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Unconventional Gas Exploration and Extraction (UGEE) Joint Research Programme

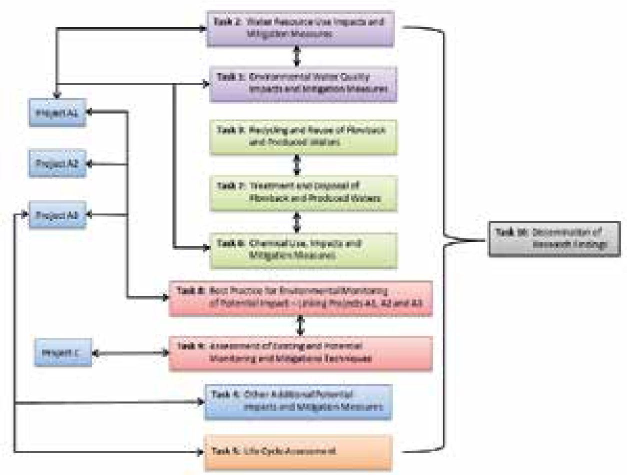
Integrated Synthesis Report

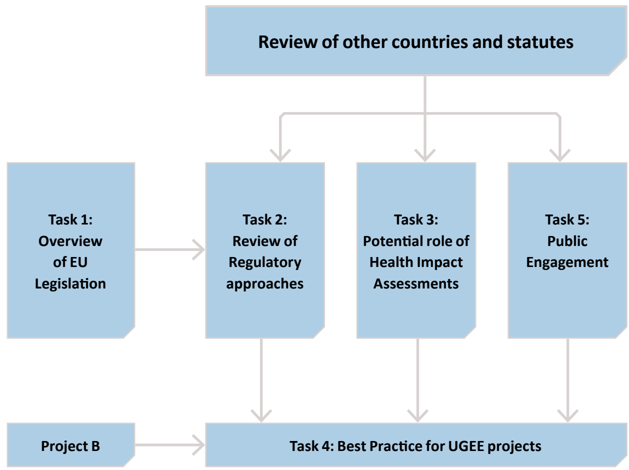
Authors: Alan Hooper, Dawn Keating and Roger Olsen


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


Ambient air quality monitoring sampling intake


Broadband seismometer deployed in a field pit





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Funding Organisations

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)

Integrated Synthesis Report

by

CDM Smith Ireland Ltd

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

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UGEE JRP Internal Review Panels

This report is a synthesis of five projects. Each project had an Internal Review Panel as per: 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 Ltd to carry out a 24-month research programme looking at the potential impacts on the environment and human health from UGEE projects/operations (including construction, operation and after-care).

The UGEE Joint Research Programme (JRP)[1] is composed of five interlinked projects designed to produce the scientific basis of the programme that will assist regulators – in both Ireland and Northern Ireland – in making informed decisions about whether or not it is environmentally safe to allow fracking. As well as conducting research in the island of Ireland, the UGEE JRP looked at and collated evidence from other countries.

The UGEE JRP has examined the processes, impacts and mitigation measures associated with hydraulic fracturing around the world. International regulatory frameworks and the suitability of legislation in Northern Ireland and Ireland were reviewed and potential gaps were identified.

Public concern about hydraulic fracturing generally focuses on health, water resources, induced seismic activity and emissions of greenhouse gases, although in some areas potential changes in the character of the environment have been raised as a matter of concern. The relative importance of these issues varies from place to place and with time.

This study concluded that UGEE projects/operations comprise multiple activities over a period of up to 25 years, which have the potential to impact both human health and the environment. However, many of these activities are conventional, in the sense that they are infrastructure developments that are not unique, within both Ireland and Northern Ireland, and consequently the relevant legislation and the regulation of these activities are well established and broadly accepted by society. Examples of these activities are access road construction, site preparation and materials transport. These types of activities across many industries have well-established impacts and measures associated with them to mitigate their impacts.

Other activities and impacts that are specific to hydraulic fracturing and/or conventional oil and gas projects were also identified; in most cases, the proper application of best practice by the industry, supported by regulatory control, adequately mitigates these impacts.

The programme concluded that many of the activities associated with UGEE projects/operations could proceed on the island of Ireland, while protecting the environment and human health, using the best practices identified in Project B and applying the current regulations, together with a small number of additions and modifications complemented by adequate implementation and enforcement.

Three specific impacts were identified for which the effectiveness of mitigation measures remains unproven because of lack of data. These three impacts relate to groundwater contamination by failed borehole casings, groundwater contamination from migration of pollutants through fractures created by hydraulic fracturing, and long-term leakage of methane from capped wells following cessation of production. Baseline monitoring of surface water and groundwater, structural geology, fault zones and also seismic activity would contribute to a better understanding of the two groundwater contamination issues.

There is a lack of a clear agreement on the magnitude of air quality impacts caused by UGEE activities, although there is consensus about the compounds or families of compounds emitted.

1 www.ugeeresearch.ie

The findings of the study were drawn from the following five interlocking studies:

- Baseline Characterisation:
  - Project A1: Groundwater, Surface Water and Associated Ecosystems;
  - Project A2: Seismicity;
  - Project A3: Air Quality;
- Impacts and Mitigation Measures:
  - Project B: UGEE Projects/Operations: Impacts and Mitigation Measures; and
- Regulatory Framework:
  - Project C: Regulatory Framework for Environmental Protection.

Projects A1, A2, A3 and B focused on the Northwest Carboniferous Basin and the Clare Basin, where licences have been awarded as preliminary authorisations or exploration licences by the governments of Ireland and Northern Ireland.

Water

Full details of the work relating to groundwater, surface water and associated ecosystems can be found in *Final and Summary Reports 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems*. The two main components of the project were the characterisation of the two case study areas and the development of a specification for a sub-regional baseline monitoring programme in each study area.

There is a general consensus in published research that it is both desirable and necessary to undertake baseline monitoring that produces publicly available data and is a shared responsibility of the operators and the regulators; in many water environments, the quantitative aspects of baseline monitoring are as important to consider as the qualitative aspects.

The key to risk identification and mitigation in the water environment is to understand Source–Pathway–Receptor (S-P-R) relationships at any proposed UGEE site. The S-P-R relationships that are specific to a particular UGEE project would have to be addressed individually once any such development plans are presented.

Both the EPA and the Northern Ireland Environment Agency already carry out comprehensive environmental monitoring of aquatic environments in Ireland and Northern Ireland, respectively, under initiatives linked to the implementation of the European Union Water Framework Directive (WFD) and relevant national statutory instruments that have followed this directive.

Existing environmental pressures on water resources and aquatic ecosystems derive from land use and economic activities that take place within the case study areas. They involve both diffuse and point sources of pollution, as well as abstractions. Several rivers and lakes in both study areas currently fail to meet the WFD “good status” objectives. The groundwaters are currently classified as being of good quantitative status, although some have poor chemical status.

In the Northwest Carboniferous Basin, groundwater is extensively used for public and private water supplies and the water is sourced from both wells and springs. In the Clare Basin, groundwater is sourced for private water supplies, notably from shallow wells that serve single houses and farms, as well as commercial/industrial facilities. There are no groundwater-sourced public or group water schemes directly within the UGEE licence area in the Clare Basin. The majority of public and group water scheme supplies are sourced from Doo Lough.

Groundwater also has a supportive ecological function, by providing and maintaining baseflow to surface waters and to groundwater-dependent habitats during prolonged dry weather conditions; this is more significant in the Northwest Carboniferous Basin.

The water use requirements of hydraulic fracturing processes in the two case study areas were assessed based on the “probable commercial scenarios” developed in Project B; the available water resources in the two case study areas were also described and, together, these provided a means of identifying potential impacts from water abstractions.

Any future proposals for UGEE-related abstractions would have to be assessed on a case-by-case basis, with detailed and specific information on drilling and hydraulic fracturing schedules, in order to assess temporal and cumulative impacts, particularly on small streams and lakes. Identifying and documenting volumetric impact is relevant in a regulatory context, but it is the ecological impact that will ultimately determine whether or not an abstraction authorisation should be granted.

The bedrock aquifers in both study areas are viable sources of water to meet demands, at least in part.

Potential future UGEE-related abstractions would have to be evaluated at both local and catchment levels. UGEE activity is rarely confined to single locations and so abstractions may have a cumulative impact that would need to be addressed by appropriate monitoring. 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).

The characterisation and knowledge of deep geological and hydrogeological conditions represent the principal data gaps associated with both case study areas. These gaps affect knowledge about the extent to which deeper groundwater flow systems are present and may be hydraulically connected to shallow aquifers and receptors to whether or not open natural fractures exist in deeper bedrock formations, and to the chemistry 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. Both study areas would benefit from deep hydrogeological characterisation.

Because UGEE activity is case and location specific, improved characterisation work should be carried out where UGEE activity is most likely to take place. However, a sub-regional approach would not necessarily produce the answers that are needed at the case- and location-specific scale.

A precautionary approach to sub-regional baseline monitoring that is comprehensive in scope and extent and would be capable of describing general environmental pressures, distinguishing the impacts of any UGEE-related activity from general environmental pressures and addressing cumulative impacts across catchments should be adopted.

The sub-regional baseline monitoring should be receptor focused and long term. The recommended baseline monitoring programmes in *Final and Summary Reports 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems* include groundwater sampling of existing public and private supply wells, springs and potential new monitoring wells; groundwater-level monitoring in select, existing and any potential new monitoring wells; sampling of lakes and streams in designated protected areas; and hydrometric monitoring of spring discharges and stream flows where particular data gaps exist. The monitoring recommendations are shown in Figures ES.1 and ES.2.

The recommended sub-regional baseline monitoring programmes also include specifications for parameters that should be measured, recommendations for installation of new monitoring wells, sampling of stream sediments and monitoring of a small number of designated groundwater-dependent habitats.

Seismicity

Full details of the work relating to seismicity can be found in *Final and Summary Reports 2: Baseline Characterisation of Seismicity*.

The process of hydraulic fracturing is generally accompanied by microseismicity, usually defined as earthquakes with magnitudes of 2 or less that are too small to be felt. Two types of induced events can be defined: "fracked" events, whose size is constrained by the energy of the injection process and are too small to be felt; and "triggered" events in pre-existing geological faults, whose size depends largely on the amount of stored-up elastic strain energy already present in the rocks and can rarely be felt at the surface.

Deep well injection of water or wastewater from hydraulic fracturing and other industries, such as geothermal energy projects, has been associated with higher magnitude induced events that can have significant surface effects.

Seismicity associated with international UGEE projects/operations was reviewed and the potential for induced earthquakes in the study areas assessed.

It is clear that natural seismic activity in the island of Ireland is low and it is much lower than in the neighbouring countries of Wales, England and Scotland. Current theory suggests that triggered earthquake activity is likely to be the result of the amplification of the existing seismicity; the low background activity in the island of Ireland suggests that it is extremely unlikely that hydraulic fracturing, using best practice, will have any potentially troublesome seismic consequences to normal receptors. However, background seismicity is known to be spatially very variable and the lack of monitoring in the two study areas means that the actual background levels there remain unknown. Before any estimate can be made of the likely triggered seismicity,

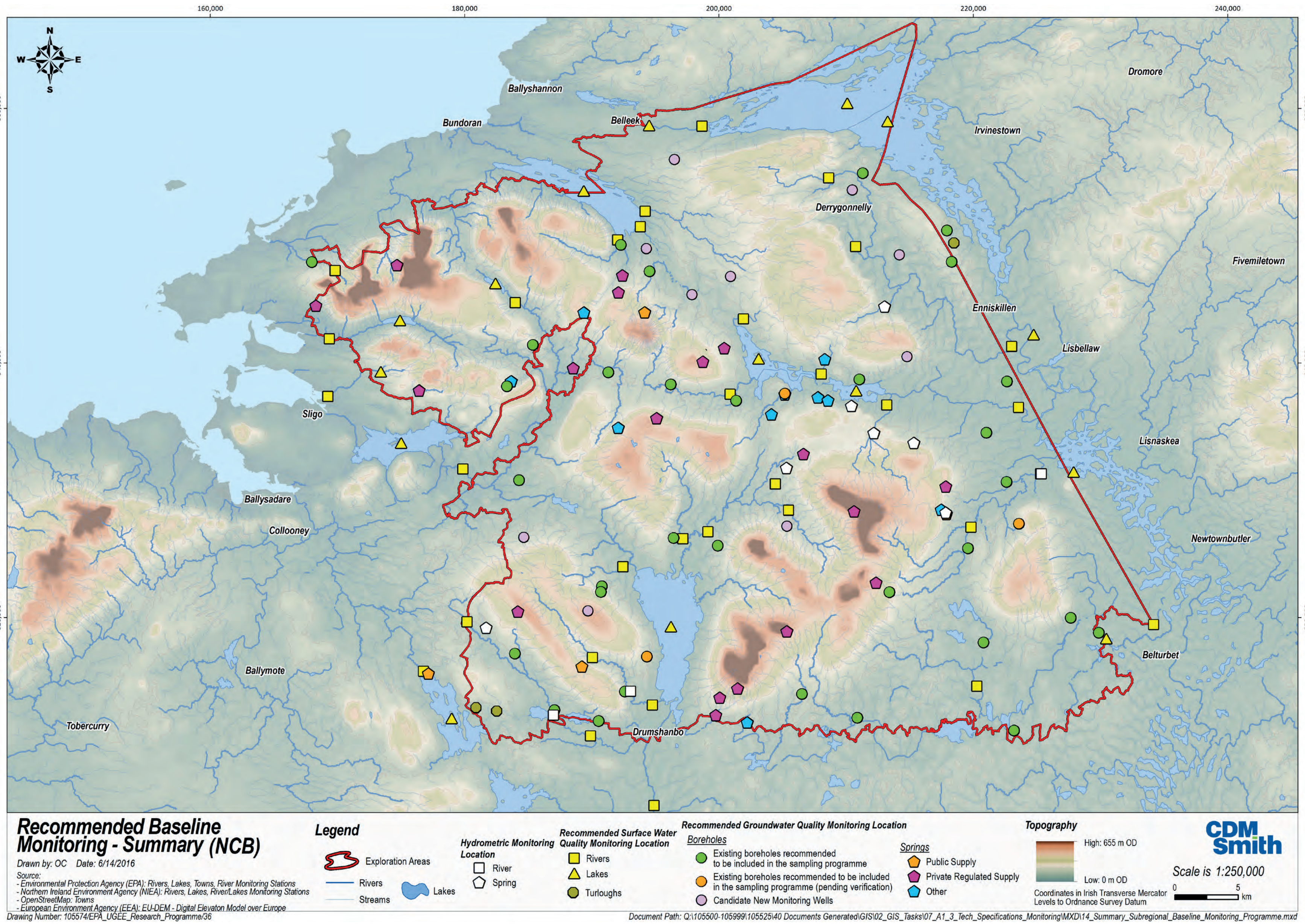

Figure ES.1. Overview of recommended monitoring stations in the Northwest Carboniferous Basin study area.

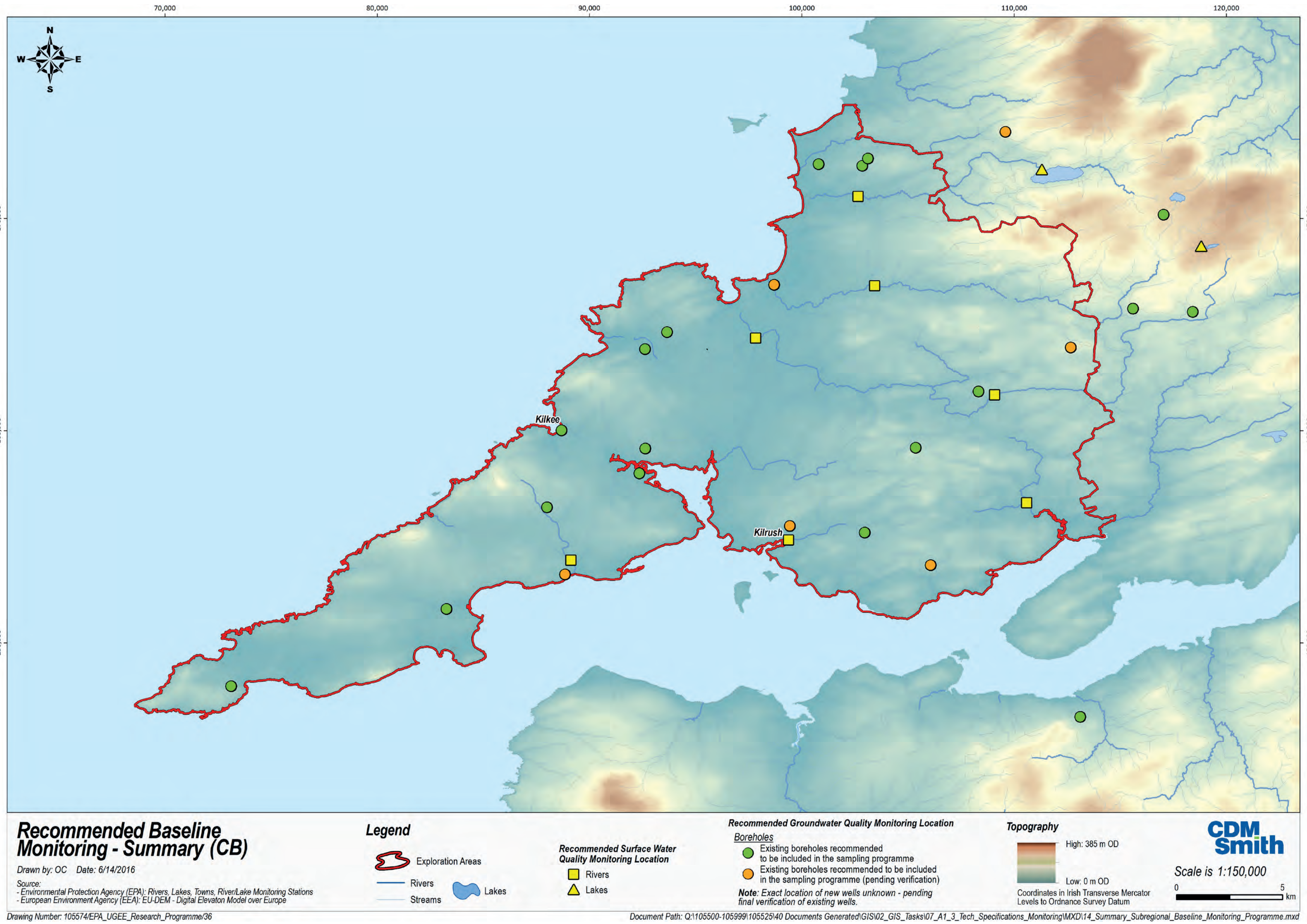

Figure ES.2. Overview of recommended monitoring stations in the Clare Basin study area.

knowledge of the background activity is required. Consequently, detailed baseline monitoring should be an essential requirement of any future unconventional gas exploration and extraction.

It is important to quantitatively monitor any ground deformation from UGEE projects/operations in order to gauge potential damage and to address any potential concerns of the public and policymakers regarding impacts to the environment.

Data and new analytical methods, such as the interferometric synthetic aperture radar (InSAR) technique, are available for the island of Ireland. In combination with the InSAR technique, complementary *in situ* methods, such as the Global Navigation Satellite System (GNSS) and tiltmeters, could be deployed, since integrating different monitoring techniques provides better and more detailed information on deformation.

Modelling of possible ground motions for realistic examples of earthquakes with magnitudes in the range of those previously observed in Ireland suggests that ground velocities are unlikely to exceed typical levels at which cosmetic damage might occur. Cosmetic damage could be observed within a few kilometres of the source of an earthquake with a magnitude of 3; however, for damage to be observed at the surface, the earthquake source would need to be very shallow, i.e. less than a few kilometres. Proper regulation would not permit hydraulic fracturing where pre-existing shallow fault zones exist. Similarly, larger earthquakes, with magnitudes of 4.0 or above, are only likely to approach the limits for cosmetic damage at distances of less than 10 km.

Advanced modelling approaches were developed to forecast the triggered seismicity surrounding a hydraulic fracturing operation for a series of scenarios given different reference activity levels and baseline network qualities.

Knowledge of existing fault structures has a significant effect on the success of the seismicity forecasts and systematic errors are introduced into induced rate estimates by assuming homogeneous reference rates (which was necessary here, in the absence of adequate information describing the structural geology).

In addition, current seismicity catalogues for the study areas are completely inadequate for forecast modelling on the study areas' spatial scales and to the standard necessary. The necessary use of synthetic catalogues in this work, to represent hypothetical baseline scenarios, allowed an illustration of the nature of the uncertainties that might be expected.

