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Unconventional Gas Exploration and Extraction (UGEE) Joint Research Programme

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

Authors: Henning Moe, Oriol Ciurana, Pat Barrett 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)

Summary Report 1:

Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems

by

CDM Smith Ireland Ltd

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Finally, CDM Smith is indebted to the British Geological Survey for allowing the project team to participate in the sampling for dissolved methane gas in groundwater in England.

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

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Executive Summary

Unconventional gas exploration and 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 and involves field studies (baseline monitoring of water and seismicity) as well as an extensive desk-based literature review of UGEE practices and regulations worldwide. The UGEE JRP has been designed to produce the scientific basis, which will assist regulators in both Ireland and Northern Ireland, in making an informed decision about whether or not 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.

Baseline monitoring is frequently cited as a pre-condition for licensing of unconventional gas exploration and extraction (UGEE) activity. Therefore, the Terms of Reference and scope of work for the Joint Research Project (JRP) on the environmental impacts of UGEE identified a requirement to identify, evaluate and undertake appropriate potential baseline monitoring requirements for water, air and seismicity (earthquake activity). Requirements for baseline monitoring are embodied in the (2014/70/EU) EC Recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing, but a review of international literature provides relatively little on the specifics of baseline monitoring.

Following a comprehensive assessment of the two study areas and the existing provisions for monitoring, the JRP made proposals for baseline monitoring for the assessment of water and naturally occurring seismicity, with a window of up to 2 years proposed to complete the aforementioned baseline monitoring programme. Consequently, such a baseline monitoring programme would result in the overall findings of the research being delivered after the project deadline of 2016.

The original timeline for the research envisaged that the entire programme, including water and seismicity baseline data acquisition, would conclude by 2016. The steering committee considered that, were the baseline acquisition to commence, the revised timeline for the overall research programme would now be to report in 2018 at the earliest. The decision was therefore taken to prepare an integrated synthesis report now, 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 programme proposed by the JRP remains valid and the report includes a recommendation that such a programme should be implemented in advance of the consideration of any application for a Petroleum Exploration Licence (Ireland) or an application to carry out high-volume hydraulic fracturing (Northern Ireland). It should be noted that such a baseline monitoring programme should provide independent information 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 project 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 (NCB) and the Clare Basin (CB). The research conducted as part of Project A1 is guided by the

2 www.ugeeresearch.ie

Source–Pathway–Receptor (S-P-R) Model of environmental risk assessment, which has served as the basis for most other water resource and environmental protection programmes in 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 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 dikes. The stratigraphy comprises a range of shale, sandstone and limestone formations, which are well correlated across the basin. Regional strike-slip faults trending north-east to south-west extend through the entire stratigraphic sequence. These are accompanied by smaller conjugate sets of normal and reverse faults that trend mainly north-west to south-east. 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. 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.

Towards the centre of the NCB, where the Bundoran Shale Formation is deeply buried and past gas exploration activity was focused, the “vertical separation distance” to the principal shallow bedrock aquifers and associated receptors ranges between approximately 250 and 570 m (average 426 m), reflecting spatial variations in the thickness and structure of the intervening Mullaghmore Sandstone and Benbulben Shale Formations.

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.

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 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.

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 the presence and patterns of natural, open fracture networks at depth have not been well 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 or not 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 be addressed only through further hydrogeological characterisation, especially of the Mullaghmore Sandstone and Benbulben Shale Formations. Although the predominantly 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.

Clare Basin

Prospective unconventional gas exploration in the CB would be targeted in the Clare Shale Formation. Horizontal hydraulic fracturing would likely require the drilling of wells 800–1200 m in 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, predominantly, of 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 would likely be determined by the presence of through-cutting faults rather than any stratigraphic or lithological controls.

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 with the NCB. Groundwater is used and sourced for private water supply, notably from drilled wells, which are typically less than 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 (GWSs) 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.

There is a possibility that a deeper and potentially subregional groundwater flow component may be present in the CB, as suggested by reported “fresh water” strikes at approximately 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 subregional groundwater flow component towards the coastlines 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 geological investigation, including deep drilling and borehole geophysical logging. Identification of faulting would benefit from detailed surface geophysical survey work. Deep hydrogeological characterisation would equally benefit from drilling, hydraulic testing, sampling and monitoring of new deep wells, to depths of several hundred metres.

Risk of Environmental Impact

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

Potential pathways are of natural origin or 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 environment (to approximately 200 m in 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 subregional scale and are well mapped and field verified. They are (1) the available water resources represented by lakes, streams and aquifers; (2) associated water supplies (abstractions); (3) registered protected areas; and (4) groundwater-dependent terrestrial ecosystems (GWDTEs).

The different modes of potential impact on water-related receptors are summarised in Figure ES.1. 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 Mitigation Measures* of the UGEE JRP (CDMS, 2016). Details of appropriate mitigation measures to address well construction practices are most appropriately addressed as part of the review process of potential future licence 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 the regulatory authorities.

Existing groundwater protection policies in Ireland and Northern Ireland are aimed at mitigating risks of contamination from surface sources of contamination, as guided by principles of groundwater vulnerability and related mapping by the Geological Survey of Ireland (GSI) and Geological Survey of Northern Ireland (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 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.

UGEE-related liquids and fluids are mostly a concern when these are returned to the surface as flowback or production waters (*Final Report 4*; CDMS, 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. 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.

Baseline Monitoring Best Practice

Baseline monitoring is required should UGEE-related activity plans become known or proceed in the future. The purpose of baseline monitoring is to document existing environmental conditions and to be able to identify and track changes (i.e. potential impact) over time. Existing environmental pressures and conditions in both case study areas are already well described by the EPA and NIEA based on monitoring initiatives linked with the implementation of the European Union (EU) Water Framework Directive (WFD) and the national statutory instruments that have followed. However, WFD monitoring is not specifically designed to address UGEE-related operations, and baseline monitoring associated with UGEE would include many additional parameters that could be used to fingerprint UGEE-related contamination and distinguish UGEE impact from existing environmental pressures.

A precautionary approach to baseline monitoring dictates that monitoring should be comprehensive in scope and extent, and should allow cumulative impacts to be identified across a wider area (i.e. a broader potential UGEE footprint). Firm plans for UGEE development 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,

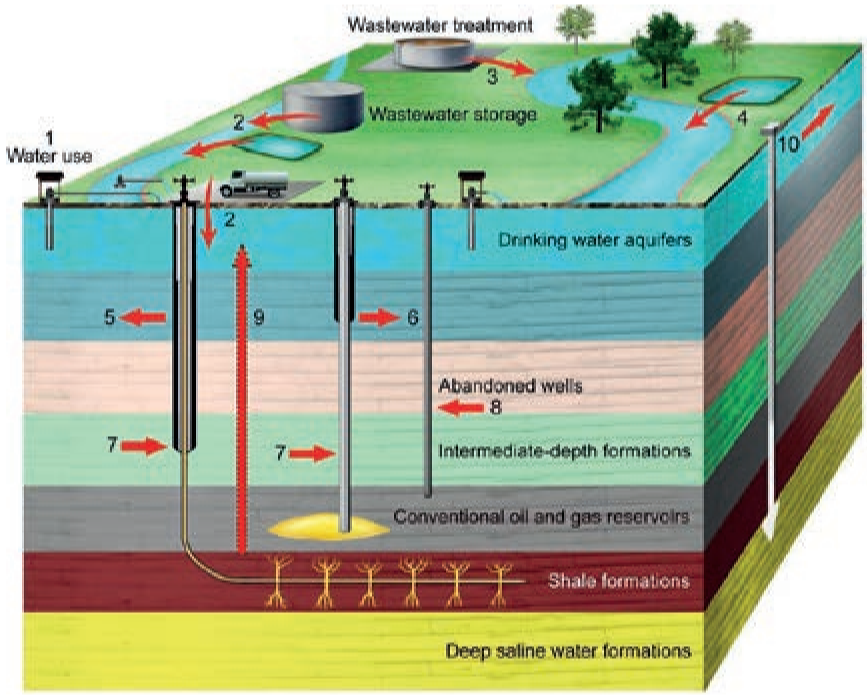

Figure ES.1. Potential modes of UGEE impact on water resources. Schematic illustration (not to scale) of possible modes of water impacts associated with UGEE. (1) Over-abstraction of water from streams, lakes or shallow aquifers – higher risks of impacts during low flow conditions. (2) Contamination 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). (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 other, abandoned, 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. (10) Shallow aquifer contamination through leaking of injection wells (possible but unlikely future scenario). Modified from Vengosh *et al*. (2014).

a subregional 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 no specific guidance on for how long a subregional baseline monitoring programme should be carried out. Baseline monitoring is a longer term commitment, if trends are to be identified and tracked. It is considered that developing a baseline picture of parameters that have hitherto not been analysed (e.g. methane, stable isotopes) would require a minimum of 1 to 2 years.

International best practice requires that groundwater samples be 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. 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. Methane 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. Therefore, a baseline understanding of methane in groundwater is needed, drawing on practical experiences by the British Geological Survey (BGS), which has conducted similar monitoring of dissolved methane in England and Wales. An appropriate and recommended starting point for baseline monitoring in the island of Ireland would be to adopt and adapt the techniques and methods of the BGS.

Approach towards the Design of Subregional Baseline Monitoring Programmes

Comprehensive subregional baseline monitoring programmes have been designed for the two case 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.

The approach that was followed in the design of monitoring networks builds on past and existing monitoring initiatives to take advantage of monitoring data that already exist, thereby reducing the potential for duplication of effort and associated costs. It uses conceptual hydrogeological models to select sampling and measurement locations based on identified data gaps, and responds to best-practice information on baseline monitoring in international literature, particularly with respect to parameters that should be included for laboratory analyses.

The selected monitoring stations must also be "representative", which implies that monitoring (1) is carried out at appropriate locations (in three dimensions); (2) is conducted at appropriate times; and (3) produces data (groundwater flow, discharge, quality) that describe the hydrogeological systems in question, taking account of temporal variations and the hydraulic interactions that may take place between groundwater, surface water and aquatic ecosystems within the system.

Given the significant financial burden that such a baseline monitoring programme places on available resources, the designed programme allows flexibility in implementation, whereby monitoring is adapted to actual findings, with respect to both what is monitored for and where and when sampling is carried out. Such "adaptive monitoring" can result in significant cost savings over time, without compromising on project objectives. Should UGEE activity plans become known in the future, baseline monitoring can also be adjusted geographically. Accordingly, monitoring strategies and programmes may evolve in time, as new data become available and new monitoring installations become active.

Recommendation for Subregional Baseline Monitoring Programmes

The recommended subregional baseline monitoring programmes in the UGEE licence areas of the NCB and CB study areas are summarised in Table ES.1 and shown in Figures ES.2 and ES.3. 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 than 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.

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 three petrifying springs with tufa formations in the West Fermanagh Scarplands Special Area of Conservation, to be selected after field verification.

Turloughs, petrifying springs with tufa formation and calcareous fens are significantly groundwater-dependent and should be retained as appropriate candidates for subregional baseline monitoring purposes in the future. However, establishing representative baseline monitoring programmes for such environments is challenging, since the majority of habitats are geographically

Table ES.1. Summary of recommended baseline monitoring

Parameter	No. of stations	
	NCB (area: 2200.40 km^2)	CB (area: 495.65 km^2)
Groundwater quality – wells (PWS + GWS + private)	35	22[a]
Groundwater quality – wells (new)[b]	10	2
Groundwater quality – springs (PWS + GWS)	25	–
Groundwater quality – springs (other)[c]	10	–
Surface water quality – streams	29	7
Surface water quality – lakes	15	2
Surface water quality – turloughs[d]	3	–
Groundwater quality – petrifying springs[e]	6	–
Hydrometric – stream flow	3	–
Hydrometric – spring discharge	7	–
Hydrometric – groundwater levels	20	10
Stream sediments[f]	30	15

[a]Estimated, to be finalised. 18 sites are accessible for sampling; a further six 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 would be on areas where prospective UGEE activity has been flagged, e.g. Kilcoo Cross, Arigna/Drumkeeran and Dowra. New monitoring wells in the CB would be located towards the central and south-eastern parts of the UGEE licence area, with final recommendations to be provided after final verification of existing wells. For the purposes of this report, two wells would be expected to be drilled and installed in the CB.

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

[d]Groundwater-dependent habitats within Special Areas of Conservation (SACs) in the NCB.

[e]Two clusters, of three petrifying springs each, are proposed for monitoring.

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

PWS, public water scheme.

widespread but occur as individual entities that 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 provide indications of only 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 location-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 details about future planned UGEE activities become known.

Monitoring of GWDTEs should in all cases be considered when scoping, planning and assessing future UGEE activity at specified locations. The onus of prior study and monitoring should be placed on the 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. 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. 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 they were present above screening criteria, further analysis of stable isotopes would be conducted to establish the origin of the methane (thermogenic or biogenic).

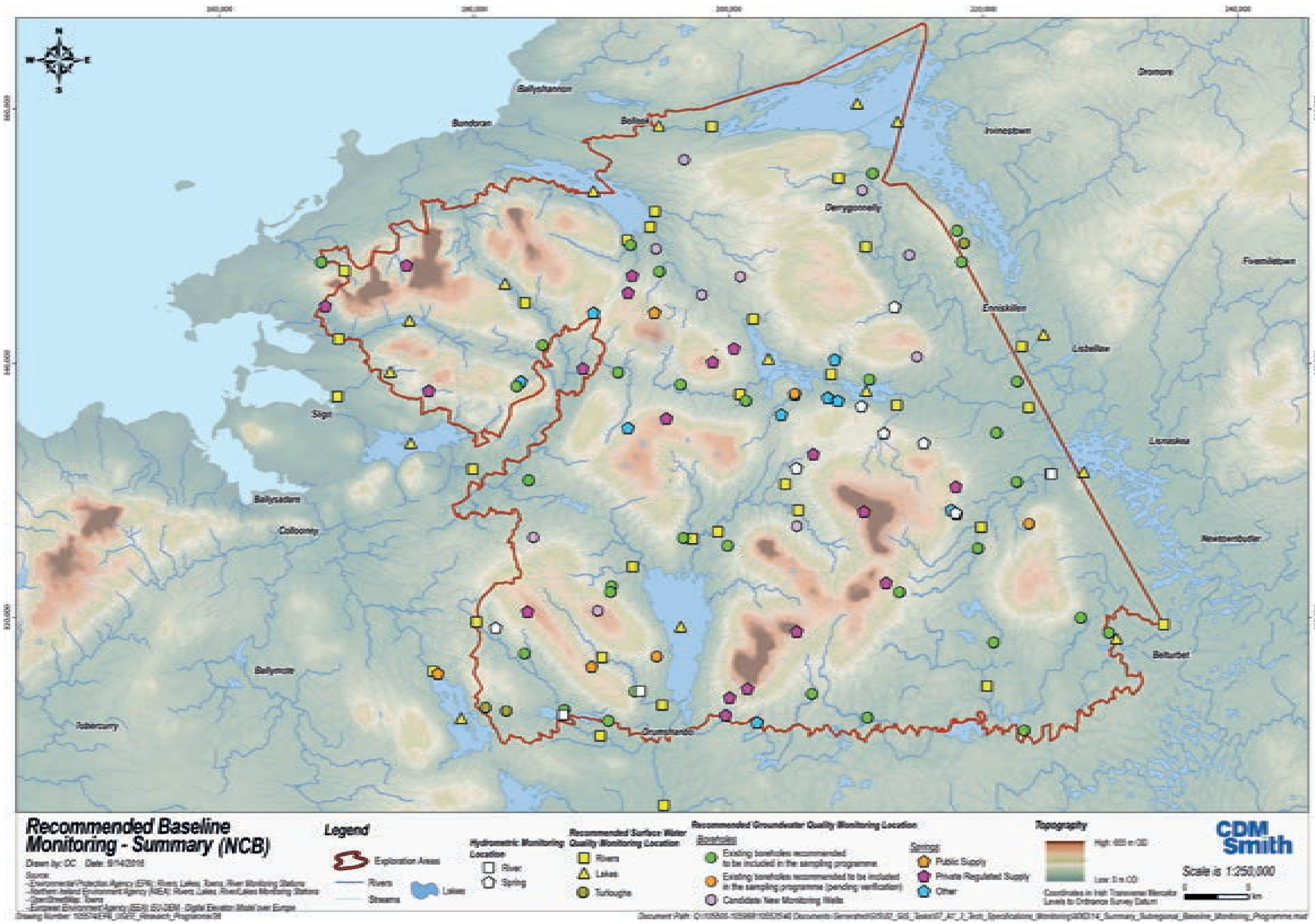

Figure ES.2. Overview of recommended monitoring stations for groundwater and surface water, NCB study area.

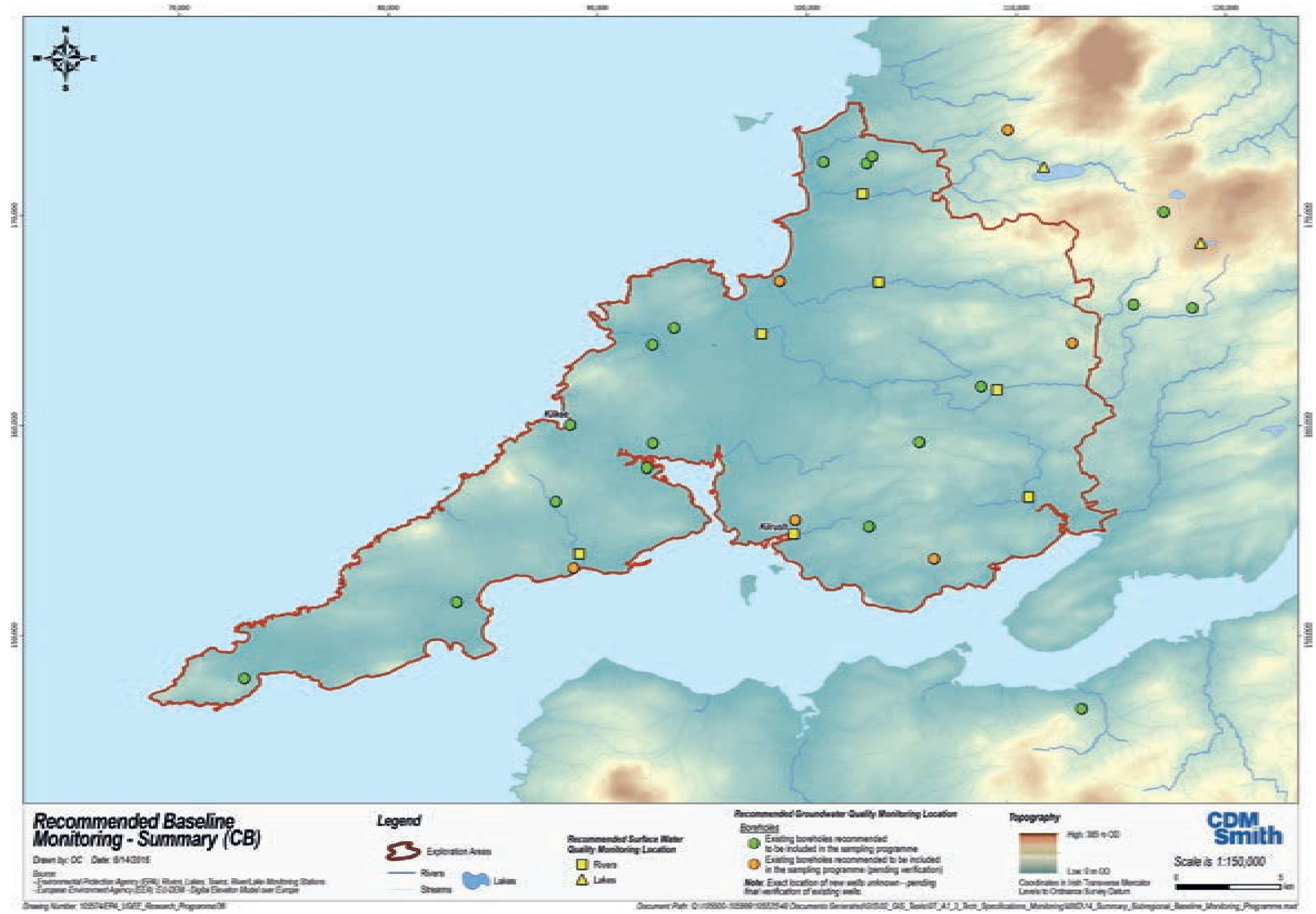

Figure ES.3. Overview of recommended monitoring stations for groundwater and surface water, CB study area.

