional gas exploration is targeted in the Bundoran Shale Formation, see Figure ES1. Based on the structural geometry of the NCB, horizontal hydraulic fracturing would require the initial vertical drilling and construction of boreholes to depths of 700–1300 m below ground surface. Figure ES2 depicts a conceptual hydrogeological cross-section of the NCB. Towards the centre of the NCB, where the Bundoran Shale Formation is deeply buried and past gas exploration activity was focussed, the "vertical separation distance" (Davies *et al.*, 2012) to the principal shallow bedrock aquifers and associated receptors ranges between approximately 250 and 570 m (average 426 m), as recorded in 10 past gas exploration wells for which data exist. The wide range reflects spatial variations in the thickness and structure of the intervening Mullaghmore Sandstone and Benbulben Shale Formations.

The main potential receptors of potential contamination from above-ground or underground UGEE activity would be surface waters and shallow bedrock aquifers. The primary shallow bedrock aquifer is represented by the Dartry Limestone Formation which is extensively karstified, whereby open conduits act as preferential pathways of water flow underground. In this hydrogeological environment, there is considerable hydraulic interaction between groundwater and surface water, and associated downgradient receptors are particularly susceptible to both surface and potential underground sources of contamination.

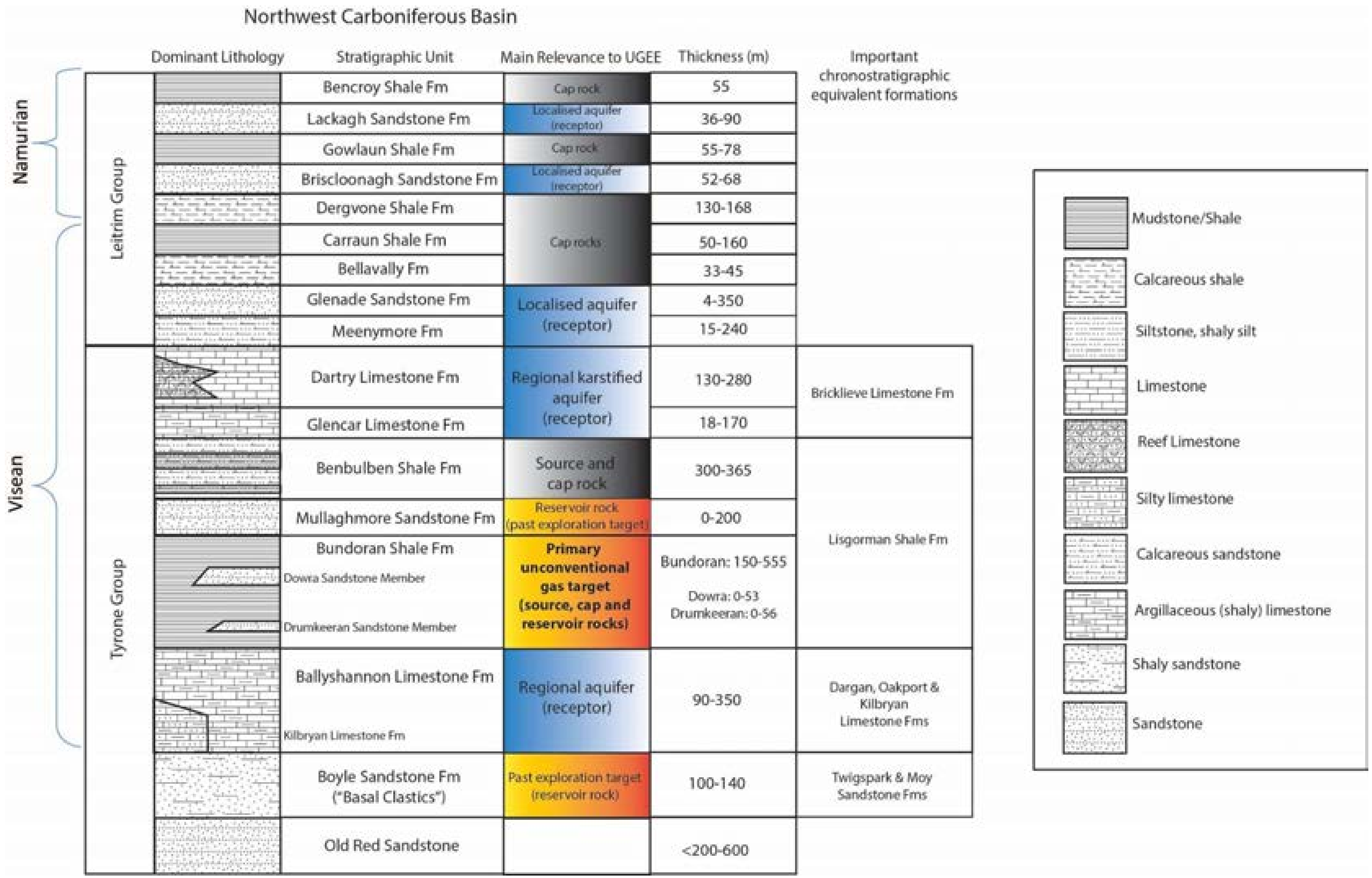


Figure ES1. Simplified stratigraphy of the NCB study area.

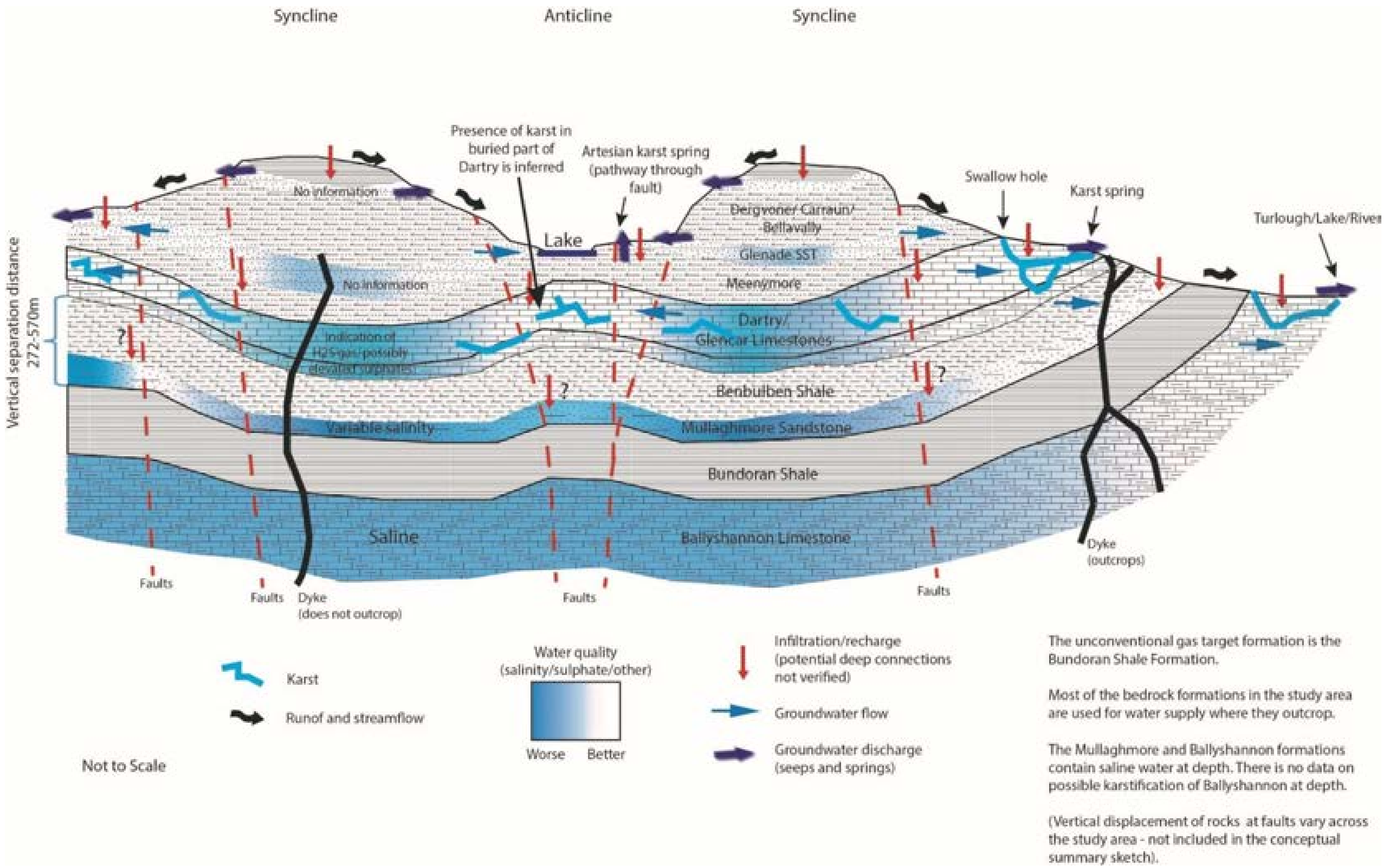


Figure ES2. Conceptual hydrogeological cross-section of the NCB.

Most of the bedrock formations in the NCB represent groundwater resources. These are abstracted for both public and private supplies in and near their outcrop areas where groundwater quality is suitable for supply purposes. Groundwater is sourced from drilled boreholes (which are typically less than 100–150 m deep), shallow dug or bored wells (which are typically only a few metres deep), and springs. Groundwater also has an ecological supporting function, by providing and maintaining baseflow to surface waters and groundwater-dependent habitats. This is ecologically important, especially during prolonged dry weather conditions, when water levels and stream flows are low.

Accordingly, all groundwater and surface water resources are vulnerable to potential sources of contamination associated with UGEE activity. Several groundwater dependent terrestrial ecosystems have also been mapped in the UGEE licence area. For these reasons, any future planning of UGEE-related activity should be guided by groundwater vulnerability concepts and existing vulnerability maps as implemented by both the Geological Survey of Ireland (GSI) and the Geological Survey of Northern Ireland (GSNI).

Potential hydrogeological connections between the unconventional gas target formation and shallow receptors are inferred rather than proven. Such connections would exist where open fracture networks are present in the deeper intervening formations, notably the Mullaghmore Sandstone and Benbulben Shale Formations. Although geological structures and fracture patterns at ground surface have been mapped and are well described in existing literature, the potential presence and patterns of natural, open fracture networks at depth are not conclusively demonstrated or characterised. Their presence is inferred from records of saline formation waters in gas-tested sandstone formations and acoustic televiewer images of presumed open fractures in the Mullaghmore Sandstone Formation (the main target of gas exploration activity in the past). Such open fractures would represent potential pathways of vertical contaminant migration, especially of dissolved, naturally occurring gases, including methane, from hydraulic fracturing operations.

Whether deep saline formation waters are 'fossil' or are part of active (even if slow moving) groundwater flow systems is not yet understood. The existing data are sparse and do not provide a sufficient database from which conclusive hydrogeological interpretations can be made. Accordingly, the important questions about potential hydrogeological connections between the unconventional gas target formation and shallow receptors can only be addressed through further hydrogeological characterisation, especially of the Mullaghmore Sandstone and Benbulben Shale Formations which overlie the Bundoran Shale Formation (the UGEE target formation). Deep hydrogeological characterisation would benefit from drilling, geophysical logging, hydraulic testing, sampling and monitoring of new deep wells, to several hundred metre depths.

Although the dominantly shale (clay-rich) lithology of the Benbulben Shale Formation could be expected to impede movement of water (and contaminants), the potential presence of natural fracture pathways across the formation cannot be ruled out. As noted by one of the exploration companies in the context of recommendations for future horizontal hydraulic fracturing, "*Natural fracture systems are expected to be prevalent although their specific intensity variations and trends are not yet understood*". Thus, the degree of natural protection that the clay/shale-rich Benbulben Shale Formation would offer is not yet demonstrated. As well, the degree to which "fracture stimulation" during hydraulic fracturing in the Bundoran Shale Formation may propagate vertically upwards (and through the Benbulben Shale Formation) requires further study and investigation.

Conceptual hydrogeological models in the island of Ireland context generally consider that the occurrence of significant water-bearing fractures decreases with depth. Due to the typical depths of domestic and most water supply or commercial boreholes, there is little information available about fracture flow at depths greater than 200 m. However, inflows have been encountered and are recorded in deeper boreholes and mine workings, indicating that hydraulically open and connected fractures can occur at depth. The potential presence of open fractures in deeper sandstone formations could be explained by the structural geology of the general study area, in which an observed sinistral (left-lateral) movement and rotation of the regional NW-SW trending strike-slip fault system would imply a dilatory influence on fracture sets.

Clare Basin

Prospective unconventional gas exploration in the Clare Basin (CB) would be targeted in the Clare Shale Formation, see Figure ES3. Horizontal hydraulic fracturing would likely require the drilling of wells to 800–1200 m depth, mostly towards the central axis of the sedimentary basin, which is adjacent to, and broadly parallel with, the Shannon Estuary and Loop Head peninsula. Away from the estuary and peninsula, the Clare Shale Formation thins and is structurally too shallow to be considered a viable source rock for unconventional gas.

The bedrock formations above the Clare Shale Formation are characterised by significant lithological heterogeneity, comprising, dominantly, sandstone and siltstone units, which are interlayered with shale and mudstone units. From the available information, there does not appear to be a regionally continuous caprock above the Clare Shale Formation that would be equivalent to the Benbulben Shale Formation in the NCB, and that would effectively separate the unconventional gas target from shallow water resources and associated ecosystems. Accordingly, and conceptually, potential UGEE-related migration of natural gas and other constituents might be less constrained than in the NCB. The potential for contaminant migration will likely be determined by the presence of through-cutting faults rather than any stratigraphic or lithological controls.

A conceptual hydrogeological cross-section of the CB is presented in Figure ES4. Shallow water resources are mainly represented by localised groundwater flow systems and streams. Groundwater provides baseflow to streams and supports water levels in areas of peat. There are few groundwater-dependent habitats compared to the NCB, and all features are associated with localised groundwater-surface water interaction systems. Groundwater is used and sourced for private water supply, notably from drilled wells which are typically less than 100–150 m deep, and from dug wells which are only a few metres deep. These serve single houses and farms, as well as commercial and industrial facilities. There are no groundwater-sourced public or group water schemes directly within the UGEE licence area. The majority of public supplies and group water schemes source water from Doo Lough, marginally to the east of the UGEE licence boundary. One groundwater-sourced GWS is located near, but outside, the UGEE licence area.

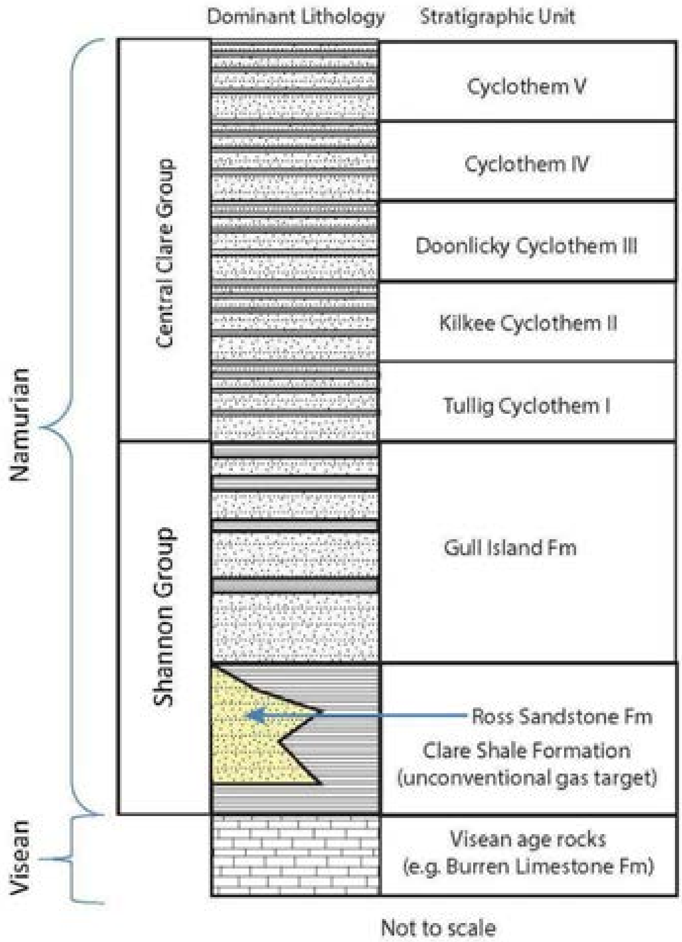


Figure ES3. Simplified lithological column – CB study area.

Groundwater flows primarily via fractures in the sandstone and siltstone units within each of the main formations that outcrop in the study area. In addition to shallow localised flow systems, there is a possibility that a deeper and potentially sub-regional groundwater flow component may be present, as suggested by reported "*fresh water*" strikes to *c.* 600 m depth in Doonbeg-1, a gas exploration well that was drilled and tested in the early 1960s. Definitive conclusions cannot be drawn without additional data, but given the hydrogeological setting of the CB study area, a sub-regional groundwater flow component towards the coastlines within the Namurian stratigraphic sequence is plausible.

Despite the relative apparent absence of faults on existing geological maps, bedrock formations have undergone structural deformation and are fractured to some extent. The extensive cover of till, the lack of outcrops across most of the study area, and the repetitive nature of the sedimentary rock succession all imply that structural complexities may simply be masked. In the context of prospective UGEE activity, structural geological characterisation would have to undergo further and more detailed investigation. Identification of faulting would benefit from detailed surface geophysical survey work.

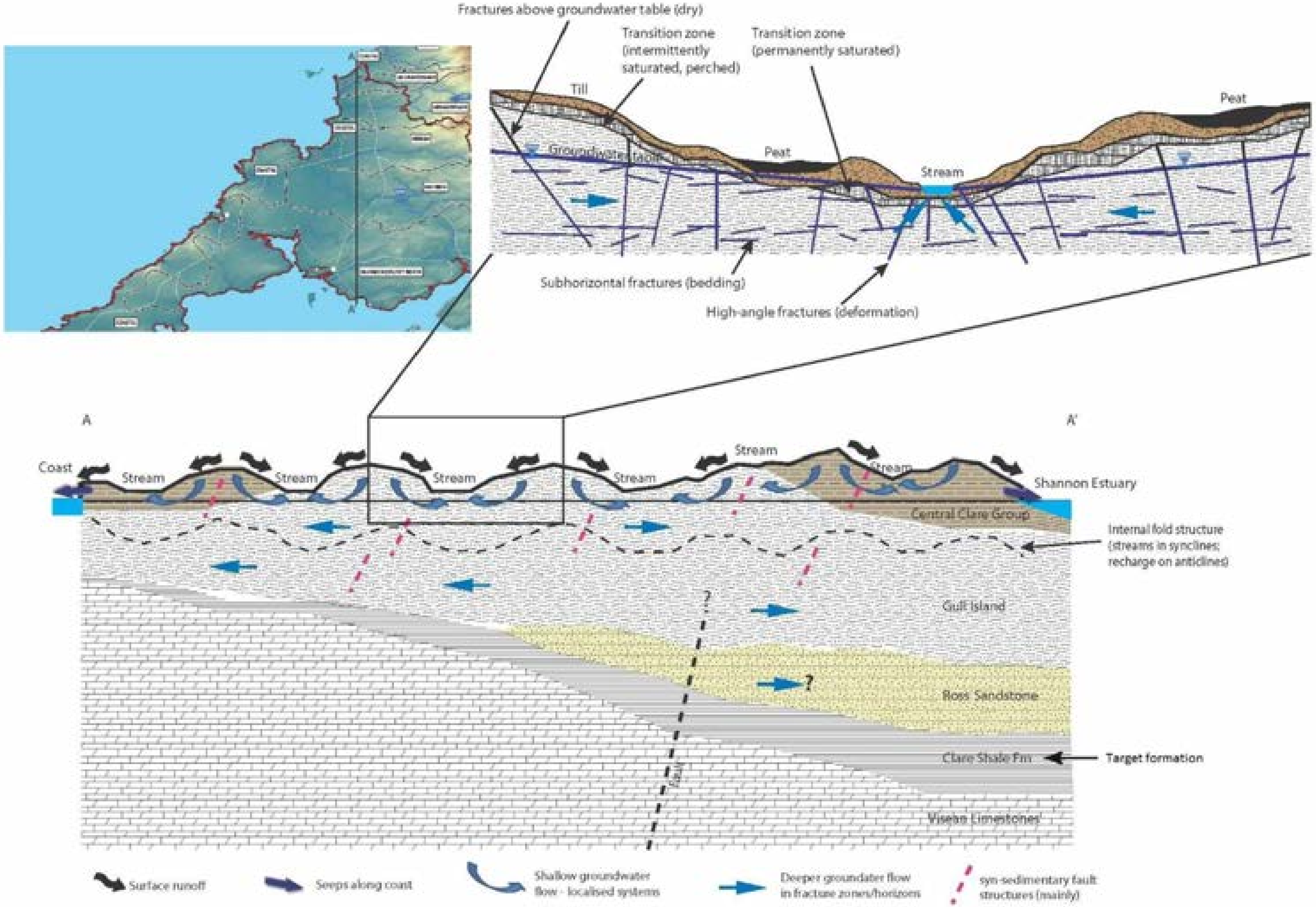


Figure ES4. Conceptual hydrogeological cross-section of the CB.

Deep hydrogeological characterisation would equally benefit from drilling, borehole geophysical logging, hydraulic testing, sampling and monitoring of new deep wells, to several hundred metre depths.

Finally, due to the till cover and generally low-permeability characteristics of the bedrock formations, the environmental risks and potential impacts on surface waters from UGEE activity at well pads are considered to be high.

Existing Monitoring and Environmental Pressures in the Study Areas

Both the EPA and the NIEA are carrying out comprehensive environmental monitoring of aquatic environments in Ireland and Northern Ireland, respectively, under initiatives linked with the implementation of the European Union (EU) Water Framework Directive (WFD) and respective national statutory instruments which have followed.

Existing environmental pressures in the case study areas (broadly, Cos. Fermanagh/Leitrim/Sligo and western Co. Clare) are mostly attributed to organic (nutrient, e.g. phosphorus) enrichment of water bodies associated with runoff and/or discharges from agriculture and wastewater treatment systems. Along with physical modifications of surface waters (e.g. dredging/channeling and river bank modifications), these have contributed to approximately 50% of surface water bodies failing to meet WFD ‘good status’ objectives. Most of the water bodies that have failed ‘good status’ objectives under the reporting requirements of the WFD predominantly did so on the basis of biological conditions (impacted quality of macroinvertebrate colonies in streams) or elevated phosphorus concentrations (streams, lakes, and groundwater). None of the water bodies failed to meet WFD ‘good status’ objectives on the basis of quantitative (abstractions) pressures, which are considered to be low, both for surface waters and groundwater.

The majority of the monitored surface water bodies do not indicate problems with regard to specific pollutants. Organic compounds and pesticides have been reported as unconfirmed single detections, but activities that may result in releases of specific pollutants are not considered to be significant. Only the Arigna River in the NCB was classified to be at ‘bad’ status. The precise cause has not been ascertained, but the river is located along the historical Connaught Coalfield, and river water quality downstream of discharges from adits shows periodically elevated concentrations of nickel and sulphate (EPA/DCENR, 2009), which may be related to sulphide leaching.

Only three groundwater bodies in the case study areas have been classified as being of poor chemical status, and all are in the NCB within Ireland. In all three cases, the assessment is based on elevated phosphorus concentrations in streams, whereby karstified limestone aquifers are inferred to contribute more than 50% of the flow and phosphorus loading to associated rivers, leading to breaches of the environmental quality standards for phosphorus in rivers. From the available data, groundwater quality does not appear to be impacted by organics or pesticides. The level of monitoring of organics and pesticides is less than for most other water quality parameters, but it is recognised that sampling frequency for different parameters is judged against, and is proportionate to, environmental risk.

Risk of Environmental Impact

Risk of environmental impact from UGEE operations is determined by source-pathway-receptor linkages and relationships. Potential sources of UGEE-related contamination are many. Some relate to UGEE operations at the ground surface whilst others relate to hydraulic fracturing operations in the deep subsurface environment.

Potential pathways are both of natural and man-made origins, and the latter can be created during UGEE activity. Natural pathways are determined by the hydrogeological characteristics of a site, and are described by subsoil and bedrock characteristics. These are conceptually well mapped and understood in the shallow subsurface environments (to approximately 200 m depth) in both case study areas, but are poorly understood and quantified in the deeper subsurface environment. Man-made pathways are mainly created during drilling and well construction activity, and caused by poor well construction practices, specifically inadequate cementation of casings and/or improper abandonment of test wells.

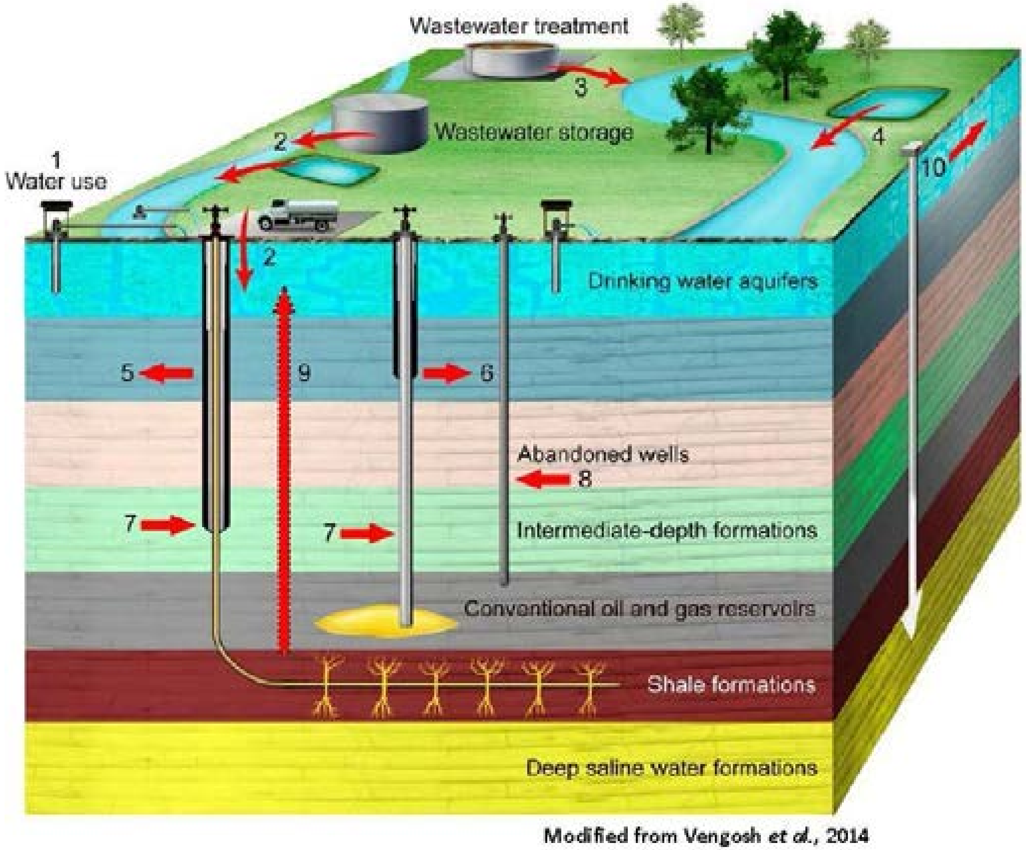
Potential water-based receptors of UGEE-related contamination in both case study areas have been identified at the sub-regional scale and are well mapped and field-verified. They are: a) the available water resources represented by lakes, streams and aquifers; b) associated water supplies (abstractions); c) registered protected areas; and d) groundwater-dependent terrestrial ecosystems.

The different modes of potential impact on water-related receptors are summarised in Figure ES5. Published studies and international literature point to two principal causes of impact:

- Poor management practices at well pads (e.g. spills, leaks and discharges associated with routine UGEE operations); and
- Migration of "*stray gas*" to shallow receptors, associated with hydraulic fracturing and resulting from migration of gas constituents through potentially both natural and artificial pathways, the latter being associated with poor well drilling, construction and/or abandonment practices.

Best practice mitigation measures to minimise the risks of spills, leaks and discharges are described in *Final Report 4: Impacts and Mitigations Measures* of the UGEE JRP (CDM Smith, 2016). Details of appropriate mitigation measures to address well construction practices are most appropriately addressed as part of the review process of potential future license applications, on a case by case basis, once details of proposed UGEE activity are presented. The review process should involve suitably qualified individuals on the part of both the planning and regulatory authorities.

Existing groundwater protection policies in Ireland and Northern Ireland are directed at mitigating risks of contamination from surface sources of contamination, as guided by principals of groundwater vulnerability and related mapping by the GSI and GSNI, as well as groundwater protection responses for potentially polluting activities. Existing policies mainly address protection of 'shallow' water resources and supplies which are typically less than 100 to 200 m deep. They do not address the risks of contamination that may result from deep hydraulic fracturing, although principles of contaminant migration are the same in both environments.



Schematic illustration (not to scale) of possible modes of water impacts associated with UGEE:

1. Over-abstraction of water from streams, lakes or shallow aquifers – higher risks of impacts during low flow conditions.
2. Contamination of surface water or groundwater from leaks and spills of waste materials and wastewater storage near drilling.
3. Disposal of inadequately treated wastewater to local streams, lakes or groundwater.
4. Leaks to waterways and/or groundwater from storage ponds.
5. Shallow aquifer contamination by stray gas that originated from the target shale gas formation through leaking well casing. The stray gas contamination can potentially be followed by salt and chemical contamination from hydraulic fracturing fluids and/or formation waters.
6. Shallow aquifer contamination by stray gas through leaking of past gas exploration wells (e.g. via casings), see also Figure 3.7.
7. Shallow aquifer contamination by stray gas that originated from intermediate geological formations through annulus leaking of past gas exploration wells (possible in NCB especially).
8. Shallow aquifer contamination through abandoned other wells (via annular spaces (no cases known in NCB or CB).
9. Flow of gas (and saline water, although unlikely) from deep formations to shallow aquifers via natural pathways; and
10. Shallow aquifer contamination through leaking of injection wells (possible but unlikely future scenario).

Figure ES5. Potential modes of UGEE-impact on water resources. Reproduced with permission from the American Chemical Society.

UGEE-related liquids and fluids are mostly a concern where these are returned to the surface as flowback or production waters (CDM Smith, 2016). In the deeper rock formations, saline formation and return waters are dense and would not be prone to upward migration (unless other driving forces overcome the density effect). Gases, including methane, behave differently, and the potential for upward migration is greater. Ultimately, risks of gas, liquid and fluid migration are case- and site-specific, depending on a wide range of characteristics, including (but not limited to) the hydraulic fracturing chemicals that are used, the natural head gradients that are present (between aquifers), the pathways and flow mechanisms that are present, the vertical separation distance between the deep target formations and shallow receptors, and the interactions with the geological media through which contaminants would be transported. Accordingly, environmental risks have to be assessed on a case- and site-specific basis during any future planning, risk assessment and licensing of potential UGEE activity.

Baseline Monitoring Best Practice

A review of baseline monitoring practices internationally yields much information about the importance and need for baseline monitoring, but relatively few examples with specifics or details of monitoring. The need for ‘sufficient’ and ‘adequate’ baseline monitoring is regarded as a pre-condition for licensing of UGEE activity, although the terms “sufficient’ and adequate’ are subjective, as technical opinions vary and the science of impact identification is still (and rapidly) evolving.

A consensus view that emerges from international literature is that a precautionary approach to baseline monitoring should be adopted which: a) is comprehensive in scope and extent; b) is capable of distinguishing between impact(s) from UGEE activity and impact(s) from existing environmental pressures; and c) allows for cumulative impacts to be identified across a larger UGEE footprint, specifically across a UGEE licence area, covering all potential aquatic receptors (groundwater, surface water, aquatic ecosystems).

To distinguish UGEE impact from other environmental pressures requires the application of complex analytical techniques in order to chemically ‘fingerprint’ environmental samples. International best practice requires that groundwater samples are analysed for a wide range of analytical parameters, including dissolved gases in water (e.g. methane), stable isotopes of gas constituents, and naturally occurring radioactive materials (NORM). One of the main goals of baseline monitoring is to document the presence or absence of naturally occurring methane (and other gas constituents) in groundwater, as methane gas is one of the primary contaminants of concern associated with hydraulic fracturing operations. Baseline monitoring for methane has not yet been undertaken in Ireland or Northern Ireland. Thus, a baseline understanding of methane in groundwater is needed.

To reduce subjective elements of technical assessment and strengthen the scientific rigour of baseline monitoring, best practice should also be followed with regard to sampling, sample handling and laboratory analytical techniques, based on clearly defined data quality objectives.

In this context, any future sampling and laboratory analytical programmes could be guided by the practical experiences by the British Geological Survey (BGS) who has conducted relevant baseline monitoring (e.g., of dissolved methane in groundwater) in England Wales. An appropriate and recommended starting point for baseline monitoring in Ireland and Northern Ireland would be to adopt and adapt the techniques and methods of the BGS.

Whilst practical experiences by the BGS and published international research are useful as guides on best practice techniques and methods, published information on baseline monitoring programmes in other countries cannot guide where monitoring in the NCB and CB should be undertaken, as this would be determined by location- and catchment-specific risk factors associated with potential sources of contamination, pathways of migration, and downstream or downgradient receptors which are described in the current report. Monitoring stations or points that are included in a baseline monitoring programme must be 'representative', which implies that monitoring is: a) carried out at appropriate locations (in three dimensions); b) conducted at appropriate times; and c) produces data (groundwater flow, discharge, quality) that describe the hydrogeological systems in question, taking account of temporal variations and the hydraulic interactions which may take place between groundwater, surface water and aquatic ecosystems within the system.

Firm plans for UGEE development in the NCB and CB study areas are not yet known. For this reason, it is assumed that UGEE projects could take place anywhere within the two study areas should UGEE activity be advanced in the future. The baseline monitoring that would be implemented as part of the UGEE JRP is, therefore, a sub-regional monitoring programme that would focus on identified potential receptors. It is different from the baseline characterisation and monitoring that would be required of UGEE operators as part of a licensing process, which would be case- and site-specific, and would be designed to monitor specific receptors.

There is also no specific guidance available on how long a sub-regional baseline monitoring programme should be carried out for. Baseline monitoring is a longer-term commitment if trends are to be identified and tracked. To develop a baseline picture of parameters that have hitherto not been analysed for (e.g. methane, stable isotopes), it is anticipated that baseline monitoring would be required for a minimum of 1 to 2 years.

Approach Towards the Design of Sub-regional Baseline Monitoring Programmes

Comprehensive sub-regional baseline monitoring programmes have been designed for the NCB and CB study areas. These are receptor-focused, i.e. they target monitoring of water resources, associated water users and aquatic ecosystems, and include laboratory analyses of substances that describe both general environmental pressures and UGEE-specific contaminants.

Potential receptors of UGEE-related contamination which have been identified in both case study areas are:

- Groundwater resources – the majority of bedrock formations within the study areas represent aquifers. Certain formations have more favourable hydrogeological characteristics and are more important aquifers than others. Thus, certain aquifers have greater 'resource value' than others, notably where groundwater is used more extensively for water supply and provide supporting conditions for surface waters and groundwater dependent habitats.
- Surface water resources – these are represented by all streams and lakes in the study areas, and include designated drinking water protected areas, designated salmonid waters, designated areas for the protection of habitats and species, as well as coastal shellfish and bathing waters.
- Groundwater-dependent habitats – both study areas contain: a) formally designated groundwater dependent terrestrial ecosystems (GWDTEs) which are included on a national Register of Special Areas of Conservation (SACs); and b) habitats with qualifying interests as GWDTEs but which have not yet been designated as such. Relevant habitats are turloughs, petrifying springs with tufa formations, fens, transition mires, active raised bogs, and alluvial forests.

Although existing environmental pressures and conditions in both case study areas are well described by the EPA and NIEA under existing WFD initiatives and respective national statutory instruments, the current monitoring is not specifically designed to address UGEE-related operations. For this reason, the sub-regional UGEE baseline monitoring programme would include many additional parameters that could be used to chemically fingerprint and distinguish UGEE impact from existing environmental pressures.

One of the main goals of the baseline monitoring programme would be to document the presence or absence of naturally occurring methane (and other natural gas constituents) in groundwater. If present, determinations of concentrations and origins of methane would be made, specifically whether the gas is of biogenic or thermogenic origins. This distinction is of significance, as thermogenic methane is most often formed during thermal decomposition of organic matter at depth under high pressures, and is associated with oil and natural gas fields, as well as coal deposits. In contrast, biogenic methane is unrelated to the processes that form fossil fuels, and is formed at low temperatures by anaerobic bacterial decomposition of sedimentary organic matter. It is most often associated with natural shallow anaerobic groundwater environments, such as peat bogs, wetlands and river/lake sediments, but also anthropogenic pollution sources such as landfills. The presence of methane gas in groundwater can, therefore, be misinterpreted if it is not sampled and assessed in the appropriate context, i.e. with consideration of its origin.

The chemical constituents and other compounds to be considered for laboratory analyses are those which: a) describe general environmental pressures; b) can be used to fingerprint both natural gas presence and their origins; and c) are capable of addressing "cumulative impact" from UGEE activities at the catchment scale. Accordingly, the approach that was followed in the design of the sub-regional baseline monitoring programmes:

1. Coordinates and builds on past and existing monitoring initiatives to take advantage of monitoring data which already exist, thereby reducing the potential for duplication of effort and associated costs;
2. Uses conceptual hydrogeological models to screen candidate sampling and measurement locations;
3. Considers the information which has been collated on potential receptors to guide the selection of monitoring points; and
4. Responds to best practice information on baseline monitoring in international literature, particularly with respect to parameters that should be included for laboratory analyses.

Whilst sub-regional baseline monitoring has to be comprehensive in scope and extent, baseline monitoring should also allow for flexibility, whereby monitoring is adapted to actual findings, both with respect to what is monitored for and where sampling is carried out. It is expected that such 'adaptive monitoring' may result in significant cost savings over time, without compromising project objectives. Two relevant examples of the 'adaptive monitoring' approach are:

1. A scenario in which dissolved natural gas constituents are not detected in a groundwater sample or the concentrations are below a specified trigger level. In this case, further isotope analysis of the sample to document the chemical fingerprint and likely source/origin of the gas constituents would not yield meaningful results, and would thus not be carried out. Similarly, if field-measured dissolved oxygen (DO) concentrations are high in groundwater, then the analysis for dissolved methane may be redundant. The trigger levels that are proposed would be those employed by the BSG for baseline monitoring of methane in England and Wales.
2. Similarly, if gross alpha and gross beta radiation screening of groundwater samples do not exceed specified threshold values, then further analysis to document activity levels of naturally occurring radioactive materials (NORM) would not be necessary since the total radioactivity levels are below relevant thresholds (dosage/health-based guidance values as described by the Office of Radiological Protection, EPA (formerly RPII).

Should plans for UGEE be authorised in the future, the baseline monitoring can also be adjusted geographically as plans for UGEE activity become known. Accordingly, monitoring strategies and programmes may evolve in time, also as new data become available and new monitoring installations become active.

Recommendation for Sub-regional Baseline Monitoring Programmes

The recommended sub-regional baseline monitoring programmes in the UGEE licence areas of the NCB and CB study areas are summarised in Table ES1 and shown in Figure ES6 and Figure ES7.

Table ES1. Summary of recommended baseline monitoring

	NCB No. of stations	CB No. of stations
Area (km^2)	**2200.40**	**495.65**
Groundwater quality – wells (PWS + GWS + private)	35	22[a]
Groundwater quality – wells (new)[b]	10	2
Groundwater quality – springs (PWS + GWS)	23	–
Groundwater quality – springs (other)[c]	10	–
Surface water quality – streams	32	7
Surface water quality – lakes	15	2
Surface water quality – turloughs	3	-
Groundwater – petrifying springs[d]	6	-
Hydrometric – stream flow	3	-
Hydrometric – spring discharge	7	-
Stream sediments[e]	30	15

[a]Estimated, to be finalised – 18 sites are accessible for sampling; a further 6 are require follow-up for verification of details or confirmation of owner agreement.

[b]New monitoring wells may need to be drilled for improved coverage in areas with data gaps. In the NCB, the emphasis is on areas where prospective UGEE activity has been flagged – Kilcoo Cross, Arigna/Drumkeeran and Dowra. New wells in the CB would be located towards the central and south-eastern part of the UGEE licence area, with final recommendations to be provided pending final verification of existing wells. Two wells is an estimated number of new wells to be drilled in the CB.

[c]Primarily large karst springs of sub-regional significance, although not used for water supply.

[d]Groundwater dependent habitats within SACs in the NCB. Two clusters of 3 petrifying springs in each cluster are proposed for monitoring to establish baseline water quality associated with these habitats.

[e]Locations not shown on figures as final locations are pending field verification of suitable sites.

The overall scope and extent of monitoring would be considerably greater in the NCB than in the CB. This partly reflects the much larger UGEE licence area of the NCB compared to the CB, but also the relative inferred complexity of the NCB with regard to its hydrogeology and range of potential receptors that have been identified. The recommended monitoring would include:

- Groundwater sampling of existing public and private supply wells, springs and potential new monitoring wells;

- Surface water sampling of lakes and streams, including designated protected areas under the WFD;
- One-time sampling and analysis of stream sediments; and
- Hydrometric monitoring of groundwater levels, spring discharges and stream flows where particular data gaps exist, mostly in the NCB.

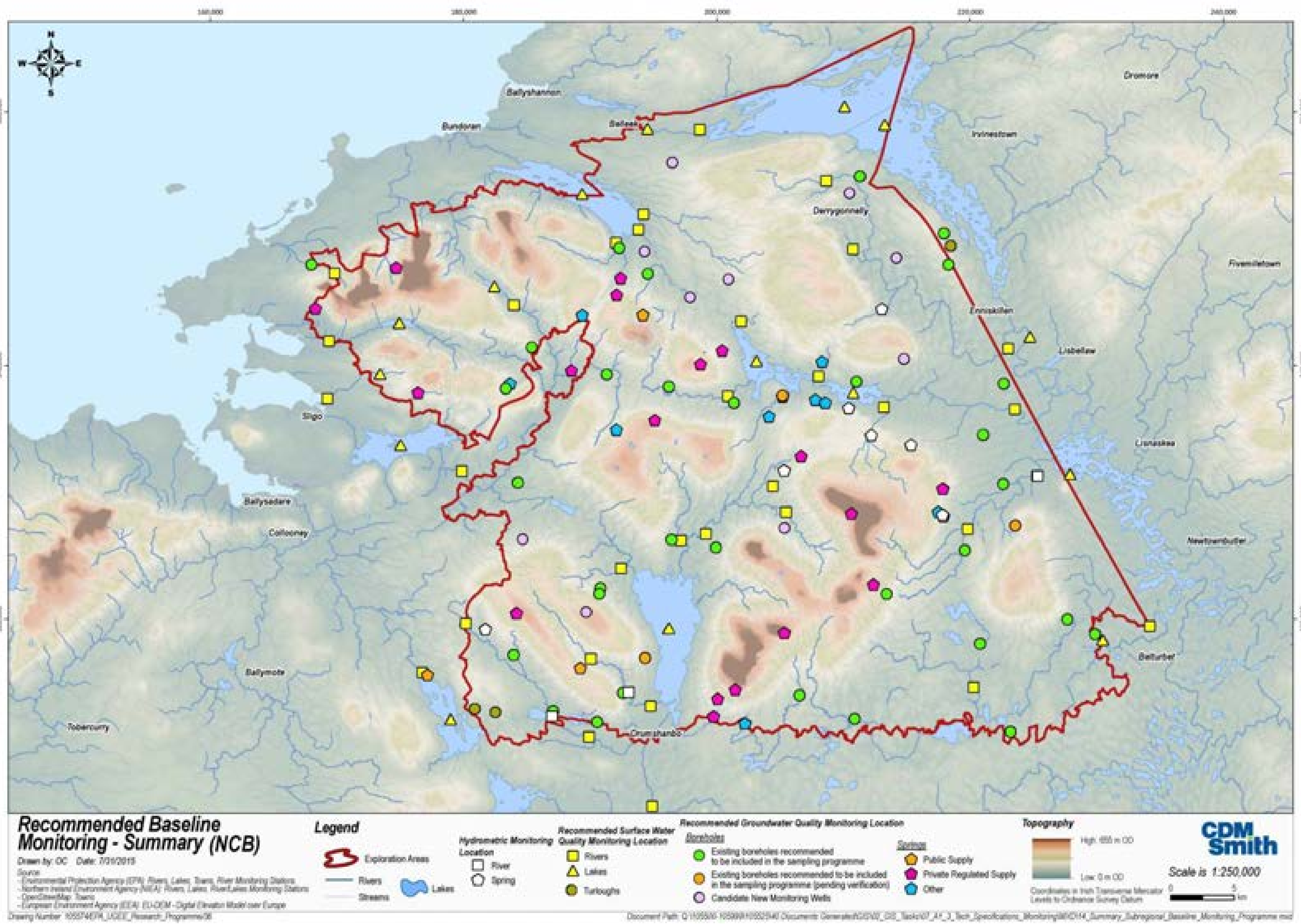


Figure ES6. Overview of recommended monitoring stations for groundwater and surface water – NCB study area.

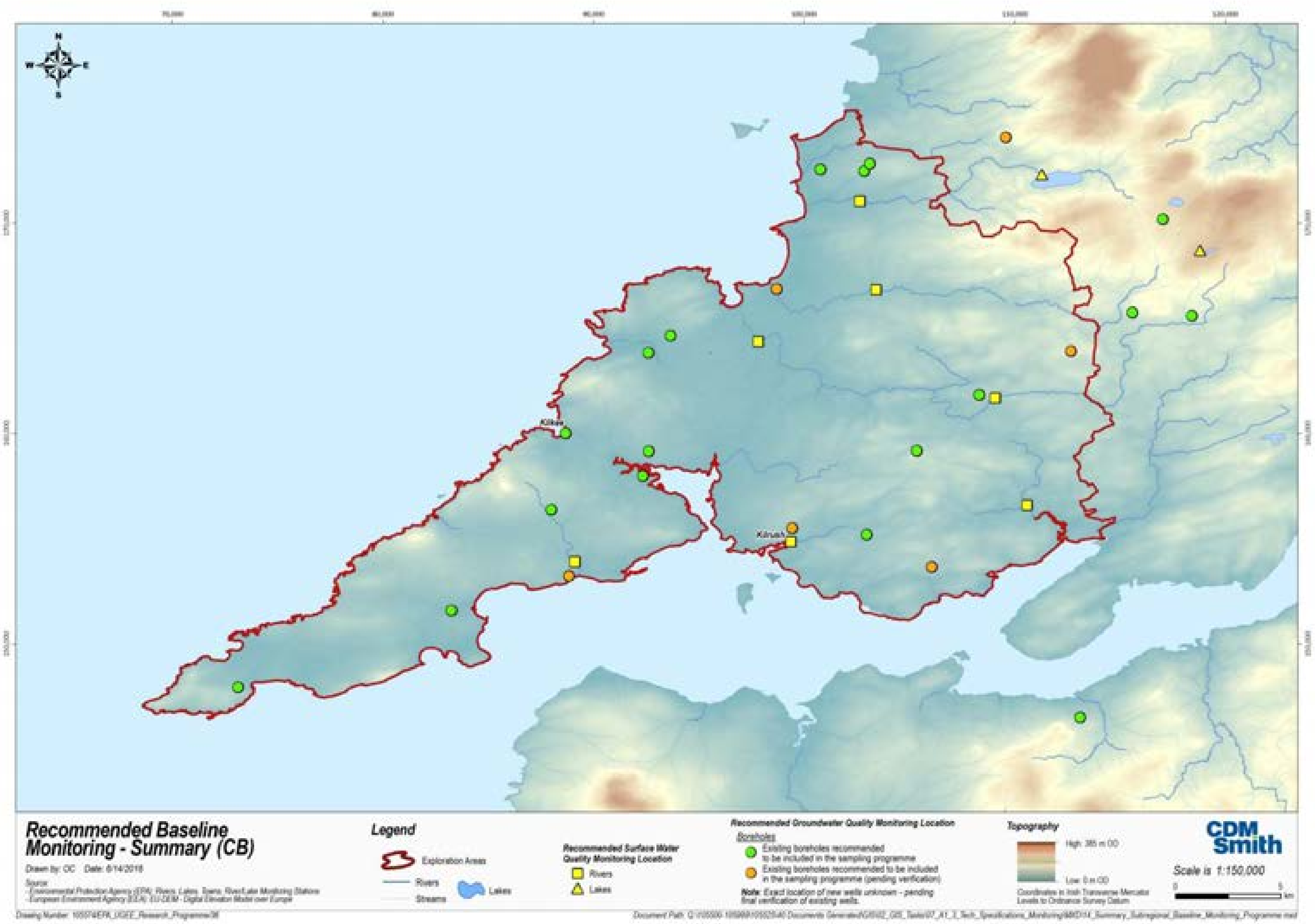


Figure ES7. Overview of recommended monitoring stations for groundwater and surface water – CB study area.

In addition, a small number of designated groundwater dependent habitats would be recommended for water quality monitoring in the NCB, as follows:

- Roosky-Fardrum Turlough;
- Loughs Augh and White (both turloughs); and
- A group of 3 petrifying springs with tufa formations in the West Fermanagh Scarplands SAC, to be selected pending field verification.

Turloughs, petrifying springs with tufa formation, and calcareous fens are significantly groundwater dependent and should be retained as appropriate candidates for sub-regional baseline monitoring purposes in the future. However, establishing representative baseline monitoring programmes for such environments is challenging since the majority of habitats are geographically widespread but occur as individual entities which are often disconnected from one another.

The environmental supporting conditions of groundwater dependent habitats are inherently site-specific, and baseline monitoring at a given site (habitat) would only provide indications of the conditions that apply to that site. Thus, to select appropriate sites, prior study involving site investigation and monitoring would be required, i.e. to identify and select suitable sites for longer-term baseline monitoring purposes. Such work would require an extended period of time (seasons).

Given the widespread distribution of individual sites, and the site-specific nature of individual sites, it is argued that prior study and baseline monitoring of GWDTEs should be conducted at a more localised scale if or when details about future planned UGEE activities become known. Such monitoring should in all cases be considered when scoping, planning and assessing future UGEE activity at specified locations, as the GWDTEs/habitats are ecologically significant and many are located within SACs. The onus of prior study and monitoring should be placed on the UGEE developer with appropriate review and supervision by regulatory bodies.

Sampling and Analysis of Water Quality

The list of recommended parameters for groundwater and surface water analyses is substantial, see Table ES2. It includes general physico-chemical parameters, nutrients, major ions, metals, trace elements and trace organics. It also includes descriptors of carbon sources and other parameters that would be rare or non-detectable in the natural settings of the case study areas and thus distinguishable from other environmental pressures that may be present. These can be used for chemical fingerprinting purposes, and such parameters include stable isotopes, radioisotopes and chemicals that are commonly associated with flowback waters (e.g. barium, bromide, strontium).

Groundwater would also be analysed for natural gas constituents, including methane. If present above screening criteria, further analysis of stable isotopes would be conducted to establish the origin of the methane (thermogenic or biogenic). Sampling and analyses would mostly be carried out on a quarterly basis.

Table ES2. List of recommended parameters for analysis of groundwater and surface water

Parameter	Groundwater	Surface water	Frequency
Dissolved natural gas components			
Dissolved methane	✓	×	Quarterly
Dissolved CO_2	✓	×	Quarterly
Hydrocarbon gases (C2 to C5)	✓	×	Quarterly

Parameter	Groundwater	Surface water	Frequency
Nutrients and general chemistry			
Ammonia	✓	✓	Quarterly
Ammonium	✓	✓	Quarterly
Nitrite as N	✓	✓	Quarterly
Nitrate as N	✓	✓	Quarterly
Orthophosphate as P	✓	✓	Quarterly
Total Phosphorus	✓	✓	Quarterly
Total Organic Carbon	✓	✓	Quarterly
Total Dissolved Solids	✓	✓	Quarterly
Total Suspended Solids	×	✓	Quarterly
Major ions			
Alkalinity	✓	✓	Quarterly
Chloride	✓	✓	Quarterly
Fluoride	✓	✓	Quarterly
Sulphate	✓	✓	Quarterly
Sodium	✓	✓	Quarterly
Potassium	✓	✓	Quarterly
Magnesium	✓	✓	Quarterly
Calcium	✓	✓	Quarterly
Iron	✓	✓	Quarterly
Manganese	✓	✓	Quarterly
Boron	✓	✓	Quarterly
Trace elements			
Aluminium	✓	✓	Quarterly
Chromium	✓	✓	Quarterly
Nickel	✓	✓	Quarterly
Copper	✓	✓	Quarterly
Zinc	✓	✓	Quarterly
Arsenic	✓	✓	Quarterly
Cadmium	✓	✓	Quarterly
Antimony	✓	✓	Quarterly
Barium	✓	✓	Quarterly
Lead	✓	✓	Quarterly
Uranium	✓	✓	Quarterly
Mercury	✓	✓	Quarterly
Cobalt	✓	✓	Quarterly
Molybdenum	✓	✓	Quarterly
Strontium	✓	✓	Quarterly
Silver	✓	✓	Quarterly
Beryllium	✓	✓	Quarterly
Bromide	✓	✓	Quarterly
Vanadium	✓	✓	Quarterly
Descriptors of carbon sources			
Dissolved organic carbon (DOC)	✓	✓	Quarterly
Dissolved inorganic carbon (DIC)	✓	✓	Quarterly
Trace organics			
Polyaromatic hydrocarbon (PAH) – full suite	✓	✓	Semi-annually (including low flow conditions)
Volatile Organic Compounds (VOCs) – full suite	✓	✓	Semi-annually (including low flow conditions)

Parameter	Groundwater	Surface water	Frequency
Stable isotopes in dissolved methane			
Hydrogen (δD)	✓	×	Quarterly (if methane detected)
Carbon ($\delta^{13}C$)	✓	×	Quarterly (if methane detected)
Oxygen ($\delta^{18}O$)	✓	×	Quarterly (if methane detected)
Naturally occurring radioactive materials (NORM)			
Gross alpha/beta	✓	✓	Quarterly
Ra-226/Ra-228	✓	✓	Quarterly (if a gross alpha/beta threshold exceeded)
Rn-222	✓	✓	Quarterly (if a gross alpha/beta threshold exceeded)

Natural gas constituents, including methane, would not be analysed for in surface water, due to the expectation that dissolved gases would be 'lost' to degassing upon exposure to the atmosphere. The US Geological Survey has carried out research on stream-based methane monitoring to identify and quantify groundwater-based methane discharging to a stream in an unconventional gas development area. The method of study (Heilweil *et al.*, 2015) is less suited for baseline monitoring at the sub-regional scale, requiring site-specific study and detailed monitoring of related groundwater-surface water interaction systems. The method has, however, value at the local (sub-catchment) scale for monitoring of location-specific UGEE activity, and should be considered when establishing terms and conditions of case-specific monitoring with UGEE developers, at and near individual UGEE sites.

Sampling and Analysis of Stream Sediments

Sampling of stream sediments would be recommended to conduct gross alpha and gross beta screening, and to conduct further analysis of radium isotopes if relevant screening thresholds are exceeded. Although this would be a one-time characterisation effort, it is considered important because radium isotopes are the principal UGEE-related contaminants of concern in sediments and radium data from stream sediments are not yet available in either of the two study areas. Recommended sample locations have not yet been defined, requiring prior field verification to locate low-energy environments where sediments accumulate. In the NCB, this should be coordinated as much as possible with sample locations from the existing Tellus Border[3] datasets of other NORM and metals.

Hydrometric Monitoring

Data gaps in existing hydrometric monitoring networks have been identified, and additional monitoring for sub-regional monitoring purposes is recommended to record the hydraulic characteristics of springs and streams whose hydraulic responses to meteorological conditions remain poorly quantified. Permanent new monitoring infrastructure is not proposed, rather monitoring would be conducted with temporary installations of staff gauges, transducers/data loggers, and taking manual spot measurements. Manual spot measurements would be periodically carried out to develop rating curves, where the ultimate objective would be to document seasonal and/or storm-related high and low flow conditions, as well as discharge recession characteristics.

Due to the very large number of springs present, it would not be possible to measure all. Priorities would be given to springs that are used for public and private regulated water supply, especially karst springs. Transducers would record water level, pH, temperature and electrical conductivity to allow for estimation of time-lags of water pulses moving through karstified flow systems. Specific streams

3 See www.tellusborder.eu and www.tellus.ie

that would be monitored in a similar manner are on the Swanlinbar, Arigna, and Feorish River catchments.

Up to 20 wells would be similarly monitored with installed transducers in the NCB and up to 10 wells would be monitored in the CB. The purpose would be to document natural fluctuations and longer-term responses to changes hydrometeorological conditions.

In both study areas, lake water levels are actively monitored with automatic recorders in all of the major lakes which are used for water supply purposes. Monitoring of the smaller lakes is not considered important in the sub-regional context, but could become important in the local-scale context if future UGEE activity would target such lakes for water supply.

Monitoring for Impact from UGEE-related Abstractions

UGEE operations require water, and the highest water demands would occur during the hydraulic fracturing programmes at individual wells. Hydrometric monitoring of potential impact from UGEE-related abstractions would have to be considered on a case- and site-specific basis in the future should UGEE licensing proceed. Details of monitoring requirements can only be defined or recommended once proposed UGEE plans are presented. It is expected that UGEE companies would try to source water locally and to implement appropriate measures to reduce overall demands.

Available water resources are represented by rainwater, lakes and reservoirs, streams and rivers, and groundwater in bedrock aquifers. There is capacity to supply water use requirements of potential future UGEE development in both study areas, but this would ultimately be conditioned and influenced by *how* and *where* the development would proceed. Local supply options are considerably wider in the NCB compared to the CB study area. It would still be important to define and address the timing, duration and locations of total water demands as part of a licensing review process, involving suitably qualified hydrologists and aquatic ecologists.

Capacity would have to be judged by actual total demand, with a clear understanding of timelines of total demands. For the peak 'probable commercial' build-out scenarios defined in *Final Report 4: Impacts and Mitigation Measures* of the UGEE JRP (CDM Smith, 2016), the total potential demand is driven by how many wells are hydraulically fractured in the same time period. Water demands would likely have to be supplied from multiple sources in parallel, and for this reason, future UGEE-related abstraction plans would have to be carefully defined to understand the timeline of total demands, individually and cumulatively, with the involvement of relevant stakeholders and regulatory bodies.

Risks of *volumetric* impacts would be lower in large lakes and streams, and greater in small lakes and streams. Identifying and documenting volumetric impact is relevant in a regulatory context, but ultimately, impact from abstractions are more appropriately described by changes to *ecological* reference conditions (e.g. macroinvertebrates, hydromorphology and physico-chemical quality). In the process of licensing or granting prior authorisation of future UGEE-related abstractions, environmental reference conditions would have to be identified on a case by case basis, using site- and case-specific inputs (e.g. flow data and ecological datasets), and requiring technical judgement by specialists in related fields. The distinction between "small" and "large" abstractions is relative, depending on source, and impact assessment should be based on consideration of aquatic ecology from lines of evidence.

Existing abstraction pressures are currently considered to be low in both case study areas. Future UGEE-related abstractions would have to be considered in regards to the requirements of existing statutory instruments and efforts by the EPA and NIEA to maintain "good quantitative" and "good ecological" status of water bodies. Reductions in water level and streamflows due to abstractions would reduce the dilution potential, thereby impacting the ecological and chemical status of a related water body. As UGEE activity is rarely confined to single locations, abstractions could have a cumulative impact which would need to be addressed by appropriate monitoring.

Addressing Deep Geological and Hydrogeological Data Gaps

Specific gaps in the hydrogeological knowledge of the two study areas relate principally to potential deep groundwater flow, deep water quality, and potential hydraulic connectivity between unconventional gas target formations and shallow receptors. There are indications of water strikes to several hundred metres depth in both basins as well as the presence of variably saline formation waters in the deeper buried formations in the NCB. This may be indicative of fracture permeability and/or porosity at depth, thus a theoretical ability of deeper formations to both store and transmit groundwater, even if on a limited scale. Although such deeper saline formation waters may not be usable as a resource, their presence and characteristics could influence potential hydraulic fracturing operations, particularly with regard to the quantity and quality of flowback and production waters at the surface. Deep hydrogeological characteristics would also influence the risk of vertical migration of contaminants from hydraulic fracturing operations, especially natural gas constituents (e.g. methane). Detailed hydrogeological characterisation of deeper formations is, therefore, recommended in the future.

Key technical questions about deep water resources and hydrogeological characteristics can only be addressed by a combination of surface geophysical surveys (e.g. fault identification), drilling, borehole geophysical logging and hydraulic testing, sampling and monitoring of deep wells. Such work would be targeted in both the unconventional gas target formations and the intervening formations that separate these from shallow receptors (e.g. the Benbulben Shale formation in the NCB). The resulting boreholes could subsequently be converted and used as "*sentinel wells*" or 'warning wells' to provide information on groundwater levels and quality. Thus, their locations and positions would have to be planned carefully to have geographic relevance to any future UGEE sites. The data generated from such deep investigative work would benefit both the characterisation of existing water resources and the assessment of environmental risk associated with hydraulic fracturing.

With the objectives of the UGEE JRP in mind, a distinction is made between recommendations for receptor-focused baseline monitoring at the sub-regional scale and recommendations for improved geological/hydrogeological characterisation. It is argued that because UGEE activity is case- and location-specific, improved characterisation work of deeper hydrogeological conditions should be carried out where UGEE activity is most likely to be targeted or planned. A broader, sub-regional approach to characterisation would provide valuable data, but findings at one location can always be questioned or challenged in the context of another location, and a sub-regional approach would not necessarily produce the answers that are needed at the location-specific scale of an individual hydraulic fracturing site.

For this reason, the onus for location-specific characterisation would be on the UGEE companies, under terms of legislation and conditions set by regulators. The same applies for siting of well pads and the monitoring of day-to-day activities if or when future UGEE activity takes place.