Robust forecasts of the hazard-relevant parameters of induced catalogues can only be made using a high-quality baseline network and local sensor networks deployed during operations, together with current best practice in data analysis. The low background rates of seismicity observed in current Irish catalogues have two contrasting implications:

- The dearth of data means that robust forecasts of the main parameters are not possible.
- Hydraulic fracturing projects in the island of Ireland are extremely unlikely to have any potentially troublesome seismic consequences for normal receptors; however, this conclusion will require confirmation by examination of good-quality baseline catalogues.

Seismic baseline monitoring is necessary to establish the rate of naturally occurring seismicity in an area, which can then be compared with the seismicity recorded during any hydraulic fracturing operations; it should provide a publicly available catalogue and would also locate active faults and map seismic noise levels in detail.

Existing seismic networks in the island of Ireland are not sufficient to detect and locate all local earthquakes with magnitudes greater than ML 0.5 (local magnitude) (events with $ML < 0.5$ are unlikely to be felt by humans or to cause any structural damage) in the two study areas. Local networks for the two study areas with inter-station spacings between 15 and 25 km were designed; these could reliably locate all such events during a baseline study, which should operate for at least 2 years. This would require the deployment of at least 12 seismometers in the Northern Carboniferous Basin and 10 seismometers in the Clare Basin.

The process of hydraulically fracturing a well generates microseismic events, but, as presently implemented for shale gas recovery, the general consensus among seismologists is that this does not pose a high risk for inducing felt, damaging or destructive earthquakes. To date, there are only five documented examples of earthquakes with $ML > 2$ that have been conclusively linked to hydraulic fracturing.

In contrast, evidence of changes in observed seismicity due to triggered events, linked to long-term disposal of wastewater from the hydrocarbon and other industries, suggests that this activity may pose a greater seismic risk than UGEE operations. Although presently prohibited under the Mining Waste Directive, any changes to, or reinterpretation of, the regulatory regime and resultant proposed disposal of wastewater from hydraulic fracturing by deep injection would require careful hazard assessment as well as monitoring and mitigation strategies. It should be noted that reinjection is permitted, in principle, in Germany and England.

The enhanced geothermal systems industry has developed a series of measures to address induced seismicity that may be considered as industry best practice and, as such, may be considered appropriate for mitigating the risk of induced seismicity in UGEE operations.

There remain gaps in the existing knowledge of induced seismicity. For example, the pre-existing state of stress and pore pressure acting on a fault are usually unknown. Triggered events can be initiated by very small stress perturbations; however, the potential for such events depends very much on the geological context and, given the low levels of background seismicity, the probability of large triggered events in the island of Ireland can be considered low.

During any hydraulic fracturing operations, real-time site-specific seismic monitoring and detailed recording of injection parameters are necessary to reduce uncertainties in earthquake locations and to compare the temporal evolution of seismic activity with operational activities.

In this study, a stochastic model (random and evolving with time) of induced seismicity, which adopted the distribution of microseismic event sizes from other wells, was developed to allow modelling of the formation of fractures from widely accepted empirical scaling relations. Because of the paucity of available data for the two study areas, the parameters used for the model are for illustration; they should be replaced by values determined initially from a baseline survey and then from updates in near real time during any hydraulic fracturing operations.

There is clear evidence that vertical fractures can propagate into shallow depths; if the hydraulic fracturing is sufficiently shallow, there is a risk that these fractures might interact with aquifers. Data show an upwards extent of microseismicity of approximately 100 m, with a worst-case event extending up to 300 m above the perforation. Fracture lengths show a strong decrease in probability with length. However, there is a relatively long tail on the statistical distribution, which can never reach a probability of zero, suggesting that there could be very rare large events.

Combining the distance of the microseismic event from the perforation and the length of fracture associated with the larger events, it was estimated that in about 95% of projects the shallowest fractures are less than 300 m above the perforation, but that there is a small finite probability that fractures may extend beyond 500 m above the hydraulic fracturing zone. This should inform regulatory requirements regarding the vertical separation of hydraulic fracturing from aquifers, but should be verified (and refined) after the collection of comprehensive baseline data.

During hydraulic fracturing, the permeability of the entire rock volume is increased by a set of fractures that could connect any permeable (pre-existing) throughgoing fault to the fracked volume and thereby potentially connect the fracked volume to the surface. This process has not been addressed in this study, as it is site specific, requiring detailed local data to establish the presence or absence of such permeable thoroughgoing fault pathways. Two- and three-dimensional seismic surveys, which would be expected to be undertaken by the operators prior to any hydraulic fracturing activity, will provide further subsurface knowledge that will enable better characterisation of subsurface geology, including the location of fault zones.

The absence of site-specific baseline data available at the time of the study limited the efficacy of the models that were developed to predict seismicity and the lengths of fractures generated by UGEE operations and, in turn, the risk of migration of pollutants along these fractures to subsurface aquifers in the study areas. This deficit should be addressed by a programme of baseline monitoring of at least 2-years' duration prior to the licensing of any hydraulic fracturing. In the event of hydraulic fracturing taking place, more detailed real-time seismic monitoring should be undertaken during exploration and production and used to further update the model predictions.

Baseline Characterisation of Air Quality

Full details of the work relating to air quality can be found in *Final and Summary Reports 3: Baseline Characterisation of Air Quality*.

UGEE projects/operations can result in the emission of some pollutants that, if present in high enough concentrations, are associated with possible adverse health effects through direct external contact or through inhalation. The sources of air pollution from shale gas and related activities vary, depending on the stage of the project.

Very few, if any, methodologically rigorous studies have examined the potential cause–effect relationships of UGEE activities and actual health outcomes in hazard analyses, in terms of exposure pathways and the health outcomes related to air emissions. Despite a lack of a clear agreement on the magnitude of air quality impacts caused by UGEE activities, the available literature appears to broadly agree on the compounds, or families of compounds, associated with UGEE activities, even if estimations of the quantity of emissions vary (as further addressed in *Final and Summary Reports 3: Baseline Characterisation of Air Quality*). The Environmental Impact Assessment (EIA) associated with any proposed UGEE project should, therefore, address the predicted emissions and associated impacts in the context of project-specific details, technologies and characteristics as rigorously as possible, underpinned by a precautionary approach. The precautionary approach is also fundamental to a Strategic Environmental Assessment (SEA) or Health Impact Assessment (HIA) (should it be carried out) and must be considered if potentially adverse environmental effects are predicted or if there is sufficient scientific uncertainty relating to air quality impacts.

There are several potential air pollutants from UGEE projects/operations. Methane is the primary component of shale gas and most emissions have occurred during well completion when the “frack fluids” flow back to the surface; however, there is concern that long-term emissions can occur after completion through leaks from capped wells.

Air quality limits and target values across the island of Ireland are defined in EU legislation. Guidelines published by the World Health Organization (WHO), which are designed to offer guidance in reducing the health impacts of air pollution, supplement national and European legislation.

A review of seven jurisdictions where commercial UGEE operations are ongoing found that, in all cases, a full baseline characterisation of air quality had not been carried out prior to the commencement of operations. This has been highlighted as an important information gap and recommendations for baseline studies and extensive investigations into potential air quality impacts have been made in many studies.

Ireland and Northern Ireland have separate ambient air quality monitoring networks. In Northern Ireland, the monitoring programme is supplemented by regional air quality modelling. Supplementary air quality baseline monitoring would be needed for UGEE impact assessments on a project-by-project basis. Proposed air quality monitoring on a pollutant-by-pollutant basis, together with the rationale supporting it, is set out in more detail in *Final and Summary Reports 3: Baseline Characterisation of Air Quality*.

Operations and Mitigation

Full details of the work relating to UGEE projects/operations, impacts and mitigation measures can be found in *Final and Summary Reports 4: Impacts and Mitigation Measures*.

The work identified and examined the potential impacts of UGEE projects/operations on the environment and human health as well as mitigation measures to counteract these impacts. The evaluations were focused on conditions in the island of Ireland, particularly the case study areas identified, and were based on probable commercial scenarios in these areas.

The probable commercial scenario approach was used to assess the potential impacts on the environment and human health and the mitigation measures. This approach standardises assumptions made about future UGEE activities, given the uncertainty of whether developments will proceed in the island of Ireland and, if so, how they will take place. At this stage, the chosen probable commercial scenarios do not take account of potential exclusions zones, such as Natura 2000 sites or Areas of Outstanding Natural Beauty. The probable commercial scenarios are described in *Final and Summary Reports 4: Impacts and Mitigation Measures*.

In general terms, UGEE projects develop in identifiable stages from initial assessments through to closure. The activities and potential impacts vary according to the activities in each stage and are described in *Final and Summary Reports 4: Impacts and Mitigation Measures*. The planning and prior authorisation phase of UGEE-related activity is, arguably, the most important phase of UGEE development. Whereas implementation of prevention and mitigation measures safeguards against spills and leaks (and therefore potential impact), planning establishes rules, expectations and common understanding.

Water quality can be affected by various aspects of UGEE activities. Storm water runoff occurring from roads and drilling pads can be addressed by mitigation measures that are generally available; these would significantly limit the potential impacts if implemented and maintained properly. Surface chemical spills and leaks would be likely to occur and operators must be prepared with appropriate responses and mitigation measures. In addition, fluids associated with drilling and hydraulic fracturing operations, together with natural gas constituents that are present or released, represent potential sources of groundwater contamination if these migrate to the near-surface environment via natural, induced or artificial pathways.

Accidental spills of flowback and produced water can be expected from UGEE-related activities and, although the overall risk of impact from transport-related spills of flowback and produced water is considered to be low, these could result in an environmental impact.

All of the issues above require appropriate regulation and enforcement.

Overall, deep hydraulic fracturing is not likely to result in a direct flow pathway into shallow aquifers if adequate separation distances are maintained in excess of the predicted fracture lengths described in section 1.2; extreme lengths of 500 m are possible, but with site-specific baseline data this estimate could be refined through further modelling. The primary risk of groundwater quality impact is stray gas migration from the gas production zone as a result of an improper, faulty or failed production casing and/or poor or improper cement grouting of the casing.

UGEE projects necessitate the use of water resources for several purposes, including drilling operations, well construction, hydraulic fracturing, sanitation and equipment washing. The probable commercial scenarios were used to define the potential water use requirements in the two case study areas and these were then compared with the available resources to enable the identification of potential impacts.

The risks of impact from lake abstractions are considered to be small for the larger lakes, although site-specific studies would be necessary to take account of ecosystems and water balance.

The majority of streams in the two study areas could be sensitive to stream abstractions. It appears unlikely that the total water demand for UGEE-related activities could, or would, be sourced from a single catchment or stream, especially during low-flow conditions.

The well yields of the aquifers in the study areas cannot be predicted with certainty without detailed studies. However, existing groundwater abstractions in the two study areas are small and groundwater would potentially be a viable source of water to meet demands, at least in part.

As noted in section 1.1, any future proposals for UGEE-related abstractions would have to be assessed on a case-by-case basis and evaluated at both local and catchment level.

The recycling and reuse of flowback and produced water is potentially an important measure to reduce the impact of water resource requirements for UGEE projects/operations. However, this may be limited by current regulations in Ireland and Northern Ireland.

Impacts on other receptors that were not specifically addressed in other sections of the work (such as water quality and water resources) were addressed. The assessment of potential impacts and associated mitigation measures is site specific and, at this stage, only general conclusions can be drawn. Nonetheless, it is estimated that most potential impacts range from imperceptible to moderate, depending on the proximity to receptors and magnitude of cumulative impacts. One of the main areas where uncertainties are liable to remain relates to the quantification of long-term greenhouse gas emissions.

The life cycle environmental assessment of UGEE projects/operations was evaluated from a literature review and experience from other jurisdictions and compared with similar published assessments of other energy sources.

During project operations, the well completion stage was found to be the most significant source of emissions, followed by drilling and hydraulic fracturing. Effective implementation of mitigation measures relating to these activities would, therefore, have the most impact on overall levels of emissions. However, as is the case for conventional sources of gas, emissions are dominated by the results of combustion at the electricity generation plant, which typically represents approximately 90% of the total greenhouse gas emissions impact.

UGEE-generated electricity is reported to have a greater impact than conventional gas on certain life cycle indicators (for example, marine aquatic eco-toxicity potential and terrestrial eco-toxicity potential) but a significantly reduced impact on others (for example, freshwater eco-toxicity potential and eutrophication potential).

The use of chemicals, particularly additives in hydraulic fracturing solutions, has been a major concern of the public, regulators and the scientific community in recent years. The primary concern has been the use of chemicals that may have potential impacts on human health and/or the environment through the potential contamination of groundwater and the large number of different chemicals used.

The hazard classifications of the chemicals were assessed, based on existing European legislation. There are a few examples of fracturing processes that do not use chemicals or certain groups of additives; however, studies concluded that more research would be required before fracturing fluids that do not rely on chemical additives are commercially viable.

Treatment and disposal methods were identified and assessed; disposal options linked to the available treatment options were also reviewed and assessed. Experience in the USA shows that publicly owned or municipal treatment plants cannot adequately treat flowback and produced waters; US regional facilities have been established by the commercial sector and similar facilities would be needed in the island of Ireland. In Ireland and Northern Ireland, deep well injection may not be a viable disposal option because of restrictions in the Mining Waste Directive. Any changes to the regulatory regime and resultant proposed disposal of wastewater from hydraulic fracturing by deep injection would require careful hazard assessment, as well as monitoring and mitigation strategies. It should be noted that this is permitted, in principle, in Germany and England; in England, reinjection of wastewater already occurs from conventional oil and gas production.

Technologies exist to adequately treat flowback and produced water for reuse as hydraulic fracturing fluids or direct discharge into streams and lakes. Based on the probable extent of UGEE development in Ireland and Northern Ireland and the likely volumes of flowback and produced waters, the best management option would be the use of centralised treatment facilities with the proper treatment technologies. These would be needed in the island of Ireland before any large-scale production. On-site treatment at individual well pads using modular units is likely to be implemented during initial development.

Both on-site and centralised treatment facilities should be subject to appropriate regulations, approvals, oversight and inspections by regulatory bodies that are specific to UGEE projects/operations.

Environmental monitoring is needed before, during and after UGEE activities at both sub-regional and local scales. This is required at each stage, i.e. baseline monitoring prior to any construction or operations; operational monitoring during construction, drilling, hydraulic fracturing and production activities; and post-closure monitoring conducted following completion of gas production, well decommissioning and site restoration.

Specific requirements should include monitoring of surface and groundwater during the construction and operational stage to detect any potential impacts on groundwater quality or related receptors; post-closure monitoring of methane gas is considered especially important at the wellhead of production wells in the post-closure stage.

The monitoring programmes should also address soils, subsoils and baseline ground gas sampling; long-term methane monitoring is necessary to detect possible cement or well deterioration after decommissioning. A clear conceptual site model should be developed to understand the linkages between groundwater and surface water; the monitoring of environmental supporting conditions of freshwater and wetland habitats may also be required for ecologically sensitive areas.

This precautionary approach should underpin the recommendations for the compounds to be included in the list to be monitored for air quality purposes.

Seismic monitoring should include adequate baseline monitoring to characterise the regional structural geology and seismic characteristics of the area. Real-time high-resolution monitoring during operations should be linked to a traffic light system.

Monitoring at the scale of individual well pads and hydraulic fracturing operations, as well as at the sub-regional scale, is needed.

Monitoring and mitigation measures were compiled from an extensive literature review of measures and techniques that are currently being used or recommended for UGEE operations. These were considered in the context of various activities within UGEE projects/operations and, while these measures and monitoring techniques are not considered to be prescriptive in scope and specifications, they do represent a range of measures that may be considered in the specification of an operational management plan and environmental management plan.

Regulatory Regime

Full details of the work relating to the regulatory framework for environmental protection can be found in *Final and Summary Reports 5: Regulatory Framework for Environmental Protection*. It was found that the EU legislative framework is comprehensive, but that potential gaps exist as most directives and regulations do not specifically address UGEE projects or the deep underground environment. However, the European Commission Recommendation (2014/70/EU) "on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing" indicates how gaps should be addressed.

The European Commission is currently reviewing the scope of the Best Available Techniques (BAT) Reference Document (BREF) regarding the Mining Waste Directive and is also considering the development of a BREF that focuses on hydrocarbon exploration and production that would encompass UGEE.

A selection of countries and North American states was identified for review and five were selected, in consultation with the steering committee, for detailed assessment. This assessment examined Denmark, Germany, the UK and the states of Pennsylvania and Colorado, identifying their regulatory approach and specific requirements through the project's life cycle, together with a comparative analysis of the approaches.

It was concluded that an EU-wide approach to well integrity standards and compulsory EIA for UGEE projects/operations could be of benefit and that specific legislation could clarify areas where variation in interpretations of regulations across Member States of the EU may lead to different approaches. In addition, public engagement may need development in the EU countries analysed (except in Denmark, where EIA is compulsory for UGEE and public consultation is a requirement).

The US states provided examples of how a mature, rule-based system leads to specific controls and guarantees related to UGEE, although there was a lack of consistency between the states.

HIA provides a framework for an evidenced-based assessment of potential effects of UGEE on the health of a population and the distribution of those effects. It can also raise awareness among stakeholders of health implications, be an aid to transparent decision making and be a tool to engage stakeholders and support the identification of mitigation measures.

A potential disadvantage of HIA is the absence of a legal basis, which may limit its influence. HIAs can also be resource intensive and have a long duration.

At this early stage of development of UGEE and HIA in the island of Ireland, the incorporation of HIA within EIAs as a best-practice requirement is likely to be the best approach, as this will allow developments in the understanding of UGEE and in the practice of HIA to be accommodated. In addition, developments in HIA for UGEE in other countries should be tracked and the Irish approach adapted where improvements are identified.

Regulatory enforcement requirements and best operational practice (collectively identified as measures) were identified through links to Project B and Task 1 of Project C and by reference to a previous assessment by the European Commission.

The regulation of UGEE on the island of Ireland has been considered in reference to national legislation and to specific guidance on regulation for UGEE in Northern Ireland,[2] and by considering whether or not measures were definitely required by EU or Irish legislation.

Measures that may be required and, therefore, have a degree of uncertainty, could be required and implemented through land use planning, petroleum authorisation or licensing conditions issued by the Department of Communications, Energy and Natural Resources/Department for the Economy or conditions set in EPA licences (Ireland) or environmental permits and licences (Northern Ireland).

2 Department of Energy and Climate Change, 2013. Onshore oil and gas exploration in the UK: regulation and best practice – Northern Ireland.

The results of the work were also mapped on to island of Ireland regulations to consider whether or not these impose any additional requirements.

Public engagement was addressed through the detailed review of five case studies, which represent a range of project types and consultation approaches, to identify good practice and potential areas for enhancing engagement. The application of the Aarhus Convention and EIA and SEA Directives to proposed plans and projects involving UGEE was also reviewed. This analysis considered the stages in the planning and consent application process at which public information and participation are required and how these requirements can be best implemented in the context of the Irish national regulatory framework and the development of a public consultation strategy in the island of Ireland.

Several conclusions were drawn from the review: the geographical scope, duration and scale of consultation should be relevant to the scale of the plan or programme for consultation; a broad range of stakeholders and consultees should be engaged and their availability considered; the format of the consultation should be driven by stakeholders, and consultation is required at all stages of UGEE projects; and, finally, the consultation process should be managed by advocates of the consultation and engagement process rather than by advocates of the project. Evaluation of a consultation process needs to be an integral part of the whole process and should be continuous and responsive to change.

Conclusions

The scope of the UGEE JRP was developed to address two key questions: can UGEE projects/operations be carried out in the island of Ireland while also protecting the environment and human health; and what is "best environmental practice" in relation to UGEE projects/operations?

The programme concluded that many of the activities associated with UGEE projects/operations could proceed on the island of Ireland, while protecting the environment and human health, using the best practices identified in Project B and applying the current regulations, together with a small number of additions and modifications complemented by adequate implementation and enforcement. However, there are three main potential impacts where the data and/or experience do not allow a conclusive assessment of their consequences and these would require clarification before environmental protection and human health can be ensured:

1. Pollution of groundwater aquifers due to failure or deterioration of well integrity. The drilling and construction of wells is a routine activity in the water and oil and gas sectors, and standards for their design and construction are well established. However, experience shows that there are examples of failed wells or those where well integrity has deteriorated. It is believed that a rigorous process of design, design review, construction supervision and operational monitoring (with remedial works if necessary) could mitigate this impact, although this cannot be demonstrated without further evidence. There is incomplete knowledge of the aquifer systems in the two study areas, with specific data gaps related to the "deep" hydrogeological characterisation of these areas and how the deeper groundwater flow systems may be hydraulically connected to shallow aquifers and receptors. As a consequence, the impacts cannot be reliably addressed in the absence of baseline monitoring data; such data should be collected over a period of 12 months prior to licensing of any hydraulic fracturing activities.
2. The fracking process intentionally generates cracks in the rocks that typically extend to 100–200 m; however, statistical analysis suggests that they can extend up to 300 m and, in very rare circumstances, up to 500 m. The separation between the fracking activity and the base of the aquifer should exceed these distances to mitigate the risk of pollutant and gas migration to the aquifer; this distance could be reduced if impermeable rock layers separate the two. However, the risk of pollutant and gas migration from the newly fractured shale rocks (after fracking) into the overlying aquifers may be compounded or increased by the existence of pre-existing permeable faults that could provide pathways for pollutants and gas between the two separate layers. The seismic elements of this programme have developed a new approach to evaluate fracture propagation and length, which requires site-specific data on seismic activity, rock characteristics and existing fracture networks to refine these estimates for the two study areas. These data would come from baseline monitoring (originally anticipated to be within the scope of work

for the programme) and more detailed monitoring during UGEE operations.