Natural gas constituents, including methane, would not be analysed for in surface water, given 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 subregional scale, requiring site-specific study and detailed monitoring of related groundwater–surface water interaction systems. The method has, however, value at the local (subcatchment) 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 is 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, as well as prior co-ordination with the existing GSI Tellus Research Project[3] team.

Hydrometric Monitoring

Data gaps in existing hydrometric monitoring networks have been identified, and additional monitoring for subregional 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 and transducers/data loggers, and by 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.

Given the very large number of springs present, it would not be possible to measure all of them. 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 the estimation of time-lags of water pulses moving through karstified flow systems.

Specific streams that would be monitored in a similar manner are in 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 in hydrometeorological conditions.

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

Monitoring for Potential Impact of UGEE-related Abstractions

Hydrometric monitoring of potential impact from UGEE-related abstractions would have to be considered on a case- and location-specific basis in the future should UGEE licensing proceed. Details of monitoring requirements can be defined or recommended only 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. 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 than in 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.

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

Existing abstraction pressures are currently considered to be low in both case study areas. Future UGEE-related abstractions would have to be considered with regard 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 affecting the ecological and chemical status of a related water body.

Addressing Deep Geological and Hydrogeological Data Gaps

Specific gaps in the hydrogeological knowledge of the two study areas relate to potential deep groundwater flow, deep water quality and potential hydraulic connectivity between unconventional gas target formations and shallow receptors. Key technical questions about deep water resources and hydrogeological characteristics can be addressed only by a combination of surface geophysical surveys (e.g. fault identification), drilling, geophysical logging of boreholes 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 subregional scale and recommendations for improved geological/hydrogeological characterisation. It is argued that, because UGEE activity is case- and location-specific, improved work to characterise deeper hydrogeological conditions should be carried out where UGEE activity is most likely to be targeted or planned. A broader, subregional 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 subregional approach would not necessarily produce the answers that are needed at the location-specific scale of an individual hydraulic fracturing site.

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

1 Introduction

1.1 Overview of the UGEE Joint Research Programme

Unconventional gas exploration and 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] was composed of five interlinked projects and involves field studies (baseline monitoring of water and seismicity) as well as an extensive desk-based literature review of UGEE practices and regulations worldwide, as follows:

- 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, informed by conceptual hydrogeological models.
- 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 (EISs).
- Project B (UGEE Projects/Operations: Impacts & Mitigation Measures) covered the identification and a detailed examination of the potential impacts on the environment and human health, as well as successful 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 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 the context of the island of Ireland.

The UGEE JRP was designed to assist regulators – in both Ireland and Northern Ireland – to make informed decisions about whether or not fracking is environmentally safe, by collating evidence from other countries and placing this in the context of the island of Ireland.

1.2 Scope, Objectives and Goals of Project A1

Project A1, summarised by its scope in Figure 1.1, had two primary components:

- *characterisation* of two case study areas, shown in Figure 1.2, to help understand the three-dimensional relationship between potential sources of contamination and the near-surface environment; and
- specification of subregional *baseline monitoring* of groundwater, surface water and associated ecosystems, informed by the results of the characterisation, including conceptual hydrogeological models.

Project A1 had the following principal objectives:

- to describe the subregional 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 can guide the design of baseline monitoring networks that are representative of known or inferred pathways of water movement (thus also of potential contaminant migration);
- to summarise existing environmental pressures and monitoring activity in the case study areas;

4 www.ugeeresearch.ie

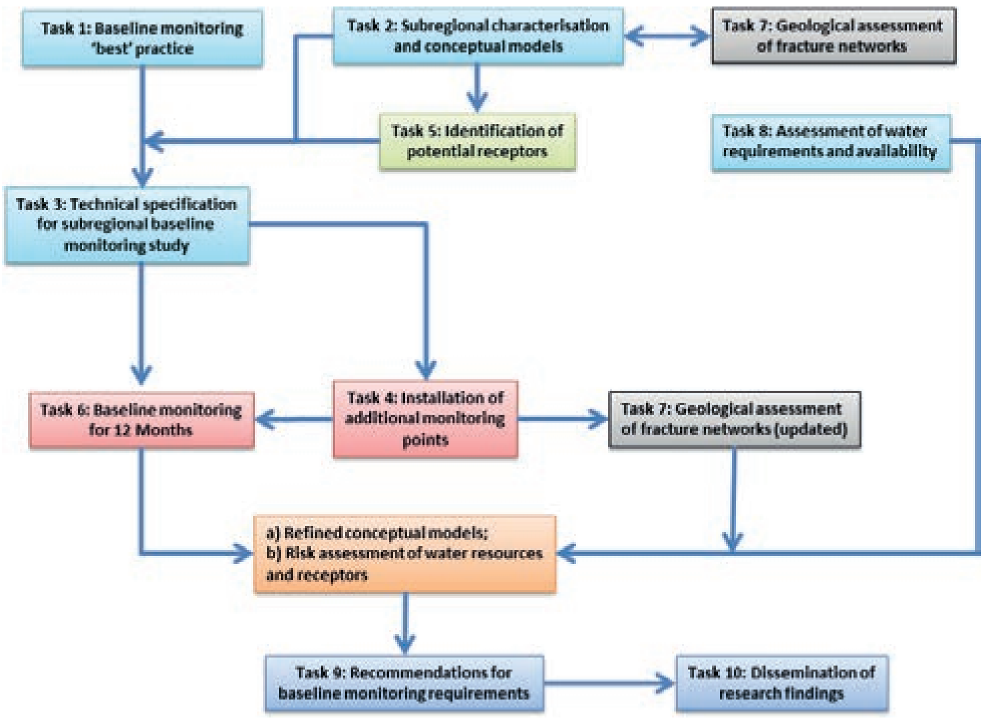

Figure 1.1. Tasks of Project A1 of the UGEE JRP.

Figure 1.2. Overview of the case study areas of the UGEE JRP.

- 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 subregional 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 principal goals of Project A1 were:

- 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 subregional 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 future decision making 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, associated ecosystems). The reporting would, therefore, serve to assist the UGEE JRP participants in piloting co-ordinated and integrated subregional baseline monitoring programmes in both Ireland and Northern Ireland.

1.3 Project A1 Methodology

The work carried out as part of Project A1 has involved literature review and field surveys. The literature review was comprehensive, and relevant information was collated from it 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 publicly 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-learnt 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 (BGS).

1.4 Information Sources

Reference materials were researched and collated from a wide range of research and public bodies engaged in environmental matters in both Ireland and Northern Ireland. Past hydrocarbon exploration files were also sourced from the Petroleum Affairs Division (PAD) of the DCENR and from the Geological Survey of Northern Ireland (GSNI). The PAD files were made available under the 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 Northwest Carboniferous Basin (NCB) study area (nine in County Fermanagh, and six in Counties Cavan and Leitrim). In comparison, three gas exploration wells were drilled and tested in County Clare, with two of them being located in or near the Clare Basin (CB) study area. The wells are summarised in Table 1.1 and their locations are shown in Figure 1.3.

Table 1.1. 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
		Mullaghnawinna 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

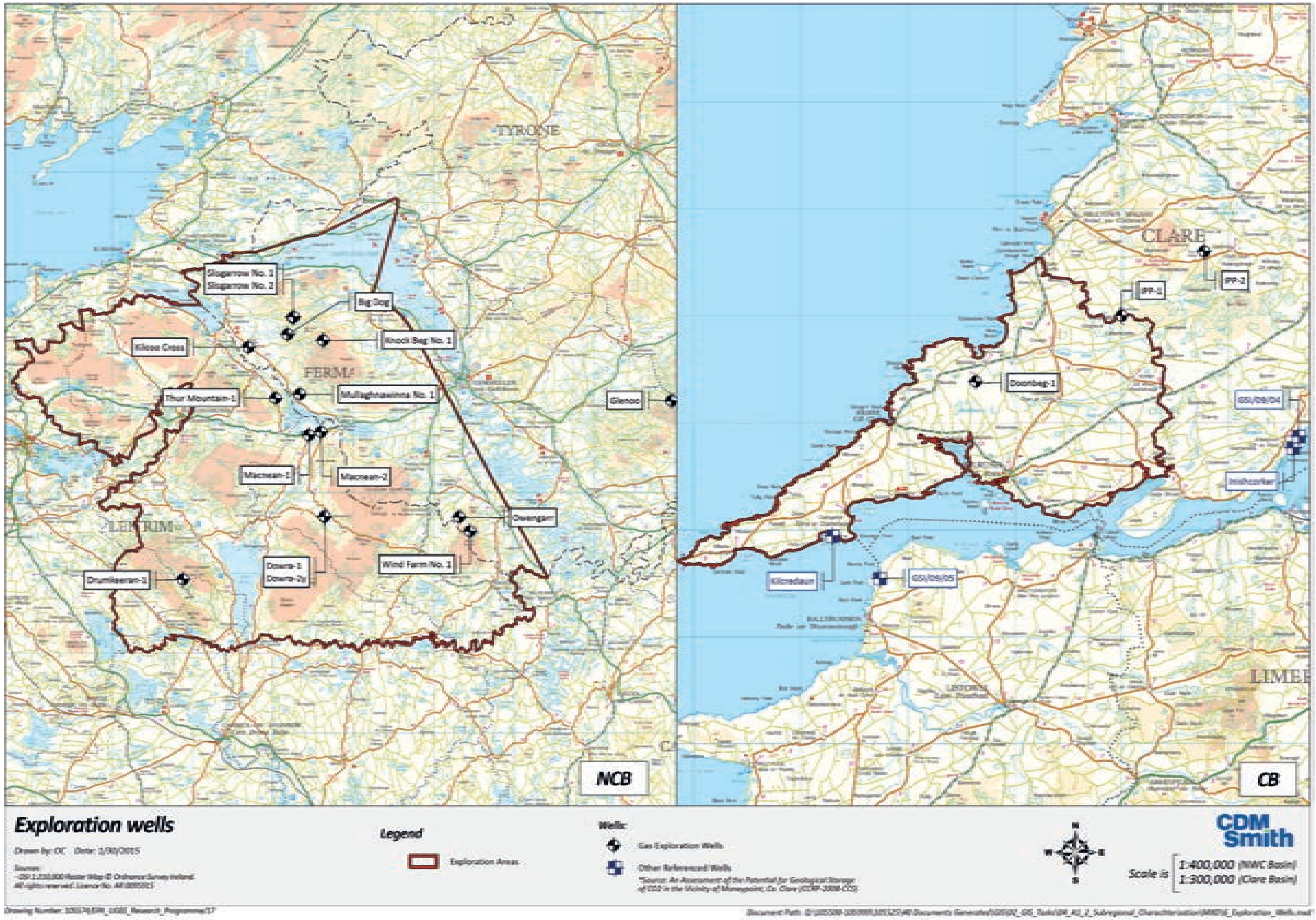

Figure 1.3. Existing deep gas exploration wells in the UGEE study areas.

2 Hydrogeological Summary of the Two Study Areas

2.1 Northwest Carboniferous Basin

The NCB is a stratigraphically and structurally complex sedimentary basin comprising a range of shale, sandstone and limestone formations. The rock formations are extensively faulted and are in certain parts intruded by volcanic dikes. Regional-scale 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 the fault displacements, different geological formations are juxtaposed against one another at numerous locations.

The stratigraphy of the NCB is summarised in Figure 2.1. Prospective unconventional gas exploration is targeted in the Bundoran Shale Formation. Horizontal hydraulic fracturing would require the initial vertical drilling and construction of boreholes to depths of 700–1300 m below ground surface.

The main 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 and its chronostratigraphic equivalents (e.g. the Bricklieve Limestone Formation). These are extensively karstified, whereby open conduits act as preferential pathways for water to flow underground. Any contaminants that enter such systems can be transported over large distances in short periods of time (measured in hours or days) without attenuation mechanisms other than dilution and mixing. Associated downgradient receptors would, accordingly, be susceptible to both surface and potential underground sources of contamination associated with UGEE. There is considerable hydraulic interaction between groundwater and surface water in karstified limestone areas.

Figure 2.2 depicts a conceptual hydrogeological cross-section of the NCB. Most of the bedrock formations represent groundwater resources in and near their outcrop areas where groundwater quality is suitable for supply purposes. Groundwater is extensively used for public and private water supply. It is sourced from drilled boreholes (which are typically less than 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 an especially important function during prolonged dry weather conditions.

All groundwater and surface water resources are vulnerable to potential sources of contamination associated with UGEE activity, depending on case-specific circumstances. For these reasons, any future planning of UGEE-related activity should be guided by groundwater vulnerability concepts as implemented by both the Geological Survey of Ireland (GSI) and the GSNI.

The "vertical separation distance" (Davies *et al.*, 2012) between the top of the Bundoran Shale Formation (source rock and unconventional gas target) and the base of the shallow aquifers (potential receptor) in the study area ranges between approximately 250 and 570 m (average 426 m) as recorded in reports from 10 past gas exploration wells for which data exist. The wide range reflects spatial variations in the combined thicknesses of the intervening Mullaghmore Sandstone and Benbulben Shale Formations.

Based on existing and available data, 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 formations, notably across the Mullaghmore Sandstone and Benbulben Shale Formations. Such open fractures would represent potential pathways of vertical contaminant migration, especially of dissolved, naturally occurring gases, including methane, from hydraulic fracturing operations.

Although geological structures and fracture patterns at ground surface are mapped and well described in existing literature, the potential presence and patterns of open fracture networks at depth are not conclusively demonstrated or characterised. Their presence is inferred from completion reports of past gas exploration wells which reference (1) the presence of saline formation waters in deep sandstones that were tested for gas potential; (2) influx of water into the gas exploration wells during the gas-testing phase; and (3) acoustic

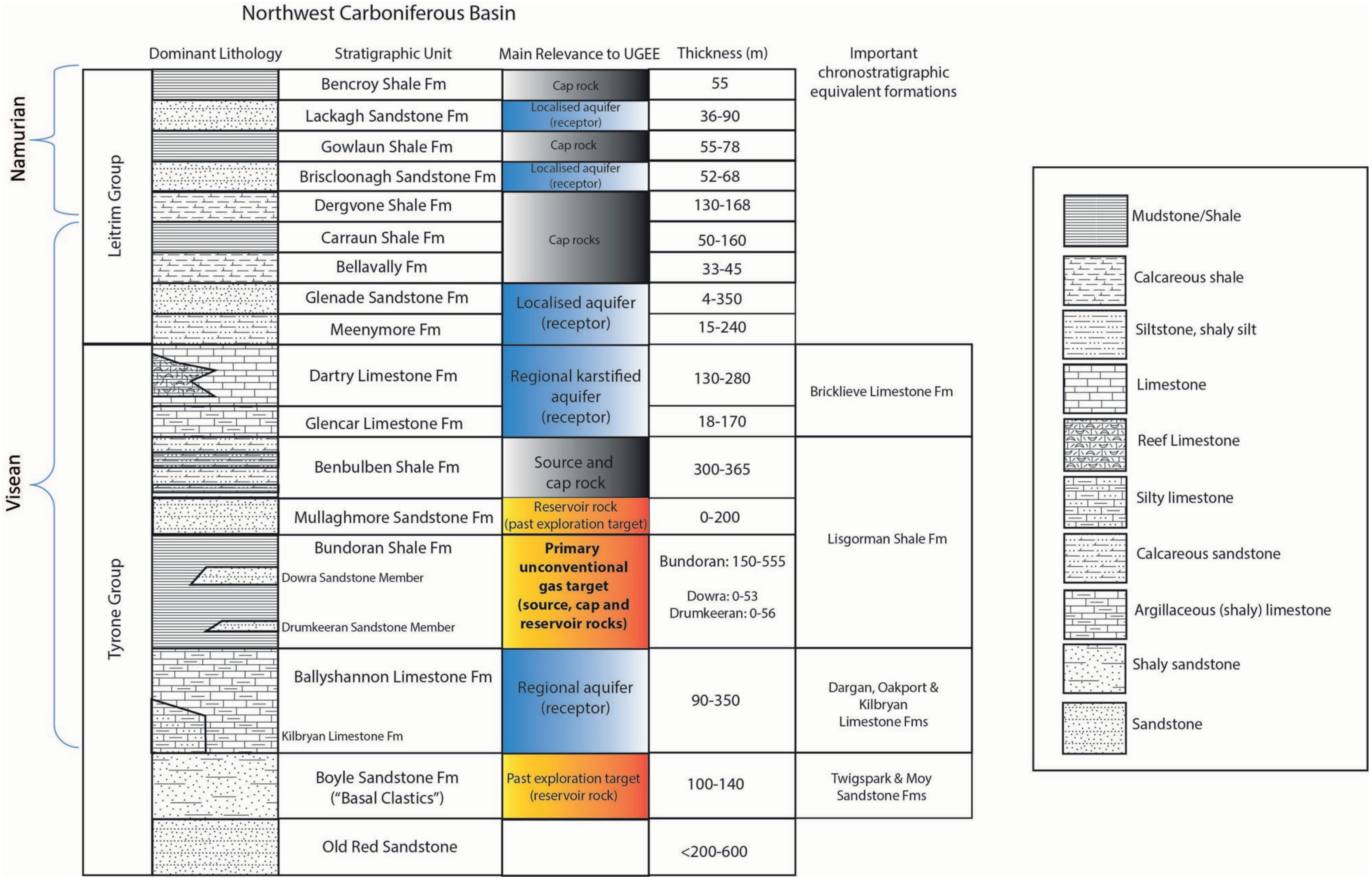

Figure 2.1. Simplified stratigraphy of the NCB study area.

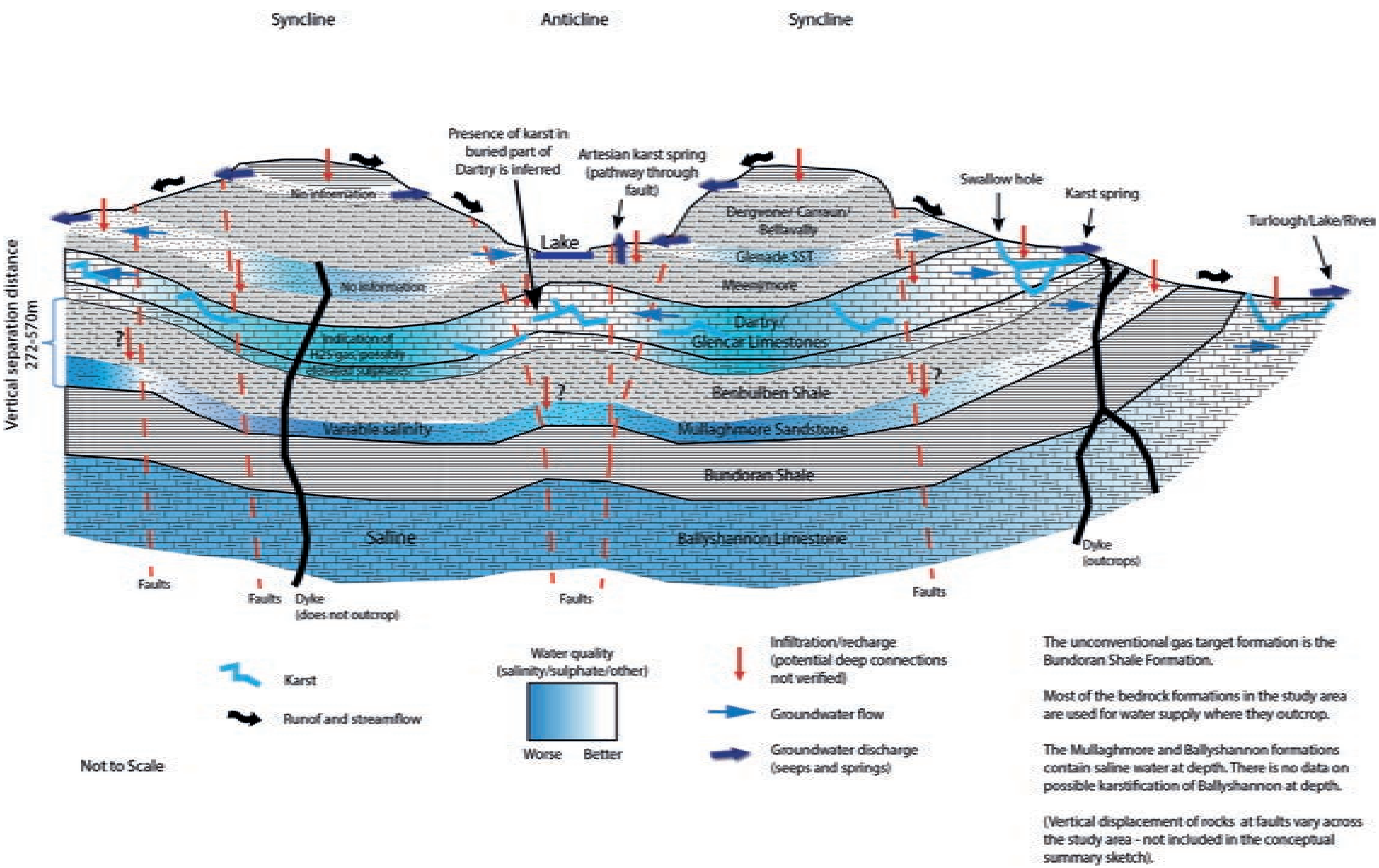

Figure 2.2. Conceptual hydrogeological cross-section of the NCB.

televiewer images of presumed open fractures in the Mullaghmore Sandstone Formation (the main target of gas exploration activity in the past).