1 Introduction

Unconventional Gas Exploration & Extraction (UGEE) involves hydraulic fracturing (fracking) of low permeability rock to permit the extraction of natural gas on a commercial scale from unconventional sources, such as shale gas deposits, coal seams and tight sandstone. The Environmental Protection Agency (EPA), the Department of Communications, Energy and Natural Resources (DCENR) and the Northern Ireland Environment Agency (NIEA) awarded a contract in August 2014 to a consortium led by CDM Smith Ireland Limited to carry out a 24-month research programme looking at the potential impacts on the environment and human health from UGEE projects and operations (including construction, operation and after-care).

The UGEE Joint Research Programme (JRP)[4] is composed of five interlinked projects which address the key topics of water, air and seismicity. The research work has involved extensive desk-based literature reviews of UGEE practices and regulations worldwide, as well as field surveys in two case study areas – the Northwest Carboniferous and Clare Shale Basins.

The UGEE JRP has been designed to produce the scientific basis, which will assist regulators – both North and South – in making an informed decision about whether it is environmentally safe to allow fracking. The environmental impacts of UGEE projects/operations to be considered are those arising from UGEE projects/operations in their totality, not just from fracking activities. All stages of UGEE projects/operations must be considered (i.e. including construction, commissioning, operation, decommissioning and aftercare, as well as off-site and other developments).

1.1 Context

In Ireland, Onshore Petroleum Licensing Options were awarded in March 2011, as preliminary authorisations, to three exploration companies seeking to assess the unconventional gas potential within the Northwest Carboniferous Basin (NCB) and the Clare Basin (CB). In Northern Ireland, one exploration company secured a Petroleum Licence from the Department of Enterprise, Trade and Investment (DETI) to explore the potential for unconventional gas reserves in Co. Fermanagh, within the NCB. The specific UGEE exploration areas are shown in Figure 1.1, based on the licences that were held until recently.

In Ireland, exploration drilling, including drilling that would involve hydraulic fracturing, is not allowed under current Licensing Options. Nonetheless, two of the three companies have submitted applications for follow-on licences, which would include exploration drilling. The DCENR is not considering these applications further until the findings of this UGEE Joint Research Programme have been published. Also, the DCENR will not consider any applications for exploration authorisations in other onshore areas until the UGEE Research Programme has concluded. In Northern Ireland, the referenced DETI licence was terminated as the licence conditions (a 'drill or drop' work programme requiring specified exploration, including drilling a stratigraphic borehole, in the first three years and, before the end of Year Three, a commitment to drilling an exploration well within the following two years) were not met.

4 www.ugeeresearch.ie

Figure 1.1. Overview of the case study areas of the UGEE JRP

In May 2012, the Environmental Protection Agency (EPA) released the report from a preliminary study "Hydraulic Fracturing or 'Fracking': A Short Summary of Current Knowledge and Potential Environmental Impacts"[5]. This short desk study was conducted for the EPA by the University of Aberdeen and provided an introduction to the environmental aspects of UGEE projects/operations including a review of regulatory approaches used in other countries and areas for further investigation and research. In brief, the study highlighted:

- The importance of adequate knowledge of local geology in order to assess potential impacts on groundwater quality and the possibility of induced seismic activity;
- The importance of well integrity for preventing groundwater contamination;
- The uncertainty regarding the "carbon footprint" of unconventional gas in comparison to conventional natural gas. This is an important climate change issue;

5 http://www.epa.ie/pubs/reports/research/sss/epa-strivesmallscalestudyreport.html

- Baseline studies are needed before drilling begins (surface water; groundwater; seismic); and
- UGEE is a relatively new area of research (i.e. only a limited number of published, peer-reviewed, scientific studies are available in this area).

The information provided by the preliminary research project was used along with other sources, such as European Commission reports[6], to develop the Terms of Reference for a more comprehensive Research Programme. Between the 11th January and 8th March 2013, the EPA administered a Public Consultation[7] in relation to the draft Terms of Reference[8] for this Research Programme. Submissions[9] were assessed and relevant comments taken into account when finalising the document.

In order to assist government bodies in making informed decisions about any potential future licensing and management of UGEE projects/operations on the island of Ireland, comprehensive knowledge of the potential impacts of this process on the environment and human health is required. This knowledge will be generated from a number of sources, including EU and international research, and through this programme of research.

The key questions to be addressed by the UGEE JRP are:

1. Can UGEE projects/operations be carried out in the island of Ireland whilst also protecting the environment and human health?
2. What is 'best environmental practice' in relation to UGEE projects/operations?

1.2 Overview of the UGEE Joint Research Programme

The UGEE Joint Research Programme (JRP)[10] is composed of five interlinked projects:

Baseline Characterisation:

- Project-A1 (Groundwater, Surface Water and Associated Ecosystems) (http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee research/ugeeresearchprogramme/projecta1/)
- Project-A2 (Seismicity) (http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee research/ugeeresearchprogramme/projecta2/)
- Project-A3 (Air Quality) (http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee research/ugeeresearchprogramme/projecta3/)

Impacts & Mitigation Measures:

- Project-B: UGEE Projects/Operations: Impacts & Mitigation Measures http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee research/ugeeresearchprogramme/projectb/

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6 http://ec.europa.eu/energy/studies/energy_en.htm

7 http://www.epa.ie/newsandevents/news/2013/name,51286,en.html

8 http://www.epa.ie/pubs/reports/research/ugeejointresearchprogramme/ugeeresearchrevisedtermsofreference.html

9 http://erc.epa.ie/public_consultation/

10 www.ugeeresearch.ie

Regulatory Framework:

- Project-C: Regulatory Framework for Environmental Protection http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee research/ugeeresearchprogramme/projectc/

Project A1 (Groundwater, Surface Water and Associated Ecosystems) involved the characterisation of two case study areas to examine environmental risk factors associated with hydraulic fracturing and to prepare specifications for *baseline monitoring* of groundwater, surface water and associated ecosystems.

Project A2 (Seismicity) dealt with the baseline characterisation of seismicity, which is required to enable potential impacts to be assessed.

Project A3 (Air Quality) dealt with the requirements and needs for additional air baseline monitoring (frequency, location and types of pollutants to be covered) in the context of Environmental Impact Statements (EIS) in particular.

Project B (UGEE Projects/Operations: Impacts & Mitigation Measures) covered the identification and detailed examination of potential impacts on the environment and human health, as well as appropriate mitigation measures to counteract these impacts, associated with UGEE projects/operations that have come to the fore worldwide using published reports and other sources. Project B also involved a comprehensive assessment of potential, cumulative environmental impacts of "commercially probable scenarios" of UGEE projects/operations.

Project C (Regulatory Framework for Environmental Protection) was aimed at identifying all regulatory requirements, including gaps in existing regulations and best operational practices associated with the establishment and operation of UGEE projects/operations in an island of Ireland context. Project C was designed to assist regulators (both North and South) in fulfilling their statutory roles regarding UGEE.

The UGEE JRP is funded by the EPA, DCENR and NIEA. It is managed by a steering committee comprising the EPA, the Department of Environment, Community & Local Government; DCENR; the Geological Survey of Ireland; Commission for Energy Regulation; An Bord Pleanála; NIEA, the Geological Survey of Northern Ireland and the Health Services Executive.

1.3 Project A1: Groundwater, Surface Water and Associated Ecosystems

Summarised by its scope in Figure 1.2, Project A1, which is the subject of the current report, has two principal components of study:

- *Characterisation* of the two case study areas to help understand the 3–dimensional relationship between potential sources of contamination and the near-surface environment; and
- *Baseline monitoring* of groundwater, surface water and associated ecosystems, informed by the results of the characterisation, including conceptual hydrogeological models.

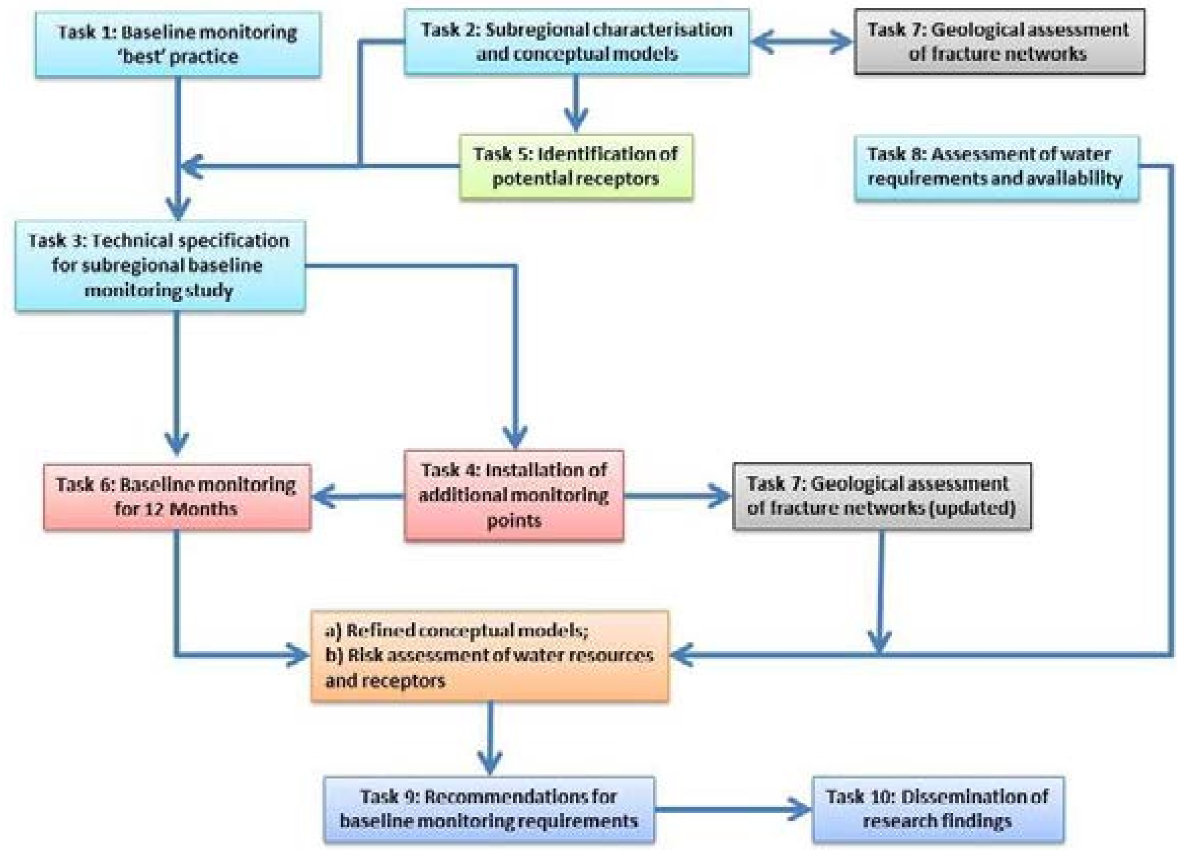


Figure 1.2. Tasks of Project A1 of the UGEE Joint Research Programme.

The research of Project A1 is guided by the source-pathway-receptor (S-P-R) model of environmental risk assessment which has served as the basis for most other water resources and environmental protection programmes on the island of Ireland, notably the river basin district projects led by EPA and NIEA, as well as the groundwater source protection work led by the EPA and GSI in Ireland. These efforts are supported by statutory instruments which were enacted in connection with the EU Water Framework Directive (WFD).

Requirements for baseline monitoring are embodied in the European Parliament resolution on the "Environmental impacts of shale gas and shale oil extraction activities" (2011/2308(INI)). Thus, baseline monitoring would be required should UGEE-related activity plans become known or proceed in the future. For this reason, the TOR and scope of work for the UGEE JRP included the design and specification of potential baseline monitoring programmes for water, as well as air and the analysis of seismic activity.

The original timeline for the research envisaged that the entire programme, including water, air and seismic baseline acquisition, would conclude by 2016. Following a comprehensive assessment of the two case study areas, the Steering Committee has considered that were the baseline acquisition to commence, the estimated timeline for the overall research programme to report would now be in 2018 at the earliest. Consequently, baseline monitoring programmes would result in the overall findings of the research being delivered after the project deadline of 2016. The decision was therefore taken to prepare a synthesis report drawing together the conclusions of the research to date in order that these findings could be reviewed and policy decisions formulated with regard to the use of this technology in Ireland.

It is noted that the baseline monitoring programmes proposed by the JRP remain valid and such programmes should be implemented in advance of any application for a UGEE licence. It should be noted that such baseline monitoring programmes should provide independent information on water, air and seismic activity and is therefore different from any baseline characterisation and monitoring that would be required of UGEE operators as part of a licensing process, which would be case- and site-specific, and would be designed to monitor specific receptors.

1.4 Objectives and Goals

To contribute towards addressing the two key research questions which were presented in Section 1.1, Project A1 has the following principal *objectives*:

- To describe the sub-regional scale geology and hydrogeology of the case study areas;
- To define available water resources in each case study area;
- To develop conceptual hydrogeological models which would guide the design of a baseline monitoring network that is representative of known or inferred pathways of water movement (thus also potential contaminant migration);
- To summarise existing environmental pressures and monitoring activity in the case study areas;
- To summarise baseline monitoring 'best practice' associated with UGEE activity, from international literature;
- To clarify and summarise the main receptors of potential UGEE-related contamination which would be specific to the two case study areas;
- To highlight inferred data and information gaps which would require future characterisation work;
- To provide recommendations for sub-regional baseline monitoring for each of the two case study areas; and
- To document and justify the recommended baseline monitoring programme for groundwater, surface water and aquatic ecosystems.

The main *goals* of Project A1 are:

- To describe the data that should be developed in order to be able to identify potential future impact from UGEE activity by distinguishing UGEE-related contamination from other environmental pressures that are already present in the case study areas, at the sub-regional scale;
- To highlight geological structures and hydrogeological controls on groundwater and surface water flow, and risk of impact on associated aquatic ecosystems (receptors);
- To clarify relevant and suitable monitoring approaches, guided by conceptual hydrogeological models;
- To flag potential investment needs in new monitoring infrastructure; and
- To inform and assist the decision making future regarding baseline monitoring implementation.

Accordingly, Project A1 provides guidance towards decision making about future baseline monitoring, in respect of what should be sampled and analysed for, where samples should be collected, and how monitoring should be carried out (groundwater, surface water, aquatic ecosystems). This report would, therefore, serve to assist the UGEE JRP Steering Committee in piloting a coordinated and integrated sub-regional baseline monitoring programme in both Ireland and Northern Ireland.

1.5 Organisation of Report

This report is organised according to the two principal components of Project A1 that were referenced in Section 1.3:

- A physical, hydrogeological and environmental *characterisation* of the two case study areas;
- A description of *baseline monitoring* requirements, international best practice and recommendations for sub-regional baseline monitoring of groundwater, surface water and aquatic ecosystems in each of the two case study areas.

1.6 Methodology

The preparation of this report has involved literature review and field surveys. The literature review was comprehensive, from which relevant information was collated on a wide range of UGEE-related scientific topics. Materials researched included; peer-reviewed academic and professional journals; peer-reviewed research publications; university theses; scientific guidance by national and regional panels and/or public bodies; consultancy reports; opinions and summaries by professional organisations; and publically available presentations and papers by the UGEE industry. Much of the information that was used originates from countries where UGEE has taken place or is planned, with an emphasis on lessons-learned documentation.

Field surveys were carried out to become familiar with the details of each study area, with regard to geomorphology, geology, hydrogeology, land uses, existing environmental pressures and designated protected areas. Field surveys were also carried out to identify and verify existing groundwater abstraction points and to ground-truth potential future baseline sampling locations or monitoring stations. Furthermore, the project team, visited and participated in baseline monitoring of groundwater for methane in England, hosted by the British Geological Survey.

1.7 Data and Information Sources

The preparation of this report also involved the extensive use of data and reference materials that were sourced from publically available resources in Ireland and Northern Ireland, notably:

- Environmental Protection Agency;
- Northern Ireland Environment Agency;
- Geological Survey of Ireland;
- Geological Survey of Northern Ireland;
- Petroleum Affairs Division of the Department of Communications, Energy and Natural Resources;
- Department of Enterprise, Trade and Investment;
- Ordnance Survey of Ireland;
- British Geological Survey;
- National Parks and Wildlife Services;
- Ordnance Survey of Ireland;
- Office of Public Works;

- Rivers Agency;
- Local authorities; and
- Waterways Ireland.

Source materials used are referenced throughout this report, and a reference bibliography is included in Section 15.

1.7.1 Notes on geological maps

Geological maps used for the sub-regional characterisation of the NCB and CB study areas are summarised in Table 1.1.

Table 1.1. Bedrock maps used in sub-regional characterisation

Survey	Published	Scale	Geographical coverage
Northwest Carboniferous Basin			
GSI	2015	1:500,000	Ireland
GSNI	1997	1:250,000	North of Ireland
MacDermot *et al*.	1996	1:100,000	Sligo-Leitrim
GSNI	1994	1:50,000	Kesh
GSNI	1991	1:50,000	Derrygonnelly and Marble Arch
GSNI	1982	1:50,000	Enniskillen
GSNI	2005	1:50,000	Lisnaskea
Clare Basin			
Sleeman and Pracht	1999	1:100,000	Shannon Estuary

These are accompanied by map explanations, memoirs and regional guides. Key reference documents used are summarised in Table 1.2. In Ireland, the geological maps are supplemented by recent mapping of Quaternary geology (GSI, 2015) and subsoils (Fealy *et al.*, 2009).

Table 1.2. Geological regional guides, map explanations and memoirs

Authorship	Year	Title	Related map coverage (see Table 1.1)
Northwest Carboniferous Basin			
Waters	2011	A Revised Correlation of the Carboniferous Rocks in the British Isles	N/A
Mitchell	2004a	The Geology of Northern Ireland	GSNI, 1997
Legg *et al*.	1998	Geology of the country around Derrygonnelly and Marble Arch	GSNI, 1991
MacDermot *et al*.	1996	A geological description of Sligo, Leitrim and adjoining parts of Cavan, Fermanagh, Mayo and Roscommon	MacDermot *et al*., 1996
Clare Basin			
Sleeman and Pracht	1999	A geological description of the Shannon Estuary region including parts of Clare, Limerick and Kerry	Sleeman *et al*., 1999

1.7.2 Notes on hydrocarbon exploration files

The hydrocarbon exploration files that have been reviewed were sourced from the PAD of the DCENR and from the GSNI. The PAD files were made available under terms and conditions of a signed data access agreement between CDM Smith and the DCENR. The documents consist of well completion reports and specific study and interpretative reports prepared by, or produced for, the exploration companies.

Since the early 1960s, 15 gas exploration wells have been drilled and tested within the NCB study area (nine in Co. Fermanagh, and six in Cos. Cavan and Leitrim). In comparison, three gas exploration wells were drilled and tested in Co. Clare, with two of them being located in or near the CB study area. The wells are summarised in Table 1.3 and their locations shown in Figure 1.3. The dates of drilling are important as they determine whether or not the geological findings were included in geological map and cross-section compilations by the GSI and GSNI. For example, findings from Big Dog (1965), Kilcoo Cross (1985/86) and Slisgarrow-1 (1984) were incorporated into the Derrygonnelly and Marble Arch geological map and cross section (GSNI, 1991), whereas Knock Beg, Mullanawinna and Slisgarrow-2 were drilled in 2001, i.e. after the publication of the same sheet.

In addition to the mapping and well data, the gas exploration companies have undertaken seismic surveys. For the purposes of this current report, relevant datasets are referenced in the context of geological interpretations published by respective exploration companies. Gravimetric survey results are also available from the available exploration documents (ERA, 1986). A further source of geophysical data is the Tellus Border project, an EU-funded cross-border geo-environmental mapping project led by the GSI, GSNI, Queen's University Belfast (QUB) and Dundalk Institute of Technology (DkIT). This project built upon an earlier similar initiative in Northern Ireland and included aerial surveys (measurements) of magnetic fields, radiometrics and electrical conductivity in the Ireland/Northern Ireland border region. Outcomes from the surveys are referenced as appropriate throughout this report.

Table 1.3. Summary of existing deep gas exploration wells

Study area	County	Well	Year Drilled	X	Y	Total drilled depth (m)	Formation span (spudded/total depth)
CB	Clare	Doonbeg-1	1962/1963	96332	163670	3266	Gull Island/ Ringmoylan Shale
		IPP-1	1980	109674	171260	1210	Central Clare Group (unspecified)/ Undifferentiated Visèan Limestone
		IPP-2	1980	115844	175317	917	Central Clare Group (unspecified)/ Undifferentiated Visèan Limestone
NCB	Cavan	Dowra-1	1962	206505	326932	1830	Meenymore Sandstone/ Old Red Sandstone
		Dowra-2y	2001	206436	326991	1342	Meenymore/Ballyshannon
		Macnean-1	1963	206253	337124	1651	Dartry/Old Red Sandstone
		Macnean-2	1984	206905	337539	1514	Dartry/Old Red Sandstone
	Fermanagh	Big Dog	1965	201865	349672	2002	Dartry/Basal Clastics
		Glenoo	1965/1966	249620	341420	2106	Dartry/Old Red Sandstone
		Kilcoo Cross	1985	196950	348100	1910	Dartry/Moinian Quartzite
		Knock Beg No. 1	2001	206258	348955	909	Glenade Sandstone/ Bundoran Shale
		Mullanawinna No. 1	2001	203350	342220	986	Glenade Sandstone/ Bundoran Shale
		Owengarr	1965	223205	326935	2041	Dartry/Old Red Sandstone
		Slisgarrow No. 1	1984	202500	351800	1999	Meenymore/Basal Clastics
		Slisgarrow No. 2	2001	202567	351853	816	Meenymore/Bundoran Shale
		Wind Farm No. 1	2001	224538	325160	1352	Glenade Sandstone/ Bundoran Shale
	Leitrim	Drumkeeran-1	1984	189249	319147	2510	Dergvone Shale/ Old Red Sandstone
		Thur Mountain-1	2001/2002	200333	341726	1431	Glenade Sandstone/Ballyshannon Limestone

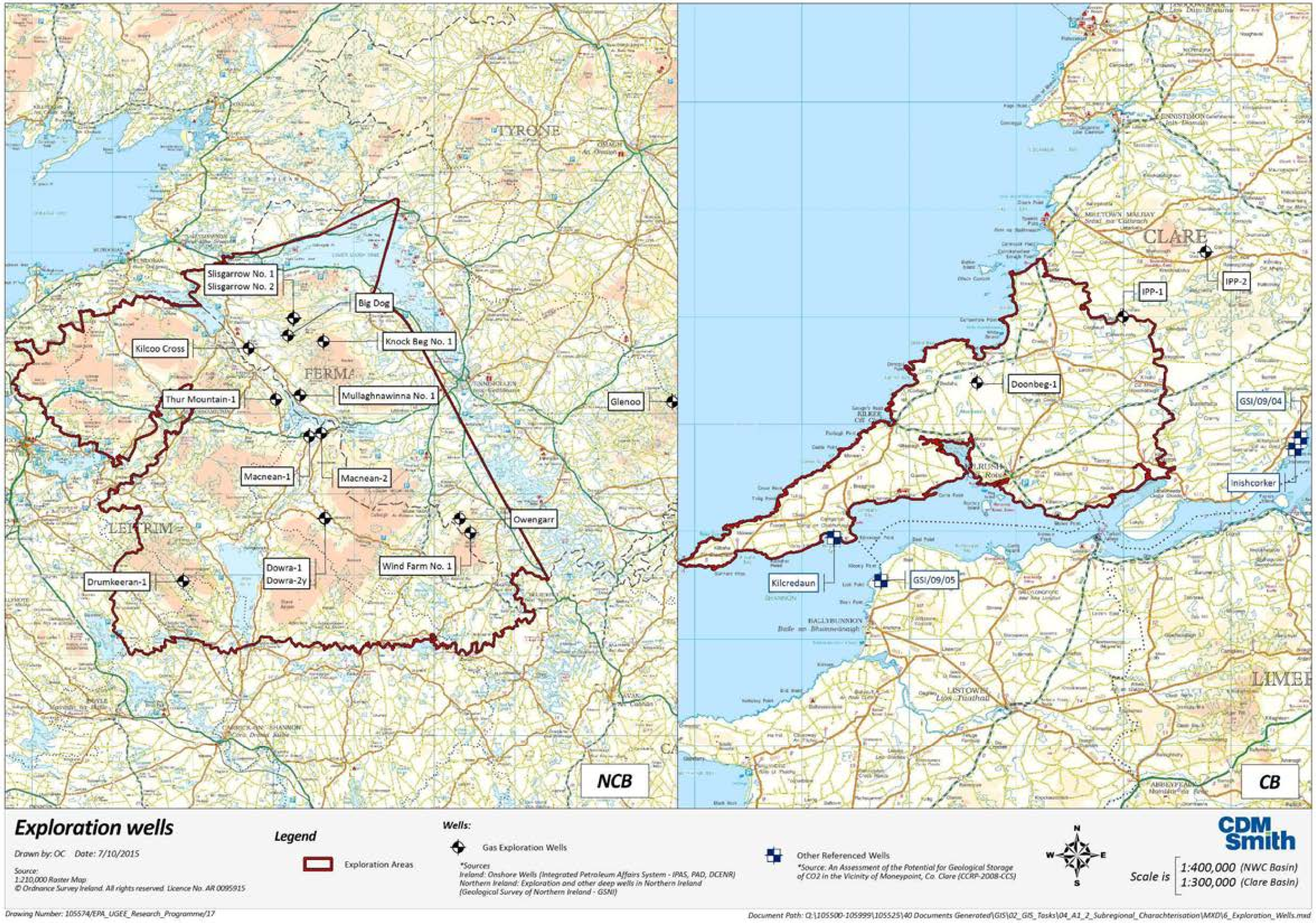


Figure 1.3. Existing deep gas exploration wells in the UGEE study areas.

2 Northwest Carboniferous Basin

2.1 Physiography

The physiography of the Northwest Carboniferous Basin (NCB) study area is defined by distinct upland and lowland regions as indicated by the topographic map in Figure 2.1. Upland regions (above *c.* 150 metres Ordnance Datum, mOD) include:

- The Truskmore, Slievemore and Arroo Mountains in the west, i.e. hilltops between Lough Gill and Lough Melvin;
- The Benbeg and Cuilcagh Mountains in the east; and
- Several mountains surrounding Lough Allen in the south-central part of the study area, e.g. Arigna, Slieve Anierin, and Lackagh Mountains.

The mountains tend to be flat-topped or gently undulating, and are mostly covered by blanket peat and heath which are supported by high rainfall at higher elevations, see Section 2.2.

Lowland regions (below *c.* 150 mOD) are characterised by U-shaped valleys (‘glens’) in the west and broad, open valley floors in the north, east and south. The lowland regions host important lakes, including Loughs Erne, Melvin, Macnean and Allen, which are described further in Section 2.3.

The transition from upland to lowland is often delimited by topographic escarpments or relatively steep slope changes that are marked by scree deposits, rock slides, and soil/peat slides. The escarpments tend to coincide with harder (less erosive) rock types such as limestones and sandstones, compared to softer shale and mudstones which are associated with more gentle slopes. This gives the overall mountainside topography a step-like appearance.

Overall, elevations range from approximately 50 mOD at Lough Allen to more than 600 mOD at Cuilcagh, Truskmore and Slievemore Mountains. The physiography is largely shaped by glacial processes and associated landforms, which are further described in Section 2.5.

2.2 Rainfall/Meteorology

The 30-year annual average rainfall distribution for the period 1981–2010 (Met Éireann, 2015) is shown in Figure 2.2, and ranges from 800 to 2400 mm/yr across the study area. The wide range in average rainfall reflect topography, and the higher rainfall values correlate with upland areas, notably the Benbulben/Truskmore, Cuilcagh and Slieve an Iarainn Mountains which receive between 2000 and 2400 mm/yr.

Rainfall varies considerably between summer and winter. The 30-year average winter rainfall (December through January) ranges between 200 and 700 mm/yr, whilst the 30-year average summer rainfall (June through August) ranges between 200 and 500 mm/yr.

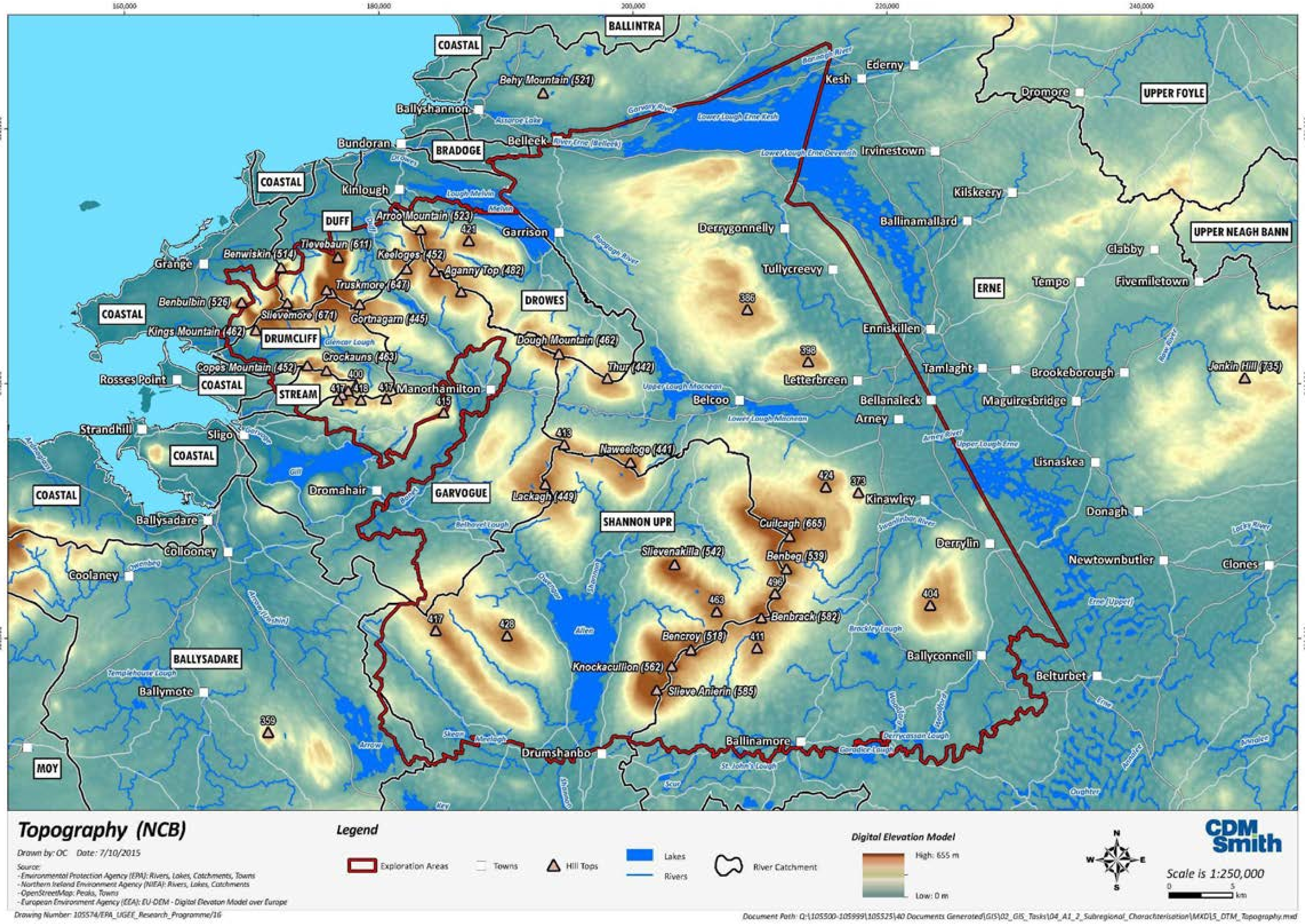


Figure 2.1. Topographic map – NCB study area.

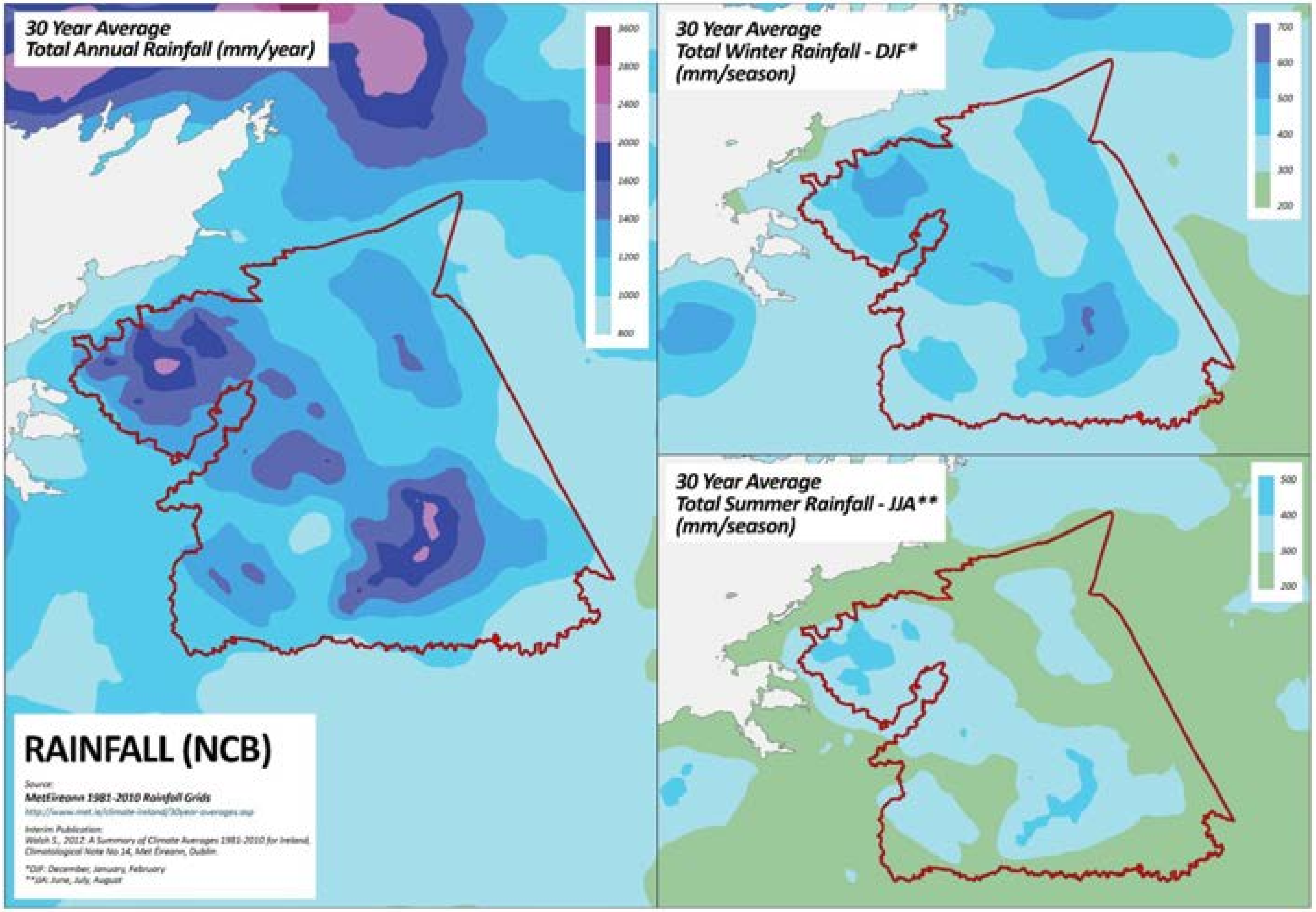


Figure 2.2. Average annual rainfall distribution (1981–2010) – NCB study area. From Walsh (2012) and Met Éireann (2015).

In 2014/2015, the estimated monthly potential evapotranspiration (PE) rate at the recently established Finner weather station (located approximately 5.5 km NW of the study area) ranged between approximately 10 mm/month in November and 80 mm/month in June, as shown in Figure 2.3. The total monthly rainfall in the same period ranged between 39.1 mm/month to 197.9 mm/month.

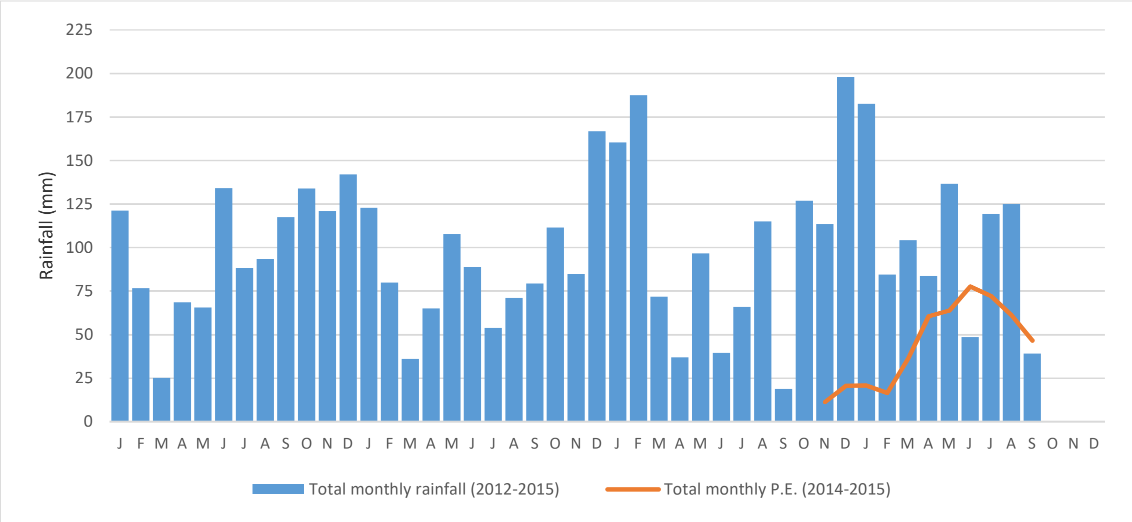


Figure 2.3. Total monthly rainfall and P.E. at Finner weather station.

2.3 Lakes

There are numerous lakes in the NCB study area, ranging in size from 0.004 km^2 (Lough Nacroagh) to 103.8 km^2 (Lower Lough Erne). The principal lakes, see Figure 2.1 and Table 2.1, are located in lowland, valley settings whilst smaller lakes tend to be located in uplands. Lakes that are present in valleys occupy inter-drumlin areas which form a complex hydrological system of interconnected lakes, bogs and wet meadows (wetlands) in which flooding occurs frequently.

The largest lakes are the Upper and Lower Lough Erne, Upper and Lower Loughs Macnean, Lough Allen, and Lough Melvin. Other large lakes near the study area boundaries are Loughs Gill and Arrow. Lakes are important for recreational uses, including fisheries (Kelly *et al.*, 2012), hosting several important species of trout, salmon, and char. Lakes are also abstracted for public and private water supplies (see Section 5). For the majority of abstracted lakes, water balance and/or design studies have been researched with relevant public bodies, but few details have emerged. Bathymetry has been mapped for 33 lakes within or adjoining the UGEE licence area, see Appendix A, and information on lake volumes can be assigned for the surveyed lakes. Upper and Lower Lough Erne, Lough Melvin, Lough Gill, Lough Arrow, Upper and Lower Lough Macnean, and Lough Allen are all equipped with staff gauges for water level measurements, and hydrographs are also presented in Appendix A.

Table 2.1. Summary of the largest lakes (>50 ha) in the NCB

Lough (Name)	WFD Code	Area (km^2)	County	Bathymetric survey (Y/N) (max. depth)
Allen	IE_SH_26_716	33.46	Leitrim/Roscommon	Y (42.5 m)[g]
Arrow	IE_WE_35_159	12.47	Sligo/Roscommon	nd
Belhavel	IE_WE_35_155	1.01	Leitrim	nd
Brackley	IE_NW_36_577	1.67	Cavan	nd
Bunerky	IE_NW_36_624	0.75	Cavan	nd
Derrycassan	IE_NW_36_514	1.62	Cavan/Leitrim	nd
Erne Devenish Lower	UKGBNI3NW0007	46.06	Fermanagh	nd
Erne Kesh Lower	UKGBNI3NW0006	57.78	Fermanagh	nd
Erne Upper	UKGBNI3NW0008	32.18	Fermanagh	Y (21 m)[a]
Garadice	IE_NW_36_648	3.89	Leitrim	nd
Gill	IE_WE_35_158	13.81	Leitrim/Sligo	nd
Glenade	IE_WE_35_156	0.74	Leitrim	Y (11.5 m)[c]
Glencar	IE_WE_35_139	1.15	Leitrim	Y (19 m)[d]
Kilywilly	IE_NW_36_513	0.56	Cavan	nd
Macnean Lower	UKGBNI3NW0014/IE_NW_36_445	4.44	Leitrim/Cavan/Fermanagh	Y (approx. 8 m)[g]
Macnean Upper	UKGBNI3NW0011/IE_NW_36_673	9.91	Leitrim/Cavan/Fermanagh	Y(22.7 m)[b]
Meelagh	IE_SH_26_711	1.16	Roscommon	nd
Melvin	UKGBNI3NW0033/IE_NW_35_160	22.06	Leitrim/Fermanagh	Y(45 m)[e]
Scolban	UKGBNI3NW0022	0.66	Fermanagh	nd
Skean	IE_SH_26_673	1.14	Sligo	nd
St John's	IE_NW_36_642	1.46	Leitrim	nd

[a]Inland Fisheries Ireland, 2010.
[b]Inland Fisheries Ireland, 2010a.
[c]Kelly *et al.*, 2014;
[d]Kelly *et al.,* 2014a.
[e]Kelly *et al.,* 2012.
[f]National Parks and Wildlife, 2009.
[g]Tierney *et al.,* 2010.
nd, no data.

The available level hydrographs show relatively stable water levels over time, with the possible exception of the station at Rosscor (236001) which is associated with Lower Lough Erne. This station shows slightly lower water levels, but similar seasonal fluctuations, from 2010 to present compared to the period of record 1999–2009. Hydrographs for Gowly (36071), Wood Island (36073) and Ballinacur (36091) display a considerable change in water level regimes in 1994. This is linked to the dredging and opening of the Shannon-Erne Waterway (SEW), see Figure 2.4.

Loughs Erne and Allen are regulated water bodies. Water levels in Lough Erne are managed in context of the Ballyshannon hydroelectric power scheme, and the temporal variability of water levels is gauged and controlled to maintain the ecological significance ('value') of the lake system. The regulatory schemes are described in relevant flood and fish studies (e.g. ESBI, 2003; IFI, 2010; JBA 2013).

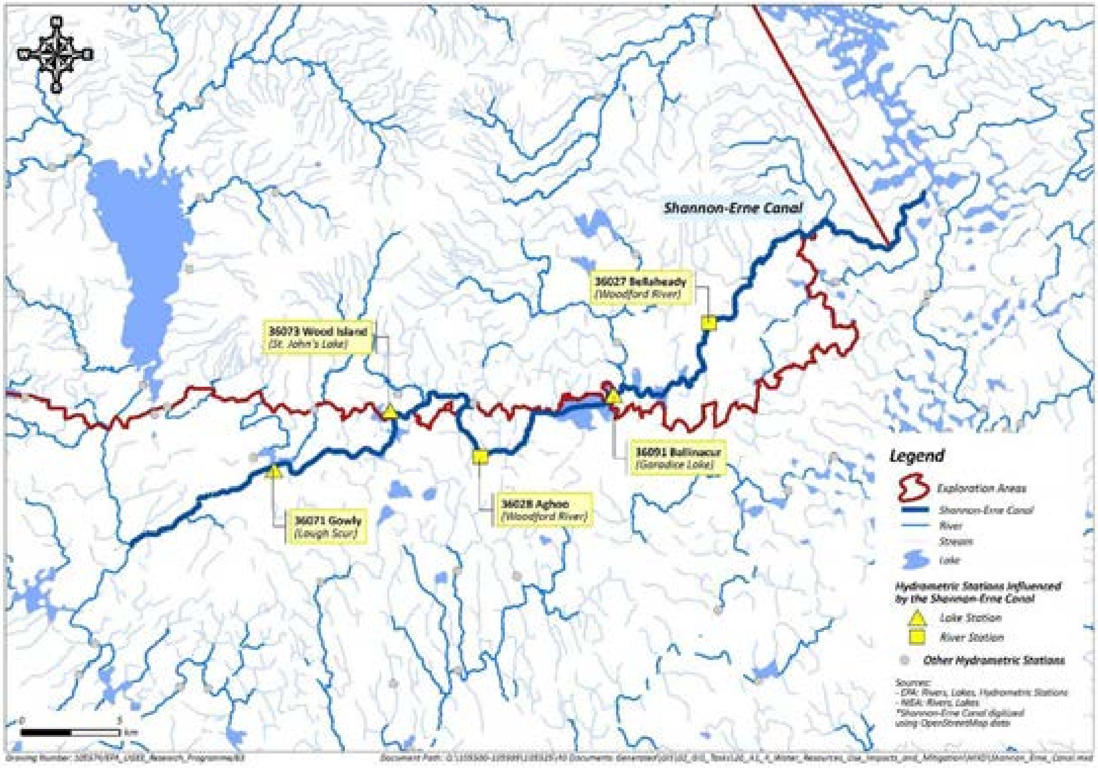


Figure 2.4. Shannon-Erne Waterway.

The Lough Erne drainage system includes a designated RAMSAR site, an Area of Special Scientific Interest, and several Special Area of Conservation (NIEA, 2014b).

Water levels and outlows from Lough Allen are managed according to "The Regulations and Guidelines for the Control of the River Shannon" (ESB, 2003; with minor revision in 2008).

2.4 Streams and Rivers

Drainage patterns in the NCB study area are influenced by the underlying geology and the landforms which have resulted from past glacial action. The majority of streams and rivers originate on high-rainfall, peat-covered hilltops which are underlain by low-permeability bedrock formations or flat-topped mountains in limestone terrains. Numerous streams originate as springs. Drainage patterns tend to be radial where low-permeability bedrock is present, and dendritic where limestones are present, with streams discharging to lakes in valley settings or westward directly to the sea).

The mountains reach maximum elevations in the range of 400 mOD to 671 mOD, and define the boundaries of catchments whose streams and rivers ultimately drain west to the coastline or south to the River Shannon. Important rivers are the Erne, Arney, Swanlinbar, Woodford, Arigna, Shannon, Owengar, Glencar and Glenade.

The Lough Erne and Lough Allen drainage systems account for approximately 43% and 36% of the total UGEE license area, respectively. Both systems are regulated by dams, lock gates or sluices. The Erne drainage system is hydrologically complex. It is partially sourced from several large karst springs (e.g. Marble Arch, Cascade Springs) at the margins of the Derrygonnelly and Cuilcagh Mountains. It incorporates several lakes, including Upper and Lower Lough Macnean. The Erne drainage system is shaped by a drumlin landscape at lower elevations, whereby water courses occupy inter-drumlin areas to form a system of interconnected lakes, bogs and wet meadows (wetlands). Hydraulic gradients through this system are relatively flat and flooding occurs frequently.

The Lough Allen catchment is part of the headwaters of the River Shannon system. It includes Lough Allen, which receives water from two main sources: a) direct contribution from streams that originate on surrounding hilltops; and b) indirect contribution, via a stream, from “Shannon Pot”, a spring that is regarded to be “the source of the Shannon River”. Hydraulic gradients in the Lough Allen catchment are relatively steep compared to the Erne.

The western mountains display steeper and narrower valleys, with exposed cliffs, scree slopes and ‘rotational slips’ of large blocks of rock. These features were created by glacial processes and, to a lesser extent, present-day erosion of limestone and sandstone cliffs. In western catchments, streams cut narrow upland valleys (gullies) before entering Lough Gill or flowing to the sea. Waterfalls occur where streams cross harder geological layers (e.g. cherty limestones at Glencar). Harder rock types such as chert can also support the base formation of blanket peat. The limestones are otherwise well drained, and in some places form patches of limestone pavement.

There are 33 active gauging stations in the NCB study area, see Figure 2.5, of which 28 are stream flow recorder sites and 5 are equipped with staff gauges for water level recording. Several of these are dedicated to measure flows in small, individual subcatchments, e.g. inflow to lakes, whilst others are located at the downstream ends of very large catchments, thus providing data on the sum total outflow from large areas.

Stream hydrographs and flow duration curves (FDCs) are depicted in Appendix B for stations with more than 6 years of continuous record. Using the hydrometric data obtained from the EPA and Office of Public Works (OPW) in Ireland, and the Rivers Agency (RA) in Northern Ireland, the daily mean and 95-percentile (Q_{95}) flows (i.e. the flow that is exceeded 95% of the time) are summarised in Table 2.2 from stations with long-term records. Flow statistics for ungauged catchments in Ireland were estimated using the EPA’s HydroTool. Flow statistics for ungauged catchments in Northern Ireland were estimated by transposing specific runoff estimates from gauging stations in neighbouring catchments that have similar physical characteristics. Flow statistics in ungauged catchments that cover karstified limestones are assigned low confidence given the dynamic nature and range of flows that characterise such catchments, and which cannot be captured with simplified estimation methods.

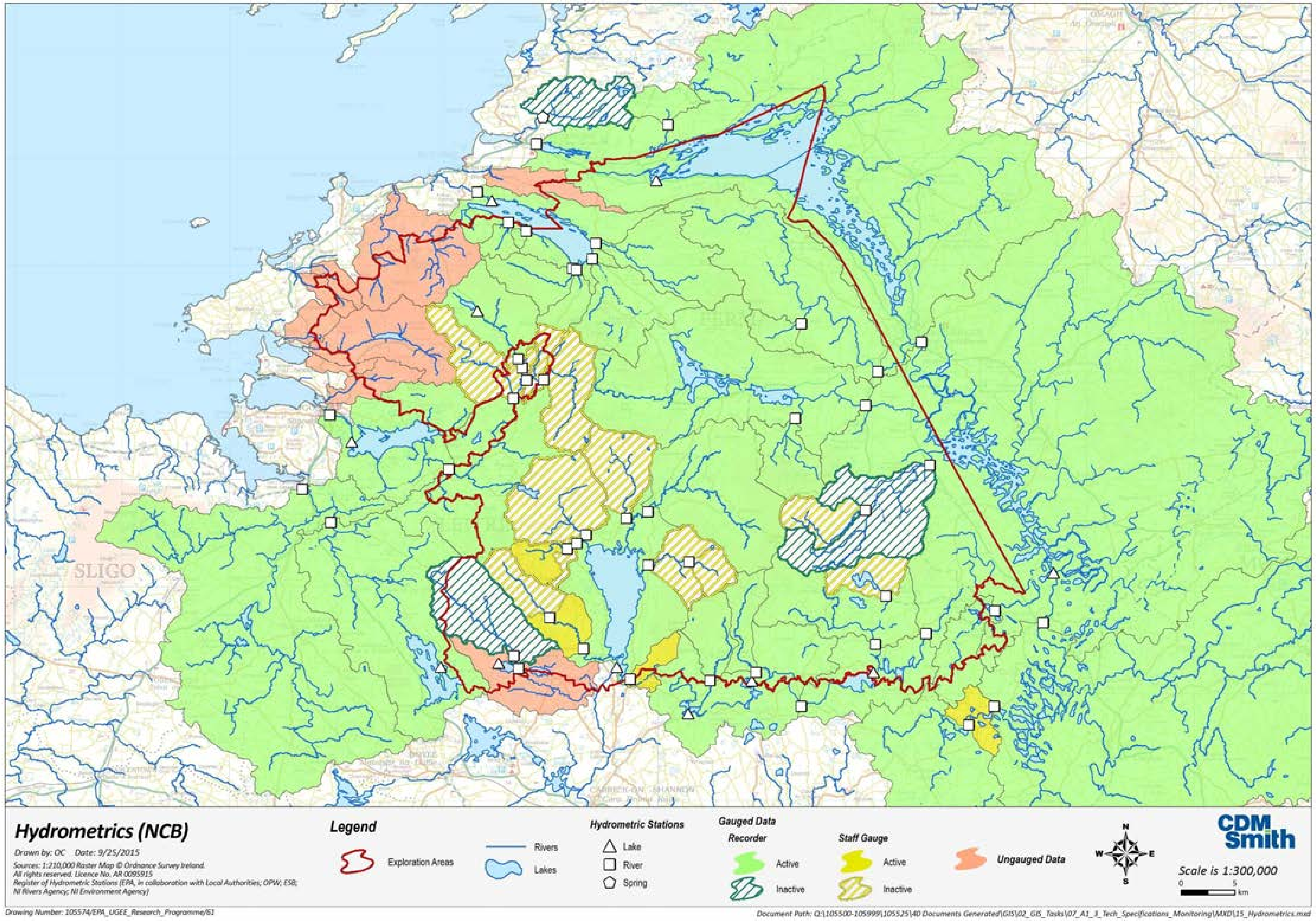


Figure 2.5. Locations of hydrometric monitoring stations – NCB study area.

Table 2.2. Summary of estimated flows in the NCB study area

Gauged catchments[a] (derived from measured data)					
Parameter	**Unit**	**Northwest Carboniferous Basin**			
		Min	**Max**	**Mean**	**Median**
Q_{95} Flow	m^3/s	0.06	2.17	0.80	0.34
Mean Flow	m^3/s	0.89	28.56	8.44	4.86
Specific Runoff (Q_{95})	$m^3/s/km^2$	0.0011	0.0066	0.0035	0.0034
Specific Runoff (mean)	$m^3/s/km^2$	0.0191	0.0777	0.0386	0.0372
Ungauged catchments[b] (derived from HydroTool)					
Parameter	**Unit**	**Northwest Carboniferous Basin**			
		Min	**Max**	**Mean**	**Median**
Q_{95} Flow	m^3/s	0.02	1.045	0.2165	0.105
Mean Flow	m^3/s	0.12	6.634	1.3807	0.54
Specific Runoff (Q_{95})	$m^3/s/km^2$	0.0024	0.0063	0.0039	0.0038
Specific Runoff (mean)	$m^3/s/km^2$	0.0165	0.0255	0.0209	0.021

[a]Based on 11 gauging stations with long-term continuous records period 1946–2015)

[b]Result from HydroTool in 11 catchments. Not used in catchments with karst limestone

Figures 2.6 to 2.9 depict the hydrographs and FDCs for four representative gauging stations in four separate catchments:

- Glenaniff gauging station, which measures flow in a dominantly limestone catchment near Lough Melvin;
- Bellaheady gauging station, which measures flow in a dominantly limestone catchment in the upper parts of the Lough Erne drainage system;
- Kiltybardan gauging station, which measures flow in a dominantly shale and sandstone catchment near Lough Melvin; and
- Dowra gauging station, which measures flow in a mixed shale and sandstone catchment which drains into Lough Allen.

These gauging stations are highlighted because they illustrate different hydrological responses to rainfall and flow in the NCB study area:

- Glenaniff – this is a quick response catchment. The steeper-slope section of the FDC reflects surface runoff and near-surface pathways of water movement. The flatter low-flow section of the curve represents inferred groundwater contributions to the measured stream flow. The latter are sustained, but the contributions are volumetrically small (per unit area of discharge to the stream) compared to the shorter-duration peak runoff contributions during rainfall events.

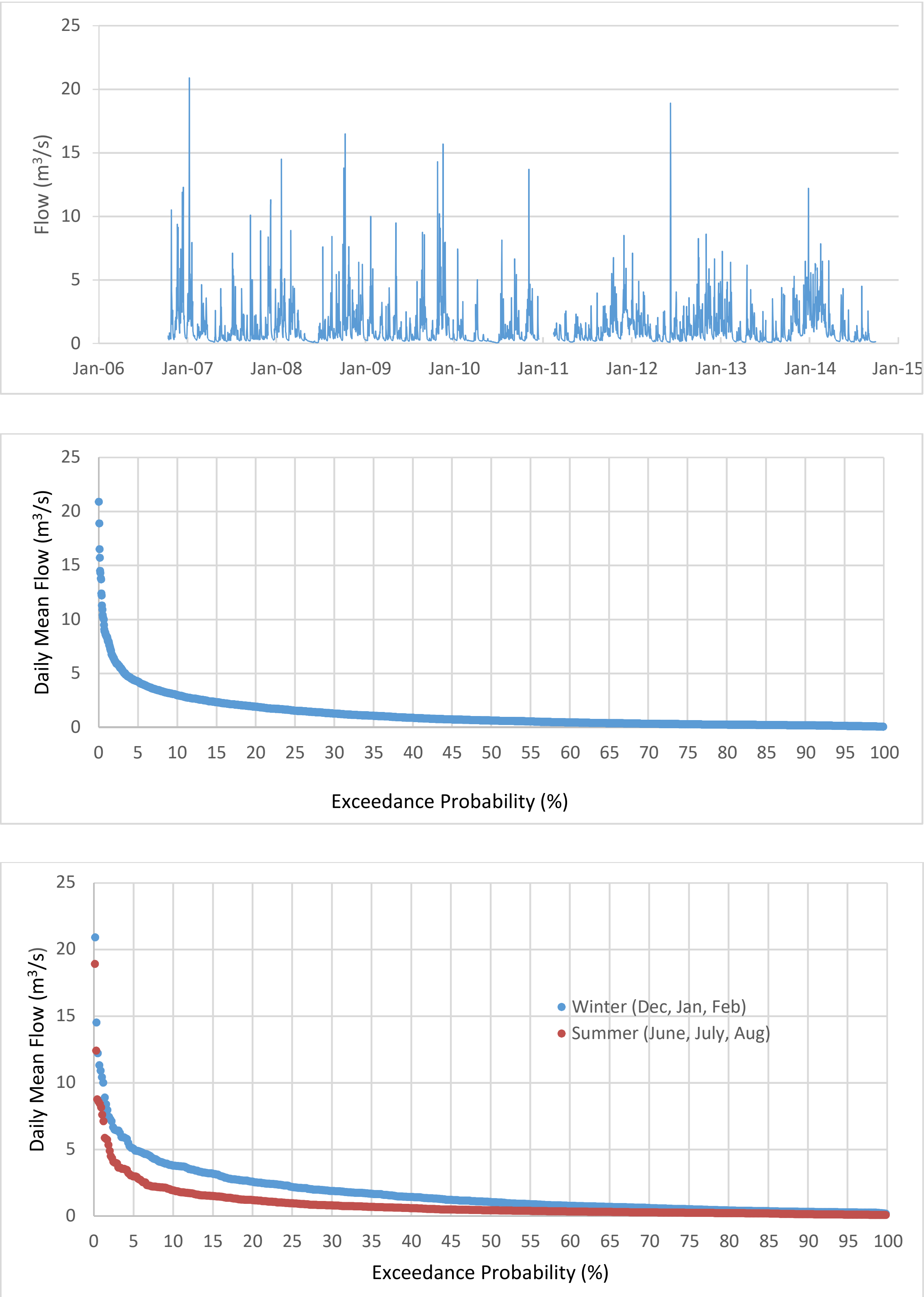


Figure 2.6. Hydrograph and flow duration curves – Glenaniff.

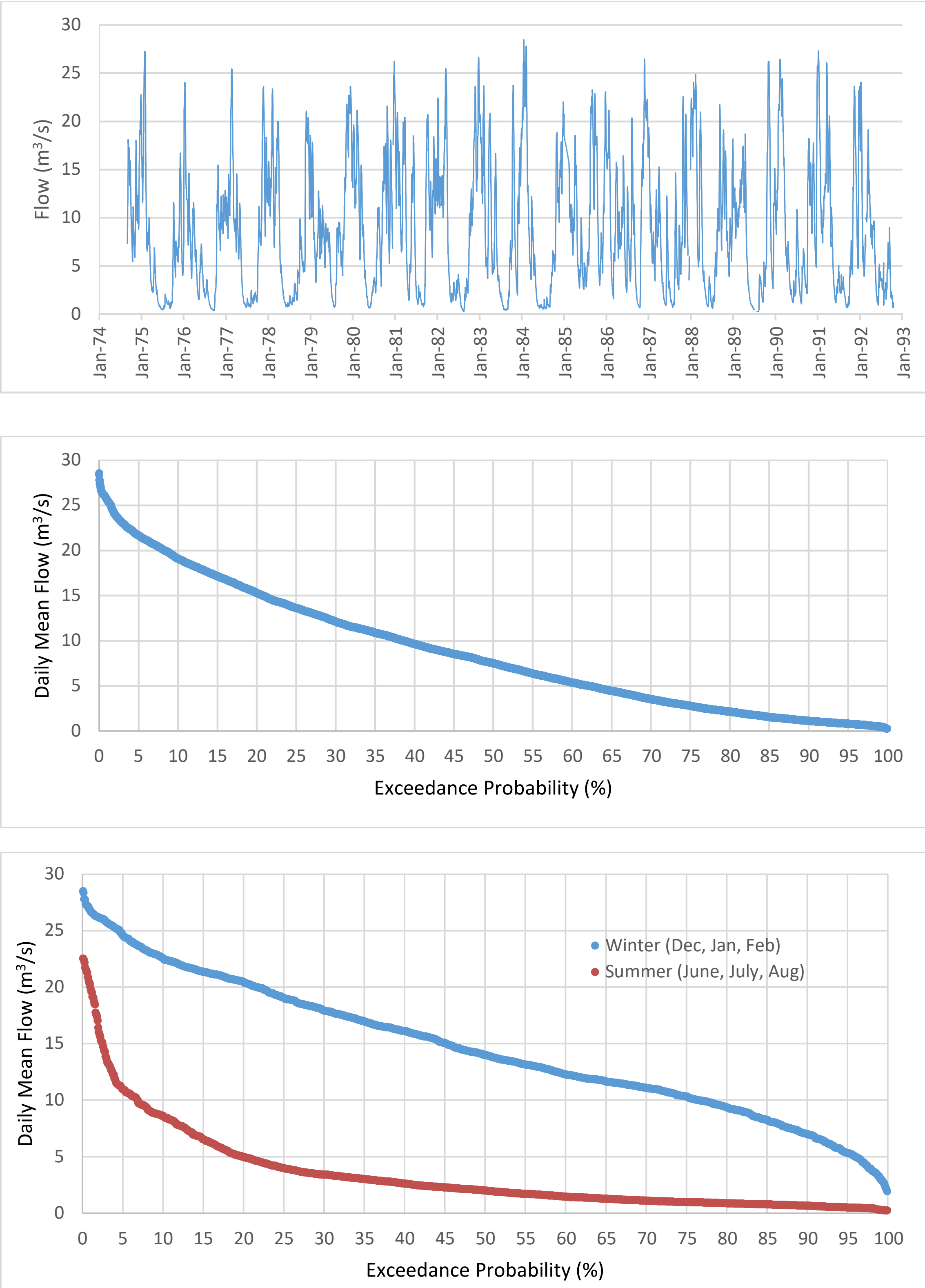


Figure 2.7. Hydrograph and flow duration curves – Bellaheady.

