Potential impacts of hydraulic fracturing on air, soil and water quality in the vicinity of coal seam gas well sites in the Surat Basin, Queensland: water and soil monitoring plan

Task 5 Report

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The Gas Industry Social and Environmental Research Alliance (GISERA) undertakes publicly-reported research that addresses the socio-economic and environmental impacts of Australia's natural gas industries.
GISERA was co-founded by CSIRO and Australia Pacific LNG in July 2011. For further information visit gisera.org.au.

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This report was supported by the Gas Industry Social and Environmental Research Alliance (GISERA). GISERA is a collaboration between CSIRO, Commonwealth and State governments and industry established to undertake publicly-reported independent research. The purpose of GISERA is to provide quality assured scientific research and information to communities living in gas development regions focusing on social and environmental topics including: groundwater and surface water, biodiversity, land management, the marine environment, and socio-economic impacts. The governance structure for GISERA is designed to provide for and protect research independence and transparency. Visit gisera.org.au for more information about GISERA's governance structure, projects and research findings.

We are grateful to Prof Thomas Borch (Professor of Environmental Chemistry, Colorado State University, Fort Collins, Colorado, USA) for his thorough review and suggestions for improvements in the study design, which could only partially be accepted due the nature and scope of the project. Dr Graeme Batley is thanked for his comments and guidance on the study design as an internal CSIRO reviewer.

Executive summary

This document outlines a water and soil monitoring plan which underpins a study of the potential impacts of hydraulic fracturing on air, soil and water quality in the vicinity of coal seam gas well sites. The study is to be conducted at two locations in the Surat Basin, Queensland and will involve the collection of samples of surface waters, groundwater, fluids from the hydraulic fracturing (HF) operations, produced water and soils.

The collection of 113 water samples and 40 soil samples is planned, with these samples undergoing 22 analytical procedures to determine the concentration of more than 150 potential contaminants including organics, inorganics and radionuclides. The number of samples for each category was dictated by the site conditions (number of wells, surface water bodies) as well as time and resource constraints. The list of contaminants for analysis was developed following a review of recent relevant published literature on CSG operations and covers both inorganic and organic chemicals (including those occurring naturally (geogenic)) that may be potential contaminants of soil and waters.

The majority of the sampling activities will be conducted between July 2017 and early 2018. Sampling locations and the timing of sampling will be finalised through consultation with Origin Energy (the gas field operators) during the next stage of project development. It is anticipated that refinements to the sampling plan will be made as the project progresses and water and soil quality information is accumulated.

CSIRO staff will make a number of site visits during the course of the study in order to: (a) undertake specialist sampling; (b) oversee sampling of operations conducted by contractors; and (c) gain familiarity with the study sites.

Given the unpredictable nature of spills, field sampling of spill-impacted soils was not deemed feasible. Hence a laboratory scenario study was preferred. The scenario-based study will involve exposing soil samples representative of the different soil types from across the region, to HF fluids and flowback waters. The degradation and stability of the added contaminants over time will then be measured. Biological indices such as respiration and nitrification will also be measured to provide key information on the consequences of chemical spills on soil quality, broadly defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. Only a part of soil quality assessments, viz. microbiological functions, was feasible in this project.

The outcomes of the project will be communicated to stakeholders (including industry, government and community) utilising the GISERA (Gas Industry Social and Environmental Research Alliance) communication and outreach facilities. Accompanying on-line report publication, communication of the results of this study is likely to include media interviews, information videos

and fact sheets available on the GISERA website (gisera.org.au), and the sharing of this content on social media platforms.

1 Introduction

1.1 Background

Over the last decade, coal seam gas (CSG) which goes by the name of coalbed methane in North America, has been a rapid growth industry in Australia. CSG development has expanded relatively rapidly in eastern Australia, with proven and probable reserves increasing more than tenfold over the last decade. The development of the CSG industry has escalated with its trajectory predicted to grow into the future as gas supplies become a major and important fuel source in the transition to a low carbon future (Nghiem et al., 2011; Bhutto et al., 2013). Australia's annual CSG production has increased from 1 petajoule (1 PJ = 10^{15} joules) in 1996 to 240 PJ (0.2 tcf (trillion cubic feet)) in 2010-11, around 10% of Australia's total gas production. Of the 2010-11 production of CSG, Queensland produced 234 PJ (0.2 tcf) (or 97%) from the Bowen (121 PJ, 0.1 tcf) and Surat (113 PJ, 0.1 tcf) basins (Geoscience Australia & BREE, 2014).