In the island of Ireland context, conceptual hydrogeological models generally consider that the occurrence of significant water-bearing fractures decreases with depth. Because of the typical depths of water supply 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 exploration boreholes and mine workings, indicating that hydraulically open and interconnected fractures can occur at depth. Their prevalence and nature, however, remain poorly characterised. The potential presence of open fractures in deeper sandstone formations in the NCB study area could be explained by the structural geology of the region, in which an observed sinistral (left-lateral) movement and rotation of regional NE–SW trending strike-slip faults imply the development of potential dilatation zones.

Whether the reported deep saline formation waters are "fossil" or are part of active 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, important questions about hydrogeological connections between the unconventional target formations and shallow receptors can be addressed only through further hydrogeological characterisation, involving drilling, hydraulic testing, sampling and monitoring.

The key formations to characterise geologically in an UGEE context are the Mullaghmore Sandstone and Benbulben Shale Formations. Although the predominantly shale (clay-rich) lithology of the Benbulben Shale Formation would be expected to result in the sealing of fractures, the potential presence of fracture pathways across the Benbulben Shale Formation cannot be ruled out, as (1) it contains calcareous units and (2) the NCB is extensively faulted. As noted by Schlumberger, 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. In addition, 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.

2.2 Clare Basin

It is inferred that prospective unconventional gas exploration in the CB would be targeted in the Clare Shale Formation. Horizontal hydraulic fracturing would likely require the drilling of wells to 800–1200 m in depth 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 too shallow to be considered a viable source rock for unconventional gas.

The stratigraphic sequence of the CB study area is summarised in Figure 2.3. The bedrock formations above the Clare Shale Formation are characterised by significant lithological heterogeneity in three dimensions as a function of the depositional history of the basin. The rocks are predominantly sandstone and siltstone units of deltaic and turbiditic origin, interlayered with shale and mudstone units. Turbiditic sands can be isolated by surrounding fine-grained sediments or can be intercutting, and may, therefore, be interconnected in three dimensions.

From the available information, there does not appear to be a regionally continuous caprock above the Clare Shale Formation (e.g. equivalent to the Benbulben Shale Formation in the NCB) that would effectively separate the unconventional gas target from shallow water resources and associated ecosystems, or would offer natural protection from potential vertical transport of gas and potential other contaminants. Rather, if deep open fracture networks are present in the main sandstone formations throughout the CB, the stratigraphic variations observed at outcrop and in the few wells that have been drilled to date suggest that migration of UGEE-related contaminants to shallow aquifer units might be less constrained than in the NCB. Nonetheless, the permeability and porosities of the sandstone formations are generally low, with fracture permeability/porosity dominating any gas, liquid or fluid flow. In this scenario, the potential for contaminant migration would likely be determined by the presence of through-cutting faults rather than any stratigraphic or lithological controls.

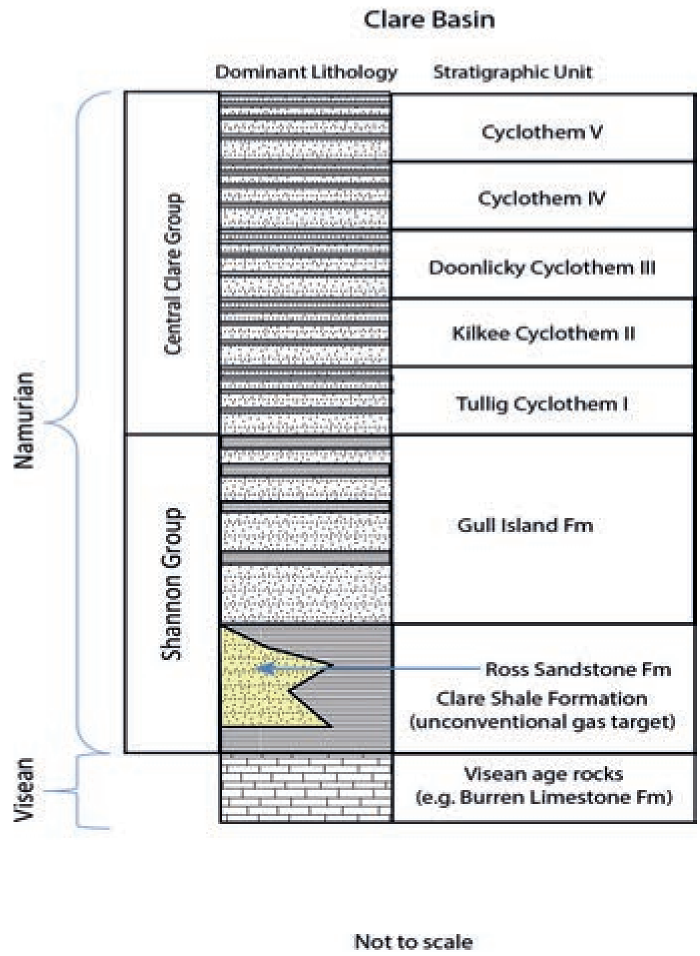

Figure 2.3. Simplified lithological column of the CB study area.

A conceptual hydrogeological cross-section of the CB is presented in Figure 2.4. 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 generally few groundwater-dependent habitats in the CB. Alkaline fens, an active raised bog and an area with humid dune slacks have been mapped by the National Parks and Wildlife Service (NPWS) within or near the UGEE licence boundaries, which are associated with localised groundwater–surface water interaction systems.

Groundwater is sourced for private water supply, notably from drilled boreholes, which are typically less than 150 m deep, and from dug or bored wells, which are only a few metres deep. These serve single houses and farms, as well as commercial/industrial facilities. There are no groundwater-sourced public water schemes (PWSs) or group water schemes (GWSs) directly within the UGEE licence area. The majority of PWS and GWS supplies are sourced 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.

Groundwater flows primarily via fractures in sandstone and siltstone units. In addition to shallow localised flow systems, it is possible that a deeper and potentially subregional groundwater flow system is present, as suggested by reported fresh water strikes at *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 subregional groundwater flow component towards the coastlines within the Namurian stratigraphic sequence is plausible.

Despite the relative absence of faults on existing geological maps and the apparent structural “simplicity” of the CB compared with the NCB, 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

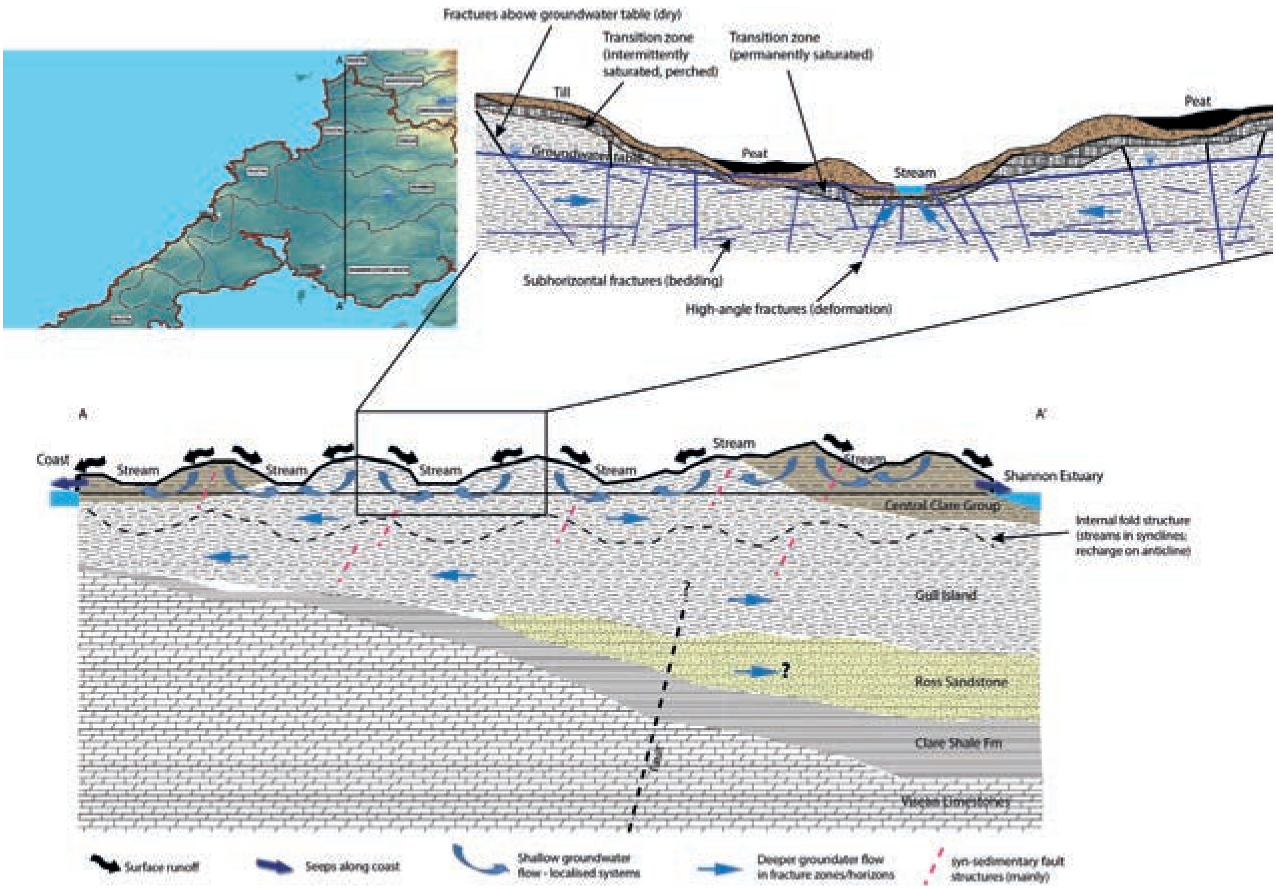

Figure 2.4. Conceptual hydrogeological cross-section of the CB.

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 geological investigation, including deep drilling and borehole geophysical logging. Identification of faulting would benefit from detailed surface geophysical survey work. Deep hydrogeological characterisation would equally benefit from investigative work involving drilling, hydraulic testing, sampling and monitoring of new wells to depths of several hundred metres.

Finally, owing 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.

3 Risk of Environmental Impact

Risks of environmental impact from UGEE operations are defined by operational practices, the natural hydrogeological conditions of a UGEE location, and the presence and susceptibility of potential receptors of contamination. Risk factors were assessed in both case study areas using the Source–Pathway–Receptor (S-P-R) Model of environmental risk assessment, which has served as the basis for most water resources and environmental protection programmes in the island of Ireland in recent years. It describes linkages between contaminant sources, pathways of contaminant migration and downgradient receptors.

Existing groundwater protection policies in Ireland and Northern Ireland are aimed at identifying and mitigating risks of contamination from surface sources of contamination to “shallow aquifers”, which are those used for water supply purposes, typically limited to depths of less than 200 m. They do not address the risks of contamination from deeper sources of contamination, such as those that may result from hydraulic fracturing, although principles of contaminant migration are the same in both environments.

3.1 Potential Sources of Contamination

There are many potential sources of UGEE-related contamination. Some are related to UGEE operations at the ground surface. Others are related to hydraulic fracturing in the subsurface environment. A useful summary of potential “modes of impact” was shown in Figure ES.1 (adapted from Vengosh *et al.*, 2014).

UGEE activity involves the drilling and construction of deep vertical and horizontal wells, followed by hydraulic fracturing and, potentially, longer term operations. Each stage of a UGEE project carries environmental risk. Risks are both location-specific, at individual drill pads, and general, across wider, cumulative footprints of operations at multiple sites.

3.1.1 Surface sources of contamination

Contamination from surface sources can result from:

- accidental or deliberate spills and leaks due to poor handling, storage and/or containment of fuel, chemicals and waste fluids; and
- discharges of chemicals and (insufficiently treated) waste fluids to streams, lakes and the ground (the last resulting in contamination of groundwater).

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 (*Final Report 4*; CDMS, 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 (CDMS, 2016).

3.1.2 Underground sources of contamination

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

- mobilisation of naturally occurring gas constituents;
- 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
- 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 (*Final Report 4*; CDMS, 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.

In both case study areas, it is considered unlikely that liquids and fluids associated with hydraulic fracturing would migrate upwards to shallow receptors, but it cannot be discounted. Such migration would require a sufficiently large and sustained driving force to "push" the contaminants to heights where they come above 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 County Cavan, and past geothermal studies refer to steep geothermal gradients in western County 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.

3.2 Potential Pathways

Pathways between potential sources of contamination and receptors can be natural or man-made.

3.2.1 Natural pathways

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

Subsoils

Subsoils offer natural protection of groundwater resources from surface sources of contamination. Subsoil characteristics determine the infiltration capacity of a given site and influence the attenuation potential of contaminant concentrations that migrate vertically through the subsoil profile.

Maps of subsoil types and groundwater vulnerability are available for both Ireland and Northern Ireland. Groundwater vulnerability maps, prepared and published by the GSI and GSNI, incorporate information on subsoil thickness and permeability. These maps are prepared at the catchment or subregional 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.

Bedrock aquifers

The principal groundwater resources in both case study areas are associated with bedrock aquifers. In such aquifers, groundwater flows via fractures and fissures. In the case of karstified limestones, groundwater also flows preferentially via open solution conduits.

All rock formations are classified by the GSI and GSNI as aquifers, and some aquifers are considered to be more "productive" than others, implying a greater resource value. There is no specified depth limit to the classification, but this does not imply that all bedrock formations are aquifers at great depth, since fracturing may be absent and water quality may be such that it is not potable and not economically or technologically feasible to treat.

In fractured bedrock aquifers, the migration of contaminants requires a network of interconnected, open fractures. In both case study areas, the available information about open fracture networks is sparse. Conceptually, fracturing decreases with depth. However, both study areas are structurally folded and faulted, and such deformation can enhance fracture permeability, especially in brittle sandstone and limestone formations. Supply wells are often sited at or near mapped faults, to try to increase the probability of achieving higher well yields. However, it should be acknowledged that faults which cross lower permeability formations, such as shales, can also act to impede movement of water because of the smearing of clay minerals along fault planes, effectively resulting in the sealing of fractures, as documented by Daly *et al.* (1980) in the Castlecomer Plateau.

The sparsity of deep hydrogeological data in both case study areas is a significant data gap and constrains the ability to draw definitive conclusions about the effectiveness of bedrock formations as “barriers” to vertical contaminant migration. In layered geological systems with vertical hydraulic gradients, the lower permeability formations will control the potential vertical transport of contaminants and associated migration rates. In the NCB, the principal lower permeability formation which separates the deep unconventional gas target from the main shallow receptor is the Benbulben Shale Formation. In the CB, there is no obvious equivalent formation, and, although several shale and mudstone units are present above the Clare Shale Formation, their geometric distribution and hydrogeological function are poorly understood and quantified.

Accordingly, characterisation and mapping of deep bedrock characteristics and open fracture systems should be a future requirement with regard to environmental risk assessment of location-specific UGEE operations.

3.2.2 Man-made pathways

Man-made pathways can be created by and during the UGEE activity. Such pathways are mainly related to poor well construction practices, specifically inadequate cementation of well casings and/or improper abandonment of test wells. Proper well construction and abandonment practices are highlighted as a first line of defence, with the recognition that regulatory inspection and verification of cementing operations and checks on well integrity are necessary, both during and following UGEE activity. A useful conceptual model of pathways associated with UGEE that is frequently cited in international literature is reproduced in Figure 3.1. It depicts possible pathways from depth and highlights how contaminants, notably gas, can migrate upwards to shallow aquifers via (1) annular spaces outside well casings and (2) open fractures across bedrock formations. A third pathway would be present if an exploration borehole were improperly sealed or abandoned. It should be noted that the sketch is conceptual; it is not to scale and does not imply that any or all of the pathways would be present at any given site.

Several abandoned wells from past gas exploration activity exist within the two case study areas. According to available well completion reports, well abandonment entailed “plugging” each well with cement at select depth intervals. Thus, the past gas exploration wells are not completely filled in, and the wells would offer “opportunity” for gas migration from deeper formations if, for example, the cementing operations were not properly executed or if the cement quality had degraded since the date of abandonment. Potential escape of natural gas prior to, during and following any future nearby UGEE activity could be tested by conducting gas monitoring at respective wellheads.

Questions about well integrity, as a potential pathway for natural gas, also apply to the quality of the cement that is injected or otherwise emplaced in the annular space between the drilled borehole walls and the outside of well casings. The quality of the steel casing itself is also an important pathway factor, e.g. if the steel has corroded or is deformed to the point where holes or cracks are present.

In terms of potential future UGEE activity, details of appropriate mitigation measures to address well construction practices are most appropriately addressed as part of any future licence application and review process, on a case-by-case basis, once details of proposed UGEE activity are presented. This process should involve suitably qualified individuals on the part of both the planning and regulatory authorities.

3.3 Potential Water-based Receptors of Contamination

Potential water-based receptors of UGEE-related contamination in both case study areas are (1) the available water resources represented by lakes, streams and aquifers; (2) associated water supplies (abstractions); (3) registered protected areas; and (4) groundwater-dependent terrestrial ecosystems (GWDTEs). Potential receptors of airborne pollution are addressed in *Final Report 3: Baseline Characterisation of Air Quality* of the UGEE JRP.