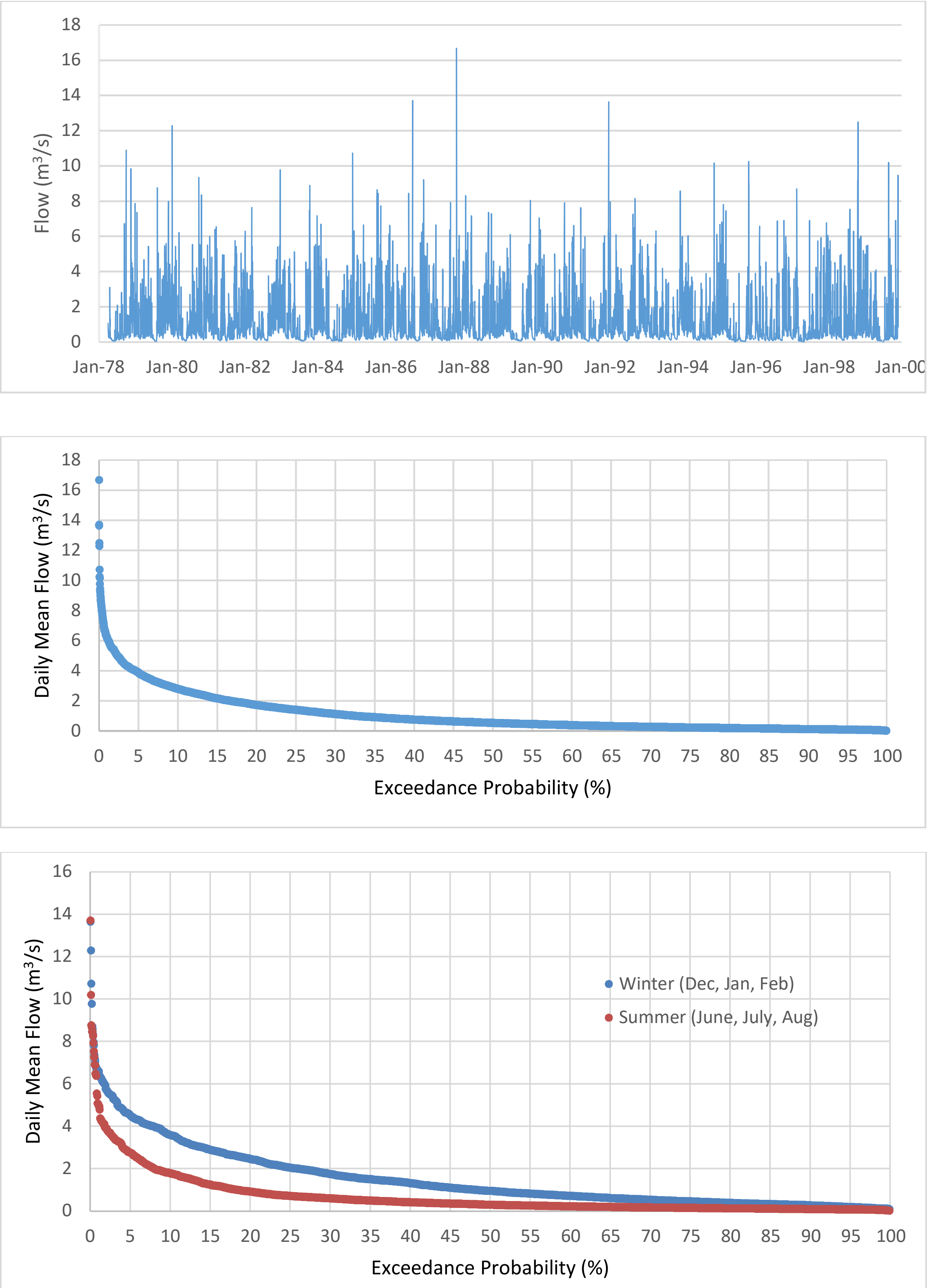
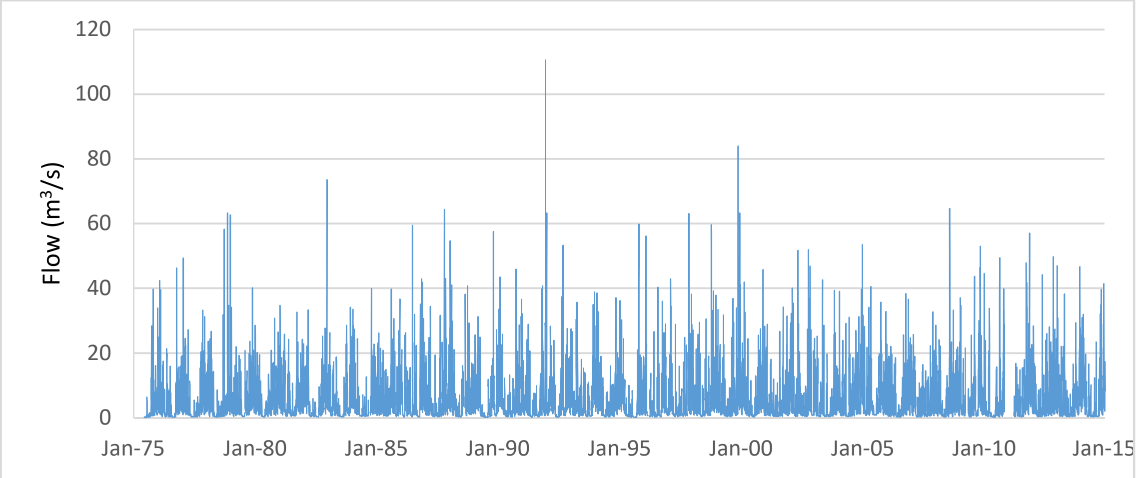
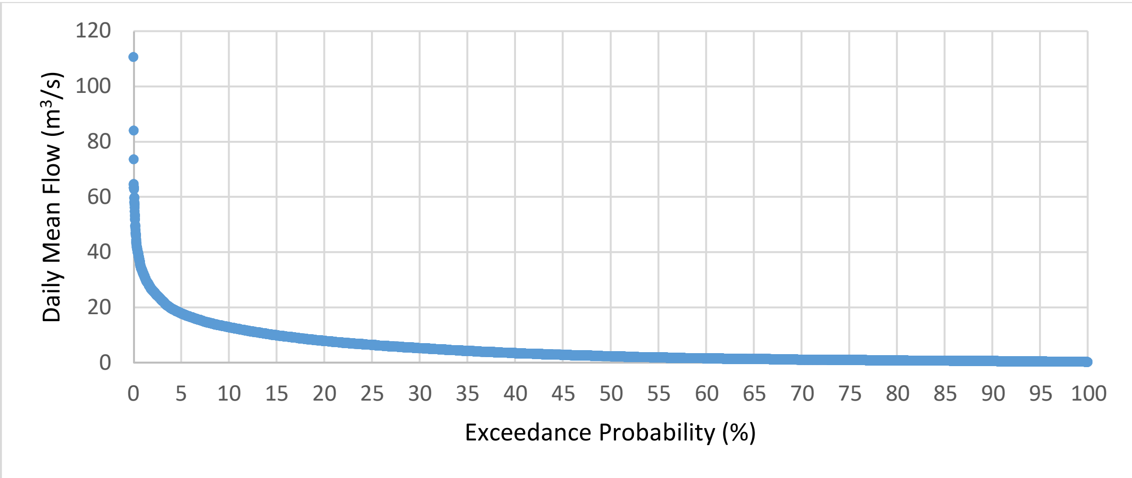


Figure 2.8. Hydrograph and flow duration curves – Kiltybardan.





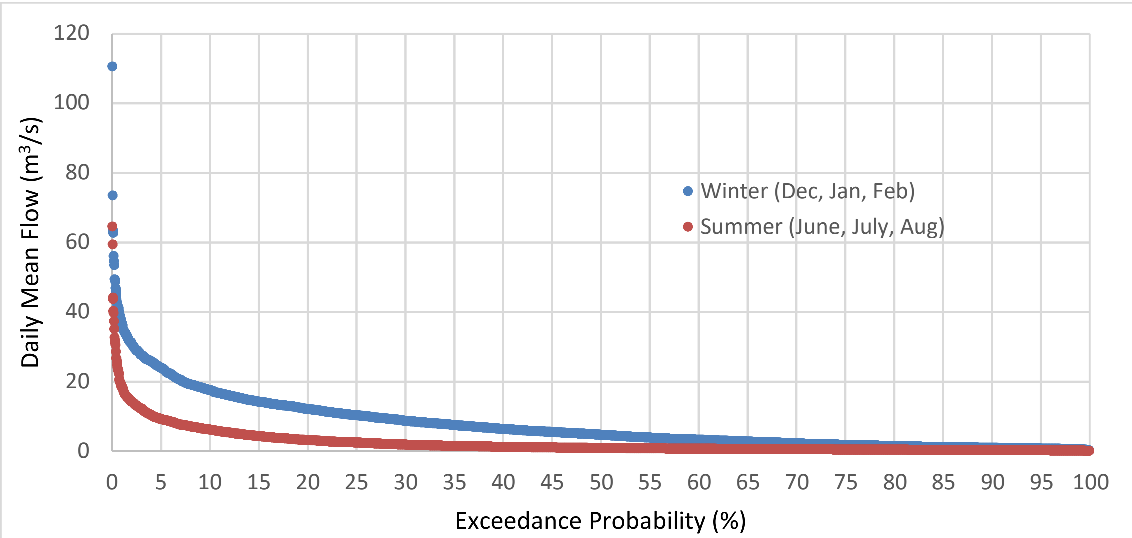


Figure 2.9. Hydrograph and flow duration curves – Dowra.

- Bellaheady – this is also a quick response catchment. The hydrograph shows a distinct seasonality with sustained higher flows in the winter months compared to Glenaniff, indicating that water is stored. Situated on the Woodford River (see station 35054 in Figure 2.4), the hydrograph is likely influenced by the regulating mechanism of the Shannon-Erne Waterway.
- Kiltybardan – this is another quick response catchment. However, compared to other hydrographs, the flow recessions are steeper and shorter *between* individual rainfall events, reflecting rapid runoff and a very small volumetric baseflow component. The response is explained by the steep-sided nature and low-permeability of the bedrock within the catchment, which enhances runoff via overland and near-surface pathways.
- Dowra – this hydrograph is similar to Kiltybardan. However, the flashy response at Dowra may also in part be influenced by flow contribution from 'Shannon Pot', a karst spring which discharges from the underlying Dartry Limestone aquifer at the top of the gauged catchment. The Shannon Pot spring is poorly quantified, and its overall influence on the hydrograph is uncertain.

The implication of these hydrographs in the NCB is that rainfall runoff coefficients are high and groundwater baseflow contributions are, on the whole, small, even if the latter are important in maintaining baseflow during prolonged dry weather conditions. This characteristic is typical of 'poorly productive bedrock' settings which are present across most of the NCB study area (see Section 2.6).

Streams that originate as large karst springs in the Cuilcagh Mountains in Co. Fermanagh (e.g. at Marble Arch caves) are relatively poorly quantified in terms of their hydrological responses, end-member flows, and discharge characteristics. The nearest gauging station in a karst catchment is at Tilery Bridge, downstream of Lower Lough Macnean. As shown in Figure 2.10, the hydrograph and flow duration curve shows influence of storage, and is located downstream from Lower Lough Macnean, which acts as the natural storage regulating mechanism for discharges from contributing catchments.

2.5 Quaternary Geology

The glacial past of the study area is extensively documented in available literature (e.g. Thorn, 1985; Coxon and Browne, 1991; Legg *et al.*, 1998; GSI, 2015). Glacial erosive and sedimentary processes have shaped characteristic landforms such as U-shaped river valleys, drumlins, ribbed moraines and eskers. Most notably, the NCB is part of the glacial "*drumlin belt*" which extends from Clew Bay in the west of Ireland to Antrim in the northeast (Vernon, 1966; Meehan *et al.*, 2014). The drumlin belt is defined by thousands of streamlined, oval-shaped hillocks in the lowland regions which can be tens of metres high and several hundred metres long. The drumlins are superimposed on larger, arcuate "ribbed moraine' structures (Dunlop and Clark, 2006; Lemon, 2009; Meehan *et al.*, 2014) which tend to be orthogonal to drumlin orientations, often include several drumlins, and which collectively can be up to 70 m high, 1 km wide and 20 kms long (GSI, 2015).

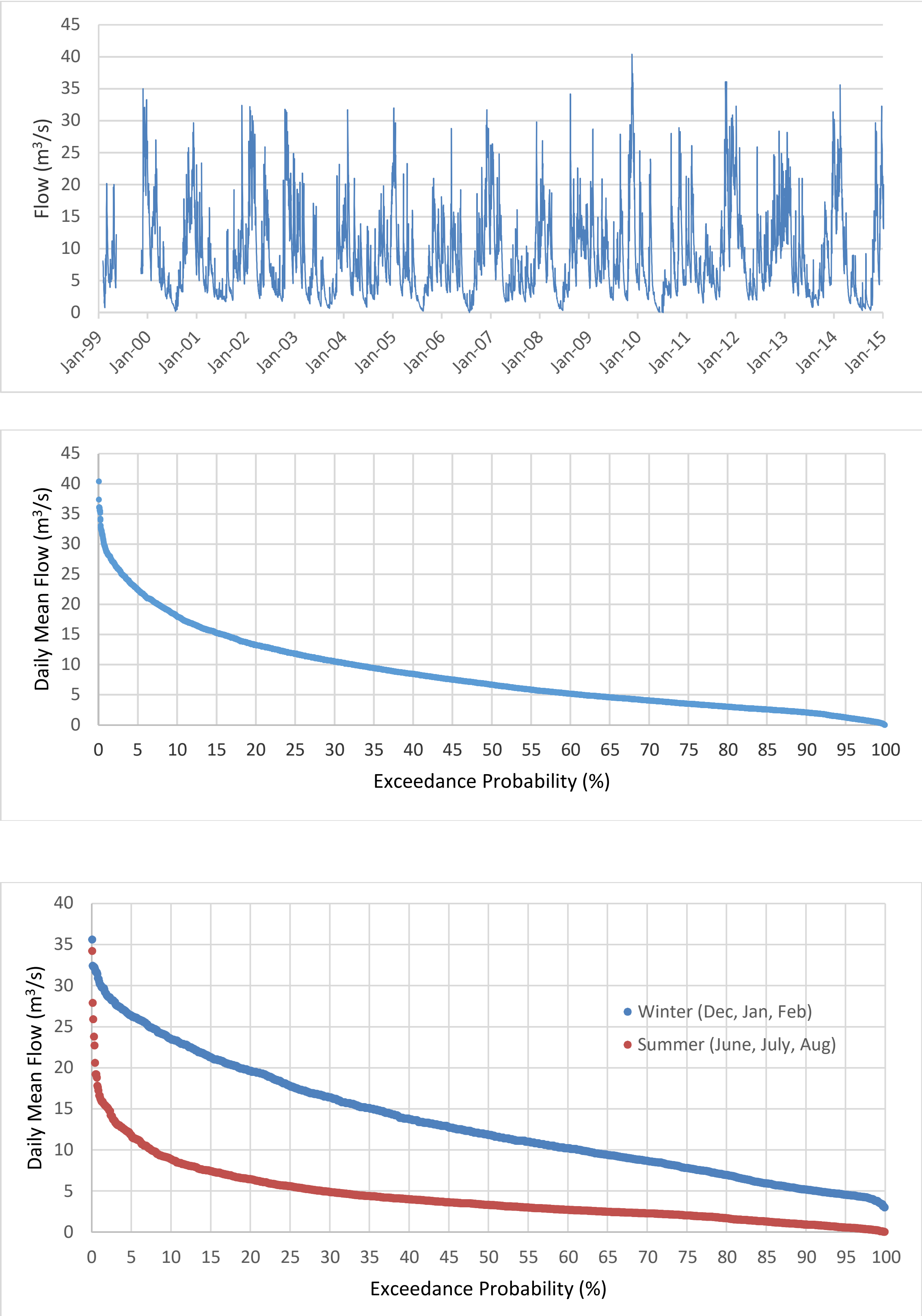


Figure 2.10. Hydrograph and flow duration curves – Tilery Bridge.

The drumlins, along with the glacially carved U-shaped valleys, are clearly visible on the topography map in Figure 2.1. They are further defined by the Quaternary map shown in Figure 2.11. The long axis of drumlins indicates ice movement primarily to the west and northwest (Legg *et al.*, 1998; GSI, 2015). The drumlins are comprised of glacial till deposits ('boulder clay') which, along with peat, define the main subsoil compositions in the region. The till is a heterogeneous mix of unconsolidated clay, silt, sand, gravel, pebbles and boulders which is generally unsorted, unbedded and densely packed. Tills derived from underlying sandstone and shale bedrock formations dominate the study area, and are described as "*soft to stiff, gravelly MUD with sandy silt/clay matrix, with pebble to cobble, angular to subrounded sandstone, shale and occasional limestone clasts*" (GSI, 2015). Till derived from carbonate (e.g. primarily limestone) formations is the second most common type of till, and is described as "*firm/stiff, gravelly MUD to muddy GRAVEL with sandy silt/clay matrix, and pebble to cobble angular to subrounded limestone, chert and occasional sandstone/shale clasts*".

The till is interspersed and sometimes interbedded with glacial outwash (meltwater) deposits (see Figure 2.11), represented by 'sands and gravels' which are stratified and of localised extent within the study area. The till is also locally overlain by more recent (Holocene age) alluvial sediments and lacustrine deposits (e.g. lake marl). Post-glacial alluvial sediments are spatially more extensive than glacial outwash deposits and are noted in most river valleys across the study area, e.g. Blackwater, Yellow and Swanlinbar rivers to the southeast of Cuilcagh Mountains, as wells as River Bonet near Manorhamilton.

The peat is also a post-glacial deposit, and there are three types recognised in the study area: blanket peat, raised bog and fens. The three types are differentiated by their origins – blanket peat covers gently undulating ground in upland regions (above c. 150 mOD) as a function of high rainfall, whereas raised bogs are discreet, dome-shaped masses of peat occupying former lakes or shallow depressions, mostly in lowland regions. Fens are similar to raised bogs but are differentiated on the basis of plant communities which tend to form on limestone terrains, being dependent on less acidic conditions than in raised bogs.

The thickness distribution of the Quaternary deposits have been interpreted by the GSI in Ireland for the area that is covered by Sheet 26 of the 1:50,000 scale Discovery Series maps of the Ordnance Survey of Ireland (OSI). Shown in Figure 2.12, the thickness, defined as 'depth to bedrock', ranges from 0 to 58 m across the mapped area (GSI, 2015). The majority of deposits are >10 m thick, occupying lowland regions which are dominated by glacial till and interdrumlin peat (GSI, 2015). Areas of thin or absent Quaternary cover are individually small but widespread throughout the study area, coinciding mostly with the upland regions. This distribution and pattern describes the majority of the UGEE licence area. It is also reported (GSI, 2015) that the thickness of tills in limestone bedrock areas is generally shallower than in sandstone/shale areas, which is attributed to the softer nature of siliclastic rocks compared to the limestones, i.e. softer rocks being more susceptible to glacial erosive action.

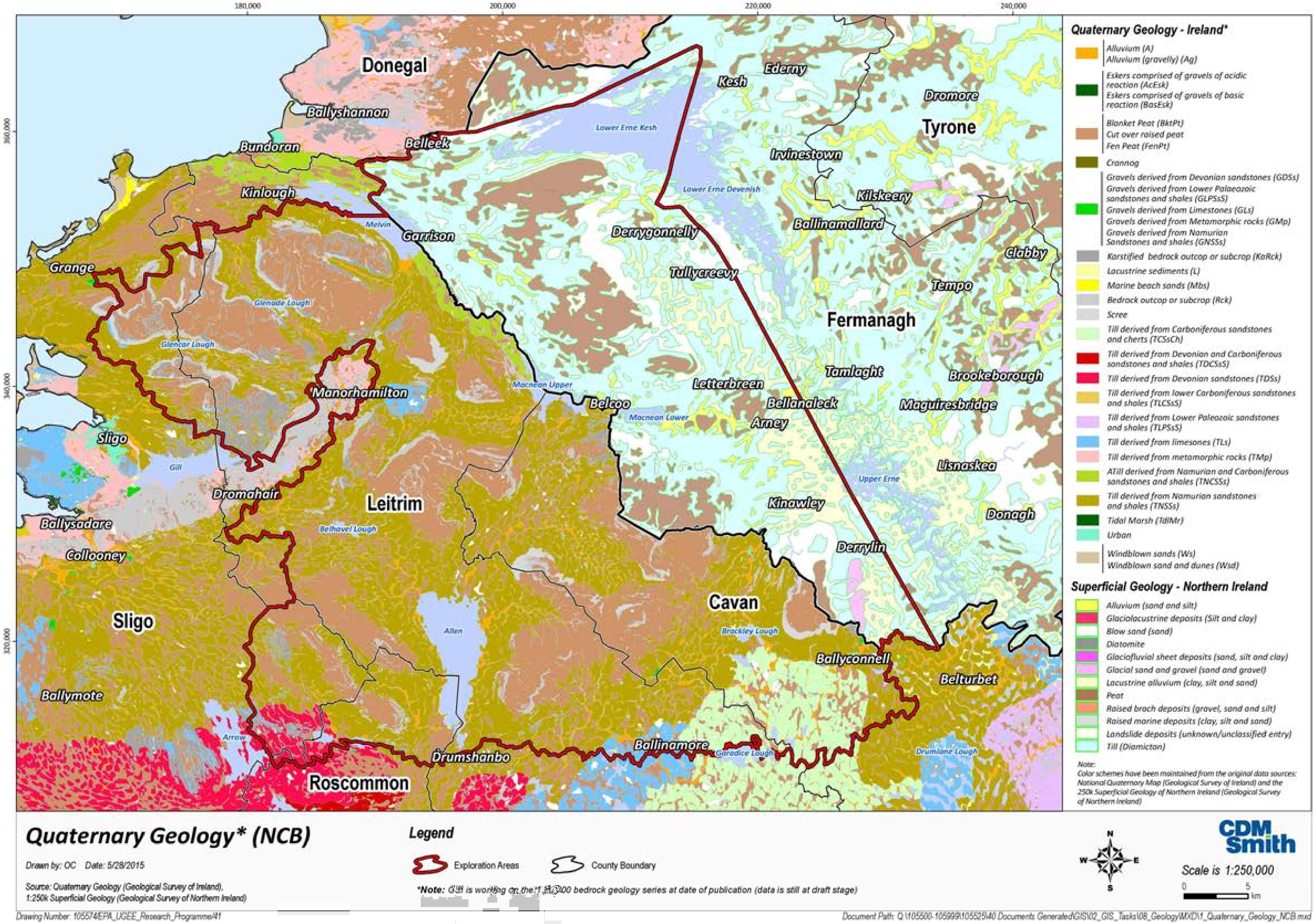


Figure 2.11. Quaternary geologic map – NCB study area.

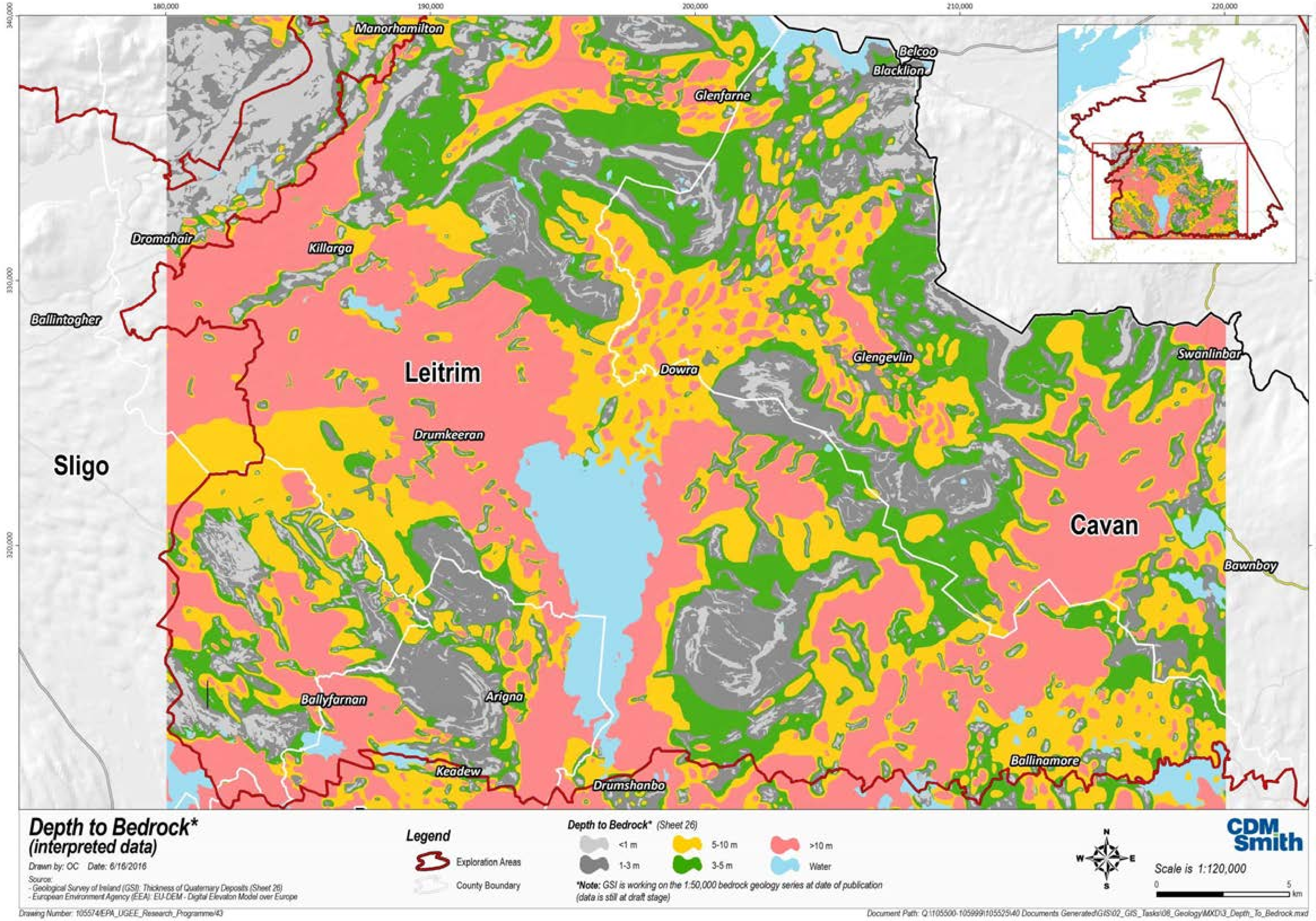


Figure 2.12. Thickness map of Quaternary deposits – Sheet 26 of the OSI.

2.6 Bedrock Geology

The bedrock geology of the NCB has been extensively studied by public bodies such as the GSI and GSNI, academic research institutions, as well as both oil and gas and mineral exploration companies. Accordingly, a significant volume of geological literature is available in the public domain. The most up-to-date stratigraphical overview is provided by Mitchell and Somerville (2011) and Somerville and Waters (2011), while the most recent publications on the structural geology are provided by Worthington and Walsh (2011) and Cooper *et al.* (2012).

A bedrock geological map of the NCB study area is presented in Figure 2.13, and is compiled from the 1:100,000 bedrock series map of Sligo-Leitrim (MacDermot *et al*., 1996) and the 1:250,000 bedrock map of Northern Ireland (GSNI, 1997). Details on the stratigraphy and structural geology are described in Sections 2.7 and 2.8, respectively. For reference purposes in this report, the NCB is divided into three main geological 'subdivisions', see Figure 2.14, as follows:

1. Sligo Syncline: a regional syncline structure which trends NE-SW, is bounded to the west by the shoreline (structure extends offshore) and by the Ox Mountains to the east.
2. Ballymote Syncline: a syncline structure which trends NE-SW, and extends from the Ox Mountains in the west and the Lough Allen Basin in the east.
3. Lough Allen Basin: a regional syncline structure which trends NW-SE and extends to Lower Lough Erne in the north, Upper Lough Erne in the east, and Curlew Mountains in the south/southeast.

Each is described further in Section 2.8. A recent and as yet unpublished 1:50,000 scale bedrock map has also been prepared by the GSI for the area covered by Sheet 26 of the Ordnance Survey of Ireland (OSI). Reproduced in Figure 2.15 the map broadly confirms the 1:100,000 scale map but adds structural detail to the Lough Allen Basin subdivision, specifically mapped and inferred traces of faults.

2.7 Stratigraphy

The stratigraphy that is most relevant to the UGEE JRP is summarised in Figure 2.16. It is defined by rocks of the Tyrone and Leitrim Groups (MacDermot *et al*., 1996; Legg *et al*., 1998; Mitchell, 2004b). The Tyrone Group is of Lower and Middle Carboniferous (late-Tournasian and Viséan) age. It comprises a thick and variable sequence of mainly limestones, sandstones and shales. The combined maximum total thickness of the sequence is approximately 2100 m in the centre of the Lough Allen Basin. The base of the Tyrone Group is marked by the "Basal Clastics" which overlie Devonian Old Red Sandstones. In literature, the term "Basal Clastics" describes the Boyle Sandstone Formation in the Lough Allen Basin, the Moy Sandstone Formation in parts of the Ballymote Syncline, and the Twigspark Formation in the Sligo Syncline (Philcox *et al*., 1992; MacDermot *et al*., 1996).

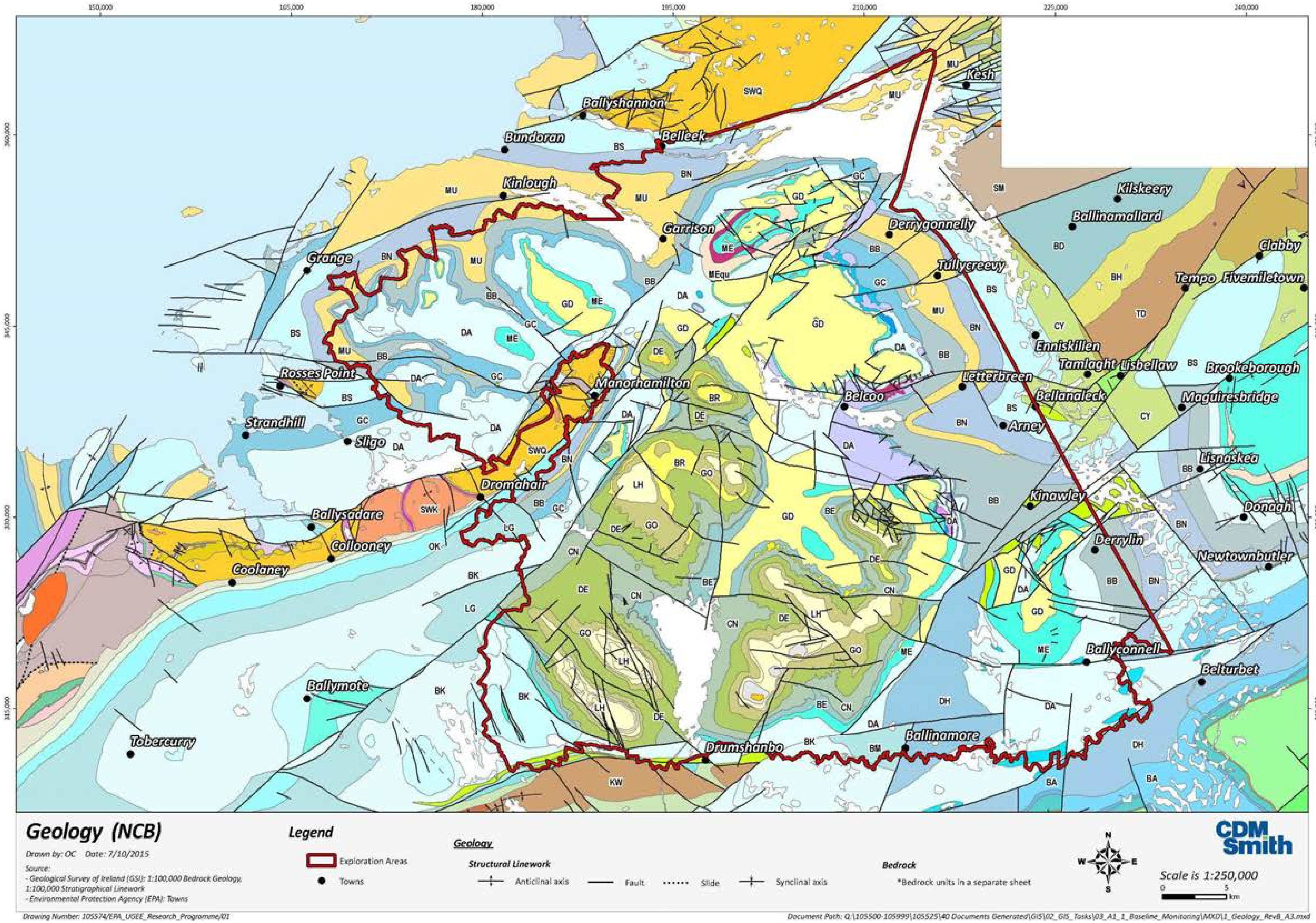


Figure 2.13. 1:100,000 scale bedrock geology map – NCB study area.

Geology

Bedrock:

Shale Formations:

- BB: Benbulben Shale Formation
- BE: Bellavally Shale Formation
- BH: Bencroy Shale Formation
- BN: Bundoran Shale Formation
- CN: Carraun Shale Formation
- DE: Dergvone Shale Formation
- DH: Drumgesh Shale Formation
- GO: Gowlaun Shale Formation
- KE: Keenaghan Shale Formation
- LG: Lisgorman Shale Formation

Limestone Formations:

- mk: Mudbank limestone
- BA: Ballysteen Formation
- BK: Bricklieve Limestone Formation
- BKlmk: in Bricklieve Limestone Formation
- BKL: Bricklieve Limestone Formation (lower)
- BKLmk: in Bricklieve Limestone Formation
- BKU: Bricklieve Limestone Formation (upper)
- BM: Ballymore Limestone Formation
- BS: Ballyshannon Limestone Formation
- CNdg: Doagh Limestone Member
- DA: Dartry Limestone Formation
- DAcr: Carn Limestone Member
- DAcr: Crinoidal limestone
- DAcr: in Dartry Limestone Formation
- DAcw: Carrickmacsparrow Limestone Member
- DAdo: in Dartry Limestone Formation
- DAkb: Knockmore Reef, bedded facies
- DAkn: Knockmore Limestone Member
- DAlg: Legacurry Member
- DAmk: in Dartry Limestone Formation
- GC: Glencar Limestone Formation
- KL: Kilbryan Limestone Formation
- OK: Oakport Limestone Formation

Sandstone Formations:

- BEdo: Doobally Sandstone
- BH: Ballyreagh Conglomerate Formation
- BHss: Bencroy Sandstone Member
- BR: Briscloonagh Sandstone Formation
- BSbc: Basal sandstones
- CY: Clogher Valley Formation
- GD: Glenade Sandstone Formation
- LH: Lackagh Sandstone Formation
- KW: Keadew Formation
- MEqu: Quarry Sandstone Member
- MU: Mullaghmore Sandstone Formation
- TW: Twigspark Formation

Other Formations:

- D: Dolerite and Gabbro
- DEln: Lacoon Flagstone Member
- GF: Greyfield Formation
- ME: Meenymore Formation
- MEgl: Glen Member
- Mb: Metabasite
- NAM: Namurian (undifferentiated)
- S: Serpentinite
- SWQ: Slishwood Division, Psammitic Paragneiss
- SWQbas: Slishwood Division, Psammitic Paragneiss

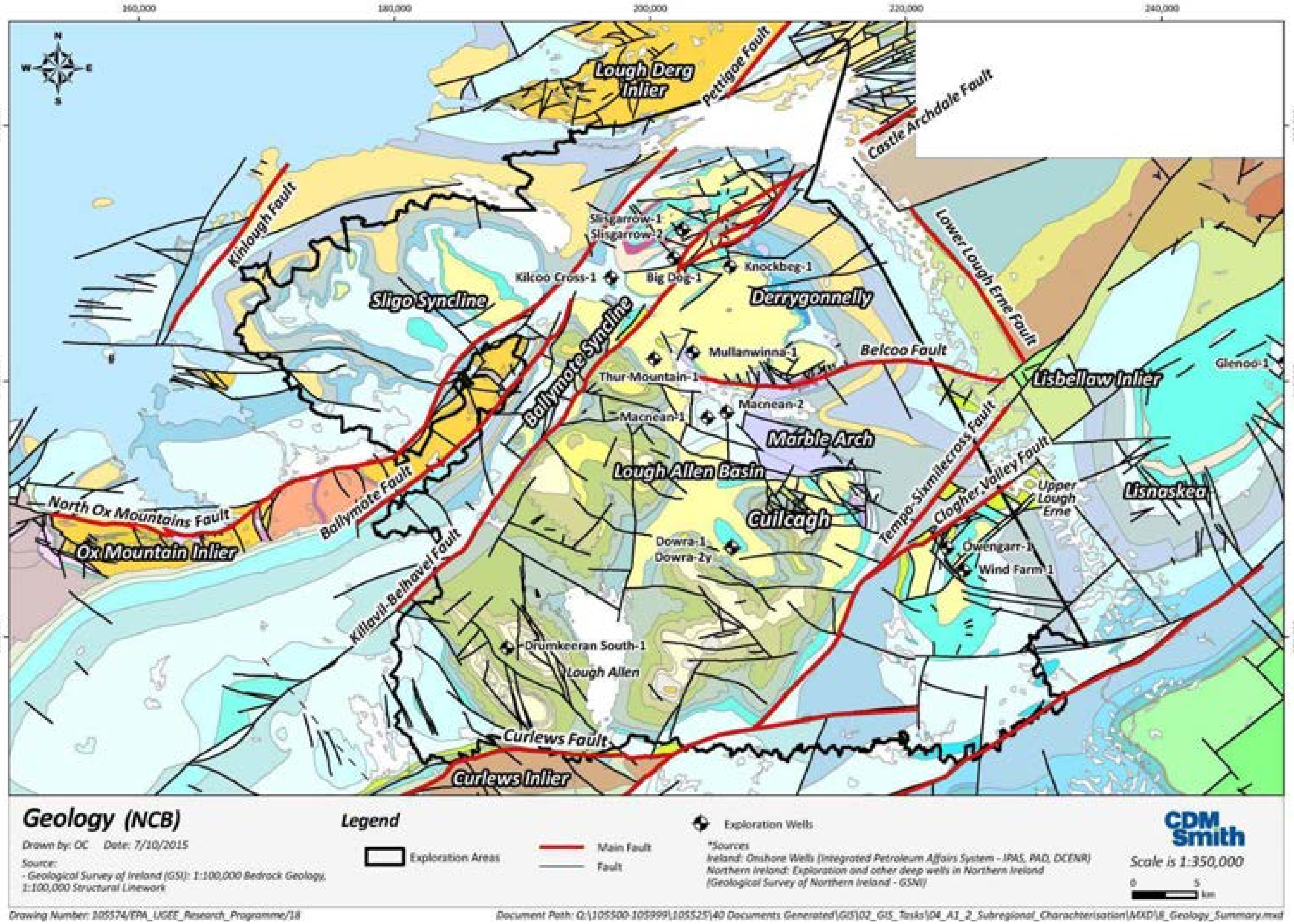


Figure 2.14. Geological subdivisions – NCB study area.

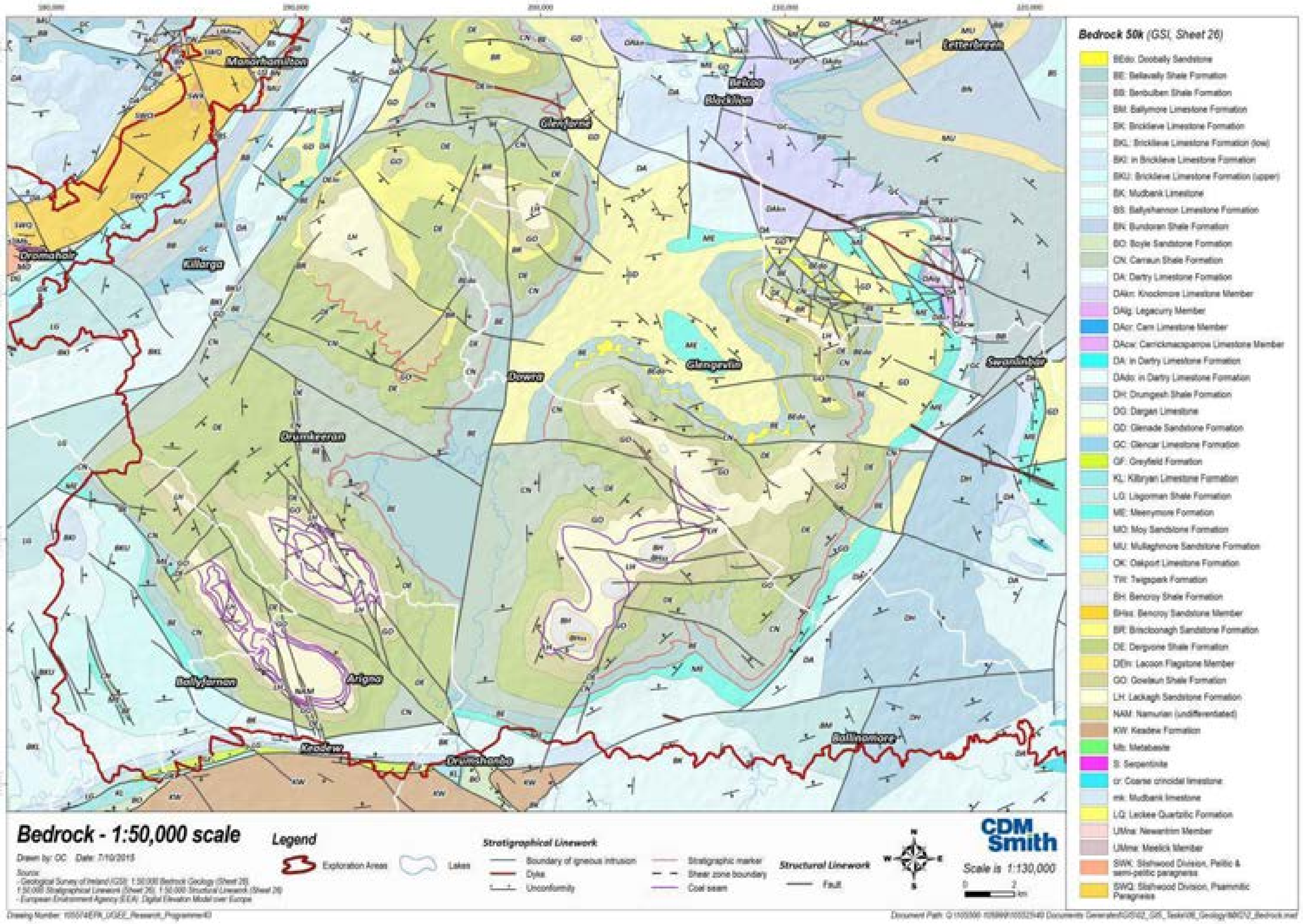


Figure 2.15. 1:50,000 scale bedrock geology map for Sheet 26.

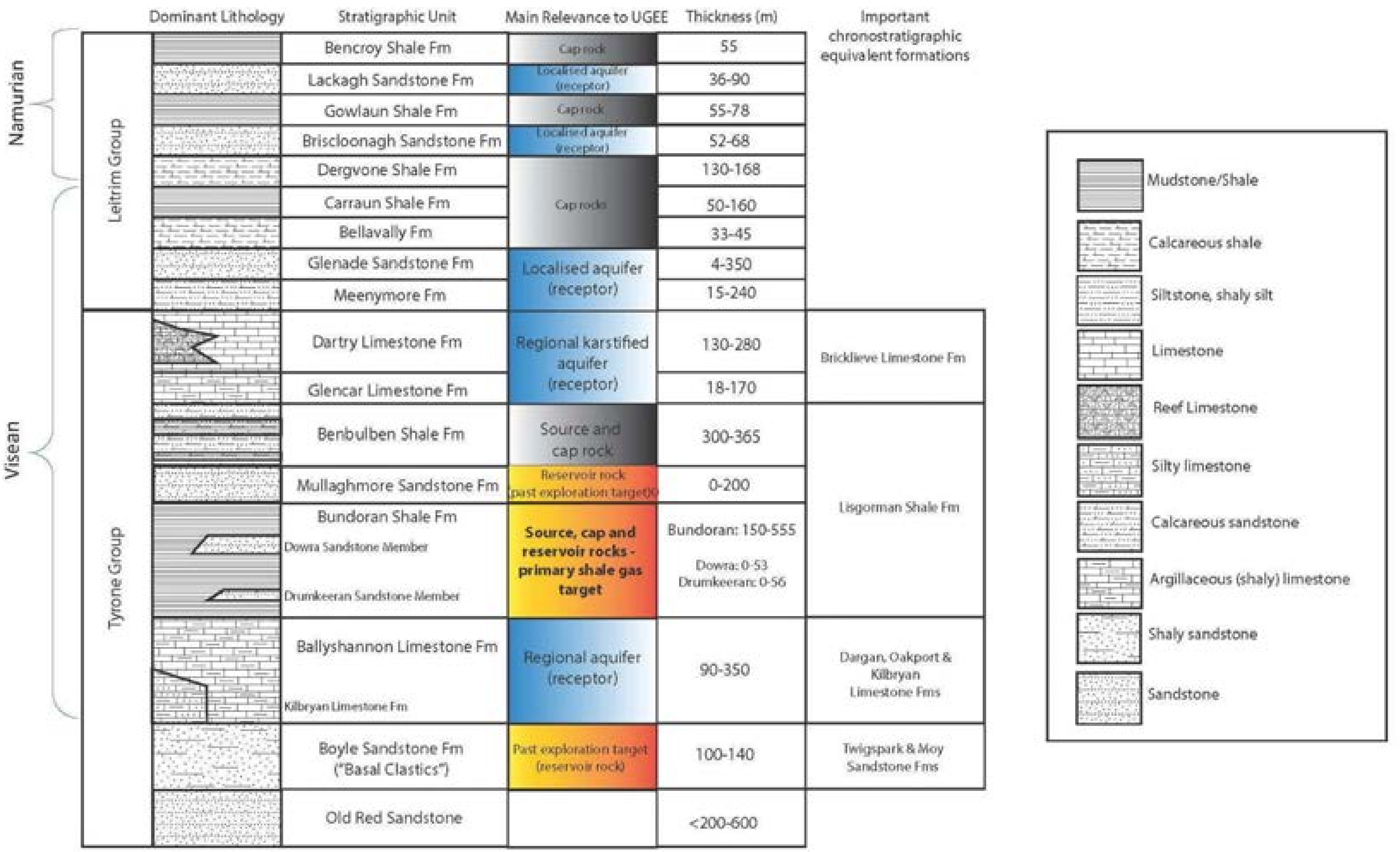


Figure 2.16. Simplified stratigraphy of the NCB study area.

Thickness and facies variations of the Basal Clastics, Kilbryan and Ballyshannon Limestone Formations, and the Bundoran Shale Formation reflect differential structural subsidence within the basin. The overlying Leitrim Group is of Middle and Upper Carboniferous (late-Viséan and Namurian) age and comprises mainly shale, mudstone and sandstone formations, some of which include thin and fossiliferous marine bands (as marker horizons) and which impart 'cyclicity' to the stratigraphic sequence (Legg *et al.*, 1998). The Leitrim Group rocks are mostly present on hilltops in the Lough Allen Basin, e.g. at Arigna, Slieve Anierin and Cuilcagh.

With regard to unconventional gas potential, the main source rocks of hydrocarbons, including natural gas, are the primary shale formations. Shales and argillaceous limestones can also be considered as potential cap rocks where they overlie reservoir rocks, e.g. the Benbulben Shale Formation is a potential cap rock for gas stored in the Mullaghmore Sandstone Formation.

Details of lithologies associated with individual formations in each of the geological subdivisions across the NCB are provided in Appendix C. For reference purposes, a stratigraphic correlation chart is shown in Figure 2.17 for the Sligo Syncline, Ballymote Syncline, and the Lough Allen Basin (to Lisnaskea, east of the Lough Allen Basin). Outcrop patterns for each of the main formations are shown in Appendix D.

2.7.1 Formations targeted for unconventional gas exploration

Past hydrocarbon exploration in the Lough Allen Basin (see Table 1.3 and Figure 1.3) has primarily targeted sandstones of the Tyrone Group, notably:

- The Mullaghmore Sandstone Formation;
- The Dowra and Drumkeeran Sandstone Members of the Bundoran Shale Formation; and
- The "Basal Clastics".

Marathon Oil Ltd. & Ambassador English Oil Co. drilled five exploration boreholes between 1962 and 1965, three of which were located within the Lough Allen Basin, one slightly outside the basin (Owengar), and one far removed from the basin (Glenoo). The Dowra and Drumkeeran Sandstone Members, as well as the Basal Clastics were tested for gas flows.

Aran Energy Plc re-entered an existing well (Dowra No. 1) and drilled four new exploration boreholes in the Lough Allen Basin between 1980 and 1984, targeting the gas testing activity on the Dowra Sandstone Member. Dowra No. 1 was hydraulically fractured (gel/sand) as a vertical well, increasing gas flow rates almost ten-fold compared to the result in the early 1960s, but the achieved flow rate could not be sustained (MacDermot *et al*., 1996).

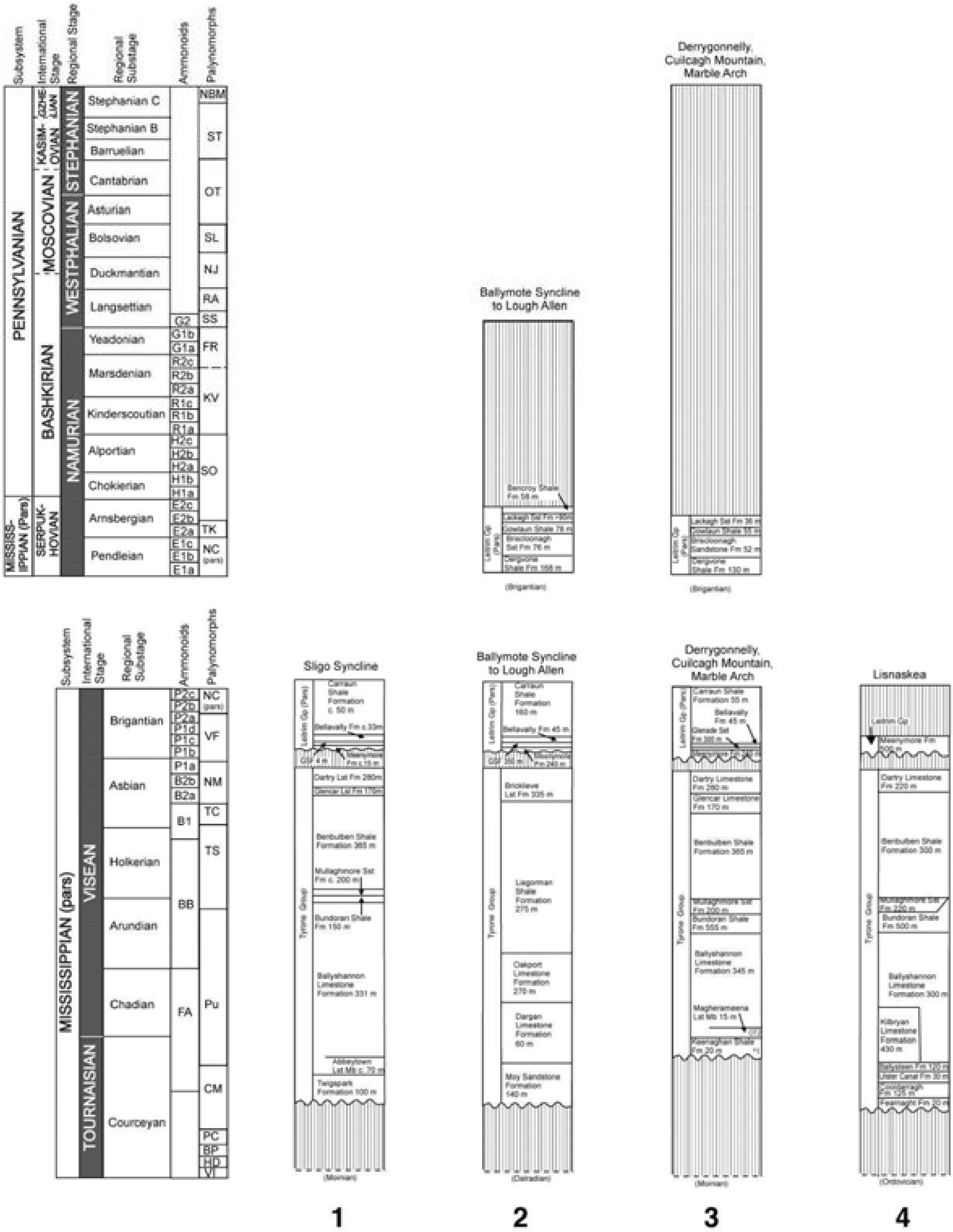


Figure 2.17. Compiled stratigraphical correlation chart for the NCB study area.

Evergreen Resources Inc. drilled six new exploration boreholes in and adjacent to the Lough Allen Basin in 2001 and 2002, targeting the Mullaghmore Sandstone Formation in each well tested and the Dowra Sandstone in one well (Dowra No. 2). Each of the wells were hydraulically fractured (gel/sand/N_2) as vertical wells, and extended well tests carried out, but gas flows were poor and many of the tests carried out in the Mullaghmore Sandstone were affected by inflows of formation waters into the wells (see Section 2.11).

Thus, the Dowra and Mullaghmore Sandstones have been the focus of exploration to date. The up to 50 m thick Dowra Sandstone Member of the Bundoran Shale Formation is not known to outcrop and does not appear on existing surface geological maps. Its extent is inferred from borehole logs, including Dowra (1 and 2), Macnean (1 and 2), Big Dog, Owengarr, Drumkeeran No. 1, Kilcoo Cross and Thur Mountain.

The Mullaghmore Sandstone Formation outcrops to the west and north in the NCB, and is up to 200 m thick. It thins to the south within the Lough Allen Basin and is described as a thin siltstone in Drumkeeran No. 1.

As recorded in well completion and subsequent interpretive reports, past drilling and testing has left many questions open about the gas prospect of the Lough Allen Basin. Even though gas “shows” have been reported in most of the Tyrone Group formations in most of the exploration wells drilled within the Lough Allen Basin to date, the same reports have concluded that gas production is not feasible or economical from the wells as drilled, installed and tested. Gas flow-testing has also indicated that the gas reservoirs of deeper sandstones are in part under-pressured, i.e. pore pressures are lower than hydrostatic pressure.

Despite the doubts that have been expressed about the hydrocarbon prospectivity of the NCB (e.g. Green *et al.*, 2000), re-interpretation of seismic survey data, spectral imaging and numerical modelling of hydraulic fracturing operations has suggested that horizontal wells in the Bundoran Shale Formation, including the Dowra Sandstone Member, may be able to sustain commercial production of unconventional gas in certain parts of the Lough Allen Basin (Schlumberger, 2005a, 2006). This has prompted a renewed focus on UGEE activity in the NCB, where the Bundoran Shale Formation has become the subject of unconventional gas attention (Reay, 2012), notably at Kilcoo Cross and near Lake Allen (e.g. Drumkeeran, Arigna and Dowra).

In the Drumkeeran No.1 well, gas shows were also reported from rocks of the Leitrim Group, notably in the Meenymore Sandstone and the Dergvone and Carraun Shales. The majority of the gas detections (as recorded and reported during drilling) were of “C1” gas (methane) with fewer detections and lower concentrations of C2 to C5 gas constituents (i.e. propane, ethane, butane, etc.). As outlined in Section 9, detections of the full range of C1 to C5 constituents would indicate that gas may be of thermogenic origin. In this context, it is important to note that thin bituminous coal seams are present within the Lackagh Sandstone Formation of the Leitrim Group, which were historically mined in the “Connaught Coalfield” surrounding Lough Allen.

Leitrim Group rocks are structurally too shallow to be considered for UGEE activity. Future plans for unconventional gas exploration and testing in the NCB target the Bundoran Shale Formation.

2.7.2 Depths of key formations

Structural positions and depths of unconventional gas target formations are important considerations in assessing the environmental risks of potential future hydraulic fracturing operations. Two relevant metrics are: a) depths to the unconventional gas target formation (i.e. depth of fracturing operations); and b) the ‘vertical separation distance’ (Davies *et al.*, 2012) between the hydraulic fracturing and near-surface receptors of potential contamination (see Section 2.7). In the case of the NCB, the primary unconventional gas target is the Bundoran Shale Formation, and the primary near-surface receptors are the groundwater resources (aquifers) that overlie the unconventional gas target. The regionally most significant groundwater resources are represented by the Dartry and Glencar Limestone Formations and their chronostratigraphic equivalents, although other formations (such as the Mullaghmore Sandstone Formation which directly overlies the Bundoran Shale Formation) are also of hydrogeological relevance.

Indicative depth ranges of the named formations in the NCB are summarised in Table 2.3, as derived from available well completion and interpretive reports. With regard to the metrics referenced above:

- The depth to the top of the Bundoran Shale Formation (source rock) ranges between 493 and 973 m below ground surface in exploration wells drilled to date. This range corresponds to elevations (referenced to Ordnance Datum) between –390 mOD and –783 mOD. The large range partly reflects folding and the considerable faulting that characterises the NCB study area (described in Section 2.6).
- The vertical separation distances between the top of the Bundoran Shale Formation and the base of the Dartry/Glencar limestone aquifer system ranges between 272 and 570 m where data exist.

Vertical separation distances between UGEE target formations and overlying aquifers is a topic of considerable debate in international literature (e.g. Davies *et al*., 2012), in context of the potential fracture propagation that may result from hydraulic fracturing programmes, which is both case- and site-specific.

Finally, from Table 2.3 it can be inferred that hydraulic fracturing wells in the Bundoran Shale Formation would have to be drilled to minimum depths of 700–1300 m in order to reach the middle sections of the formation in the Lough Allen Basin, depending on location within the basin.

Table 2.3. Depth ranges of key formations in exploration wells

	Slisgarrow (210 mOD)[a,b]	Big Dog (183 mOD)[a]	Knock Beg (332 mOD)[a]	Kilcoo Cross (110 mOD)[a]	Mullana-winna (80 mOD)[a]	Thur Mountain (129 mOD)[a]	Macnean (60 mOD)[a,b]	Dowra (120 mOD)[a,b]	Drumkeeran (251 mOD)[a]	Owengarr (102 mOD)[a]	Glenoo (181 mOD)[a]
Formation/ Member	**Approximate depths to top of formation (m below ground surface)**										
Dartry Limestone	81–161	0–91[c]	118–302[d]	0–79	64–378[d]	140–509[d]	0–192	58–414	213–674	0–186[c]	0–36[c]
Glencar Limestone	161–180			79–250			192–244	414–488	674–701		
Benbulben Shale	180–560	>91[c]–408	302–620	250–448	378–710	509–759	244–407	488–737	701–932	>186[c]–485	>36[c]–343
Mullaghmore Sandstone	560–750	408–625	620–777	448–666	710–863	759–896	407–493	737–847	932–973	485–591	343–571
Bundoran Shale	750–1176	625–1180	777 (TD[e] = 909)	666–1103	863 (TD[e] = 973)	896–1420	493–980	847–1307	973–1645	591–1085	571–1042
Ballyshannon Limestone	1176–1,926[f]	1180–1524	–	1103–1441	–	1420->1431 (TD)[e]	980–1245	1307–1566	1645–2030	1085–1294	1042–1317
Vertical separation distance (m) between base Dartry/Glencar and top Bundoran	570	534	475	416	485	387	249	359	272	405	535

[a]Approximate ground surface elevations

[b]Slisgarrow 2 depths are used to the top of the Bundoran. The borehole ended in the Bundoran, thus Slisgarrow 1 data are used below the top of the Bundoran. Slisgarrow 2 log is more recent. Same applies to the Macnean and Dowra pairs of wells.

[c]Base of Dartry is defined as “top of Upper Calp Shale” in older log, but this is not directly equivalent to the Benbulben Shale Formation.

[d]Logs report Dartry/Glencar as one unit.

[e]TD = total depth

[f]Some of the Bundoran Shale Fm may be cut out by fault in this well.

2.8 Basin Structures

The NCB is a structurally complex, fault-bounded sedimentary basin (Price and Max, 1988; Philcox *et al*., 1992; Mitchell, 2004c; Worthington and Walsh, 2011). Faulting also shapes internal basin structures. The NCB is interpreted to be a "pull-apart" basin as described by Mann *et al.* (1983) and Quinn (2006). Such basins are shaped by extension forces resulting from strike-slip (lateral) movements of the earth's crust. In the case of the NCB, the strike-slip faults, as reproduced in Figure 2.18 (Worthington and Walsh, 2011), are of regional significance. These faults have a dominant NE-SW trend, and are associated with the structural development of the "Caledonides", a chain of mountains which extend from Scandinavia through New Brunswick and the Appalachians in North America and where similar structural basins host unconventional gas resources.

Based on stratigraphic correlations from geological mapping and borehole data, as well as interpretations of seismic and gravimetric survey data, Price and Max (1988) and Philcox *et al*. (1992) described fault blocks that form deep structural highs and lows, where deep regional fault structures accommodate more than 500 m of vertical displacement. This is shown conceptually in Figure 2.19, which is reproduced from Worthington and Walsh (2011) and which follows the red line marked "Fig 5a" in Figure 2.18. It identifies the "Ballyshannon High" (west towards the Sligo Syncline) and the "Dowra-Macnean High" (in the Lough Allen Basin).