3. Gas emissions have been cited by the public as an issue of concern from a human health viewpoint. During active operations, these can be adequately managed by mitigation measures that address the health and safety of the workforce who would have a much higher level of exposure than the general public. Following the closure of a well, it is sealed and capped to prevent egress of gas. However, there is evidence from conventional oil and gas wells that this closure process is not always successful or may deteriorate over time, with the result that stray gas leakage has occurred at sites. Neither the reasons for this nor the scale of the emissions are known quantitatively and therefore their impact cannot be reliably assessed until further data are available. Methane is an important greenhouse gas and therefore this is an issue of concern, although it should be noted that approximately 90% of greenhouse gas emissions are likely to occur during the generation of electricity rather than at the production stage.

Prior to any authorisation for hydraulic fracturing, these issues should be better resolved. Adequately designed baseline monitoring programmes for water and seismicity will assist in improving the site-specific knowledge and therefore the assessment of the risk of groundwater contamination by well failure and of induced seismicity in the two study areas. Baseline monitoring was not undertaken prior to preparation of this report (see section 1.3).

Similarly, two- and three-dimensional seismic surveys, which would be expected to be undertaken by the operators prior to any hydraulic fracturing activity, will provide further subsurface knowledge that will enable better characterisation of subsurface geology, hydrogeology and natural seismic activity.

Long-term gas emissions are more difficult to address, since local datasets are not available. In the long term, post-closure methane emissions are the subject of ongoing international studies, but these will take time to conclude. If UGEE projects are initiated, then it is recommended that more complete closure, testing of closure procedures (cementing, etc.) and then long-term monitoring should be specified. In other jurisdictions, funding for post-closure monitoring has been arranged through the provision of a bond by the developer and this should be considered in Ireland and Northern Ireland if any hydraulic fracturing projects are to be undertaken.

Existing regulations in Ireland and Northern Ireland have broad applicability to potential UGEE project/operations, but there remain some potential deficiencies and ambiguities that should be clarified, notably in relation to the Mining Waste Directive, whether or not EIA is required (especially for small-scale projects), the requirement for SEA at national, regional or multiproject levels and the protection of air and water.

The European Commission Recommendation (2014/70/EU) and emerging best practice attempt to cover gaps in underground risk protection, but there is no guarantee that the proposed approaches will be required by regulators or adopted by industry. Many of the potential uncertainties in legislation could be clarified through guidance that clearly identifies how legislation will be applied. Best practice guidance should, therefore, be adopted or developed for UGEE operations in the island of Ireland. The guidance should, as a minimum, address all the points raised in the European Commission Recommendation and in this project.

Should any hydraulic fracturing proceed on the island of Ireland, and recognising that the development of both UGEE and HIA are in the early stages of development in the island of Ireland, incorporating HIA within EIAs as a best-practice requirement is likely to be the best approach, as this will allow developments in the understanding of UGEE and in the HIA practice that should be accommodated. In addition, developments in HIA for UGEE in other countries should be tracked, and the Irish approach adapted where improvements are identified.

1 Introduction

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/operations (including construction, operation and after-care).

The UGEE Joint Research Programme (JRP)[3] was designed as five interlinked projects, which include field studies (baseline monitoring of water and seismicity) and an extensive desk-based literature review of UGEE practices and regulations worldwide. The scope of the work was published for public consultation and, on the basis of the submissions, modified to accommodate a wide range of views and opinions. The programme has been designed to produce the scientific basis that will assist regulators – in both Ireland and Northern Ireland – in making informed decisions about whether it is environmentally safe or not to permit UGEE projects/operations involving fracking. As well as conducting research in the island of Ireland, the UGEE JRP looked at and collated evidence from other countries.

The environmental impacts of UGEE projects/operations considered were those arising from all UGEE projects/operations, not just from hydraulic fracturing activities. All stages of UGEE projects/operations were considered (i.e. including construction, commissioning, operation, decommissioning and aftercare, as well as off-site and other developments).

1.1 Context

In Ireland, onshore petroleum licensing options were awarded in March 2011, as preliminary authorisations, to three exploration companies seeking to assess the shale gas potential within the Northwest Carboniferous Basin (NCB) and the Clare Basin (CB). In Northern Ireland, one exploration company secured a Petroleum Licence from the Department of Enterprise, Trade and Investment (DETI) to explore the potential for shale gas reserves in County Fermanagh, within the NCB. The specific UGEE exploration areas involved are shown in Figure 1.1, based on previously held licences.

In Ireland, exploration drilling, including drilling that involves hydraulic fracturing, is not allowed under current licensing options. Nonetheless, two of the three companies have submitted applications for follow-on licences, which would include exploration drilling. The DCENR is not considering these applications further until the findings of the UGEE JRP have been published. In addition, the DCENR will not consider any applications for exploration authorisations in other onshore areas until the UGEE JRP has concluded. In Northern

Figure 1.1. Overview of the case study areas of the UGEE Joint Research Programme.

3 www.ugeeresearch.ie

Ireland, the DETI licence described above was terminated, as the licence conditions (a "drill or drop" work programme requiring specified exploration, including drilling a stratigraphic borehole, in the first 3 years and, before the end of year 3, a commitment to drilling and exploration within the following 2 years) were not met.

In May 2012, the EPA released the report from a preliminary study *Hydraulic Fracturing or "Fracking": A Short Summary of Current Knowledge and Potential Environmental Impacts.*[4] This short desk-based study was conducted for the EPA by the University of Aberdeen and provided an introduction to the environmental aspects of UGEE projects/operations, including a review of regulatory approaches used in other countries and areas for further investigation and research.

In brief, some of the key findings of the study were as follows:

- the importance of adequate knowledge of local geology in order to assess potential impacts on groundwater quality and the possibility of induced seismic activity;
- the importance of well integrity for preventing groundwater contamination;
- the uncertainty regarding the "carbon footprint" of shale gas in comparison to conventional natural gas, which is an important climate change issue;
- the need of baseline studies before drilling begins (surface water; groundwater; seismic); and
- the newness of UGEE as an area of research (i.e. only a limited number of published, peer-reviewed, scientific studies are available in this area).

The information provided by the preliminary research project was used, along with other sources, such as European Commission (EC) reports,[5] to develop the terms of reference for a more comprehensive research programme. Between 11 January and 8 March 2013, the EPA administered a public consultation[6] in relation to the draft terms of reference[7] for this research programme. Submissions[8] were assessed and relevant comments taken into account, when finalising the scope of work.

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

The key questions addressed by the UGEE JRP were as follows:

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

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

1.2 Objectives and Goals of the Integrated Synthesis Report

This *UGEE Joint Research Programme Integrated Synthesis Report* is an integrated summary of the research undertaken under the UGEE JRP, linking the five Projects (A1, A2, A3, B and C). It is intended to be a concise, plain English account of the overall research, including key conclusions from the work. The underlying objective is to outline the pressures and impacts resulting from UGEE projects, consider potential mitigation measures, assess the adequacy of the regulatory framework, recommend appropriate improvements and, as far as possible, assess the potential impacts of UGEE projects from an environmental and health viewpoint.

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

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

6 http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee%20research/2013publicconsultation/

7 http://www.epa.ie/pubs/reports/research/ugeejointresearchprogramme/drafttermsofreferenceforugeeresearchprogramme.html

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

1.3 Overview of the UGEE Joint Research Programme

The main aim of the UGEE JRP was to further the understanding of potential impacts on the environment and human health from UGEE projects/operations. It comprised five separate but interlinked projects, as follows:

- Baseline Characterisation:
  - Project A1: Groundwater, Surface Water and Associated Ecosystems;
  - Project A2: Seismicity;
  - Project A3: Air Quality;
- Impacts and Mitigation Measures:
  - Project B: UGEE Projects/Operations: Impacts and Mitigation Measures;
- Regulatory Framework:
  - Project-C: Regulatory Framework for Environmental Protection.

Baseline monitoring is frequently cited as a pre-condition for licensing of UGEE activity. Therefore, the terms of reference and scope of work for the UGEE JRP identified a requirement to identify, evaluate and undertake appropriate potential baseline monitoring requirements for water, air and the analysis of seismic activity. Requirements for baseline monitoring are defined in the European Parliament resolution "Environmental impacts of shale gas and shale oil extraction activities" [2011/2308(INI)], although a review of international literature provided relatively little information on the specifics of baseline monitoring.

Following a comprehensive assessment of the two study areas, the JRP made proposals for baseline monitoring for the assessment of water, air and the analysis of seismic activity with a window of up to 2 years to complete the monitoring programme. This timeline for the baseline monitoring programme would mean that the overall findings of the research would be delivered after the project deadline of 2016.

The original timeline for the research envisaged that the entire programme, including water, air and seismic baseline data acquisition, would conclude by 2016. The steering committee considered that, were the baseline data acquisition to commence, the estimated timeline for the overall research programme to conclude would now be in 2018, at the earliest. The decision was therefore taken to prepare a synthesis report drawing together the conclusions of the research to date, in order that these findings could be reviewed and policy decisions formulated with regard to the use of this technology in the island of Ireland.

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

The absence of the recommended baseline data inhibited assessment of two of the three key pressures that are highlighted by the JRP as having a significant level of impact uncertainty:

- groundwater pollution as a result of failure or deterioration of borehole integrity; and
- groundwater pollution from pollutant transport through induced and natural fractures.

The third pressure, for which there was inadequate information in the literature, is the emission of stray methane gas following project closure; baseline monitoring would not improve knowledge of this issue.

1.4 Project A1: Groundwater, Surface Water and Associated Ecosystems

Project A1, summarised by its scope in Figure 1.2, initially had two primary components:

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

The research covered by Project A1 includes:

- the importance of geology and hydrogeology in environmental protection and considerations of human health (e.g. drinking water);

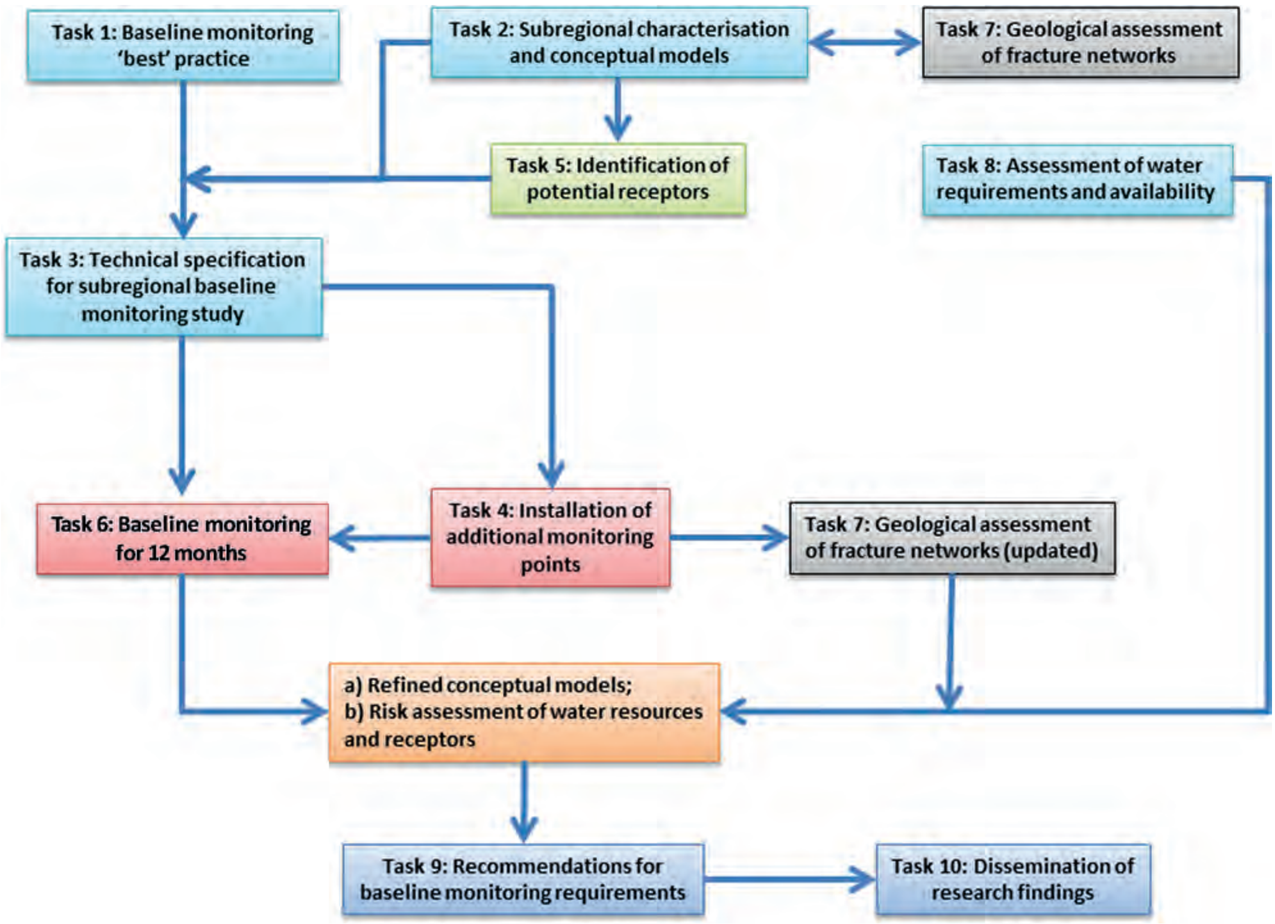

Figure 1.2. Tasks of Project A1 of the UGEE Joint Research Programme.

- assessment of existing baseline monitoring and recommendations for future development of the baseline monitoring network in order to inform best practice, in the island of Ireland context; as noted in section 1.3, the baseline monitoring was not implemented prior to the preparation of this report;
- increasing geological and hydrogeological knowledge and the development of a conceptual understanding, in the context of the case study areas;
- evaluation of the connectivity between the unconventional gas source rocks and water resources; and
- evaluation of the water requirements of UGEE projects/operations (for an individual, a typical pad and for each permit area) in the context of the study areas and assessment of whether the local catchments could meet these requirements or not without adverse environmental impacts.

The following reports were produced from Project A1:

- *Final Report 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems*; and
- *Summary Report 1*: *Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems*.

1.5 Project A2: Seismicity

Baseline characterisation of seismicity is required for the potential impacts of UGEE projects/operations to be assessed. The research covered by Project A2 (Seismicity) comprised seven tasks:

- Task 1: assessment of existing baseline monitoring operated worldwide for UGEE projects/operations;
- Task 2: evaluation of methodologies for the monitoring of ground deformation that may be associated with UGEE projects/operations;

- Task 3: assessment of existing data on natural seismicity in the island of Ireland;
- Task 4: assessment of the magnitude and physical effects of induced seismicity that may be associated with UGEE projects/operations in the island of Ireland;
- Task 5: defining the technical specification for sub-regional seismic baseline monitoring;
- Task 8: examination of global experience of seismic events stimulated by UGEE operations; and
- Task 9: assessment of pre-fracturing modelling techniques.

The structure of Project A2 is shown in Figure 1.3. Tasks 6 and 7, relating to the monitoring, were not progressed prior to the preparation of this report, as noted in section 1.3.

The following reports were produced from Project A2:

- *Final Report 2: Baseline Characterisation of Seismicity*; and
- *Summary Report 2: Baseline Characterisation of Seismicity*.

1.6 Project A3: Baseline Characterisation of Air Quality

Potential air emissions from UGEE projects/operations may originate from sources such as:

- trucks and drilling equipment;
- natural gas processing and transport;
- fugitive emissions;
- evaporative emissions of chemicals from wastewater;
- spills and well blow-outs; and
- post-operation leakages from well.

Project A3 (Air Quality) assessed the requirements and needs for additional air baseline monitoring (frequency, location and types of pollutants to be covered) in the context of Environmental Impact Statements (EIS). The Environmental Impact Assessment (EIA) Directive (2011/92/EU) refers to impacts on air, such as air quality (pollutants, suspended particles); odour; noise; vibration and radiation. Existing sources of air pollution were identified and the components of any existing air pollution identified and quantified. Potential emissions

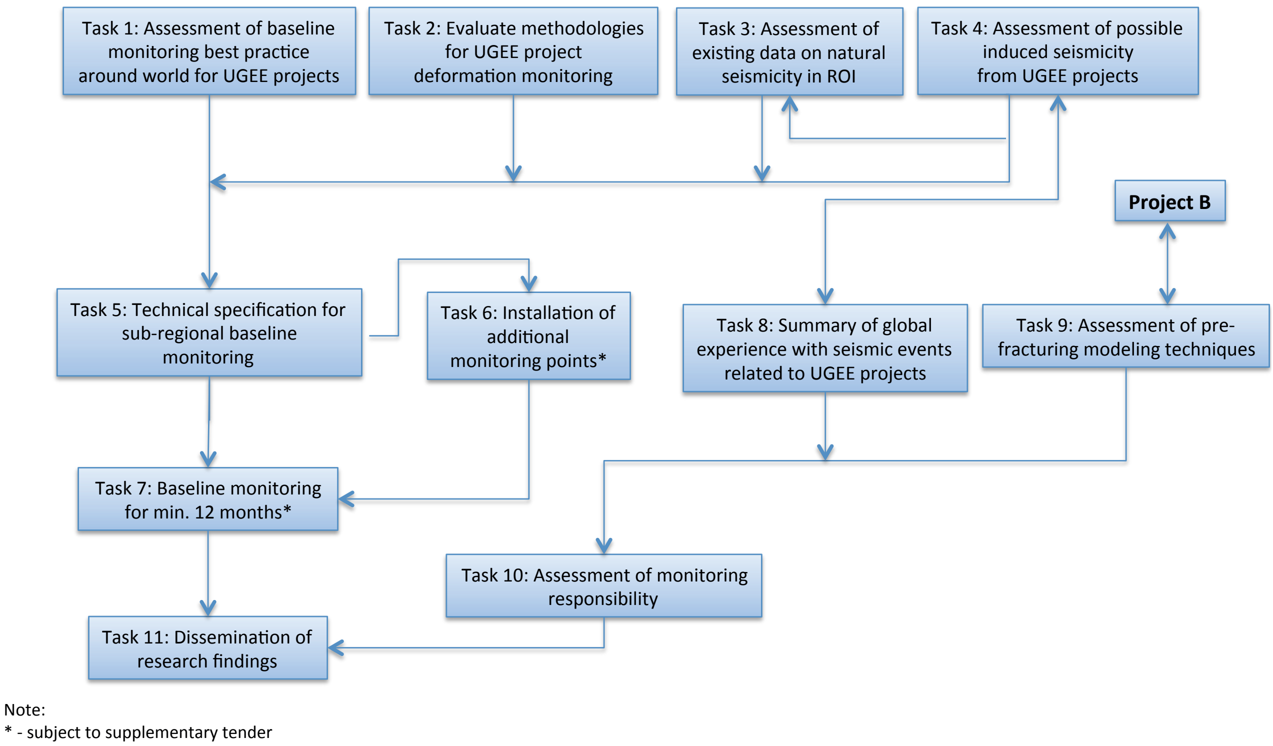

Figure 1.3. Tasks of Project A2 of the UGEE Joint Research Programme.