CSG extraction involves drilling a network of wells across the designated gas field to depths that intersect the key coal seams. The evolved gas is piped to a local processing facility and then piped to the coast for liquefaction and overseas distribution. In order to increase the yield of methane, a proportion of wells undergo a stimulation process known as hydraulic fracturing (HF). Various descriptions of the HF process are available (e.g. DEHP, 2016). Not all wells require hydraulic fracturing and it is estimated that around 20- 40% of the wells in Australia will be hydraulically fractured during their lifetime (CSIRO, 2016).

Despite significant monitoring by industry and regulatory oversight of the industry at both State and Federal levels, there is still widespread public concern for the environmental impacts of HF, in particular the threats posed by the cocktail of industrial chemicals used in HF and also geogenic contaminants that may be mobilised during the HF process.

The Gas Industry Social and Environmental Research Alliance (GISERA) is a collaboration between CSIRO, Commonwealth and State governments and industry established to undertake publicly-reported independent research. The purpose of GISERA is to provide quality assured scientific research and information to communities living in gas development regions focusing on social and environmental topics including: groundwater and surface water, biodiversity, land management, the marine environment, and socio-economic impacts. The governance structure for GISERA is designed to provide for and protect research independence and transparency.

GISERA aims to:

- Carry out research and provide information for the benefit of Australian communities in CSG and shale gas regions and related industry
- Inform governments and policy-makers of key research outcomes.

In response to the concerns around HF, a project has recently been established within GISERA to investigate the impacts HF on air, soil and water quality (https://gisera.org.au/project/air-water-and-soil-impacts-of-hydraulic-fracturing/). The project comprises two stages.

- Phase 1: Review of the state of knowledge of impacts of hydraulic fracturing on air, water and soil resources and development of a field program to measure surface water quality impacts before, during and after HF operations.
- Phase 2: Implementation of the study planned in Phase 1.

Overall, the project will generate a number of outputs including a final report, research papers, and presentations/briefings to various stakeholders.

This document provides the study rationale, sampling plan and overview of methodologies for the water and soil components and is the major product of phase 1.

1.2 Study Aims

The aims of the study are as follows:

(i) To quantify the impacts of HF operations on the concentrations of contaminants in nearby surface waters, groundwater and soils.

(ii) To assess the concentrations of HF chemicals and geogenic contaminants in flowback and produced waters resulting from CSG HF operations.

(iii) To check compliance of contaminant concentrations in the collected water and soil samples with relevant Australian water and soil quality guideline values.

(iv) To conduct a laboratory assessment of various scenarios involving spillage of hydraulic fracturing chemicals and flowback waters onto various soils types representative of the Surat Basin.

The following topics are out of scope of the project:

Long-term impacts of hydraulic stimulation: Given the short timeframe of this study (maximum 6 months post stimulation monitoring), the long-term impacts of hydraulic stimulation is not being considered in this study. Some contaminants, if persistent in the system, may take a much longer time (years) to travel to the receiving environments. Where possible, we will rely on stable tracers (fluorobenzoic acid, FBA) used during hydraulic stimulation as a marker of the sources of pollution.

***Impacts of drilling and well construction*:** This is not possible as the wells at the proposed study sites were drilled in 2015 and 2016. Recent studies have pointed out that well integrity is the number one concern with respect to causing environmental problems in the long term (Aaron et al., 2017)

***Impacts of HF on deep groundwater*:** There are no means of accessing deep groundwater samples from the study sites.

Groundwater contamination with methane. This is out of scope of this project and may be covered under other GISERA projects.

***Ecological risk assessment*:** The study is not designed to provide an ecotoxicological assessment of chemicals or to deliver a formal risk assessment. Ecotoxicological impact assessment of chemicals associated with hydraulic stimulation process and gas exploration is of fundamental importance in risk assessment but it is out of scope in this study.