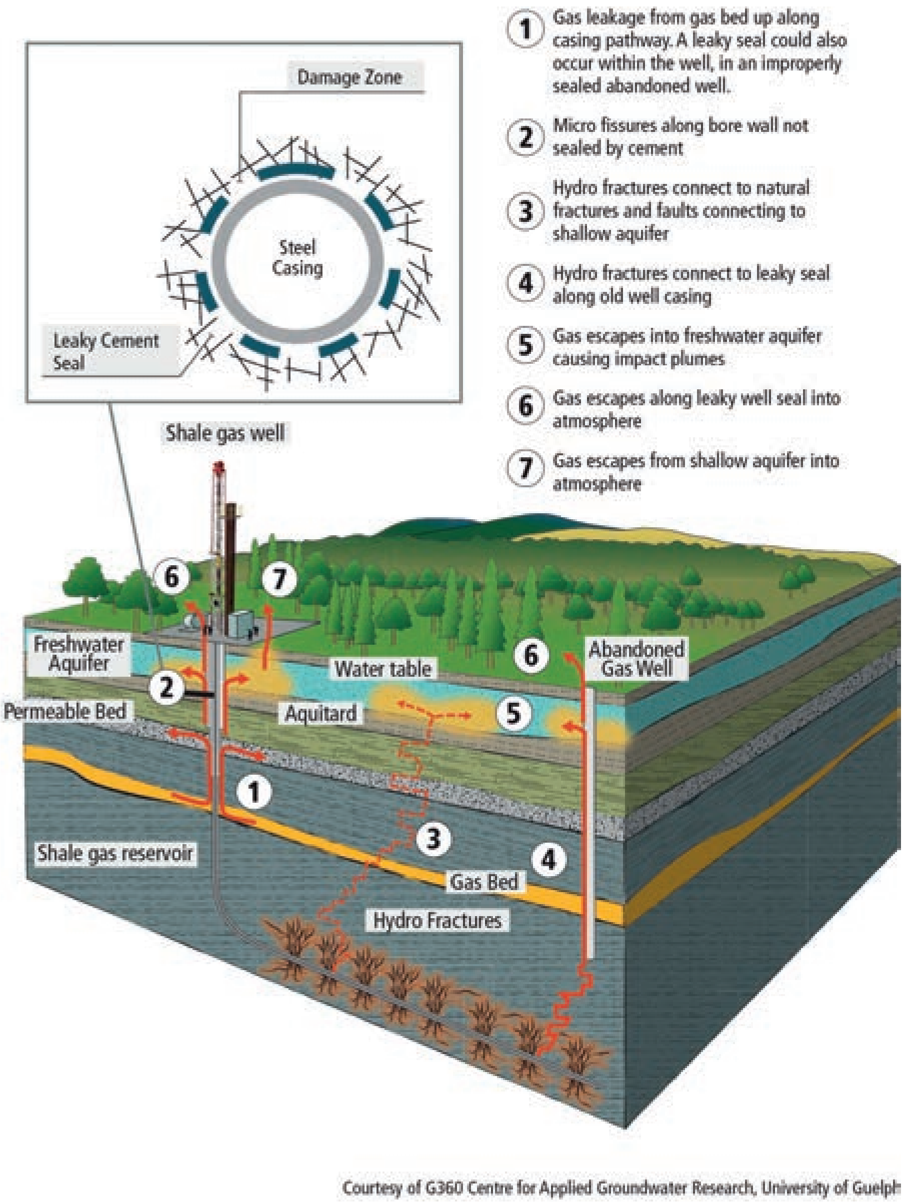

Figure 3.1. Potential underground pathways associated with UGEE activity.

All lakes, streams and aquifers in the two case study areas are potential receptors of UGEE-related contamination. Many of these are pumped for water supply purposes. Aquifers also provide important groundwater baseflow to surface water bodies. In the NCB, regionally important limestone aquifers are also associated with important aquatic ecosystems, providing supporting conditions for GWDTEs.

In terms of being a resource receptor, there is no fixed depth which can be assigned to define when groundwater ceases to be a usable water resource. This is relevant because hydraulic fracturing operations can affect groundwater quality. The UK Technical Advisory Group (UKTAG) on the Water Framework Directive (WFD) defined 400 m below ground level as a depth below which it may become increasingly difficult to obtain (1) adequate quantities of groundwater for supply purposes and (2) water of a quality that can be used for potable supply purposes. The 400-m depth limit was defined in the context of delineating WFD groundwater bodies for reporting purposes to the European Commission (EC). It should not be interpreted or regarded as a fixed limit for usable groundwater resources in either of the UGEE case study areas.

In the CB study area, “fresh water” strikes at approximately 600 m depth were noted in the Doonbeg gas exploration well. In the NCB study area, saline formation waters of variable concentrations (depending on depth and location) were recorded in tested sandstone formations at depth. This indicates that groundwater quality may deteriorate with depth and that, beyond a certain depth, the resource value of groundwater, e.g. as a usable source of water supply, is lost. Depths, configurations and circumstances of such water-quality deterioration remain unmapped (generally) and are poorly understood.

3.3.1 Abstractions (water supplies)

Public and private regulated abstractions from groundwater which have been verified as part of the UGEE JRP are shown in Figure 3.2 (wells) and Figure 3.3 (springs) for the NCB study area. In the CB study area, there are no groundwater-based PWSs or GWSs within the UGEE licence boundary. However, two GWSs are located near and to the east of the boundary, as shown in Figure 3.4. In both study areas, groundwater is an important source of water for single homes, farms and industry/commerce. A ground-truthing survey of such wells was carried out as part of the UGEE JRP, and, although dozens of such wells were visited (examples are shown as green dots in Figures 3.2 and 3.4), it was not possible within the timeframe of the survey to identify or visit all private wells. Verified river and lake abstractions used for public and (known) private supplies are presented in Figures 3.5 and 3.6.

3.3.2 Registered protected areas

A Register of Protected Areas for water-dependent habitats and species is maintained by the EPA (2015) in Ireland and by the NIEA (2014) in Northern Ireland. These are compiled in accordance with Article 6 of the WFD. The Register comprises the following:

- EU-designated (Natura 2000) sites, notably Special Areas of Conservation (SACs) and Special Protected Areas (SPAs); and
- national-level designated sites, notably proposed Natural Heritage Areas (pNHAs) and Natural Heritage Areas (NHAs) in Ireland, and Areas of Special Scientific Interest (ASSIs) in Northern Ireland.

SACs are protected sites under the EC Habitats Directive. They cover approximately 326 km^2, equivalent to 12%, of the UGEE licence areas, and include raised bogs, blanket bogs, turloughs, sand dunes, machairs, heaths, lakes, rivers, woodlands, estuaries and sea inlets. In Ireland, 25 species are afforded protection under the EC Habitats Directive, including salmon, otter and the freshwater pearl mussel. Some SACs are groundwater-dependent, and many are formally designated as GWDTEs.

SPAs are protected sites under the EC Birds Directive. This directive covers the protection of rare and vulnerable species of wild birds and regularly occurring migratory species. SPAs cover approximately 19.2 km^2, equivalent to less than 1%, of the UGEE licence areas.

NHAs are areas in Ireland which are considered important for the habitats that are present or house species of plants and animals whose habitat needs protection. All NHAs in the two case study areas are bogs. There are additional proposed pNHAs, which were published on a non-statutory basis in 1995 and have limited legal protection under Local Authority Development Plans. Several pNHAs have overlapping designations as SACs and/or SPAs.

ASSIs are designated in Northern Ireland under the Environment Order (Northern Ireland) 2002, because of specific flora, fauna and/or geological features. Several ASSIs have overlapping designations as SACs and/or SPAs.

In Northern Ireland, there are additional areas designated as WFD protected areas for habitats and species. However, the boundaries around particular habitats have not been delineated. The differences in designation between Ireland and Northern Ireland have meant that some cross-border Natura 2000 sites are not completely designated as WFD protected areas, such as the Lough Melvin SAC.

Areas designated to protect economically significant species were established under earlier European directives which aimed to protect shellfish (79/923/EEC) and freshwater fish (78/659/EEC), notably in salmonid waters.

3.3.3 Groundwater-dependent terrestrial ecosystems

Some SACs are also designated as GWDTEs. These are wetlands where the associated ecology depends on groundwater for supporting conditions, including groundwater level, flow or discharge, and/or chemistry (e.g. nutrient fluxes, alkalinity).

Figure 3.2. Groundwater abstractions from wells, NCB study area.

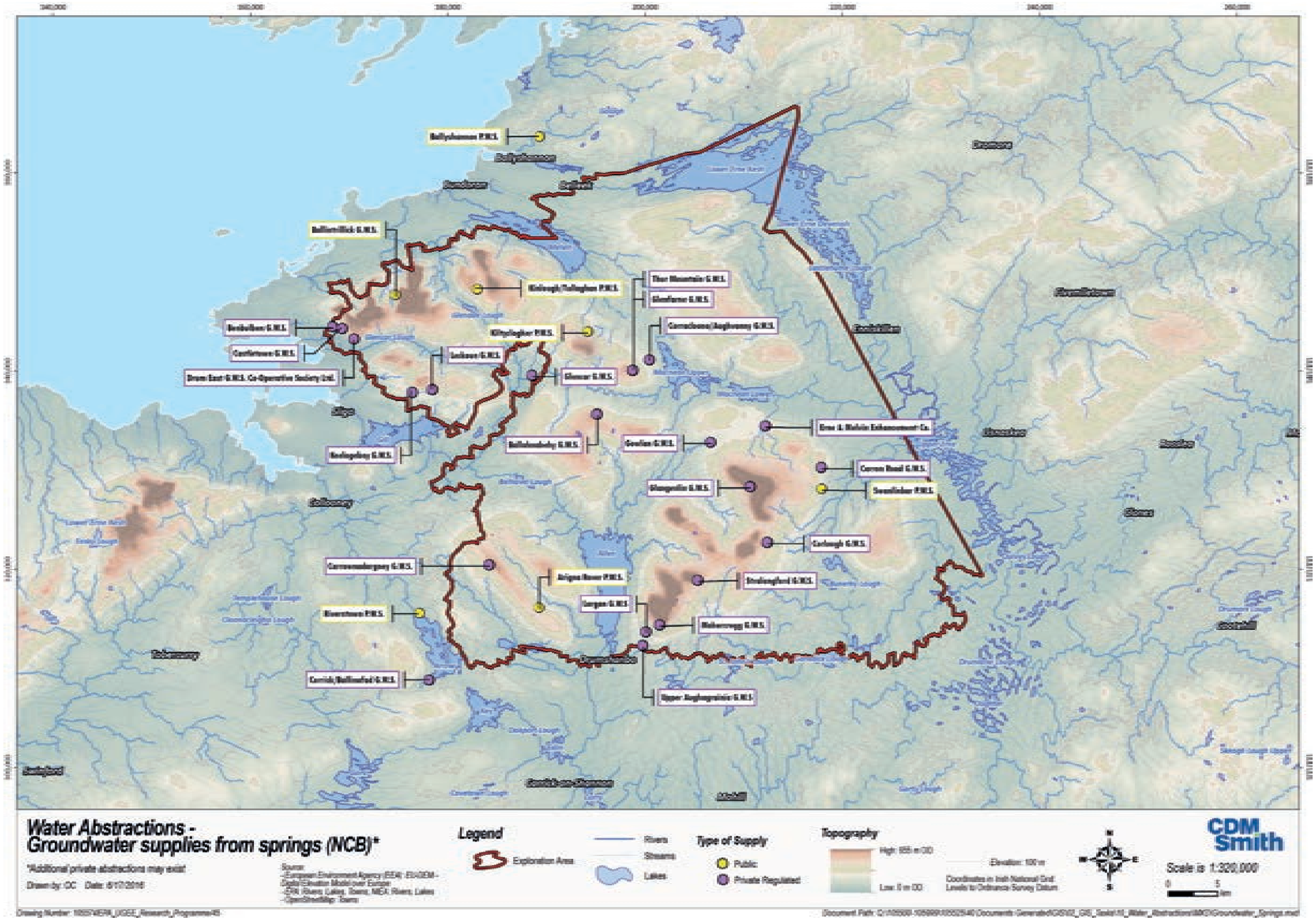

Figure 3.3. Groundwater abstractions from springs, NCB study area.

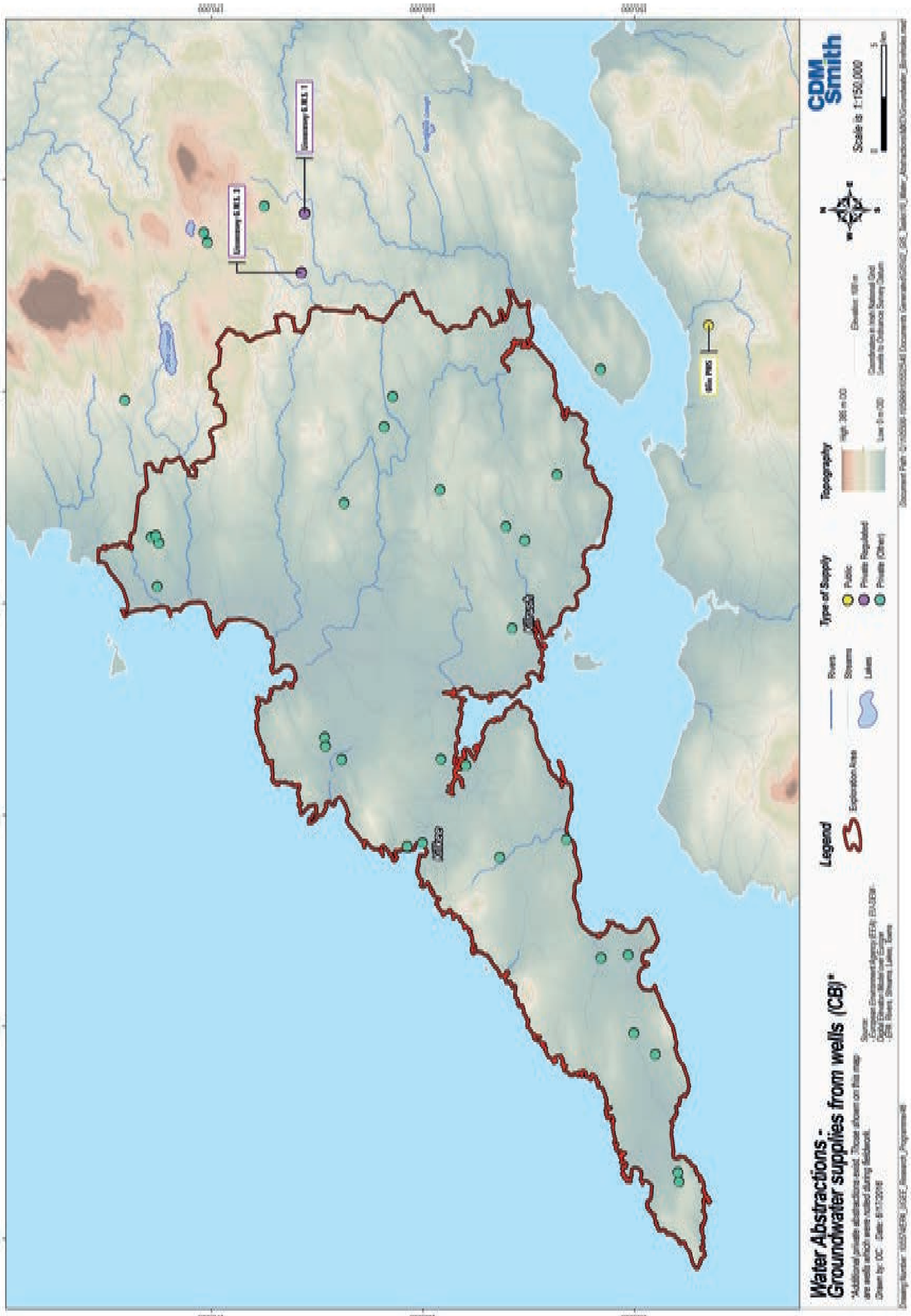

Figure 3.4. Groundwater abstractions from wells, CB study area.

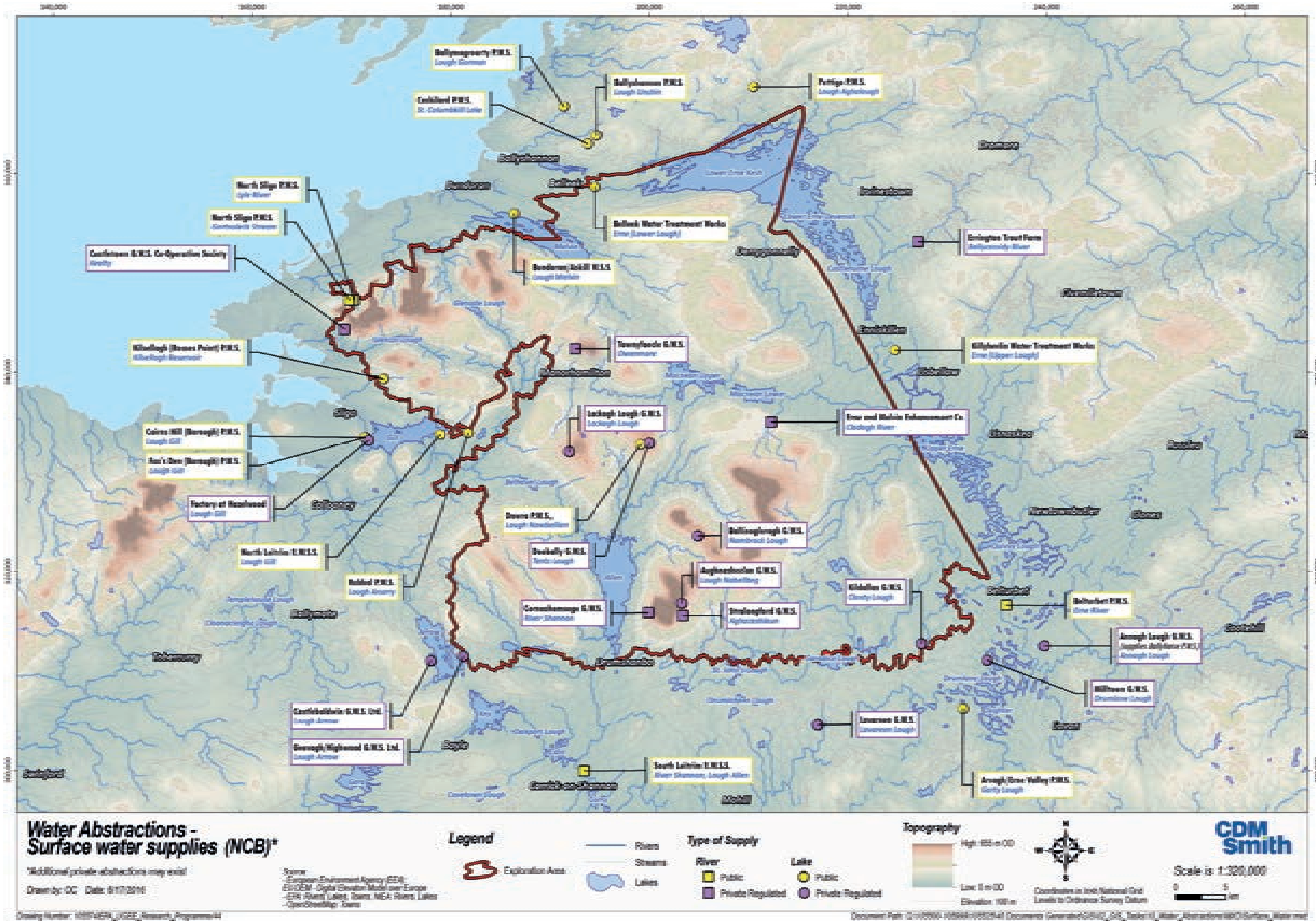

Figure 3.5. Surface water abstractions, NCB study area.