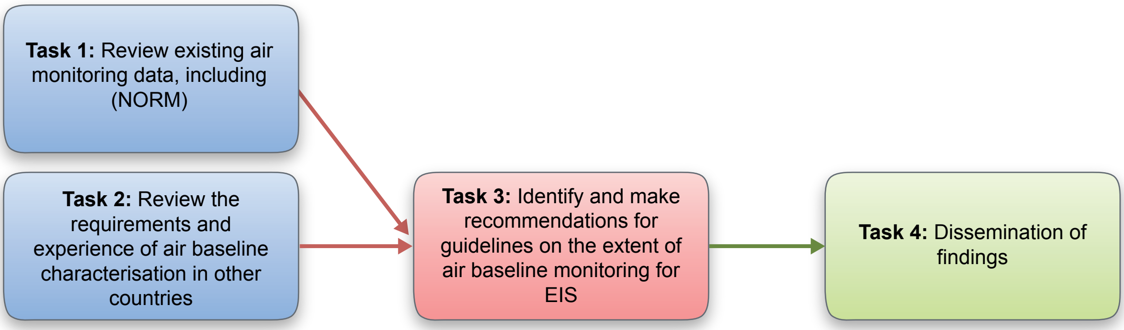

Figure 1.4. Tasks of Project A3 of the UGEE Joint Research Programme.

covered include, but were not limited to, monitoring requirements under the EIA Directive.

The tasks addressed by this project are shown in Figure 1.4.

The following reports were produced from Project A3:

- *Final Report 3: Baseline Characterisation of Air Quality*; and
- *Summary Report 3: Baseline Characterisation of Air Quality*.

1.7 Project B: Impacts and Mitigation Measures

Project B involved the assessment of the impacts and mitigation measures for UGEE projects/operations. The objectives of Project B included:

- the identification and detailed evaluation of the potential impacts on the environment and human health associated with UGEE projects/operations; and
- the identification and evaluation of successful mitigation measures for the potential impacts.

The EIA Directive will apply to all UGEE projects/operations where hydraulic fracturing is proposed. The outputs from Project B will assist regulators who may be required to assess EIAs for UGEE projects in the future to understand the potential impacts that should be considered by the applicants and the information required to evaluate the proposed mitigation measures effectively.

There were nine tasks within Project B, each dealing with specific elements of the impacts and mitigation measures of UGEE projects (Figure 1.5):

- Task 1: environmental water quality impacts and mitigation measures;
- Task 2: water resource use impacts and mitigation measures;
- Task 3: recycling and reuse of flowback and produced waters;
- Task 4: other additional potential impacts and mitigation measures;
- Task 5: life cycle assessment;
- Task 6: chemical use, impacts and mitigation measures;
- Task 7: treatment and disposal of flowback and produced waters;
- Task 8: best practice for environmental monitoring of potential impact – linking Projects A1, A2 and A3;
- Task 9: assessment of existing and potential monitoring and mitigation techniques.

The following reports were produced from Project B:

- *Final Report 4: Impacts and Mitigation Measures*; and
- *Summary Report 4: Impacts and Mitigation Measures*.

1.8 Project C: Regulatory Framework for Environmental Protection

Project C focused on the regulatory framework for environmental protection for UGEE projects/operations. Project C comprised four main tasks (Figure 1.6) and five primary components:

1. review of EU environmental legislation;
2. review of regulatory approaches in other countries;
3. assessment of the potential role of Health Impact Assessment (HIA);

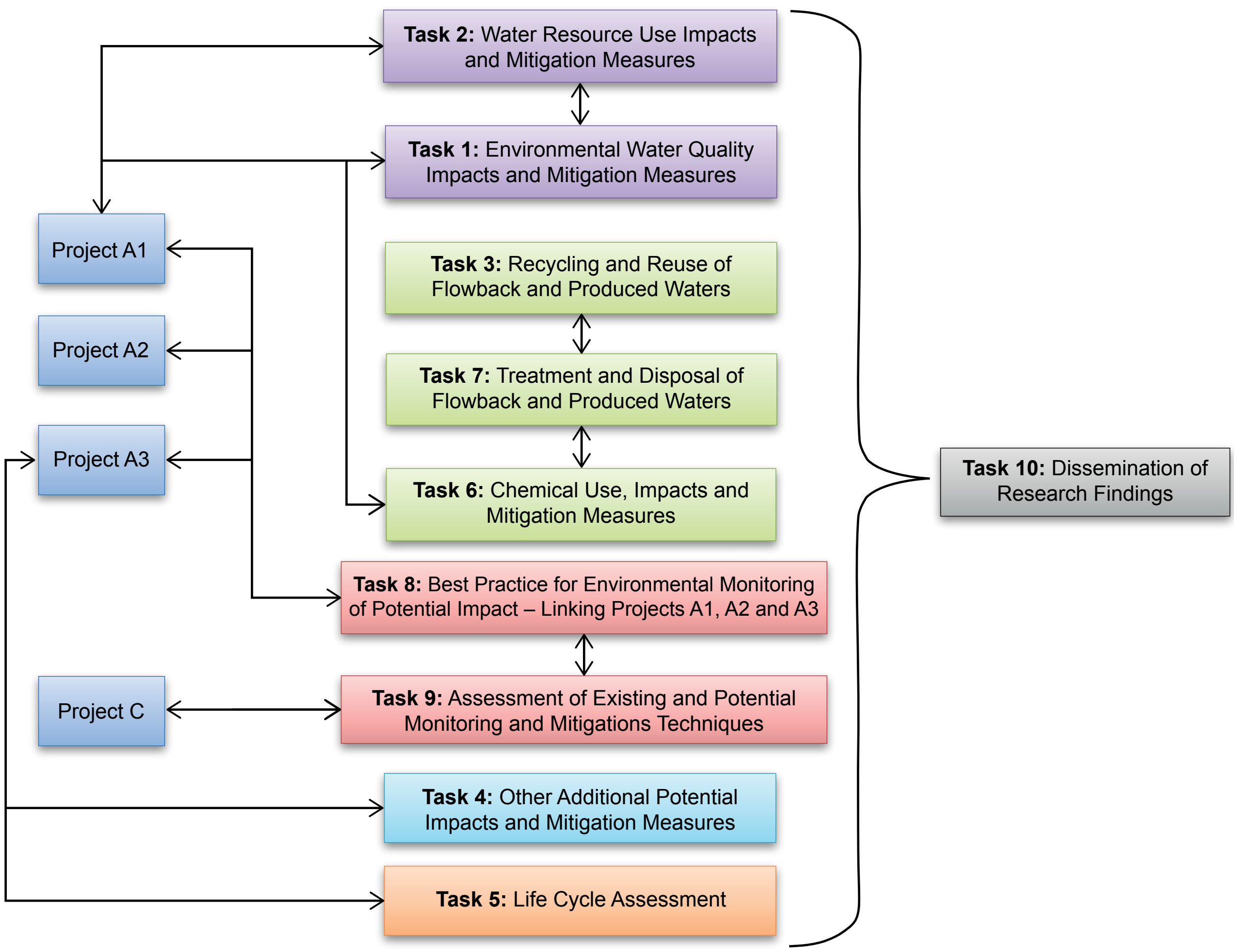

Figure 1.5. Tasks of Project B of the UGEE Joint Research Programme.

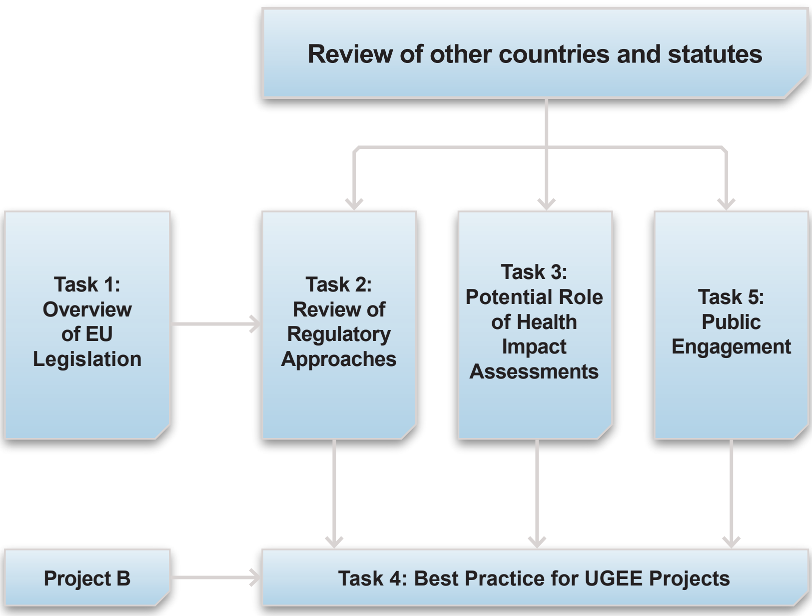

Figure 1.6. Tasks of Project C of the UGEE Joint Research Programme.

4. best practice for UGEE projects/operations; and
5. review of examples of public engagement in UGEE.

The following reports were produced from Project C:

- *Final Report 5: Regulatory Framework for Environmental Protection*; and
- *Summary Report 5: Regulatory Framework for Environmental Protection*.

1.9 Report Structure

This report provides an overview of each of the five interlinked projects in Chapters 2–6.

Chapter 7 summarises the potential impacts of the activities associated with any potential UGEE projects/operations, together with a review of the effectiveness of existing legislation and mitigation measures to address these impacts.

Conclusions are drawn in Chapter 8.

2 Groundwater, Surface Water and Associated Ecosystems

Project A1 specifically addressed groundwater, surface water and associated ecosystems and initially comprised two primary components:

- characterisation of the case study areas to help understand the three-dimensional relationship between potential sources of contamination and the near-surface environment; and
- baseline monitoring of groundwater, surface water and associated ecosystems, informed by the results of the characterisation, including conceptual hydrogeological models; this element of the research programme was not progressed.

Potential UGEE-related activity, including hydraulic fracturing, carries environmental risks that are well described in international literature. As a consequence, environmental baseline characterisation and monitoring are necessary prior to any UGEE activity taking place as a means of (1) assessing the risks to the environment; and (2) identifying and taking measures to mitigate potential environmental impacts in the future.

Full details of the work relating to groundwater, surface water and associated ecosystems can be found in *Final and Summary Reports 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems*.

2.1 Baseline Monitoring Best Practice

The primary objectives were to summarise existing monitoring activity and environmental pressures in the case study areas; to summarise baseline monitoring “best practice” in international literature; to highlight inferred data gaps; and to provide recommendations for sub-regional baseline monitoring of groundwater, surface water and associated ecosystems.

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)]. The purpose of baseline monitoring is to produce data that can be used to develop a better understanding of the water environment (surface and subsurface) and to describe environmental conditions before any UGEE activity has started and therefore to identify, assess, and monitor potential impacts in the future (i.e. after potential UGEE activity has started).

The baseline monitoring defined under this JRP is a sub-regional monitoring programme that covers both case study areas. This is different from the baseline monitoring that would be required of UGEE operators as part of the licensing process and would be case- and site-specific and designed to ensure protection of specific receptors.

2.2 International Best Practice

Information on baseline monitoring is mostly guided by the literature in countries where UGEE projects have been implemented or planned.

The general consensus on baseline monitoring from published research suggests that it is both desirable and necessary (1) to identify and be able respond to impact; and (2) to address questions of accountability. The published research suggests that baseline monitoring is historically inadequate in many places where UGEE activity has taken place; that it should be made publicly available; that it is a shared responsibility of the operators and the regulators; and that, in many water environments, the quantitative aspects of baseline monitoring are as important as the qualitative aspects.

As a result of the many parameters involved, the logistical and financial burden of baseline groundwater monitoring can be significant and there is a need to make decisions about “common” or “indicator” compounds that signal the presence of UGEE-related contaminants.

Surface water impacts may be of local scale (associated with individual drill pads) or may cumulatively take on added significance at the catchment scale; they can be of a physical nature as well as of a chemical nature. The potential impacts are associated with both controlled (licensed) and uncontrolled (deliberate/accidental) discharges to surface waters.

Waste fluids may retain trace chemicals and contain metals (e.g. barium and strontium) and/or naturally occurring radioactive materials (NORM), which can adsorb to stream sediments in proximity to surface water discharge locations.

International literature indicates a wide range of water requirements, which depend on circumstances. Large abstractions, even for short durations, can cause environmental stresses and impacts, depending on the source of the water and the conditions of the water resource at the time of the abstraction. The assessment of abstractions and water availability has to consider the different water balance components and status indicators of catchments.

2.3 Best Practice in an Island of Ireland Context

The decisions about baseline monitoring must consider the hydro(geo)logical settings of the case study areas, which describe potential pathways of contamination and determine the risk of contamination of receptors. The key to risk identification and mitigation is to understand Source–Pathway–Receptor (S-P-R) relationships at any proposed UGEE sites.

Groundwater flow in the two case study areas is expected to be influenced by the lithological (physical geological) characteristics of the areas, the degree of faulting and fracturing of bedrock aquifers and the presence or absence of karst conduits in limestone formations.

The siting of operational monitoring of any potential future UGEE operations should take into account groundwater vulnerability (the susceptibility of an aquifer to become contaminated from surface sources of pollution), which is assessed on the basis of a range of risk factors.

2.4 Summary of Existing Monitoring

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 EU Water Framework Directive (WFD) (200/60/EC) and relevant national statutory instruments that have followed.

2.5 Existing Environmental Pressures and Water Status

Existing environmental pressures on water resources and aquatic ecosystems derive from land use and economic activities that take place within the case study areas. They involve both diffuse and point sources of pollution, as well as abstractions. These have been assessed by the EPA and the NIEA as part of WFD reporting. For each water body, a status classification has been prepared, which describes the extent to which quantitative and qualitative pressures have impacted on the environmental conditions.

Several river water bodies in both study areas fail to meet the WFD good status objectives (approximately 60% in the CB and approximately 30% in the NCB).

All the lakes within the CB area are too small to be classified for the WFD; in the NCB, the majority of lakes are of moderate status, with one lake of poor and one lake of bad status.

All groundwater bodies in the CB are of good quantitative and chemical status and therefore abstraction levels are currently considered to be sustainable; there are no known issues with groundwater chemistry or resulting impacts on drinking water or surface water bodies. All groundwater bodies in the NCB study area are considered to be of good quantitative status, with three classified as being of poor chemical status.

2.6 Recommendations for Baseline Monitoring

The sub-regional monitoring approach recommended for the two case study areas is receptor focused and targets analyses of constituents and compounds that (1) describe general environmental pressures; (2) can be used to fingerprint both natural gas presence/origins and other chemical impacts; and (3) address the cumulative impact of UGEE activities at the catchment scale. Gaps in the existing monitoring networks were identified and a sub-regional baseline monitoring programme was recommended, which includes:

- groundwater sampling of existing public and private supply wells, springs and potential new monitoring wells;
- groundwater level monitoring in select, existing and any potential new monitoring wells;
- surface water sampling of lakes and streams, including designated protected areas under the WFD;
- hydrometric monitoring of spring discharges and stream flows at a limited number of locations (in the NCB only) where particular data gaps exist; and

- sediment monitoring in rivers and lakes for chemical constituents of flowback and production waters.

S–P–R relationships are conceptually well understood in the case study areas that have been examined as part of the UGEE JRP. However, plans for UGEE activity at individual locations are not yet known, therefore S–P–R relationships that are specific to a particular UGEE project would have to be addressed individually should such plans be presented.

2.7 Sub-regional Characterisation and Conceptual Hydrogeological Models

Tasks 2, 5 and 7 developed a geological characterisation of each study area, conceptual hydrogeological models, an updated assessment of potential receptors and a summary of implications for the baseline monitoring programme. These implications were as follows: wells and springs that are used for public and private regulated water supplies should be prioritised, but a select number of private unregulated wells should also be included; to the extent practicable, all of the main bedrock formations in the two study areas should be represented in the sampling programme; both streams and lakes should be sampled; and it was recommended that screening be carried out on sediments and that further analysis of radium isotopes be conducted for characterisation purposes.

A subset of designated groundwater-dependent terrestrial ecosystems (GWDTEs) or habitats with qualifying interests as GWDTEs should be considered further in the baseline monitoring programme.

2.8 Addressing Deep Geological/Hydrogeological Data Gaps

The characterisation and knowledge of deep geological and hydrogeological conditions represent the principal data gaps associated with both case study areas. Specific gaps in the hydrogeological knowledge of the two study areas relate to potential deep groundwater flow, deep water quality and hydraulic connectivity between unconventional gas target formations and shallow receptors. 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.

2.9 Sub-regional Baseline Monitoring Programme

It was recommended that a precautionary approach to sub-regional baseline monitoring that is comprehensive in scope and extent should be adopted; this would be capable of:

- describing general environmental pressures;
- distinguishing the impacts of UGEE-related activity from general environmental pressures; and
- addressing cumulative impacts across catchments.

Sub-regional baseline monitoring should be receptor focused and is a long-term commitment.

The recommended programme addresses all of the major groundwater, surface water and aquatic ecosystem receptors in the two case study areas. With a sub-regional focus, the monitoring programme will not address all monitoring needs that are local scale or case specific but will provide information about baseline conditions at the catchment scale.

Much of the data will be similar to that provided by existing monitoring initiatives that have been undertaken by public bodies in both Ireland and Northern Ireland. However, the collection of data that are not commonly gathered through routine sampling and analysis was recommended; principal among the new parameters are natural gas constituents and NORM in groundwater.

The recommended baseline monitoring programme builds on existing monitoring initiatives to avoid duplication and allows for a degree of flexibility in the implementation of its findings, without compromising on project objectives. Accordingly, an approach of “adaptive monitoring” was recommended.

The baseline monitoring programme that was specified includes groundwater sampling (existing water supply wells, springs and new monitoring wells), rivers and lakes, stream sediments and hydrometric monitoring of spring discharges and stream flows.

Both study areas share a common data gap related to deep hydrogeological characteristics and conditions. Detailed hydrogeological characterisation of deeper formations is, therefore, needed in the future. Because the environmental risks associated with hydraulic fracturing operations are both case- and location-specific, the onus of deep hydrogeological characterisation should be placed on UGEE companies, under the terms of legislation and conditions set by regulators.

2.10 Quantitative Assessment of Water Resources

The potential water use requirements of hydraulic fracturing in the two case study areas were calculated based on the probable commercial scenarios developed in Project B. The available water resources in the two case study areas were also described and together these provided a means of identifying potential impacts from water abstractions.

Any future proposals for UGEE-related abstractions would have to be assessed on a case-by-case basis, with detailed and specific information provided about drilling and hydraulic fracturing schedules in order to assess temporal and cumulative impacts, particularly on small streams and lakes in the study areas.

Available water resources are represented by rainwater, lakes and reservoirs, streams and rivers, and groundwater in bedrock aquifers. Existing abstraction pressures are currently low and capacity is available to supply potential future UGEE development in both study areas, although this would ultimately be conditioned and influenced by how and where the development would proceed, both spatially and temporally.

Identifying and documenting volumetric impact is relevant in a regulatory context, but it is ecological impact that ultimately determines if an abstraction authorisation should be granted or not.

The bedrock aquifers in both study areas are viable sources of water to meet demands, at least in part.

Potential future UGEE-related abstractions would have to be evaluated at both local and catchment level. As UGEE activity is rarely confined to a single location, abstractions may have a cumulative impact that would need to be addressed by appropriate monitoring.

Best practices in relation to UGEE-related abstractions indicate that 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). However, regional baseline monitoring should be undertaken by public authorities (for example, the baseline monitoring of the two study areas originally intended to be included in this JRP); project and site-specific monitoring and reference conditions assessment would be expected to be undertaken by the industry as part of the planning process.

3 Seismicity

The process of hydraulic fracturing is generally accompanied by microseismicity, usually defined as earthquakes with magnitudes of 2 or less that are too small to be felt. Two types of induced events can be defined: “fracked” events, whose size is constrained by the energy of the injection process; and “triggered” events, whose size depends largely on the amount of stored-up elastic strain energy already present in the rocks.

It is clear that natural seismic activity in the island of Ireland is low and it is much lower than in the neighbouring countries of Wales, England and Scotland. Since the frequency and magnitude of triggered events are directly linked to the natural seismicity of an area, it is extremely unlikely that hydraulic fracturing will have any potentially troublesome seismic consequences for normal receptors. The size of fracked events is constrained by the energy used in the fracking process and the general consensus in published literature is that the process of hydraulic fracturing, as presently implemented for shale gas recovery, does not pose a high risk for inducing felt, damaging or destructive earthquakes.

A series of tasks were undertaken to assess seismicity associated with UGEE projects/operations, both internationally and in the study areas. These are outlined in the following sections. Full details of the work relating to seismicity can be found in *Final and Summary Reports 2: Baseline Characterisation of Seismicity*.

3.1 Assessment of Existing Baseline Monitoring Operated Worldwide for UGEE Projects/Operations

The fundamental principles of earthquakes and seismology that are important for seismic monitoring were examined, including frequency–magnitude distributions for earthquakes and how activity rates are likely to affect the duration of monitoring required both before commencement and after cessation of any UGEE operations. Requirements for reliable detection and location of earthquakes were also considered, particularly with respect to how station density needs to increase in order to detect and locate smaller earthquakes in any given region.

The geothermal industry has implemented baseline monitoring extensively and examples of this were described. The application of microseismic monitoring to monitor the fractured volume in UGEE projects/operations was also described.