***Impacts of HF on human health*:** The study will not determine the impacts of HF on human health. However, the data from the study will be made be publicly available for potential use in future work specifically targeting the impact of CSG activities on human health.

***National or Regional assessment of HF impacts*:** The study design presented here will be used to assess the impact of HF activity on water and soil quality for two locations in the Surat Basin. It is not intended to be a national or regional assessment. However, with proper contextualisation and consideration of differences between locations and differences in industry practices, the outcomes of the study may provide insights into likely impacts at other locations.

1.3 Contaminant sources and pathways

Over the last four years, the environmental contaminants team at CSIRO has been involved in a national assessment of the impacts on hydraulic fracturing chemicals on the environment. Unfortunately, the large number of reports generated from the assessment are not currently available to the public. However, the knowledge gained through participation in this program has been used to frame the current study. A conceptual model of potential contaminant interactions from CSG operations in Australia which originates from the national assessment program is presented in Figure 1. Note that the current study is largely driven by stakeholder and public concerns over the impacts of HF and focusses on surface and shallow groundwater impacts which are not necessarily supported by the available scientific knowledge. An area of particular concern to the public is the composition and fate of both HF fluids, flowback waters and produced waters. Flowback and produced waters will contain geogenic contaminants and possibly transformation products arising from the HF chemical degradation and/or their interactions with geological materials. A limited set of transformation products are being considered, that have been chosen based on a literature review and current analytical capabilities.

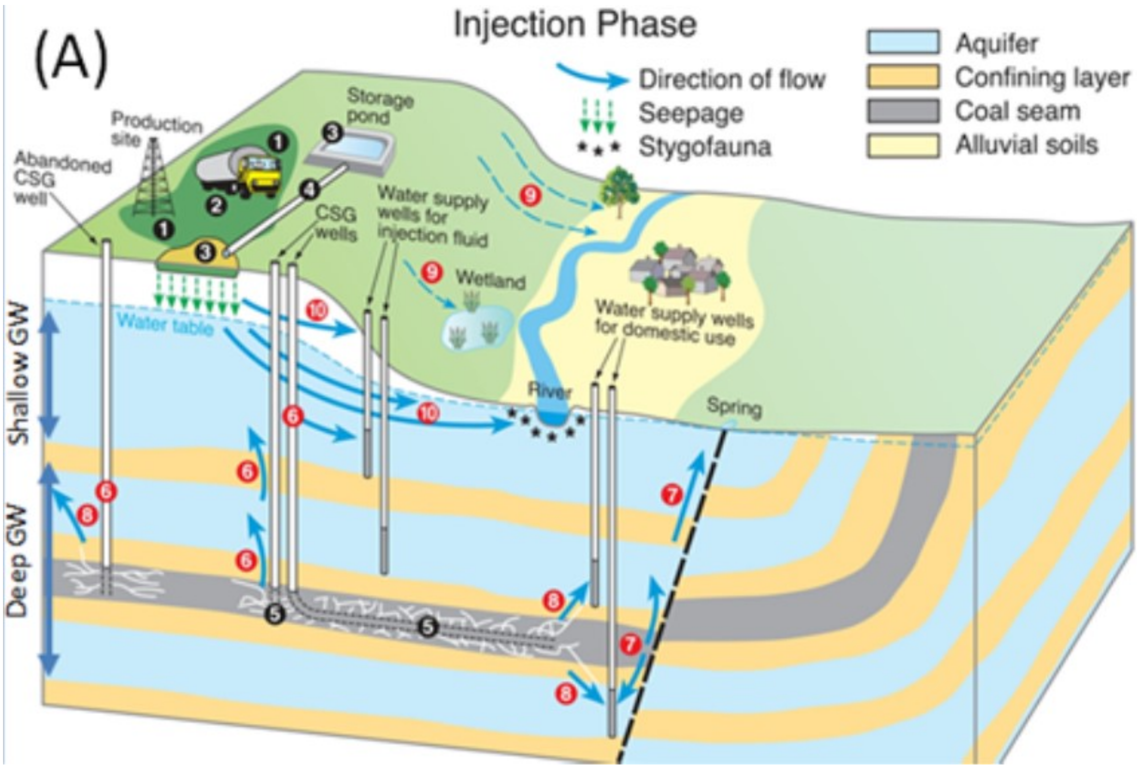

Figure 1. Conceptual diagram of hydraulic fracturing and potential impact pathways (courtesy of Dirk Mallants, CSIRO).