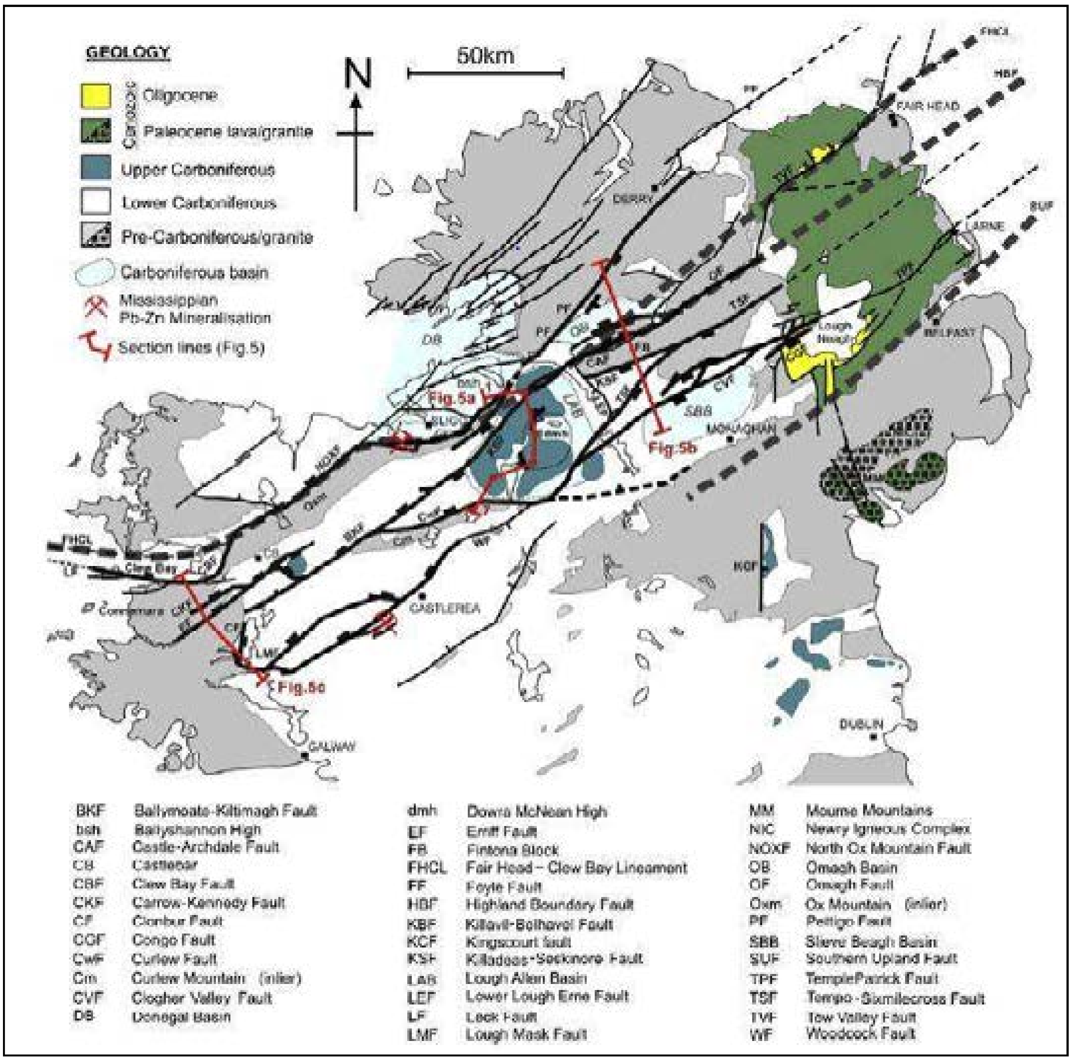
The Kilavil-Belhavel Fault in Figure 2.19 marks the approximate western extent of the Lough Allen Basin (see Figure 2.14), described further below, as well as the position of the "*Drumkeeran-Slisgarrow Trough*" which was described by Legg *et al*. (1998), where faulting has resulted in sequence thickening of deeper formations such as the Ballyshannon Limestone.

2.8.1 Sligo Syncline

The Sligo Syncline is a regional NE-SW trending syncline with shallow limbs that dip gently at 5–15˚. The NE-SW trending Kinlough Fault cuts through the Tyrone Group with mapped displacements in the order of tens to several hundred metres, depending on position within the structure. The Kinlough Fault appears to splay off from the North Ox Mountain Fault which bounds the Sligo Syncline at the faulted contact with the Ox Mountain Inlier to the east. A perpendicular, NW-SE trending cross-fold is mapped to the NW of Manorhamilton at the northern end of the Ox Mountain Inlier.

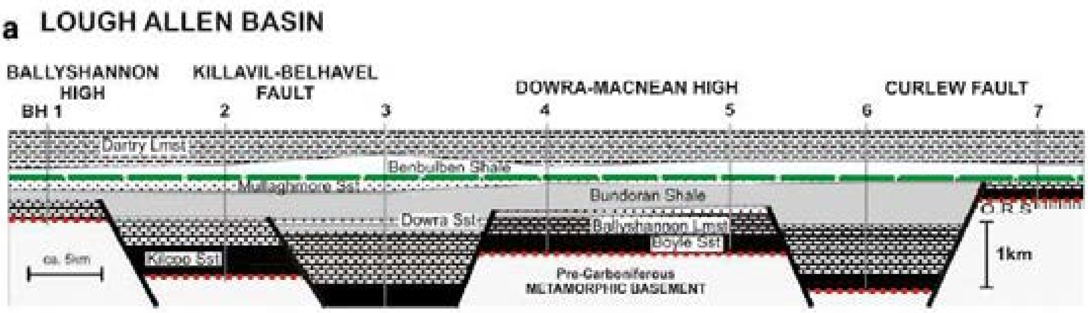
2.8.2 Ballymote Syncline

The Ballymote Syncline is a regional NE-SW trending syncline structure with limbs that dip mostly less than 10˚. The structure is bounded to the NW by the Ox Mountain Inlier and to the SE by the Curlew Mountain Inlier. The NE-SW trending Kilavil-Belhavel Fault intercepts the structure in the Bricklieve Mountains near Lough Arrow, effectively dividing the main syncline into: a) Ballymote to the NW of the fault; and b) Lough Allen to the SE of the fault. Variations in the plunge of the fold axis gives the Ballymote Syncline a 'dome and basin' appearance which is further intercepted by NW-SE faults.



Source: Worthington & Walsh, 2011

Figure 2.18. Simplified diagram of regional fault structures. Reproduced with permission from Elsevier.



Source: Worthington & Walsh, 2011

Figure 2.19. Conceptual section of structural highs and lows across the NCB. Reproduced with permission from Elsevier.

2.8.3 Lough Allen Basin

The Lough Allen Basin is a regional, fault-bounded and gentle NW-SE trending syncline structure which plunges at low angles to the west-northwest and incorporates the Derrygonnelly, Cuilcagh Mountain and Lough Allen areas. It is fault-bounded by the regionally significant and NE-SW trending Kilavil-Belhavel Fault to the west, the Curlew Fault to the southeast and east, and the 'Lower Lough Erne Fault' to the north. The latter marks the southern boundary of the "Fintona Block", a faulted sequence of older Devonian rocks to the north of Lough Erne.

Secondary folds and flexures are superimposed on the main structure with a similar NW-SE trend but shorter wavelengths. These include the Arigna Anticline, Macnean Anticline, Cuilcagh Syncline, and Owenmore Anticline. Dips are generally gentle (less than 20˚) except near major fault lines where drag folds, shorter fold wavelengths, and resulting greater dip angles (40–50˚) can be observed. Valleys tend to correlate with axes of anticlines, and hilltop ridges (e.g. Cuilcagh) tend to correlate with axes of synclines. Many fold structures are cross-cut by faults, which affect outcrop patterns on both a sub-regional and local scale.

2.8.4 Faults

Faulting in the NCB is complex. Strike-slip faults are of regional extent and trend mostly NE-SW and E-W. These faults can display both lateral and vertical displacement of rocks. Strike-slip faults include the Killavil-Belhavel Fault and the Curlew Fault in Ireland, which appear to extend as the Castle-Archdale Fault, and the Clogher Valley/Tempo-Sixmilecross Faults in Northern Ireland, respectively (see Figure 2.18). Deformations along the NE-SW trending structural lines are significant. For example, the Killavil-Belhavel Fault is marked both by lateral strike-slip movement measured on the km-scale (Cooper *et al*., 2012) and by vertical displacements of several hundred metres (Worthington and Walsh, 2011). It has been noted that downthrow is mostly to the NW in the southern part of the NCB and to the SE in the northern part of the NCB (Worthington and Walsh (2011). The NE-SW trending strike-slip faults extend throughout the Carboniferous sequence of rocks and by inference they were active through the Carboniferous Period. They also offset Paleogene (Tertiary) dykes (Cooper *et al*., 2012) indicating that strike-slip movement was also active through the Paleogene Period. The strike-slip faults show an apparent sinistral (left-lateral) movement.

As mapped by the GSI and GSNI, the regional strike-slip faults have created conjugate sets of normal and reverse faults that trend mainly NW-SE, WNW-ESE and NNW-SSE. The NW-SE faults are particularly prevalent in the Lough Allen Basin, and the combined geometry of the faulting divides the region into distinct fault blocks with 'horst and graben' structures. Millar (1990) concluded that the majority of faults are of an extensional nature, and also documented that strike-slip faults tend to be steeper (60–90˚) than normal/reverse faults (10–80˚). There are numerous examples of 'inversion faulting' in the NCB, whereby formations are uplifted relative to others, e.g. in the Ballymote Syncline between Manorhamilton and Lough Erne. Price and Max (1988) noted that NE-SW trending faults between the Kilavil-Belhavel and Curlew Faults (which passes E-W just south of Lough Allen) result from regional dextral stress patterns. Similar conclusions about dextral and extensional stress patterns within the Lough Allen Basin were noted by Legg *et al*. (1998) in relation to observed offsets of formations along the E-W trending Belcoo Fault near Cuilcagh Mountain.

Figure 2.20 is a useful 'reference cross-section' at the regional scale, sourced from MacDermot *et al.* (1996). It covers the entire basin, includes the entire relevant stratigraphic column for the UGEE Joint Research Programme, and demonstrates the regional structural controls on basin geometry. The section runs from NW to SE across the NCB, from the coastline in the Sligo Syncline, through the Ox Mountain Inlier, through the Lough Allen Basin and to the Curlew Mountains in the southeast.

The cross-section does not capture structural details within the NCB. For example, Figure 2.21 shows the GSI-published geological map of the Manorhamilton area, which is marked by extensive faulting and steeply E-SE dipping beds at the eastern margin of the Ox Mountain Inlier. The formations are step-faulted and folded such that the Ballyshannon Limestone Formation, which outcrops near the Ox Mountain Inlier, becomes deeply buried over a relatively short distance of only a few kms. ERA (1986) noted that steep dips towards the Ballymote and Killavil-Belhavel Faults occur within narrow zones which are accompanied by fault-breccia development. The Ox Mountain and Curlew Mountain Inliers are similarly associated with parallel-step normal faults, each with total vertical displacements of several hundred metres. Figure 2.21 also indicates how the Mullaghmore and Ballyshannon Limestone Formations can occur alongside the Bundoran Shale Formation due to fault displacement. At a location immediately to the west of Derrygonnelly, the Dartry and Glencar Limestone Formations are juxtaposed against both the Bundoran Shale and Ballyshannon Limestone Formations.

2.8.5 Fracture patterns

The NCB is extensively faulted and structural deformation has resulted in fracturing of bedrock. Units that are of a brittle nature (e.g. consolidated sandstones, limestones, and volcanics) are more susceptible to fracturing than units that are of a ductile nature (e.g. shales and mudstones), as the latter have a greater content of argillaceous materials (i.e. clay minerals). The Benbulben Shale Formation is mainly a calcareous shale, with minor limestone and siltstone (e.g. in the Drumkeeran No. 1 well as described in Aran 1985b). The implication is that shale and mudstone formations can also exhibit brittle rock characteristics depending on lithological detail. From petrographic studies, Tamboran (2012) references the brittle nature of the Bundoran Shale Formation as an attribute and reason for targeting hydraulic fracturing in this formation.

Available information on fracture patterns is derived mainly from detailed mapping by Millar (1990), Brown (2005) and initial publication by Moore and Walsh (2013). The literature documents a strong N-S component to joints and veins, as well as important secondary fracture components oriented WNW-ESE. Millar (1990) mapped fracture sets in Carboniferous rocks at 96 locations (‘stations’) across the NCB, involving more than 12,000 measurements. As shown in Figure 2.22, a dominant N-S orientation emerged overall (note, horizontal line = E-W), but differences were noted in the various ‘sub-basins’ of the NCB, e.g. Millar’s ‘Killavil-Belhavel Fault’ subdivision (in the Ballymote Syncline) displays a more prominent NNE-SSW fracture set compared to the ‘Lough Allen Basin’ subdivision.

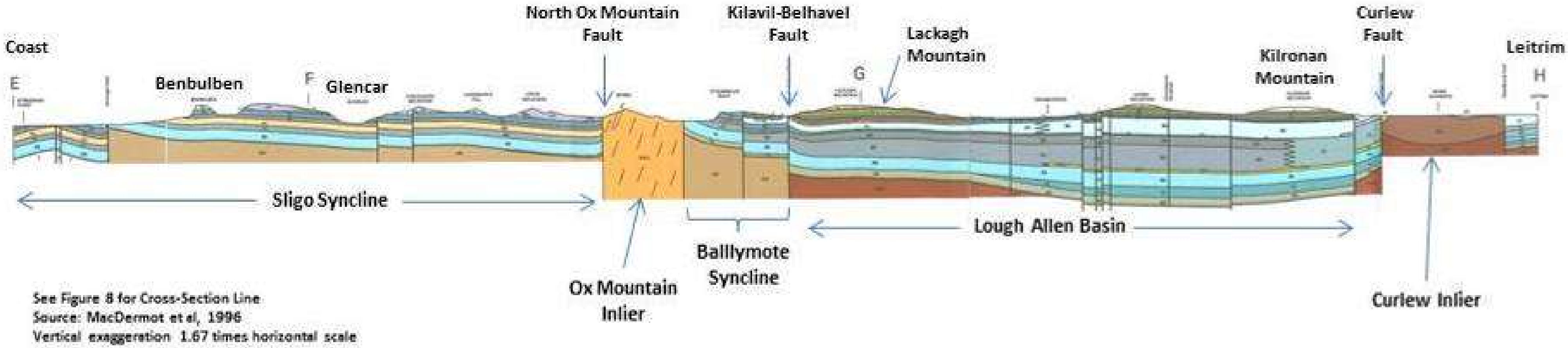
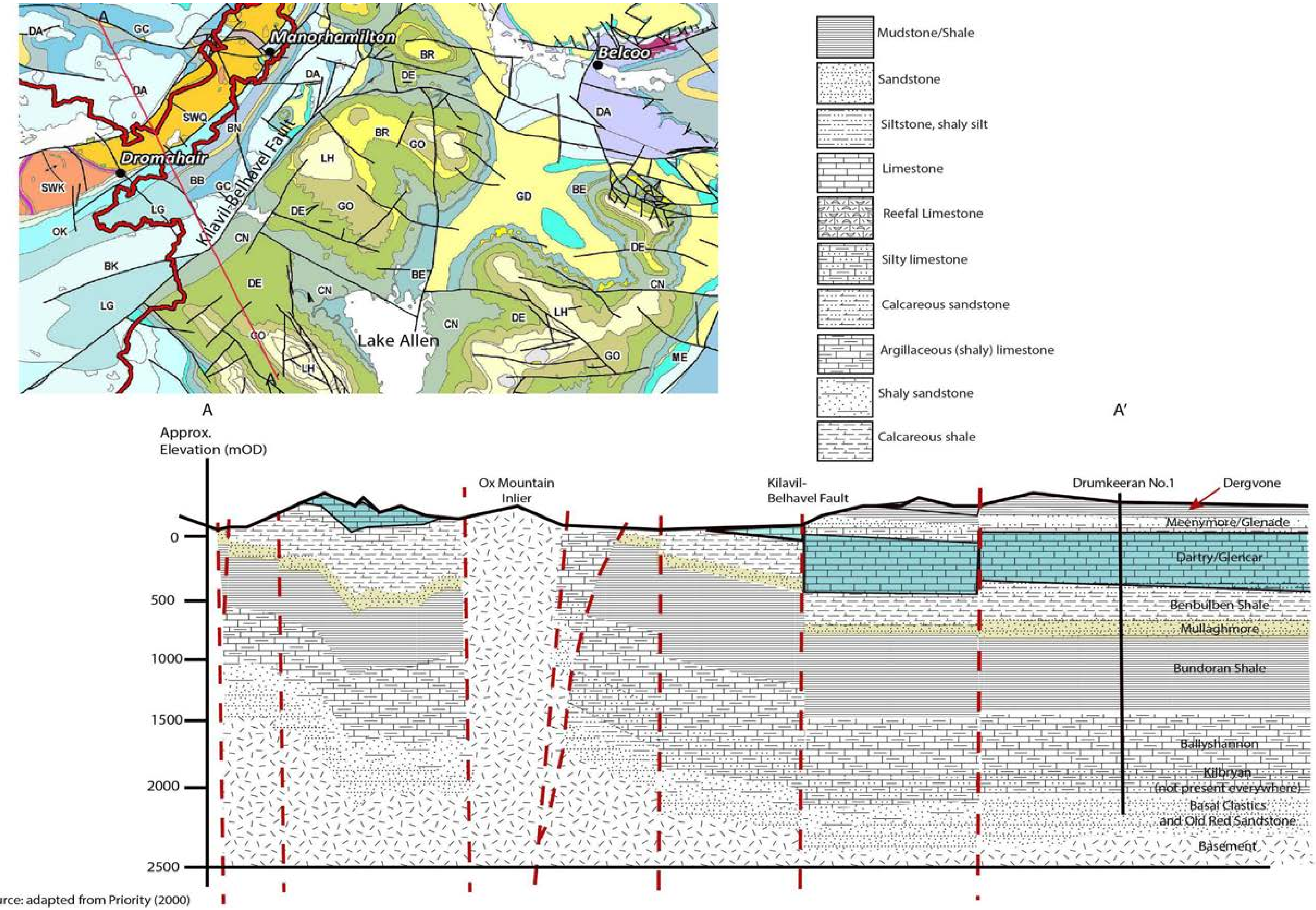


Figure 2.20. Simplified regional cross-section across the NCB. © Geological Survey Ireland.



Source: adapted from Priority (2000)

Figure 2.21. Sketch of step faulting near the Ox Mountain Inlier (from Priority Oil & Gas, 2000).

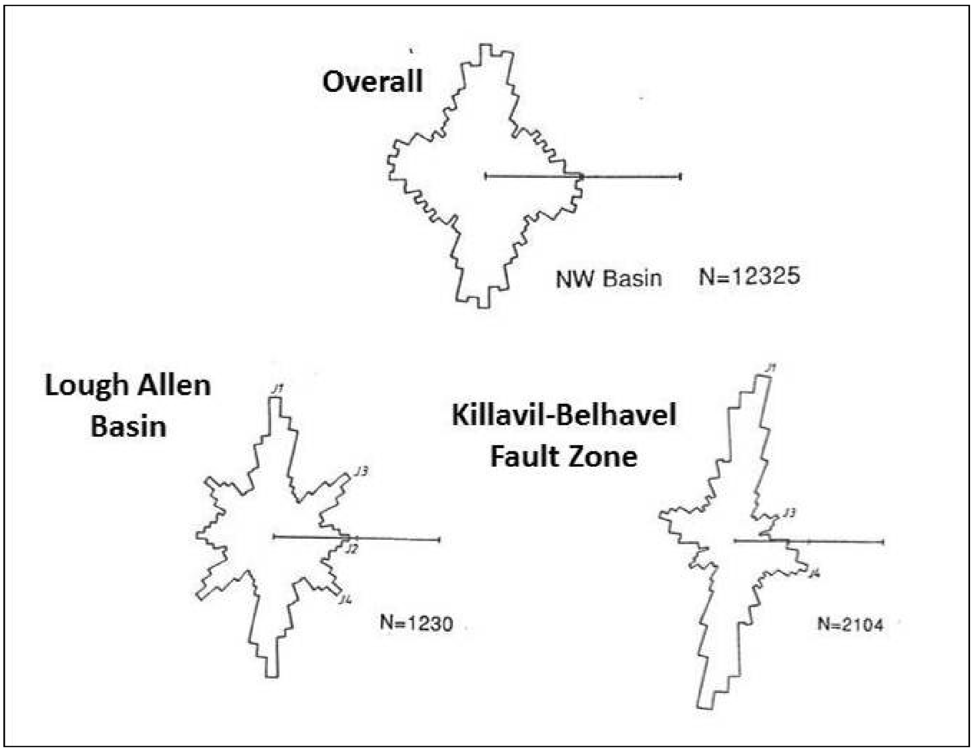


Figure 2.22. Mapped fracture orientations in the NCB study area (from Millar, 1990).

Millar (1990) further examined whether fracture patterns were different in sandstones and limestones, and concluded that fracture trends are similar in both lithologies. Millar (1990) also proposed a relative sequence of fracture development, and observed that NE-SW and N-S fractures are present throughout the Carboniferous succession. The N-S overprint is supported by the mapping of other location-specific researchers, e.g. Brown (2005) in the Cuilcagh Mountains, Heaney (1991) in the Dartry Hills in Co. Leitrim, and Thorn *et al*. (1990) in the karst of Co. Sligo. The work by Brown (2005) includes fracture orientation measurements below ground in cave systems. The data highlight secondary NW-SE and WNW-ESE fracture patterns as well, which confirms measurements by Millar (1990). N-S joints have been assigned importance with regard to cave development in different areas of the NCB (Burns, 1985; Thorn *et al*., 1990). It is further noted that several cave systems mapped by speleologists in Co. Fermanagh have approximate and principal N-S and NW-SE orientations (Burns, 1985; Brown, 2005).

Regional scale lineament analyses from Landsat imagery were conducted by both Millar (1990) and ERA (1986). Both reported NE-SW, NW-SE and WNW-ESE lineaments, the former being dominant. Millar (1990) noted that although fewer in number, the WNW-ESE lineaments appear to be regionally as significant as the NE-SW lineaments due to their persistence (continuous lengths) across the region. Both ERA (1986) and Millar (1990) noted that the WNW-ESE lineaments may be associated with a sinistral component of movement.

The dominant N-S, E-W and NW-SE fracture and lineament components are recognisable in the bathymetries of Lough Allen, Lower and Upper Lough Macnean, and Lough Melvin, see Figure 2.23, thus a structural geological influence on lake bathymetry is inferred.

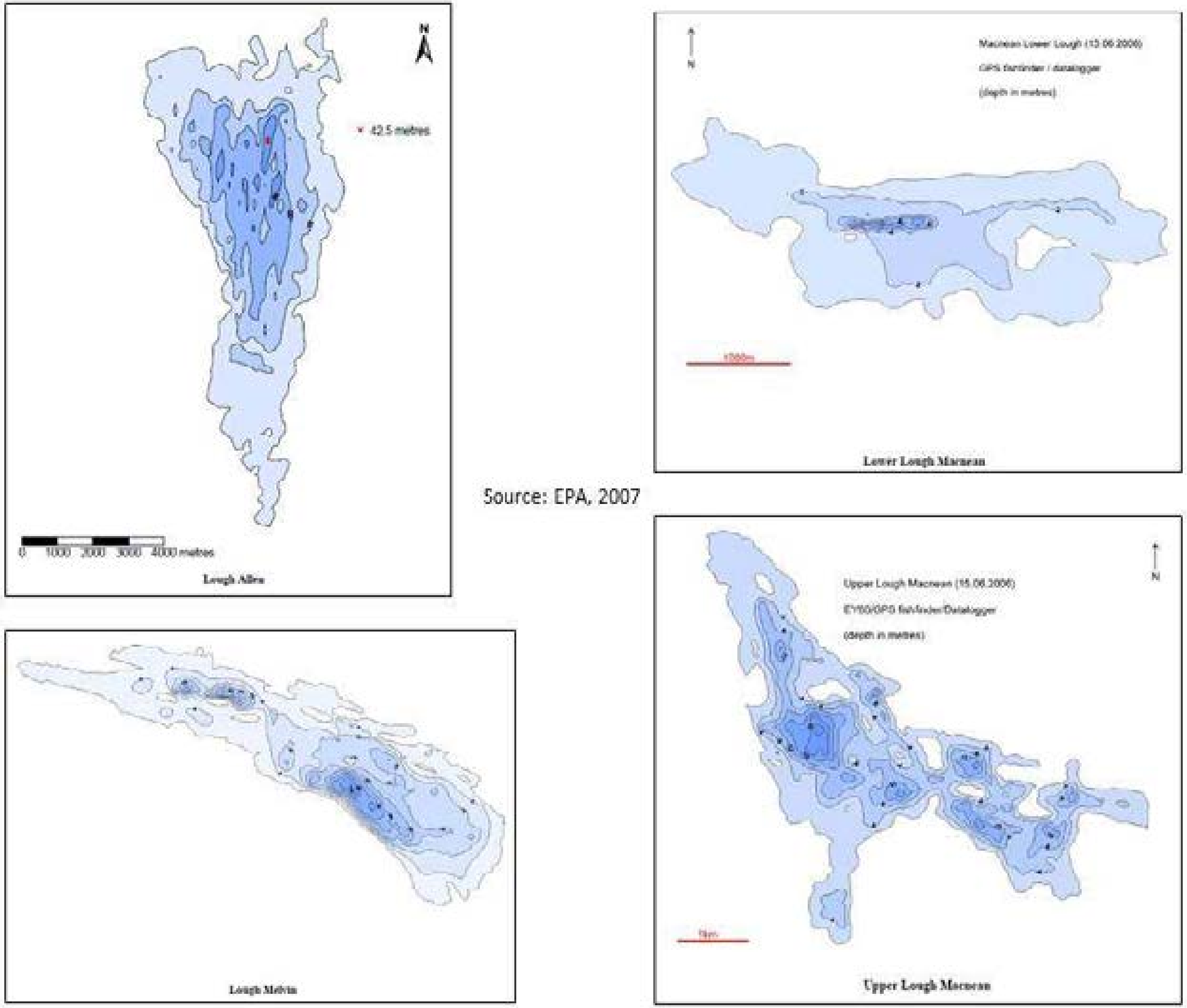


Figure 2.23. Inferred structural influence on lake bathymetry.

From ongoing study of fracture patterns and groundwater potential in post-Devonian (mainly Carboniferous) rocks, Moore and Walsh (2013) summarised the relationship between faults and fracture patterns as depicted in Figure 2.24. This 'model' combines elements of Tertiary (Paleogene) strike-slip movement which is re-activated along older ('Caledonian') NE-SW fault structures and which both cross-cuts normal faults and generates shear structures (including veins) at oblique angles to the main NE-SW trending structures.

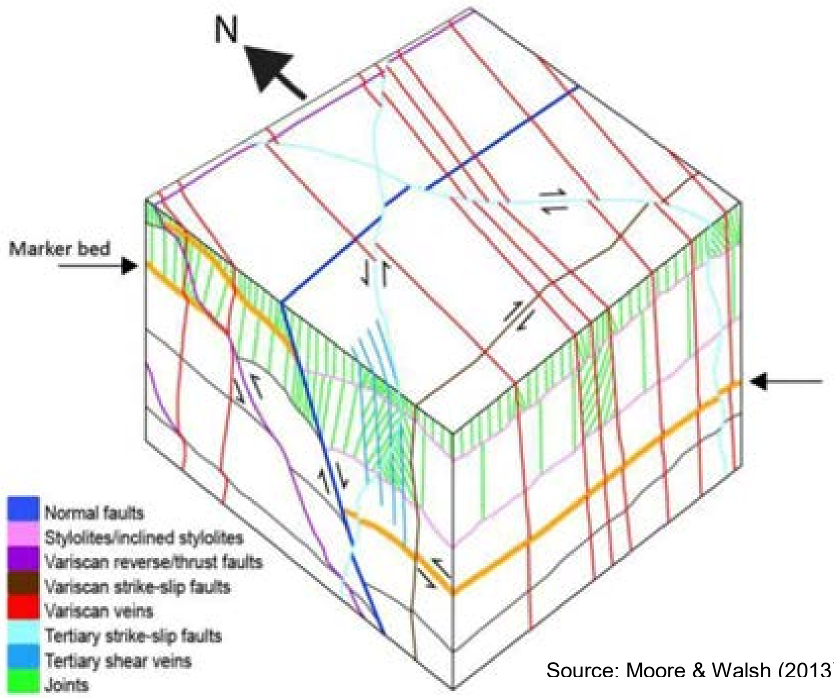


Figure 2.24. Schematic diagram of post-Devonian fault and fracture systems. © Geological Survey Ireland.

Finally, veins in the Lough Allen Basin have been explored for mineral exploitation, including zinc, gold, and barite. The former Benbulben mine works at Glencarbury exploited a near vertical and NNW-SSE oriented barite vein which is 3 m across on average and approximately 2.5 km long (McAteer and Parkes, 2004).

2.8.6 Dyke swarms

Dykes are linear igneous bodies which have intruded through the host rock. They tend to occupy pre-existing discontinuities or fractures and fissures that may have opened at the time of their formation. Most dykes are composed of dolerite or basalt that is jointed and/or fractured. Many dykes also display faulted margins which indicate post-intrusion movement of the structures they occupy.

They can be regionally or locally important, depending on the scale of intrusion (width and length), and dykes can act to compartmentalise a rock volume to some degree. Within the NCB, the single largest mapped dyke is the 'Cuilcagh dyke' (GSNI, 1998) which trends WNW-ESE along the northern margin of Cuilcagh Mountains. As explained in Section 2.9.2, this dyke appears to exert a hydraulic influence on groundwater flow in the karst of the Cuilcagh Mountains.

The acquisition and interpretation of Tellus Border aerial geophysical datasets (Cooper *et al*., 2012; Anderson *et al*., 2013; Young and Donald, 2013) has revealed numerous Paleogene dykes in the region of study. As shown in Figure 2.25, five different dyke swarms were identified from Tellus magnetic imagery (Anderson *et al*., 2013). Two of these, the Killala and Erne dyke swarms, cross the NCB with an approximate WNW-ESE trend. It should be noted that the resolution of the Tellus surveys does not allow for all possible dykes to be imaged regionally (Young and Donald, 2013).

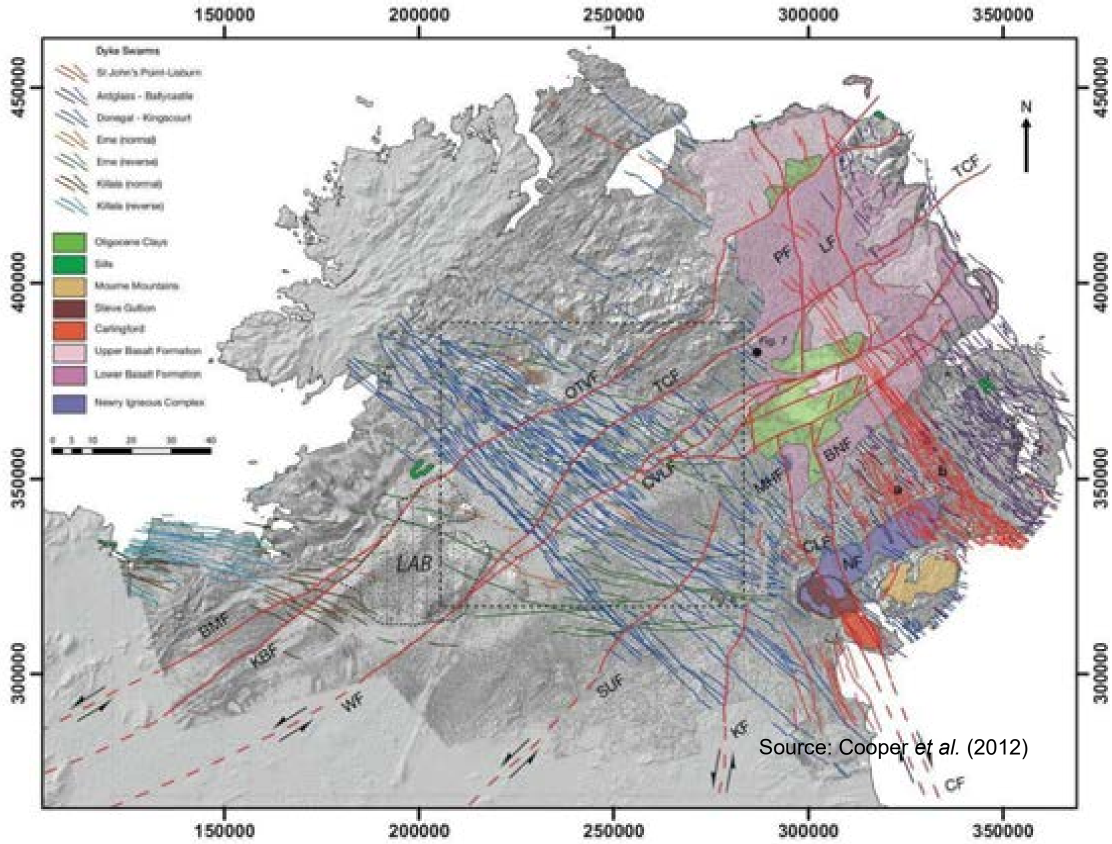


Figure 2.25. Dyke swarms interpreted from Tellus Border data.

The resolution of the imagery also has the effect of grouping a number of thin dykes into single entities where they are closely spaced, such that they appear as a single anomaly rather than individual linear features. In Northern Ireland, relationships have been identified which support syn- and post-magmatic faulting of the dyke swarms (Cooper *et al*., 2012). For example, sinistral lateral offsets across the Tempo-Sixmilecross and Omagh Thrust faults of up to 2.5 km and 0.65 km respectively, have been mapped, which suggests that the regional NE-SW trending faults were active also after the Paleogene Period.

2.9 Hydrogeology

The hydrogeology of the NCB is defined by three types of groundwater flow systems:

- Conduit flow systems in karstified limestone rocks;
- Fracture flow systems in fractured bedrock (including non-karstified limestones); and
- Interstitial flow systems in unconsolidated sand and gravel deposits.

2.9.1 Conduit flow systems in karstified limestone aquifers

The principal aquifers in the NCB are karstified limestone aquifers, mainly represented by the Dartry Limestone Formation. The Ballyshannon Limestone Formation is also karstified but does not exhibit the widespread cave systems that define the Dartry limestones.

The limestones represent the primary groundwater resources in the region. They are used for water supply purposes and are of ecological significance, which implies they are the primary resources at risk from environmental pollution. Karst conduits also act as preferential pathways for groundwater flow, which makes associated receptors such as water supplies and groundwater-dependent ecosystems particularly susceptible to contamination.

As indicated in Figure 2.26, the Dartry and Ballyshannon Formations are classified as *'Rkc*' or '*Rkd*' aquifers in Ireland, and as '*Bh(f-k)*' aquifers in Northern Ireland, by the GSI and GSNI, respectively. As presented in Appendix E, the '*Rkc*' designation refers to a regionally important karstified limestone aquifer in which movement of water takes place primarily via conduits, e.g. solutionally enlarged fissures and cave systems. The '*Rkd*' designation refers to a regionally important karstified limestone aquifer in which movement of water takes place primarily via fractures and fissures rather than conduits, although some conduit flow may also be present. The '*Bh(f-k)*' designation in Northern Ireland refers to a '*highly productive aquifer*' which has a karstic element to groundwater flow.

Figure 2.27 shows karst features that are currently available in the karst databases of the GSI and GSNI. It should be noted that this may not be a comprehensive register of all existing karst features, rather it reflects features which have been mapped and recorded in the database to date. Karstification is evidenced by landforms and hydrological features such as enclosed depressions, dolines, dry valleys, turloughs, swallow holes and springs. Significant cave systems are present across the NCB, including Marble Arch caves in Co. Fermanagh, Bricklieve caves in Co. Sligo, Shannon caves in Co. Cavan, and North Dartry caves in Co. Leitrim. The karst systems of the Dartry and Bricklieve Limestone Formations have undergone hydrogeological study in the past (e.g. Gunn, 1982, 1996, 1997; Thorn, 1985; Thorn *et al*., 1990; Kelly *et al*., 2003; Brown, 2005), including dye tracer studies which established connection points between sinking streams and resurgences at springs.

In the Cuilcagh Mountains, the limestone units of the Glencar Limestone Formation also transmit groundwater. There are no references to cave development in the Glencar limestones, and the degree to which the Glencar is karstified is not clear. Brown (2005) considers the shales towards the top of the Glencar as a likely barrier to further karst development vertically.

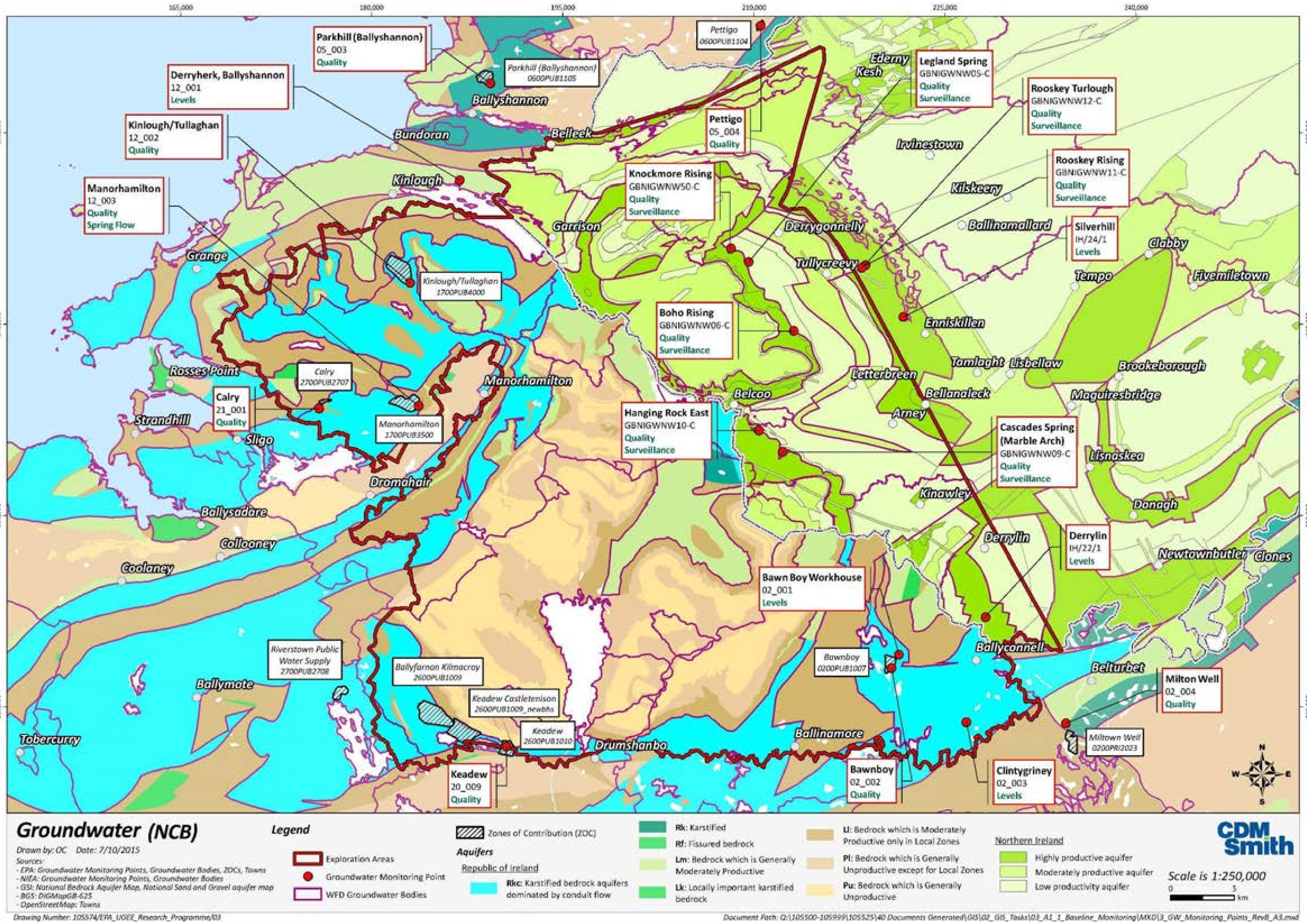


Figure 2.26. Bedrock aquifer types and WFD monitoring points – NCB study area.

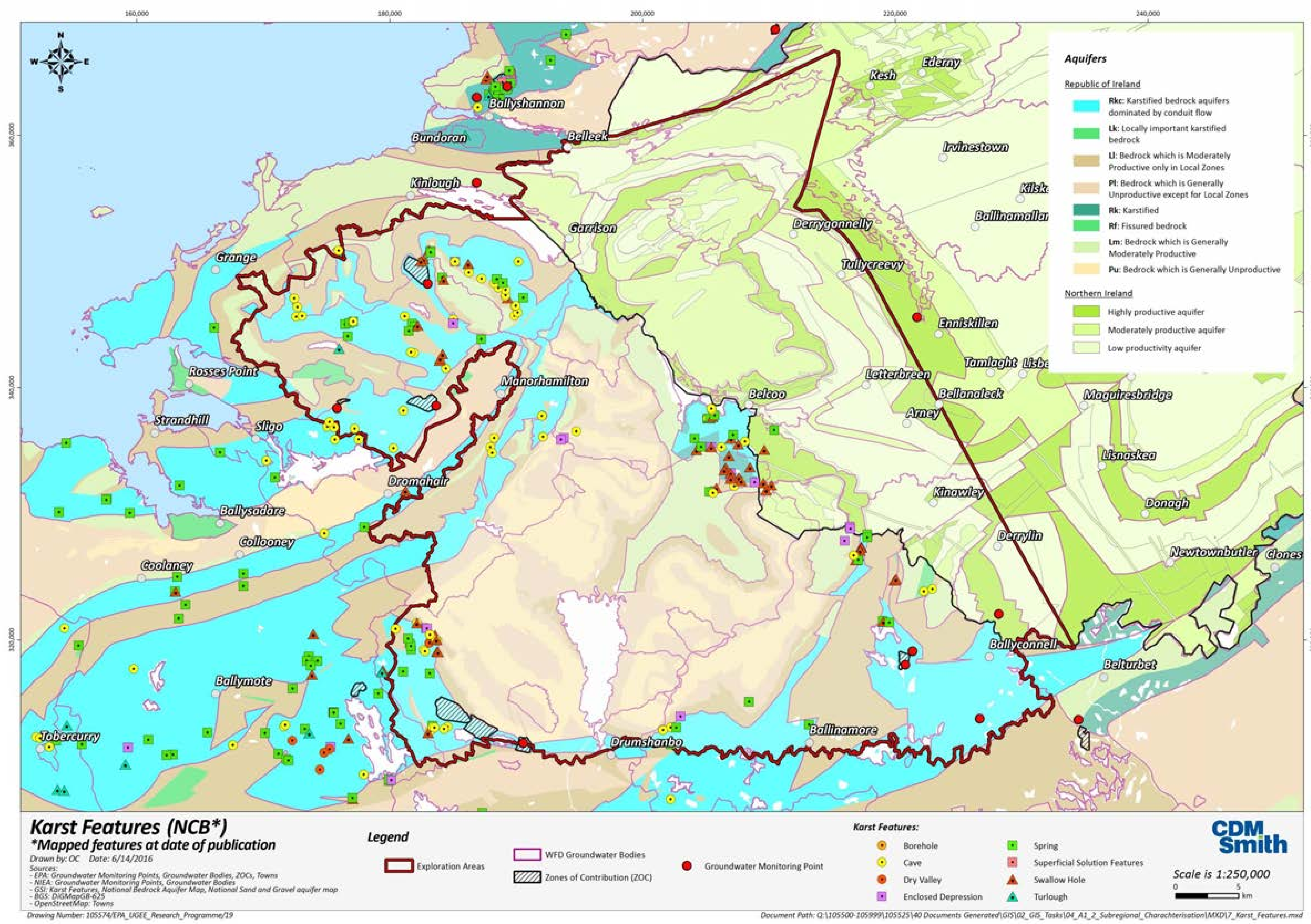


Figure 2.27. Karst features in existing databases in the NCB study area.

Thus, conceptually, the depth to the base of the Dartry Limestone Formation (and its chronostratigraphic equivalents) represents a possible maximum depth of karstification.

Even if the Glencar is not extensively karstified, groundwater in the two formations may still be hydraulically connected via open fracture networks. Accordingly, the Dartry and Glencar Limestone Formations may act as a single hydrogeological unit across much of the study area. The chrono-stratigraphically equivalent formation, the Bricklieve Limestone, also serves as an important karstified limestone aquifer to the south in the Bricklieve Mountains and Ballymote Syncline.

Available karst studies in the region provide important insights into the main characteristics and functionality of the regionally important karst aquifers. Specifically:

- The karst gives rise to several important rivers and streams throughout the region;
- The karst provides supporting conditions for groundwater dependent lakes and associated (terrestrial) ecosystems; and
- The karstic flow systems are important sources of public water supply.

The main hydrogeological characteristics of the karstified flow systems can be summarised as follows:

- Groundwater flow is complex and difficult to predict. Flow takes place along discrete and interconnected conduits which can: a) concentrate flow from multiple locations towards single springs; or b) result in ‘braiding’ of flow through conduit systems, as the example in Figure 2.28 shows, whereby streams that sink at individual swallow holes emerge at several downgradient springs in different flow headings from the injection point (Thorn, 1985; Gunn, 1996; Brown, 2005).
- Based on cave system map information, N-S joint systems exert an apparent control on cave passage directions in both the Geevagh upland karst (Thorn *et al*., 1990) and Cuilcagh Mountains (Brown, 2005). Though N-S flow pathways have been established from dye tracer tests, examples also exist of underground pathways that cut across both geological structures and hydrological drainage patterns.
- Flow systems tend to be localised and compartmentalised as a result of structural controls and potential barriers to flow. Brown (2005) demonstrates that flow systems and catchments associated with individual springs are constrained by fault blocks in eastern part of the Cuilcagh Mountains.
- Flow directions and gradients may change spatially and temporally as a function of hydrometeorological conditions.

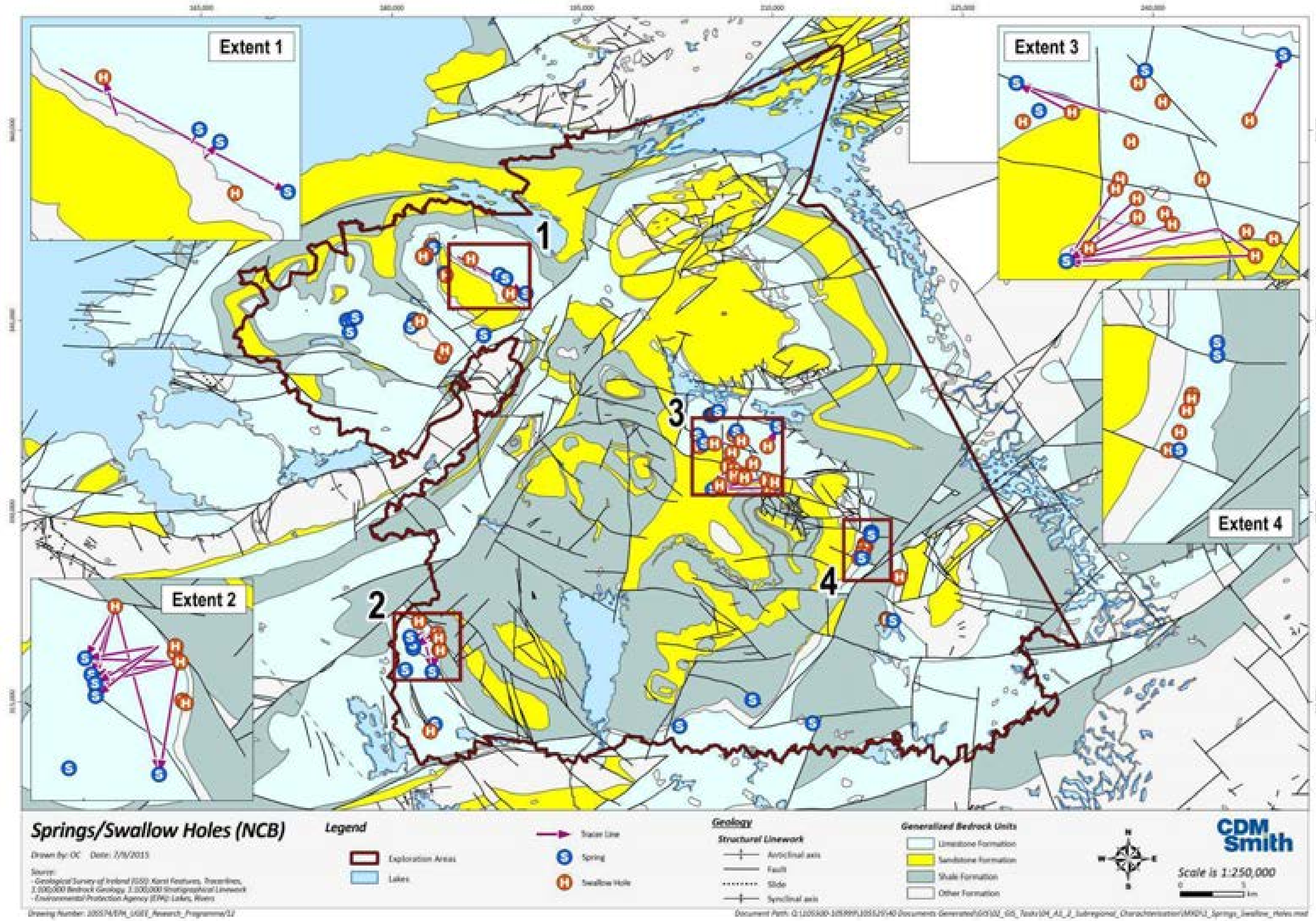


Figure 2.28. Swallow holes, springs, and tracer pathways in the NCB study area.

Generally, there is a high degree of interconnection between groundwater and surface water in karstified limestone areas, and groundwater contributes significant baseflow to the streams and rivers. In some systems, where water sinks and reappears at springs over short distances, the differentiation between groundwater and surface water can be blurred.

With specific reference to existing karst studies in the NCB, the following characteristics are also highlighted:

- Larger cave systems are associated with actively sinking streams. Several caves in the Cuilcagh Mountains and Geevagh uplands descend from their ground surface entrances to their outlet springs within short horizontal distances on the ground (Brown, 2005). However, there are also several examples of more complex, longer flow paths. For example, tracing to the 'Shannon Pot' demonstrated conduit flow paths over several km which were parallel (i.e. along strike) to principal geological structures and oblique to surface water drainage. Accordingly, streams and rivers cannot be assumed to represent hydrogeological divides.
- The largest established spring catchments are associated with Marble Arch (25 km^2), 'Shannon Pot' (15.2 km^2) and the Prod's-Cascade cave system (10.4 km^2).
- Discharge volumes/rates vary significantly according to hydrometeorological conditions, with rapid response time to rainfall events.
- Reported flow velocities ("straight-line velocities" between dye injection and discharge points) range from approximately 3 m/hr to greater than 169 m/hr (Thorn *et al*., 1990) under different hydrometeorological and flow conditions in the Geevagh uplands alone. In the Bricklieve karst, marginally outside the UGEE exploration area, velocities ranging from 25 m/hr to 51 m/hr were reported by the same authors. Brown (2005) further summarised flow velocities between 20 m/hr and 300+ m/hr in the cave systems of Cuilcagh Mountains.
- Hydraulic gradients are relatively steep, with reported values between approximately 0.05 and 0.1 in the Geevagh karst, 0.03 to 0.075 in the Bricklieve karst, and 0.02 to 0.1 in the Cuilcagh and Shannon karst.
- Dye mass balance considerations and hydrochemical assessment of spring water quality indicate that karst flow has elements of both fissure and conduit flow. Thorn *et al.* (1990) reported less than 20% conduit flow for some springs and 90–100% at others. Thus, it is important to note that karstified limestones also transmit groundwater via fissures.

Thorn *et al*. (1990) noted that the degree of concentration of recharge is a primary distinguishing characteristic between karst areas of the Geevagh and Bricklieve uplands, which manifests as differences in hydrochemical behaviour and tracer mass balances. The karst of the Geevagh uplands recharges predominantly by runoff from a shale cover which sinks underground at swallow holes on the limestone, whereas the karst on the Bricklieve Mountains is recharged diffusively by direct precipitation on the limestones formations. The karst at Cuilcagh Mountain is similar to Geevagh in this regard.

Water quality studies of karstic springs in the NCB have noted positive correlations between rainfall and bacteria counts at springs, as well as spring discharges and bacteria counts (Thorn and Coxon, 1992). Bacterial contamination of karstic derived water is extensively documented in both Ireland and Northern Ireland. The chemistry of groundwater in karst aquifers is also a reflection of recharge type and the origins of the recharging water (e.g. whether karst water originates as runoff on shale outcrops, or on till or peat).

In addition to the karst of the Dartry Limestone Formation, the Ballyshannon Limestone Formation forms a second important limestone aquifer in the region, notably where it outcrops to the north along the Lough Erne drainage system and to the west in the Sligo Syncline. It sources water to public water supplies and provides supporting conditions for groundwater dependent lakes and ecosystems such as the Roosky Turlough in Co. Fermanagh and Lough Gorman in Co. Donegal.

One of the major karst springs in the study area, the 'Shannon Pot', is hydrogeologically anomalous to most other major karst springs in three ways:

- It discharges from the Meenymore Formation (Brown, 2005), but its catchment is within the Dartry flow system, thus, its discharge mechanism is inferred to be fracture/fault related under confined/artesian conditions;
- It discharges groundwater with elevated sulphate concentrations during high flow events (Brown, 2005) which implies possible contribution from deeper circulation (see Section 5.3.1) and/or longer residence time of the associated groundwater;
- Its defined catchment extends mostly E-W in an area where other documented spring catchments extend mostly N-S in the Cuilcagh Mountain area.

The E-W catchment orientation is parallel to the E-W structural trend along the northern margin of the Cuilcagh Mountains. It is noted by Gunn (1996) and Brown (2005) that the Cuilcagh Dyke cuts across the Dartry Limestone Formation and may influence the hydrogeology to the north and south of the linear structure. Both authors observe that to the north of the dyke, groundwater drains in a northerly direction in the Erne catchments, whilst to the south of the dyke, groundwater drains west to Shannon Pot, parallel to the dyke and the strike of the Lough Allen Basin syncline. On this basis, Brown (2005) divided the karst into the 'Erne Karst' (draining south-north) and the 'Cuilcagh Karst' (draining east-west).

2.9.2 Fracture flow systems in bedrock formations

All of the bedrock formations in the NCB, including the karstified limestones, are fractured bedrock aquifers. Their relative significance as flow systems and groundwater resources relate to their 'fracture permeability', whereby groundwater storage and movement (i.e. availability) occurs via a 3–D network of open and interconnected fractures and fissures. Some rock types are more prone to fracturing than others and, on this basis, are considered 'better' aquifers than others. Brittle rock types such as sandstones, limestones and volcanic intrusives are expected to exhibit greater fracture permeability than ductile rock types such as shales and mudstones due to the higher clay contents of the latter. Although shales may have local importance for water supply to single homes and farms, they tend overall to be regarded as "poor aquifers", as recognised by the aquifer classification schemes of the GSI and GSNI, which in turn considers the likelihood of fracture development and connectivity.

In Ireland, the sandstone formations of the NCB, notably the Glenade and Mullaghmore Sandstones, are classified by the GSI as '*Lm*' aquifers. Lm aquifers are considered '*locally important aquifers: bedrock that is generally moderately productive*'. The equivalent classification in Northern Ireland is '*moderately productive aquifers*', dominated by fracture flow. In comparison, the shale formations are classified in Ireland either as:

- 'Ll' aquifers, 'locally important bedrock aquifers which are moderately productive only in local zones', where the latter is typically a reference to fracture/fault zones; or as
- *'Pu'* or '*Pl*' aquifers, '*generally unproductive' or 'generally unproductive except in local zones'*, depending on the principal lithologies of the various rock formations. In Northern Ireland, shale formations are generally classified as '*Bl(f)*', '*low productive aquifers'*.

The shale formations are less important for public water supplies, but can be important for private supplies (e.g. domestic wells for single homes or farms). The higher clay contents of shales and mudstones render them, theoretically, less conducive to open fracture development. There is direct evidence from mapped outcrops (Moore and Walsh, 2013) in the NCB that structural deformation of shales can result in the formation of ‘fault gouge’, which is a clay-rich zone that develops from rock movement along fault planes in shale lithologies. Thus, while faulting of brittle rock types tends to create zones of enhanced fracture permeability facilitating the transport of groundwater, faulting of ductile rocks can have the opposite effect of sealing and preventing the movement of water (and gas) across fault zones. This principle is depicted in

Figure 2.29, whereby: a) enhanced fracture zones result in shallower groundwater flow gradients whilst maintaining hydraulic continuity across the feature; and b) fault gouge results in the steepening of groundwater gradients across the feature by impeding flow on the upgradient side, potentially disrupting and deflecting flow patterns.

The effects of fault displacements on groundwater flow systems in similar rock types to those of the NCB are documented by Daly *et al. (*1980) in the Castlecomer plateau in Cos. Kilkenny, Laois and Carlow. The Castlecomer study area was divided into three structural blocks on the basis of fault patterns, and supported by piezometric and hydrochemistry data. The study describes how vertical displacements at faults interrupt both the hydraulic connectivity between the blocks and the groundwater chemistry within the main aquifers.

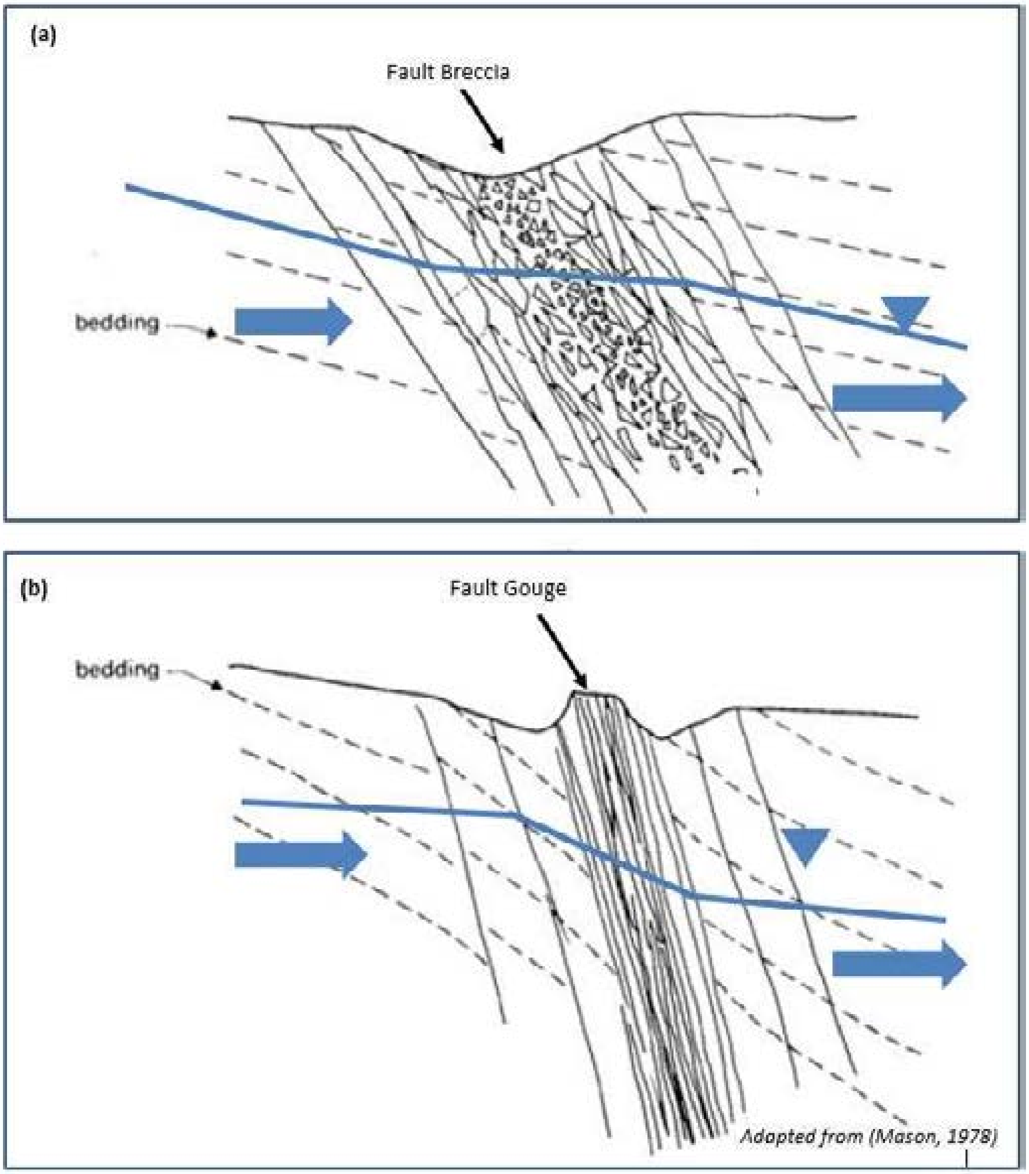


Figure 2.29. Influence of (a) enhanced permeability fault breccia and (b) low permeability fault gouge on flow gradients.

In the case of the Castlecomer plateau, it was concluded that the hydraulic connectivity is limited by the vertical juxtapositioning of formations with contrasting hydraulic characteristics against one another. In one case, faulting displaced sandstones so that the aquifer was disrupted by faulting to such an extent that lower-permeability formations on the downgradient side of the fault resulted in groundwater flow being deflected in other directions.

Hydrogeological information on bedrock aquifers in the NCB is mostly sourced from Groundwater Protection Scheme reports by the GSI (e.g. Monaghan and Cavan), source protection reports for public water supplies, and summary descriptions of relevant groundwater bodies prepared in draft by the GSI and GSNI for WFD reporting purposes (GSI, 2004; NIEA, 2012). Key hydrogeological characteristics of the fractured bedrock aquifers are summarised as follows:

- Groundwater moves through open fissures, joints and bedding planes. Flow is expected to be concentrated towards and along fault zones and brecciated dyke margins which, due to their higher fracture permeabilities, serve as both hydrogeological sinks and as primary pathways for groundwater flow. The shape and geometry of the fracture zones influence both flow directions and gradients. Fracture geometry and permeability are a function of lithological characteristics and the degree of structural deformation in any given catchment.