It was concluded that baseline monitoring should be an essential requirement of any future UGEE-related operations and that the extensive experience of seismic monitoring in the geothermal industry may be considered as best practice for UGEE.

Current best estimates of the seismicity rate across the island of Ireland are low and a long period of baseline monitoring may be required to determine the rates of seismicity in each of the two study areas reliably. Detailed monitoring will be required in each study area to detect any unusual seismicity that may suggest that seismicity rates are higher in the study areas than generally in the island of Ireland, or that there is seismicity associated with any specific fault structure. A monitoring period of between 1 and 2 years may be appropriate for this purpose.

3.2 Evaluation of Methodologies for the Monitoring of Ground Deformation Associated With UGEE Projects/Operations

Ground deformation from UGEE projects/operations will not necessarily result in damage to structures, but it is important to monitor the motion at surface quantitatively to gauge potential damage and to address the potential concerns of the public and policymakers regarding impacts to the environment.

This task focused on data availability and presented the results of a study on the feasibility of InSAR for the island of Ireland using elevation and land cover data. It was concluded that adequate volumes of archive data are available. However, further analysis of the data would be required to verify this.

In addition to the regional coverage possible with InSAR, this technique also benefits from an archive of data from 1992 that can be used to establish a baseline of surface motion over any site where tiltmeters or Global Navigation Satellite Systems (GNSS) were not already installed prior to operations.

Since InSAR monitoring is generally applied to urban areas (due to the presence of abundant reflectors or scatterers, which are important for this technique), this task also examined its potential for monitoring ground deformation in non-urban areas of the island of Ireland. Over 90% of the island of Ireland consists of predominantly rural land cover types and would therefore have few persistent scatterers per km^2. However, other analysis techniques, such as Intermittent Small Baseline Subset (ISBAS), significantly increase the number and density of scatterers, offering significant advantages for the interpretation of ground motion.

The availability of data and new analysis methods mean that this technique is valid for the island of Ireland and specifically for the study sites in County Clare and the NCB, and therefore should be a requirement of any proposed UGEE projects.

In combination with the InSAR technique, complementary *in situ* methods such as GNSS and tiltmeters could be deployed, since integrating monitoring techniques provides better and more detailed information on deformation.

3.3 Assessment of Existing Data on Natural Seismicity in the Island of Ireland

An updated review of earthquakes in the island of Ireland was undertaken, combining historical data from available sources with modern instrumental data, to construct a single coherent catalogue. This catalogue was then used to estimate the background rate of natural seismicity that represents a numerical expression of the expected likely future seismicity of the region and that is consistent with the expected low strain rates.

Earthquake activity in the island of Ireland was found to be low, with nearly all of the seismic activity from both instrumental and historical sources concentrated around the coast; there is an almost complete absence of seismicity inland.

Using this catalogue, the calculated earthquake activity rates for the island of Ireland were found to vary depending on the assumed level of completeness of the catalogue. Using the same catalogue completeness thresholds as for Britain suggests that there should be an earthquake with a magnitude of 4 Mw or greater, somewhere in the island of Ireland and the surrounding offshore area, approximately every 476 years. However, given that the island of Ireland is a low seismicity region and that data are sparse, the calculated activity rates significantly overestimate the observed seismicity. The average activity rate for Britain suggests that there should be an equivalent magnitude earthquake approximately every 6 years. The reasons for the dramatic difference remain poorly understood, given the geological and tectonic similarity between the island of Ireland and Britain.

Modelling of possible ground motions for realistic examples of earthquakes with magnitudes in the range of those previously observed in Ireland suggests that ground velocities are unlikely to exceed typical levels at which cosmetic damage might occur. Cosmetic damage could be observed within a few kilometres of the source of an earthquake with a magnitude of 3; however, for damage to be observed at the surface, the earthquake source would need to be very shallow, i.e. less than a few kilometres. Proper regulation would not permit hydraulic fracturing where pre-existing shallow fault zones exist. Similarly, larger earthquakes, with magnitudes of 4.0 or above, are only likely to approach the limits for cosmetic damage at distances of less than 10 km.

3.4 Assessment of the Magnitude and Physical Effects of Induced Seismicity That May Be Associated with UGEE Projects/ Operations in the Island of Ireland

State-of-the-art developments in Coulomb Rate State theory (which states that stress increases promote and decreases inhibit fault failure), together with statistical methods, were applied to model and forecast the triggered seismicity surrounding a hydraulic fracturing operation. Forecasts were derived for a series of scenarios given different reference activity levels and assumed baseline network qualities.

The existing fault network has a first-order effect on the success of the seismicity forecasts. Important information on the active structure could be obtained from detailed structural studies (as part of any baseline monitoring studies) and also from any available high-quality focal mechanisms of very-well-recorded earthquakes in the area. Significant systematic errors are introduced into induced rate estimates by assuming homogeneous reference rates.

Current seismic catalogues for the study areas are completely inadequate for forecast modelling on the spatial scales of the study areas and to the standard necessary. The necessary use of synthetic catalogues in this study to represent hypothetical baseline scenarios allowed the illustration of the nature of the uncertainties that might be expected.

Robust forecasts of the relevant parameters can only be made using a high-quality monitoring network and current best practice in data analysis. This should be augmented by denser local monitoring networks that should be deployed during any extraction operations.

The low background rate of seismicity observed in current Irish catalogues has two contrasting implications:

- From a scientific perspective, the dearth of data is unlikely to allow robust forecasts of the main parameters.
- In terms of impacts, this means that hydraulic fracturing projects in the island of Ireland are extremely unlikely to have any potentially troublesome seismic consequences for normal receptors. However, this conclusion would require confirmation by examination of good-quality baseline catalogues, for example those derived from a seismic monitoring programme.

3.5 Technical Specification for Sub-regional Seismic Baseline Monitoring

Seismic baseline monitoring is necessary to establish the rate of naturally occurring seismicity in an area; this can be used to quantify any induced seismicity by comparing the seismicity recorded during the operational phase of any UGEE project with the baseline. Baseline monitoring should provide a publicly available catalogue and is also useful to locate active faults and to map seismic noise levels in detail.

A detection threshold value of magnitude 0.5 ML was chosen for the baseline monitoring. This level of activity is unlikely to be felt by humans or to cause any superficial structural damage, and is consistent with the limit recommended for cessation of injection under the UK traffic light scheme for hydraulic fracturing operations. Depending on earthquake depth and local ground properties in general, only events with magnitudes $ML \geq 2$ are perceptible to humans and only events with magnitudes $ML \geq 2.7$ are thought have the potential to cause minor damage.

Existing seismic networks in the island of Ireland are not sufficient to detect and locate all local earthquakes with magnitudes $ML \geq 0.5$ in the two study areas. Local networks with inter-station spacings between 15 and 25 km were designed, which could reliably locate all such events during a baseline study. These should operate for at least 2 years in the two study areas and will require the deployment of at least 12 seismometers in the NCB and 10 seismometers in the CB.

Borehole seismometer installations are not necessary for the baseline study. However, if there is a complete absence of bedrock or stiff soil over a significant part of the area of interest, some shallow borehole sensors may be required.

3.6 Task 8: Examination of Global Experience of Seismic Events Stimulated by UGEE Operations

An extensive international review of induced seismicity from UGEE operations was undertaken, discussing examples of recent seismicity related to wastewater disposal in the eastern United States. Where possible, available UGEE data from recent examples, such as the induced seismicity in Blackpool, UK, and other locations, was used to investigate the controlling factors for induced seismicity during fluid injection and examine the relationships between injection volume and pressure, and induced seismicity.

The general consensus is that the process of hydraulic fracturing a well, as presently implemented for shale gas recovery, does not pose a high risk for inducing felt, damaging or destructive earthquakes. However, most sites of UGEE operations lack independent instrumentation for monitoring induced seismicity and earthquakes with magnitudes of 2.5 or less are unlikely to be felt or even detected unless local seismic monitoring networks are in place. There are at least five documented examples of earthquakes with magnitudes greater than 2 that have been conclusively linked to hydraulic fracturing for shale gas exploration/recovery:

- Blackpool, UK, in 2011, with an earthquake of magnitude 2.3 ML.
  - Garvin County, south-central Oklahoma, in 2011, where the largest earthquake had a magnitude of 2.9 ML.
  - Horn River, Canada, in 2011, with a largest magnitude of 3.8 ML;
  - Montney Trend, Canada, from May 2013 to October 2014, where 15 earthquakes had magnitudes of 3.0 ML or larger (the largest being 4.4). To date, this is the largest known earthquake triggered by hydraulic fracture operations in a hydrocarbon field anywhere in the world.
  - Crooked Lake, Alberta, Canada, in 2013–2104, where the largest event in the sequence had a magnitude of 3.8 Mw. Earthquake activity has continued in this region and a magnitude 4.4 earthquake on 12 January 2016, 15 km west-northwest of Fox Creek, is also suspected to be due to hydraulic fracturing.

It is likely that an earthquake similar in magnitude to the largest that occurred in Montney Trend, Canada, (4.4 Mw) would be strongly felt and could even cause some superficial damage. In addition, if an earthquake of such a magnitude were to occur in the island of Ireland, where felt seismicity is very rare, it would be likely to cause rather more concern among the local population than it would in other parts of the world, where earthquakes of this magnitude are more frequent. However, the maximum magnitudes observed in Blackpool and Garvin County would be unlikely to cause any damage, although they could be felt by people close to the epicentre and may cause some concern.

However, the growing body of evidence of changes in observed seismicity rates and significant earthquakes linked to long-term disposal of wastewater from the hydrocarbon and other industries suggests that this activity may pose a rather greater seismic risk. At present, the Mining Waste Directive (MWD) (2006/21/EC) prevents disposal of waste from extractive industries, but there is a difference of view about reuse and/or disposal of wastewater from hydraulic fracturing in some countries. Should this be considered appropriate in the island of Ireland, detailed hazard assessments would be necessary together with detailed real-time monitoring and adequate mitigation strategies.

Experience of induced seismicity in the enhanced geothermal systems industry has led to a series of measures to address induced seismicity that may be considered as industry best practice, and, as such, may be considered appropriate for mitigating the risk of induced seismicity in UGEE operations.

There remain a number of gaps in the existing knowledge of induced seismicity. For example, the pre-existing state of stress and pore pressure acting on a fault are usually unknown. Triggered events can be initiated by very small stress perturbations; however, the potential for such events depends very much on the geological context and, given the low levels of background seismicity, the probability of large triggered events in the island of Ireland can be considered as low.

Seismological methods alone cannot discriminate between man-made and natural tectonic earthquakes. Site-specific seismic monitoring and detailed recording of injection parameters during hydraulic fracturing was recommended to reduce uncertainties in earthquake locations and to compare the temporal evolution of seismic activity with any hydraulic fracture operations.

3.7 Assessment of Pre-fracturing Modelling Techniques

Microseismic monitoring observations are likely to provide a reasonable guide to the distribution of fracturing activity surrounding any particular well. This task assessed the approach of using the locations of microearthquakes generated by fracturing, together with techniques from crustal seismology, to identify the volume surrounding a perforation that is experiencing fracturing.

Published data on microseismicity related to hydraulic fracturing (perforation) were reviewed and a stochastic approach was developed, which, assuming the same distribution of event sizes from other wells, allows the modelling of the formation of fractures using widely accepted empirical scaling relations. Each seismic event is extended in space, so fractures generated by microearthquakes extend beyond the fractured volume by an amount that is related to the location of the event and the fracture length producing it. The length of this extension is related to the magnitude of the microearthquake, therefore information regarding the location and magnitude of seismicity allows the estimation of the likely maximum extent of fracturing from the perforation.

The parameters used for the model described here can only be for illustration; they should be replaced by values determined initially from a baseline survey and subsequently updated in near-real-time during any hydraulic fracturing operation. Results were presented for a synthetic scenario and added to the statistics of seismicity data from North America.

There is clear evidence that vertical fractures can propagate into shallow depths and that their vertical extent is likely to be insensitive to depth; if the fracking is sufficiently shallow, there is a risk that these fractures might interact with aquifers. Data show an upwards extent of microseismicity of approximately 100 m, with a worst-case event extending up to 300 m above the perforation. Variability in microseismic magnitude appears to be controlled by sub-horizontal layering and is largely insensitive to frack depth.

If, as is suggested for fracked (not triggered) seismicity, a well-defined upper magnitude limit exists because it is dependent on the energy injected, this limit is, in general, "soft", meaning that for any particular project, there will be an uncertainty in the maximum observed magnitude. Fracture lengths show a strong decrease in probability with length. However, there is a relatively long tail on the statistical distribution and, since this can never reach a probability of zero, there remains a very low probability of (i.e. very rare) large events.

Results suggest that, for long-term hydraulic fracturing projects, maximum fracture lengths of up to several hundred metres could be expected. The expected worst-case vertical extent of fracturing might be up to 500 m, although the joint probability of such a large event occurring at a great distance from the perforation is very small.

During hydraulic fracturing, the permeability of the entire rock volume is increased by a set of fractures connecting any pre-existing throughgoing fault to the fracked volume, potentially connecting the fracked volume to the surface. This process has not been addressed in this study, as it is site-specific and requires detailed local data.

3.8 Baseline Monitoring

Seven of the nine technical tasks originally planned for this project were completed.

As noted in section 1.3, the proposed baseline monitoring had not been implemented at the time of preparation of this report. The absence of detailed site-specific data limited the efficacy of the models (developed in Tasks 4 and 9) to assess the lengths of fracture generated by UGEE operations and, in turn, the risk of migration of pollutants along these fractures to subsurface aquifers in the study areas. While the worst-case scenario of 500 m fracture lengths should inform the regulatory approach to any hydraulic fracturing projects, it might be expected that the availability of baseline data and further modelling would allow refinement of this length estimate.

4 Air Quality

Full details of the work relating to air quality can be found in *Final and Summary Reports 3: Baseline Characterisation of Air Quality*.

UGEE projects/operations can result in the emission of some pollutants that, if present in high enough concentrations, are associated with possible health effects through direct external contact or through inhalation. In addition, pollution can be caused by the processes used during UGEE operations, increased traffic and the use of diesel-fuelled machinery. Leaking equipment can also result in fugitive emissions.

Emissions from multiple well developments in an area or region could have potentially significant impacts on air quality. However, when assessed on a site-by-site basis, these emissions are typically intermittent and are not unique to UGEE activities. Background levels of these pollutants, as a result of other activities, including industry, transport and domestic fuel consumption, and secondary pollutants from atmospheric processes vary geographically at local, regional and national scales.

The sources of air pollution from shale gas and related activities vary in a way that is dependent on the stage of the project.

4.1 Pollutants

The main emissions resulting from UGEE projects/operations are shown in Figure 4.1, but it should be noted that much of the primary data originates from the USA and that the European regulatory framework would result in different operational practices and therefore different reductions or variations in associated overall emissions.

Methane is the primary component of shale gas and most emissions have occurred during well completion when the "frack fluids" can flow back to the surface; however, these emissions can now be controlled by collecting and separating the gas. Since methane is a powerful greenhouse gas (GHG) (with an effect that is 28–34 times greater than that of carbon dioxide over a 100-year period), there is concern that long-term emissions can occur after completion through leaks from capped wells.

4.2 Air Quality Legislation and Guidelines

Air quality limits and target values across the island of Ireland are defined by EU legislation and the provisions

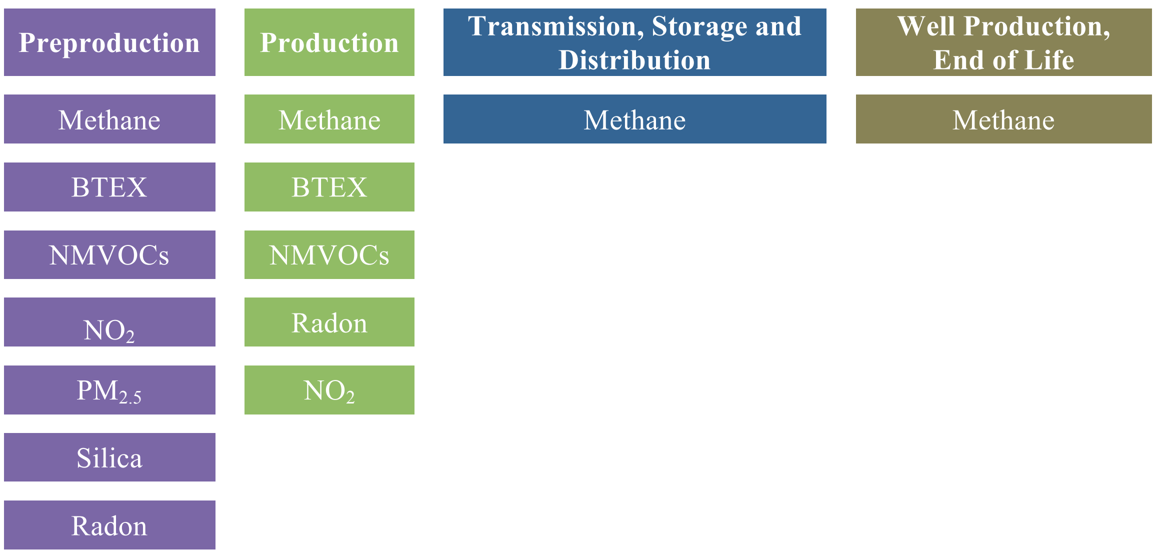

Figure 4.1. Key species emitted to the atmosphere during specific stages of UGEE projects/operations.

of the Air Quality Directives[9] have been transposed into legislation in Ireland and Northern Ireland. In addition, *The Air Quality Strategy for England, Scotland, Wales and Northern Ireland* provides a comprehensive framework for tackling air pollution in Northern Ireland.

Guidelines published by the World Health Organization (WHO), which are designed to offer guidance in reducing the health impacts of air pollution, supplement national and European legislation.

4.3 Monitoring Networks

Ireland and Northern Ireland have separate ambient air quality monitoring networks. The network in Ireland network consists of 32 monitoring stations operated by the EPA. Northern Ireland has 18 monitoring stations operated by the district councils and the monitoring programme is supplemented by regional air quality modelling. The Northern Ireland administration is responsible for air quality policy and legislation in that jurisdiction, but also adheres to an overall UK air quality strategy.

Both Ireland and Northern Ireland also assess ambient radioactivity from natural and man-made sources, radioactivity in foods, drinking water and in the marine environment. There are 20 permanent radiation-monitoring stations across the island of Ireland (15 in the Ireland and 5 in Northern Ireland).

4.4 International Requirements and Baseline Characterisation

A review of seven jurisdictions (Canada, France, Germany, Poland, South Africa, the UK and the USA), where commercial UGEE operations are ongoing, found that, in all cases, a full baseline characterisation of air quality had not been carried out prior to the commencement of operations. In many cases the lack of baseline characterisation prior to the commencement of UGEE activities has been highlighted as an important information gap.

Recommendations for baseline studies and extensive investigations into potential air quality impacts have been made in many studies across all jurisdictions prior to UGEE projects/operations.

4.5 Conclusions

While an extensive ambient air monitoring network is in operation across the island of Ireland, supplementary air quality baseline monitoring would be needed for UGEE impact assessment on a project-by-project basis.

Despite a lack of a clear agreement on the magnitude of air quality impacts caused by UGEE activities, the available literature appears to broadly agree on the compounds or families of compounds associated with UGEE activities, even if estimations of the quantity of emissions vary.

Very few, if any, methodologically rigorous studies have examined the potential cause–effect relationships of UGEE activities with respect to air emissions. In many cases, adverse health impacts were attributed to these activities as a precaution. The evidence currently available is not sufficient to rule in, or rule out, significant or specific, future or cumulative health impacts of UGEE activities. Therefore, this study adopted a risk assessment approach to consider the primary air quality pollutants that should be considered.

The air quality monitoring proposals, on a pollutant-by-pollutant basis, together with the rationale supporting them, are set out in more detail in *Final Report 3: Baseline Characterisation of Air Quality*.

9 CAFE Directive (2008/50/EC) and Fourth Daughter Directive (2004/107/EC).

5 Impacts and Mitigation Measures for UGEE Projects/Operations

Project B identified and examined the potential impacts of UGEE projects/operations on the environment and human health, and mitigation measures to counteract these impacts. The assessment was framed within the context of commercially probable scenarios in the island of Ireland to give a realistic scale for the impacts. Full details of the work relating to UGEE projects/operations, impacts and mitigation measures can be found in *Final and Summary Reports 4: Impacts and Mitigation Measures*.

Published reports and regulatory criteria were reviewed, supplemented by practical experience gained by the authors through prior project work relating to the environmental mitigation of impacts associated with the oil and gas industry. The evaluations were focused on conditions in the island of Ireland, particularly the case study areas identified, and commercially probable scenarios in these areas.