1.4 Study Area

The study will be conducted at Origin Energy CSG sites within the Surat Basin Queensland, Australia around the established gas fields of Combabula and Condabri. The Surat Basin (Figure 2 and Figure 3) is an area of intensive CSG extraction in Australia.

Sampling locations and the timing will be finalised through consultation with Origin Energy staff when required. It is also anticipated that refinements to the sampling plan will be made as the project progresses and water and soil quality information is accumulated. Hence the program outlined below is an adaptive program that will evolve as more information on the HF program becomes available.

Figure 2. Map of the Surat Basin

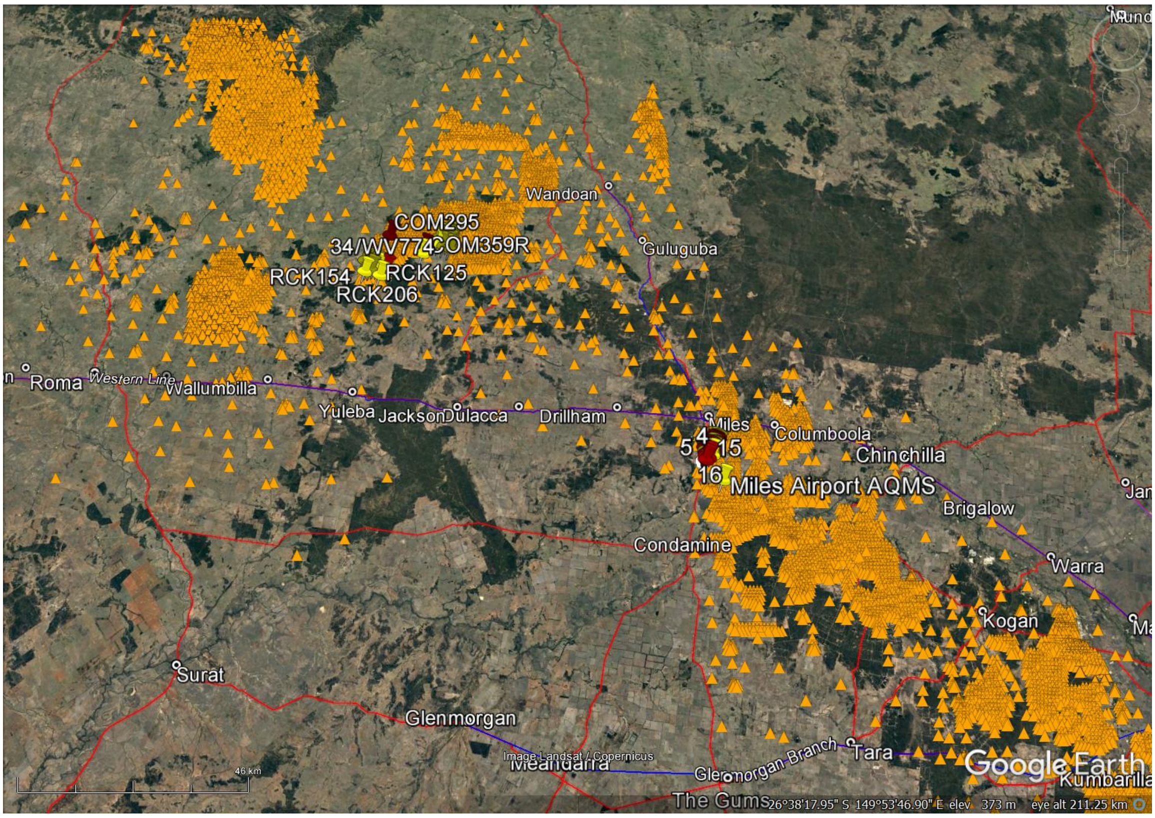

Figure 3. Local map showing CSG wells (orange triangles) in the vicinity of the two study sites (denoted by the red pins).