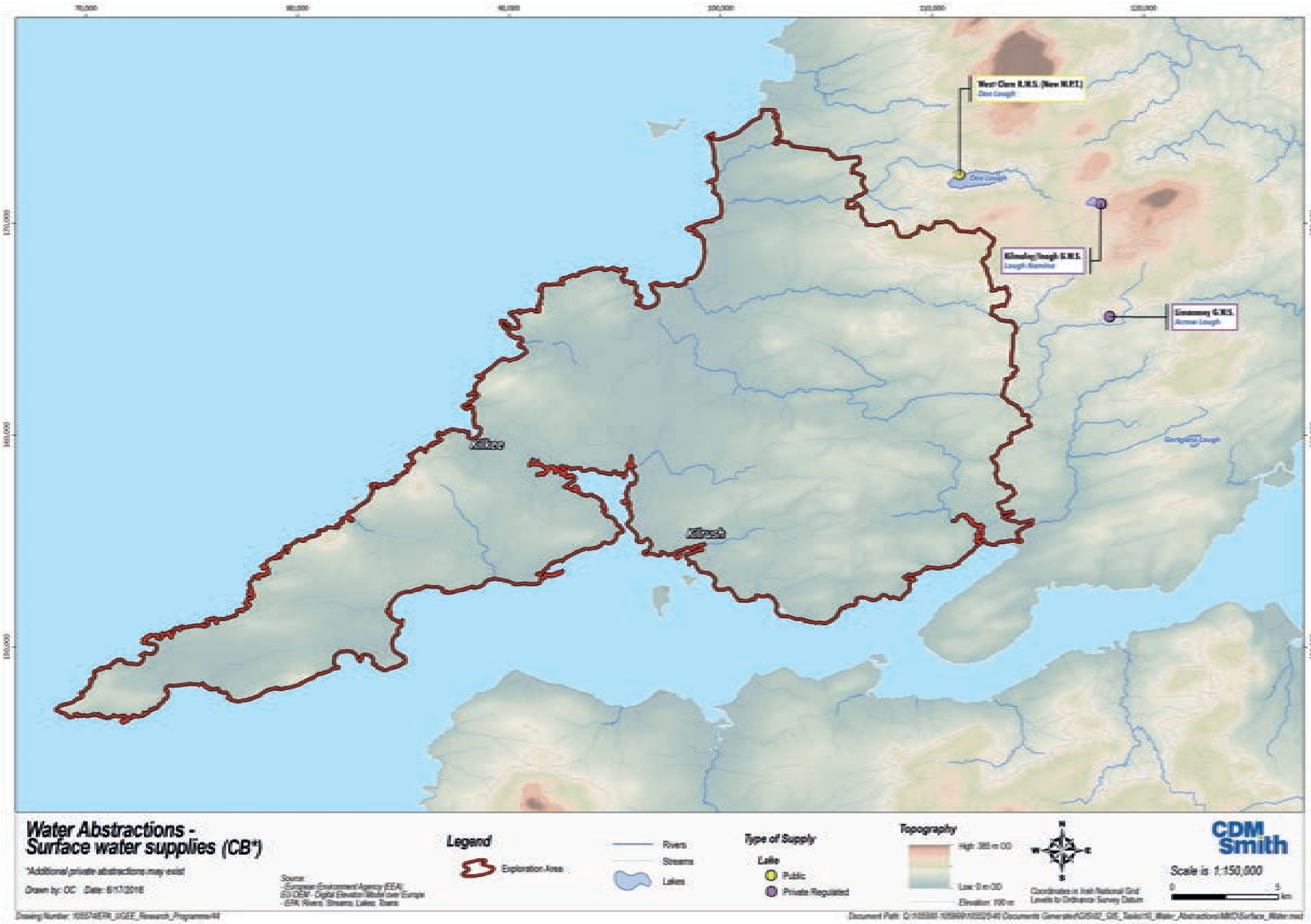

Figure 3.6. Surface water abstractions, CB study area.

In Ireland, GWDTEs contain habitats that are listed under the EU Habitats Directive. GWDTEs can be protected as SACs. Only GWDTEs that were considered to be at risk of failing WFD environmental objectives were originally included on the Register of SACs in Ireland, and none are located within the two UGEE licence areas. In Northern Ireland, six GWDTEs in the NCB study area were identified by the NIEA, including active blanket and raised bogs, petrifying springs, alluvial forests, alkaline fens and turloughs. Two have been prioritised by the GSNI based on further assessment:

- West Fermanagh Scarplands SAC, which has several petrifying springs; and
- Rooskey and Fardrum Turloughs SAC, which is considered to be "at risk" of failing WFD environmental objectives on the basis of elevated nitrate concentrations in related groundwater bodies.

Additional, but undesignated, GWDTEs are present in both the NCB and CB study areas. A research project of GWDTEs in Ireland, undertaken by Kimberley and Coxon (2013), identified 11 different habitat types which can be considered "most groundwater-dependent". These were checked against the qualifying interests of designated SACs and SPAs, and 9 of 17 SACs that were not designated as GWDTEs on the WFD Register of Protected Areas were flagged as having Annex I habitat-type attributes (i.e. qualifying interests). In 2013, the NPWS (NPWS, 2013a,b) and the Joint Nature Conservation Committee (JNCC, 2013) published reports on the conservation status of all habitats and species listed in the annexes of the Habitats Directive as required under Article 17 of the Directive. Accordingly, the availability of information on GWDTEs has been advanced in recent years.

3.4 Potential Quantitative Risks of Impact

UGEE projects require water for several purposes, including drilling, well construction, hydraulic fracturing and routine site operations (e.g. sanitation, equipment washing). The amount of water that is needed is case-specific, as a function of the plans and targets set by the exploration companies, the depths and lengths of drilling involved and the properties of geological formations encountered.

Firm plans and details of potential future UGEE projects in Ireland and Northern Ireland are as yet not known. Accordingly, the actual volumes of water that would be needed are also not known. For guidance purposes, ranges of potential water use requirements for UGEE operations were researched from published international literature. The highest water use requirements are associated with the hydraulic fracturing programme, over relatively short periods of time, normally measured in days. Cited water demands for hydraulic fracturing in Europe generally range between 5000 and 15,000 m^3 per well, although higher and lower values can apply depending on case-specific circumstances, which are determined by how a hydraulic fracturing programme is implemented. For example, if the programme at a single well required 15,000 m^3 of water over a 3-day period, the maximum daily water demand would be 5000 m^3/day for the single well, assuming the same quantity was used each day. If the duration were shorter, or greater volumes of water were needed, the daily demand would increase. More significantly, if identical programmes were carried out at multiple wells concurrently, the total daily demand would become significantly greater.

The required water would likely be sourced from available water resources within or close to the licence areas. It is expected that UGEE developers would try to source water as close as possible to individual well pads. Precisely how and where the water is sourced would likely be determined by practical considerations of supply, as the source defines costs – specifically the costs of planning, licensing, constructing and maintaining abstractions versus the costs of purchasing and transporting water from existing water supply schemes in the region.

There is capacity to supply UGEE water use requirements in both study areas, but this would be conditioned and influenced, both spatially and temporally, by the *how* and *where* questions of development. Local supply options are considerably wider in the NCB study area than in the CB study area.

A quantitative assessment of available water resources in the two case study areas indicates that smaller streams and lakes would be vulnerable to potential UGEE-related abstractions. Larger streams and lakes would be less vulnerable, but further distinction cannot be made without lake- and stream-specific knowledge about environmental reference conditions and sensitivities of associated ecosystems, as well as water balance studies that define relevant flow and level metrics and, in the case of lakes, throughflow (turnover rates). In all cases, vulnerability to abstraction must be reviewed and pre-authorised with inputs from both stakeholders and regulatory bodies, on a case-by-case basis.

To illustrate potential vulnerability to abstractions, the estimated daily maximum water demand of 5000 m^3 for a single hydraulic fracturing well was compared with the estimated 95-percentile (Q_{95}) flow of streams. The Q_{95} flow is the streamflow that is exceeded 95% of the time, and is often used to describe environmental low-flow conditions in a given catchment. As depicted in Figures 3.7 and 3.8, numerous streams would be unable to support an abstraction of 5000 m^3/day for a single-well operation during estimated natural-flow conditions in both case study areas.

Groundwater is a viable source of water in the NCB, but the ability to develop a sufficient supply to meet demands would likely require extensive exploration and testing.

Capacity to supply 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 (CDMS, 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.

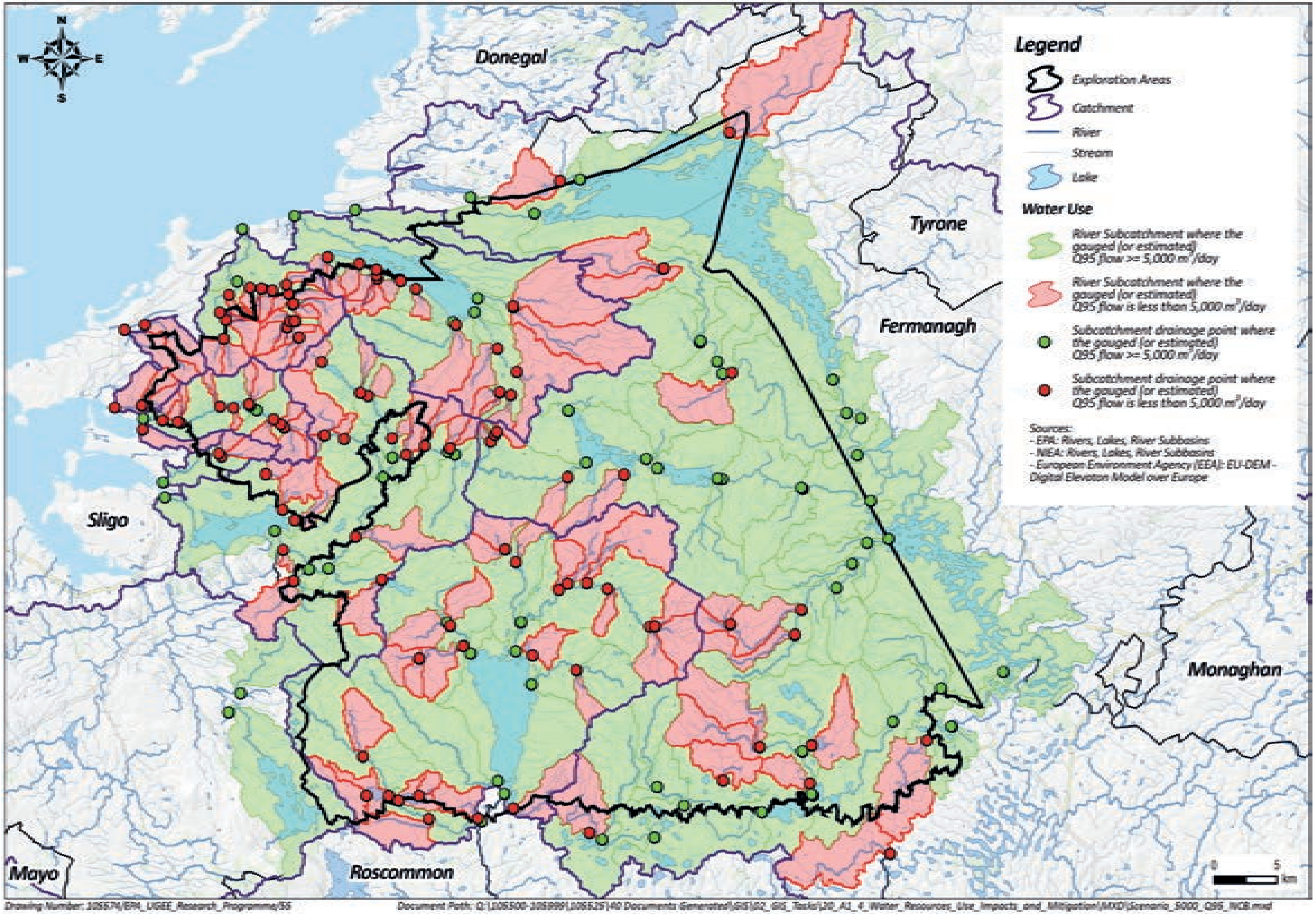

Figure 3.7. Comparison of daily water demand of 5000 m³/day and estimated Q_{95} flows, NCB study area.

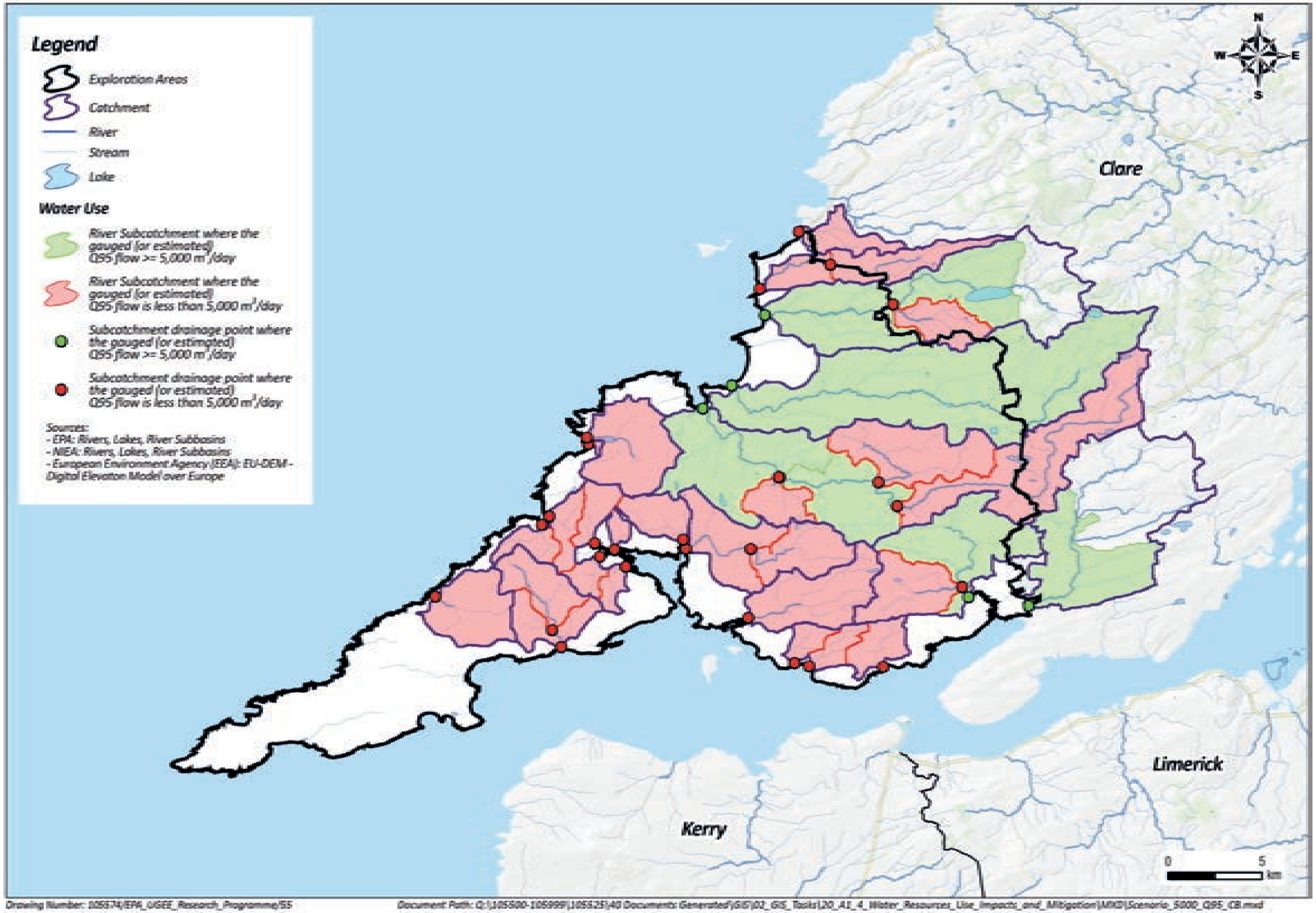

Figure 3.8. Comparison of daily water demand of 5000 m³/day and estimated Q_{95} flows, CB study area.

4 Existing Environmental Pressures

Both the EPA and the NIEA are carrying out comprehensive environmental monitoring of aquatic environments in Ireland and Northern Ireland, respectively, under initiatives linked to the implementation of the WFD and national statutory instruments that have followed.

4.1 Water Quality

Water-quality impacts on surface water bodies in the case study areas are mostly attributed to nutrient enrichment from runoff and/or discharges from agriculture and wastewater treatment systems. Along with physical modifications (e.g. dredging, channelling and river bank modifications), these sources are estimated to have contributed to the fact that approximately 50% of surface water bodies have failed to meet WFD “good status” objectives, partly because of their impact on the quality of macroinvertebrate colonies in streams and/or elevated phosphorus concentrations in streams, lakes and groundwater.

The majority of the monitored surface water bodies do not indicate problems with regard to specific pollutants. Organic (hydrocarbon) compounds and pesticides are detected episodically, but not consistently. Only the Arigna river in the NCB was classified by the EPA as being 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 from mine adit discharges shows periodically elevated concentrations of nickel and sulfate (EPA/DCENR, 2009), which may be related to sulfide leaching.

Only three groundwater bodies in the case study areas have been classified as having 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 exceedances of the environmental quality standard 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 proportional to, environmental risk.

4.2 Water Quantity

Abstractions are generally not considered to be a significant existing environmental pressure in the two case study areas. Although several lakes and streams are classified as being at “less than good” ecological status, none failed the status classification tests by EPA and NIEA because of abstraction pressures alone. Although abstractions may influence the ecological conditions in individual water bodies, they are not considered to be a single, direct cause of failed WFD status objectives, as reported in the first cycle of river basin management plans (2009–2014).

5 Baseline Monitoring Best Practice

5.1 Purpose

Baseline monitoring would be carried out to document existing environmental conditions prior to UGEE activity, so that potential changes in conditions (i.e. impact) over time could be identified and tracked. Existing monitoring initiatives by the EPA and NIEA and other public bodies in the study areas (e.g. WFD and drinking water-quality monitoring) are not specifically designed to address UGEE-related operations, but are nonetheless relevant and useful to document impacts from existing environmental pressures. Baseline monitoring programmes designed in a UGEE context would include many additional parameters that would be used to distinguish between impacts from UGEE projects and impacts from existing environmental pressures.

5.2 Requirement

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)]. In January 2014, the European Commission also issued a Communication (EC, 2014a), with guidance on the exploration and production of unconventional gas, and a Recommendation (EC, 2014b), containing non-binding "minimum principles" that UGEE projects should comply with. The latter is directed at implementation. A stated objective of the Recommendation is "to ensure that environmental impacts and risks arising from the techniques used for exploration and exploitation activities, both as regards individual projects and cumulative developments, are adequately identified and managed."

5.3 International Best Practice

A review of UGEE-related baseline monitoring practices internationally yields much information about the importance and need for baseline monitoring, but relatively little on the specifics of baseline monitoring (i.e. the *where, why, how* and *how often*). This is likely because of the case- and location-specific nature of UGEE-related monitoring. Nonetheless, common approaches can be discerned from published research and lessons learnt. Consensus views that emerge are:

1. Baseline monitoring is both desirable and necessary to identify and respond to impact, as well as to address questions of accountability.
2. Baseline monitoring data should be made publicly available, as a responsibility and as a step towards building trust and transparency in process and operations.
3. Baseline monitoring is a shared responsibility between those who are licensed to carry out UGEE projects and those who regulate UGEE projects.
4. Quantitative aspects of baseline monitoring, addressing water resources' availability, are as important to consider as qualitative aspects of monitoring and addressing water quality. Water flow, level and discharge characteristics directly influence the health of aquatic habitats and ecosystems.

Baseline monitoring is frequently cited as a precondition for licensing of UGEE activity. A recent comprehensive panel review of the unconventional gas industry in Canada (CCA, 2014) concluded that "in most instances, shale gas extraction has proceeded without sufficient environmental baseline data being collected." Importantly, the panel review concluded that data on environmental impact are as yet "not conclusive" and that some of the "possible environmental and health effects of shale gas development may take decades to become apparent. These include the creation of subsurface pathways between the shale horizons being fractured and fresh groundwater, gas seepage along abandoned wells, and cumulative effects on the land and communities. Similarly, monitoring strategies, data, and information on the effectiveness of mitigation measures take time to develop, acquire, and assess."

The CCA panel review also notes that a paucity of pre-development baseline data makes impact identification both challenging and subject to dispute. Claims of impact on the environment and human health from the unconventional gas industry are well documented in the media, and such claims tend to be accompanied by counter-claims from the oil and gas industry. Questions that tend to dominate the discourse on impact are (1) are “sufficient” data available and (2) how “good”, “adequate” or “conclusive” are the data?

5.4 Principal Contaminants of Concern

Contaminants of concern are many. At individual drill sites or well pads, drilling and well construction operations mostly employ methods which use non-toxic chemical additives. In contrast, hydraulic fracturing typically involves the use of chemicals which incorporate biocides, corrosion inhibitors, weighting agents and pH buffers. Some additives are non-toxic but others involve acids and organic compounds which are reactive and can be toxic.

The unconventional gas industry has long been criticised for its lack of transparency about the chemicals it uses as additives, often claiming they are “trade secrets”. Regulations in most countries now require full or “substantial” disclosure for authorisation prior to use.

Chemicals are also present in flowback and production waters, which require management that involves treatment and discharge or other means of disposal. Flowback and production waters can contain naturally occurring gases, chemical compounds (e.g. of the initial fracturing fluid), breakdown products and substances that may become mobilised from the geological formations by the fracturing process. Key signature constituents include strontium, barium, bromine, salts, hydrocarbons and NORM.

It should be noted that the additives that would be used for any future UGEE activity in the case study areas are not yet known. The chemicals and their relative proportions would be influenced by the natural waters that are present in the unconventional gas target formations and the case-specific nature and objectives of the hydraulic fracturing operations.