The "probable commercial scenario" approach was used (see section 5.1) to assess the potential impacts on the environment and human health and the mitigation measures. The probable commercial scenarios are described in *Final and Summary Reports 4: Impacts and Mitigation Measures*.

In general terms, UGEE projects develop in identifiable stages, from initial assessments through to closure. The activities and potential impacts vary according to the activities in each stage and are described in *Final and Summary Reports 4: Impacts and Mitigation Measures*.

5.1 Probable Commercial Scenarios

The probable commercial scenario approach was used to provide a realistic context for the assessment of the impacts on the environment and human health and the appropriate mitigation measures. This is a realistic quantification of the potential scales and speeds of development of any type of hydraulic fracturing industry in the two study areas and is a way of standardising assumptions made about future UGEE activities, given the uncertainty of whether developments will proceed in Ireland and, if so, how they would proceed. The parameters used in the probable commercial scenarios were based on the EC study,[10] a review of literature, the geology and source formations in the study areas and the physical sizes and characteristics of the actual lease areas (for parameters such as the typical number of wells, well depth and water consumption). The values selected were typically presented as ranges to provide evaluations under various best-, moderate- and worst-case impact scenarios. Spatial restrictions, such as buffer or exclusion zones related to the location of Natura 2000 and other sites with national or international environmental designations within the study areas, have not been applied to the probable commercial scenarios.

5.2 Water Quality

Storm-water runoff occurring from roads and drilling pads can be addressed by mitigation measures that are generally available and would significantly limit the potential impacts if implemented and maintained properly. Storm-water runoff is not unique to UGEE operations; however, risks still exist with regard to accidental spills, unanticipated events (e.g. rainfall exceeding design capacities), inadequate designs and implementation and lack of proper maintenance. A need still exists for appropriate regulations, approvals, oversight and inspections by regulatory bodies specific to UGEE projects/operations.

Surface chemical spills and leaks will occur and operators must be prepared with appropriate responses and mitigation measures. Even with the presence of laws, regulations, approvals and best practices/techniques, spills and leaks happen and, therefore, regulatory oversight and inspections are needed.

Fluids associated with drilling and hydraulic fracturing operations represent potential sources of contamination

10 AMEC, 2014. *Technical Support for Assessing the Need for a Risk Management Framework for Unconventional Gas Extraction*. Report for the European Commission Directorate-General for Environment, August 2014. Available online: http://ec.europa.eu/environment/integration/energy/pdf/risk_mgmt_fwk.pdf

in the groundwater environment. Natural gas constituents that are naturally present or are released as a result of hydraulic fracturing operations are also potential sources of contamination, if these migrate to the near-surface environment via natural, induced or artificial pathways. Overall, deep hydraulic fracturing is not likely to result in a direct flow pathway into shallow aquifers if adequate separation distances are maintained. The worst-case fracture length estimated in the seismic studies (*Final and Summary Reports 2: Baseline Characterisation of Seismicity*) is 500 m and this should inform the regulatory requirements of any proposed hydraulic fracturing, although it is expected that this estimate could be refined with additional modelling once baseline monitoring data (including seismic surveys) are available. The primary risk of groundwater quality impact is stray gas migration from the gas production zone as a result of an improper, faulty or failed production casing and/or poor or improper cement grouting of casing.

Current records document that spills of flowback and produced water can be expected from UGEE-related activities and that risks of impacts would reflect the care and adequacy of operations and case- and site-specific risks.

The overall risk of impact from transport-related spills of flowback and produced water is considered to be low. This does not preclude the fact that a spill could result in an environmental impact.

The planning and prior authorisation phase of UGEE-related activity is, arguably, the most important phase of UGEE development. Whereas implementation of prevention and mitigation measures safeguard against spills and leaks (and therefore potential impact), planning will establish rules, expectations and common understanding.

5.3 Water Resources

UGEE projects require water for several purposes, including drilling operations, well construction, hydraulic fracturing, sanitation and equipment washing. Case-specific circumstances would determine actual water demands at any given well pad. For guidance purposes, ranges of water use requirements for UGEE projects/operations were researched from published international literature and applied to the specific characteristics of the study areas.

The probable commercial scenarios were used to define the potential water use requirements. The available water resources in the two case study areas were assessed and the water use requirements and available water resources were compared to identify potential causes of environmental impact within the context of existing legislation and regulations and the metrics that are used by regulatory bodies in describing and reporting on the ecological status objectives of the WFD.

The risks of impact from lake abstractions are considered to be small, but this depends on how the water demands develop both spatially and temporally. The risks would be greater in small lakes compared with large lakes. Site-specific, case-by-case studies must be conducted, taking account of ecosystems and related environmental sensitivities, as well as water balance studies, which define inflow, outflow and throughflow.

The available data implies that the majority of streams in the two study areas are sensitive to stream abstractions. Applications for abstractions should be reviewed in context of catchment hydrological conditions on a case-by-case basis. In reality, it appears unlikely that the total water demand for UGEE-related activities can or would be sourced from a single catchment or stream, especially during low-flow conditions.

The hydrogeological characteristics of the bedrock aquifers in the two case study areas are complex. The well yields from the aquifers in the two study areas cannot be predicted with certainty without detailed studies. However, existing groundwater abstractions in the two study areas are low and groundwater is a viable source of water to meet demands, at least in part.

5.4 Recycling and Reuse of Flowback and Produced Waters

The recycling and reuse of flowback and produced water is potentially an important measure to reduce the impact of water resource requirements for UGEE projects/operations. However, this may be limited by the MWD (in relation to the disposal of waste from extractive industries) in Ireland and Northern Ireland.

5.5 Other Potential Impacts and Mitigation Measures

Impacts on other receptors that had not been specifically addressed in other sections of the work, such as the evaluation of impacts and mitigation measures on water quality and resources, were addressed.

The assessment of potential impacts and associated mitigation measures is site specific and, therefore, can only be generalised at this stage. Nonetheless, it is estimated that most potential impacts range from imperceptible to moderate, depending on the proximity to receptors and magnitude of cumulative impacts. One of the main areas where uncertainties are liable to remain relate to the quantification of long-term GHG emissions.

5.6 Life Cycle Assessment

The life cycle environmental assessment of UGEE projects/operations was evaluated using both a literature review and experience from other jurisdictions and these data were then compared with similar published assessments of other energy sources. Life cycle assessment measures the environmental footprint over the entire project lifetime. The process is naturally iterative, as the quality and completeness of information and its plausibility is constantly being evaluated and tested.

Significant variability was seen in reported estimates of GHG emissions, which reflected different management practices. During project operations, the well completion stage was found to be the most significant source of emissions, followed by drilling and hydraulic fracturing. Effective implementation of mitigation measures relating to these activities would, therefore, have the most impact on overall levels of emissions.

As is the case for conventional sources of gas, emissions are dominated by the combustion at the electricity generation plant, which typically represents around 90% of the total GHG emissions impact. Consequently, in terms of overall emissions, the benefit of implementing mitigation measures at the exploration and exploitation stages would be limited in reducing overall levels of GHG emissions. However, the future development of large-scale carbon capture and storage for power plants may affect this comparison.

Comparison of UGEE-generated electricity to other methods showed highly variable results, depending on both the life cycle indicator under consideration and the method of power generation. UGEE-generated electricity is reported to have a much greater impact than conventional gas on life cycle indicators, such as human toxicity potential, marine aquatic eco-toxicity potential and terrestrial eco-toxicity potential. However, this reported high impact is associated with the disposal of drilling waste to land (landfarming) in the jurisdictions considered, for example disposal of drilling waste to land accounts for 65% of the marine aquatic eco-toxicity potential, but would not be permitted in Ireland or Northern Ireland.

UGEE-generated electricity was estimated to have a significantly reduced impact on other life cycle indicators, for example freshwater eco-toxicity potential, eutrophication potential and abiotic depletion of elements.

5.7 Chemicals

The use of chemicals, particularly additives to hydraulic fracturing solutions, has been a major concern of the public, regulators and the scientific community in recent years. The primary concern has been the use of chemicals that may have the potential to impact human health and/or the environment through the potential contamination of groundwater and the large number of different chemicals used.

The hazard classifications of the chemicals were assessed based on existing European legislation. There are currently no regulations in Ireland or Northern Ireland for the public disclosure of the chemicals used in UGEE operations. The Environment Agency (EA, England and Wales) and the Scottish Environmental Protection Agency have powers to obtain full disclosure of chemicals used in hydraulic fracturing, and therefore it is likely the EPA and NIEA have similar powers that they can invoke. (EA requires full public disclosure, whereas SEPA requires disclosure to SEPA but not to the public.)

It is technically feasible to replace hazardous chemicals in fracturing fluids and there are a few examples of fracturing processes that do not use chemicals or certain groups of additives at all; however, studies concluded that more research will be required before fracturing fluids that do not rely on chemical additives are commercially viable.

5.8 Flowback and Produced Waters

Disposal and treatment of flowback and produced water are a major concern. Treatment and disposal methods were identified and assessed and disposal options linked to the available treatment options were also reviewed and assessed.

Experience in the USA shows that publicly owned, or municipal, treatment plants cannot adequately treat flowback and produced waters. Based on the probable extent of UGEE development in Ireland and Northern Ireland and the likely volumes of flowback and produced waters, the best management option for wastewater treatment would be the use of centralised treatment facilities with the proper treatment technologies. It would be expected that these would be provided by the UGEE operators or wastewater utilities/contractors rather than by the municipal sector and would be required to be in place before large-scale hydraulic fracturing could take place.

On-site treatment at individual well pads using modular units is likely to be implemented during initial development in the study areas until adequate volumes of waters are produced to maintain centralised treatment facilities.

In Ireland and Northern Ireland, deep well injection may not be a viable disposal option because of restrictions in the MWD. Any changes to, or interpretation of, the regulatory regime affecting the proposed disposal of wastewater from hydraulic fracturing by deep injection would require careful hazard assessment as well as monitoring and mitigation strategies. It should be noted that reinjection is permitted, in principle, in Germany and England where the relevant EU legislation is the same as legislation in the island of Ireland. Technologies exist to treat flowback and produced water adequately for reuse as hydraulic fracturing fluids, should this be permitted, or to directly discharge it into streams and lakes.

Both on-site and centralised treatment facilities should be subject to the appropriate regulations, approvals, oversight and inspections by regulatory bodies that are specific to UGEE projects/operations.

5.9 Environmental Monitoring

Sub-regional baseline monitoring is described in *Final and Summary Reports 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems*, *Final and Summary Reports 2: Baseline Characterisation of Seismicity* and *Final and Summary Reports 3: Baseline Characterisation of Air Quality* for water, seismicity and air quality, respectively. In this summary, the recommended sub-regional baseline monitoring programmes in *Final and Summary Reports 1* are reconciled with baseline, operational and post-operational monitoring at the local scale.

Environmental monitoring is needed before, during and after UGEE activities at both sub-regional and local scales. There are three types of environmental monitoring that relate to the different stages of UGEE activity: baseline monitoring prior to any construction or operations; operational monitoring during construction, drilling, hydraulic fracturing and production activities; and post-closure monitoring conducted after completion of gas production, well decommissioning and site restoration.

Specific requirements should include monitoring of groundwater during the construction and operational stage to detect any potential impacts on groundwater quality or related receptors; post-closure monitoring of methane gas is considered especially important at the wellhead of production wells in the post-closure stage.

Soils and subsoils are relevant in the context of potential impacts from surface sources of contamination on shallow receptors (groundwater resources, surface waters, ecosystems and water supplies).

A site-specific baseline ground gas sampling and analysis programme should be developed in line with current best practice guidance for landfills, taking account of site-specific geology and soil pathway considerations. A long-term methane monitoring programme should also be developed to detect possible cement or well deterioration following decommissioning. Funding for post-closure monitoring could be arranged through the provision of a bond by the developer, with a provisional monitoring programme set out for the first 5 years (quarterly at appropriate times of the year in years 1, 3 and 5), to be reviewed at 5-year intervals thereafter, pending review of results and agreement between the regulatory bodies and developer.

Surface water bodies are important potential receptors to UGEE projects and it is important to develop a clear conceptual site model to understand the linkages between groundwater and surface water at a site-specific scale prior to any UGEE projects being undertaken.

Characterisation of the impacts on ecosystems and wildlife would depend on the location of the well pad and its proximity to sensitive habitats or species. Monitoring the environment-supporting conditions of freshwater and wetland habitats may also be required.

The precautionary approach should underpin the recommendation of the compounds that should be assessed in air quality monitoring.

Seismic monitoring should include adequate seismic reflection data and baseline monitoring to characterise the regional structural geology and natural seismic characteristics of the area. Detailed monitoring during operations should be linked to a traffic light system.

In addition to the temporal aspect of monitoring, consideration of scale is important. Monitoring at the scale of individual well pads and hydraulic fracturing operations, as well as at the sub-regional scale, is needed.

5.10 Assessment of Existing and Potential Monitoring and Mitigations

Monitoring and mitigation measures were compiled from an extensive literature review of measures and techniques being used or recommended for UGEE operations. These measures and monitoring techniques are not considered to be prescriptive in scope and specifications, but represent measures that may be considered in the specification of an operational management plan and environmental management plan.

The validity of each measure or technique was considered in terms of its applicability to Ireland and Northern Ireland contexts and the scale at which the measure applies. While, in general, insufficient information exists to thoroughly evaluate the effectiveness of individual standalone mitigation measures, it was found that extensive documentation exists with respect to the management of risks, the effective mitigation of potential impacts and the specification of best practice.

Monitoring and mitigation measures were considered for different aspects of UGEE projects/operations as follows:

- During predevelopment, well pad identification and initial site access, mitigation measures will relate to the locations of UGEE infrastructure and can limit the magnitude of environmental effects or remove them entirely. Certain ecologically important areas or environments may only be fully protected if certain activities are precluded in proximity to the receptors.
- In terms of seismic conditions and geology, a thorough understanding of the geological and hydrogeological environment, together with an appropriate monitoring programme, can minimise risks to groundwater via pathways that could be intersected by the fractured rock volume and also of triggered seismicity in pre-existing faults.
- Measures that focus on structural well design and integrity testing reduce the likelihood of well failure, which could result in significant underground and surface air and water contamination.
- Management and monitoring of fracturing/flowback operations is important to ensure that the fracturing is proceeding as planned and that associated impacts are avoided.
- During production, in common with the development of any industrial site, good site-management practices are important to minimise potential environmental impacts. Proper management of flowback fluids is also critically important for the protection of the environment. Measures relating to operations following hydraulic fracturing, water management and solid waste management should also be included as part of a suite of mitigation measures.
- Decommissioning of the well should be considered at the design stage so that the well can be safely and satisfactorily decommissioned. It is proposed that funding for post-closure monitoring is arranged through the provision of a bond by the developer, with a provisional monitoring programme set out for the first 5 years to be reviewed at 5-year intervals thereafter, dependent on review of the results and agreement between the regulatory bodies and developer.

In order to effectively and safely manage risks, a comprehensive, multipronged approach is necessary, involving five distinct, mutually reinforcing elements as detailed in *Final and Summary Reports 4: Impacts and Mitigation Measures*.

6 Regulatory Framework for Environmental Protection

The aim of Project C was to progress the identification of regulatory requirements and the identification of operational best practice for environmental protection in the context of the island of Ireland. Full details of the work relating to the regulatory framework for environmental protection can be found in *Final and Summary Reports 5: Regulatory Framework for Environmental Protection*. The work comprised five tasks, described below.

6.1 Overview of European Union Environmental Legislation Applicable to UGEE Projects/Operations

The JRP undertook a review and assessment of the key aspects of the *acquis communautaire* (the body of common rights and obligations that is binding on all the EU Member States) including particular reference to the EC Recommendation (2014/70/EU) "on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing" and the legislation referred to therein. An assessment was made as to how the EU acquis translates to legislation in Ireland and Northern Ireland.

The relevant legislation was then mapped to the UGEE life cycle and assessed in terms of the extent to which it addresses environmental risks from UGEE.

It was found that the EU framework is comprehensive, but that potential gaps exist, as most directives and regulations do not specifically address UGEE projects or explicitly address the deep underground environment. However, EC Recommendation 2014/70/EU indicates how such gaps should be addressed.

The EC is currently reviewing the scope of the Best Available Techniques (BAT) Reference Document (BREF) for the MWD and also considering the development of a BREF focussed on hydrocarbon exploration and production, which would encompass UGEE.

6.2 Examination of the Regulatory Approaches of Other Countries

A selection of countries and North American states was identified for review and five were selected (Colorado, Denmark, Germany, Pennsylvania and the UK), in consultation with the steering committee, for detailed assessment.

A desk-based study of each country/state was undertaken and "datasheets" were prepared, which identify their regulatory approaches and specific requirements through the project life cycle, together with a comparative analysis of the approaches. Stakeholder interviews were conducted, where necessary, to verify information and ensure correct interpretation.

The jurisdictions selected facilitated consideration of potential cross-border issues from a regulatory perspective and also facilitated a comparative analysis of the ways in which different UGEE activities are regulated.

It was concluded that:

- An EU-wide approach to well integrity standards and compulsory EIA for UGEE projects/operations could be of benefit.
- Specific legislation could clarify areas where variation in interpretation across Member States of the EU may lead to different approaches.
- Public engagement may need development in the EU countries analysed (except Denmark where EIA is compulsory for UGEE that necessitates public consultation).
- The United States provides examples of how a mature, rule-based system leads to specific controls and guarantees related to UGEE; although there is also a lack of consistency between states.

6.3 Potential Role of Health Impact Assessment in the Regulation of UGEE Projects/Operations

To inform this evaluation, a high-level review of literature concerning the potential health impacts of UGEE projects/operations was undertaken alongside an overview of the existing regulatory framework in terms of health impacts arising from UGEE. A case-study analysis of health assessments (both HIA and non-HIA) was undertaken in relation to UGEE plans and projects to help determine the scope and effectiveness of HIA elsewhere and lessons that could be applied in the context of the island of Ireland. Existing guidance on HIA in Ireland and Northern Ireland was reviewed.

HIA provides a framework for an evidenced-based assessment of the potential effects of UGEE on the health of a population and the distribution of those effects. It can also raise awareness among stakeholders of health implications, be an aid to transparent decision making and be a tool to engage stakeholders and support the identification of mitigation measures.

A potential disadvantage of HIA is the absence of a legal basis, which may limit its influence. HIAs can be resource intensive and have a long duration; they can also require the availability of, and access to, adequate health care data.

Existing guidance on HIA is generic in the island of Ireland and for the oil and gas sector level. The complexities of UGEE and the range of potential health impacts mean that there may be merit in developing sector-specific guidance on the application of HIA to UGEE.

At this early stage of development of UGEE and HIA in the island of Ireland, incorporating HIA within EIAs as a best-practice requirement is likely to be the best approach, as this will allow developments in the understanding of UGEE and in the practice of HIA to be accommodated. In addition, developments in HIA for UGEE in other countries should be tracked and the Irish approach adapted where potential improvements are identified.

6.4 Best Practice for UGEE Projects/Operations

Enforcement requirements and best operational practice for UGEE, which have been collectively identified as measures, were established through links to Project B, Task 1 of Project C and by reference to the EC study.[11]

The measures that are not specifically required by EU or island of Ireland legislation, but that may be required for regulation of UGEE, could be applied through:

- land use planning;
- petroleum authorisation or licensing conditions issued by DCENR (Ireland) and DETI (Northern Ireland);
- conditions set in EPA licences (Ireland) or environmental permits and licences (Northern Ireland) covering discharges to groundwater, water abstraction, waste management, pollution prevention, radioactive substances and protection of conservation areas; and
- typical practice by industry; measures that are likely to be adopted by operators, regardless of legislation or regulatory requirements.

Many of the risks posed by UGEE at the surface can be addressed by a combination of regulations and typical industry best practice. However, the analysis found that a coherent and comprehensive approach had not been developed for a number of UGEE issues.

The review found that there is a lack of clarity regarding the effectiveness of some of the existing EU legislative framework, notably:

- There is no BAT guidance covering UGEE with respect to mining waste. The existing MWD BREF does not cover UGEE, although work is in progress to revise the MWD BREF and also develop a new hydrocarbons BREF that encompasses both UGEE and conventional oil and gas. However, until the revised MWD BREF or hydrocarbons BREF are available, BAT is subject to interpretation by regulators and operators.
- It is not clear whether EIA is required or not (especially for small-scale projects).
- The regulations regarding the protection of air and water require clarification.