Study site 1: Condabri

Site 1 (WAP2) is a farmland property of approximately 1030 ha located between Miles and Condamine (26°45’21’’ S, 150°10’49’’E). The property is predominantly flat, semi-arid open grassland with stands of native tree vegetation (Figure 4). Dogwood Creek, an ephemeral surface waterway, borders the western boundary of the property and the Leichhardt Highway borders the eastern boundary.

The predominant soil types here are essentially those that are typical of the Surat Basin (Table A2). In total, seven soil types were noted to be present across the project area. These included Dermosol, Sodosol, Hydrosol, Kandosol, Rudosol and Vertisol. The majority of soils present in the project area have formed from quaternary alluvium containing sand, silt mud and gravel (Chinchilla 1:250,000 geology sheet SG56-9). More information on these soils is available in a technical report by CPB Contractors, commissioned by Origin (CWD 15 Soil Survey Technical Report no Q-4560-15-TR-0030; 16 Dec 2016).

The property contains 19 CSG wells, grid spaced at ~ 600 – 700 m intervals. The wells are operated by APLNG and Origin Energy Resources Pty Ltd. Rig release dates indicate that the wells were drilled and constructed between August and September 2015, with an additional well constructed in August 2016 (Source: Qld Globe). Well depths range from 740 – 860 m and target the Walloon Coal Measures. The wells are scheduled to undergo some form of wellbore stimulation in June and July 2017 after which they will be brought on-line and connected to the gas and water pipeline network (Origin Energy, personal communication). Twelve of the wells will undergo HF.

Dogwood Creek runs along the western boundary of the property. The area to the west of Dogwood Creek is dominated by farmland with ~ 5 CSG wells within a 5 km radius of the boundary. In contrast, the area to the east of the property, bounded by the Leichhardt Highway, is dominated by farmland with a high density of CSG wells (grid spaced ~ 600 – 700 m) (Figure 4). The wells in this area are serviced by a network of pipelines and vents, which connect to the Condabri Central Gas Processing Facility which is approximately 5 km to the south of the study site.

A site familiarisation visit to this site was undertaken by CSIRO staff on 12 April 2017 in order to inspect the study area, make contact with key Origin Energy staff and organise field logistics.

Figure 4. Map showing the location of the Condabri field site (WAP2); shaded in yellow. The orange triangles are the CSG wells and the blue dots denote registered water boreholes.

Study site 2

Site 2 (Combabula) is a farmland property located approximately 100 km northwest of Miles (26°16'46'' S, 149°33'22''E). Similar to Site 1, the property is predominantly flat, semi-arid open grassland with stands of native tree vegetation (Figure 5). An ephemeral creek runs through the property.

The property has over 30 drilled wells, grid spaced at ~ 600 – 700 m intervals. Twenty-three of the wells are scheduled to undergo some form of well bore stimulation in July and August 2017 after which they will be brought on-line and connected to the gas and water pipeline network (Origin Energy, personal communication). The wells in this area are serviced by a network of pipelines and vents, which connect to the nearby Reedy Creek central Gas Processing Facility.