5.5 Baseline Monitoring of Groundwater Quality

The list of chemical parameters that are relevant to baseline monitoring of groundwater quality is comprehensive, and covers:

- dissolved gas constituents (e.g. methane, ethane, propane);
- stable isotopes of natural gas constituents, including methane;
- dissolved organic and inorganic carbon;
- general physico-chemical parameters (e.g. pH, redox, temperature, specific conductance);
- major ions;
- salts;
- metals;
- nutrients;
- organic hydrocarbons;
- hydraulic fracturing chemicals and possible reaction/degradation products (depending on which chemicals are used in the hydraulic fracturing process);
- trace elements; and
- NORM, including radon.

As a result, the logistical and financial burden of baseline monitoring can be significant. For practical and cost reasons, there is a need to consider “common” or “indicator” compounds that signal the presence of UGEE-related contaminants. This is accomplished by “chemical fingerprinting”.

Methane is the primary constituent of natural gas and the primary contaminant of concern. It is, accordingly, an indicator of potential impact from hydraulic fracturing and a focus of baseline monitoring programmes. However, methane has to be considered in its appropriate context, as methane can be of thermogenic or biogenic origin. The distinction is significant because biogenic methane is unrelated to the processes that form fossil fuels; it is formed at low temperatures by anaerobic bacterial decomposition of sedimentary organic matter. It is most often associated with natural shallow anaerobic environments such as peat bogs, wetlands and river/lake sediments, but can also be generated from anthropogenic pollution sources such as landfills, farm wastes and septic tanks. In contrast, thermogenic methane is most often associated with oil and natural gas fields, as well as coal deposits, and is formed during thermal decomposition of organic matter at depth under high pressures.

Thus, the presence of methane gas in groundwater can be misinterpreted if it is not assessed in its proper context of origin. For this reason, the attribution of methane origin should be established through chemical fingerprinting, which is a complex science involving specialised sampling techniques, laboratory capability, analysis (stable isotopes and noble gases) and personnel to interpret the data.

5.6 Baseline Monitoring of Surface Water Quality

Baseline monitoring for surface water quality has received comparatively little attention in international literature, yet the potential for UGEE-related impact across catchments is significant, from both onsite and offsite activity, individually and cumulatively.

Impacts on water quality can result from both controlled (licensed) and uncontrolled (deliberate/accidental) discharges, spills and leaks of chemicals, fuels and waste fluids. Impacts on surface water quality can also be of a physical nature. Land disturbances from drilling and well pad operations, as well as transportation and construction activity, can result in the release and increased transport of sediments in streams and lakes.

Monitoring approaches for surface waters are, arguably, less complicated than for groundwater. Nonetheless, monitoring needs to be comprehensive in scope given the wide range of potential contaminants that are associated with UGEE operations. In addition, monitoring and interpreting dissolved gases in surface water are made more complicated by the potential for degassing in the surface (atmospheric) environment, and because the dissolved gases in surface water may originate in groundwater baseflow. This makes pathway identification and quantification of groundwater contributions to stream flows an essential element of technical assessment.

5.7 Baseline Monitoring of Stream Sediments

Waste fluids associated with UGEE, such as drilling fluids and flowback water, even though they are typically de-sanded and de-silted, can be difficult to contain. Waste fluids may also contain metals (e.g. barium and strontium) and retain trace chemicals as well as NORM which can adsorb to stream sediments in proximity to surface water discharge locations. Disposal of NORM-rich waste fluids to freshwater streams or lakes/ponds is highlighted as a source of contamination in published research in the USA. Accordingly, the accumulation of NORM, notably radium, in sediments in freshwater environments should be considered during baseline and any subsequent operational monitoring.

5.8 Baseline Monitoring of Water Quantity

Quantitative aspects of UGEE projects are as important to consider as qualitative aspects. Accordingly, hydrometric monitoring is necessary to quantify and assess the available water resources. As described in section 3.4, UGEE operations require water for several purposes, and total daily demands can be significant, especially if multiple hydraulic fracturing programmes are active in parallel.

Depending on how and where UGEE development would take place, water demands would likely have to be supplied from multiple sources of water in parallel. 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.

Quantitative assessment of water resource availability and potential impact requires hydrometric data. Relevant hydrometric monitoring is currently taking place within both case study areas by several public bodies including, in Ireland, Met Éireann, EPA, GSI, Office of Public Works (OPW) and local authorities and, in Northern Ireland, Met Service NIEA, Rivers Agency and GSNI.

To reduce demands and potential environmental impacts, opportunities should be sought to mitigate potential abstraction impacts by:

- reducing demand for abstraction, e.g. by treating and recycling flowback water;
- spreading abstractions to multiple different sources of water;
- directing abstractions towards lower sections of catchments (higher order streams) or larger lakes;
- avoiding abstractions from ecologically sensitive catchments; and
- timing operations to avoid overlap between maximum demand periods and low-flow or low-level conditions in streams and lakes, respectively.

Any UGEE-related abstraction would be subject to existing control measures (systems of “prior authorisation”) in both Ireland and Northern Ireland. It should be noted that, in the NCB, several surface and groundwater bodies are shared between Ireland and Northern Ireland. In such cases, Article 3 of the WFD

(Coordination of administrative arrangements within river basin districts) requires Member States to co-ordinate water resource management. Accordingly, the study and prior authorisation of future abstractions of shared water resources and associated ecosystems in the NCB would require co-ordination amongst the relevant regulatory bodies in Ireland and Northern Ireland.

6 Design of Subregional Baseline Monitoring Programmes

A consensus view that emerges from international literature is that a precautionary approach to subregional baseline monitoring should be adopted. This approach dictates that monitoring should be comprehensive in scope and extent, and should allow cumulative impacts to be identified across a wider area (i.e. a broader potential UGEE footprint). Firm plans for UGEE development 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 a subregional 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.

In designing the recommended subregional baseline monitoring programmes, the approach that has been followed:

1. co-ordinates 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 and chemical fingerprinting purposes.

Subregional baseline monitoring programmes that would be capable of documenting existing environmental pressures and identifying potential impact from UGEE activity at the subregional scale would, by default, have to be comprehensive in scale, scope and extent. The associated burden on resources would also be significant. For this reason, an approach of "adaptive monitoring" is recommended, which allows modification of the monitoring programme as new data become available and new monitoring installations become active.

In addition, a tiered approach of sample analysis is proposed, whereby analytical screening using lower cost parameters gives information about the need for more detailed analyses of higher cost parameters. A relevant example is the approach of the BGS to deciding on which samples to analyse for stable isotopes in groundwater. If dissolved methane is absent or concentrations are below a certain threshold value, then isotopic fingerprint analysis of methane is dropped. Similarly, if field-measured dissolved oxygen concentrations are high in groundwater, then the analysis for dissolved methane may be considered redundant. Comparably, if gross alpha and gross beta radiation screening of groundwater samples does not exceed specified threshold values, then further analysis to document activity levels of NORM is unlikely to yield meaningful results.

It should be cautioned that experiences from baseline monitoring approaches in other countries are useful as guidance, but may not always be directly applicable to the island of Ireland, as baseline monitoring has to consider knowledge about specific water users, ecosystems and the hydrogeological conditions that determine environmental risk.

6.1 Groundwater

The ability to establish a representative subregional baseline monitoring network for groundwater is challenging, for several reasons:

- Several different bedrock formations are present with different lithological characteristics and potential influences on natural groundwater quality.
- Several different aquifer types and potential receptors are also present.
- Groundwater and surface water interactions are significant, especially in the karstified limestone environments of the NCB.

- Groundwater levels and chemistry in different bedrock aquifers are subject to temporal variations, in both the short term and the long term (episodic vs seasonal).
- The baseline monitoring network must incorporate suitable locations for the sampling and analysis of dissolved naturally occurring gases in groundwater, especially methane. This requires that raw water samples can be collected which have not been exposed to the atmosphere. To date, such monitoring has not been carried out in the island of Ireland. The challenges involved thus include the need to research, adopt and implement appropriate sampling methods.

The design of suitable monitoring networks in the two study areas followed these basic principles:

- Monitoring points were selected from a conceptual understanding of pathways and groundwater flow in the different aquifers, at the catchment scale.
- Candidate monitoring points were screened and field-verified to ensure that representative samples can be obtained.
- Existing WFD monitoring points were included to take advantage of the existing database and to allow continuation of sampling at sites where longer term records exist.
- All public and private regulated groundwater supplies were prioritised for sampling. Selected wells have been inspected in the field and are deemed suitable for sampling purposes, pending minor works such as the installation of raw water sampling taps.
- All public and private regulated water supplies sourced from springs and used for human consumption and/or livestock were also prioritised for sampling.
- Other private groundwater supplies, represented mostly by private wells that supply single homes, farms and commercial activities, were also included, provided they met certain standards with regard to well construction details.

Most bedrock aquifers, even poorly permeable aquifers, are used for water supply to some extent. Thus, all of the key bedrock formations in respective study areas were considered for representation in the monitoring programme. In addition, springs and/or wells in the former Connaught Coalfield near Lough Allen were included, as the chemical signature of the coalfield in groundwater was considered important to document for baseline analytical purposes.

Springs are groundwater discharges. It is recognised that some of the spring water in karstified flow systems has short residence times in the subsurface environment. The karstic spring water has nonetheless interacted with groundwater in the surrounding rocks and, as concluded by the EPA (2014), “a river or stream that sinks should be regarded as groundwater unless defensible evidence exists that diffuse dispersion (through fracture systems) is not important for a given site or setting.”

6.1.1 Private supply wells

Private supply wells were included for consideration in the monitoring networks and a ground-truthing survey of private wells was carried out in both case study areas. Emphasis was placed on well construction details and obtaining permission to sample from the well owner, provided the well was deemed suitable for sampling purposes. Wells with cement-grouted casing and/or appropriate wellhead protection measures were prioritised.

Groundwater impact studies in the USA and baseline monitoring programmes in both Canada and the UK have all made use of domestic wells. The advantage of incorporating private wells is the ability to document the groundwater quality of private water supplies prior to, during and following any UGEE operations. Private well samples would be representative of the groundwater that is accessed and used and the wells would provide improved spatial coverage in areas where public and private regulated supply wells are absent.

6.1.2 Former abstraction wells

A small number of idle, former public and private supply wells are present in the CB study area. These are presently covered over and have not been in use for many years (in some cases 20 years or more). A ground-truthing survey indicated that several such wells can be accessed and used for sampling purposes, pending minor works such as securing wellheads, measuring total depths and checking for potential blockages, airlifting to clean the wells, and lowering a camera to video-inspect the physical integrity of the wells. If deemed suitable, they could be included in a baseline sampling programme, partly because it would cost less than the drilling and installation of potential new wells.

6.1.3 New monitoring wells

The ground-truthing survey of existing abstraction wells and springs highlighted gaps in the spatial coverage of wells for sampling purposes in both case study areas. Thus, the drilling and installation of new dedicated monitoring wells would be helpful in addressing spatial gaps.

Any new wells that would be drilled would be prioritised in general areas which have been flagged as "prospects" for UGEE activity, either as presented by exploration companies in public forums or as described in the exploration files which are held by the PAD of the DCENR and the GSNI. The main prospects are considered to be near Kilcoo Cross, Arigna/Drumkeeran and Dowra, although this would be subject to verification if future plans for UGEE are presented.

New monitoring wells would be installed in a similar manner to public supply wells in order to represent and document receptor conditions, i.e. the quality of groundwater that is used or accessed for water supply purposes and/or discharges to surface water bodies via shallow groundwater pathways. Accordingly, new monitoring wells would be drilled in key bedrock formations within or near their outcrop areas to depths of approximately 150–250 m, as a guide, to provide the technical opportunity to access and explore groundwater systems that are slightly deeper than is usual in the island of Ireland context, yet allow the installation of wells for monitoring purposes that are consistent with existing abstraction wells in respective study areas. Final well installation depths would be determined by findings during drilling and likely also by consideration of budgetary constraints. The wells would be installed so that they could be pumped as supply wells in order to draw on larger volumes of groundwater to obtain samples that are representative of water-quality conditions in the aquifers they monitor.

New wells would be constructed to high standards, following best-practice guidelines and experiences (e.g. IGI, 2007). An approach similar to that adopted for the EPA "poorly productive aquifer" drilling programme (EPA, 2010) would be applicable.

Candidate sites for drilling would have to be field-verified in advance, and locations would have to be adjusted in the field as necessary, based on site access and landowner agreements. Practical matters related to the siting of new wells would affect the final costs of baseline monitoring programmes, and should, therefore, be concluded prior to any tendering for drilling services.

Subsequent to the conclusion of baseline monitoring, the wells could be used for other purposes, e.g. as supply wells or incorporated into existing WFD monitoring networks. The data that are collected during drilling, testing and monitoring of the new wells would add value to the general hydrogeological characterisation of fractured bedrock aquifers in the island of Ireland.

The new wells would not be sufficiently deep to address the critically important technical questions about hydrogeological conditions of deeper bedrock formations. Although a subregional approach to deep hydrogeological characterisation (and subsequent monitoring) would provide valuable data, the environmental risks of hydraulic fracturing are case- and location-specific. Thus, a subregional approach would not necessarily produce the answers that are needed at the case- and location-specific scale for individual UGEE sites. For this reason, it is argued that detailed hydrogeological characterisation and subsequent monitoring of deeper bedrock formations are best addressed when the locations, circumstances and plans for prospective UGEE activity become known. The onus of related works would be placed on the UGEE companies, as determined by statutory instruments and the terms and conditions set and supervised by relevant planning and regulatory bodies.

6.1.4 Abandoned gas exploration wells

Past, abandoned hydrocarbon exploration wells in the study areas represent potential man-made pathways for gas migration from deeper formations. Although these wells were partly plugged and/or sealed at the time of exploration, very little is known about the present-day physical integrity of the wells, specifically:

- the condition of wellheads at the surface;
- the steel casings that were used for well construction purposes;
- the cement plugs that were emplaced at different depths inside the wells; and
- the cement grout in the annular spaces between the steel casings and borehole walls.

Surveys of these wells would, therefore, be recommended as part of future UGEE-related monitoring to:

- Check the potential presence of natural gas (methane) at the wellheads and in soils close to wellheads.
- Verify if the wellheads can be safely and securely opened for further well integrity inspection.
- Determine if the wells could serve as potential monitoring points in a baseline monitoring programme and subsequently during any nearby UGEE operations. If the wellheads are accessible and can be opened, sounding inside the wells would verify the depth of the first blockage, which should correspond to the first cement plug that is indicated on existing well abandonment drawings prepared by the exploration companies. Different findings would indicate potentially different completion details or well integrity issues (e.g. casing collapse), from which decisions about the next inspection steps would be made.

The end goal would be a decision about potential use of these wells for monitoring purposes, based on the combined consideration of technical feasibility, cost and risk of causing damage.

6.2 Surface Water

The existing WFD monitoring networks for surface water bodies would serve as the basis for subregional baseline sampling programmes. The existing network for rivers and lakes is extensive, in particular the operational monitoring network which targets specific "poor ecological status" cases and tracks identified environmental pressures.

Like that for groundwater, the objective would be to take advantage of the longer term water-quality records that exist. There are overlaps between parameters analysed for WFD purposes and parameters recommended for UGEE project purposes, so cost savings would be achieved by integrating the sampling programmes. The list of parameters for the UGEE project would, however, be more extensive than for the WFD monitoring. The additional data would provide new insights into the baseline environmental conditions of related catchments.

Recommended analytical parameters for baseline monitoring purposes differ from groundwater monitoring, as follows:

- Dissolved gases would not be included, but would be relevant at a later time at local and subcatchment scales near planned sites, should UGEE licensing be considered in the future.
- Emphasis would be placed on physico-chemical parameters and salts, i.e. indicators of intensive land use modifications (e.g. soil movement and channelling) and accidental/deliberate releases of sludges and wastewater discharges from drill pad operations, as well as the management of flowback waters.

If UGEE proceeds in the future, it can be argued that detailed baseline monitoring of surface waters would be most relevant near drill pads and related installations. It can also be argued that surface water monitoring would only serve to flag episodic releases or discharges from individual operations. Whilst such arguments have relevance, surface water should be considered in a broader perspective for baseline monitoring purposes, notably establishing baseline conditions of UGEE-relevant parameters across catchments, thereby addressing the question of potential cumulative impact within each licence area.

It would be further recommended that continuous monitoring of certain field parameters be considered in a baseline monitoring programme. Relatively inexpensive automatic data-logger installations would be proposed, which would measure specific conductivity (as a proxy for salinity), temperature, pH and turbidity. Continuous measurements of field parameters are proposed because subregional monitoring must be able to document and describe the variability of parameters that is characteristic of, for example, karstified limestone aquifers, both seasonally and during individual, episodic rainstorm events. Such installations would be arranged for in a subset of selected rivers and lakes.

Both the EPA and NIEA implement extensive monitoring networks for biological elements under the WFD, and the results of Q-values in Ireland and the ballast water management plan biotic score system in Northern Ireland could be accessed in the future to assist in the description of existing environmental conditions and the assessment of potential impacts.

6.2.1 Water Framework Directive Register of Protected Areas

Surface water bodies which include protected areas would be prioritised for baseline monitoring purposes because of their inherent value as a resource and sensitivity as a potential receptor. Accordingly, Drinking Water Protected Areas, Salmonid Waters, Margaritifera (including freshwater pearl mussel) Sensitive Areas and other surface water bodies within designated WFD-protected areas for habitats or species would be represented in the sampling programme. In addition, it would be recommended to monitor coastal shellfish waters directly. The main streams that discharge into the shellfish waters would be included in a recommended monitoring network, as would streams that flow into coastal bathing water protected areas.

Nitrate is not a contaminant of particular concern for UGEE projects, so nitrate-sensitive areas are less relevant to UGEE-related baseline monitoring.

Finally, monitoring locations associated with specific point sources, e.g. wastewater treatment plant discharges, are not representative of catchment or subregional conditions. Accordingly, they would not be included in baseline monitoring, although discharge and environmental data produced by responsible public bodies would be collated and included in the overall assessment of potential impact.

6.3 GWDTEs

Turloughs, petrifying springs with tufa formation, and calcareous fens were retained as the most appropriate candidates for subregional baseline monitoring purposes. 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 specific conditions that apply to that site. Thus, to select appropriate sites, prior study involving site investigation and monitoring would be required, in order to identify and select suitable sites for longer term baseline monitoring purposes. Such work would require an extended period of time (over several seasons).

In the context of potential impact from UGEE, the objectives of GWDTE monitoring would be to monitor and fingerprint the chemical-isotopic signature of methane and to describe and monitor the hydrogeological supporting conditions of each site. Designing and implementing a subregional monitoring network of GWDTEs is particularly challenging, since multiple sites would be involved over an extended period of time (several seasons), and baseline monitoring could begin only once a suitable, representative monitoring network was established.

Given the wide distribution of individual sites, and their location-specific nature, it is argued that prior study and baseline monitoring of GWDTEs should be conducted at a more localised scale if details about future planned UGEE activities become known. In that way, the prior study can target the specific habitats that could be affected by individual UGEE projects. Monitoring of GWDTEs should in all cases be considered when scoping, planning and assessing future UGEE activity at specified locations. The onus of prior study and monitoring should be placed on the developer, with appropriate review and supervision by regulatory bodies.

6.4 Hydrometric Monitoring

There are four basic relevant categories of hydrometric monitoring:

- groundwater levels;
- spring discharges;
- stream flows and water levels; and
- lake and reservoir levels.

6.4.1 Groundwater levels

Groundwater levels are currently monitored in five wells within or near the NCB study area under WFD monitoring initiatives by the EPA and NIEA. Groundwater level monitoring is not carried out in the CB. Augmented groundwater level monitoring would be recommended in both study areas to document natural fluctuations and longer term responses of key formations to hydrometeorological conditions. Monitoring would be carried out using pressure transducers that can also record temperature, pH and electrical conductivity.

6.4.2 Spring discharges

There are hundreds of springs present in the two study areas, of which only a fraction are likely to be represented in available mapping. Despite their hydrogeological and ecological significance, spring discharge records are sparse. This is a significant data gap, particularly in the NCB, where large springs discharge from karstified limestone aquifers, and springs are used for water supply.