- Flow paths tend to be short and flow systems tend to be localised. Groundwater will tend to discharge to rivers, streams and lake margins under prevailing gradients, which are influenced by topography, rock types, geological structures, and on a local scale, the presence of abstractions.
- Local flow systems in some formations may be superimposed on larger flow systems in others, guided by stratigraphic variations (e.g. perching) and regionally significant discharge areas (e.g. Upper and Lower Lough Erne, Lough Allen, and the coastline).
- In fractured and fissured limestones, 'diffuse' groundwater flow via fractures may interact with and be influenced by preferential flow through conduits. For example, during low-flow conditions, diffuse flow in the bedrock matrix may be towards open conduits, whereas during high-flow conditions, the hydraulic gradient may be reversed and diffuse flow may be away from open conduits (if these are pressurised).

Available hydraulic property information is summarised in Table 2.4. The fractured bedrock aquifers are low-porosity and low-permeability rocks. Fracture permeability may be enhanced in fault and brecciated dykes zones, if fractures are open. In this regard, the sandstones and non-karstified limestones are assigned greater significance and importance as groundwater resources compared to the shale-dominated rocks.

Estimates of hydraulic properties for fractured bedrock formations are based on test pumping of relatively shallow wells (<200 m) in areas where the exploited formations are at or close to ground surface. From regional information, transmissivity values of approximately 10–50 m^2/d can be expected for the 'diffuse' fracture systems associated with sandstones and non-karstified limestones, whereas lower values, generally <10 m^2/d, are expected for shale formations and other ductile-type lithologies. Effective porosities are expected to be extremely low (<1–2%) as the rocks are cemented and primary porosity is mostly absent.

With regard to dykes, both Reilly and MacDermot (1983) and Legg *et al*. (1998) have noted that margins of dykes can be brecciated (i.e. faulted and fractured), and while several dykes are in evidence at the surface (and described by Legg *et al.*, 1998), dykes have also been intercepted at depth during drilling, notably in Dowra No.1 at 1585 m depth. There are no known supply wells installed in brecciated dyke margins in the NCB. Nonetheless, dykes are expected to provide fracture permeability where they are present. One significant dyke, the Cuilcagh Dyke, has been mapped in a WNW-ESE direction along the northern escarpment of the Cuilcagh Mountains (GSNI, 1991; 1998). The dyke is coincident with the Cuilcagh Fault which cross-cuts other structural elements in the area (Legg *et al.*, 1998), and runs parallel to the roughly E-W trending Belcoo Fault. The path of the dyke is accordingly inferred to be structurally controlled.

Table 2.4. Available hydraulic property information

Formation	Aquifer type and classification[a] (GSI/GSNI)	Summary of hydraulic properties[b]
Bencroy	Pu (not present in NI)	Formation-specific data are not available. For 'Ll aquifers', transmissivity values of 10–20 m^2/d can be expected based on data collated nationally by the GSI. For 'Pl and Pu aquifers', transmissivities are expected to be <10 m^2/d. Effective porosity and specific yield is low, possibly <1%. Storage properties are low due to a general absence of primary porosity and limited fracture permeability. Transmissivities may be higher in or near fault zones (>100 m^2/d). Low permeability shale formations would tend to act as "flow barriers" to underlying aquifer units, but some vertical leakage via enhanced permeability zones such as faults may occur.
Lackagh	Pu (not present in NI)	
Gowlaun	Pl/Bl (f)	
Briscloonagh	Ll/Bl (f)	
Dergvone	Pu/Bl (f)	
Carraun	Pl/Bl (f)	
Bellavally	Ll/Bl (f)	
Glenade	Lm/Bm(f)	Formation-specific data are not available. As a relatively 'clean' sandstone formation, transmissivity values of 10–50 m^2/d can be expected based on data for the Mullaghmore Formation. Transmissivities may be higher at fault zones (>100 m^2/d). Storage properties are low, and unconfined sections of the sandstone aquifers are expected have specific yields of a few per cent only.
Meenymore	Ll/Bl (f)	Similar to the Glenade Formation in areas, and sections where the Meenymore Formation comprises sandstone units (e.g. where the Carnmore Sandstone Member is present).
Dartry	Rkc/Bh(f-k)	Represents the main aquifer in the NCB. Reported yields of public water supply wells range between 43–400 m^3/d. The formation is extensively karstified and chrono-stratigraphic equivalent karstified formations exist in the Bricklieve Mountains and the Geevagh upland areas in southern Co. Sligo/northern Co. Roscommon. The karst is extensively studied, including dye tracer tests (see 2.6.1 and 4.3). In the Newton Ballyconnel groundwater basin (GWB), well hydrographs show annual variations of water levels up to 8 m, which is indicative of low-storage aquifers. There are limited quantitative data on the hydraulic properties of the fractured, non-karstified limestones. Although outside the UGEE study area, the estimated "bulk transmissivity" of the Dartry Formation at Knockatallon "*is around 50 m^2/d, with local zones of relatively high fracture permeability*" (Misstear *et al.*, 2008). Hydraulic gradients in the diffuse fracture systems are expected to be higher than in the karstified flow systems. Hydraulic gradients of 0.01–0.02 are reported for the Glencar and Carrowmore East GWBs.
Glencar	Ll/Bl (f)	The formation is considered to have limited production potential generally, but contains limestone units in some areas which may partly be karstified and which may be hydraulically connected with the Dartry Limestone.
Benbulben Shale	Ll/Bl (f)	Considered to have limited production potential from a water supply point of view. Reported well yields in 8 wells in the Ballinamore-Swanlinbar GWB range from 24–130 m^3/d. Transmissivity values of <15 m^2/d and <10 m^2/d are reported in the Drumcliff-Strandhill and Rossiver GWBs, respectively. Storage properties are expected to be very low. The effective thickness of Ll aquifers are very limited, comprising an upper weathered zone of a few metres and below a zone (10–20 m deep) of interconnected fractures and fissures. Low permeability shale formations would tend to act as "flow barriers" to underlying aquifer units, but some vertical leakage via enhanced permeability zones such as faults may occur.

Formation	Aquifer type and classification[a] (GSI/GSNI)	Summary of hydraulic properties[b]
Mullaghmore Sandstone	Lm/Bm (f)	Where it outcrops, the formation represents a locally important aquifer. Reported well yields from 5 wells in the Drumcliff Strandhill GWB range from 109–196 m^3/d (and includes one artesian, i.e. naturally flowing, well). Transmissivity estimates of 10–50 m^2/d are reported, although higher values (100–150 m^2/d) may be expected at and near faults. Storage properties are expected to be low.
Bundoran Shale	Ll/Bl (f)	One well yield of 130 m^3/d is reported from a borehole in the Ballaghnatrillick GWB, which is higher than would be expected for a dominantly shale formation. Transmissivity values are generally <10 m^2/d, and storage properties are expected to be low.
Ballyshannon Limestone	Mainly Rkd/Bh (f-k) (Rkc in some locations)	A regionally important regional aquifer. Less well studied and quantified compared to the Dartry/Glencar aquifer, but is partly karstified where it outcrops. Also shows evidence of epikarst development. Formation is associated with the Fardrum and Rooskey GWDTE in NI and the Dunmuckrum Turloughs in Ireland. Reported well yields range from 109–1090 m^3/d and specific capacities of 4–168 $m^3/d/m$ are reported for the same wells. Storage properties are expected to be low, as indicated by EPA monitoring point (well ID Don040) which displays annual variation in groundwater levels up to 25 m. Reported spring discharges range from 500–5000 m^3/d, the latter being associated with the Ballyshannon South GWB, marginally outside the UGEE study area. Transmissivity estimates are variable, between 1 m2/d (Glencar GWB) to greater than >2000 m^2/d (Rosses Point GWB), with the latter is indicative of karst. Values of approximately 500 m^2/d were reported for two wells near the town of Ballyshannon (Lee and Daly, 2005). Values of 10–15 m2/d and 10–50 m2/d are referenced for the 'Lower Impure Limestone' unit of the Ballyshannon Limestone and the Oakport Limestone (Lee and Kelly, 2003) in the southern part of the UGEE study area, respectively. Reported estimates of specific yield range from 0.01– 0.02% (Grange East GWB) to 1–2% (Rosses Point GWB). Hydraulic gradients of 0.01–0.02 are referenced by Lee and Daly (2005) and Lee and Kelly (2003).
Basal Clastics	Ll (Boyle Sst), Lm (Moy Sst), Pl (Twigspark Fm)	Formation-specific data in the project area are scarce as these formations are deeply buried several hundreds of metres below ground. A transmissivity value of 15–20 m^2/d is referenced for the Boyle Sandstone in northern Roscommon (Lee and Kelly, 2003).

[a]Mainly derived from draft groundwater body descriptions by the GSI (2004) and GSNI (2012), as well as specific cited references. GSI has developed a database of "Irish Aquifer Properties" which is updated at present and which incorporates data from the work behind the cited references.

[b]See Appendix C for definitions.

NI, Northern Ireland.

The mapped trace of the dyke was adjusted by Brown (2005) from a combination of geophysical survey work and landform interpretations. Of hydrogeological significance, Brown (2005) notes that the Cuilcagh Dyke is sufficiently displaced by faults at two locations, leaving ‘gaps’ which may provide hydraulic continuity of groundwater movement across the dyke structure.

2.9.3 Sand and gravel aquifers

The karstified and fractured bedrock aquifers are overlain by subsoils comprising glacial till deposits, and to a minor extent, glacial outwash and recent alluvial sediments along stream courses. Based on existing mapping, there are no identified (known) sand and gravel bodies that could serve as aquifers for water supply purposes in the study area. Glacial outwash and alluvial sediments may have a function in storing water in river valleys, but overall, and on the basis of existing information, such sand and gravel bodies are deemed to be of minor hydrogeological significance in the NCB

2.9.4 Groundwater resources

The available groundwater resources of the NCB study area are primarily represented by bedrock aquifers. Alluvial sediments are present along stream courses, and small mapped sand and gravel bodies are also present, but these are of limited spatial extent (see Figure 2.11).

All bedrock formations are by definition aquifers, but some are of greater hydrogeological significance, or resource ‘value’, than others, which is recognised in the aquifer classification schemes of the GSI (DELG/EPA/GSI, 1999) and GSNI (Ball *et al.*, 2005). The primary aquifer is the karstified limestones of the Dartry Limestone Formation. The shale, sandstone and mudstone formations, as well as argillaceous limestones and volcanic rocks, are also aquifers, but these are mapped as ‘poorly productive aquifers’ (PPAs) by both the GSI and GSNI. The PPAs have low storage and low-permeability characteristics, and tend to be associated with small, localised groundwater flow systems (GWG, 2005). Accordingly, boreholes drilled in PPAs tend to result in low yields, except in fault zones where the probability of enhanced fracturing and permeability can increase the transmissive capacities of the same rocks.

Although the groundwater flux through bedrock aquifers such as PPAs can be small, the baseflow components are important to surface water bodies (e.g. streams) and associated aquatic biota, especially during prolonged dry weather events. In such periods, groundwater baseflow to streams may account for 100% of stream flows (e.g. during the summer drought of 2010), but would only represent a very small fraction of stream flow during wet weather events and peak flow conditions (Misstear *et al*., 2009; O’Brien *et al*., 2013). Actual contributions depend on catchment-specific characteristics, pathways and flow systems. This is supported by recharge and hydrograph separation studies, using rainfall-runoff modelling techniques, which were carried out in support of WFD implementation projects in Ireland and Northern Ireland (e.g. GWG, 2005; RPS, 2008).

Besides the hydraulic properties of bedrock formations, groundwater availability is also a function of:

- Depth, e.g. whether formations store and/or transmit groundwater at depth and whether boreholes can be drilled within limits of technical feasibility and reasonable cost;
- Recharge from rainfall, i.e. the extent to which groundwater is replenished; and
- Groundwater quality, i.e. whether the formation waters can be naturally exploited without extensive treatment.

As documented in Sections 2.6 through 2.8, the primary aquifers (the karstified limestones of the Dartry Limestone Formation) become deeply buried towards the central parts of the UGEE licence area, within the ‘Lough Allen Basin’ subdivision of the NCB. Accordingly, the aquifers become increasingly inaccessible for water supply purposes. As documented in Section 2.10, certain formations are also known to store (and possibly transmit) variably saline formation waters at depth, which implies that the 'resource value' is diminished with depth.

Bedrock aquifers are recharged by the proportion of rainwater that infiltrates into the groundwater environment. The principal factors that control recharge to an aquifer are effective rainfall (the available recharge), the nature and thickness of overlying soils and subsoils, slope and land use. The nature of bedrock is also important, and sections of bedrock aquifers with a greater storage and transmissive capacities have greater capacity to receive and accept the available recharge than sections of bedrock that are impermeable. These characteristics are summarised by Misstear and Fitzsimons (2007), Misstear *et al.* (2009) and are represented in the updated national recharge map which is prepared and published by the GSI for Ireland using existing hydrogeological and meteorological spatial datasets (Hunter Williams *et al.*, 2013). Reproduced in Figure 2.30, the estimated long-term average recharge rates in the NCB study area range from <50 to approximately 900 mm/yr. The lower values apply to areas covered by peat and thick low-permeability subsoils. The higher values apply to areas where subsoils are thin or absent and where the underlying bedrock is mapped by the GSI as regionally important and productive (mostly karstified limestones in the NCB).

The ability of an aquifer to accept all of the recharge is a function of its hydraulic properties. For example, low storage and transmissive characteristics limit the amount of recharge that can be accommodated in the available bedrock volume. Thus, a portion of the available recharge is 'rejected'. In PPAs especially, this is most often translated to enhanced surface runoff and water movement along shallow pathways, including the 'transition zone' (Moe *et al.*, 2010; Kelly *et al.*, 2015) and transport to and via field drains to streams (Deakin, 2014). Accordingly, recharge 'caps' have been proposed and are typically considered for different types of PPAs (Hunter Williams *et al.*, 2013).

A similar recharge map has not been produced for the section of the NCB that is within Northern Ireland, but the same principles apply – higher recharge rates are expected where infiltration potential is greater and bedrock aquifer can accept the available recharge.

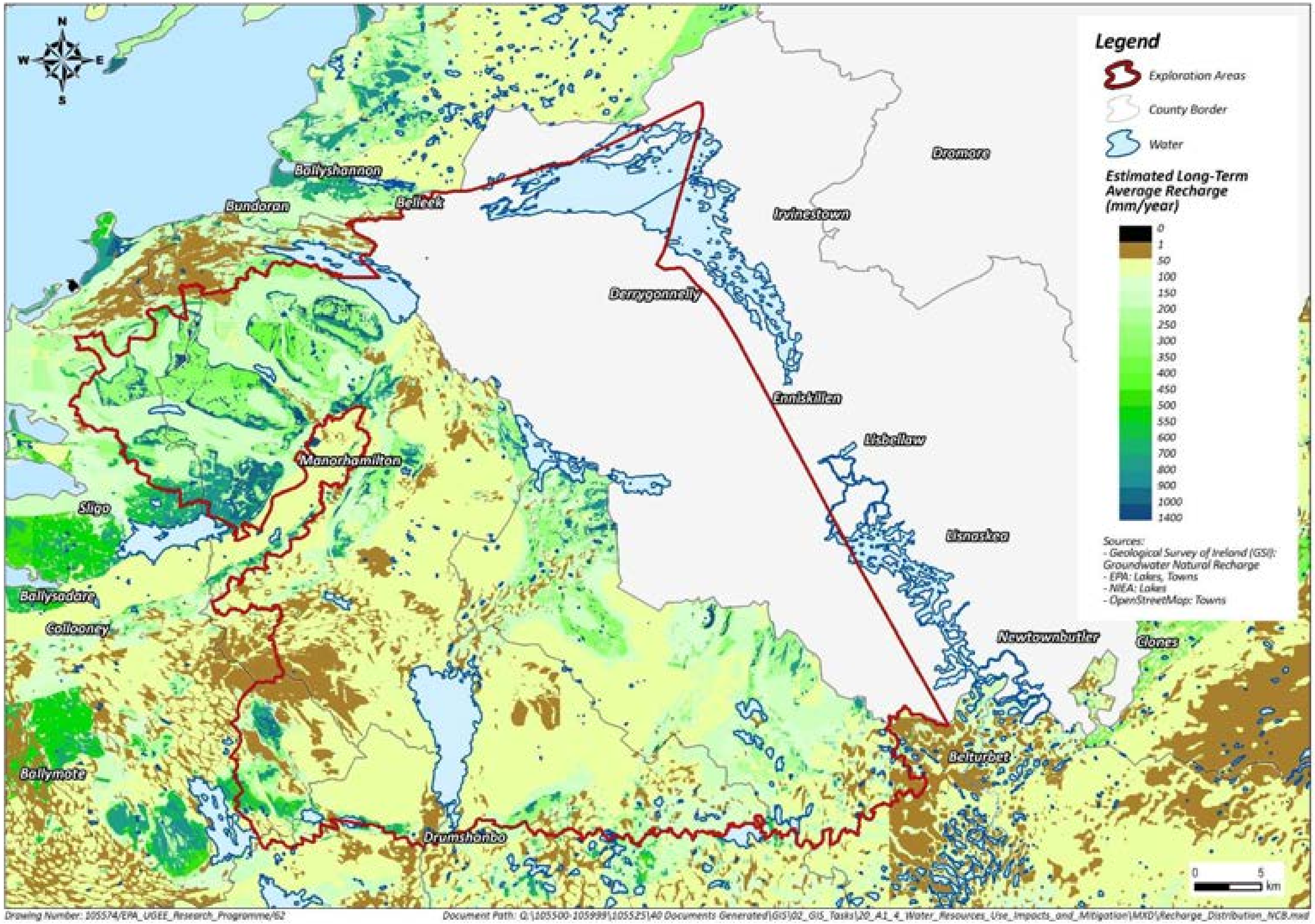


Figure 2.30. Estimated recharge distribution – NCB study area in Ireland.

Constraints that apply to the national recharge map in Ireland are:

- The map is intended as a guide for water balance estimation purposes at the groundwater body scale (i.e. catchment or sub-regional scale);
- Local-scale differences should be expected, as determined by local-scale features and characteristics which cannot not be captured by the scale of spatial datasets used in the recharge estimation methodology (e.g. local subsoil thickness or permeability variations, presence of point recharge sources such as dolines in karstified limestones);
- The map represents long-term average recharge, and does not document seasonal variability (e.g. summer/winter); and

Recharge values are not fixed. Lowering of water levels frees up ‘space’ for additional recharge if this is available. With regard to bedrock hydraulic properties, the available ‘space’ for water storage and movement in fractured bedrock aquifers is limited to that offered by open fracture networks and primary or secondary porosities of sedimentary rocks. In the context of the hydrogeology of the NCB study area, values of 1–2% of the total formation volume are frequently cited, as indicated by aquifer test results and hydrographs from individual wells (Hunter Williams *et al*., 2013). Water level fluctuations in bedrock aquifers with low storage properties can be several metres over seasons, also displaying rapid responses to rainfall. Water level fluctuations in aquifers with more favourable characteristics as groundwater resources tend to be more subdued over time.

The transmissive capacity (transmissivity, T) of an aquifer is a function of its thickness and fracture permeability (hydraulic conductivity, K), which is a measure of the ease with which water can be transmitted. Based on aquifer testing, published values of T can range over several orders of magnitude, depending on the degree and extent of fracturing in a given aquifer *at any given location*. Bedrock aquifers are heterogeneous in three dimensions, and there is no means of predicting storage or transmissivity characteristics with certainty. The probability of intersecting water-bearing fracture networks and achieving higher well yields tends to increase near geological fault zones in limestone and sandstone formations, where the brittle nature of the rocks and structural deformation combine to increase the probability of enhancing fracturing and fracture permeability.

2.9.5 Springs

There are hundreds of springs present in the NCB study area. Only a fraction are likely represented on available maps. They are an important source of water for both public and private regulated water supplies. Springs are groundwater discharge points which also give rise to stream flow throughout the study area. Accordingly, they play an important role in providing baseflow to surface water bodies and supporting conditions for groundwater-dependent ecosystems.

Springs are present everywhere and emerge from all bedrock types. They are both stratigraphically and structurally controlled. Despite their hydrogeological and ecological significance, spring discharge records are sparse to non-existent. Only one spring at Manorhamilton in the NCB is equipped for automatic discharge measurement. The general lack of spring discharge data represents a significant data gap, particularly where springs are used for water supply and where large springs discharge from karstified limestone aquifers. Discharges from the latter can be on the order of several hundred litres per second (l/s).

2.10 Groundwater Quality

Table 2.5 lists groundwater quality monitoring stations within the NCB, arranged by geological formation. These include WFD monitoring stations sampled by the EPA and NIEA, as well as public and private regulated supplies that are historically monitored by local authorities.

Table 2.5. Summary of groundwater monitoring locations within study areas

Bedrock formation	No. of WFD groundwater quality monitoring locations	No. of drinking water quality –groundwater monitoring locations – boreholes	No. of public/private regulated supplies from springs
Lackagh Sandstone			1
Gowlaun Shale		2	3
Briscloonagh Sandstone			4
Carraun Shale			1
Dergvone Shale			2
Bellavally Shale			1
Glenade Sandstone			1
Dartry Limestone	4	16	3
Bricklieve Limestone	1	2	
Glencar Limestone	4		
Benbulben Shale			4
Mullaghmore Sandstone			1
Bundoran Shale		1	
Ballyshannon Limestone	1		

The WFD monitoring points reflect the limestones that overlie the unconventional gas target (i.e. Bundoran Shale Formation). In contrast, public and private drinking water quality stations are associated with several different bedrock formations, and sourced where they outcrop or are close to ground surface. The exception referenced above is the Ballyshannon Limestone Formation which underlies the Bundoran Shale Formation. Table 2.6 summarises groundwater quality data for WFD monitoring points in the main aquifer, the Dartry Limestone Formation, covering the period from 1997 to 2013. The monitoring points (see Figure 2.26) are:

- Bawnboy (NW_G_031_0200_002);
- Kinlough/Tullaghan (WE_G_0060_1700_002);
- Manorhamilton (WE_G_0042_1700_003); and
- Boho Rising (GBNIGWNW06-C).

Table 2.6. Summary of water quality – Dartry Limestone Formation (1997–2013)

Parameters	Units	Natural back-ground[a]	Count	Min.	Max.	Median	Mean	St. dev.
pH	pH	-	94	6.7	8.5	7.4	7.44	0.36
Alkalinity	mg/l $CaCO_3$	-	118	53.1	340	173	182	64.8
Conductivity	µS/cm	-	97	121	1233	381	370	145
Total Hardness	mg/l $CaCO_3$	-	115	26.0	368	189	182	75.0
Turbidity	NTU	-	110	<0.1	40.6	0.95	3.28	6.88
Nitrate	mg/l NO_3	3.3	118	<0.36	6.0	2.4	2.41	1.25
Molybdate Reactive Phosphorus	mg/l P	-	117	<0.003	0.6	0.013	0.025	0.06
Chloride	mg/l Cl	18	118	4.6	29.0	12.4	12.3	2.98
Fluoride	mg/l F	-	108	<0.1	0.5	0.075	0.081	0.06
Sulphate	mg/l SO_4	10	118	<1	31.5	5	6.14	4.79

Parameters	Units	Natural back-ground[a]	Count	Min.	Max.	Median	Mean	St. dev.
Sodium	mg/l Na	19	117	4.4	20.1	7.69	7.70	1.87
Potassium	mg/l K	2.8	118	<0.2	5.8	0.895	1.02	0.86
Magnesium	mg/l Mg	14	117	1.4	20.7	8.16	8.53	5.26
Calcium	mg/l Ca	132	118	21.7	108	64.4	60.7	19.0
Iron	µg/l Fe	130	118	<2.5	1820	19.7	102	247
Manganese	µg/l Mn	32	117	<1	341	3	12.4	36.2
Barium	µg/l Ba	162	103	<5	73.0	11	20.1	15.5

[a]Baker *et al.,* 2007

Included in the table are the minimum, maximum, mean, median and standard deviation (St. Dev.) of reported parameters. Where the measured values were below the detection limit, these results were substituted with a value of half the limit of detection for the purposes of calculating the relevant statistics.

The concentration of nitrate (NO_3) in the Dartry Limestone Formation ranges from <0.36 mg/l to 6.0 mg/l, with a mean of 2.41 mg/l. These values are well below the EU Drinking Water Directive maximum admissible concentration (MAC) of 50 mg/l and the groundwater threshold value (Groundwater Regulations S.I. No. 9 of 2010) of 37.5 mg/l. The mean is also below the most stringent groundwater nitrate threshold values of 4 mg/l proposed for GWDTEs set by the UK Technical Advisory Group (UKTAG). The concentration of Molybdate Reactive Phosphorus (MRP) ranges from <0.003 mg/l to 0.2 mg/l with a mean of 0.020 mg/l. This mean is below the groundwater threshold value (Groundwater Regulations S.I. No. 9 of 2010) of 0.035 mg/l, although there were 4 exceedances of the threshold in the period of record.

Six samples were analysed for select volatile organic compounds (VOCs) and hydrocarbons between 1997 and 2013. The only detections were single detections of Bromodichloromethane (0.10 µg/l) and Dibromochloromethane (0.42 µg/l). These are both trihalomethanes and the concentrations were below the EU Drinking Water Directive maximum admissible concentration (MAC) for trihalomethanes of 100 µg/l and the groundwater threshold value of 75 µg/l.

Table 2.7 summarises the groundwater quality data for the WFD monitoring points in the Glencar Limestone Formation, which may be hydraulically connected to the Dartry Limestone Formation.

Table 2.7. Summary of water quality – Glencar Limestone Formation (2007–2013)

Parameters	Units	Natural back-ground[a]	Count	Min.	Max.	Median	Mean	St. dev.
pH	pH	-	48	6.36	8.90	7.40	7.48	0.59
Alkalinity	mg/l $CaCO_3$	-	52	53.5	382	176	176	60.8
Conductivity	µS/cm	-	48	117	1323	380	399	179
Total Hardness	mg/l $CaCO_3$	-	55	58	279	176	167	67.2
Turbidity	NTU	-	56	<0.11	32	0.95	2.97	5.28
Nitrate	mg/l NO_3	3.3	57	<0.13	6.64	1.94	2.36	1.32
Molybdate Reactive Phosphorus	mg/l P	-	33	<0.004	0.2	0.008	0.020	0.04
Chloride	mg/l Cl	18	56	7.8	19.4	12.4	12.6	2.77
Fluoride	mg/l F	-	43	<0.048	0.300	0.075	0.105	0.07
Sulphate	mg/l SO_4	10	57	<0.1	24.0	4.9	4.93	3.52

Parameters	Units	Natural back-ground[a]	Count	Min.	Max.	Median	Mean	St. dev.
Sodium	mg/l Na	19	57	4.96	25.0	7.5	7.87	2.65
Potassium	mg/l K	2.8	57	<0.18	2.67	0.6	0.73	0.41
Magnesium	mg/l Mg	14	57	1.71	26	5.11	5.88	4
Calcium	mg/l Ca	132	56	48.5	96.7	73.2	74.7	13.9
Iron	µg/l Fe	130	33	<2	115	8.00	30.7	41.5
Manganese	µg/l Mn	32	57	<0.1	116	1.9	9.73	17.7
Barium	µg/l Ba	162	42	3.5	27	11.7	13.4	5.50

[a]Baker *et al.* 2007

The data cover the period from 2007 to 2013 for the following four monitoring points (see Figure 2.26 for locations):

- Calry (WE_G_0042_2700_001);/
- Legland Spring (GBNIGWNW05-C);
- Hanging Rock East (GBNIGWNW10-C); and
- Knockmore Rising (GBNIGWNW50-C).

Nitrate (NO_3) concentrations ranged from <0.13 mg/l to 6.64 mg/l, with a mean of 2.36 mg/l; all of which are below the relevant standards and threshold values referenced above. MRP ranged in concentration from <0.004 mg/l to 0.2 mg/l, with mean of 0.020 mg/l. There were two exceedances of the MRP threshold of 0.035 mg/l in the period of record.

Approximately 30 samples were analysed for pesticides, VOCs and hydrocarbons between 2008 and 2013. Detections were of the pesticides 2,4-Dichlorophenoxyacetic acid (2,4–D) at 0.07 µg/l, 2-methyl-4-chlorophenoxyacetic acid (MCPA) at 1.52 µg/l, and Azinphos-methyl at 0.005 µg/l. MCPA exceeded the drinking water standard of 0.1 µg/l. None of the detections were confirmed in subsequent sampling rounds. Trihalomethanes (THM) were detected as follows: chloroform at 140 µg/l and bromodichloromethane at 18.9 µg/l in one sample in June 2009. The total concentrations exceeded the EU Drinking Water Directive maximum admissible concentration (MAC) of 100 µg/l as well as the groundwater threshold value of 75 µg/l. None of the detections were confirmed in subsequent samples. The cause(s) of the single detections have not been ascertained.

In addition to the WFD-related data from the Dartry and Glencar Limestone Formations, limited data for the Ballyshannon Limestone is available for the Ballyshannon public water supply which is located marginally outside the UGEE study area but is part of the Sligo Syncline structure. The water is sourced from springs and back-up wells in the same formation, and EPA data between 2003 and 2010 indicate the following:

- Alkalinity (mg/L HCO_3): 176–420; mean 306
- Hardness (mg/L $CaCO_3$): 206–437; mean 320
- Conductivity (µS/cm): 420–714; mean 591

The mean nitrate concentration in the same period was 10 mg/l (as NO_3), with a maximum of 18 mg/l (as NO_3). The mean ammonium concentration was 0.024 mg/l-N, with a maximum of 0.095 mg/l-N. The average MRP concentration was 0.009 mg/l-P, with a maximum of 0.06 mg/l-P.

2.10.1 Naturally occurring radioactive materials

Naturally occurring radioactive materials (NORM) are the radioactive elements uranium (U) and thorium (Th), their decay products (e.g. polonium, radium and radon), as well as potassium (K-40). NORM compounds are naturally present in geological formations, and can be present in the deeper saline formation waters. They can also be present in drill cuttings, i.e. derived from formation minerals, and in drilling muds. As described in Section 10, NORM would be recommended to be included in the sub-regional baseline monitoring of the UGEE Joint Research Programme.

Existing water quality monitoring data for NORM are sparse. The EPA office of radiological protection (formerly Radiological Protection Institute of Ireland, RPII) measured radioactivity levels between 2007 and 2011 in the groundwater supplies that are part of EPA's WFD groundwater monitoring network (Dowdall *et al.*, 2013). Gross alpha and beta screening was carried out for 203 sources, eight of which are located in or near the UGEE licence area in the NCB:

- Co. Cavan – Bawnboy PWS
- Co. Donegal – Ballyshannon/Parkhill PWS; Pettigo PWS
- Co. Leitrim – Kinlough/Tullaghan PWS; Manorhamilton PWS
- Co. Roscommon – Rockingham PWS; Keadew PWS
- Co. Sligo – Calry PWS

In all sources, the measured gross beta activity was less than the screening concentration of 1000 mBq/l (Dowdall *et al.*, 2013), thus further analysis for individual radionuclides contributing to the gross beta activity was not carried out.

For 28 of 203 sources screened, the gross alpha activity was above the screening threshold of 100 mBq/l. These sources were pursued for further analyses to determine the radionuclides contributing to the gross alpha activity, specifically U, radium-226 and polonium-210. Of the eight specific sources listed above, only the Keadew and Pettigo supplies were amongst the 28 sources pursued for further analysis. The Keadew supply pumps groundwater from the Bricklieve Limestone Formation (chrono-stratigraphically equivalent to the Dartry Limestone Formation), whereas Pettigo pumps groundwater (at least partly) from the Ballyshannon Limestone Formation (GSI, 2005). At Keadew, U is reported as the primary contributor to the gross alpha activity. At Pettigo, there was confirmed contribution from both U and radium-226. Importantly, none of the 28 sources, including the 8 sources in or near the UGEE licence area, had activity concentrations that exceeded a radiation dose of 0.1 mSv/yr, which is the specified exposure limit in Statutory Instrument (S.I.) 278 of 2007 (relating to the EC drinking water directive).

A total of 217 sources across the country were also screened for dissolved radon (Rn) in groundwater. All samples complied with the screening limit (500 Bq/l) recommended by the RPII (Dowdall *et al.*, 2013). The study also concluded that no correlation was found between Rn and U activity concentrations.

An equivalent study for surface water has not been carried out, but the former RPII has conducted checks of radioactivity in Irish drinking water from large public supplies since the 1980s. Results to date indicate that levels of radioactivity in public supplies comply with the total indicative dose (TID), a parametric standard that is used for radioactivity as defined by the EC drinking water directive.

Elements such as U and Rn are soluble in water and may be taken up by groundwater. Accordingly, the data produced from the Tellus Border project (www.tellusborder.eu) are of further relevance to the NCB study area. Topsoil, stream sediment and stream samples were analysed for a wide range of major and trace elements, including U, Th and K-40. The topsoil and stream sediment data have been statistically evaluated and classified according to the underlying bedrock geology (Gallagher *et al.*, 2015a,b). Spectral aerial measurements of U, Th and K-40 are also available, and results are described below.

2.10.1.1 Topsoils

Tellus Border topsoil data are summarised in a draft, to-be-published report by the GSI (Gallagher *et al.*, 2015a). The data indicate, in part, bedrock influence at a broad level (e.g. Leitrim Group vs Tyrone Group, sandstone/shale vs limestone), but mostly, peat appears to be the main influence on the distribution of the NORM concentrations measured, as well as the other major and trace elements. The mapped extent of blanket peat in the Lough Allen uplands, which illustrates the spatial significance of peat cover, is highlighted in red colours in Figure 2.31. Peat also occurs to a minor extent in small pockets in the lowlands, in hollows between drumlins. The remaining colours in Figure 2.31 represent the Quaternary cover materials which were described in Section 2.5.

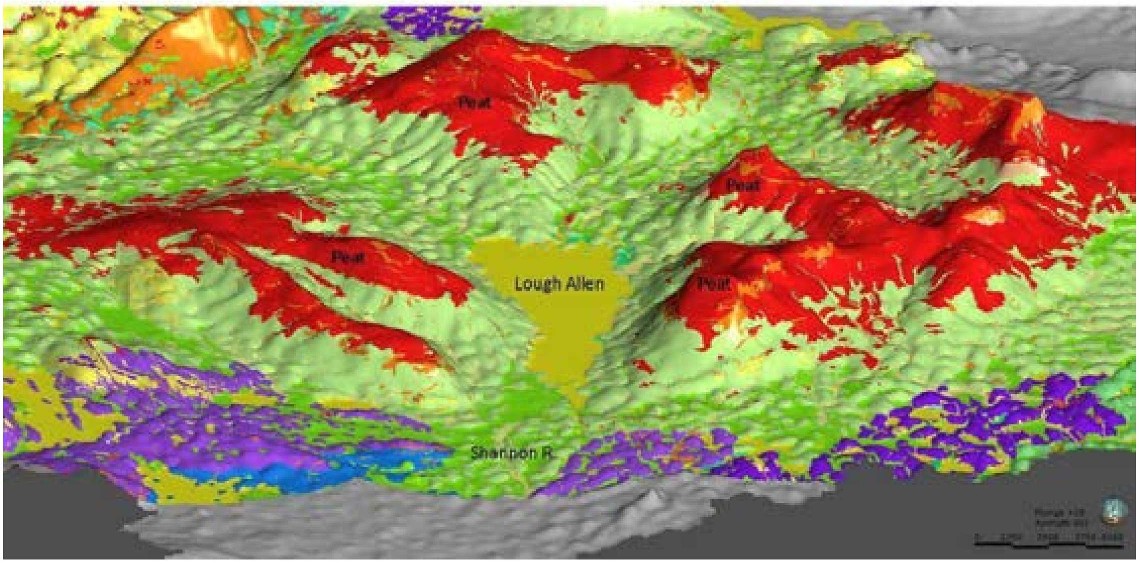


Figure 2.31. Peat cover (red) in the Lough Allen uplands.

With reference to the UGEE licence area, concentrations of K-40 are reportedly lower on the hilltops around Lough Allen compared to elsewhere in the study area. Even though a bedrock correlation to the shales of the Leitrim Group could be expected (K-40 concentrations would be higher where clay minerals are present in sedimentary rocks), peaty topsoils in the region as a whole are reported to have much lower concentrations of K-40 that non-peaty topsoils.

The equivalent distribution of U is described as relatively random and concentration changes occur over short distances. This may partly reflect the relative mobility of U in the environment although Gallagher *et al.* (2015a) note that peaty soils generally have a median U concentration which is approximately half that of non-peaty topsoils. Th concentrations show a similar random distribution to U. Th can be strongly sorbed to clays and would thus have higher concentrations in shales than in less clay-rich lithologies. Unlike U, Th has very low solubility (as ThO_2) in neutral waters, thus limestones would be expected to have low Th concentrations. A pattern to this effect is not reported from the available data.

Lower concentrations of other elements are also reported for peat areas relative to non-peat topsoils, including iron, manganese, copper, nickel, zinc and chromium. In contrast, the peat increases the relative concentrations of certain other elements. Metals such as molybdenum and arsenic can form sulphide minerals in sulphate reducing conditions. Relatively high molybdenum concentrations occur in topsoils in the uplands surrounding Lough Allen, and a good correlation with U and arsenic is reported by Gallagher *et al.* (2015a). Regarding arsenic, this is relatively mobile under mildly reducing conditions. Under sulphate reducing conditions, arsenic and sulfides will form. In the Tellus Border region as a whole, peaty topsoils reportedly have lower concentrations of arsenic than non-peaty topsoils. One possible explanation is the presence of coal (indicative of reducing conditions) and ironstone (arsenopyrite) in the Leitrim Group rocks.

2.10.1.2 Stream sediments

Tellus Border stream sediment data are summarised in a draft to-be-published report by the GSI (Gallagher *et al.*, 2015b). The samples were analysed for 21 geochemical parameters, including U, Th and K-40. High U concentrations in stream sediments are mapped over the upland regions surrounding Lough Allen, see Figure 2.32. In the study area, the higher concentrations appear to be 'centred' on the Leitrim Group rocks, and the distribution becomes dispersed away from the hilltops, which could reflect the relative mobility of U (dissolved in water). U is water soluble under oxidising conditions and is mostly affected by redox potential (Eh). The soluble U complex is an oxidised U species (U6+). Under reducing conditions, the U is reduced to UO_2 (U4+) – this would occur in the peat or shale. U can, therefore be expected to be leached from soils and mobilised from acid peat areas, either via streams or by infiltration to the groundwater environment. Hodgson and Ture (2014) describe results from aerial radiometric surveys (measuring spectral U, Th and K-40 counts) which feature the detection of higher U signals in surface water drainage from uplands around Lough Allen, see Figure 2.33, inferring that this could be sourced from the shale-dominated rocks of the Leitrim Group. The black coloured areas are attenuated signals associated with peat and open water.

The stream sediment distribution of Th shows similar elevated concentrations in the uplands region of Lough Allen. Gallagher *et al*. (2015b) noted that within the Lough Allen area, stream sediments that overlie the Meenymore Formation have higher Th concentrations than "*Visean shelf limestones and shales (Ballyshannon Limestone Formation, Bundoran Shale Formation, etc.)*". Thus, a bedrock control (Leitrim Group) is inferred from the Th distribution. Th is less mobile than U. It forms a solid, very insoluble ThO_2 over most Eh-pH conditions, so lower Th concentrations would be expected.

Stream sediment data for K-40 are more nuanced but, overall, concentrations tend to be lower on limestone terrain (limestones do not have a readily available source of K-40), with the lowest concentrations on the Bricklieve Limestone in the Ballymore Syncline and the Dartry Limestone around Cuilcagh Mountain. Elements such as copper, nickel, cobalt, iron, molybdenum and vanadium all show elevated concentrations that correlate with each other (and U) and which are inferred to be associated with: a) Leitrim Group rocks (based on distribution); and b) a "*shale source*" (Gallagher *et al.*, 2015b).

In contrast, and of relevance to the understanding of phosphorus in the region, stream sediment phosphorus (P_2O_5) appears to be higher in limestone areas compared to non-carbonate areas (notably, higher concentrations are reported in the Bricklieve and Geevagh karst areas near Lough Arrow, as well as the Dartry Limestone karst along the north side of Cuilcagh Mountain, compared to the hills surrounding Lough Allen). Thus, the Tellus Border stream sediment data offer a more convincing picture of potential bedrock controls on distributions of NORM (and other elements) compared to topsoil data. A missing data element from the Tellus data set, and which is important to note in the context of UGEE baseline monitoring, is radium (see Section 9).

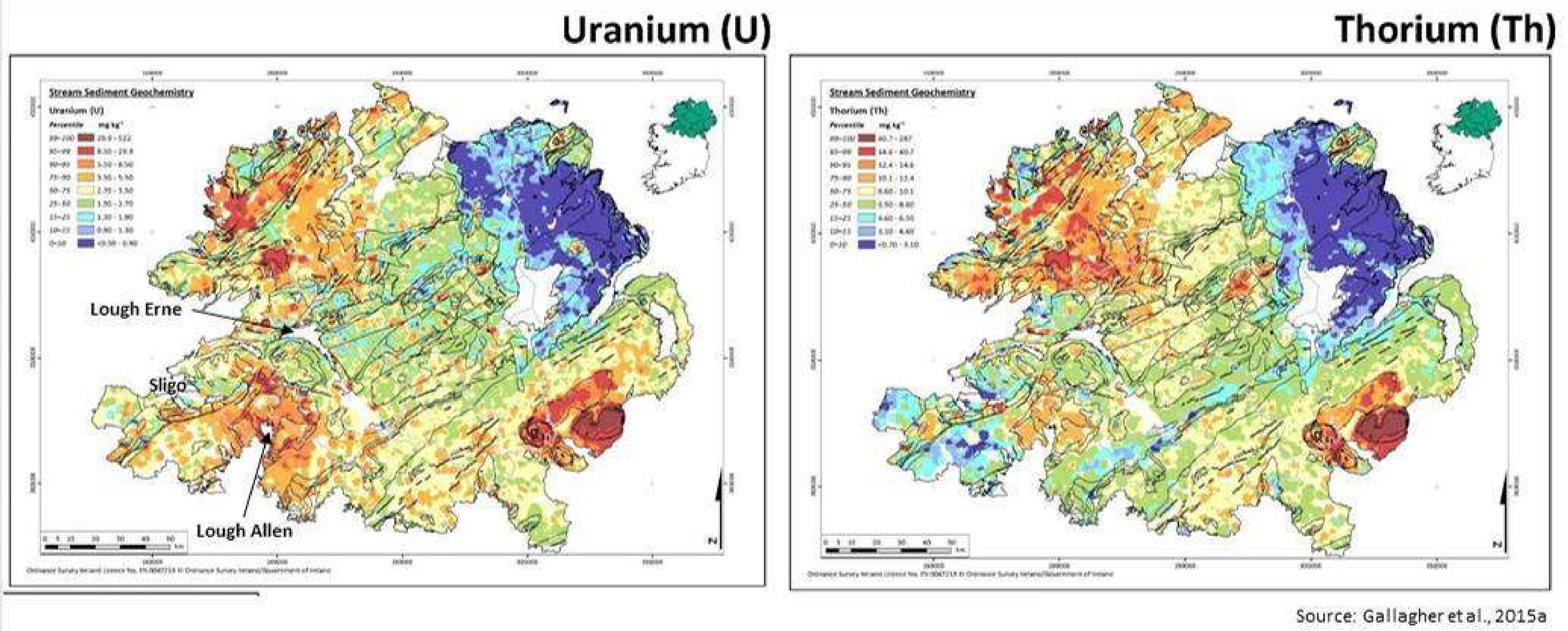
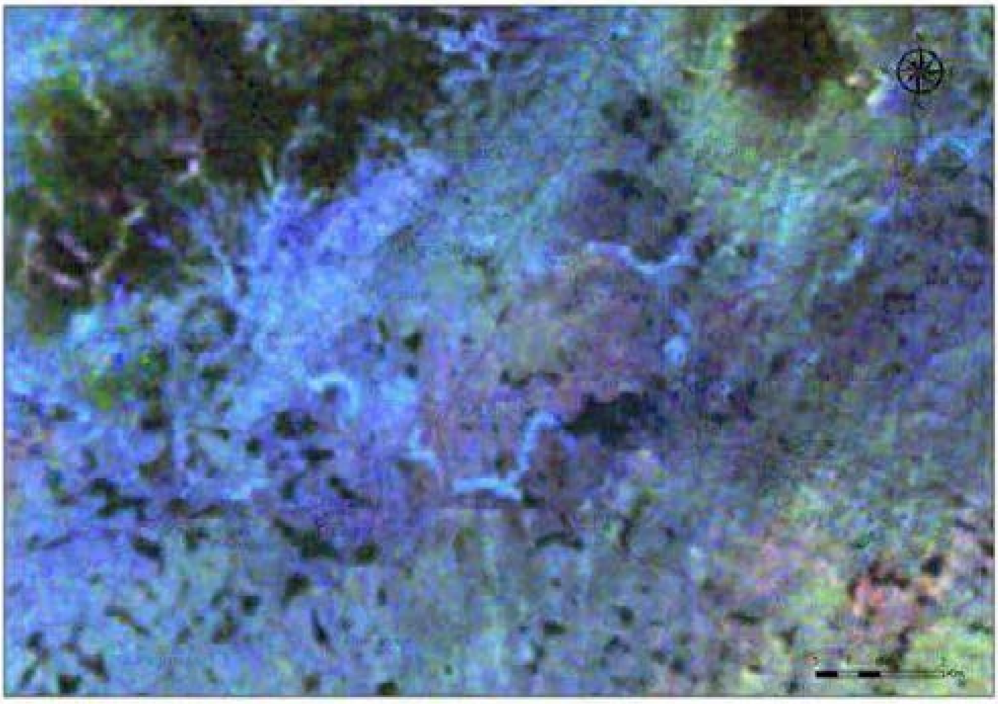


Figure 2.32. U and Th distributions from Tellus Border stream sediment samples. © Geological Survey Ireland.



Source: Hodgson and Ture, 2014

Figure 2.33. Radiometric ternary map of U 'highs' (blues) in a stream in Co. Leitrim. © Geological Survey Ireland.

2.10.1.3 Surface water (streams)

A similar statistical distribution study of Tellus Border data has not yet been undertaken for stream samples. Nonetheless, the data from Ireland are included in the Tellus Border project web-viewer, and from this certain patterns emerge with regard to the NORM that were analysed, as follows:

- U concentrations, see Figure 2.34, show a diffuse distribution across the study area although the highest concentrations coincide with areas of Leitrim Group rocks in streams surrounding Lough Allen and the uplands between Belcoo and Manorhamilton.
- Th concentrations shows a similar pattern to uranium, but the overall distribution is less pronounced, presumably because Th is less soluble in water.
- K-40 concentrations in streams are lower on the hilltops in peaty areas across the region.

2.10.2 Radon

Radon (Rn) is a decay product of U, and the national sampling programme carried out between 2007 and 2011 concluded that Rn in 217 groundwater samples complied nationally with the screening limit (500 Bq/l) recommended by the former RPII.

A national model of Rn risk in Ireland (Hodgson *et al.*, 2014) concluded that a relationship exists between Rn high values (indoor air) and the GSI-mapped distribution of "Rkc" karstified aquifers in which groundwater flow is dominated by conduits. The relationship is based on a "*multivariate linear regression model which used average indoor radon values per bedrock unit, groundwater recharge coefficient, aquifer type and depth to bedrock*" as inputs.

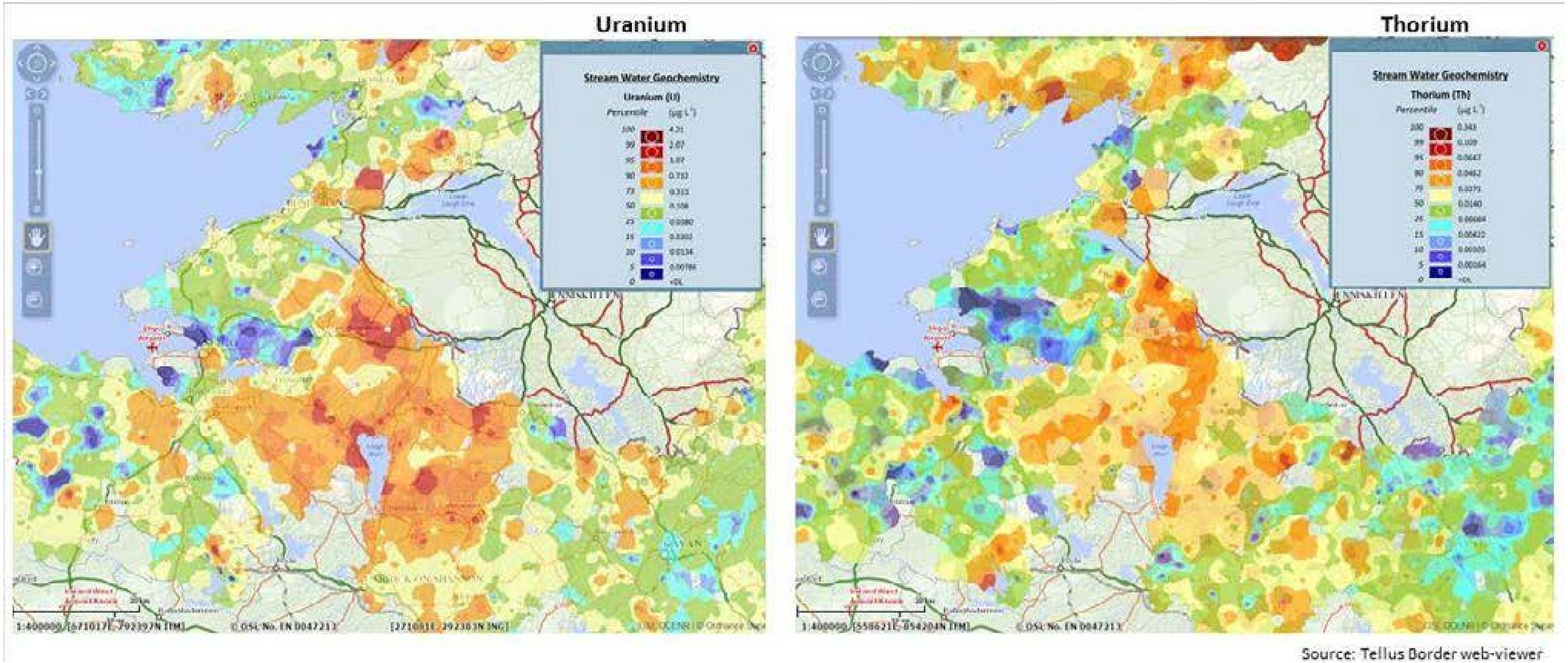


Figure 2.34. U and Th distributions from Tellus Border stream samples. © Geological Survey Ireland.

Whilst karst may thus be important in transporting (dissolved) Rn gas (and U) in groundwater to natural discharge points such as springs, it is worth noting that degassing of Rn can also take place in the conduits if these are only partially filled with water (i.e. not pressurised). The apparent relationship would nonetheless be an important factor to consider when reviewing baseline monitoring data from karst areas and monitoring points in the NCB.

2.11 Deep Hydrogeological Information

Very little is known about the hydrogeology of the UGEE-related formations at depth, i.e. where they become structurally 'buried' up to several hundred metres below ground. Recognising that the oil and gas industry is rarely concerned with hydrogeology (except when groundwater becomes a problem for drilling and testing operations), anecdotal hydrogeological information was extracted from annotations in exploration well completion reports, as summarised in Table 2.8. Even if anecdotal, the annotations provide important clues about hydrogeological conditions at depth.

2.11.1 Dartry Limestone Formation

With specific reference to the Dartry Limestone Formation (the main groundwater resource and potential receptor), there are several records of losses of circulation and water influxes in respective boreholes during drilling operations. The deepest references to losses of circulation and water influx in the Dartry Limestone Formation in the gas exploration wells are *c.* 277 m in Thur Mountain No.1 and 297 m in Dowra No. 1, corresponding to elevations of approximately –150 mOD and –100 mOD, respectively. The records do not specify whether these occurrences were associated with karst conduits or water-yielding fracture zones.

Dartry water quality is anecdotally noted in well logs as being 'fresh' (inferred low salinity), but there are also records of "*sulphurous water*", e.g. in Dowra No.1, Dowra No.2 and Slisgarrow No.2. The well completion report for Dowra No.1 includes the following text:

> "The following water zones were encountered:
>
> 20 to 50 ft: Large volume, not measurable, fresh water with slight sulphur odour
>
> 80 to 100 ft: Large volume, not measureable, fresh water
>
> 345 to 400 ft: 15 Bbls/hr, fresh sulphur water
>
> 693 to 721 ft: 1000 Bbls/hr, fresh sulphur water
>
> 721 to 775 ft: 200 Bbls/hr, fresh sulphur water
>
> The major sulphur water zone, 693 to 721 ft, was cemented off, but additional sulphur water, 200 bbls/hr entered the borehole from 721 to 775 ft".

In the above text, the "*Bbls/hr*" refers to barrels per hour, where 1 barrel = 159 litres. Thus, 1000 Bbls/hr = 159 m^3/hr, which is a significant volume in any context, and which could imply intersection of a karst conduit.

Table 2.8. Summary of hydrogeological information extracted from well completion reports

Well name/reference	Drilled	Hydrogeological information
Dowra No.1/ Ambassador (1962)	1962	The well completion report references "*caving*" and "*sulphur water*" at a depth of 695 ft (*c.* 210 m) in the Dartry Limestone, corresponding to an elevation of *c.* –91 mOD. The reported quantity of water evacuated (air-lifted) during drilling at this depth was 1000 barrels per hr (BPH), which is equivalent to 3816 m^3/d using a conversion factor of 1 barrel = 159 litres (recognising that conversions may not be entirely precise on the basis of potential temperature effects on density/viscosity of fluids). The well completion report also references "fracture porosity" from 623–725 ft, and loss of circulation during drilling from 695–705 ft, as well as recovery of "*brecciated vuggy limestone*" in a core from 700–705 ft. The well logs make further references to "*reef breccia*", "*traces of bitumen along [core] fractures*" and "*sulphur smell on breaking the core*" at this depth. After cementing the water-yielding interval to "*gain control*" of the drilling operation, air-lifting from 15 BPH to 200 BPH was further noted from 721–723 ft, after which the drilling switched to a mud-based operation. Loss of circulation was also noted at 893–975 ft depth, corresponding to an elevation range between c. –152 and –177 mOD, although the cause and nature of the losses, and a quantitative account of the losses, are not recorded.
Macnean No. 1/ Ambassador (1963b) and Finavera (2004)	1963	The well was 'dust drilled' to 4507 ft, and water inflow was noted at 4525 ft near the contact between Ballyshannon and "Basal Clastics". Salinity (as chloride) is reported as 65,000 ppm Cl. Deep formation water was lifted out using pressurised nitrogen at 144 "bls/day" (i.e. barrels per day) during a drill stem test at a 4525 ft, equivalent to approximately 23 m^3/day. Moreover, "*loss of circulation*" (unspecified) was reported from 5060 ft, in the Basal Clastics, indicative of fracture permeability. The first drill stem test at 4500–4516 ft failed as the packer could not be set due to "*5 ft of caving*". "*Vertical fractures*" (3 mm aperture) "*filled with calcite*" were reported from core descriptions of 4547–4553 ft (in sandstone). A 1-inch filter cake was reported from the calliper log, indicative of porosity, although "*no visible effective porosity or permeability*" was described from the core.
Big Dog No. 1/ Marathon Ltd & Ambassador English Oil Co. (1965a)	1965	Groundwater was encountered at 60 ft depth in the Dartry Formation. At 143 ft, the reported discharge during drilling was 10 BPH (38.2 m^3/d), with a salinity of 85 ppm. No further water was reported until saline water was noted in the Mullaghmore Formation, at depths between 1410 and 2000 ft. The reported discharge rate was 15 BPH (57.2 m^3/d) with salinity ranging between 6000 and approximately 40,000 ppm from "*pure formation water*". There is reference to "*estimated 8–10% porosity*" from sandstone cores, as well as "*possibly slight permeability*" in the same. In the Basal Clastics, below 5800 ft, discharge rates of 3 BPH (11.5 m^3/day) are reported, with a salinity increase to 118,000 ppm.
Owengarr/ Marathon Ltd & Ambassador English Oil Co. (1965b)	1965	Groundwater was struck at 40 ft depth, with a reported discharge of 30 BPH. Discharges from the borehole during drilling in the Dartry Formation are reported as 100 BPH at 294 ft, 150 BPH at 415 ft depth, and 300 BPH at 342 ft depth. The salinity ranged from 200–380 ppm in the same interval. The Dartry was cased and cemented at 610 ft depth. Below the Dartry, the borehole "*produced*" 5 BPH from 1190 to 1930 ft depth, with a reported salinity of 830 ppm. There was no appreciable increase in the "*production*" through shales to 3100 ft. The next reference to water is associated with drilling mud only, whereby the measured salinity of the mud increased (unspecified) in the Basal Clastics.

Well name/reference	Drilled	Hydrogeological information
Glenoo/ Marathon Ltd & Ambassador English Oil Co. (1966)	1965	Groundwater was encountered at 140 ft depth in the Glencar Formation. 15 BPH was discharged from 140–1900 ft depth, with a reported salinity of 83 ppm. The formation was cemented off and the borehole remained "*mostly dry*" below the Dartry. Salinity reportedly increased from 1450 to 7500 ppm between depths of 4320 and 5315 ft, below the Ballyshannon Limestone. The estimated discharge is noted to have increased from 2 BPH to 50 BPH upon a reaching a 40 ft "*lime formation*" at 6885 ft. This was accompanied by a reported increase in salinity from 13,400 to 53,400 ppm.
Macnean-2/ Aran (1985a)	1984	The well completion report references potential "*Pleistocene cave fill*" at 213–228 ft depth in the Dartry Formation, corresponding to elevations of *c.* –5 and –10 mOD. No issues with water circulation during the drilling through the Darty and Glencar Formations are recorded. In the Basal Clastics, which was gas tested, the following information is provided: "*It is probable that only a small quantity of water of unknown salinity was produced*". During the gas drill stem test, only drilling mud was assumed to have been recovered. Core descriptions reference a potential fault at 2240 ft depth in the Bundoran Shale, with a possible throw of 100–150 ft based on lithological observations above and below the inferred fault. In the Dartry, there are references to "*former cavities*" which range upwards in size from "*birdseyes*" and which are infilled with recrystallized calcite. There is also reference to "*internal sediment filling remaining cavity*".
Drumkeeran-1/ Aran (1985b)	1984	The well completion report does not reference water strikes or formation water salinities. There is reference to "*indications of a concentrated fracture zone*" at approximately 4600 ft, which became the target for a drill stem test in Bundoran Shale Formation, and "*no formation fluids were recovered from the drillpipe*".
Kilcoo Cross/ Aran (1985c)	1985	Loss of circulation (LOC) is reported at 70 ft depth, and "complete LOC" is reported at 140 ft depth, both in the Dartry Formation, corresponding to an elevation of c. +67 mOD. Estimates of water "*production*" (i.e. discharge at surface during drilling) are not recorded. References to "still no circulation" are noted at 422 ft and 721 ft depths, implying the drillers may have experienced further LOC during continued drilling. During the LOC, the well completion report notes that "*3 or 4 water bowsers were working 24 hours a day to supply water to sustain the drilling operation*", also noting that the water was sourced from local streams. There is no indication that the drillers attempted to case and cement the intervals in question, rather this was done upon encountering the Benbulben Shale at 770 ft depth. A drill stem test was carried out in the Mullaghmore with a packer setting of 1670 ft depth, and "*minute quantities of [formation] water with a salinity of 70,000 ppm*" is recorded.

Well name/reference	Drilled	Hydrogeological information
Slisgarrow No. 1/ Aran (1985d)	1984	The well completion report references interpreted cave infilling in the Dartry Limestone, e.g. a 20 ft section containing "*sandstone and shale materials*" within the limestone sequence. It is postulated by Aran Energy Ltd. that the fill may be associated with sub-aerial exposure of the Dartry Formation, prior to Meenymore deposition, as the overlying Meenymore Sandstone represents a shallow water environment and contains both shales and evaporites. From the dipmeter survey of the borehole, a marked change in formation dip angles and direction is recorded at 3860 ft depth, and is inferred by Aran Energy Ltd. to be a "*possible fault*" between the Bundoran Shale and Ballyshannon Limestone. Slickensides are noted on samples. Other "likely" faults are reported below this depth, e.g. at c. 4860 ft and 4973 ft, and includes reference to "*associated veining and fracturing*". An interval from 6325 to 6557 depth, in the Basal Clastics, was drill stem tested, and the well completion report references "*the interval is believed to have produced water only*" (unspecified), noting that "*An analysis carried out on this fluid showed 1500–2300 pm Cl, slightly less than the 3800 ppm Cl in the [drilling] mud*".
Dowra No. 2/ Evergreen Resources Inc. (2001a)	2001	The well completion report from "Dowra-2y" references "*heavy*" loss of mud from 707–745 ft in the Dartry Formation, recording losses of 60–80 BPH in this interval. This depth interval corresponds to an elevation range between *c.* –95 and –105 mOD. It also references a need to stop drilling at 745 ft "*to make water*" (inferred to mean remove water before continuing to drill). The report further references H_2S gas in the formation water in the Dartry Formation, at concentrations up to "*20 ppm in the blooie line*".
Knock Beg No. 1/ Evergreen Resources Inc. (2002a)	2001	The borehole was reported as "wet" at 195 ft in the Meenymore Sandstone. The "*Well produced 100 bls of water/hr*" through the Meenymore Sandstone, then "*watered out*" at 576 ft, in the Dartry Limestone, whereby the drillers reported "*large water flow in fractured limestone*" producing an estimated 400–600 BPH. The latter depth corresponds to an elevation of *c.* +156 mOD. During vertical hydraulic fracturing of the Mullaghmore Sandstone (2036 to 2550 ft depth), Schlumberger (2005b) references "*water production*" from the Mullaghmore to be "220+ bbl/d", equivalent to approximately 35+ m^3/d. Moreover, *"The well produced significant volumes of water, suggesting that one of the hydraulic fractures had communicated with a water bearing fracture system. The under-pressured nature of the reservoir system did not allow for the fluid to flow to surface, repeatedly killing the well…..As a result, the testing was abandoned due to inability to dispose of produced fluid*".
Thur Mountain-1/ Evergreen Resources Inc. (2001b)	2001	The well completion report records water inflow at 10–40 BPH from the shallow Glenade Sandstone; and >40 BPH (unspecified) at 910 ft depth in the Dartry Limestone, corresponding to an elevation of *c.* –148 mOD. At 910 ft, H_2S gas at 6 ppm was also recorded. Schlumberger (2005b) reported that a fluid sample from the Mullaghmore Sandstone was analysed in the laboratory with a "salinity" (chloride?) value of 96,000 ppm. The sample was considered to be formation water, and was reported to be "*moderately acidic*" and "*heavily contaminated with suspended matter (potentially dissolved iron precipitating out when exposed to air)*".
Mullanawinna No. 1/ Evergreen Resources Inc. (2002b)	2001	During drilling in the Glenade Sandstone, the borehole reportedly produced "*very little water*" in "*very hard sandstone*". Upon entering the Dartry, the borehole was reported to be "*making*" 50 BPH at 576 ft depth, corresponding to an elevation of *c.* –95 mOD. There are no references to water strikes or "*production*" below this.