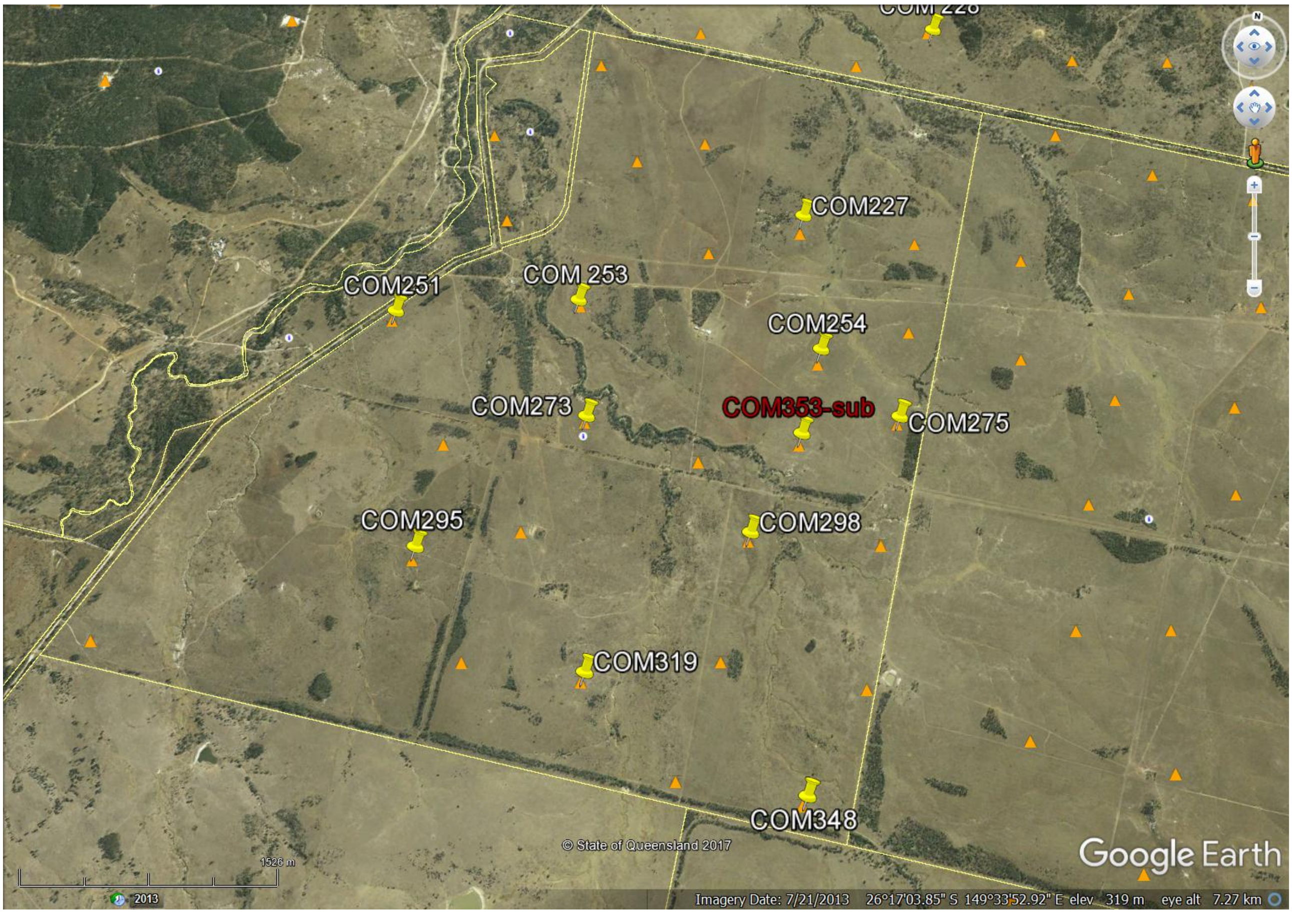

Figure 5. Map showing the location of the Combabula field site. The orange triangles denote the CSG wells.

2 Water and Soil Sampling Plan

2.1 Overview

This section provides details of the proposed water and soil sampling program. The timing of sampling will be finalised through consultation with Origin Energy staff during the next stage of project development. Most activities will be conducted in the period from July to December 2017, with some residual sampling occurring in early 2018. It is also anticipated that refinements to the sampling plan will be made as the project progresses and water and soil quality information is accumulated.

The sample types that will be collected comprise surface waters, groundwaters, fluids from the HF operations, produced water and soils. Further details are given in the sections below. The sample types and proposed number of samples are summarised in Table 2.

2.2 Background Information

Historical data from previous Origin Energy HF operations, as well as the prospective monitoring to be undertaken by third party providers on behalf of Origin at the study site, will be made available for the proposed study. It should be noted that the industry monitoring programs are designed to check compliance against regulatory limits (see below) and do not necessarily utilise analytical methods with the sensitivity to measure actual concentrations of contaminants in samples.