There are potential gaps in EU and national legislation with regard to underground risks, because these have not previously been considered in detail. The EC Recommendation (2014/70/EU) and emerging best practice attempt to cover these gaps, but there is no guarantee that the proposed approaches will be required by regulators or adopted by industry, which means there is uncertainty and a lack of confidence in whether environmental protection issues would be effectively and coherently addressed or not. In addition, although the EC Recommendation lays down minimum principles as a common basis for UGEE in the EU, it is not legally binding on Member States.

11 Amec, 2014. Technical Support for Assessing the Need for a Risk Management Framework for Unconventional Gas Extraction. Report for the European Commission Directorate-General for Environment, August 2014. Available online: http://ec.europa.eu/environment/integration/energy/pdf/risk_mgmt_fwk.pdf

Many of the potential uncertainties in legislation could be resolved through guidance that clearly identifies how legislation will be applied. Best-practice guidance should, therefore, be adopted or developed for UGEE operations in the island of Ireland. The guidance should, as a minimum, address all the points raised in the EC Recommendation and in this project.

6.5 Public Engagement

An initial review was undertaken of 10 public engagement processes carried out in Europe and North America and, in consultation with the steering committee, five case studies representing a range of project types and consultation approaches were identified for more detailed review and assessment to identify good practice and potential areas for enhancing engagement.

Where possible, the co-ordinators of the consultation processes were interviewed to obtain further information and to review the successes and failures of the processes to help define good practice.

The application of the Aarhus Convention, the EIA Directive and SEA Directive (2001/42/EC) to proposed plans and projects involving UGEE was also reviewed. This review considered the stages in the planning and consent application process where public information and participation are required and how these requirements can best be implemented in the context of the Irish national regulatory framework and the development of a public consultation strategy in the island of Ireland.

The review concluded that:

- The geographical scope, duration and scale of consultation should be relevant to the scale of the plan or programme being consulted upon.
- The timing and duration of the consultation should consider consultee availability, and the format of the consultation should be driven by stakeholders and be responsive to their needs.
- Stakeholder input is required at all stages of UGEE projects.
- A broad range of stakeholders and consultees should be engaged.
- The consultation process should be managed by advocates of the consultation and engagement process rather than advocates of the project.
- Evaluation of each consultation process needs to be an integral part of the whole process and should be continuous and responsive to change.

7 Impacts, Mitigation and Regulations

In this chapter, the main UGEE activities throughout a project life cycle have been assessed in terms of their potential risks to the environment and human health in the two study areas. This assessment has been based on the findings of Project A1, A2, A3 and B, and taking existing legislation (Project C) and the effectiveness of available mitigation measures (Project B) into account.

The development of a UGEE project comprises many activities over a period of 15–25 years. Here, these have been grouped into four principal stages. The definitions of the various stages are different in *Final and Summary Reports 4: Impacts and Mitigation Measures* and *Final and Summary Reports 5: Regulatory Framework for Environmental Protection* and this report, *UGEE Joint Research Programme Integrated Synthesis Report*, reflecting the purpose of each report. For example, *Final and Summary Reports 5* deal primarily with regulations and have a preponderance of information relating to the pre-planning and planning stages of UGEE projects and to the post-closure period. *Final and Summary Reports 4* deal primarily with operations and mitigation measures and therefore focus primarily on the exploration and exploitation stages of UGEE projects; this report deals with the entire project life cycle and assesses impacts throughout each project and also attempts to rationalise the different types and intensities of impacts at various stages of the life cycle.

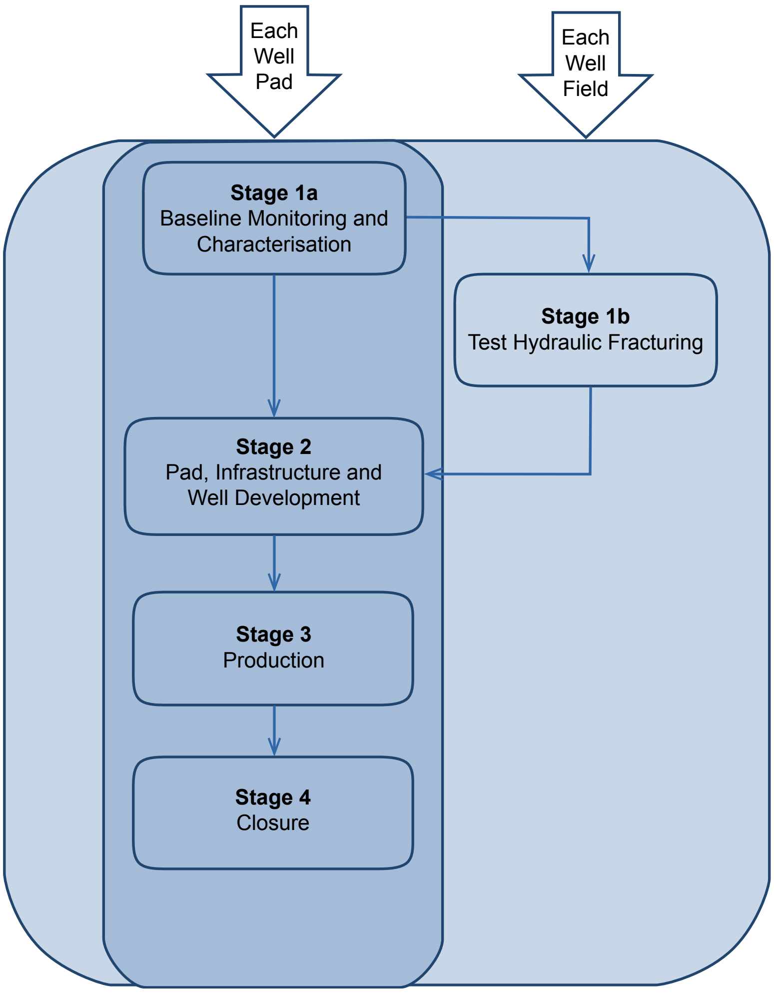

Figure 7.1. Stages of UGEE projects/operations.

For this report, a further stage (Stage 1b: test hydraulic fracturing) has been added (Figure 7.1) to the four principal stages discussed in *Final and Summary Reports 4: Impacts and Mitigation Measures* and *Final and Summary Reports 5: Regulatory Framework for Environmental Protection*. Test hydraulic fracturing involves fracturing on a very limited scale to test the viability of commercial extraction and differs significantly from the other preparatory activities defined in Stage 1a. The stages in this report, and in *Final and Summary Reports 4* and *Final and Summary Reports 5*, are presented in Table 7.1.

Stage 1b (in this report) only takes place at the outset of the overall project to evaluate the gas production characteristics of the shale rock.

The principal activities associated with each stage are presented in Table 7.2. It can be seen that some activities occur in more than one stage, but the scale of each activity can vary considerably between the different stages. For example, construction of access roads and well pads at the exploration stage would take place at a limited number of sites and would be of a temporary nature, whereas, during production, there would be many more, larger-scale and semi-permanent facilities constructed; similarly, hydraulic fracturing (and associated water and chemical usage) during exploration would be limited, whereas, in the production stage, it would occur at every well throughout the field.

7.1 Impact Assessment Tables

Table 7.2 lists the principal activities associated with each stage of UGEE projects/operations in this report. The associated potential impacts, measures and applicable regulations for each stage are then presented in Tables 7.3–7.7. The majority of potential impacts have been drawn from *Final and Summary Reports 4: Impacts and Mitigation Measures*, impacts have also been drawn from *Final and Summary Reports 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems*, *Final and Summary Reports 2: Baseline Characterisation of Seismicity*, and *Final and Summary Reports 3: Baseline Characterisation of Air Quality*. The regulations (and gaps) that apply to the each activity have been informed by *Final and Summary Reports 5: Regulatory Framework for Environmental Protection*.

The potential impacts of each activity, without the application of suitable mitigation activities and regulations, have been assessed on the basis of the likely nature and scale (from the probable commercial scenarios, which include concurrent developments across the licence area) of each activity during the entire duration of each stage. The assessment was carried out by the principal authors of *Final and Summary Reports 4: Impacts and Mitigation Measures* and reflects their collective and informed opinion of the likely nature and scale of each activity. The potential impacts for each activity have been assigned into one of five categories (as defined in *Final and Summary Reports 4*), taking account of both severity and duration, as follows:

- **Imperceptible**: capable of measurement but without noticeable consequences, e.g. a planned or unplanned discharge that does not result in exceedance of environmental quality standards, criteria or guidelines;
- **Minor**: causes noticeable changes in the character of the environment without affecting its sensitivities, e.g. a planned or unplanned discharge that could result in exceedance of an environmental quality guideline in the immediate vicinity of the release point, but would not be expected to have significant environmental or health effects (ecosystem functions are not affected);

Table 7.1. Life cycle stages

Integrated Synthesis Report	Final and Summary Reports 4	Final and Summary Reports 5
Stage 1a: Baseline monitoring and characterisation Stage 1b: Test hydraulic fracturing [at initial site(s)]	Stage 1: Pre-development	Stage 1: Pre-development
Stage 2: Pad, infrastructure and well development	Stage 2: Well design and construction, hydraulic fracturing and well completion	Stage 2: Exploration, appraisal and production
Stage 3: Production	Stage 3: Production	
Stage 4: Closure	Stage 4: Project cessation, well closure and decommissioning	Stage 3: Decommissioning and closure

Table 7.2. Activities associated with each stage of UGEE projects/operations

Stage 1a activities: baseline monitoring and characterisation	Stage 1b activities: exploration drilling and test hydraulic fracturing	Stage 2 activities: pad infrastructure and well development	Stage 3 activities: production	Stage 4 activities: closure
Seismic surveys				
Baseline monitoring	Baseline monitoring	Baseline monitoring		
Geological borehole drilling				
Site(s) selection				
Temporary access construction				
Cuttings disposal	Cuttings disposal	Cuttings disposal		
	Temporary road construction			
	Temporary pad construction			
	Temporary pad facilities			
	Abstraction	Abstraction		
	Drilling	Drilling (vertical and horizontal)		
	NORM disposal	NORM disposal		
	Water storage structures	Water storage structures		
	Water transport	Water transport (road or pipe)		
	Well construction/ completion	Multiple well construction/completion		
	Test hydraulic fracturing	Hydraulic fracturing		
	Wastewater storage treatment and disposal	Wastewater (flowback) storage treatment and disposal	Wastewater (produced) storage treatment and disposal	
	Transport of polluting materials (including chemicals)	Transport of polluting materials (including chemicals)	Transport of polluting materials	
	Gas separation, collection and transport	Gas separation, collection and transport	Gas separation, collection and transport	
		Road construction		
		Full-scale pad expansion and construction		
		Impoundment structures		
		Storage facilities		
			Operational monitoring	
			Removal of equipment and facilities	
			Removal of chemical storage	
			Removal of abstraction/ transport equipment	
				Well closure/capping
				Site restoration
				Post-operational monitoring
				Following closure

- **Moderate**: alters the character of the environment in a manner that is consistent with existing and emerging trends, e.g. a discharge or incident resulting in potential effects on natural ecosystems in the vicinity of the release point or incident; ongoing effects on people in the vicinity of a site due to impacts such as noise, odour or traffic;
- **Significant:** by its character, magnitude, duration or intensity, alters a sensitive aspect of the environment, e.g. an ongoing discharge resulting in persistent exceedances of European environmental quality standards or guidelines; permanent degradation of a protected habitat; and
- **Profound:** obliterates sensitive characteristics, e.g. a pollution incident resulting in harm to the health of members of the public over a wide area due to contamination of drinking water supplies; an accident resulting in death or serious injury to workers and/or members of the public.

In Tables 7.3 to 7.7, the potential impacts of each activity during each of the five project stages, as shown in Figure 7.1, are colour coded, with the lightest purple colour indicating “imperceptible” and darkest shade “significant” (no impacts were considered as “Profound”). Each colour-coded cell therefore represents a potential impact from the relevant activity, during the stage being considered, which is imperceptible, minor, moderate or significant if no mitigation or regulatory control is implemented. Unshaded cells denote that there is no impact for that issue from that particular activity. Where alternative approaches to specific activities are possible, impacts from both have been included; for example, water and wastewater transport, which could be carried out by either pipeline or lorry, was assessed on the basis of both methods being used and impacts from both experienced.

It should be emphasised that both the impact and possible mitigation measure(s) will often be site dependent; for this reason, the assessment can only be generic but, in general, a conservative approach has been taken, i.e. the classification is based on the greater potential impact.

At the foot of each table, there are four rows (established processes, existing relevant regulations, regulatory modifications and regulatory additions) that consider how each activity is addressed within the current regulatory environment (independently of the magnitude of the potential impacts).

1. **Established processes**: this considers whether the activity is an established activity within developments or projects in the island of Ireland and, therefore, whether there is a “standard” regulatory process already in operation or not. Each activity is assessed in terms of whether or not there is an established process in the regulatory environment to manage it and is also assessed to ensure that the appropriate mitigation measures are implemented. Where the activity is “routine”, i.e. something that is commonly addressed in other infrastructure or development projects, it is assumed that both the regulations and the process of implementing them are adequate to mitigate potential impacts and protect the environment and human health. If so, it is coloured green. However, if it is a process without an established track record of being successfully managed and regulated, then it is coloured yellow (as is the case for well construction/completion, hydraulic fracturing, gas separation, collection and transport, and well closure and capping).

2. **Existing relevant regulations**: this summarises the existing regulations that are in place to address and manage the activity. The existing relevant regulations are identified (note that the acronyms are defined in the list of abbreviations). Since these are already in existence and regularly used, they are viewed as satisfactory for their purpose and coloured green.

3. **Regulatory modifications**: this considers whether modifications to existing regulations are required in order to ensure the protection of human and/or environmental health. Requirements for any necessary modifications to the existing regulations identified from *Final and Summary Reports 5: Regulatory Framework for Environmental Protection* are noted. These are coded green if the regulations are judged to be satisfactory in their present form and require no addition or modification and yellow if action is required to amend the regulations prior to initiation of UGEE projects/operations.

   The regulations that would benefit from enhancement or modification are as follows:

   - A Strategic Environmental Assessment (SEA) is usually understood to be required for large-scale programmes that include developments in several areas of a country or region. However,

Table 7.3. Stage 1a: Baseline monitoring and characterisation

Potential impact	Activity						Effectiveness of measures
	Seismic surveys	Baseline monitoring	Geological boreholes	Site(s) selection	Temporary access construction	Cuttings disposal	
Surface water quality							
Groundwater quality							
Surface water levels/ quantities							
Groundwater levels/quantities							
Habitat loss or fragmentation							
Transport/growth of invasive species							
Increase in suspended and benthic sediments							
Storm water runoff of contaminants							
Soil contamination							
Wildlife disturbance from site operations							
Air quality and dust							
Post-closure emissions							
Loss of farm/amenity land							
Deterioration of road conditions							
Disturbance/damage through excavation							
Impact on viewshed/ landscape							
Increased noise/light levels at sensitive receptors							
Increase in local traffic/ congestion							
Increase in roadside air emissions							
Potential road safety issues							
Risks of spillages/accidents							
Potential influx of workers causing local population growth							
Unfelt earthquakes							
Felt earthquakes							
Potential negative perception of area as clean and unpolluted							
Established processes?	Yes	Yes	Yes	Yes	Yes	Yes	
Existing relevant regulations	Planning HD/BD	Planning WFD	Planning	EIAD Planning HD/BD	EIAD Planning	EIAD MWD Planning	
Regulatory modifications	None	None	None	SEA for regional impacts	None	None	
Regulatory additions	None	None	None	None	None	None	

See the key on p. 41.

it likely that the hydraulic fracturing industry, at least in the early phases of exploitation, would develop in relatively small increments and that each individual project would not necessarily require an SEA. This would lead to the absence of any consolidated environmental impact assessment of the industry, and also to the absence of the large-scale consultation and HIA that would or could be a component of the SEA. The requirement for an SEA should be clarified for the UGEE industry prior to any large-scale activity.

- Although some abstractions are licensed in Ireland, the process requires revision in light of the requirements of the WFD and should be strengthened to provide a clearer evaluation process, along with an assessment of its adequacy to protect the environment and human health or mitigate potential impacts.
- The requirements for geological, hydrogeological and seismic monitoring should be included in planning regulations for both exploration and production.

4. **Regulatory additions**: what new regulations are required to protect human and/or environmental health adequately? Additional regulations are identified where it is considered that existing statutes are inadequate, even after modifications or additions. As above, green indicates that no new regulations are required and yellow indicates that existing regulations could be applied to the UGEE industry with satisfactory results or that new regulations are required. These are shown for the activity that requires the additional regulation.
   - The MWD is interpreted in some EU countries (though not in Germany and England) to prohibit re-injection of wastewater (flowback and produced water) from hydraulic fracturing. It is possible that the treatment of this water and its reuse in the hydraulic fracturing process in some locations could significantly reduce both water abstraction demand and wastewater discharge and would, therefore, provide an overall benefit to the environment. Therefore, this should be reviewed in the context of UGEE projects.
   - The requirement to collect adequate data throughout the project life cycle, particularly in relation to geology, hydrogeology and seismic activity, could be incorporated into planning regulations, but should be clearly defined within mandatory good practice guidelines.
   - The EU framework of legislation is comprehensive, but potential gaps exist as most Directives and Regulations do not specifically address UGEE projects or explicitly address the deep underground environment. However, EC Recommendation 2014/70/EU indicates how such gaps should be addressed and how this legislation should be incorporated into the regulatory requirements in Ireland and Northern Ireland.
   - Good practice construction/deconstruction practices, remedial measures for well failure [to supplement the Petroleum (Exploration and Extraction) Safety Act (PEESA)] are required in Ireland].
   - There should be a requirement for post-closure monitoring and a financial bond system for remediation

It is noted that the EIA Directive does not always specifically apply to small projects, as they are not explicitly listed in the Annexed Activities of this directive. As noted above for SEAs, it likely that the hydraulic fracturing industry, at least in the early phases of exploitation, would develop in relatively small increments and each individual project would not necessarily require an EIA unless this is clarified by regulation.

Finally, the potential impact of activities, following the application of appropriate mitigation measures and best practice guidance as outlined in *Final and Summary Reports 4: Impacts and Mitigation Measures*, are summarised in the last column of Tables 7.2–7.7. This column therefore represents the assessment of impacts in practice, as opposed to the potential impacts without mitigation. Green indicates the impacts that can be satisfactorily addressed by known measures, if amended where necessary, and properly implemented. Orange indicates impacts for which there is inadequate knowledge to determine whether existing measures and best practice are effective or not. This is not to say that impacts are inevitable, but rather that there is inadequate evidence to be certain that they will not be avoided.

When each stage is considered, both in terms of the numbers of potential impacts and the severity of those impacts (pre-mitigation), it was found that Stage 2 (pad infrastructure and well development) has the greatest

Table 7.4. Stage 1b: Exploration drilling and test hydraulic fracturing

Potential impact	Activity								
	Baseline monitoring	Temporary road construction	Temporary pad construction	Temporary pad facilities	Abstraction	Drilling	Cuttings disposal	NORM disposal	Water storage
Surface water quality									
Groundwater quality									
Surface water levels/ quantities									
Groundwater levels/quantities									
Habitat loss or fragmentation									
Transport/growth of invasive species									
Increase in suspended and benthic sediments									
Stormwater runoff of contaminants									
Soil contamination									
Wildlife disturbance from site operations									
Air quality and dust									
Post closure emissions									
Loss of farm/amenity land									
Deterioration of road conditions									
Disturbance/damage through excavation									
Impact on viewshed/ landscape									
Increased noise/light levels at sensitive receptors									
Increase in local traffic/ congestion									
Increase in roadside air emissions									
Potential road safety issues									
Risks of spillages/accidents									
Potential influx of workers causing local population growth									
Unfelt earthquakes									
Felt earthquakes									
Potential negative perception of area as clean and unpolluted									
Established processes?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Exisiting relevant regulations	Planning WFD	EIAD Planning HD/BD	EIAD Planning	EIAD Planning	Water Pollution Act, WFD, GWD, HD/ BD, Planning, WAIR (NI)	EIAD, MWD, Planning, WFD, GWD, OMND, PEESA (IE)	EIAD MWD Planning	EIAD MWD Planning NORM	EIAD Planning
Regulatory modifications	None	None	None	None	Strengthening of abstractions licensing (IE)	None	None	None	None
Regulatory additions	None	None	None	None	Implications of MWD for recycling	None	None	None	None
Note		EIAD may not always apply for small projects				EIAD may not always apply for small projects			

See the key on p. 41.