Well name/reference	Drilled	Hydrogeological information
Slisgarrow No. 2/ Evergreen Resources Inc. (2002c)	2001	The well completion report indicates a relatively dry borehole throughout drilling. However, gas tests in the Mullaghmore Sandstone were abandoned due to "*fluid loading*", with no further details provided.
Wind Farm No. 1	2001	No specific information is available. Well was not tested due to absence of sandstones.

Well completion reports also document gas detections during drilling in the Dartry, e.g. hydrogen sulphide (H_2S) to 200 ppm and "*traces of C1*" (methane) in Dowra No. 2, "*C1 to C3*" (i.e. methane, ethane, propane) in Slisgarrow No. 2.

"*Sulphur water*" is also reported from the Shannon Pot spring. Brown (2005) describes chemical variance of the spring water quality as a function of flow conditions, specifically that higher strontium and sulphate concentrations, as well as isotopically heavier sulphate values, discharge during high flow conditions. Brown (2005) attributes the heavier isotope values to sulphate reduction which requires anoxic conditions, and concludes that some of the water which discharges during high flow conditions may have circulated within a "*deeper part*" of the Dartry aquifer system. The source of the sulphate could be sulphide minerals (e.g. pyrite), and although the source of sulphides is not conclusive, candidates would shale units (e.g. in the hydrogeologically linked Glencar Formation) and/or 'intramound units' (containing mud) in the Knockmore Member of the Dartry Formation, where such units are present. As noted by Brown (2005), the latter *"would place the deeper flow system c. 300 m below Shannon Pot (c. 200 m below OD).*"

2.11.2 Other formations

Below the Dartry Formation, the presence of variably saline "*formation water*" is reported in the gas-tested sections of the Mullaghmore Sandstone and Basal Clastics. Salinity information for the Dowra Sandstone is not available, partly because testing was compromised by the drilling muds that were used in the drilling operations, which affected the ability to obtain 'clean' formation samples.

In the Mullaghmore Sandstone, reports of salinity range between approximately 6000 and 100,000 ppm (excluding estimates from geophysical logging). In the Basal Clastics, the highest value reported is 118,000 ppm in Big Dog No.1, and significantly lower salinity is implied in Slisgarrow No. 1 where the formation water in the Basal Clastics reportedly contributed to reducing the salinity of the drilling fluid.

The well completion reports do not provide details about the salinity measurements and thus the circumstances that may influence or contribute to the variable salinity (which are reported either as "salinity", "NaCl", and/or "chloride" in ppm) cannot be assessed with any certainty.

There are no records of deep formation waters flowing or discharging naturally at the ground surface. Even though the deeper formations are significantly confined, the saline formation water is of higher density and, in the context of gas flow, the reservoir targets are under-pressured (Schlumberger 2005a,b), i.e. gas pressures noted in the formations are naturally below hydrostatic pressure.

Nonetheless, the reported "*water loading*" and "*water inflows"* in the tested sections (referenced in Table 2.8) indicate that formation water (i.e. groundwater) is present in the reservoir formations. The quantities referenced in Table 2.8 were measured at the surface, whereby formation waters were lifted out using nitrogen gas, which was injected in attempts to keep the boreholes free from fluids, in order to facilitate gas flow.

The mechanisms for water "*production*" during gas testing remain poorly understood. Schlumberger (2005b) attributes water in the Mullaghmore Sandstone in the Knock Beg and the Windfarm wells to "*possible fault and fracture networks*", whilst water in the Big Dog well was attributed to inflow from the Dartry/Glencar aquifer within the borehole during drilling. Schlumberger (2005b) also noted that the total water "produced" from the Mullanawinna well was less than the amount of "*gelled fluid injected in the fracturing operations"*, thus offering a possible alternative explanation in this particular instance. However, they place water production from Thur Mountain and Slisgarrow No. 2 in the context of possible "*mobile water present in the formation*".

There are no specific references to karst or water quality in the deeply buried Ballyshannon Limestone, but there are references to gas detections (mostly methane) and also the presence of variably saline formation water in the "Basal Clastics" which immediately underlies the Ballyshannon Formation. By inference, formation water in the Ballyshannon Formation can also be expected to be (mostly) saline.

2.11.3 Porosity and fracture permeability

As noted in several well completion reports, gas testing in several boreholes was affected or had to be abandoned due to the influx of water which 'choked' the gas flow. These reports provide apparent evidence of the presence of deep formation waters, which in turn indicates that the formations possess *some* degree of porosity and fracture permeability. The reported variable salinity concentrations raise questions about whether the waters are "fossil" or part of actively circulating flow systems (even if very slow).

Water production and gas test abandonment in the Knockbeg, Thur Mountain, Mulannawinna, Slisgarrow-2 and Windfarm wells have been attributed to natural fracture networks (Finavera Ltd, 2004; Schlumberger, 2005a,b). "Vertical fractures" are described in core logs of the Mullaghmore Sandstone (620–777 m depth) in the Knock Beg well, where water was "*assumed to come from a high permeability, fluid filled natural fracture which was like an aquifer*" (Evergreen Resources Inc, 2002a), and in which the well test *"…..indicated an effective permeability fifteen to thirty times better than the surrounding wells"* (Schlumberger, 2005a). It was suggested that the well might be suitable as a disposal well.

There is evidence of natural fractures from acoustic televiewer (ATV) images of sections of both the Dowra and Mullaghmore Sandstones in the Kilcoo Cross, Slisgarrow No. 2 and Thur Mountain No. 1 wells, with bed-parallel and high-angle (70–80˚+) fractures noted (Schlumberger, 2005a,b). It has also been reported that "*there is evidence that water production occurs through an open fracture network, potentially from the overlying formations, and the mechanism for water production in the Mullanawinna, Thur Mountain and Slisgarrow #2 is uncertain"* (Schlumberger, 2005a).

There is further reference to gas pressure build-up test data from the Dowra Sandstone in the Dowra No. 2 well, which according to Schlumberger (2005a), "*showed a pressure response characteristic of a dual porosity system*". A dual porosity system is a reservoir system in which flow "*effectively occurs in one porosity system, and most of the fluid is stored in the other*." *Naturally fractured reservoirs or vugular carbonates are classified as dual-porosity reservoirs, as are layered reservoirs with extreme contrasts between high-permeability and low-permeability layers"* (Schlumberger, 2015).

The consideration of a dual porosity system is of hydrogeological significance. Primary porosity is expected to have been largely destroyed by the diagenetic metamorphism which has cemented the sandstones. Despite annotations of "*no visible porosity*" in drilling returns and cores at the surface, petrographic study of cores references porosity as primary porosity. Values of 2–6% are generally reported for the Mullaghmore Sandstone, whilst values of 1–7% are typically reported for the Dowra Sandstone. An "anomalously high" value of 17% is even referenced for "an unnamed sandstone" within the "Dowra zone" (i.e. within the Bundoran Shale Formation) in Kilcoo Cross (Schlumberger, 2006).

A thin-section assessment of samples from the Mullaghmore Sandstone in the Kilcoo Cross well also reports that "primarily intergranular porosity is present although reduced by quartz overgrowths and gypsum and ferroan dolomite elements. Secondary porosity is present as oversized pores…". Porosity overall was estimated to be 5–10% (Aran Energy Plc., 1985c).

The matrix cements of the sandstones are mixed. Calcite is common, but quartz, dolomite and gypsum are also described in other petrographic analyses other than the one referenced above. Thin section studies indicate that cements have undergone diagenetic alteration, resulting in secondary porosity (Ketzer *et al.*, 2002). The alteration involves dissolution of calcite at depth (Finavera Ltd., 2006). An estimated and reported relationship between porosity and depth for the two main sandstones explored to date is reproduced (from Higgs, 2006; see also Keeley, 2006) in Figure 2.35.

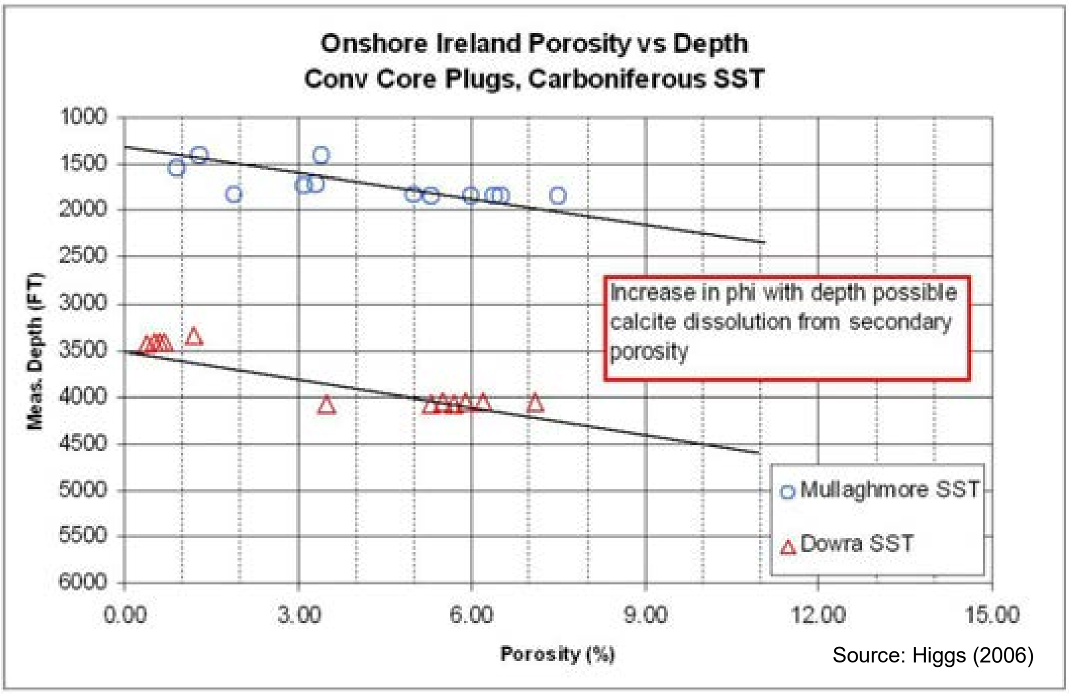


Figure 2.35. Porosity estimates versus depth (ft).

Thus, the sandstones of the NCB appear to have retained porosity, which implies that the Mullaghmore and Dowra Sandstones could store and/or transmit water, even at depth. Fracture permeability offers additional opportunity for water storage and transmittal. Based on core studies and gas pressure build-up tests, gas permeabilities of <0.5 millidarcies (mD) are generally reported for the tested sections of the Mullaghmore and Dowra Sandstones (e.g. in Kilcoo Cross, Big Dog, Slisgarrow No. 1). These are indications of low permeability in any context. In hydrogeological terms, a permeability of 1 mD represents a clay-range equivalent. Permeabilities of <0.1 mD were used for model simulations of horizontal hydraulic fracturing in the Dowra Sandstone by Schlumberger (2005a), who noted however that "*there are statistically insufficient samples to truly capture the reservoir heterogeneity…*". The highest estimated permeability value from gas tests is 1.8 mD in the Mullaghmore Sandstone in Kilcoo Cross (Schlumberger, 2005b, 2006).

Fracture permeability is the result of structural deformation. If open fractures are present in the deeper formations, and penetrate the formations between the unconventional gas target and the shallow receptors, then this has implications for the assessment of environmental risk. Open fractures are suggested in ATV-imaged sections of sandstones at depth as noted above. Structural deformation and potential fracturing is also suggested from core descriptions and dipmeter surveys which reference anomalous zones of changing dip angles and directions over short intervals, which in turn could represent faulting. A core description from Slisgarrow No. 1 recorded variations in dip angles and directions above and below a fractured interval (at approximately 3860 ft depth), marking the intersection of a fault.

3 Clare Basin

3.1 Physiography

The physiography of the Clare Basin (CB) is characterised by a broad upland region with rolling hills which slopes gently towards the coastline along the Shannon Estuary and Loop Head peninsula, see Figure 3.1. Maximum elevations within the UGEE licence area are *c.* 150 mOD near Doo Lough. Both upland and lowland areas are covered by blanket peat, mainly due to the high rainfall along the west coast of Ireland. Land use in lowlands is predominantly agricultural (grazing, cattle and sheep). Forestry is practised in both upland and lowland regions. Raised bog is also present in the lowland areas, possibly occupying former (now-infilled) lakes.

3.2 Rainfall/Meteorology

The estimated 30-year annual average rainfall for the period 1981–2010 (Met Éireann, 2015) is shown in Figure 3.2, and ranges from 800 to 1400 mm/yr across the study area. Rainfall amounts increase with elevation and Slievecallan, 390 mOD to the northeast of the UGEE licence area, receives up to 2000 mm annually.

Rainfall in the winter months is generally 300 to 400 mm/yr with a small section on the eastern side of the study area receiving between 400 and 500 mm/yr. A similar trend is observed for the summer months with rainfall between 200 and 300 mm/yr increasing to between 300 and 400 mm/yr in upland areas.

The estimated 30-year monthly potential evapotranspiration (PE) rate at Shannon Airport (located approximately 24 kms east of the UGEE licence area) ranges between approximately 13 mm/month in December and 87 mm/month in June, as shown in Figure 3.3. The mean monthly rainfall in the same period ranged between 59.2 mm/month to 104.9 mm/month.

3.3 Lakes

Lakes are absent in the UGEE licence area. However, Doo Lough is located just east of and near the licence area and serves as the main source of public water supply for western Co. Clare. Water levels in Doo Lough are regulated (impounded), and the average daily abstraction of approximately 11,500 m^3/d is below its reported ‘yield’ (i.e. capacity) of approximately 48,400 m^3/d for its design storage (Bowman *et al.*, 1983).

Two smaller natural lakes, Lough Namina and Lough Acrow, are also located near but outside the UGEE licence area to the east, supplying the Inagh-Kilmaly and Lissacasey group water schemes (GWS), respectively.

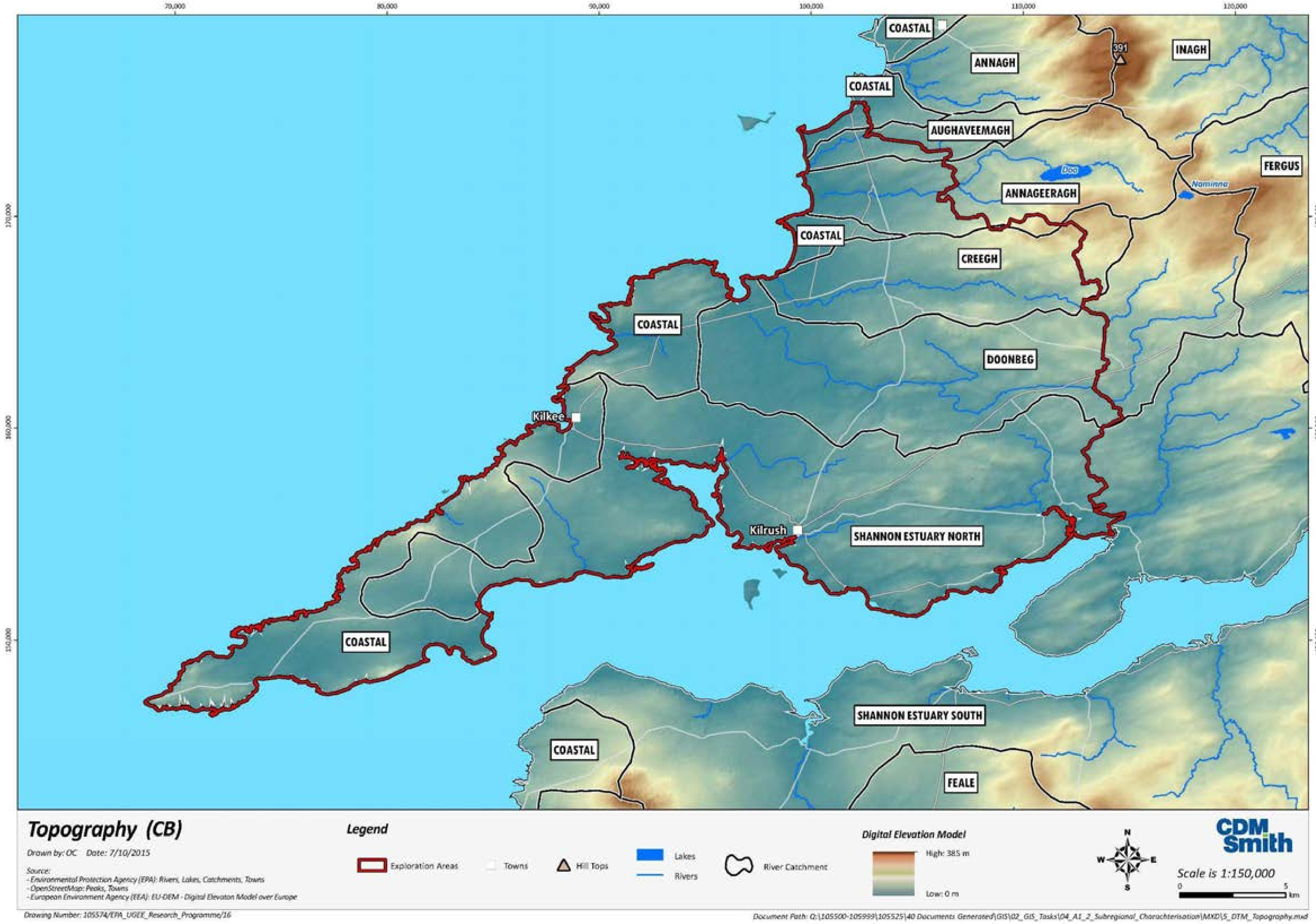


Figure 3.1. Topographic map – CB study area.

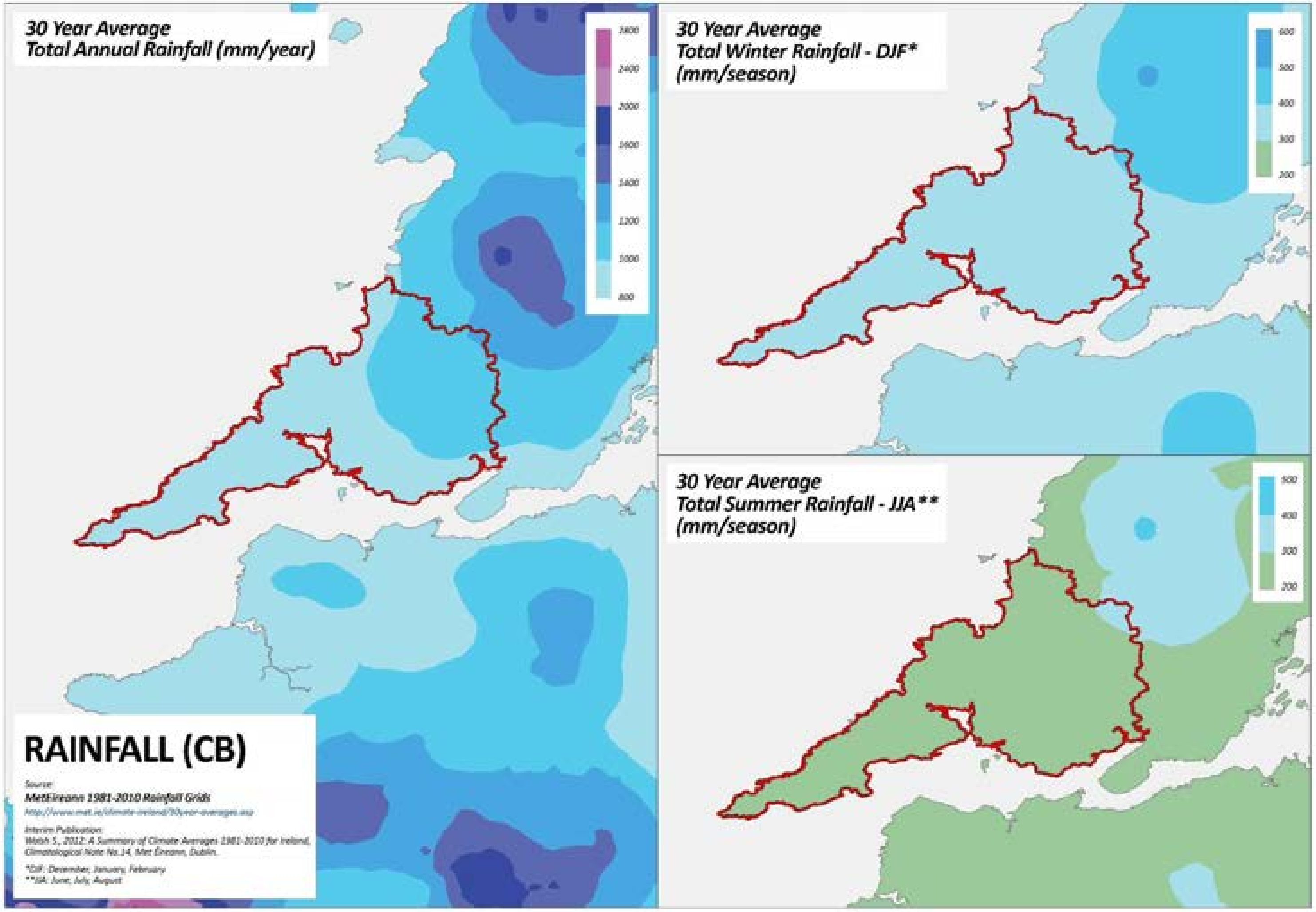


Figure 3.2. Average annual rainfall distribution (1981–2010) – CB study area. From Walsh (2012) and Met Éireann (2015).

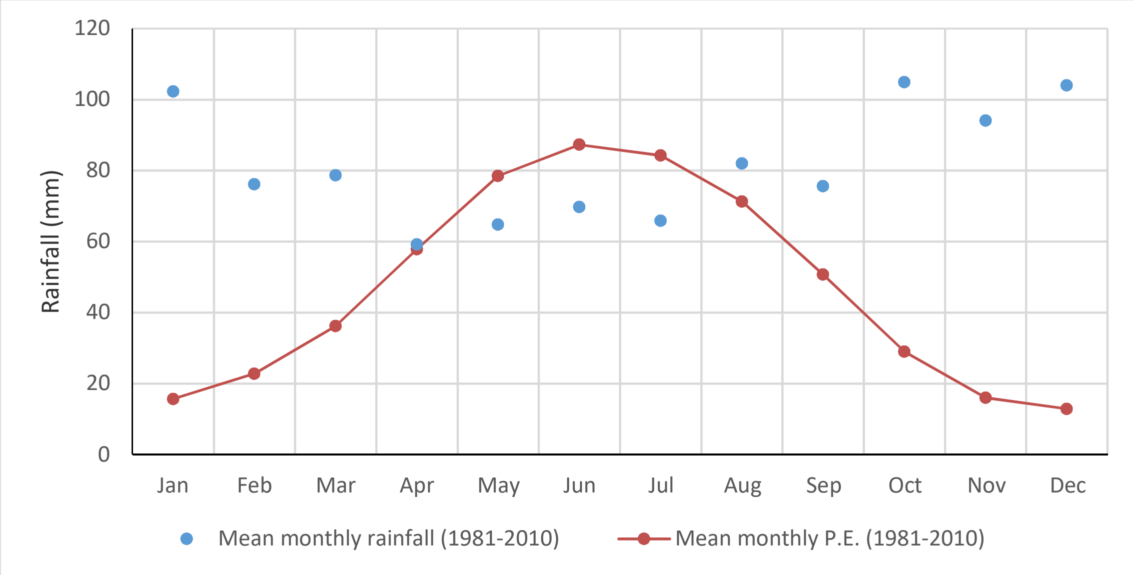


Figure 3.3. Mean monthly rainfall and P.E., Shannon Airport (1981–2010).

3.4 Streams/Rivers

Several streams rise from the higher ground in the northern and eastern parts of the study area. These flow west and south to the sea and Shannon Estuary. On Loop Head peninsula, several localised catchments drain directly to the sea over short distances.

The largest stream and associated catchment is the Doonbeg, which is also the only actively gauged stream in the study area. The hydrograph and flow duration curve for the OPW-operated Doonbeg gauging station are shown in Figure 3.4. The derived mean and Q_{95}-flows are 3.04 and 0.17 m^3/s, respectively, see Table 3.1. However, the mean flows may be underestimated as peak flows are historically truncated (pre-2012). Nonetheless, the Doonbeg hydrograph demonstrates a similar response to rainfall to gauging stations in the NCB study area.

The other catchments in the CB study area share similar physical and geological characteristics as the Doonbeg catchment. Therefore, the Doonbeg gauge can be used as a surrogate for such catchments. As well, estimates of mean and Q_{95}-flow in ungauged catchments were derived using EPA’s HydroTool (see Table 3.2), with values ranging from 0.08–0.41 and 0.01–0.05 m^3/s, respectively.

3.5 Quaternary Geology

Glacial till covers most of the immediate study area, see Figure 3.5. To the west, till exists in broad sheets that are several metres thick. To the east, the till is present as drumlins. The till is derived from the underlying Namurian bedrock (see Section 3.3) which, depending on location, has varying clay content and subsoil permeabilities (e.g. tills derived from underlying sandstones would have higher permeabilities than till derived from shale or mudstone). Towards the east, the thickness of till decreases and there are numerous areas where bedrock is close to surface or outcrops.

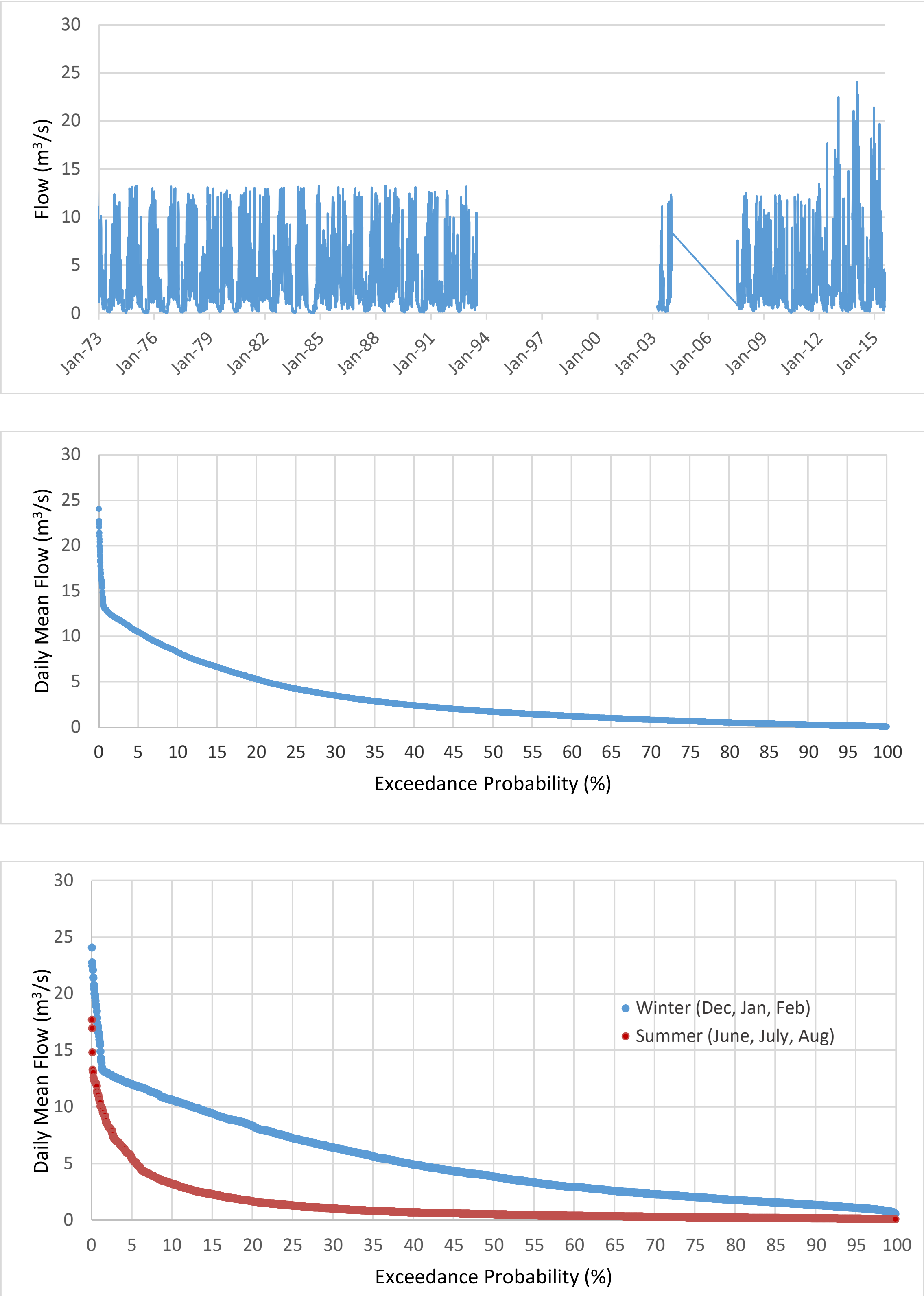


Figure 3.4. Hydrograph and flow duration curves – Doonbeg.

Table 3.1. Summary of estimated flows in the CB study areas

Gauged catchments[a] (derived from measured data)					
Parameter	**Unit**	**Clare Basin**			
		Value	**-**	**-**	**-**
Q_{95} Flow	m^3/s	0.171	-	-	-
Mean Flow	m^3/s	3.039	-	-	-
Specific Runoff (Q_{95})	$m^3/s/km^2$	0.0016	-	-	-
Specific Runoff (mean)	$m^3/s/km^2$	0.028	-	-	-
Ungauged catchments[b] (derived from HydroTool)					
Parameter	**Unit**	**Clare Basin**			
		Min	**Max**	**Mean**	**Median**
Q_{95} Flow	m^3/s	0.011	0.15	0.0548	0.038
Mean Flow	m^3/s	0.08	1.17	0.4128	0.2805
Specific Runoff (Q_{95})	$m^3/s/km^2$	0.0007	0.003	0.0019	0.0021
Specific Runoff (mean)	$m^3/s/km^2$	0.0097	0.0222	0.0143	0.0143

[a]Based on Doonbeg gauging station (period 1972–2015).

[b]Result from HydroTool in 12 catchments.

Alluvial sediments are mapped along most stream valleys in the study area. As well, localised gravel bodies are mapped in the central part of the study area towards Cooraclare and Kilmihil. These gravels both follow and cut across present day stream courses, and are considered to be associated with moraine-type deposition rather than outwash-type deposition. They are poorly stratified, contain clay and silt, and can be more than 10 m thick. They may also be partly interbedded with boulder clay materials. The datasets generated for the NCB as part of the Tellus Border project do not yet exist for the CB study area.

3.6 Bedrock Geology

The mapped bedrock geology of the CB study area is shown in Figure 3.6, as reproduced from the 1:100,000 bedrock series map published by the GSI (Sleeman and Pracht, 1999). The CB comprises a sedimentary sequence of Namurian age shales, mudstones, siltstones and sandstones resting with varying degrees of unconformity on older Viséan age limestones (Hodson, 1954; Wignall and Best, 2000), see Figure 3.7. The Viséan limestones are the same rocks that form the Burren karst landscape further north and east in Co. Clare.

3.7 Stratigraphy

The Namurian age stratigraphic sequence of the CB study area is summarised in Figure 3.8. Broadly, the Namurian stratigraphy is divided into two groups (Rider, 1974):

- Shannon Group; and
- Central Clare Group.

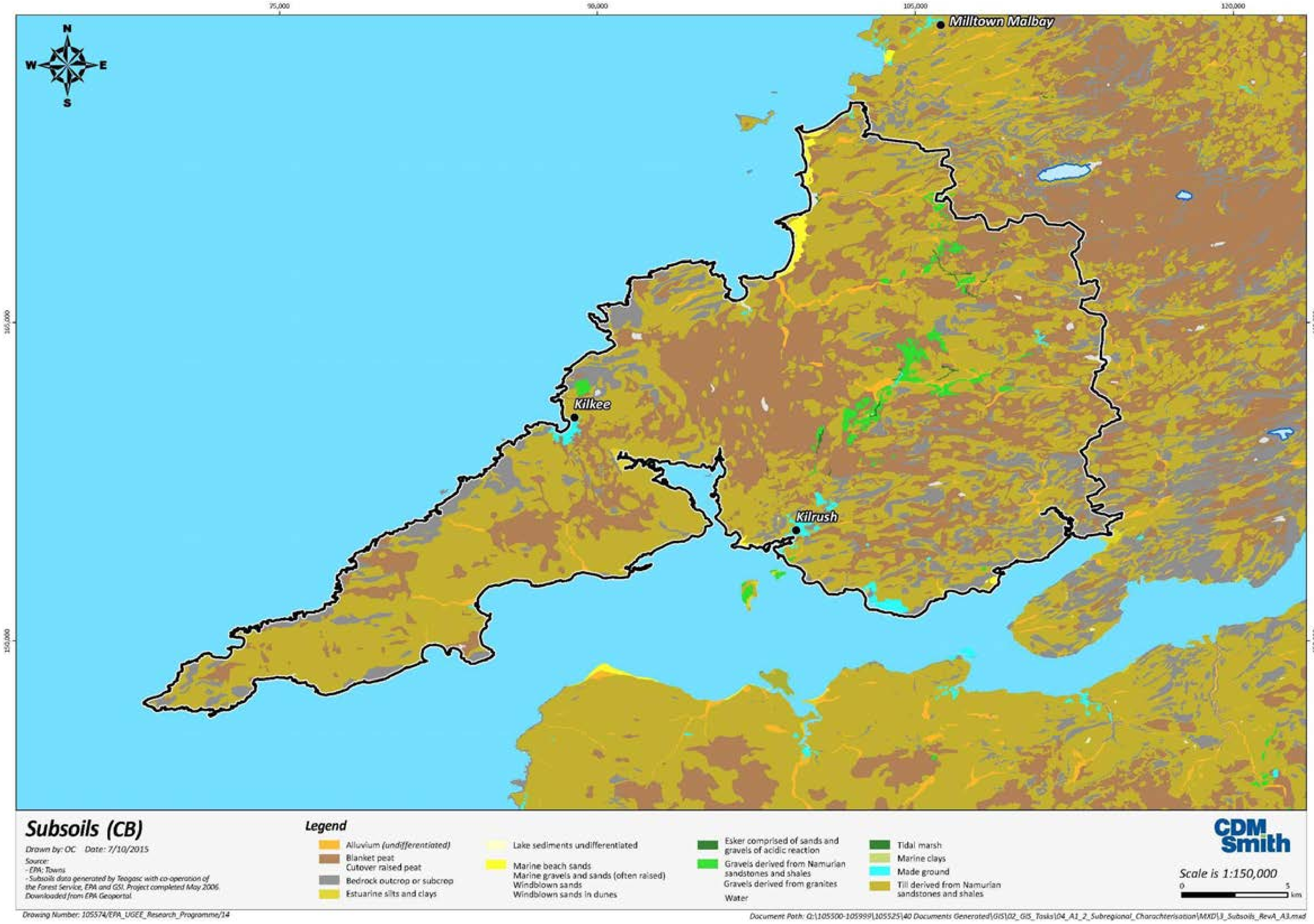


Figure 3.5. Subsoils map of the CB study area.

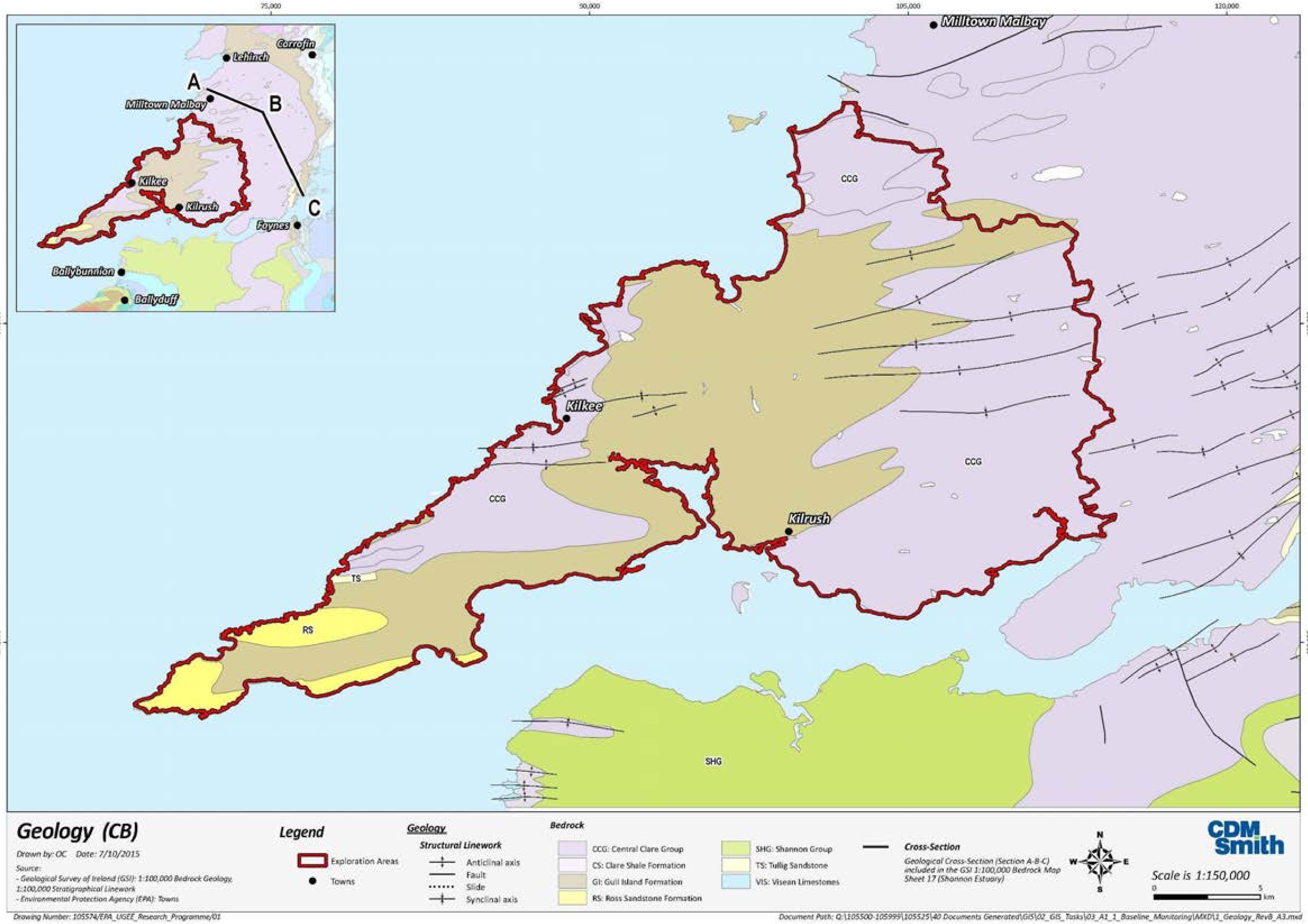


Figure 3.6. Bedrock geology map of the CB study area.

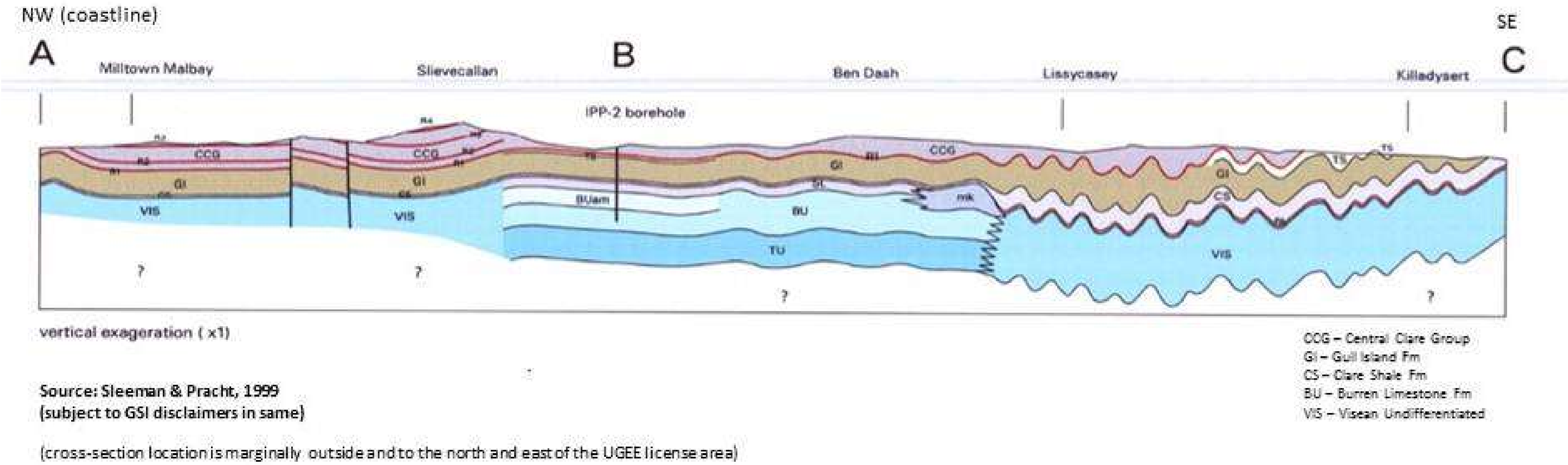


Figure 3.7. Simplified geological cross-section – CB study area. © Geological Survey Ireland.

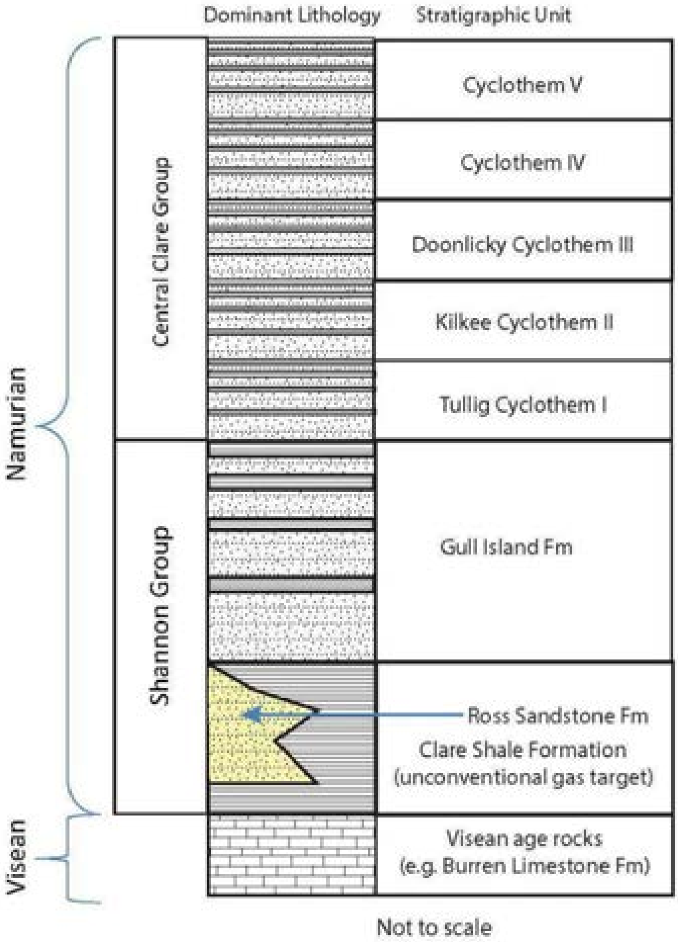


Figure 3.8. Simplified lithological column – CB study area.

The Shannon Group consists of the Clare Shale Formation, the Ross Sandstone Formation and the Gull Island Formation (Rider, 1974). The Central Clare Group consists of five fluvio-deltaic ‘cyclothems’ (Rider, 1974), as described below. The most complete lithological profile of the Namurian sequence within the study area is described from the Doonbeg-1 exploration borehole (see Figure 1.3) which was drilled in 1962/63. It penetrated 1059 m of Namurian shales and turbidites above the Visèan limestones, including 276 m of the Clare Shale Formation (Sleeman and Pracht, 1999).

3.7.1 Clare Shale Formation

The Clare Shale Formation is the unconventional gas target formation in the NCB and defines the base of the Namurian sedimentary sequence. It comprises deep-water marine shales which are distinctly dark-grey to black in colour and which, depending on location within the shale sequence, contain goniatite marker horizons, phosphate nodules and bands of mudstones with abundant pyrite (Hodson, 1954; Braithwaite, 1993). It is thinly bedded and of a platy/fissile appearance. It ranges in total thickness from approximately 10 m at the basin margins in north Co. Clare (Collinson *et al.*, 1991; Braithwaite, 1993) to 32 m in IPP-2 (Sleeman and Pracht, 1999), approximately 180 m at Loop Head (Pyles, 2008), 180 m at Ballybunnion (Sevastopulo, 2009), 213 m on Inishcorker Island (Hodson and Lewarne, 1961) and nearly 280 m in the Doonbeg-1 gas exploration well (Sleeman and Pracht, 1999).

The thinning of the formation towards the margins of the basin is the subject of debate by different researchers. From consideration of fossil records from marine bands, Wignall and Best (2000) concluded that the Clare Shale Formation sequence is "condensed" at the margins as a function of sedimentation in distal, sediment-starved locations rather than shallow-water "winnowing" on basin margins, i.e. in stratigraphic terms, the Clare Shale Formation is a product of "*unrealized accommodation space rather than a lack of accommodation space*" (Wignall and Best, 2000).

3.7.2 Ross Sandstone Formation

Along the Shannon Estuary, the Clare Shale Formation has a lateral, chrono-stratigraphic equivalent – the Ross Sandstone Formation (Wignall and Best, 2000). This formation reaches a total maximum thickness of approximately 300 m (Lien *et al*., 2003) and comprises turbidite sandstones with subordinate, parallel-bedded shales (Rider, 1974; Sleeman and Pracht, 1999). Thus, whilst the basin margins accumulated a condensed sequence of shale represented by the Clare Shale Formation, the centre of the onshore Clare Basin is characterised by deeper-water sandstone deposition.

The Ross Sandstone Formation is represented by upwards coarsening sequences of sandstones (Martinsen *et al*., 2000). The lower parts of the formation tend to be well-bedded (Sevastopulo and Wyse Jackson, 2009) or "tabular" (Martinsen *et al*., 2000), whereas the upper part of the formation is characterised by channel sandstones and turbidite slump horizons (Martinsen *et al*., 2000; Lien *et al*., 2003). The formation sequence is also punctuated by marine bands which allow for stratigraphic correlation to the north and south of the Shannon estuary (Hodson and Lewarne, 1961; Martinsen *et al*., 2000; Pyles, 2008).

The environment of deposition has been interpreted by most researchers to represent turbidite deposition on a submarine fan (Rider, 1974; Collinson *et al*., 1991; Lien *et al*., 2003). The lower, non-channelised part of the formation has been interpreted to represent the most distal area of turbidite deposition (Lien *et al*., 2003). The paleo-flow direction is inferred to be dominantly towards the north-east (Rider, 1974; Gill, 1979; Collinson *et al*., 1991; Wignall and Best, 2000; Lien *et al*., 2003).

3.7.3 Gull Island Formation

The overlying Gull Island Formation is dominated by siltstones and fine sandstones (Collinson *et al*., 1991; Wignall and Best, 2000; Martinsen *et al*., 2003; Pyles, 2008). The formation is interpreted to consist of sediments which form a major prograding slope (Sleeman and Pracht, 1999). The stratigraphic thickness is in excess of 400 m in southern Co. Clare and 130 m in northwest Co. Clare (Sleeman and Pracht, 1999). The formation is of considerable academic interest to the oil and gas industry due to the range of depositional features which are visible along the coastline in Co. Clare, which include slump structures, turbidite channel infills, 'sand volcanoes', and syn-depositional growth faults (Rider 1974, 1978; Gill, 1979). These features are indicative of high basin subsidence and deposition rates (Sleeman and Pracht, 1999; Martinsen *et al*., 2003).

From the study of deformation features and facies associations, Martinsen *et al*. (2003) divided the Gull Island Formation into a 'lower' and an 'upper' part:

- Lower: mud-dominated succession containing thin shales with both channelised and sheet turbidites of fine-grained sandstone, and frequent soft-sediment deformation features.
- Upper: mudstone-dominated succession which coarsens upwards to siltstone with "*isolated*" sandstone-filled turbidite channels, and with fewer soft-sediment deformation features.

The contact between the Gull Island Formation is gradational with the overlying Central Clare Group (CCG) and, as noted by Sleeman and Pracht (1999), the extrapolation and mapping of geological units inland is made difficult by the lack of outcrops.

3.7.4 Cyclothems of the Central Clare Group

The overlying CCG is described in the literature as repeating successions, or ‘cyclothems’, of shales/mudstone which are overlain by, siltstone, laminated sandstones and channel sandstones, and which are distinguishable on the basis of marine bands and associated fossils (Rider, 1974; Sevastopulo, 2009). Each cyclothem is described as prograding deltaic systems that culminate in distributary channel sandstones (Wignall and Best, 2000) and which are marked by erosional surfaces, i.e. paleosols, containing wood debris and other organic matter (Gill, 1979). A total of five cyclothems have been identified (Sevastopulo, 2009), from oldest to youngest: Tullig, Kilkee, Doonlicky, and Cyclothems IV and V. Both the Tullig and Kilkee cyclothems are characterised by laterally extensive fluvial sandstones. The ‘Tullig Cyclothem’ has a gradational base and the ‘Tullig Sandstone’ within the cyclothem is not easily discernible from the underling Gull Island Formation. The use of the term ‘Tullig Cyclothem’ as a stratigraphic unit has been questioned by Elliott (2000) and Sevastopulo (2009).

3.8 Basin Structures

Onshore, the Namurian rocks are mapped through West Clare, North Kerry and West Limerick (Sleeman and Pracht, 1999). Offshore, the full extent of the CB is not defined, but from interpretation of seismic surveys to the west of Galway Bay and Co. Clare, Croker (1995) suggested that the Clare Basin may extend as far as the Porcupine Basin offshore, where reports of Namurian aged strata in oil/gas exploration were noted by Sevastopulo (2009). An overall outline of onshore basin geometry surrounding the UGEE licence area is depicted in Figure 3.9, which shows the depth (m below ground level) to the top of the Clare Shale Formation, as sourced from Rübel and Loske (2009).

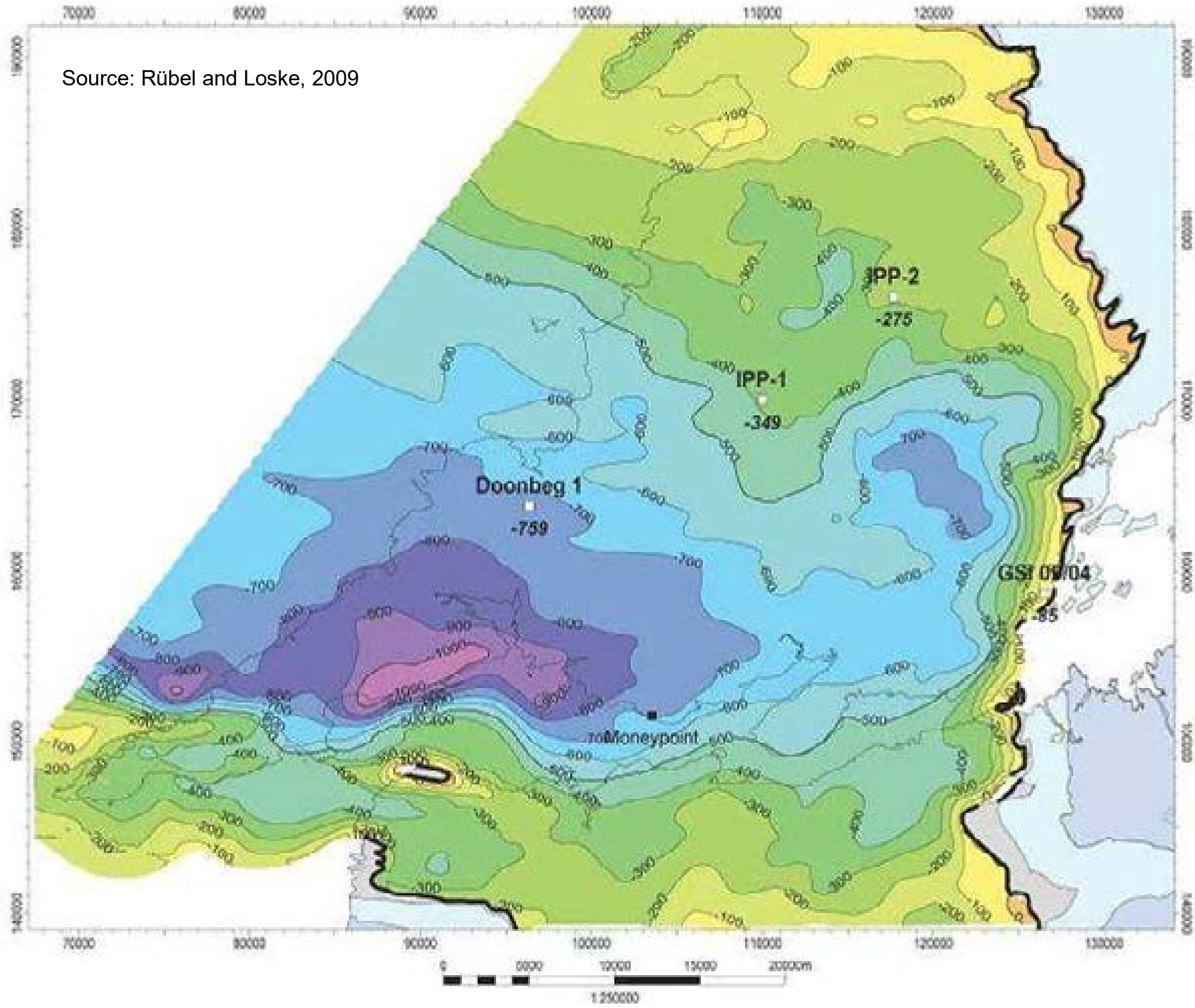


Figure 3.9. Interpreted depth (m below ground level) to the top of the Clare Shale Formation.

Within the onshore portion of the CB, the sedimentary sequence increases in thickness from its margins towards the centre of the basin which is roughly coincident with the Shannon Estuary (Lien *et al*., 2003), see Figure 3.10. An alternative schematic cross-section which is oriented NE-SW across the Shannon Estuary is presented in Figure 3.11 (wherein the vertical wavy lines represent the natural gamma logs for Doonbeg-1 and IPP-1 exploration boreholes).

Several researchers describe the CB as an elongate sedimentary basin that received sediments from a principally south-southwesterly direction (Collinson *et al*., 1991; Wignall and Best, 2000; Martinsen *et al*., 2003; Pyles, 2008; Pointon *et al*., 2012). Bresser (2000) considers the sediments of the CB to be "*typical syn-orogenic sediments indicative of the Variscan orogeny further south (south of the Irish south coast)*" which "*were deformed during northward propagation of Variscan deformation*".

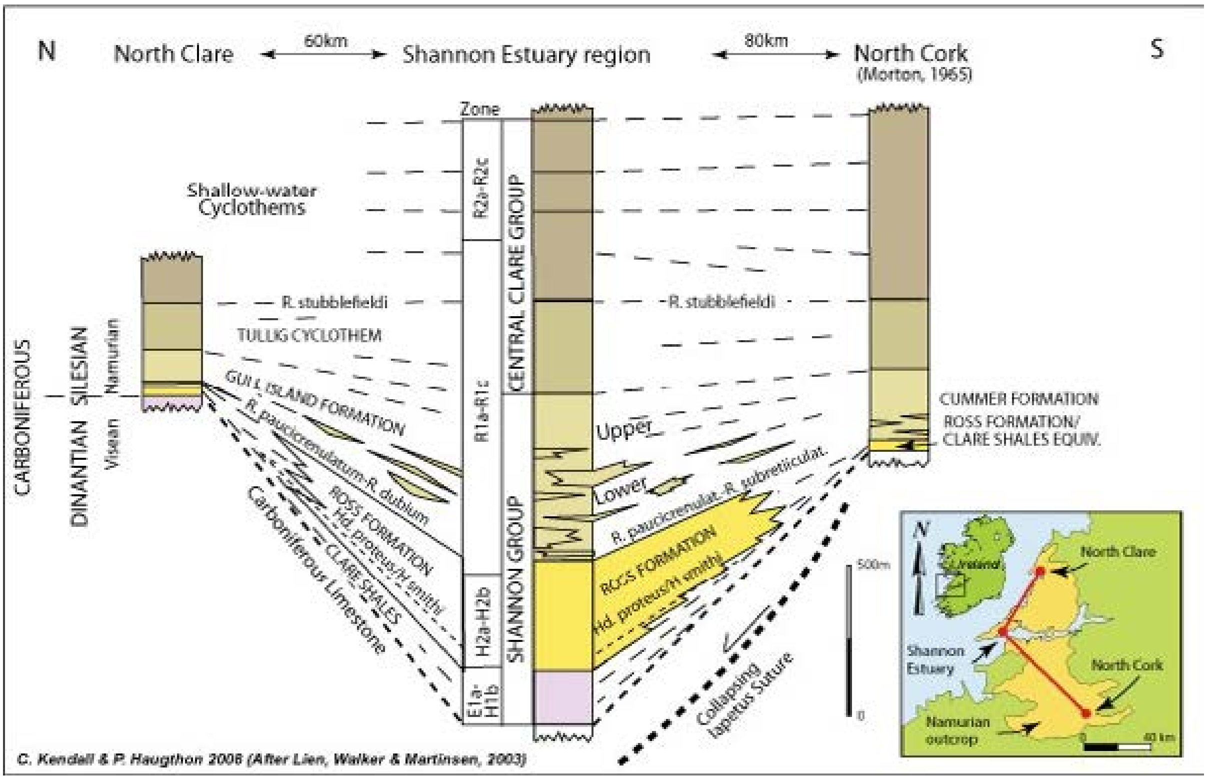
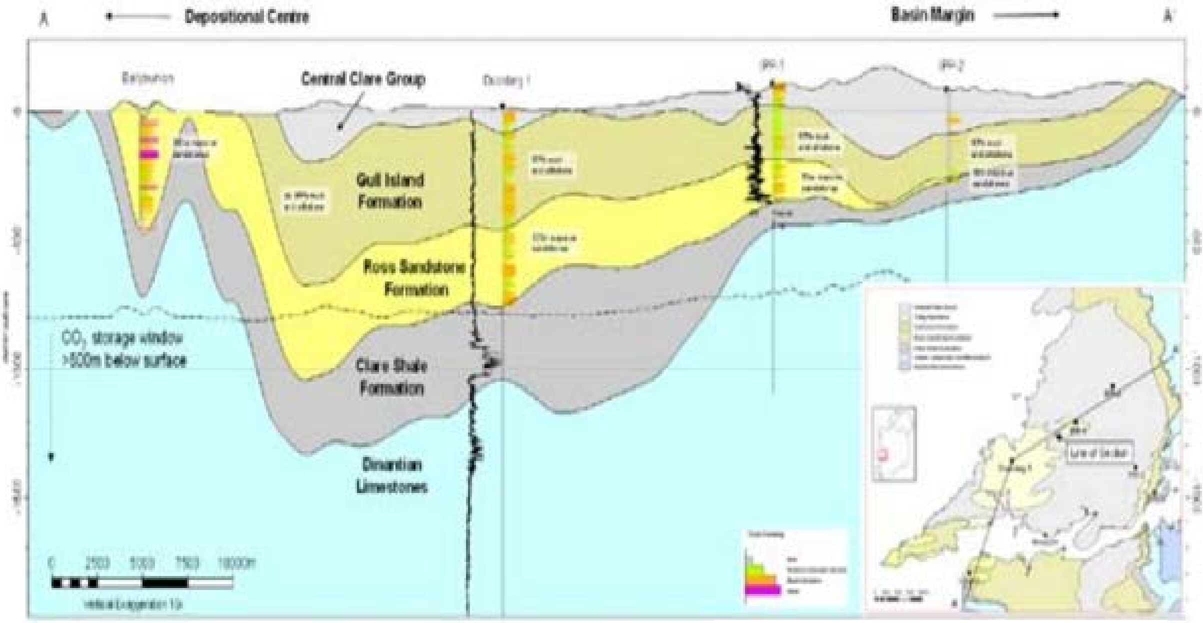


Figure 3.10. Namurian stratigraphy across the CB. Reproduced with permission from Wiley.



Source: SFI (2014)

Figure 3.11. Schematic geological cross-section NE-SW across the CB study area.