Selected springs would be recommended for discharge and water-quality monitoring. Given the very large number of springs present, it would not be possible to measure all of them. Priorities would be given to springs that are used for public and private regulated water supply. Other springs would also be included, notably certain large karst springs and other springs that contribute water to the Arigna River, which is at "bad" ecological status, possibly due to pollutant loading from abandoned mine drainage.

With regard to the timeframe of a baseline monitoring programme, it is envisaged that temporary structures involving staff gauges and slotted standpipe solutions, fitted with transducers, could serve the recommended monitoring purposes within a defined baseline monitoring period. 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. A set of transducers, recording water level, pH, temperature and electrical conductivity, would be installed on a subset of karst springs for these purposes and to allow the estimation of time-lags of water pulses moving through karstified flow systems. High-flow stages could also be recorded by simple tubes fitted with corks which float to indicate maximum levels between times of equipment maintenance or manual flow measurements.

6.4.3 Streams/rivers

There are 28 active gauging stations with automatic flow recorders that measure water levels and flows within the NCB study area, and only one such station in the CB. Many catchments do not have flow records, but estimates of key flow metrics (e.g. mean and 95 percentile flows) can be derived from estimation methods and/or tools developed for, or, by the EPA and NIEA.

Overall, stream flows and hydrological responses are considered to be reasonably well documented at the subregional scale within the two study areas, and new permanent stations would not be considered necessary for the purposes of the UGEE JRP. Existing data and published methods/tools can be used to estimate stream flows and describe expected hydrological responses in catchments. The primary data gaps inferred from the review of existing stations and data are in the Swanlinbar, Arigna and Feorish catchments (near Lough Allen and Lough Arrow) in the NCB. In these catchments, it would be recommended to conduct manual spot measurements and install temporary gauges in a similar manner to that described above for spring discharges.

6.4.4 Lakes

In the NCB study area, lake water levels are actively monitored, with automatic recorders in Lough Erne, Lough Melvin, Lough Gill, Lough Arrow, Upper and Lower Lough Macnean, and Lough Allen. Most of these are used for water supply purposes or are hydraulically regulated.

In the CB study area, Doo Lough and Lough Acrow are the only lakes of significance to the UGEE JRP. Although both are located marginally outside the UGEE licence area, Doo Lough is the main source of public water supply in western County Clare, and Lough Acrow is used to augment the supply to a GWS during high water demand periods. Doo Lough has an established long-term record of lake level data from which hydrological responses and trends can be assessed.

In the immediate context of subregional UGEE baseline monitoring, data gaps in lake level monitoring are noted in the NCB with regard to Loughs Glenade and Glencar. Both are parts of designated SACs and receive inputs from numerous streams and small springs, including petrifying springs. Both are throughflow lakes, so lake level monitoring is not considered to be a priority.

Several small lakes which are abstracted in the NCB are also not monitored. These tend to be higher-altitude lakes which supply small GWSs, in some cases only a few houses. Monitoring of such lakes is not considered important in the subregional context, but could become important in the local-scale context if future UGEE activity targets such lakes for water supply. Until the actual locations of UGEE sites and plans for water supply become known, monitoring of small upland lakes is not considered meaningful.

6.5 Stream Sediments

Chemical constituents associated with flowback and production waters can separate from the surface water and accumulate in stream sediments near points of discharge. This includes metals, radionuclides and selected high molecular weight organics. As reported by Warner *et al*. (2013) and Vengosh *et al.* (2014), radium isotopes are the principal UGEE-related contaminants of concern in sediments. Although contamination of stream sediments is primarily considered a local-scale issue in the literature, it could become a concern at the catchment scale in a scenario where multiple drill pads are active in parallel.

A database of metals and selected NORM in stream sediments was generated for the NCB as part of the Tellus Border project (Gallagher *et al.*, 2015). Radium isotopes were not included in the analyses. For this reason, further analyses of radium isotope activity levels are recommended.

In the CB, equivalent datasets to those generated by the Tellus Border project do not yet exist, but are planned for after 2017. Accordingly, and in the UGEE context, it is proposed that an overall baseline value for radioactivity should be prioritised and determined by screening for gross alpha and gross beta activity. Where relevant screening levels are exceeded, stream sediments samples would be further analysed for radium isotopes (e.g. radium-226 and radium-228).

Sampling locations would broadly correspond with surface water stations, but final locations would factor in the need to sample in low-energy flow environments, i.e. locations where sediments settle. In the NCB, the locations would, to the extent possible, also be co-ordinated with the known Tellus Border sample locations. In the CB, sampling locations would be discussed and co-ordinated in advance with the Tellus research team.

The stream sediment sampling is a one-off event for baseline characterisation purposes. It is recommended that stream sediment sampling procedures and methods be guided by the Tellus Border project for consistency purposes.

7 Summary of the Recommended Baseline Monitoring Programmes

Baseline monitoring is frequently cited as a pre-condition for licensing of unconventional gas exploration and extraction (UGEE) activity. Therefore, the Terms of Reference and scope of work for the Joint Research Project (JRP) on the environmental impacts of UGEE identified a requirement to identify, evaluate and undertake appropriate potential baseline monitoring requirements for water, air and seismicity (earthquake activity). Requirements for baseline monitoring are embodied in the (2014/70/EU) EC Recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing, but a review of international literature provides relatively little on the specifics of baseline monitoring.

Following a comprehensive assessment of the two study areas and the existing provisions for monitoring, the JRP made proposals for baseline monitoring for the assessment of water and naturally occurring seismicity, with a window of up to 2 years proposed to complete the aforementioned baseline monitoring programme. Consequently, such a baseline monitoring programme would result in the overall findings of the research being delivered after the project deadline of 2016.

The original timeline for the research envisaged that the entire programme, including water and seismicity baseline data acquisition, would conclude by 2016. The steering committee considered that, were the baseline acquisition to commence, the revised timeline for the overall research programme would now be to report in 2018 at the earliest. The decision was therefore taken to prepare an integrated synthesis report now, 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 programme proposed by the JRP remains valid and the report includes a recommendation that such a programme should be implemented in advance of the consideration of any application for a Petroleum Exploration Licence (Ireland) or an application to carry out high-volume hydraulic fracturing (Northern Ireland). It should be noted that such a baseline monitoring programme should provide independent information 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 project and site specific, and would be designed to monitor specific receptors.

The recommended subregional baseline monitoring programmes relating to groundwater, surface water and aquatic ecosystems are summarised in Figures 7.1 and 7.2 and in Table 7.1. The overall scope and extent of monitoring is considerably greater in the NCB than in the CB. This partly reflects the much larger UGEE licence area of the NCB (approximately 2200 km^2) than of the CB (approximately 496 km^2), and also the relative complexity of the NCB with regard to its hydrogeology and range of potential receptors.

The data generated would provide a consistent and comprehensive database of subregional environmental conditions in each study area. Specifically, the recommended monitoring includes:

- groundwater sampling of existing public and private supply wells, springs and potential new monitoring wells;
- surface water sampling of lakes and streams, including WFD-designated protected areas;
- stream sediment sampling;
- hydrometric measurement of spring discharges and stream flows at a limited number of locations (in the NCB only) where particular data gaps exist; and
- groundwater level measurement in selected existing wells and potential new monitoring wells that would be drilled and installed.

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

- Roosky-Fardrum Turlough;
- Loughs Augh and White (both turloughs); and
- a group of three petrifying springs with tufa formations in the West Fermanagh Scarplands SAC,

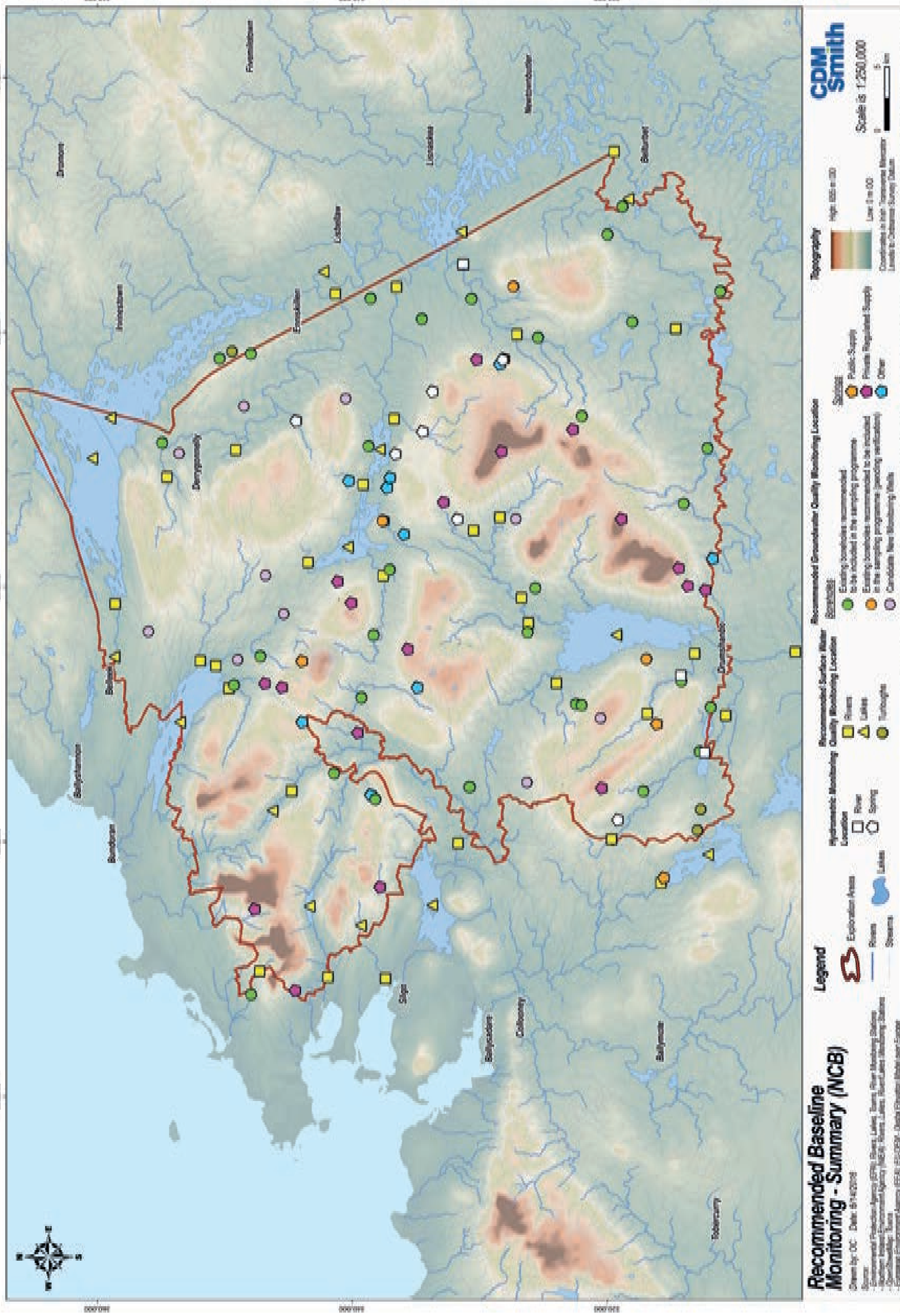

Figure 7.1. Overview of recommended monitoring stations, NCB study area.

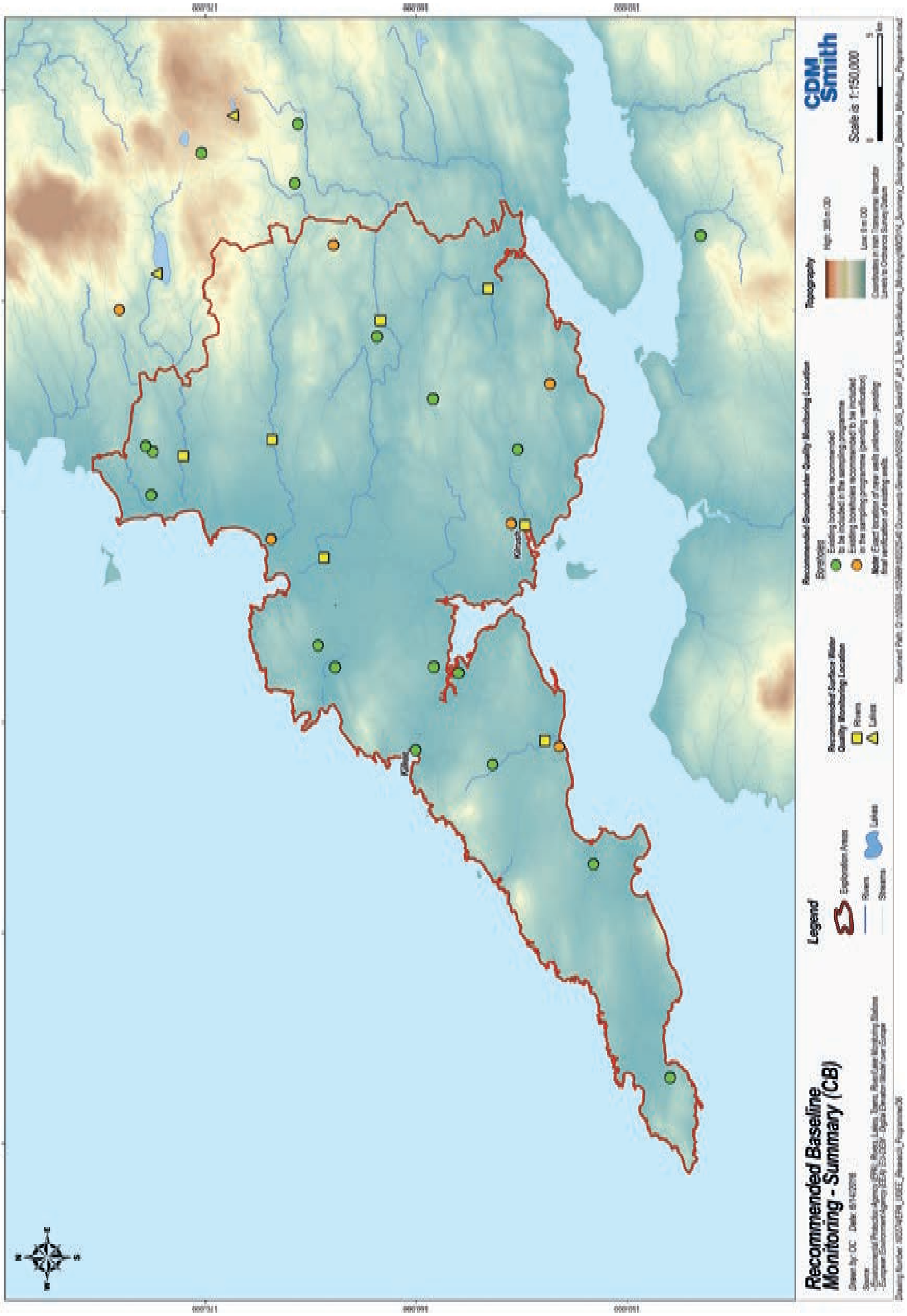

Figure 7.2. Overview of recommended monitoring stations, CB study area.

Table 7.1. Summary of recommended baseline monitoring

Parameter	No. of stations	
	NCB (area: 2200.40 km^2)	CB (area: 495.65 km^2)
Groundwater quality – wells (PWS + GWS + private)	35	22[a]
Groundwater quality – wells (new)[b]	10	2
Groundwater quality – springs (PWS + GWS)	25	–
Groundwater quality – springs (other)[c]	10	–
Surface water quality – streams	29	7
Surface water quality – lakes	15	2
Surface water quality – turloughs[d]	3	–
Groundwater quality – petrifying springs[e]	6	–
Hydrometric – stream flow	3	–
Hydrometric – spring discharge	7	–
Hydrometric – groundwater levels	20	10
Stream sediments[f]	30	15

[a]Estimated, to be finalised. 18 sites are accessible for sampling; a further six 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 would be on areas where prospective UGEE activity has been flagged, e.g. Kilcoo Cross, Arigna/Drumkeeran and Dowra. New monitoring wells in the CB would be located towards the central and south-eastern parts of the UGEE licence area, with final recommendations to be provided after final verification of existing wells. For the purposes of this report, two wells would be expected to be drilled and installed in the CB.

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

[d]Groundwater-dependent habitats within SACs in the NCB.

[e]Two clusters, of three petrifying springs each, are proposed for monitoring to establish baseline water quality associated with these habitats.

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

which would be selected after field visits and verification.

7.1 Sampling and Analysis of Water Quality

Baseline monitoring cannot account for all potential chemicals associated with UGEE. The recommended approach would be to monitor for groups of chemicals and constituents which are considered representative of UGEE activity, involving “chemical fingerprinting” of parameters that are rare or non-detectable in the natural settings of the case study areas, and that are distinguishable from other environmental pressures that may be present. Such parameters include stable isotopes, radioisotopes and chemicals that are commonly associated with flowback waters (e.g. barium, bromide, strontium).

Table 7.2 lists the parameters that would be recommended for laboratory analysis of both groundwater and surface water samples. The parameters are similar, except groundwater includes analyses for dissolved natural gas constituents and, potentially, stable isotopes of methane gas.

Decisions about laboratory analyses for NORM and stable isotopes would be based on the principles of “adaptive monitoring”, whereby initial screening of samples determine if more detailed analyses of the same samples would be warranted. For NORM, the methods used by the Radiological Protection Institute of Ireland (RPII) would be followed. The RPII applies screening limits for gross alpha and gross beta emissions. These are linked to a “total indicative dose” (TID), which is a public health metric related to exposure to radioactivity (RPII, 2013). Where a screening level is exceeded, further analysis of radium-226, radium-228 and radon is recommended. Radium is the documented main radioisotope of concern in flowback waters, and measurements of both radium-226 and radium-228 can be used to fingerprint the source (Vengosh *et al.*, 2014).

Table 7.2. List of recommended parameters for groundwater and surface water analyses

Parameter	Groundwater	Surface water	Frequency
Dissolved natural gas constituents			
Dissolved methane	✓	×	Quarterly
Dissolved CO_2	✓	×	Quarterly
Hydrocarbon gases (ethane, propane, butane and condensate)	✓	×	Quarterly
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
Sulfate	✓	✓	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

Table 7.2. Continued

Parameter	Groundwater	Surface water	Frequency
Descriptors of carbon sources			
Dissolved organic carbon	✓	✓	Quarterly
Dissolved inorganic carbon	✓	✓	Quarterly
Trace organics			
Polyaromatic hydrocarbon – full suite	✓	✓	Semi-annually (including low-flow conditions)
Volatile organic compounds – full suite	✓	✓	Semi-annually (including low-flow conditions)
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)
NORM			
Gross alpha/beta	✓	✓	Quarterly
Radium-226/radium-228	✓	✓	Quarterly (if a gross alpha/beta threshold exceeded)
Radon-222	✓	✓	Quarterly (if a gross alpha/beta threshold exceeded)

Regarding the analysis for dissolved natural gas (methane) in groundwater, the sampling and analytical methods employed by the BGS in England, Scotland and Wales would be recommended. These use screening limits for dissolved methane to decide whether fingerprinting of the gas is needed in order to determine source and origin of the gas.

The recommendation to exclude methane monitoring of surface water in a subregional baseline monitoring programme is based on the potential and expectation that dissolved gases in waters which are exposed to the atmosphere are likely to be "lost" as a result of degassing. The same applies to springs when groundwater becomes exposed to the atmosphere. Thus, analysis of dissolved gases and associated isotopic compositions would be recommended only for raw (untreated) groundwater samples which are collected from wells, in setups where the water is not exposed to the atmosphere prior to sampling. Results obtained from karstified limestone aquifers would need to be assessed with caution, as unconfined conditions can develop in conduits, resulting in degassing. Methane gas may be degassed in the vicinity of conduits but also remain present elsewhere in the bedrock aquifer where confined conditions apply.