Under the Petroleum Regulation 2004, companies are required to submit well completion reports for each well stimulated by HF. These reports provide detailed accounts of the well integrity testing, perforation, HF stages (number and depth), the types and volumes of input chemicals, proppants and water used at each stage, and HF diagnostic data used to track the HF progress at each stage. The completion reports for the wells that undergo HF at the study site will be provided by Origin Energy to CSIRO following their submission to and approval from the regulatory body.

Queensland's Department of Environment and Heritage Protection (DEHP) issue Environmental Authorities (EAs) that permit CSG companies to perform petroleum activities including HF. As part of this, the EA companies are required to provide stimulation impact monitoring plans for each site and undertake the prescribed monitoring and analysis to ensure the HF activity complies with the conditions of the EA. The prescribed monitoring activities include:

- Baseline - landholder bore water quality and CSG well water quality before HF
- HF operations – HF fluids composition and concentrations and aquifer connection
- HF well produced fluids- initial flowback and produced water quality

Industry monitoring is usually undertaken by third-party providers and the data reported directly to the CSG companies. These data will be reviewed during the study.

2.3 Hydraulic Fracturing Operations

2.3.1 Overview of activities

The study will target six wells and collect waters during the main HF operation and also produced waters during the gas production phase. This will be achieved by initial intensive sampling followed by occasional sampling over a six-month period. The location of wells to be sampled will depend on industry-driven HF schedules but is likely to be two wells at the Condabri site and four at the Combabula sites as the preferred selection, however, this will be subject to timings and operational issues associated with these sites.

Following completion of HF operations, flowback waters are removed from the well pad (via tankers) and treated at a local wastewater treatment facility. Produced waters are piped to a central water treatment facility and treated by reverse osmosis (RO). The reject brines are stored in purpose-built storage ponds. The RO water is used for various purposes including (non-food) crop irrigation (if the water quality meets Australian standards for irrigation water quality) and use in industrial processes.

2.3.2 Hydraulic fracturing fluid

The chemical formulations of HF fluids used at the CSG wells under investigation will be provided by Origin Energy. In addition, six samples of the HF fluid (one per each well to be monitored) will also be collected and analysed by CSIRO to confirm its composition.

2.3.3 Flowback waters

A critical aspect of the study will be the sampling of wells during and after HF. Two wells will be studied in detail with 12 samples each, taken over the duration of the fracturing operation (typically one week). A further 4 wells will be sampled at 5 time points over the duration of flowback water collection. The timing of flowback water sample collection will be decided in the field and will be influenced by the flow rates of flowback waters which can vary significantly between wells.

Ancillary data (e.g. volume of flowback water, temperature etc.) will be collected for each fracturing operation in order to assist in data interpretation.

2.3.4 Produced waters

Produced waters will be sampled from the six wells that were sampled for flowback waters during the production phase. Samples will be taken from the gas-liquid separator well head. The two wells that were intensively sampled during HF (flowback) will be intensively sampled during production (6 samples taken over a 6-month period). For the remaining 4 wells, there will be three sampling events per well over a 6-month period. The exact timing of the sampling events will be determined following the completion of HF and commissioning of each well.

2.3.5 Water treatment facility (WTF) waters

Samples of raw water, post-treatment water and reject brines will be taken at the Condabri WTF on 3 occasions over the study period (total of 9 samples). It should be noted that the WTF receives and treats water from all of the CSG bores situated across the Condabri gas field. The data generated will therefore give a general view of water treatment operations rather than specific information relating to the two study areas.

2.4 Surface water sampling sites

The major surface water resources within the Condabri study area are Dogwood Creek (Figure 6) and a number of farm dams. Upstream of the study site, Dogwood Creek flows through the township of Miles and receives inputs from town's sewage treatment works. It is therefore important to include a sampling location upstream of the study site. Samples will be collected at 4 points: upstream, downstream and two locations at the study site. There will be three sampling events: during (2 occasions) and several months after HF operations have ceased. The collection of surface water samples prior to HF is not feasible at this site as engineering work has already commenced.

At the Combabula study site, creek flow is ephemeral and lack of water flows is likely to affect the feasibility of taking water samples. Given this practical limitation, surface water sampling at this site will be largely restricted to three farm dams. There will be four sampling events: before, during (2 occasions) and after HF operations. Additional creek samples may be taken if there is sufficient water flow.