3.8.1 Structural geology

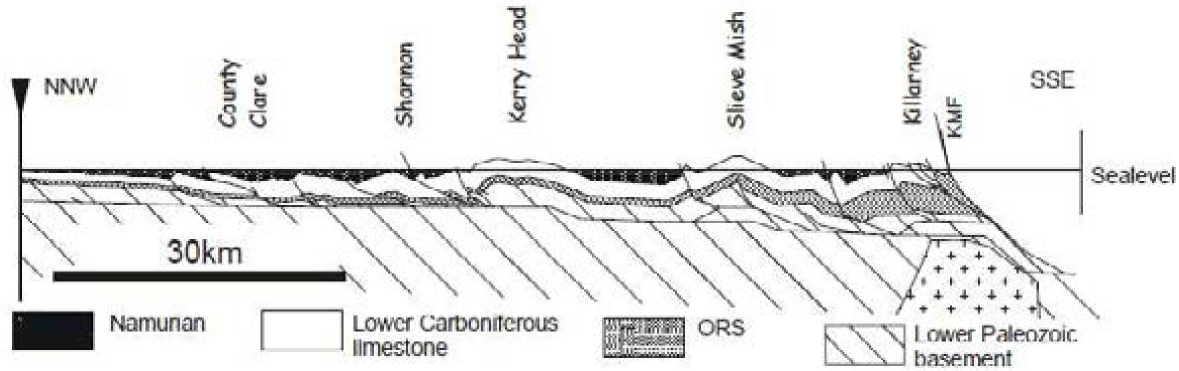
Structural geological maps of the CB are included in Appendix F, reproduced from the EPA-led Climate Change Research Programme which examined the potential for underground carbon dioxide sequestration in deep sedimentary basins in Ireland (Farrelly *et al*., 2010). In the UGEE study area, the Namurian age rocks are gently deformed in a series of parallel, roughly E-W trending folds, with limbs that generally dip between 10 to 50 degrees (Sleeman and Pracht, 1999) and which cross the study area with fold wavelengths on the km-scale. Localised folding at the m-scale, including box folding (Dolan, 1984), is superimposed on the regional folds. Fold structures are influenced by lithology, whereby thinner shale units develop small-scale chevron-folding, over-turning and thrust-structures at the m-scale, which in turn influences the prevalence of cleavage in fissile shales (Gill, 1979).

The 1:100,000 scale bedrock map that was presented in Figure 3.6 shows a general absence of faulting within the Namurian sequence. Minor ENE-WSW trending faults (i.e. parallel to principal fold axes) are mapped in the Milltown Malbay/Slievecallan area to the north, but the general absence of significant faulting is in contrast with the structural complexities of older rocks to the south and east of the CB, where steep folding and both E-W and N-S faulting is documented in Devonian Old Red Sandstones (e.g. in the Slieve Aughty/Bearnagh Mountains and to the southeast in Lower Carboniferous limestones in the Fergus river valley). N-S faulting is roughly coincident with the NNE-SSW trending 'Fergus Shear Zone' (Coller, 1984).

The absence of faults on existing maps does not mean that faults are not present. In the context of the Quaternary cover which extends across much of the study area and the similarities of lithologies in the various formations, it is possible that faulting is simply difficult to spot or map. Indicators of apparent faulting can be seen along the exposed cliffs on Loop Head Peninsula, see Figure 3.12, and a large cutting from a trial well at Lough Naminna appear to show slickensides.

Bresser (2000) and Naylor and Shannon (2011) both commented on the apparent absence of structural complexity in the CB study area. Bresser (2000) postulated that the Variscan deformation "(folding, thrusting and cleavage formation) dies out towards the north and in northern County Clare the Lower Carboniferous carbonates and Upper Carboniferous siliciclastics are nearly undeformed". Based on geological mapping and kinematic structural modelling, Bresser (2000) proposes that a former passive continental sedimentary basin (the "Munster Basin") was detached from the underlying basement during the Variscan orogeny, producing basal thrust-sheets of Devonian to Carboniferous age sediments, which not extend up into the Namurian sequence, see Figure 3.13. In this conceptual model, the "intensity" of compressional deformation decreases from south to north in Ireland. Bresser (2000) nonetheless acknowledged that smaller thrust faults could still occur within the Namurian sequence, not as manifestations of deep-seated faulting, but rather as localised features to accommodate folding between units of contrasting petrophysical characteristics (e.g. brittle versus ductile rocks).

Figure 3.12. Examples of faulting/shearing in the CB study area.



Source: Bresser (2000)

Figure 3.13. Conceptual cross-section of Variscan basal detachment and thrust faulting.

With regard to faulting and fracture patterns, Fitzgerald *et al.* (1994) and Bresser (2000) both describe an ENE-WSW dextral strike-slip component ("transpression") to the main N-S compressional deformation. Preliminary findings from mapping of post-Devonian rocks by Moore and Walsh (2013) acknowledge a lateral (dextral) shear component to the Variscan deformation, resulting in conjugate sets of high-angle veins and strike-slip-related fractures. The presence of minor fractures, veins and vein-breccia in or near the study area are noted in core logs within the UGEE study area (Philcox, 2009a–e), whereas Farrelly *et al.* (2010) describe "*some brittle deformation*", referring to small-scale thrust, strike-slip, and "*subordinate*" extensional faults, also noting that additional mapping and study is required to "*determine the tenor of these structures*".

3.9 Hydrogeology

The hydrogeology and the available groundwater resources of the CB study area are defined by Namurian bedrock formations, which are generally considered to be 'poorly productive aquifers' from a water resources point of view. Based on lithological characteristics and available well data, the Clare Shale Formation has been categorised by the GSI as a '*Pu*' aquifer (generally unproductive) whilst the overlying formations are all categorised as '*Ll*' aquifers (locally important and moderately productive only in local zones).

Although there are no public groundwater supplies within the UGEE licence boundaries, private boreholes are used for water supply. The bedrock aquifers provide water to single homes, farms and commercial facilities (e.g. hotels, water bottling plant).

The estimated recharge distribution across the UGEE licence area, based on the national recharge map, is shown in Figure 3.14, and ranges from <50 mm/yr to 150 mm/yr, the upper value representing a recharge cap which is based on the PPA aquifer classification, and which is subject to the same influences that were described in Section 2.9.4.

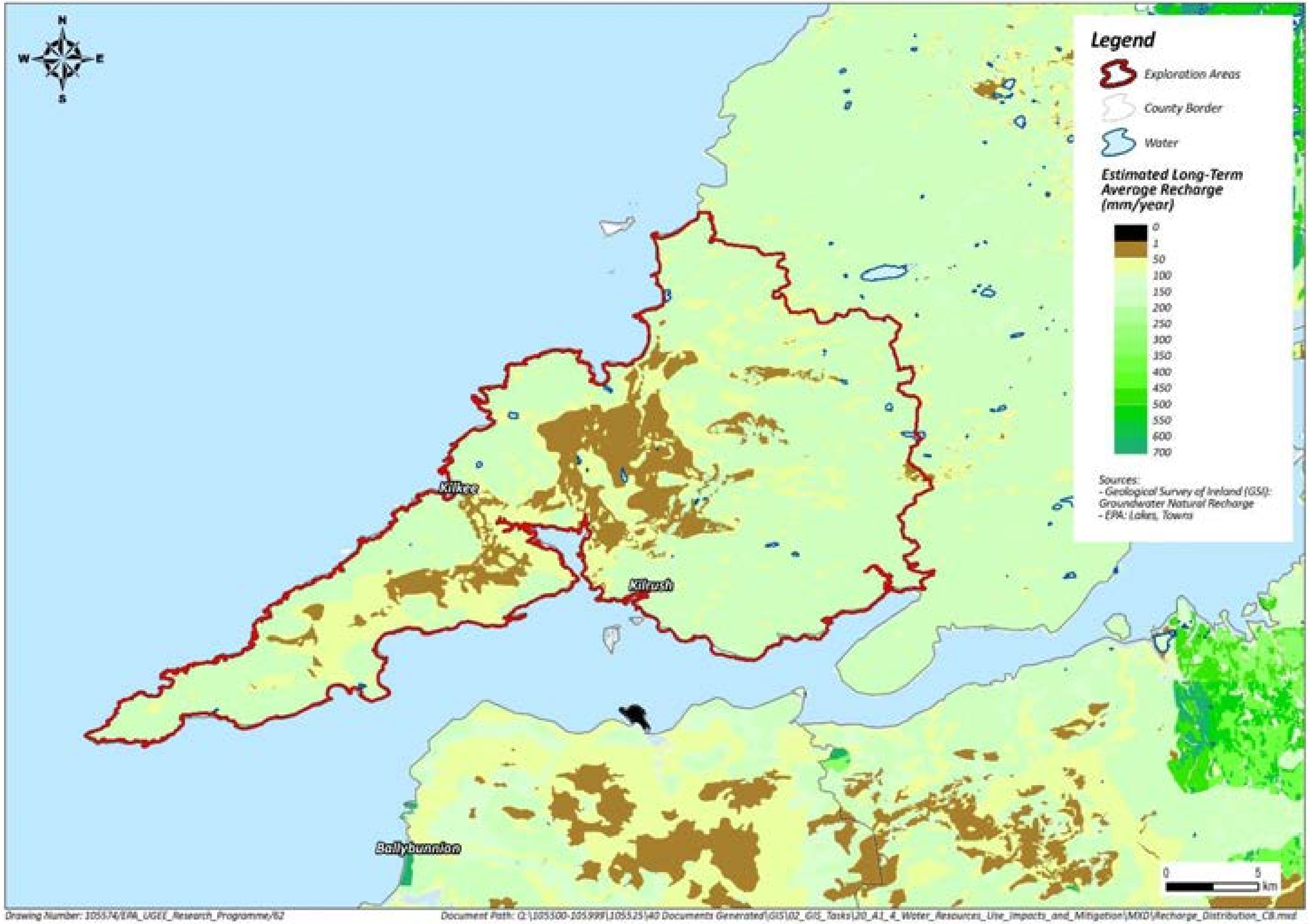


Figure 3.14. Estimated recharge distribution – CB study area.

Groundwater flow in the Namurian rocks takes place via open fractures and fissures. Primary porosity has mostly been destroyed by low-grade diagenetic metamorphism (Bresser, 2000; Farrelly *et al.*, 2010), and both carbonate and quartz cements are present (Graham, 2009). The diagenesis is potentially related to both deep sediment burial and high thermal gradients which have been documented by Brock and Barton (1984).

Even if the Namurian sequence does not appear to be extensively faulted in the manner observed in the NCB, the bedrock formations have fracture permeability. The primary fracture sets are associated with planar bedding and high-angle shearing. Philcox (2009a-e) describes Namurian core logs from deep boreholes in or near the study area, specifically boreholes IPP-1, IPP-2, Doonbeg-1, GSI 09/04 and GSI 09/05 (see Figure 1.3). Although not frequent, the logs reference sub-horizontal and high angle fractures, vein breccias, and cm-scale (syn-sedimentary) faults (e.g. "*stacked thrust-faults*"). Acoustic televiewer images (Farrelly *et al.*, 2010) of boreholes at Kildysert (GSI 09/05) and Faha near Ballybunnion (GSI 09/04) support Philcox's descriptions. However, it should be noted that Philcox also describes fractures that contain fine-grained sediment (e.g. mud), which raises the question of whether fractures at depth are open or closed.

Fracture permeability data are sparse and poorly quantified. Farrelly *et al*. (2010) reported low fracture permeability values of less than 0.1 millidarcies (mD) from core sample analyses of sandstones in exploration boreholes Doonbeg-1, IPP-2, GSI 09/04 and GSI 09/05. These are in contrast to reports of relatively high-yielding water supply wells in or near the study area which indicate that fracture permeability can be significant. For example, the main production well for the Lisseycasey GWS is approximately 120 m deep and operates continuously at approximately 70 m^3/hr (presumably from faulted/fractured sandstone units within the Central Clare Group). Reports from two trial wells drilled to approximately 120 m depth near Lough Naminna for the Kilmaley-Inagh GWS indicate multiple water strikes during drilling, with relatively high reported specific capacity estimates of 28 and 38 m^3/hr/m of drawdown, as well as preliminary estimates of well 'yield' in excess of 300–400 m^3/d (Deeny, 2007, 2008). The wells are located in an area mapped by the GSI as the Central Clare Group, and well logs of the trial wells references *"silts*" and "*sandstone*" with "*hard, platey shale"* (note, a nearby small quarry shows exposures of mainly sandstone with siltstone). The Glin public water supply well to the south of the Shannon Estuary pumps groundwater at 225 m^3/d from rocks that are equivalent to the Central Clare Group, and the reported estimated transmissivity ranges from 7–27 m^2/d (Hudson, 1995).

Deakin and Daly (2000) recorded a range of specific capacity values between <2 and 63 m^3/d/m for wells in the Namurian 'LI aquifer' in Co. Clare, and the highest reported yields are from wells that pump water from the Ross and Gull Island Formations. Corresponding transmissivity estimates for the 'LI aquifer' range between 1 and 20 m^2/d generally, and higher values may be achieved in some fault zones. Within the study area, faults are not obvious at ground surface, partly because of the till cover, so siting wells and intersecting enhanced permeability zones involves a degree of good fortune.

Fractured sandstone aquifers are mostly under confined conditions and the confining layers are provided by the overlying till as well as lower permeability shale and mudstone units within the main formations. Artesian flows from boreholes are not uncommon, and several private wells surveyed as part of the UGEE JRP were observed to be artesian. One of the trial wells referenced above near Lough Naminna has remained artesian (slow flow) since it was drilled in 2007.

Lithologies change rapidly with depth, and an example of the changes that can be expected in wells drilled in the study area is included in Figure 3.15 (in this case, the Ross Sandstone Formation). This has implications for groundwater flow, since the primary water-bearing horizons would be fractured sandstones and siltstones (depending on relative proportions of argillaceous materials contained within individual units). Thus, groundwater strikes at multiple intervals are expected and documented.

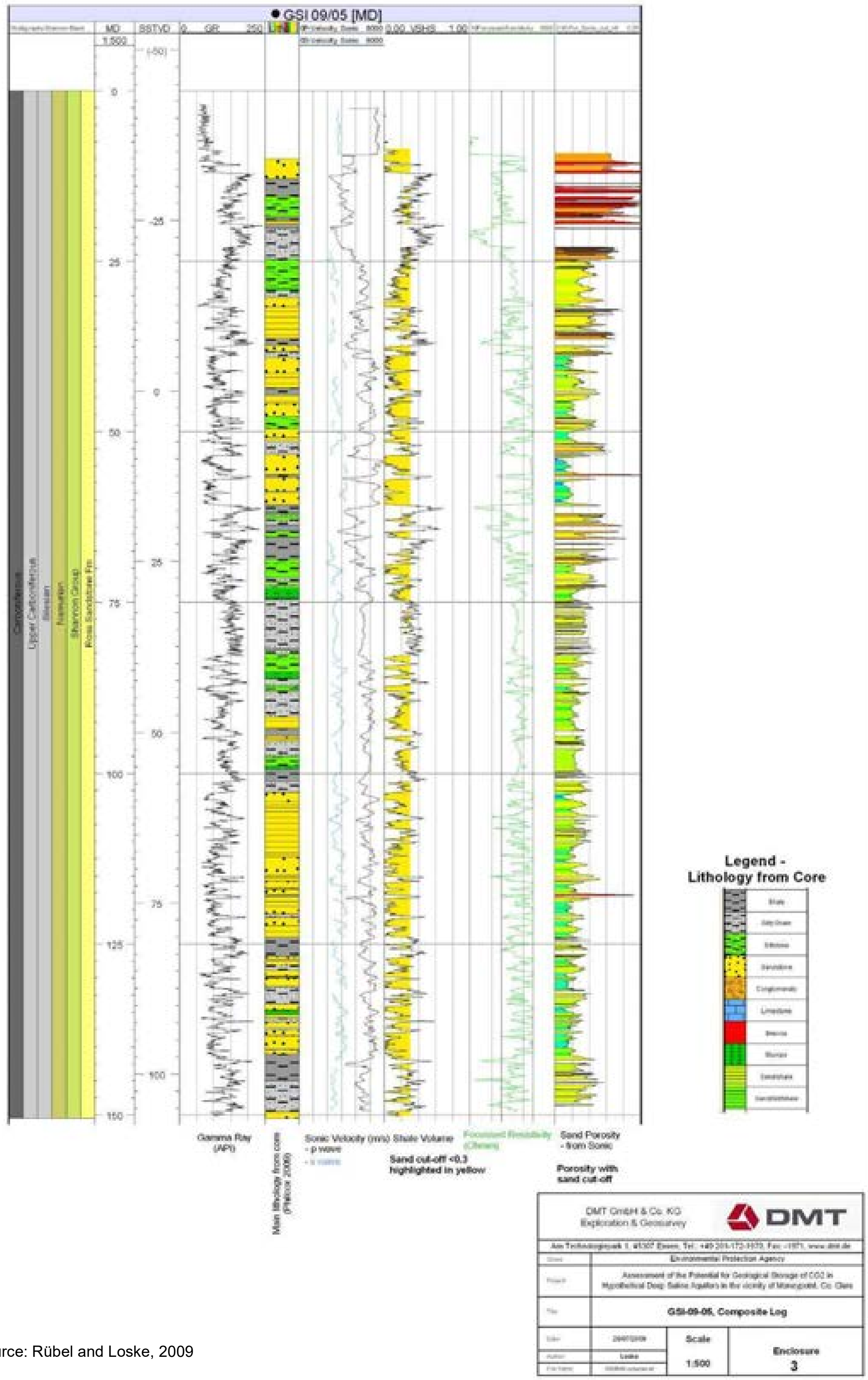
Driller's notes from one of the trial wells at Lough Naminna referenced above refers to water strikes at 5 separate intervals to 120 m depth. Brock and Barton (1984) reported artesian flow in exploration borehole IPP-2 which was drilled to a depth of 927 m, although it is not known from which depths or formation the groundwater originates. The bottom of IPP-2 reached the Burren Limestone Formation (Philcox, 2009c), but the well would also have been open to the Gull Island Formation. Furthermore, the well completion report for exploration borehole Doonbeg-1 reported '"*freshwater*" (300–400 ppm Cl) during drilling in "*sands*" from ground surface to 785 m depth (Ambassador Irish Oil Company, 1963a). The report also records that:

> "All zones of fresh water were from fractured quartzitic sandstones, partly cemented by leached loosely consolidated sandstone. Main water sands are in the following intervals: 7 to 20 ft, 70 to 110 ft, 690 to 705 ft, 795–850 ft, 1050 to 1090 ft, 1280 to 1360 ft, 1910 to 1925 ft, and possibly 2465 to 2485 ft. The well was making about 115 barrels of fresh water per hour when conversion to mud was initiated at 2196 ft".

This information indicates potential groundwater contributions to a depth of at least 1925 ft (585 m), and the 115 barrels per hour corresponds to approximately 18.25 m^3/hr. It is worth noting that the well was reportedly capped "*only with a thread connector to allow farmer the use of fresh water*". The well still exists today but there is no confirmed, available information on its overall integrity.

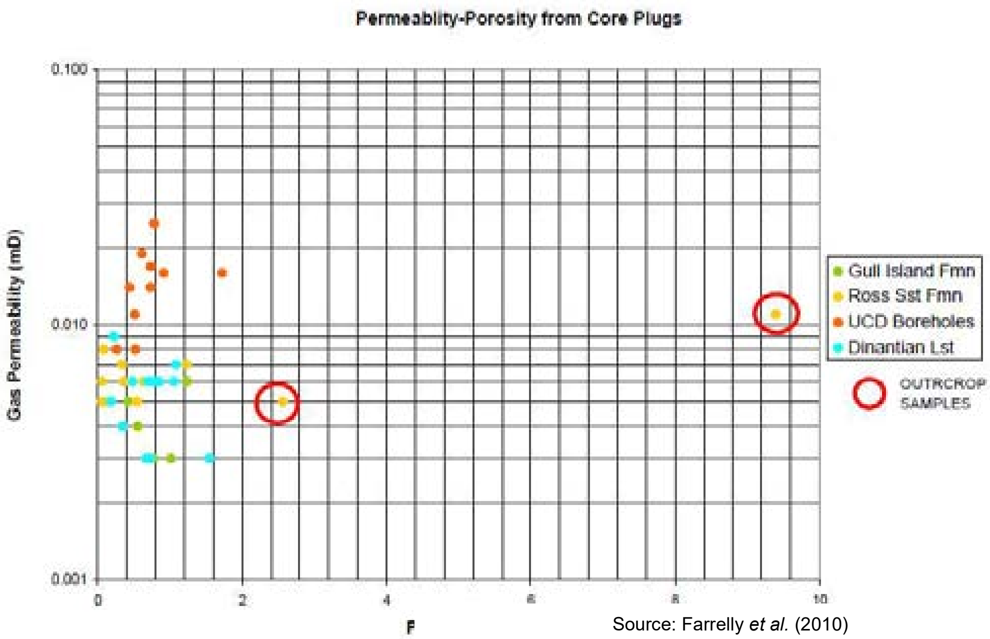
In fractured bedrock aquifers, groundwater storage is low. Based on core sample analysis, Farrelly *et al.* (2010) report formation porosities of < 2% for the Ross Sandstone and Gull Island Formations (see Figure 3.16). Rübel and Loske (2009) provide higher estimates (as secondary porosity), also citing PAD well log estimates between 2% and 7% for Namurian sandstones. On the basis of borehole geophysical logging, Rübel and Loske (2009) estimated average porosities of 7.4% for the Gull Island Formation and 5.2% for the Ross Sandstone Formation. The histograms of calculated porosities based on focused resistivity and sonic logs in GSI boreholes 09/04 and 09/05 are reproduced in Figure 3.17.

There are no specific borehole data for the Clare Shale Formation as it is not used for water supply, partly due to its great depth across most of the study area and partly because of its low permeability nature. Although shales are generally 'unproductive', shale units in the Namurian sequence are hydrogeologically significant as they: a) act as confining units; and b) affect drainage by enhancing surface runoff of rainwater where they are present at or near ground surface.



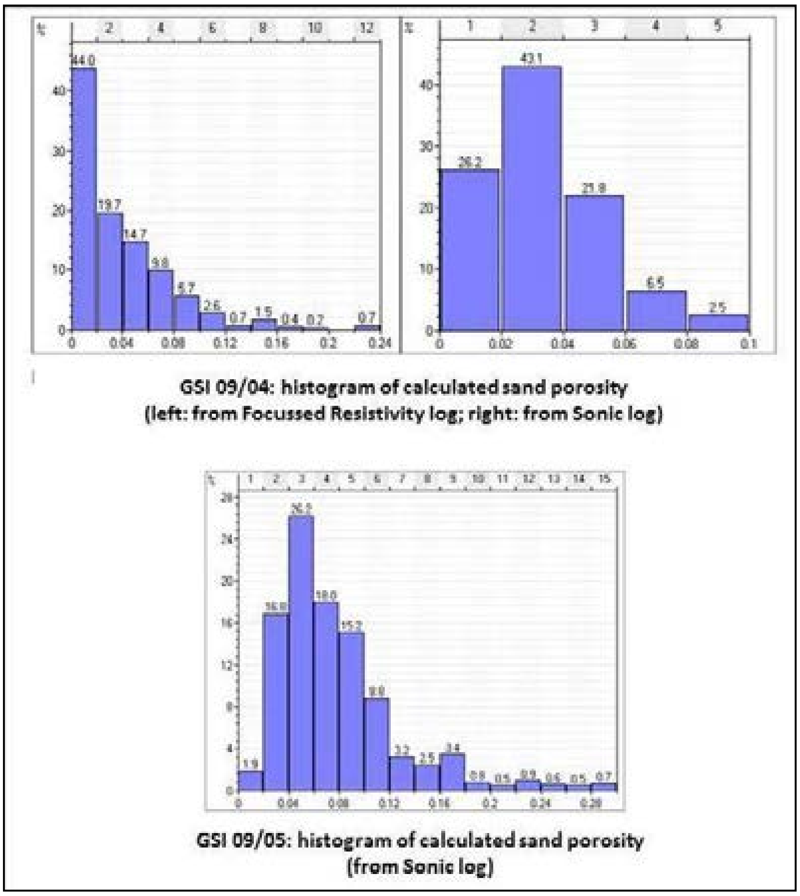
Source: Rübel and Loske, 2009

Figure 3.15. Lithological variations in the Ross Sandstone Formation.



Source: Farrelly *et al.* (2010)

Figure 3.16. Estimated gas permeability versus porosity (F) from sandstone core plugs.



Source: Farrelly *et al.* (2010)

Figure 3.17. Calculated sandstone porosity from two GSI boreholes.

3.9.1 Springs

There are many small springs throughout the UGEE licence area, but these are small, generally discharging less than 5 l/s, and none are comparable to the significantly larger springs noted in the NCB. They can nonetheless be important in providing baseflow to streams and supporting conditions for groundwater-dependent ecosystems.

3.10 Groundwater Quality

Groundwater quality data are sparse. Cronin and Deakin (2000) report ‘mixed’ water types for three sources in Namurian age rocks. They propose that cation exchange (replacement of Ca and Mg in favour of Na) can be important as a function of groundwater residence time in the various bedrock units. They also report that elevated iron and manganese concentration are common in groundwater derived from sandstone and shale formations due to the dissolution of these elements where reducing conditions occur. Elevated iron concentrations are noted by red/brown surface staining at wellheads throughout the study area, and is a common nuisance in wells that produce water from shale and sandstone formations in other parts of Co. Clare as well (Cronin and Deakin, 2000). Two former supply sources at Kilkee and Kilrush were discontinued due to elevated ammonium and chloride concentrations, as well as presence of faecal coliforms (at Kilkee), which are indicative of contamination from organic waste sources.

There are no groundwater quality monitoring stations in the UGEE licence area of the CB. The nearest EPA monitoring point is the Glin PWS to the south of the Shannon Estuary, which abstracts groundwater from undifferentiated Namurian “gritstones and shales” (Hudson, 1995). Table 3.2 summarises EPA groundwater quality data for the period 1995 to 2013.

The concentrations of nitrate and MRP are below respective groundwater threshold values (Groundwater Regulations S.I. No. 9 of 2010). Concentrations of iron and manganese are consistently elevated but are most likely of natural origin. Four samples were analysed for pesticides, VOCs and hydrocarbons in the period or record and there were no detections of related parameters in the existing dataset.

Glin was also sampled by the RPII as part of the national study on radioactivity levels in groundwater that was described in Section 2.8.2. None of the referenced screening limits were exceeded in Glin, thus no further analyses were conducted on the samples from this well.

Table 3.2. Summary of water quality – Glin (1995–2013)

Parameter	Unit	Total count (incl. <LOD)	Min.	Max.	Median	Mean	St. dev.
pH	pH	32	6.51	7.9	7.3	7.27	0.33
Conductivity	µS/cm	35	303	554	452	443	47.1
Alkalinity	mg/l $CaCO_3$	49	149	305	199	205	28.4
Total Hardness	mg/l $CaCO_3$	48	111	473	134	151	58.4
Turbidity	NTU	27	<0.1*	13.1	7.3	6.75	3.66
Nitrate	mg/l as NO_3	37	<0.3	12	0.27	1.73	2.49
Ammonium	mg/l	50	<0.01	0.458	0.29	0.263	0.094
Molybdate Reactive Phosphorus	mg/l P	43	<0.003	0.067	0.01	0.015	0.014
Dissolved Oxygen	% Sat	34	<10	82.8	25	31.3	26.8
ORP	mV	17	–238.9	157	8.8	–19.6	122
Total Coliforms	No./100ml	41	<0.1	225	0.5	7	35
Faecal Coliforms	No./100ml	41	<0.1	2	0.5	0.56	0.26
Total Organic Carbon	mg/l C	32	<0.25	50.4	1.14	2.52	8.75
Chloride	mg/l Cl	50	8.22	36.4	26	26.9	4.45
Fluoride	mg/l F	45	<0.1	0.23	0.18	0.153	0.057
Sulphate	mg/l SO_4	49	2.91	19.8	9	9.48	2.36
Sodium	mg/l Na	49	12	62.7	51	51	8.55
Potassium	mg/l K	49	0.32	2.58	1.1	1.18	0.36
Magnesium	mg/l Mg	46	9.43	23.1	11.1	11.5	2.04
Calcium	mg/l Ca	46	26.3	67.9	33.9	34.1	6.24
Iron	µg/l Fe	47	<5	1040	342	352	332
Manganese	µg/l Mn	46	<1	51,300	349	1400	7520
Barium	µg/l Ba	38	9	352	55.6	67.3	51.9
Boron	µg/l B	40	<3	172	52.7	52.4	28.1
Aluminium	µg/l Al	43	<2	33	2.5	10.7	11
Chromium	µg/l Cr	41	<0.5	26	0.5	3.1	4.93
Nickel	µg/l Ni	40	<0.5	29.1	0.5	3.02	5.84
Copper	µg/l Cu	42	<0.5	29	1	3.66	6.55
Zinc	µg/l Zn	43	<1	208	33.3	47.4	47.9
Strontium	µg/l Sr	27	22	814	654	627	156

4 Conceptual Hydrogeological Models

Conceptual hydrogeological models are simplified representations of hydrogeological systems. They are qualitative and illustrative by nature. Conceptual models describe what is known or inferred about the principal hydrogeological units of the system, groundwater pathways, and how the system interacts with surface water bodies and associated aquatic ecosystems. They are, therefore, an important tool in the source-pathway-receptor (SPR) model of risk assessment (DELG/EPA/GSI, 1999) which governs water resources protection initiatives in both Ireland and Northern Ireland.

Conceptual hydrogeological models are particularly useful in communicating how flow systems behave and interact, and how contaminants might be transported to downgradient receptors. In this report, conceptual model development emphasises *pathways* as these influence the assessment of where baseline monitoring points should be located and how samples should be collected. A key objective of baseline monitoring is to achieve ‘representative’ sampling of the flow systems that are linked with receptors. The term ‘representative’ implies that the monitoring: a) is carried out at appropriate locations (in three dimensions); b) is implemented at appropriate times; and c) produces data (groundwater flow, discharge, quality) that describe the hydrogeological system and enable a characterisation of the variations and interactions that take place within the system and the environmental elements to which it is connected, i.e. surface water bodies and GWDTEs.

Conceptual model development is an iterative process, whereby models are updated over time as new data become available through study and measurement. Conceptual models help to identify data gaps, thus guiding the further work that is needed to address scientific questions and uncertainty.

In the context of UGEE, pathways are described by location-specific hydrogeology. Thus, future EIAs and related investigations, mitigation measures and monitoring would have to assess and determine environmental risk at the appropriate case- and location-specific scales on a case-by-case basis.

At the sub-regional scale, there is a wide array of hydrogeological scenarios which apply and which have to be distilled into key *pathway* scenarios that guide the decisions to be made about sub-regional baseline monitoring. This section attempts to highlight key environmental risk factors related to the S-P-R model of risk assessment, focusing on pathways from both surface and potential subsurface sources of contamination.

4.1 Potential Sources of Contamination

Potential sources of contamination associated with UGEE-related activity are well described in international literature (Bergmann *et al.* 2014; CCA, 2014; Vengosh *et al*., 2014; USEPA, 2015). Some are related to UGEE operations at the ground surface whilst others, unlike conventional pollution studies, relate to hydraulic fracturing underground. A useful summary sketch of sources and potential “modes of impact” was provided by Vengosh *et al*. (2014) and is adapted in Figure 4.1.

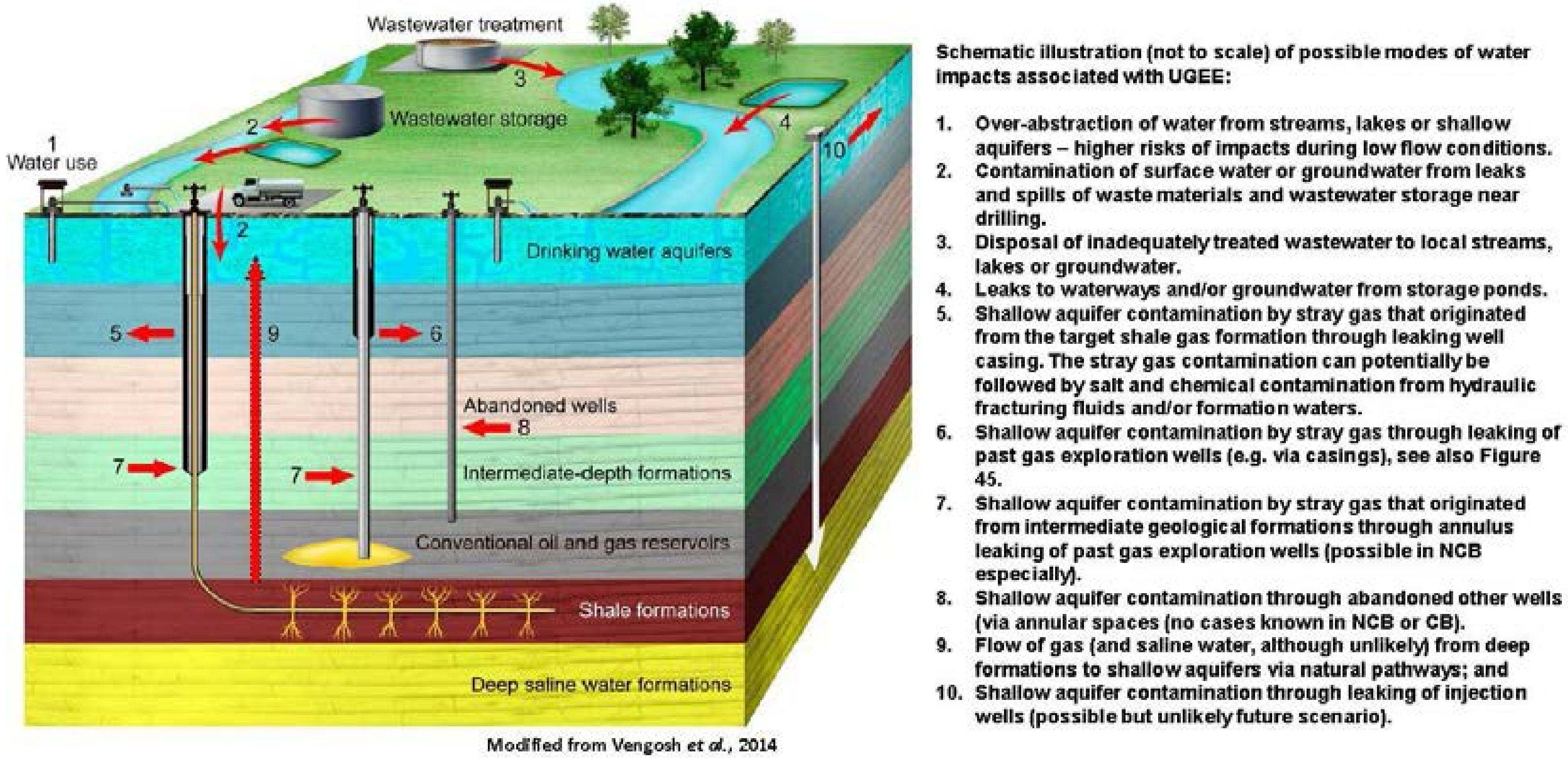


Figure 4.1. Potential modes of UGEE impact on water resources. Reproduced with permission from the American Chemical Society.

4.1.1 Surface sources of contamination

UGEE activity involves the drilling and construction of deep wells, followed by hydraulic fracturing and, potentially, longer-term operations. Each stage in the project carries environmental risk, and the work can broadly be divided into two phases: a) an exploration and testing phase; and b) an operational phase. Risks are both location-specific (associated with individual drill pads) and general (associated with the cumulative footprint of operations, including multiple well pads, movement of materials and people, as well as the construction of required infrastructure).

4.1.1.1 Exploration/testing phase

During the exploration/testing phase, well pads are constructed from which exploration wells are drilled and tested. Contamination from surface sources of pollution can result from:

(a) Accidental or deliberate spills and leaks due to poor handling, storage, and/or containment of fuel, chemicals, and waste fluids (including “flowback waters”); and

(b) Discharges of chemicals and (insufficiently treated) waste fluids to streams, lakes and ground (the latter resulting in contamination of groundwater).

Routine site activities, e.g. equipment washing, can also result in discharges to local groundwater or surface water courses. In a broader context, outside well pads, accidental or deliberate spillages of oil or chemicals can also occur, e.g. during transportation by lorries. Such items and eventualities must be factored into the environmental planning, mitigation and monitoring of any future UGEE operations.

4.1.1.2 Operational phase

During the production phase, there is less site activity and less opportunity for surface contamination, although the same risks of impact would apply if hydraulic fracturing operations were to be repeated on a subsequent occasion. Overflows or improper disposal of waste fluids, such as flowback or production waters (CDM Smith, 2016), would be the main concern. Best practice mitigation measures to minimise the risks of spills, leaks and discharges are described in *Final Report 4: Impacts and Mitigation Measures* of the UGEE JRP (CDM Smith, 2016).

4.1.2 Underground sources of contamination

Potential underground sources of contamination are associated with hydraulic fracturing operations, which can result in:

(a) Mobilisation of naturally occurring gas constituents;

(b) Migration of drilling fluids and chemicals, as well as their decomposition or transformation products, that are injected during high-volume and high-pressure hydraulic fracturing operations; and

(c) Mobilisation of chemical constituents in bedrock formations, including hydrocarbons, saline formation waters and naturally occurring radioactive materials (NORM).

UGEE-related liquids and fluids are mostly a concern where these are returned to the surface as flowback or production waters (CDM Smith, 2016). In the deeper rock formations, saline formation and return waters are dense and would not be prone to upward migration. Gases, including methane, behave differently, and the potential for upward migration is greater. However, in both cases, upward migration requires the presence of open fracture pathways to transport the contaminants through the overlying bedrock formations.

Upward migration of liquids and fluids that are associated with hydraulic fracturing to shallow receptors is considered an unlikely hydrogeological scenario in both case study areas, but cannot be discounted. Such migration would require a sufficiently large and sustained driving force to “push” the contaminants to heights where they overcome the hydraulic heads of the shallow aquifers. One potential driving force would be the overpressure that is generated at depth during the fluid injection phase of hydraulic fracturing. This, however, is a short-term operation, typically measured in days.

Another potential driving force could be the buoyancy effect of geothermal heat. Blake *et al.* (2015) document several warm springs in Ireland where the discharged water is inferred to have circulated from depths of 500 m or more via open fissure zones, indicating that thermally-driven groundwater flow from depth can occur and cannot be ruled out as a transport mechanism. Warm springs are recorded at Kingscourt in Co. Cavan, and past geothermal studies reference steep geothermal gradients in western Co. Clare and the Cavan/Fermanagh areas (Brock and Barton, 1984; Goodman *et al.*, 2004). Whether or not geothermal temperatures and gradients would be a significant driving force of liquid or fluid migration in a UGEE context cannot be concluded without further site-specific investigation.

Ultimately, risks of gas, liquid and fluid migration are case- and location-specific, depending on a wide range of characteristics, including (but not limited to) the hydraulic fracturing chemicals that are used, the pathways and flow mechanisms that are present, the vertical separation distance between the deep target formations and shallow receptors, and the interactions with the geological media through which contaminants would be transported. Accordingly, environmental risks have to be assessed on a case- and location-specific basis during any future planning, risk assessment and licensing of potential UGEE activity.

4.2 Pathways and Risk Factors

Pathways between potential sources of contamination and receptors can be of natural or man-made origins. Natural pathways are determined by the hydrogeological characteristics of a given site and area. Man-made pathways can be created by the activity taking place and the degree of care that is taken to mitigate against environmental impact. Both are described further below.

4.2.1 Natural pathways

Natural pathways are determined by the hydrogeological characteristics of a site, and are described by subsoil and bedrock features. These are conceptually well understood in both case study areas in the shallow subsurface environments to approximately 200 m depth, but are poorly understood and quantified in the deeper subsurface environment.

4.2.1.1 Subsoil characteristics

Subsoils offer natural protection of groundwater resources from surface sources of contamination. Subsoil characteristics (type, thickness and permeability) determine the infiltration capacity of a given site and influence the attenuation potential of contaminant concentrations that migrate vertically through the subsoil profile, as summarised in Figure 4.2 which is adapted from EPA guidance documents on the authorisation of discharges to groundwater (EPA, 2011a, 2014a). Once in groundwater, further vertical and horizontal movement of contaminants is influenced by bedrock types, flow mechanisms, hydraulic properties, and flow gradients, as well as (physical–chemical-biological) attenuation processes that may be acting on the contaminants during transport in a given hydrogeological setting. These principles and associated hydrogeochemical processes are further described in existing literature and guidance documents – DELG/GSI/EPA (1999) and EPA (2011a, 2014a).

To protect water resources from surface sources of contamination, groundwater vulnerability remains a key principle to consider in the planning, siting and operational monitoring of any future UGEE activity. Groundwater vulnerability refers to the intrinsic susceptibility of groundwater to become contaminated by surface or near-surface sources of pollution (DELG/EPA/GSI, 1999). Vulnerability assessment is broadly based on the combined consideration of subsoil types, thickness and permeability. Where subsoils are absent or thin, and/or have high permeabilities, vulnerability and risk of impact to groundwater are greater. Where subsoils are thick and/or have lower permeability, groundwater vulnerability is lower, but in this instance, the risk of impact is transferred to surface water receptors (via surface pathways). The presence of thick and/or low permeability subsoils implies that surface pathways to potential receptors gain importance in the risk analysis.

Maps of subsoil types and groundwater vulnerability are available in both Ireland and Northern Ireland. It should be noted that the groundwater vulnerability maps which have been published by the GSI and GSNI are prepared at the catchment or sub-regional scale and may not be sufficiently detailed to be representative of actual subsoil conditions at an individual (UGEE) location. Accordingly, the principles of vulnerability and the location-specific conditions that define susceptibility to pollution should be defined, documented and field-verified at the site-scale as part of any future UGEE planning process.

It is also worth noting that groundwater protection policies in both Ireland and Northern Ireland classify all rock formations as aquifers, whether they are ‘productive’ or ‘poorly productive’, and irrespective of depth. Practically speaking, however, the policies are directed at identifying and mitigating risks of surface contamination to ‘shallow aquifers’ which are used for water supply purposes and where the majority of water supply wells are limited to depths of <100–200 m. They do not address deep, multi-layered systems such as the NCB, and they do not address the risks of contamination from deeper sources of contamination, such as those that may result from hydraulic fracturing.

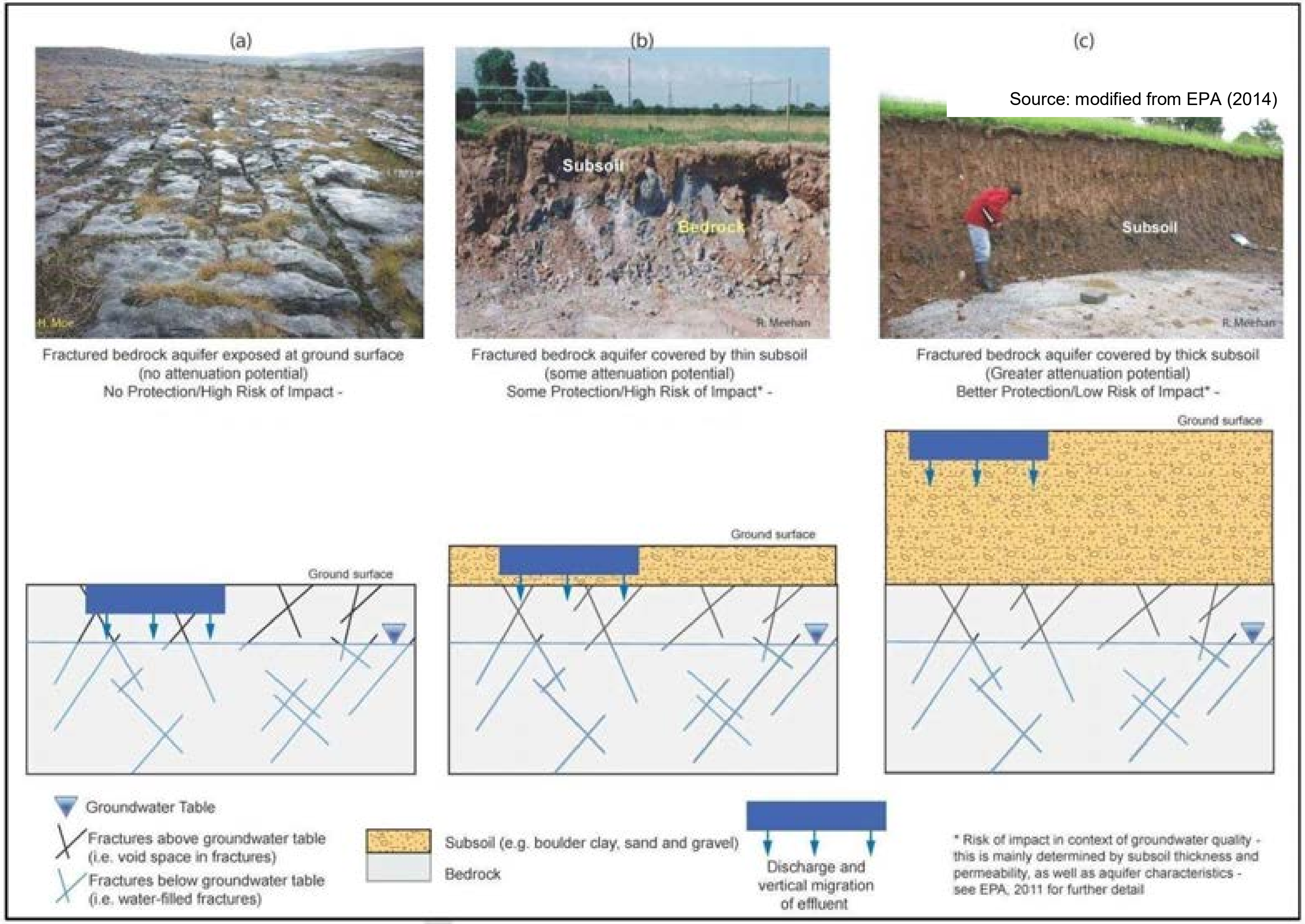


Figure 4.2. Role of subsoils as a protective layer.

4.2.1.2 Bedrock characteristics

In bedrock aquifers, groundwater flows via fractures and fissures. In the case of karstified limestones, groundwater also flows preferentially via open solution conduits. Dissolved natural gas components and chemical constituents in water migrate if and where pathways exist. Pathways in bedrock aquifers are described by fractures, fissures and solution conduits. Combined, these describe the 'permeability' of an aquifer, which is a metric of the ease with which water (and contaminants, including gas) can move through a geological medium.

Structural deformation of rocks can enhance fracture permeability, especially in brittle sandstone and limestone formations. Fracture permeability is typically enhanced where faults and brecciated margins of volcanic dyke intrusions exist. Thus, mapping of and knowledge about fracture systems is important with regard to environmental risk assessment and monitoring.

Public water supply wells are often located at or near known fault zones to increase the probability of achieving higher well yields. It is recognised, however, that depending on depths, lithologies and geological history, faults can also impede water movement and alter water chemistry, as documented by Daly *et al.* (1980) in the Castlecomer plateau.

With regard to the risk of contamination of shallow receptors from deep hydraulic fracturing operations, this is influenced by the hydrogeological characteristics of the formations that are present between the unconventional gas target formation and shallow receptors. Specifically, the effectiveness of these intervening formations as vertical "barriers" to contaminant migration depends on whether or not open fracture networks are present across the formations. Fractures are the only pathways for substantial migration of water, gas or other contaminants through the low-permeability rocks in both study areas. In horizontally layered geological systems with vertical hydraulic gradients, the formation with the lowest bulk vertical permeability would control vertical transport and migration rates.

In both study areas, the available information about open fracture networks is sparse. In the NCB, the presence of fractures at depth is documented by acoustic televiewer (ATV) images from the Mullaghmore Sandstone Formation, which also yielded formation water of variable salinity during gas testing. Even if the Mullaghmore Sandstone is generally considered to be a low-porosity and low-permeability formation, it is documented to store some water. This opens the possibility that the formation may also be hydrogeologically 'active', potentially connected via fractures to the shallow groundwater environment across the Benbulben Shale Formation. There is no direct evidence of this, but the possibility raises a very different question – if the formation water is part of an active (if slow) flow system, where does the water migrate towards?

Even less is known about the hydrogeological characteristics of the Benbulben Shale Formation. As a low-porosity and low-permeability formation, comprising a sequence of shale, calcareous shale and mudstone lithologies, the Benbulben Shale Formation should impede vertical movement of water and contaminants. Although this hydrogeological *function* is conceptually understood, the effectiveness of the Benbulben Shale Formation as a vertical barrier is not demonstrated.

Hydrogeological uncertainty relates to the potential presence of open fractures as well as the potential for hydraulic fracturing operations to induce fractures that could penetrate the combined thickness of the Mullaghmore and Benbulben formations (approximately 270–550 m, see Table 2.3).

In the CB study area, there is no apparent equivalent formation to the Benbulben Shale Formation. Many shale and mudstone units are present within the Ross Sandstone and Gull Island Formations, but they are individually thin and are believed to be laterally less continuous. Moreover, strikes of 'fresh' groundwater to depths of c. 600 m are reported from the Doonbeg-1 exploration well, where the unconventional gas target (Clare Shale Formation) was encountered at a depth of 786 m.

Once contamination reaches a shallow aquifer, horizontal pathways become important, and transport is controlled by flow patterns, flow rates/velocities, flow gradients and attenuation processes. Karst systems can preferentially transport groundwater and contaminants over large distances in short periods of time (often measured in hours) without attenuation other than dilution and mixing. Accordingly, migration of contaminants in karst systems increases the susceptibility of downgradient receptors significantly. Horizontal pathways which are relevant to the S-P-R model of risk assessment for UGEE activity are indicated in Figure 4.3 using the NCB as the example. Contaminants from both surface and underground sources of contamination can reach surface water bodies directly, and groundwater as a pathway to receptors is an important transport mechanism to consider in baseline monitoring.

4.2.2 Man-made pathways

Man-made pathways are mainly related to poor well construction practices, and there are two principal topics that are gaining increasing focus internationally as probable causes of water quality impact: a) poor or inadequate cementation of well casings; and b) improper abandonment of exploration wells.

The science of impact identification is rapidly evolving, and proper well construction and abandonment practice is highlighted as a first line of defence against risks associated with hydraulic fracturing operations, with a recognition that regulatory inspection/verification of cementing operations and checks on well integrity during drilling and construction/abandonment are necessary.

A useful conceptual model of pathways associated with UGEE which is often cited and reproduced in international literature is shown in Figure 4.4. It depicts possible pathways from depth and highlights how contaminants, notably gas, can migrate upwards to the shallow environment: a) via annular spaces outside well casings; and b) via fractures across bedrock formations (if open fracture networks are present). A third pathway would be present if the exploration borehole is improperly sealed or abandoned. As noted by CCA (2014), the sketch reproduced in Figure 4.5 is conceptual, not to scale and does not imply that any or all of the pathways would be present at any given site.

Figure 4.4 is particularly relevant to the NCB because the layering shown approximates the stratigraphy of the NCB. In Figure 4.4, the hydraulic fracturing takes place in the Bundoran Shale Formation. Gas may escape or leak into the Mullaghmore Sandstone (yellow layer), the Benbulben Shale (overlying grey/green layers) and/or into the Glencar (light grey) and Dartry Limestone aquifer (blue layer).

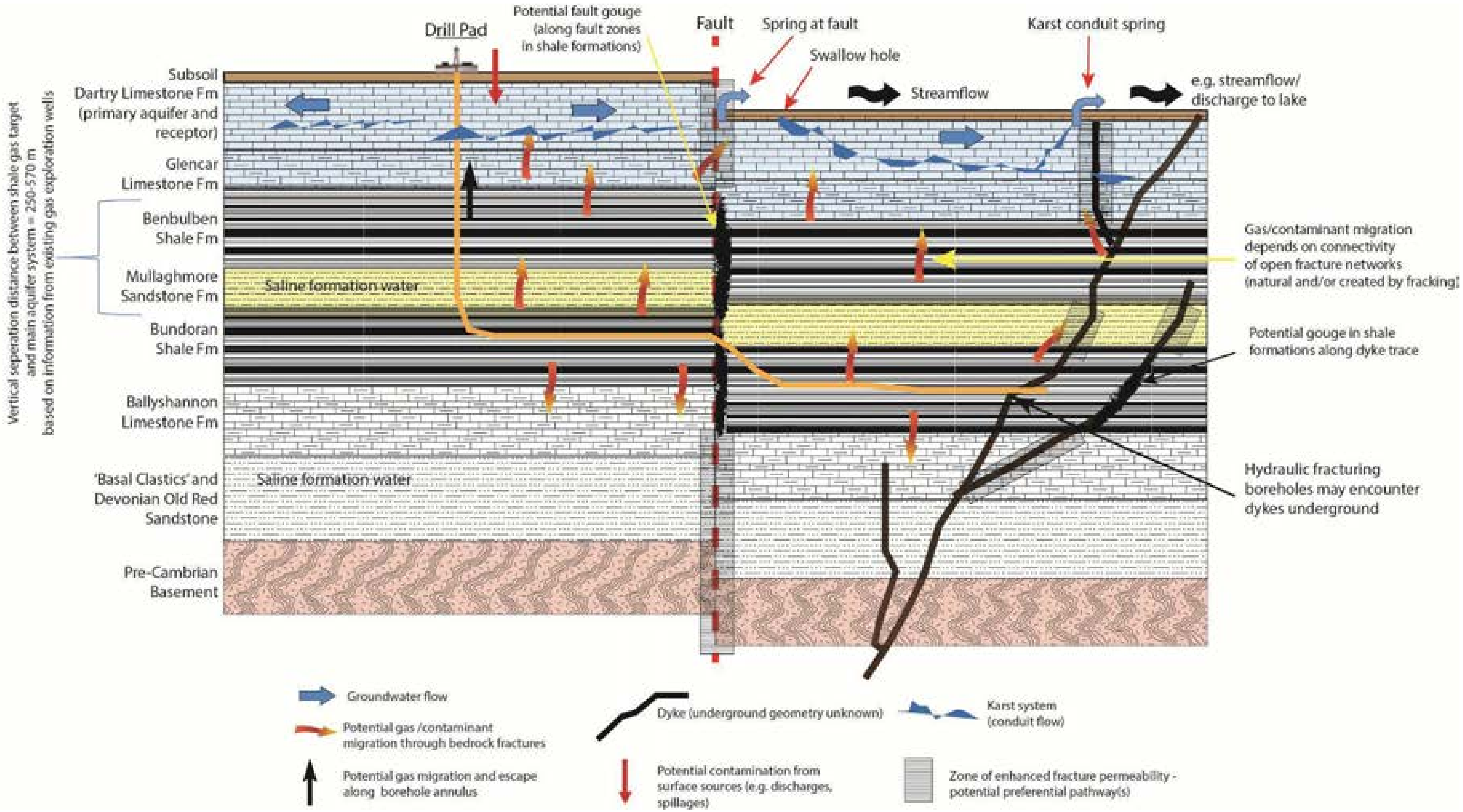


Figure 4.3. Conceptual cross-section of potential contaminant pathways (LAB).

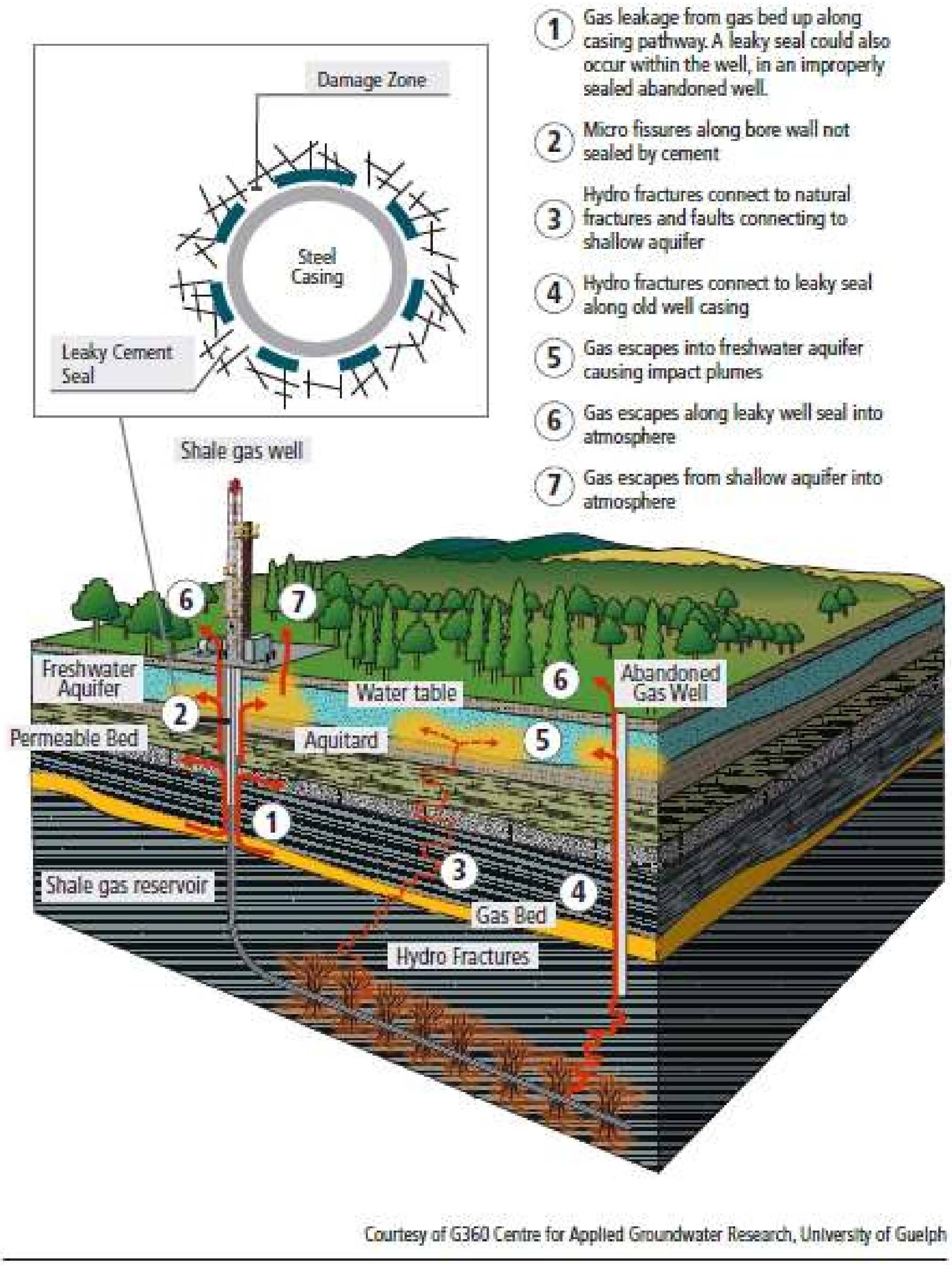


Figure 4.4. Potential underground pathways associated with UGEE activity.

With regard to both Figure 4.3 and Figure 4.4, it is worth remembering that although the stratigraphy of the NCB is 'layered', the formations are also faulted. As a result, there are locations where different formations are juxtaposed against each other. The depiction of simple layered systems has a tendency, therefore, to oversimplify formation geometries.

With regard to abandoned wells potentially acting as gas migration pathways, there are several abandoned wells within the study area from past gas exploration activity. Some of these were partly plugged with cement. Two examples of well abandonment, Kilcoo Cross and Drumkeeran No. 1, are shown in Figure 4.5. Such wells could offer pathway 'opportunity' from deeper formations if, for example, the cement plug operations were not properly executed or if the cement quality has degraded since abandonment.

Well integrity, as a potential pathway for natural gas, also applies to the quality of the cement in the annular space outside the well casings, as well as the integrity of the steel casing itself, e.g. type of material that was used and the degree of corrosion that might have taken place over time. Corroded steel could represent a further pathway for gas to the near-surface environment if/where cracks or holes develop.

As the conceptual models presented herein aim to guide the design of sub-regional, baseline monitoring networks, and monitoring takes place prior to UGEE activity, only natural pathways (perceived, inferred or documented) are given further consideration in this report. Details of well construction practice and mitigation measures would be most appropriately addressed as part of future EIA and other planning submittals by the UGEE developers on the basis of location-specific conditions and circumstances, which should be scoped, reviewed and assessed by suitably qualified individuals on the part of the regulators and planning authorities.

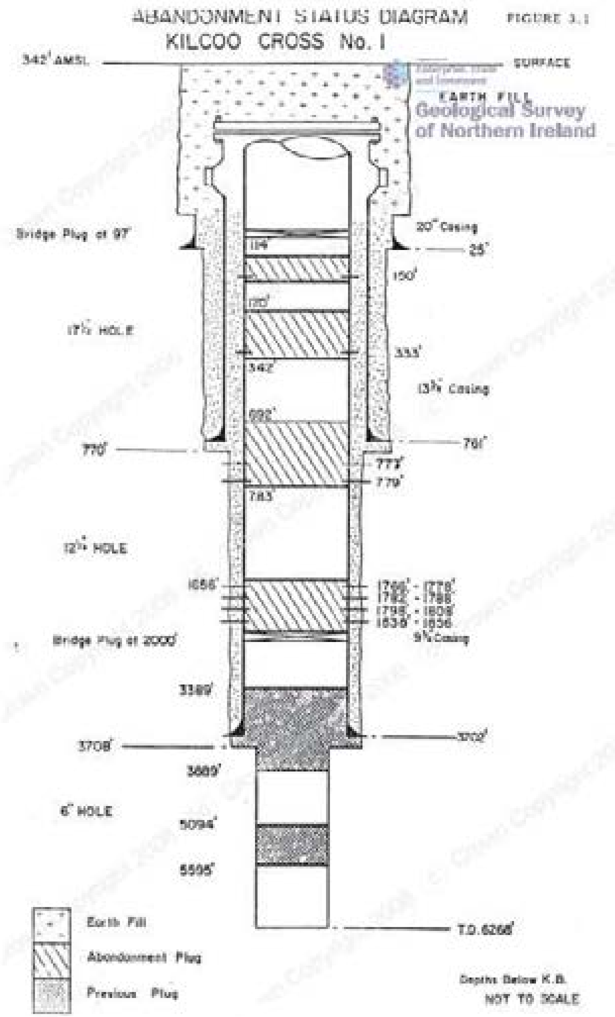
4.3 Receptors

Potential water-based receptors of UGEE-related contamination in both case study areas are: a) the available water resources represented by lakes, streams and aquifers; b) associated water supplies (abstractions); c) registered protected areas; and d) groundwater-dependent terrestrial ecosystems (GWDTEs). These are described in detail in Section 5.