Table 7.4. Continued

Potential impact	Activity						Effectiveness of measures
	Water transportation	Well construction/ completion	Test hydraulic fracturing	Wastewater storage treatment and disposal	Transport of polluting materials (incl chemicals)	Gas separation, collection and transport	
Surface water quality							
Groundwater quality							
Surface water levels/quantities							
Groundwater levels/quantities							
Habitat loss or fragmentation							
Transport/growth of invasive species							
Increase in suspended and benthic sediments							
Stormwater runoff of contaminants							
Soil contamination							
Wildlife disturbance from site operations							
Air quality and dust							
Post closure emissions							
Loss of farm/amenity land							
Deterioration of road conditions							
Disturbance/damage through excavation							
Impact on viewshed/landscape							
Increased noise/light levels at sensitive receptors							
Increase in local traffic/ congestion							
Increase in roadside air emissions							
Potential road safety issues							
Risks of spillages/accidents							
Potential influx of workers causing local population growth							
Unfelt earthquakes							
Felt earthquakes							
Potential negative perception of area as clean and unpolluted							
Established processes?	Yes	No	No	Yes	Yes	Yes (NI) Uncommon (IE)	
Exisiting relevant regulations	EIAD Planning AQD, END, NRMMD, OMND, WSR	MWD, EIAD, PEESA (IE), OIWR/BSOR (NI)	EIAD, MWD, Planning, WFD, GWD, NRMMD, OMND, END, AQD, PEESA (IE)	MWD EIAD Planning WFD	EIAD, Planning, AQD, END, NRMMD, OMND, WSR	MWD, EIAD, PEESA (IE), OIWR/BSOR (NI)	
Regulatory modifications	None	None	Geological, hydrogeological and seismic monitoring required as part of planning	None	None	None	
Regulatory additions	None	None	Adoption of EU recommendations & industry good practice guidelines; geological, hydrogeological and seismic baseline data required	None	None	None	
Note	EIAD may not always apply for small projects						

See the key on p. 41.

Table 7.5. Stage 2: Pad infrastructure and well development

Potential impact	Activity								
	Baseline monitoring	Road construction	Full-scale pad expansion and construction	Impoundment structures	Storage facilities	Abstraction	Drilling (vertical and horizontal)	Cuttings disposal	NORM disposal
Surface water quality									
Groundwater quality									
Surface water levels/quantities									
Groundwater levels/quantities									
Habitat loss or fragmentation									
Transport/growth of invasive species									
Increase in suspended and benthic sediments									
Storm water runoff of contaminants									
Soil contamination									
Wildlife disturbance from site operations									
Air quality and dust									
Post-closure emissions									
Loss of farm/amenity land									
Deterioration of road conditions									
Disturbance/damage through excavation									
Impact on viewshed/landscape									
Increased noise/light levels at sensitive receptors									
Increase in local traffic/ congestion									
Increase in roadside air emissions									
Potential road safety issues									
Risks of spillages/accidents									
Potential influx of workers causing local population growth									
Unfelt earthquakes									
Felt earthquakes									
Potential negative perception of area as clean and unpolluted									
Established processes?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Existing relevant regulations	Planning, WFD	EIAD, Planning, HD/BD	EIAD, Planning	EIAD, Planning	EIAD, Planning, BPR, IED, REACH	Water Pollution Act, WFD, GWD, HD/ BD, Planning, WAIR (NI)	EIAD, MWD, Planning, WFD, GWD, OMND, PEESA (IE)	EIAD, MWD, Planning	EIAD, MWD, Planning, NORM
Regulatory modifications	None	None	SEA for multiproject/ regional programmes	None	None	Strengthening of abstractions licensing (IE)	None	None	None
Regulatory additions	None	None	None	None	None	Implications of MWD	None	None	None
Notes		EIAD may not always apply for small projects					EIAD may not always apply for small projects		

See the key on p. 41.

Table 7.5. Continued

Potential impact	Water storage structures	Water transport (road or pipe)	Multiple well construction/ completion	Hydraulic fracturing	Wastewater (flowback) storage treatment and disposal	Transport of polluting materials (including chemicals)	Gas separation, collection and transport	Effectiveness of measures
Surface water quality								
Groundwater quality								
Surface water levels/quantities								
Groundwater levels/quantities								
Habitat loss or fragmentation								
Transport/growth of invasive species								
Increase in suspended and benthic sediments								
Storm water runoff of contaminants								
Soil contamination								
Wildlife disturbance from site operations								
Air quality and dust								
Post-closure emissions								
Loss of farm/amenity land								
Deterioration of road conditions								
Disturbance/damage through excavation								
Impact on viewshed/landscape								
Increased noise/light levels at sensitive receptors								
Increase in local traffic/congestion								
Increase in roadside air emissions								
Potential road safety issues								
Risks of spillages/accidents								
Potential influx of workers causing local population growth								
Unfelt earthquakes								
Felt earthquakes								
Potential negative perception of area as clean and unpolluted								
Established processes?	Yes	Yes	No	No	Yes	Yes	Yes (NI), uncommon (IE)	
Existing relevant regulations	EIAD, Planning	EIAD, Planning, AQD, END, NRMMD, OMND, WSR	MWD, EIAD, PEESA (IE), OIWR/BSOR (NI)	EIAD, MWD, Planning, WFD, GWD, NRMMD, OMND, END, AQD, PEESA) (IE)	MWD, EIAD, Planning, WFD	EIAD, Planning, AQD, END, NRMMD, OMND, WSR	MWD, EIAD, PEESA (IE), OIWR/ BSOR (NI)	
Regulatory modifications	None	None	None	Geological, hydrogeological and seismic monitoring required as part of planning	None	None	None	
Regulatory additions	None	None	None	Adoption of EU recommendations and industry good practice guidelines; geological, hydrogeological and seismic baseline data required	None	None	None	
Notes								

See the key on p. 41.

Table 7.6. Stage 3: Production

Potential impact	Activity							Effectiveness of measures
	Operational monitoring	Removal of equipment and facilities	Removal of chemical storage	Removal of abstraction/ transport equipment	Wastewater (produced) storage treatment and disposal	Transport of polluting materials	Gas separation, collection and transport	
Surface water quality								
Groundwater quality								
Surface water levels/ quantities								
Groundwater levels/ quantities								
Habitat loss or fragmentation								
Transport/growth of invasive species								
Increase in suspended and benthic sediments								
Storm water runoff of contaminants								
Soil contamination								
Wildlife disturbance from site operations								
Air quality and dust								
Post-closure emissions								
Loss of farm/amenity land								
Deterioration of road conditions								
Disturbance/damage through excavation								
Impact on viewshed/ landscape								
Increased noise/light levels at sensitive receptors								
Increase in local traffic/ congestion								

See the key on p. 41.

Table 7.6. Continued

Potential impact	Activity							Effectiveness of measures
	Operational monitoring	Removal of equipment and facilities	Removal of chemical storage	Removal of abstraction/ transport equipment	Wastewater (produced) storage treatment and disposal	Transport of polluting materials	Gas separation, collection and transport	
Increase in roadside air emissions								
Potential road safety issues								
Risks of spillages/ accidents								
Potential influx of workers causing local population growth								
Unfelt earthquakes								
Felt earthquakes								
Potential negative perception of area as clean and unpolluted								
Established processes?	Yes	Yes	Yes	Yes	Yes	Yes	Yes (NI), uncommon (IE)	
Existing relevant regulations	Planning, WFD	EIAD, Planning	EIAD, Planning, AQD, END, NRMMD, OMND, WSR, PEESA (IE)	EIAD, Planning, AQD, END, NRMMD, OMND, WSR, PEESA (IE)	MWD, EIAD, Planning, WFD	EIAD, Planning	MWD, EIAD, PEESA (IE), OIWR/BSOR (NI)	
Regulatory modifications	None	None	None	None	Geological, hydrogeological and seismic operational monitoring data required as part of planning	None	None	
Regulatory Additions	None	None	None	None	Adoption of EU Recommendations and Industry Good Practice Guidelines; geological, hydrogeological and seismic operational monitoring data required	None	None	

See the key on p. 41.

Table 7.7. Stage 4: Closure

Potential impact	Activity				Effectiveness of measures
	Well closure/ capping	Site restoration	Post-operational monitoring	Post-closure	
Surface water quality					
Groundwater quality					
Surface water levels/quantities					
Groundwater levels/quantities					
Habitat loss or fragmentation					
Transport/growth of invasive species					
Increase in suspended and benthic sediments					
Storm water runoff of contaminants					
Soil contamination					
Wildlife disturbance from site operations					
Air quality and dust					
Post-closure emissions					
Loss of farm/amenity land					
Deterioration of road conditions					
Disturbance/damage through excavation					
Impact on viewshed/landscape					
Increased noise/light levels at sensitive receptors					
Increase in local traffic/ congestion					
Increase in roadside air emissions					
Potential road safety issues					
Risks of spillages/accidents					
Potential influx of workers causing local population growth					
Unfelt earthquakes					
Felt earthquakes					
Potential negative perception of area as clean and unpolluted					
Established processes?	No	Yes	Yes	Yes	
Existing relevant regulations	MWD, EIAD, PEESA (IE), OIWR/ BSOR (NI)	Planning	Planning	Planning	
Regulatory modifications	None	None	None	None	
Regulatory additions	Ireland: good practice construction/ deconstruction practices, remedial measures for well failure (to supplement PEESA)	None	None	Post-closure monitoring and financial bond system for remediation	
Notes	EIAD may not always apply for small projects				

See the key on p. 41.

Key for Tables 7.3–7.7

Impact of activity	
	No impact
	Imperceptible
	Minor
	Moderate
	Significant
	Profound

aggregated potential impact and Stage 1b (test hydraulic fracturing) the second greatest. Stage 1a has the least potential impact.

In Stage 2, the use of large volumes of fresh water, hydraulic fracturing and disposal of large volumes of wastewater (flowback water) are the three activities that could cause the greatest impacts if they are not adequately regulated.

Three impacts were identified in Tables 7.2–7.7 as currently being of unsatisfactory risk status:

1. Groundwater pollution from failed borehole integrity: the pumping of water and any associated chemicals under high pressure to fracture the rocks can cause failure of the well casing if it is inadequately constructed. The well should be designed and constructed to withstand the pressures encountered, but, if it fails, then leakage of the pumped materials and the returning gas and production waters can occur to the surrounding rock. This could be at any depth and could lead to migration of pollutants into aquifers.
2. Groundwater pollution via artificially created fractures and natural geological fault zones: the process of hydraulic fracturing creates cracks in the rock through which gases can move towards the well for collection. The length of these cracks is difficult to predict (*Final and Summary Reports 2: Baseline Characterisation of Seismicity*), but the assumption of a length of 300 m, with a very low probability of 500 m, is thought to be a conservative approach. If these ruptures extend into an aquifer, then there is a possibility of gas migration and pollution of the aquifer. This same risk is higher if the rock mass has pre-existing permeable fault zones that are intersected by the fracked cracks, allowing more extensive pollutant migration. The evaluation of the risk of this occurring would necessitate detailed geological structural definition of the hydraulic fracturing site and real-time seismic monitoring of fracturing operations.
3. Post-closure gas emissions: following the completion of gas extraction, each well is sealed and capped so that any fugitive gases cannot escape. The integrity of the elements involved needs to be long term, but international experience has shown (*Final and Summary Reports 4: Impacts and Mitigation Measures*) that both conventional and unconventional wells experience some level of failure. In principle the design and implementation of these elements is straightforward, but the industry has not always succeeded in preventing leakage. The levels of gas emissions are typically low, but over a long period and for a large-scale industry, they could be significant.

The likelihood of each of these three impacts varies according to the stage of the project, but in broad terms the risk of groundwater pollution via induced and natural faults was judged to be slightly lower than the other two impacts.

Impacts from protests groups at hydraulic fracturing sites has been excluded in the assessment; if these occur they might be expected to include traffic-related impacts, pollution, population growth and a negative perception of the area. In Balcombe Down, UK, for example, it was reported that several hundred protesters from around the UK camped on farmland without planning or landowner permission, or any proper sanitation facilities, damaging the crops and the farmland and causing pollution. There was also a significant level of stress to sections of the local population.

8 Conclusions

The UGEE Research Programme has examined the process, impacts and mitigation measures associated with hydraulic fracturing around the world. International regulatory frameworks have been reviewed and the suitability of legislation in Ireland and Northern Ireland reviewed and potential gaps identified.

Public concern about hydraulic fracturing generally focuses on health, water resources, induced seismic activity and GHG emissions, although in some areas potential changes to the character of the environment are an issue. The relative importance of these issues varies from place to place and with time.

This study concluded that UGEE projects/operations comprise multiple activities, over a period of up to 25 years, which have the potential to impact both human health and the environment. However, many of these activities are conventional, in the sense that they are infrastructure developments that are frequently undertaken within both Ireland and Northern Ireland and, consequently, the legislation and regulation that relates to them are well established and widely accepted by society. Examples of these activities are access road construction, site preparation and materials transport. These types of activities, across many industries, have well-established impacts and measures to mitigate their impacts. A wide range of potential impacts was assessed (see Tables 7.2–7.7), including those relating to water, air quality, noise, landscape, seismic activity and social issues.

Project B demonstrated that operational requirements and practices in different jurisdictions vary significantly and that this relatively new industry is evolving rapidly, especially in North America. The regulatory regimes of North America are very different from those of the EU and many of the more environmentally damaging practices may not be permissible in the island of Ireland (e.g. open wastewater lagoons, flaring, disposal of wastewater by deep underground re-injection). Industry best practice guidance, such as that issued by the UK industry group, collates best practice and addresses many of the concerns raised by stakeholders.

The JRP scope was developed to address two key questions: can UGEE projects/operations be carried out in the island of Ireland while also protecting the environment and human health; and what is best environmental practice in relation to UGEE projects/operations?

The programme concluded that many of the activities associated with UGEE projects/operations could proceed on the island of Ireland, while protecting the environment and human health. This should be done using the best practices identified in *Final and Summary Reports 4: Impacts and Mitigation Measures* and applying the current regulations, together with a small number of additions and modifications that should be complemented by adequate implementation and enforcement.

However, there are three main impacts where the data and/or experience do not permit a reliable assessment of their consequences and these would require clarification before environmental protection and human health can be ensured. The three potential impacts that cannot be discounted by regulatory control and good practice are as follows:

1. Groundwater aquifers could be polluted as a result of the failure or deterioration of well integrity. The drilling and construction of wells is a routine activity in the water and oil and gas sector and standards for their design and construction are well established. However, experience shows that there are examples of wells that have failed or have deteriorated well integrity. It is believed that a rigorous process of design, design review, construction supervision and operational monitoring (with remedial works if necessary) could mitigate this impact, but this cannot be demonstrated without further evidence. Such a process should be a requirement of any UGEE operations in the island of Ireland. There is incomplete knowledge of the aquifer systems in the two study areas, with specific data gaps related to the deep hydrogeological characterisation and how the deeper groundwater flow systems may be hydraulically connected to shallow aquifers and receptors. As a consequence, the impacts cannot be reliably addressed in the absence of baseline monitoring data.

2. The fracking process intentionally generates cracks in the rocks that typically extend to 100–200 m; however statistical analysis suggests that they can extend by up to 300 m and, in extreme circumstances, by up to 500 m. If the separation between the fracking activity and the base of the aquifer is less than these distances, then there will be a risk of pollutant and gas migration to the aquifer, although this could be reduced if impermeable rock layers separate the two. This risk is compounded by the possibility of pollutant and gas migration in the newly fractured (after fracking) shale rocks towards pre-existing permeable faults that could also provide a pollutant and gas pathway to the aquifer. The seismic elements of this programme have developed a new approach to evaluate fracture propagation and length, which requires site-specific data on seismic activity, rock characteristics and existing fracture networks to refine these estimates for the two study areas. These data would come both from the baseline monitoring (originally anticipated to be within the scope of work for the programme) and from detailed monitoring during UGEE operations.
3. Gas emissions have been cited by the public to be of concern from a human health viewpoint. During active operations, these can be adequately managed by mitigation measures that address the health and safety of the workforce, who would be at a much higher level of exposure than the general public. Following closure of a well, it is sealed and capped to prevent egress of gas. However, there is evidence from conventional oil and gas wells that this closure process is not always successful or can deteriorate with time and that stray gas leakage has occurred. Neither the reasons for this, nor the scale of the emissions is quantitatively known and so their impact cannot be reliably assessed until further data are available. Methane is an important GHG and therefore this is an issue of concern, although it should be noted that approximately 90% of GHG emissions are likely to occur during the generation of electricity rather than at the production stage.

Prior to any authorisation for hydraulic fracturing, these issues should be resolved. Adequately designed baseline monitoring programmes for water and seismicity will assist in improving site-specific knowledge and therefore the assessment of the risks of groundwater contamination by well failure and induced seismicity. Similarly, two- and three-dimensional seismic surveys, which would be expected to be undertaken by the operators prior to any hydraulic fracturing activity, will provide further subsurface knowledge that will allow better characterisation of subsurface geology, hydrogeology and natural seismic activity.

Long-term gas emissions are more difficult to address, since local datasets are not available. Long term, post-closure methane emissions are the topic of ongoing studies internationally, but these studies will take time to conclude. If UGEE projects are initiated, then it is recommended that more complete closure of wells, testing of closure procedures (cementing, etc.) and long-term monitoring should be specified. Funding for post-closure monitoring could be arranged through the provision of a bond by the developer.

Existing regulations in Ireland and Northern Ireland have widespread applicability to potential UGEE project/operations, but there remain some potential deficiencies and ambiguities that should be clarified, notably in relation to the MWD BREF. These include whether an EIA is required or not (especially for small-scale projects), the requirement for a SEA at national-, regional- or multiproject-level; and the form of protection for air and water.

The EC Recommendation (2014/70/EU) and emerging best practice attempt to cover gaps in underground risk protection, but there is no guarantee that the proposed approaches will be required by regulators or adopted by industry.

Many of the potential uncertainties in legislation could be covered through guidance that clearly identifies how legislation will be applied. Best practice guidance should, therefore, be adopted or developed for UGEE operations in the island of Ireland. The guidance should, as a minimum, address all the points raised in the EC Recommendation and in this project.

At this early stage of development of UGEE and HIA in the island of Ireland, incorporating HIA within EIAs as a best-practice requirement is likely to be the best approach, as this will allow developments in the understanding of UGEE and in the practice of HIA to be accommodated. In addition, developments in HIA for UGEE in other countries should be tracked, and the approach in Ireland and Northern Ireland adapted where improvements are identified.

References

This UGEE Joint Research Programme Integrated Synthesis Report has drawn upon the final and summary reports produced for each of the five projects in the UGEE JRP:

- *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 and Mitigation Measures*;
- *Summary Report 4: Impacts and Mitigation Measures*;
- *Final Report 5: Regulatory Framework for Environmental Protection*; and
- *Summary Report 5: Regulatory Framework for Environmental Protection*.

Abbreviations

AQD	Air Quality Directive (2008/50/EC)
BAT	Best available techniques
BD	Birds Directive (2009/147/EC)
BPR	Biocidal Products Regulations
BREF	Best Available Techniques Reference Document
BSOR	Borehole Sites and Operations Regulations (Northern Ireland)
BTEX	Benzene, toluene, ethylbenzene and xylenes
CB	Clare Basin
DCENR	Department of Communications, Energy and Natural Resources
DETI	Department of Enterprise, Trade and Investment
EC	European Commission
EIA	Environmental Impact Assessment
EIAD	Environmental Impact Assessment Directive (2014/52/EU)
END	Environmental Noise Directive (2002/49/EC)
EPA	Environmental Protection Agency
EU	European Union
GHG	Greenhouse gas
GNSS	Global Navigation Satellite System
GWD	Groundwater Directive (2006/118/EC)
HIA	Health Impact Assessment
HD	Habitats Directive (92/43/EEC)
IE	Ireland
IED	Industrial Emissions Directive (2010/75/EU)
InSAR	Interferometric synthetic aperture radar
JRP	Joint Research Programme
ML	Local magnitude
MWD	Mining Waste Directive (2006/21/EC)
NCB	Northwest Carboniferous Basin
NI	Northern Ireland
NIEA	Northern Ireland Environment Agency
NMVOC	Non-methane volatile organic compound
NORM	Naturally occurring radioactive materials
NRMMD	Non Road Mobile Machinery Directive (97/68/EC)
OIWR	Offshore Installations and Wells (Design and Construction, etc.) Regulations
OMND	Outdoor Machinery Noise Directive (2000/14/EC)
PEESA	Petroleum (Exploration and Extraction) Safety Act
$PM_{2.5}$	Particulate matter with a diameter of 2.5 μm or less
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SEA	Strategic Environmental Assessment
S-P-R	Source–Pathway–Receptor (Model)
UGEE	Unconventional gas exploration and exploitation
WAIR (NI)	Water Abstraction and Impoundment (Licensing) Regulations (Northern Ireland) 2006
WFD	Water Framework Directive (200/60/EC)
WSR	Waste Shipment Regulations

Integrated Synthesis Report

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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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