The US Geological Survey has carried out research on stream-based methane monitoring to identify and quantify groundwater methane discharging to a stream in an area of unconventional gas development. The method (as reported by Heilweil *et al.*, 2015) combines "stream hydrocarbon and noble-gas measurements with mass-balance modelling to estimate thermogenic methane concentrations and fluxes in groundwater discharging to streams". It is described by the authors as the "first watershed-scale method to assess groundwater contamination from shale-gas development". A review of the method indicates that it is useful and has validity at the local (subcatchment) scale for monitoring of case-specific UGEE activity, but that it is not suited for baseline monitoring at the subregional scale, as the resources required to implement the method are significant. The method nonetheless points to study and monitoring elements which should be considered when determining the terms and conditions of operational monitoring with UGEE developers. For example, if location-specific field data and/or conceptual site models indicate that there is potential for methane gas to leak to groundwater that ultimately discharges to surface water, then dissolved methane and its isotopes should be considered for monitoring in surface waters to establish baseline concentrations at a site-specific or subcatchment scale (Heilweil *et al.*, 2015). An understanding of gaining and losing stretches of the river would also need to be determined, requiring detailed flow measurements and, potentially, tracer studies (Heilweil *et al.*, 2015). Thus, such monitoring would be recommended for consideration at the site-specific scale, after detailed evaluation of where specific discharges may occur close to actual UGEE sites.

7.2 Sampling and Analysis of Stream Sediments

Sampling of stream sediments for gross alpha and gross beta screening is recommended, whereby screening results would be used to determine if further analysis of radium isotopes should be carried out (specifically, if relevant screening thresholds are exceeded). This would be a one-time characterisation effort, but is nonetheless 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 case study areas. Suitable sampling locations would have to be identified, requiring field verification to locate low-energy environments where sediments accumulate. In the NCB, this should be co-ordinated as much as possible with the existing sample locations from the existing Tellus Border datasets of other NORM and metals. In the CB, where Tellus sediment sampling is planned in the future, potential sampling locations should be discussed and co-ordinated with the Tellus research team beforehand.

7.3 Hydrometric Monitoring

Recommended hydrometric monitoring involves measurement of groundwater levels in wells, discharges of select springs, and flow in select streams.

Groundwater level monitoring would continue in the five wells which are currently monitored for WFD quantitative status and trend identification purposes. Furthermore, a select set of additional wells in key bedrock formations would be monitored to document natural fluctuations and longer term responses to changes in hydrometeorological conditions. It is proposed that up to 20 wells would be monitored in the NCB and 10 wells would be monitored in the CB. Monitoring would partly consist of manual measurements but would also be accomplished using pressure transducers in select wells.

Discharge measurements at springs, in the NCB only, would be accomplished using temporary structures involving staff gauges and slotted standpipe solutions, fitted with pressure transducers which would also be capable of measuring temperature and electrical conductivity (EC).

Similar temporary monitoring methods and installations would be applied for three streams that are recommended for flow monitoring (Swanlinbar, Arigna and Feorish).

7.4 Monitoring for Impact from UGEE-related Abstractions

UGEE operations require water. The highest water demands would occur during the hydraulic fracturing phase at individual wells.

As a cost-saving measure, it is expected that UGEE companies would try to source water locally. Available water resources are represented by rainwater, lakes and reservoirs, streams and rivers, and groundwater in bedrock aquifers. There is capacity to supply the water use requirements of potential future UGEE development in both study areas, but this would ultimately be conditioned and influenced, both spatially and temporally, by *how* and *where* the development would proceed. Local supply options are considerably wider in the NCB study area than in the CB study area.

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 (CDMS, 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; 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 are 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, impacts 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 and/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). This requires input from and technical judgement by specialists in related fields. The distinction between "small" and "large" abstractions is relative, depending on the source of water. The accompanying impact assessment should be based on a consideration of aquatic ecology from lines of best 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 regard 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. Because UGEE activity is rarely confined to single locations, abstractions could have cumulative impacts which would need to be addressed by appropriate monitoring and mitigation measures.

7.5 Notes on the Recommended Baseline Monitoring Programmes

With regard to the sampling and documentation of naturally occurring methane in groundwater, the recommended baseline monitoring programme includes 45 sites in or near the 2200-km^2 UGEE licence area of the NCB, and more than 20 sites in or near the 496-km^2 UGEE licence area of the CB (pending verification of a small number of sites). The groundwater sampling sites are distributed across several bedrock formations which are used for water supply purposes and which, therefore, have relevance to UGEE activity. For comparison, the National Methane Baseline Survey carried out by the BGS in England, Scotland and Wales includes, to date, approximately 330 sites (mostly abstraction wells), with a focus on areas where aquifers are underlain by shale units that may be exploited for unconventional gas. The US Geological Survey (USGS, 2012) carried out baseline monitoring of methane in 66 private wells across a 5200-km^2 area in the state of New York. The USGS is also carrying out a baseline survey for dissolved gases, including methane, in groundwater from approximately 50 private wells across a 200-km^2 area prior to unconventional gas exploration in North Carolina (USGS, 2014). Kresse *et al.* (2013) further describe methane analysis of samples from 51 private wells across an area of approximately 3600 km^2 in Arkansas. Finally, Pinti *et al.* (2013) reported on results from a baseline survey of 130 private wells in a 14,000-km^2 area in Quebec in support of a government-supported strategic environmental assessment of unconventional gas development alternatives.

Density of sampling points is relevant but is not the main criterion by which "adequacy" of a monitoring network is judged. What is principally important is that monitoring is representative of the potential contaminant pathways between sources and receptors, and covers the range of identified potential receptors that are present within a defined study area.

Many of the data that would be produced from recommended baseline monitoring programmes are "standard" and similar to monitoring initiatives which are presently undertaken by public bodies in both Ireland and Northern Ireland under the current implementation of the WFD. Where WFD sample locations coincide with recommended sites for UGEE subregional baseline monitoring, cost savings could be achieved, as sampling activities would be co-ordinated to avoid duplication of effort. However, significant "new data" would also be generated for parameters that are not commonly sampled or analysed for, and which reflect the particular nature of UGEE operations. Principal amongst these are natural gas constituents, notably methane, and NORM in groundwater. Monitoring of methane in surface water is not proposed as part of the subregional baseline monitoring, as the resources required to implement relevant methods are significant, and methods are less well suited for subregional application. Rather, methane monitoring in surface water should be considered when determining terms and conditions of operational monitoring at site scale with UGEE developers.

8 Conclusions

UGEE-related activity, including hydraulic fracturing, carries environmental risk. Contaminants may be spilled at the surface, leaked or otherwise directly discharged into waterways and underlying aquifers. Contaminants, principally natural gas constituents, may also migrate from unconventional gas target formations at depth to shallow receptors as a result of hydraulic fracturing operations.

Environmental risk factors are well described in international literature. Potential surface sources of contamination are many and can, in most cases, be mitigated against with proper planning, enforcement and monitoring. Potential subsurface sources of contamination are related to hydraulic fracturing and are more difficult to guard against because of limited knowledge and inherent uncertainty about geological and hydrogeological conditions underground. Accordingly, risk mitigation requires prior characterisation of the physical–chemical systems involved at appropriate scales, in addition to employing best-practice methods. The scale and content of such investigations depend on the scale and nature of proposed UGEE operations. For this reason, the prior characterisation must be tailored to case- and location-specific circumstances, for example where UGEE activity is proposed, how many drill pads are proposed and what potential receptors of contaminants are present. Such items have to be specified and reviewed in the context of licensing. Thus, case- and location-specific investigation and monitoring requirements are specified and established as part of the licensing process.

The key to risk identification, mitigation and monitoring is to develop an understanding of S-P-R relationships for any given site and proposed operation. For the two case study areas which have been examined as part of the UGEE JRP, these relationships are conceptually well understood. However, firm plans for UGEE activity at individual locations are not yet known. Therefore, case- and location-specific risks cannot be judged until details of plans for UGEE activity are presented.

From a broader, subregional perspective, the characterisation and knowledge of deep geological and hydrogeological conditions represent the principal data gaps associated with both case study areas, notably:

- whether open natural fractures are present in deeper bedrock formations, including those that separate the unconventional gas target formations from shallow potential receptors;
- whether, and the extent to which, deeper groundwater flow systems are present and may be hydraulically connected to shallow aquifers; and
- the chemical characteristics of deeper formation waters beneath the currently exploited shallow aquifers.

On the basis of existing data and information, potential pathways and hydrogeological connections between the deep unconventional gas target formations and shallow receptors are inferred rather than proven. Deep hydrogeological data are sparse. Although conceptual models give information about likely processes and associated risk factors, the hydrogeological characterisation of both case study areas would benefit from deep hydrogeological investigation. The data gaps associated with potential deeper water resources and open fracture networks can be addressed only by a combination of surface geophysical surveys (e.g. fault identification), drilling, borehole geophysical logging, hydraulic testing, sampling and monitoring of deep wells. The objective would be to gather data about water quality, water levels and potential pathways across the intervening formations that separate the unconventional gas target formations from shallow aquifers and associated (other) receptors. Future investigation (exploration) boreholes could be converted and installed as monitoring wells, which would subsequently be used as “sentinel” wells (CCA, 2014), or “warning wells”, provided their locations and positions are geographically relevant to future UGEE sites.

Prior baseline monitoring is a requirement of planning for UGEE activity. This applies to both the subregional and site scales. Subregional baseline monitoring programmes have been designed for the two case study areas. Following best-practice guidelines in international literature, a precautionary approach has been adopted which is comprehensive in scope and extent, and would be capable of (1) describing general environmental pressures and (2) distinguishing impacts of UGEE-related activity from general environmental pressures. Importantly, baseline monitoring at the subregional scale should also be capable of addressing cumulative impacts across catchments.

Experiences from other countries are useful in guiding how baseline monitoring should be conducted, specifically the decisions about what should be monitored for and the methods of monitoring. However, information on baseline monitoring programmes in other countries cannot guide where monitoring should be undertaken in the two case study areas, as the monitoring programmes have to be designed according to the hydrogeological systems and potential receptors that are present.

The subregional baseline monitoring networks that have been designed as part of the UGEE JRP are receptor-focused and are based on conceptual hydrogeological models that define S-P-R relationships to the extent that data and information are available. The monitoring networks encompass groundwater, surface water and aquatic ecosystems in both case study areas, and provide recommendations for approaches, methods and potential new infrastructure that would be needed for implementation.

Baseline monitoring is a longer term commitment and the resulting datasets would give information about natural trends as well as potential impact. For cost-effectiveness, there is an opportunity to integrate the recommended baseline monitoring programmes with existing monitoring initiatives by public bodies in both Ireland and Northern Ireland. Any new infrastructure installed as part of the UGEE JRP could, in turn, benefit the same public agencies in the longer term.

A distinction is made in the UGEE JRP between recommendations for receptor-focused baseline monitoring at the subregional scale and recommendations for improved geological/hydrogeological characterisation. Because UGEE activity is case- and location-specific, improved characterisation work should be carried out where UGEE activity is most likely to be targeted. A subregional approach to characterisation, whereby drilling is conducted over the wider study areas, would provide valuable data, but findings at one location can always be questioned or challenged in the context of another location. A subregional approach would not necessarily produce the answers that are needed at the case- and location-specific scale. The onus for location-specific characterisation would be on the UGEE companies, under terms of legislation and conditions set forth by regulators. The same applies to the siting of well pads and the monitoring of day-to-day activities if future UGEE activity takes place.

References

Blake, S., Jones, A.G., Henry, T. *et al*., 2015. A multidisciplinary investigation of Irish warm springs and their potential for geothermal energy provision. Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015.

Brock, A. and Barton, K.J., 1984. *Equilibrium Temperature and Heat Flow Density Measurements in Ireland*. Final Report on Contract No. EG-A-1–022-EIR(H), Report EUR 9517, NUIG AGR Internal Report AGR 84/1. Available online: http://www.iretherm.ie/documents/Publications_by_Others/Brock+Barton_1984_AGR84-1.pdf (accessed 28 September 2016).

CCA (Council of Canadian Academies), 2014. *Environmental Impacts of Shale Gas Extraction in Canada*. Report from The Expert Panel of Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction. CCA, Ottawa, ON.

CDMS (CDM Smith Ireland), 2016. *Final Report 4: Environmental Impacts of Unconventional Gas Exploration & Extraction, Impacts and Mitigation Measures*. Joint Research Programme on the Environmental Impacts of Unconventional Gas Exploration and Extraction. Final Report. EPA/DCENR/NIEA. Environmental Protection Agency, Johnstown Castle, Ireland.

Daly, D., Lloyd, J.W., Misstear, B.D.R. *et al*.,1980. Fault control of groundwater flow and hydrochemistry in the aquifer system of the Castlecomer Plateau, Ireland. *Quarterly Journal of Engineering Geology* 13: 167–175.

Davies, R.J., Mathias, S.A., Moss, J. *et al*., 2012. Hydraulic fractures: how far can they go? *Marine and Petroleum Geology* 37: 1–6.

EC (European Commission), 2014a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions “The exploration and production of hydrocarbons (such as shale gas) using high volume hydraulic fracturing in the EU”. COM(2014) 23 final/2, Brussels. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0023R(01)

EC (European Commission), 2014b. “Recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing”. 2014/70/EU, 8.2.2014, Brussels. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014H0070

EPA (Environmental Protection Agency), 2010. *Poorly Productive Aquifers: Monitoring Installations and Conceptual Understanding*. Available online: http://www.epa.ie/pubs/reports/water/ground/ppa/EPA%20Poorly%20Productive%20Aquifers%20Summary%20Report.pdf (accessed 25 February 2015).

EPA (Environmental Protection Agency), 2014. *Guidance on the Authorisation of Direct Discharges to Groundwater. Draft for Consultation. January 2014*. EPA, Johnstown Castle, Ireland. Available online: http://www.epa.ie/pubs/consultation/Proposed%20Guidance%20on%20the%20Authorisation%20of%20Direct%20Discharges%20to%20Groundwater.pdf

EPA (Environmental Protection Agency), 2015. *WFD Register of Protected Areas. Published Data 26/01/2015*. Available online: http://gis.epa.ie/GetData/Download

EPA/DCENR (Environmental Protection Agency/Department of Communications, Energy and Natural Resources), 2009. Summary site descriptions. In *Historic Mine Sites – Inventory and Risk Classification Volume 1*. Available online: http://www.epa.ie/pubs/reports/land/mines/#.VEkkF_nF9qV

Gallagher, V., Knights, K., Carey, S. *et al*., 2015. *Atlas of Stream Sediment Geochemistry of the Northern Counties of Ireland. Data from the Tellus and Tellus Border Projects*. Geological Survey of Ireland, Dublin.

Goodman, R., Jones, G.L., Kelly, J. *et al*., 2004. *Geothermal Energy Resource Map of Ireland. Final Report*. Sustainable Energy Ireland. Available online: http://www.iretherm.ie/documents/Publications_by_Others/SEI2004_FinalReport.pdf (accessed 28 September 2016).

Heilweil, V.M., Grieve, P.L., Hynek, S.A. *et al*., 2015. Stream measurements locate thermogenic methane fluxes in groundwater discharge in an area of shale-gas development. *Environmental Science & Technology* 49: 4057−4065.

IGI (Institute of Geologists of Ireland), 2007. *Guidelines for Drilling Wells for Private Water Supplies (March 2007)*. IGI, Dublin.

JNCC (Joint Nature Conservation Committee), 2013. *Second Report by the United Kingdom under Article 17 on the implementation of the Directive from January 2001 to December 2006 – Conservation status assessment*. Available online: http://jncc.defra.gov.uk/pdf/Article17/FCS2007-S2030-Final.pdf

Kimberley, S. and Coxon, C., 2013. *Evaluating the Influence of Groundwater Pressures on Groundwater-dependent Wetlands. Environmental Supporting Conditions for Groundwater-dependent Terrestrial Ecosystems*. STRIVE Report. Environmental Protection Agency, Johnstown Castle, Ireland.

Kresse, T.M., Warner, N.R., Hays, P.D. *et al*., 2013. *Shallow Groundwater Quality and Geochemistry in the Fayetteville Shale Gas-Production Area, North-Central Arkansas, 2011*. US Geological Survey Scientific Investigations Report 2012–5273. US Geological Survey, Reston, VA.

NIEA (Northern Ireland Environment Agency), 2014. *WFD Register of Protected Areas*. NIEA, Belfast.

NPWS (National Parks and Wildlife Service), 2013a. The Status of Protected EU Habitats and Species in Ireland. Overview Volume 1. Unpublished Report. NPW Services and Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland.

NPWS (National Parks and Wildlife Service), 2013b. The Status of EU Protected Habitats and Species in Ireland. Habitat Assessments Volume 2. Version 1.1. Unpublished Report. NPWS and Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland. Available online: http://www.npws.ie/publications/article17assessments/article17 2013assessmentdocuments/Article17PrintVol-2 reporthabitatsv11.pdf

Pinti, D.L., Gélinas, Y., Larocque, M. *et al*., 2013. *Concentrations, sources et mécanismes de migration préférentielle des gaz d'origine naturelle (méthane, hélium, radon) dans les eaux souterraines des Basses-Terres du Saint-Laurent*. Research Report of Study E3–9. University of Quebec and Concordia University, Montreal, QC.

RPII (Radiological Protection Institute of Ireland), 2013. *Radioactivity Levels in Groundwater Sources in Ireland*. RPII, Dublin. Available online: https://www.epa.ie/pubs/reports/radiation/RPII_Groundwater_Rad_Rep_13.pdf

USGS (United States Geological Survey), 2012. New York Water Science Center Newsletter, vol. 15, October, 2012. Available online: http://www.usgs.gov/newsroom/article.asp?ID=3752#.VbqIh_lVhHw

USGS (United States Geological Survey), 2014. *North Carolina Shale Gas Baseline Groundwater Sampling Project*. Available online: http://nc.water.usgs.gov/projects/shalegas/overview.html

Vengosh, A., Jackson, R.B., Warner, N. *et al*., 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology* 48: 8334−8348.

Warner, N.R., Christie, C.A., Jackson, R.B. *et al*., 2013. Impacts of shale gas wastewater disposal on water quality in Western Pennsylvania. *Environmental Science & Technology* 47: 11849–11857.

Abbreviations

ASSI	Area of Special Scientific Interest
BGS	British Geological Survey
CB	Clare Basin
DCCAE	Department of Communications, Climate Action and Environment
DCENR	Department of Communications, Energy and Natural Resources
DfE	Department for the Economy
EIS	Environmental impact statement
EPA	Environmental Protection Agency
EU	European Union
GSI	Geological Survey of Ireland
GSNI	Geological Survey of Northern Ireland
GWDTE	Groundwater-dependent terrestrial ecosystem
GWS	Group water scheme
JRP	Joint Research Programme
NCB	Northwest Carboniferous Basin
NHA	Natural Heritage Area
NIEA	Northern Ireland Environment Agency
NORM	Naturally occurring radioactive materials
NPWS	National Parks and Wildlife Service
PAD	Petroleum Affairs Division
pNHA	Proposed Natural Heritage Area
PWS	Public water scheme
RPII	Radiological Protection Institute of Ireland
SAC	Special Area of Conservation
SPA	Special Protected Area
S-P-R	Source–Pathway–Receptor (Model)
TID	Total indicative dose
UGEE	Unconventional gas exploration and extraction
UKTAG	UK Technical Advisory Group
WFD	Water Framework Directive

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

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Unconventional gas exploration and 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 UGEE Joint Research Programme (JRP) (**www.ugeeresearch.ie**) is composed of five interlinked projects and involves field studies (baseline monitoring of water and seismicity), as well as an extensive desk-based literature review of UGEE practices and regulations worldwide. The UGEE JRP was designed to provide the scientific basis that will assist regulators - in both Northern Ireland and Ireland - to make informed decisions about whether or not it is environmentally safe to permit UGEE projects/operations involving fracking. As well as research in Ireland, the UGEE URP looks at and collates evidence from other countries.

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List of Outputs:

- Final Report 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems
- Summary Report 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems
- Final Report 2: Baseline Characterisation of Seismicity
- Summary Report 2: Baseline Characterisation of Seismicity
- Final Report 3: Baseline Characterisation of Air Quality
- Summary Report 3: Baseline Characterisation of Air Quality
- Final Report 4: Impacts & Mitigation Measures
- Summary Report 4: Impacts & Mitigation Measures
- Final Report 5: Regulatory Framework for Environmental Protection
- Summary Report 5: Regulatory Framework for Environmental Protection
- UGEE Joint Research Programme Integrated Synthesis Report

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