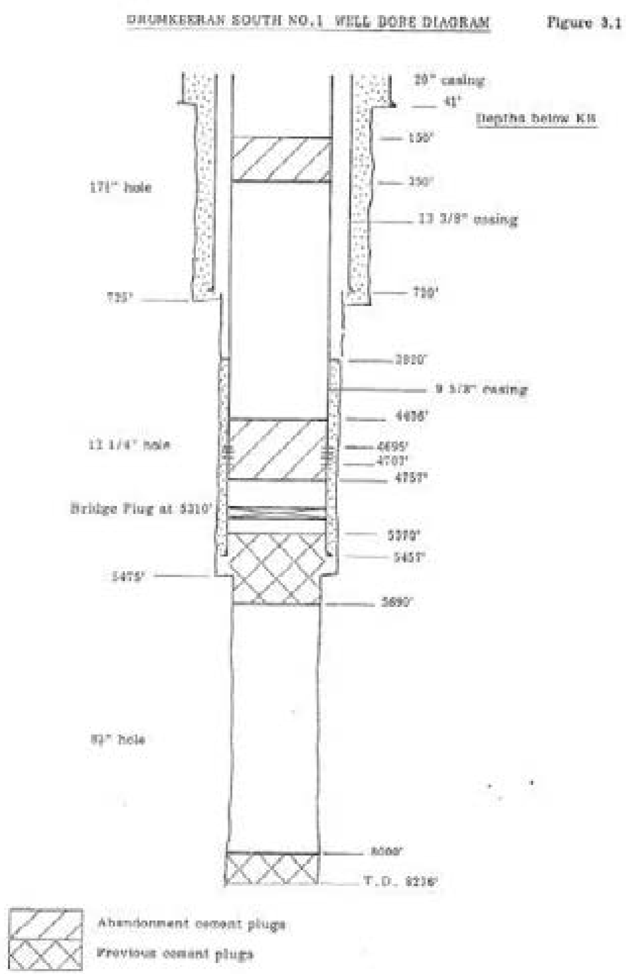
In terms of surface sources of potential contamination from UGEE activity, all water bodies and ecosystems within the UGEE licence areas are potential receptors. In terms of potential underground sources from drilling and hydraulic fracturing activity, shallow aquifers are the primary receptors, although vertical gas migration can impact on surface water bodies directly as well.

In the NCB, regionally important limestone aquifers are extensively used for water supplies and are also linked to important aquatic ecosystems. As such, they have greater “resource value” than lower category aquifers. The Dartry and Ballyshannon limestone aquifers (and their chronostratigraphic equivalents) are the primary potential receptors. However, groundwater flow systems also act as pathways, providing baseflow to surface waters and supporting conditions for GWDTEs. In this regard, all aquifers and surface water bodies become potential receptors, along with the users of the waters that are pumped from respective water bodies and formations. This is also true for the CB study area.

The specific risks of impact to any given water body or ecosystem is case- and location-specific. Risks are both quantitative (abstraction-related) and qualitative (water quality related). Even though risks have to be assessed on a case by case basis, broad and sub-regional principles and patterns emerge from the preceding sections which guide the conceptual models below.



Kilcoo Cross



Drumkeeran No. 1

Figure 4.5. Reported abandonment details of two hydrocarbon exploration boreholes. © Crown copyright 2008.

4.4 Conceptual Hydrogeological Models Relevant to the NCB

Conceptual hydrogeological models for the NCB cover a broad range of scenarios. It is not possible to describe or depict all combinations that exist, and this section highlights those that are of particular relevance to baseline monitoring. Case- and location-specific models should be developed as part of the planning process associated with future UGEE activity, factoring in relevant S-P-R risk factors at each site.

An overall conceptual model of the basin is depicted in Figure 4.6. The NCB is a layered hydrogeological system. The bedrock formations have contrasting hydrogeological properties as a function of lithology, structural deformation, and karstification. All bedrock formations have a hydrogeological function. Bedrock formations are groundwater resources for water supply purposes where they transmit groundwater, are accessible for exploitation and where groundwater quality is acceptable and usable for said purpose. The limestones are generally considered to have greater "resource value" compared to the shale and sandstone formations, although shale and sandstone formations are also used for water supply to some extent. The greater resource value assigned to the karstified limestones especially is reflected in three ways: a) they are regionally important for public and private water supply; b) they give rise to and support important habitats; and c) they represent a tourist attraction in the region (e.g. Marble Arch caves in Co. Fermanagh).

All bedrock aquifers interact with surface water bodies to different extents. Daly and Craig (2009) suggest that, in most rivers in Ireland, more than 30% of the annual average stream flow is derived from groundwater. In low-flow periods, this figure can rise to more than 90%. Thus, groundwater and surface water resources cannot be viewed in isolation. This is especially the case in the karstified limestone aquifers, where streams sink underground at swallow holes only to reappear further downstream at springs.

Although sparse, the available information indicates that groundwater quality deteriorates with depth. Specifically, variably saline formation waters have been reported in the tested sections of the Mullaghmore Sandstone Formation and the Basal Clastics in gas exploration boreholes drilled within the Lough Allen Basin subdivision. Whilst most of the referenced salinity values are high (tens of thousands to greater than 100,000 ppm), there are also references to lower salinity waters, e.g. during drilling of the Basal Clastics in the Slisgarrow No. 1 well (see Table 2.8). This raises important hydrogeological questions as to the source and origins of the salinity, and whether the deeper formations are part of deep, active (even if slow) flow systems. The latter would imply possible hydrogeological connections between deep bedrock formations and shallow aquifers. Such questions cannot, however, be concluded on with the sparse information that is available. The details and specific circumstances of the salinity measurements (which are reported as either "salinity", "NaCl", and/or "chloride" in ppm) are also not known, and thus have to be reviewed with care.

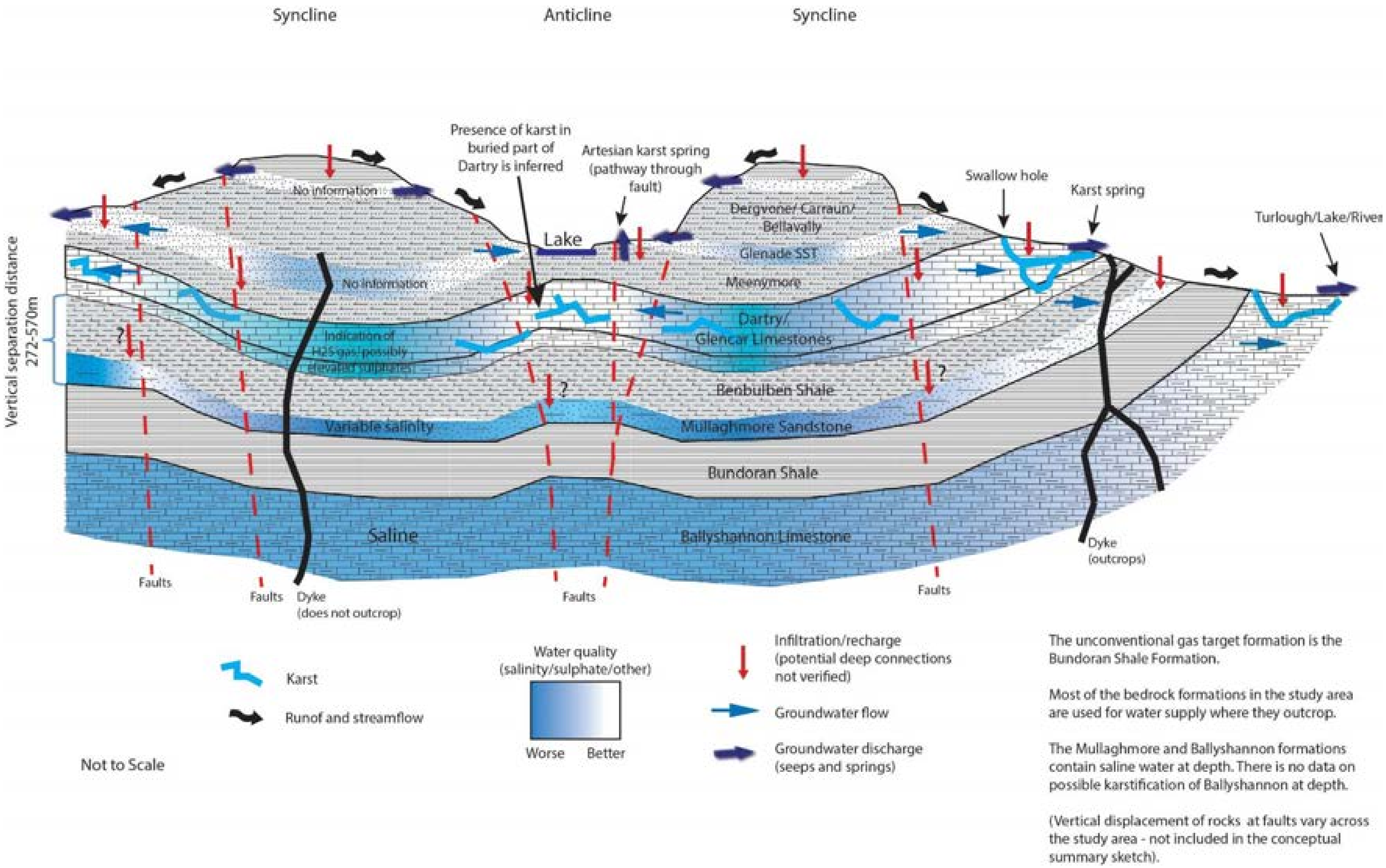


Figure 4.6. Conceptual hydrogeological model of the Lough Allen Basin.

4.4.1 Karst flow systems

The majority of hydrogeological data and information that are available for the NCB study area relate to the Dartry and Ballyshannon limestones. Both are karstified in their outcrop areas to some degree (Dartry and its stratigraphic equivalents more so than the Ballyshannon). Where they outcrop, groundwater recharges both at point locations and diffusively:

- *Point recharge* occurs at locations where surface water – runoff, streams, and/or lakes – sink underground at: a) active swallow holes or cave entrances; and b) at surface karst features such as collapse dolines and other enclosed depressions.
- *Diffuse recharge* occurs over wider areas, and recharge is directly influenced by the type and thickness of soil and subsoil present. Where soils are 'wet' or poorly drained (e.g. gley soils), and where peat is present or tills are thick and/or clay-rich (i.e. of low permeability), diffuse recharge is lower and surface runoff is enhanced. Most of the runoff ends up in drains, ditches and streams, but a proportion may also enter the groundwater environment as point recharge at karst features. Conversely, where soils are 'dry' or well drained (e.g. mineral soils), and where tills are thin or absent (i.e. of higher permeability), groundwater recharge is correspondingly greater. The relationships between soil and subsoil types, permeabilities and estimated recharge coefficients are extensively described by Misstear and Brown (2007), Misstear *et al*. (2009) and Hunter Williams *et al.* (2013).

An important question that arises in the context of UGEE is whether the limestones are also karstified away from their outcrop areas, i.e. in the deeper buried parts of the NCB. Karst conduits are especially important as horizontal pathways. Karstification of the Dartry in non-outcrop areas is suggested by reported losses of circulation and water influx during drilling of gas exploration boreholes (described in Table 2.8 for Dowra, Kilcoo Cross and Thur Mountain). The deepest reference to potential karst in the Dartry limestone is "loss of circulation" during drilling at *c.* 290 m in Dowra No.1, corresponding to an elevation of approximately –170 mOD.

Whether the reported losses of circulation during drilling were due to water-yielding fracture zones or karst conduits is not conclusively documented, but karst conduits at depth in the Dartry is possible. Brown (2005) proposed that karstification processes and vertical karst development are constrained by the underlying Glencar formation which contains shale units in the upper section. These shales may effectively impede deeper karst development and likely also the vertical movement of water, unless fracture permeability provides the necessary pathways to deeper sections.

The concept that the Glencar shale units may act as vertical "barriers" to karst development is supported by the observation that spring horizons have developed along the base of the Dartry limestones in the Cuilcagh Mountains. This scenario is depicted graphically in Figure 4.7. Runoff from the hills covered by lower-permeability rocks of the Leitrim Group sink underground in the Dartry formation before re-emerging further downstream at springs near the base of the Dartry. This represents an observed sub-regional pattern of groundwater recharge and discharge in the Lough Allen Basin.

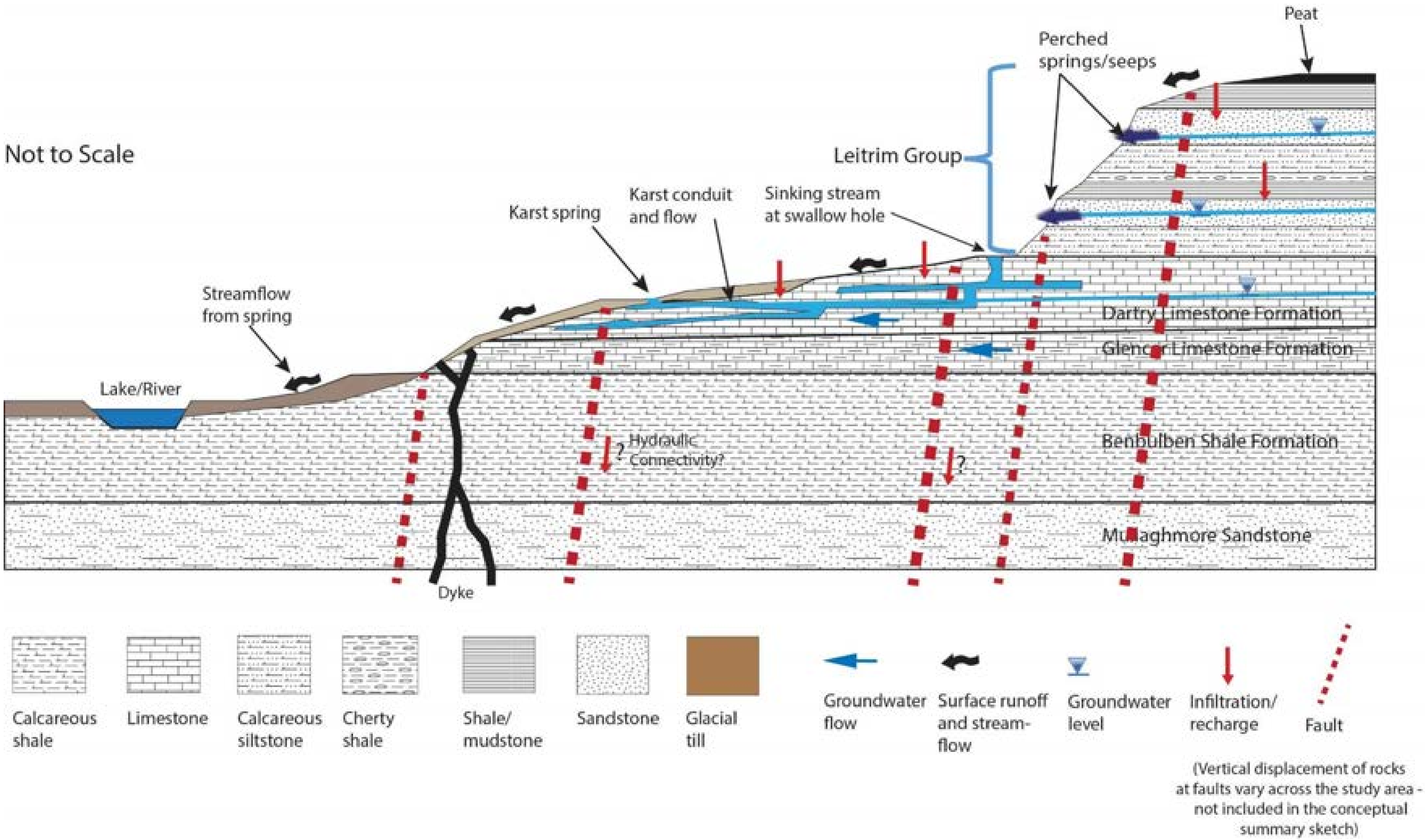


Figure 4.7. Conceptual hydrogeological model of outcrop margins in the Lough Allen Basin.

At the local (catchment) scale, karst systems can be compartmentalised with structural controls offered by fracture patterns and fault/dyke structures. Examples appear on the eastern extremity of Cuilcagh Mountains, where extensive faulting shapes outcrop patterns and the established spring catchments (summarised in Brown, 2005) are shaped/constrained by faults. A similar control was interpreted by Misstear *et al*. (2008) at Tydavnet in Co. Monaghan.

The presence of karst beneath caprock is supported by the presence of collapse dolines on the Meenymore Sandstone which overlies the Dartry Limestone. Furthermore, the karstic behaviour of the Shannon Pot spring, which emerges from the Meenymore Formation, suggests that the water originates from the Dartry Formation, given its mapped spring catchment to the east in the Cuilcagh Mountains, see Figure 4.8. The artesian discharge from the Meenymore Formation has been attributed to a fault mechanism (Brown, 2005). In this case, the Shannon Pot is linked to a conduit and potential cave system which extends along and beneath rocks of the Leitrim Group, and which may also extend further west than Shannon Pot, although further discharge points similar to the Shannon Pot are not apparent from existing mapping. Similar passage of karst conduits beneath caprock is described for the Prod's-Cascades cave system, which extends "*for much of its length….beneath non-limestone strata*" (Brown, 2005).

Unlike the high-quality groundwater which discharges from bedrock aquifers and karstified flow systems in outcrop areas, the presence of "*sulphur water*" with methane and H_2S gas is documented in past gas exploration wells where the Dartry/Glencar aquifer system is buried beneath bedrock formations of the Leitrim Group. The nature and boundaries of water quality transitions are not clear, but the implication is that recharge and active circulation of groundwater may become more restricted where the limestones are buried. This is not just a reflection of the 'present-day hydrogeology' of the basin; rather, as the NCB developed and the limestone formations became increasingly buried, the depth to which rainwater ('meteoric water') circulated would have become increasingly restricted, possibly affecting the water chemistry. Thus, buried karst in the centre of the Lough Allen Basin may, in part, be unrelated to present day topography and hydrology. The other scenario that emerges from these observations is that while active flow systems operate at the basin margins where the limestones outcrop, a deeper (and less active conduit system) may operate within the buried sections of the Dartry.

A conceptual model of increasingly restricted recharge and groundwater flow with depth of burial applies to all bedrock formations in the study area. Nonetheless, it is anticipated that *some* recharge is taking place (e.g. in the buried sections of the Dartry Limestone), either as a function of leakage from overlying units or via faults that cross-cut the formations (as mapped in the Lough Allen Basin). The hydrogeological aspects of this cannot be quantified or established with any degree of certainty. In the context of the Dartry limestones, it is acknowledged, that karstic flow systems beneath thick (100 m+) cap rocks are documented elsewhere in the world, e.g. the northern rim of the South Wales coalfield and the Mammoth Cave system in Kentucky (D. Drew, Trinity College Dublin, January 2015, personal communication), but these examples also have well-defined inputs and outputs to and from the related flow systems. It is not immediately clear, for example, where deeper 'impaired' water in the buried Dartry/Glencar sequence would discharge to, even if the Shannon Pot 'model' by Brown (2005) offers important clues.

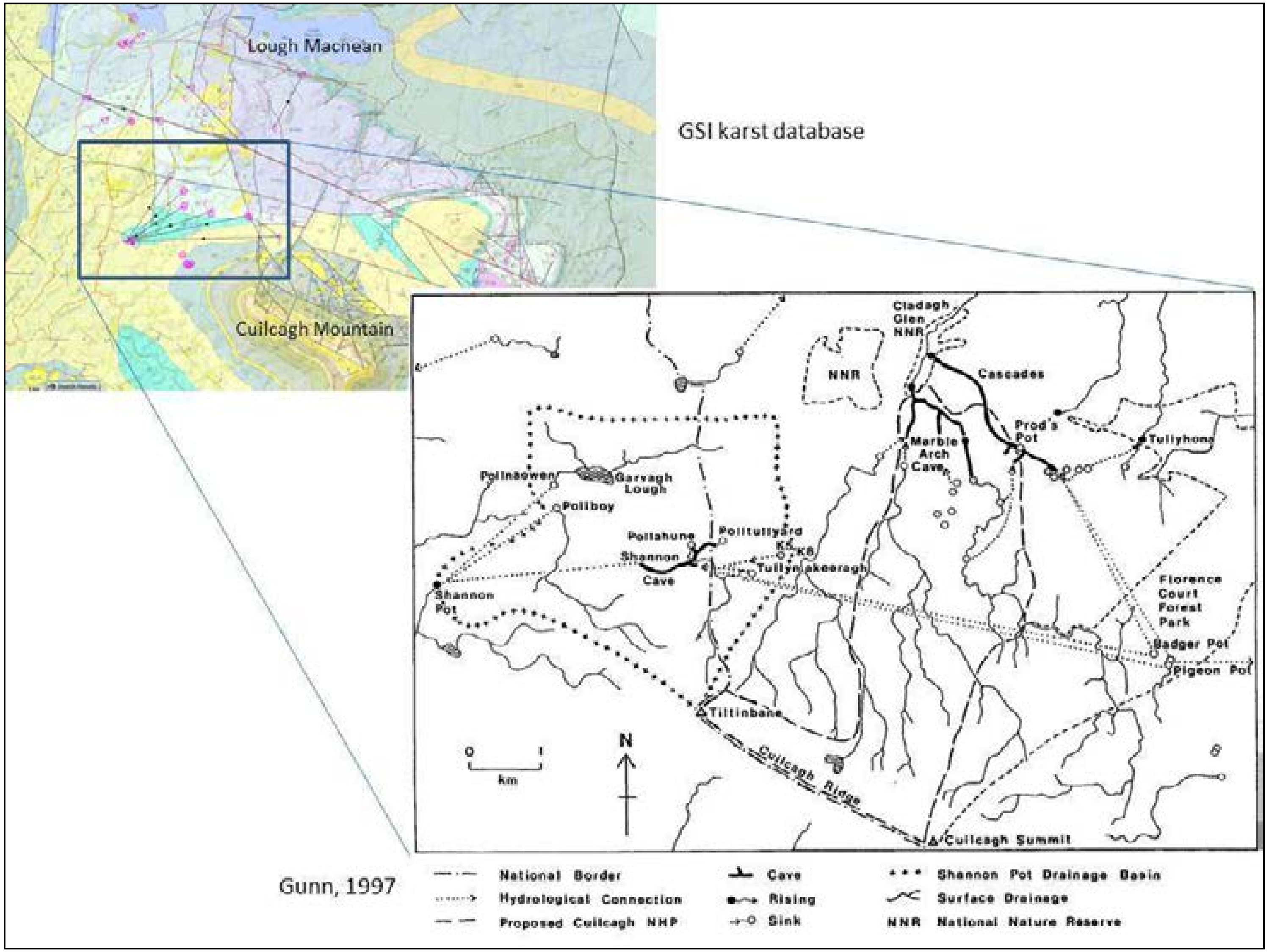


Figure 4.8. Established dye traces to the Shannon Pot.

There are no representative groundwater level data available from any of the deeper formations (below the Dartry) which would conclusively document the hydraulic relationship or connection between the shallow aquifer and deep unconventional gas target formations. The key formation in this regard is the Benbulben Shale Formation which separates the two. With knowledge of open fractures and variably saline formation waters reported from the Mullaghmore Sandstone, a hydraulic gradient and connection across the Benbulben Shale Formation cannot be ruled out. The hydraulic connectivity would be restricted by the dominant shale lithology and low-permeability characteristics of the Benbulben Shale Formation, and any connections to meteoric waters would have to be via open fracture networks, presumably in cross-cutting fault zones or along dykes.

Structural control of the roughly E-W trending “Cuilcagh Dyke” on karst flow in the Cuilcagh Mountains is described by Brown (2005), who divided the Cuilcagh Mountains area into two: the ‘Erne Karst’ and the ‘Shannon Karst’. North of the dyke, the karst drains north, towards the Erne drainage system. South of the dyke, karst flow is both to the east and west, and springs contribute to the Shannon River catchment. The Cuilcagh Syncline, which shapes the WNW-ESE trending Cuilcagh Mountains ridge, guides the Shannon karst system.

Figure 4.8 exemplifies the complexities of groundwater catchments of individual karst springs. In the case of the Shannon Pot, the different dye traces cross the surface water drainage in the same area. Groundwater movement may be structurally controlled. Complex flow patterns are documented in numerous spring catchments in the NCB, where flow from multiple point source locations converge on single springs, and conversely, flow from single point locations diverge to multiple springs. Such flow patterns are attributed to geometries of conduit networks, not just laterally, but also vertically. In the study of the Cuilcagh karst, Brown (2005) highlights “*rapid and extreme*” backing up of water and associated flooding of cave systems due to hydraulic limitations of the conduit system, noting that “*dissolutionally enlarged fractures....are at their widest near the surface. At depth the conduits tend to be narrower….”*. Conceptually, backing up of water and flooding would allow water to find alternative escape routes from conduit systems, determined by water levels and conduit geometries in any given area. “*Fracture-guided conduits*” are described in the extensively faulted section of the Cuilcagh Mountain to the east (Brown, 2005). The structural control that is observed and inferred to be exerted by dykes is also complex. On the one hand, dykes can serve as barriers on a sub-regional scale as documented above. On the other hand, dykes are also fractured and offset by faulting, which creates gaps and hydrogeological ‘opportunity’ for movement of groundwater across the dyke structures.

A different scenario is observed at the Schoolhouse and Carricknacoppan cave systems at Marble Arch on the northern margin of Cuilcagh Mountain. Here, flow crosses the Cuilcagh Dyke as a stream which originates at springs upstream of the dyke (acting as a barrier) and then sinks back underground downstream of the dyke (Brown, 2005).

Where the Ballyshannon Limestone is karstified in its outcrop areas, similar processes of flow may apply, but the limestone is not as extensively karstified as the Dartry flow system. They nonetheless provide the supporting conditions for the Rooskey Turlough GWDTE, which is a designated Special Area of Conservation (SAC). Unlike the Dartry karst, whose base level is defined by the shales of the Glencar limestone sequence, the Ballyshannon contains argillaceous members, particularly towards the base of the limestone formation. This may constrain and confine karst development in distinct horizons within the formation rather than allowing extensive and connected development throughout the formation. Based on flow characteristics, most of the Ballyshannon in the region has been mapped by the GSI as an “Rkd” aquifer, a karstic aquifer in which groundwater flow is dominated by fracture flow rather than conduit flow.

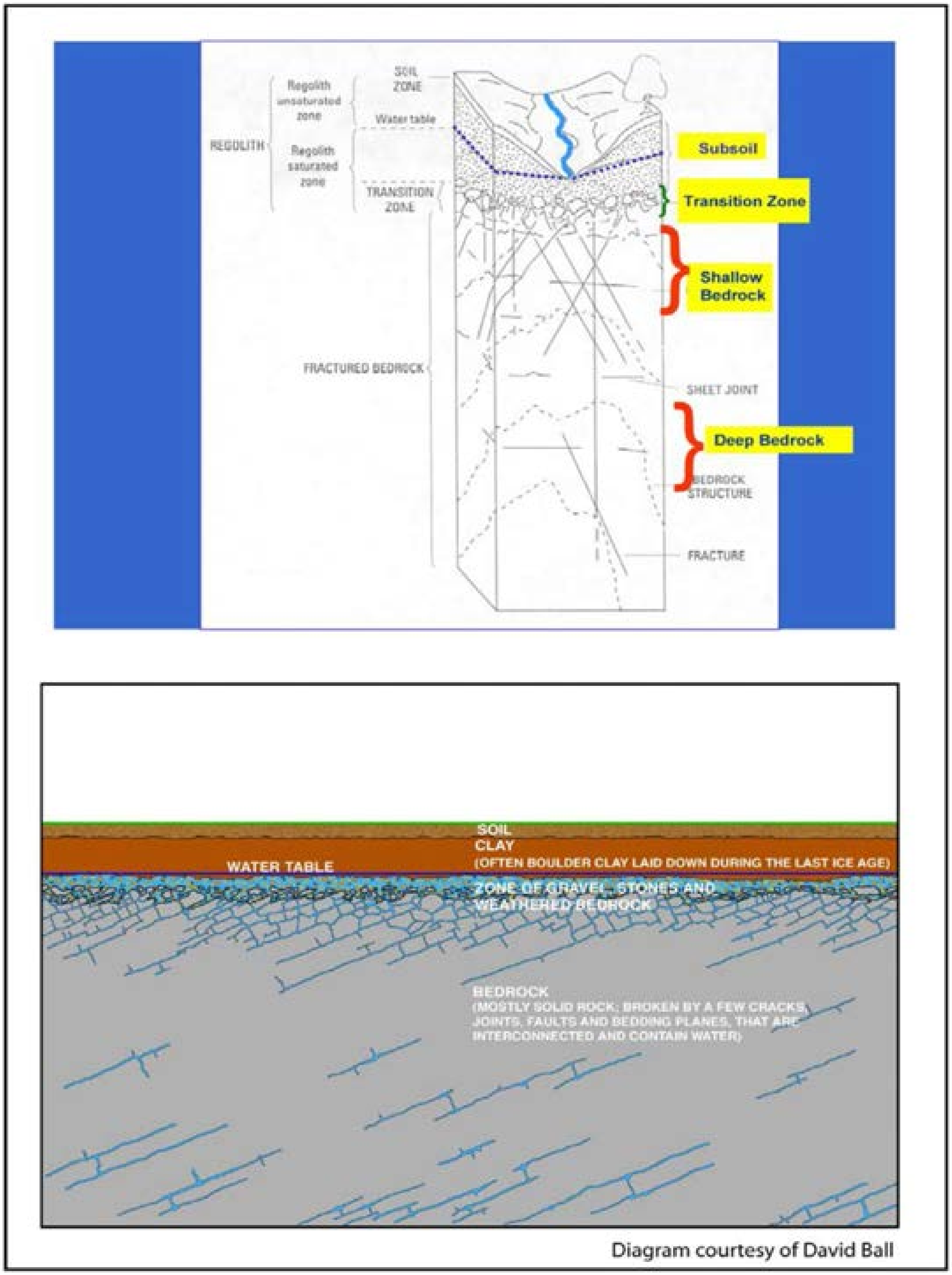
Further west in the NCB, notably towards the structurally elevated Sligo Syncline, the Dartry formations are present on flat hilltops (being more resistant to erosion). Here, rainwater infiltrates through peat and recharges the limestone formations. The groundwater emerges as numerous seeps and springs near the top level of the Benbulben Shale Formation along the margins of the mountains. The carbonate springs form tufa deposits, commonly referred to as tufa springs, which have qualifying interests as groundwater dependent terrestrial ecosystems (see Section 5).

4.4.2 Fractured bedrock flow systems

Groundwater flow in fractured bedrock takes place 'diffusely' via networks of open fractures, fissures and joints. Moore and Walsh (2013) report that bedrock fractures associated with NNW-SSE dextral faults are amongst the hydrogeologically most transmissive structures in Ireland. This applies to shallow aquifers exploited for water supply. Information on deeper fracturing is sparse. Fractures can be expected to occur in the subsurface co-planar with faults, and to increase in density with proximity to faults. Fracturing potential increases with structural deformation and higher permeability fracture zones, such as faults, serve three hydrogeological functions: a) as sinks or drains ('collector systems' of groundwater) in recharge areas; b) as (preferential) pathways; and c) as groundwater discharge zones at locations where groundwater tables and topography intersect, giving rise to springs.

In outcrop areas, 'diffuse' fracture flow would tend to follow topography and discharge to nearby streams and lakes. The bedrock aquifers provide important baseflow to streams. The regionally important aquifers are capable of accepting more recharge due to their higher bulk permeabilities than locally important or poorly productive bedrock types. Thus, they are also capable of transmitting larger quantities of water. Recharge to bedrock is determined by the presence and type of subsoil cover above the bedrock, as well as thickness and subsoil permeability. Recharge is also dependent on bedrock characteristics at any given location.

Depending on location, a 'transition zone' (IGI, 2007) may be present at the contact between bedrock and overlying subsoils, as indicated in Figure 4.9. The transition zone is confirmed present in many different types bedrock aquifers on the island of Ireland, and its hydrogeological significance in "poorly productive aquifers" (PPAs) as a shallow pathway for water and associated pollutants to local waterways is long acknowledged in Irish hydrogeological literature (e.g., Daly, 1995; Fitzsimons *et al.*, 2005; Moe *et al.*, 2010; Comte *et al.*, 2012, 2013). Most recently, Deakin (2014) also documented that the transition zone can be important in delivering pollutants to streams via shallow hydrogeological interaction with field drains and ditches, which are present throughout the NCB as an agricultural land-improvement measure.



Source: Moe *et al.*, 2010

Figure 4.9. Conceptual cross-section of the 'transition zone'.

The scale of individual flow systems is dependent on the permeability characteristics of the bedrock aquifers. The lower the permeabilities involved, the more localised the groundwater flow systems become, and the more important shallow pathways become. Flow systems in Pu/Pl/Bl (f) rocks may be tens to a few hundred metres in length only. Baseflow to rivers and streams in such flow systems are volumetrically low, but can nonetheless be ecologically significant, especially during prolonged dry weather conditions when groundwater baseflow to streams is the only contribution to stream flow.

Being of low storage and permeability characteristics, PPAs such the shale formation in the NCB are not capable of accepting all of the effective rainfall (potential recharge) that is available for recharge. Thus, a proportion of the available recharge is rejected and thus flows to streams via shallow pathways such as surface runoff and the transition zone. Where the PPAs are present, e.g. around Lough Allen, the combination of low bedrock permeability, steeper slopes, presence of peat, and high rainfall results in a significant percentage of runoff to local streams, which is well illustrated by the radial drainage patterns away from the hilltops observed in these areas (e.g. on Thur Mountain).

The scales of fractured bedrock flow systems are affected by fault patterns. Examples of structural constraints on flow in Carboniferous bedrock aquifers were provided by Daly *et al*. (1980). More recently, Misstear *et al.* (2008) concluded that the long-term sustainability of pumping the Tydavnet wellfield in Co. Monaghan is constrained by hydraulic isolation of the aquifer within a fault block which limits the spatial continuity of the aquifer in that area. The wellfield pumps groundwater from the Dartry and Meenymore formations, i.e. the same bedrock formations that are present on the NCB study area.

In Figure 4.9, the conventional hydrogeological model of fractured bedrock aquifers on the island of Ireland considers fractures to become less frequent with depth. Accordingly, fracture flow also becomes less significant with depth, unless fault zones (with enhanced permeability) are intersected. This conceptual model applies to bedrock aquifers in general terms. However, it must be acknowledged that the NCB is extensively faulted and both sub-horizontal and high-angle fractures have been reported from ATV images of the Mullaghmore Sandstone Formation to depths of more than 750 m (Thur Mountain). Unlike mapping of fracture patterns at surface, data on prevalence and characteristics of deep bedrock fracture sets are lacking. The presence of deep fractures opens the possibility that deep fracture permeability can both accommodate (store) and transit *some* groundwater (if only on a limited scale), especially along zones of structural deformation such as fault and brecciated dyke margins. In contrast to the CB, potential deep and slow groundwater movement in the NCB does not have any obvious outlets or discharge zones, at least within the Lough Allen Basin.

Permeability contrasts between formations and individual units within formations will influence groundwater flow. Perched groundwater systems form within units of higher permeability and transmissivity, and are evident in the field as spring horizons at different elevations. Examples are petrifying springs at the base of the Dartry/Glencar limestones in Co. Sligo, and springs used for public water supply within the formations of the Leitrim Group in the Lough Allen Basin (see Section 2).

Most of the bedrock formations that define the two study areas are used for water supply, including springs and private wells in the Bundoran and Benbulben Shale Formations (see Section 5). Thus, even formations that are shale-dominated transmit and supply groundwater.

In karstified limestones, fracture flow via open fractures and joints interacts hydraulically with karst conduits. If groundwater levels in the fractured sections of the limestone are higher than the hydraulic heads in the karst conduits, the conduits will act as drains, receiving water from the rock matrix. Conversely, if heads in conduits are higher than groundwater levels outside the conduits, then flow may be reversed, especially if/when the conduits are filled and pressurised. Thus, in both instances, karst conduits in fractured limestone formations exert a controlling influence on groundwater hydraulics and pathways.

4.5 Conceptual Hydrogeological Model Relevant to the CB

The general conceptual hydrogeological model for the Namurian sequence in the CB is similar to that described in Section 4.4. Lower-permeability rocks form localised flow systems, and groundwater flow is concentrated in fractured sandstone units. The lower-permeability units provide confining conditions and artesian (naturally flowing) wells have been observed at several locations in the study area.

The conceptual model presented in Figure 4.10 summarises the main hydrogeological features of the CB study area. Groundwater flow systems are localised, discharging to local streams, lakes and peat in hollows which are present along broad open valleys and which tend to follow syncline structures. Groundwater flows and discharges via shallow pathways, including the transition zone which can be observed in road cuts on higher ground and exposed bedrock/till contacts along the coastline.

Shallow, localised and perched flow systems are also evident by small iron-stained springs and seeps which are exposed on the cliff faces on the north side of Loop Head peninsula.

A significant proportion of available recharge (effective rainfall) is rejected due to the low-permeability environment (which includes an extensive cover of till, especially towards the west), resulting in enhanced surface runoff via surface pathways to streams and the coastline. Surface pathways include drains and ditches.

A deeper groundwater flow component is also considered to be present in the study area, as indicated by the reported deeper water strikes (to *c.* 600 m) in Doonbeg-1 and IPP-2. However, the nature and characteristics of this potential flow component remains largely unknown. A deeper sub-regional flow component in which groundwater flows from recharge areas on higher ground to discharge areas on the coast is plausible, but a lack of further evidence in the form of hydrogeological data means that the conceptual model remains untested.

One of the main technical challenges of characterising the hydrogeology of the CB study area is the heterogeneity of the main formations which show considerable lithological variability in three dimensions as a function of their depositional history. This variability is expected to exert an influence on flow patterns, at least on the smaller/localised scale. There are also insufficient data to draw conclusions about deeper groundwater quality, thus the precautionary principle requires an approach that considers the deeper sandstones as potential aquifers that are available as a groundwater resource.

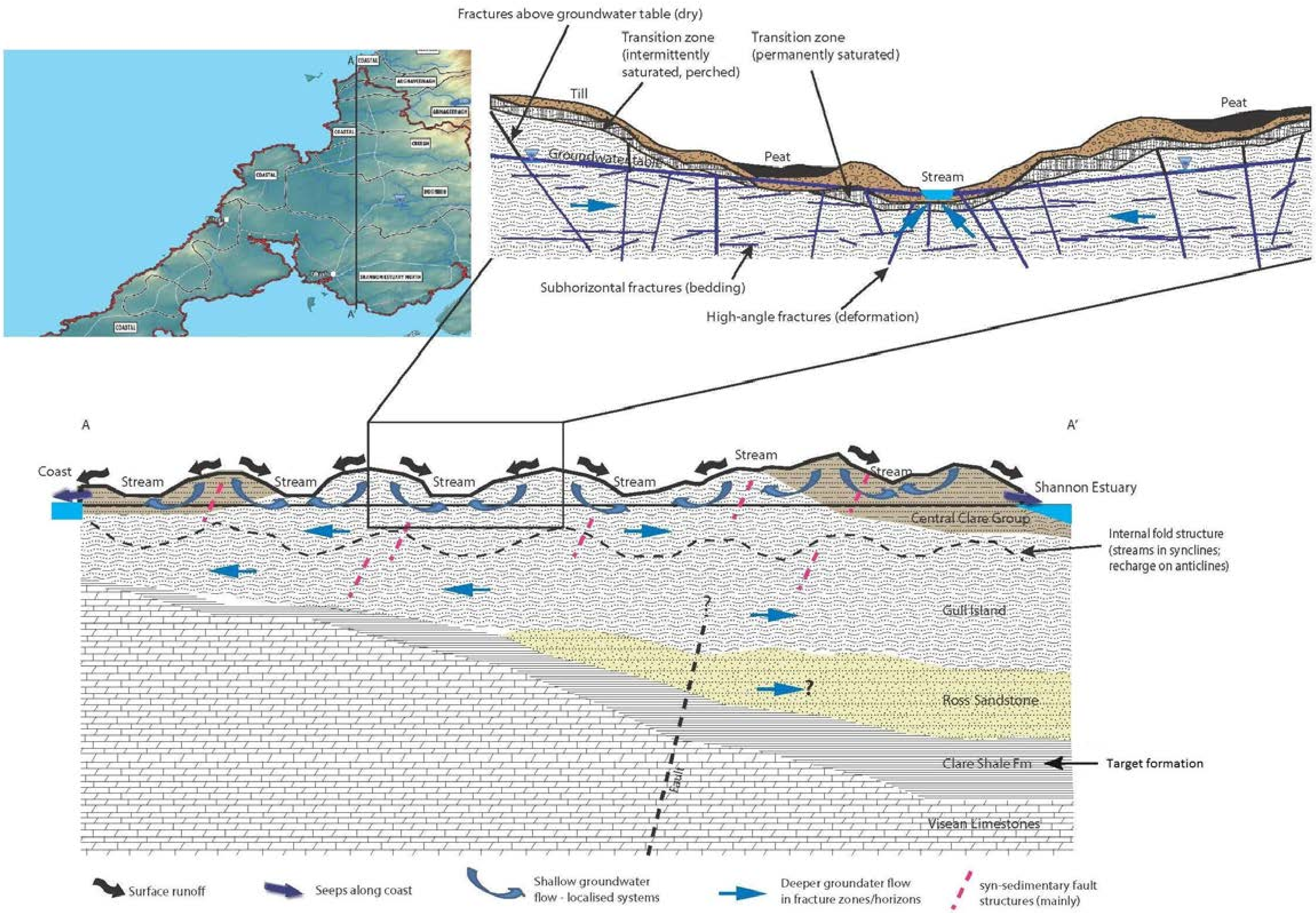


Figure 4.10. Conceptual hydrogeological cross-section of the CB.

4.6 Conceptual Models of Groundwater Dependent Terrestrial Ecosystems

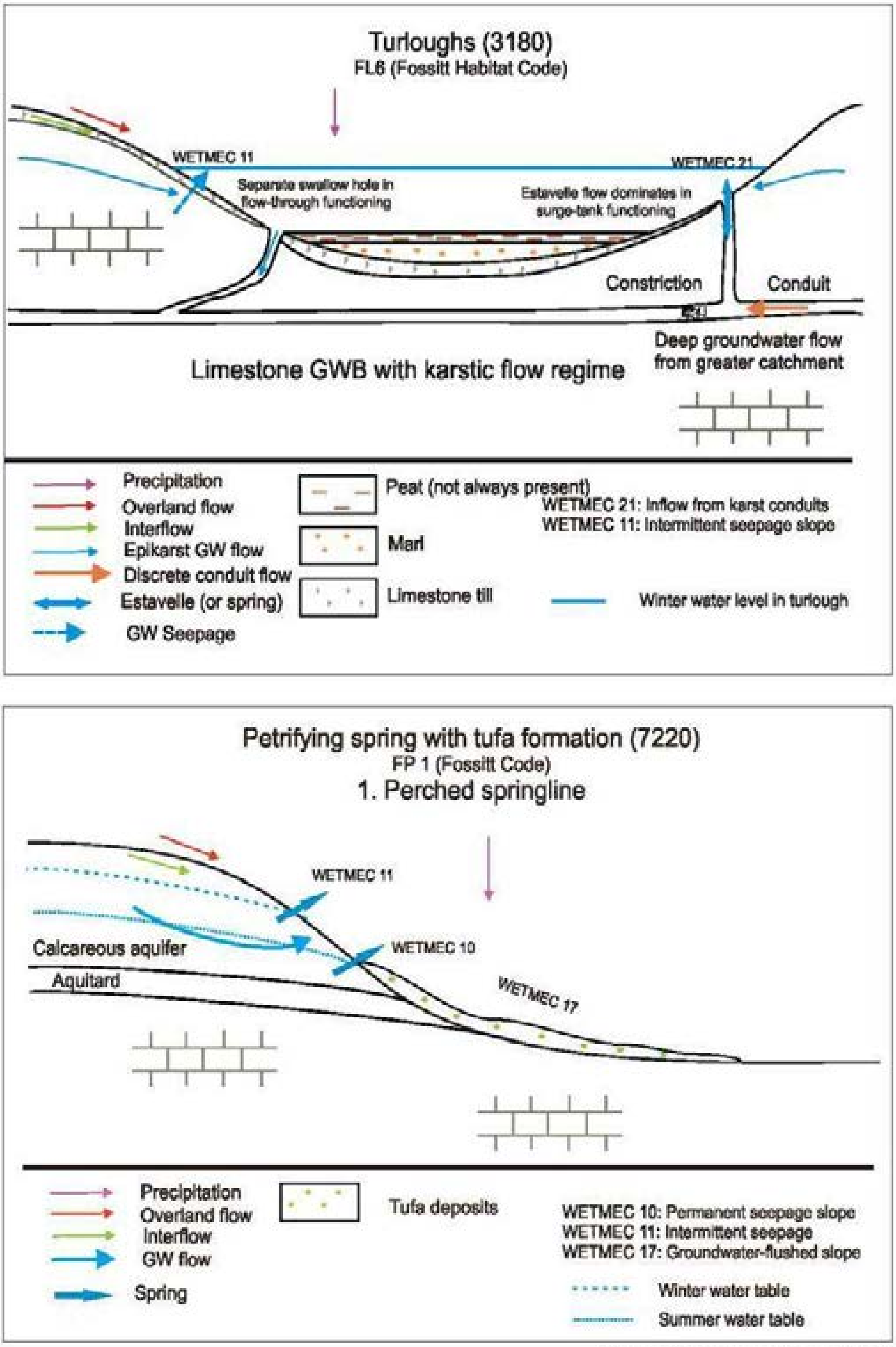
Groundwater dependent terrestrial ecosystems (GWDTEs) are groundwater-dependent wetland areas of particular ecological significance as habitats according to the EC Habitats Directive. Different types of GWDTEs have different groundwater dependencies. Whilst some are sensitive to changes in water quality, others are sensitive to changes in groundwater levels and fluxes. The understanding of hydrogeological processes and supporting functions of GWDTEs has evolved in the past several years based on WFD-related projects, including EPA STRIVE research initiatives. A particularly relevant contribution is made by Kimberley and Coxon (2013). Their study presented a series of “conceptual ecohydrogeological models” for habitat types listed in Annex I of the EC Habitats Directive (see Section 5). The models were developed within the S-P-R model of risk assessment, and highlight the key hydrogeological “needs” of common GWDTE types in Ireland.

The combination of updated GWDTE maps and conceptual ecohydrogeological models represents an important step towards improved protection of related habitats. The conceptual models do not consider pressures or potential impacts that are specific to UGEE, but are nonetheless helpful in flagging the main topics that could cause damage to the individual habitat types. As such, the models form a useful basis for determining future planning and study needs in the contexts of licensing and EIAs.

Two categories of GWDTEs that are mapped on karstified limestone aquifers in the NCB study area are turloughs and petrifying springs with tufa deposits:

- Turloughs are seasonal lakes which are associated with karst conduit flow systems. Six turloughs have been designated in the NCB study area in Ireland and two have been designated in Northern Ireland (see Section 5). The turloughs in Ireland are associated with the Dartry and the Bricklieve Limestone Formations. The turloughs in Northern Ireland are associated with the Ballyshannon Limestone Formation. The conceptual ecohydrogeological model of Kimberly and Coxon (2013) is reproduced in Figure 4.11. Turloughs are fed and drained by conduits, which control the flood levels within the lakes. In the UGEE context, the turloughs would mostly be sensitive to abstractions which could reduce the natural flood balance and extent of the lakes, as well as inputs of pollutants which could alter the chemical balance that are needed by plant communities and faunal species.
- Petrifying springs with tufa formations, see Figure 4.11, are widespread in the NCB study area, notably at spring horizons towards the base of the Dartry Limestone Formation, e.g. at Benbulben and Truskmore Mountains, Cuilcagh Mountain and the Fermanagh Scarplands (see Section 5.4). They depend on through-flux and discharge of high-alkalinity groundwater. Tufa growth is linked to the availability of calcium carbonate in solution. In addition to tufa formation, bryophytes are dominant or abundant (NPWS, 2013a). In the UGEE context, these habitats would be sensitive to reduced spring flows and lowering of water tables as a function of abstractions.

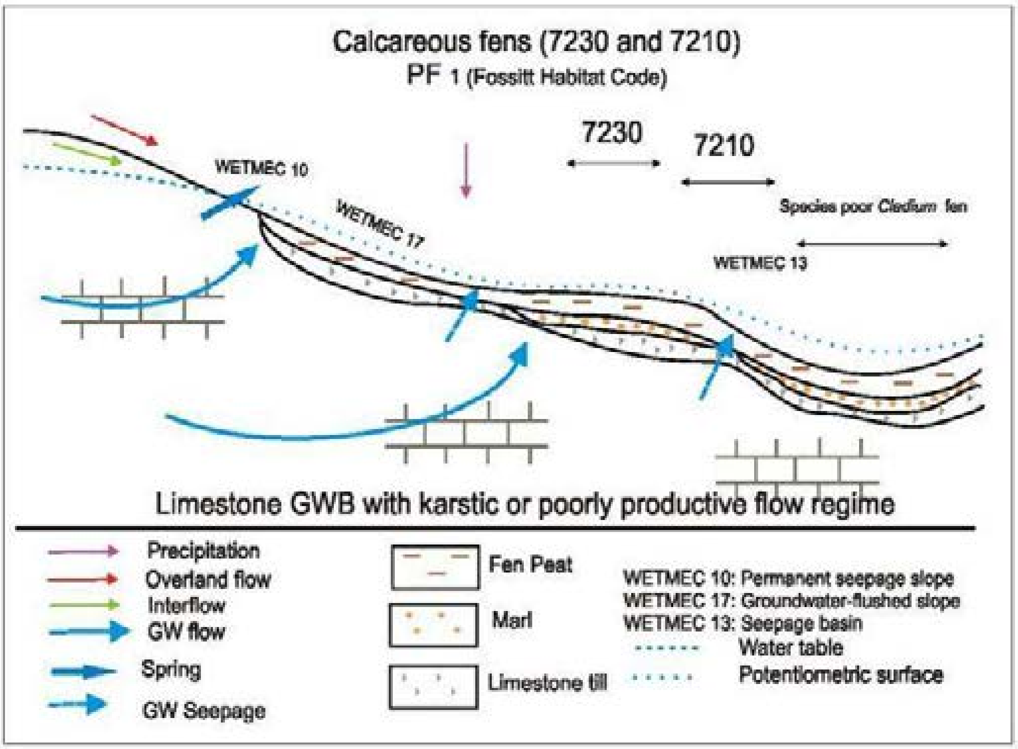
Other habitats that have qualifying interests as GWDTEs within the study areas are fens, transition mires, active raised bogs, and to a lesser extent alluvial forests and humid dune slacks.

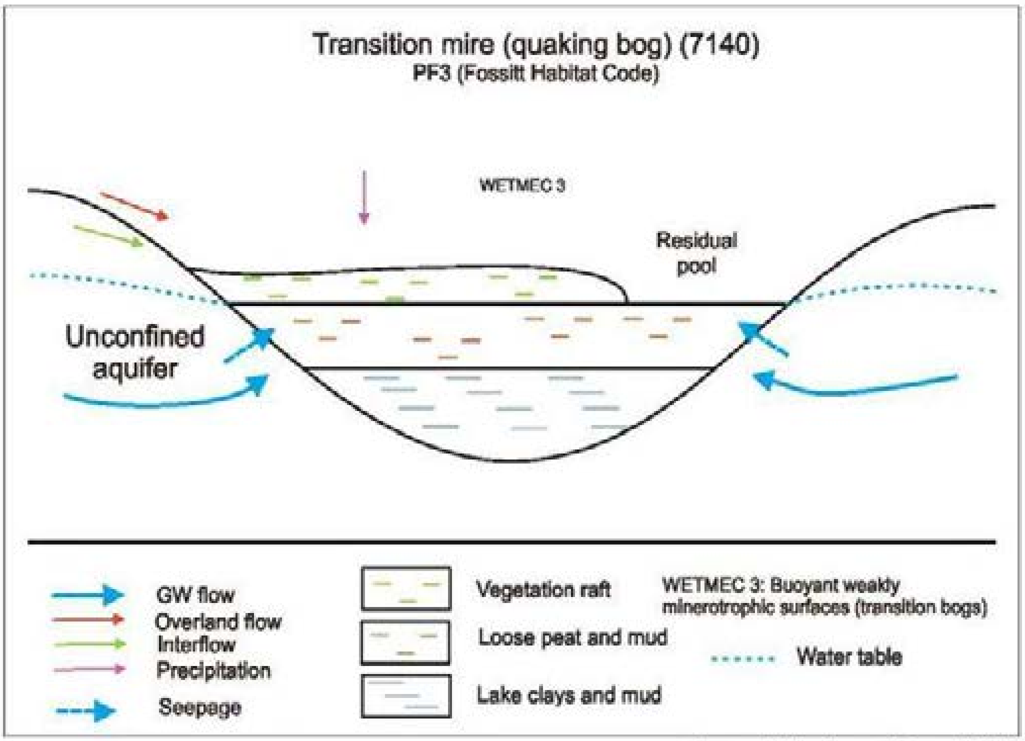


Source: Kimberley and Coxon (2013)

Figure 4.11. Conceptual model – turloughs and petrifying springs.

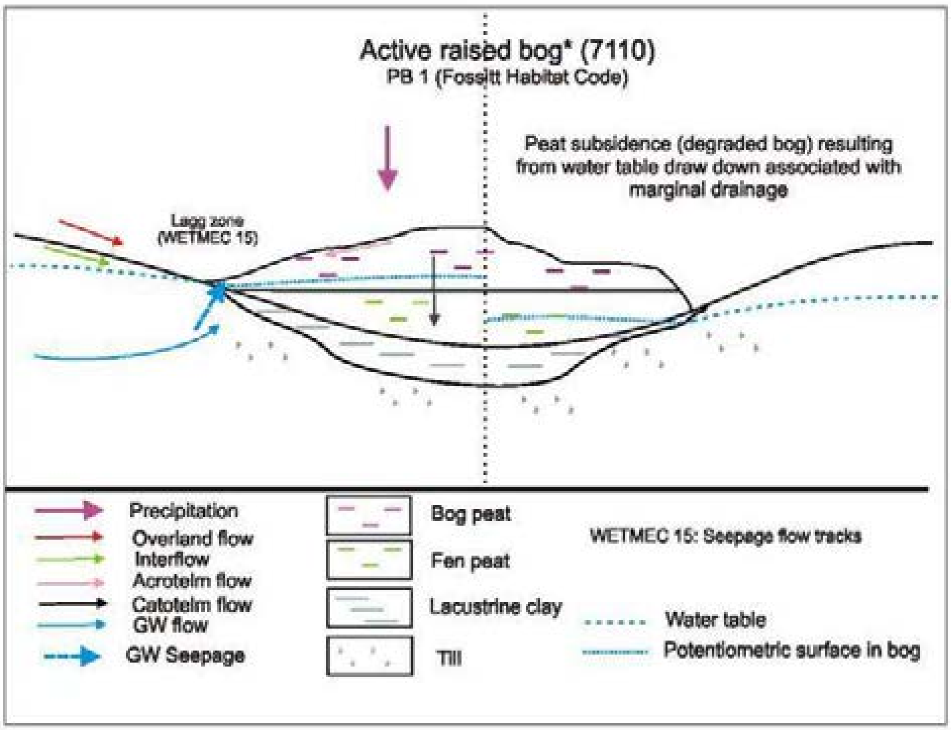
- Fens are widespread in three main SACs mapped by the NWPS in the NCB: a) Ben Bulben, Gleniff and Glenade Complex, b) Arroo Mountain and c) Cuilcagh – Anierin Uplands. They are mainly located within depressions in upland regions, adjacent to raised and blanket bogs. The fens are not differentiated on type (alkaline vs calcareous) and calcareous fens, if they are present, are considered a priority habitat for conservation under the EC Habitats Directive. Calcareous fens depend on high alkalinity waters, and are thus mostly found in hollows on limestone, limestone till or marl lakes. Alkaline fens are also mapped along alluvial river valleys, e.g. at Glenade. Fens are sensitive to groundwater through-flow at springs and seeps along fen margins, see Figure 4.12, and would thus be sensitive to drainage schemes and abstractions. Low-lying fens in river valley settings are dependent on water level conditions dictated by groundwater-surface water interaction, thus both groundwater and surface water abstractions could impact on habitat health. As they are groundwater-fed and require external (mineral rich) source of groundwater to function, fen systems would be sensitive to contaminated groundwater from UGEE operations. The specific impact of natural gas, e.g. methane, on ecosystem function is not known but would conceptually be of less relevance since fen ecosystems can generate the gas biologically (breakdown of organic matter).
- Transition mires, see Figure 4.12, are present in the NCB and are mapped in the same areas as fens. They typically develop between bogs and fens (NPWS, 2013a). The key conditions needed to sustain their ecological health are believed to be a permanently high water level with minimal water level fluctuation (NPWS, 2013a). They would thus be sensitive to changes in hydrological condition, e.g. lowering of water levels from abstractions. It should be noted that Kimberley and Coxon (2013) express uncertainty with regards to the actual significance of the groundwater dependency of transition mires.
- Active raised bogs, see Figure 4.13, are mapped in Co. Fermanagh and at one locality near Doonbeg in the CB study area. They typically form on low-permeability till or hollows of former marl lakes. NPWS (2013a) describes active raised bogs as accumulations of deep acid peat (3 to 12 m) and the term 'active' implies that peat is still forming. The bog dome is fed by precipitation and is isolated from the groundwater table (NPWS, 2013a). However, raised bogs in Ireland are still considered as GWDTEs under the WFD as research indicates that groundwater hydrostatic pressures can be important for maintaining the topography and high water table in the bog dome (Kimberly and Coxon, 2013). Accordingly, they would be most sensitive to lowering of surrounding groundwater tables, e.g. from drainage. Contaminated groundwater would generally not be considered to pose a risk to this type of habitat.
- Alluvial forests, see Figure 4.13, have been mapped around the shores of Lough Allen and along the Upper Lough Erne SAC (see Section 5.4). Their positions adjacent to the lake suggest they are dependent on lake water levels, but could also be dependent on groundwater level near the surface discharging to the lakes. Thus, lake hydraulics and groundwater-surface water interactions would be important risk factors when assessing potential impacts from UGEE-related abstractions in this setting.

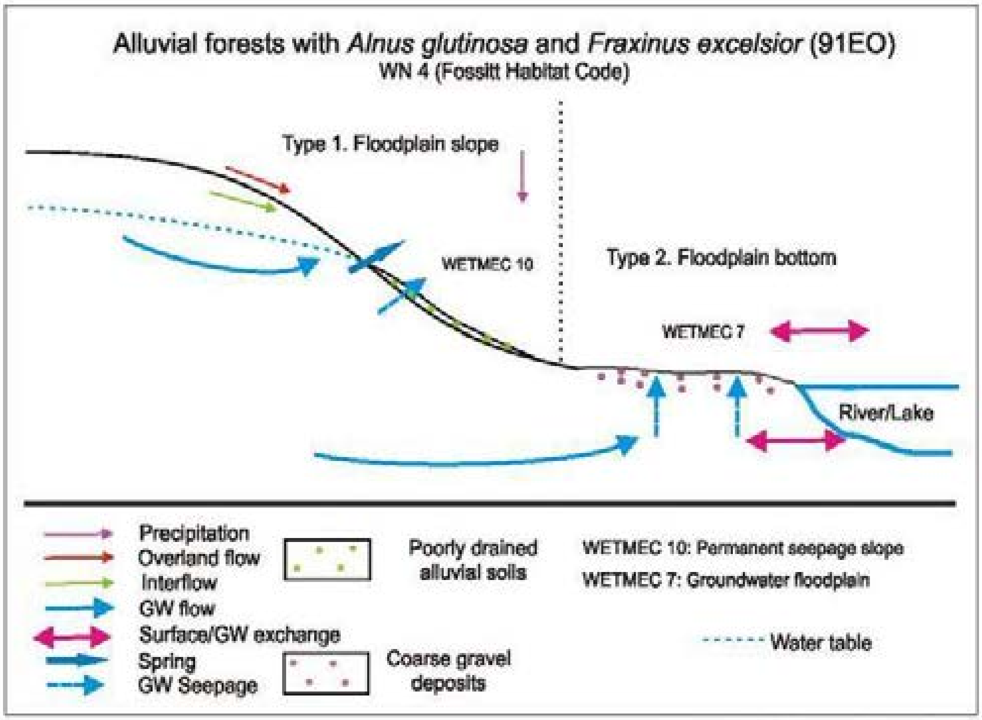




Source: Kimberley and Coxon (2013)

Figure 4.12. Conceptual model – fens and transition mires.





Source: Kimberley and Coxon (2013)

Figure 4.13. Conceptual model – active raised bogs and alluvial forests.

- Humid dune slacks are mapped at one locality only, near Doonbeg in the CB study area. They represent wet hollows between sand dunes in coastal settings. They tend to be localised and may be perched as a function of shallow underlying clay units which impede infiltration of rainwater. The habitat would be sensitive to changes in water levels, saline intrusion from over-pumping and physical changes to dunes in a loose sand environment.

In the context of their geographic localities and environmental sensitivities, it would appear that GWDTEs would primarily be at risk from surface sources of contamination, as well as drainage works and abstractions. Some of the groundwater-dependent habitats, notably fens, transition mires, and active raised bogs, are likely sources and/or reservoirs of naturally occurring methane from breakdown of organic matter, thus vertical migration of gas from depth would seem to be a secondary or less critical issue. Nonetheless, for baseline monitoring purposes, it would be prudent to document the natural presence/absence of biogenic methane gas where such gas accumulations can occur. The large number of such potential sites within the study areas (see Section 5) makes the targeting and selection of individual sites difficult without prior study and characterisation, involving field work.