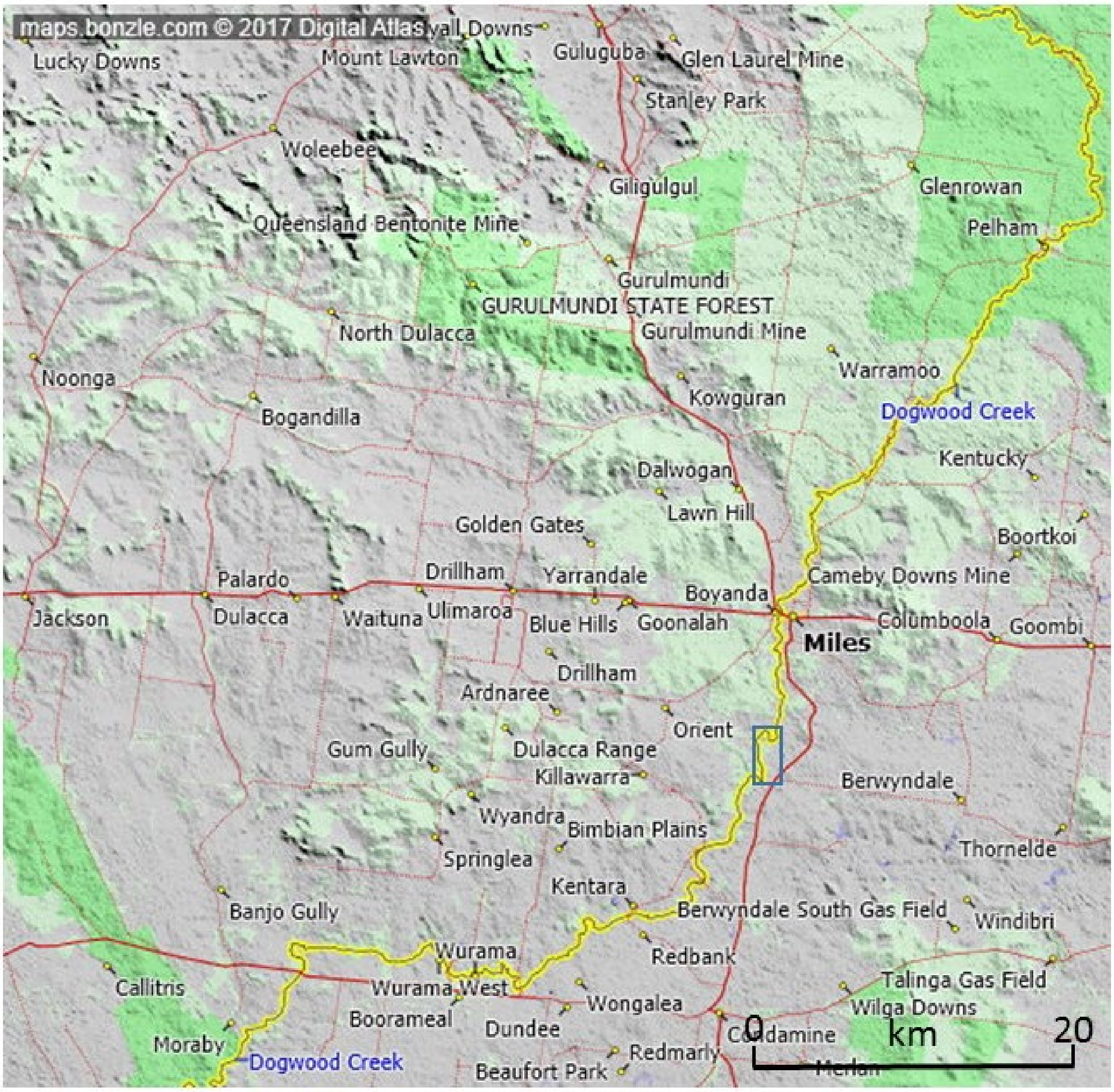

Figure 6. Map of the Condabri region showing Dogwood Creek (in yellow). The approximate location of Site 1 is indicated by the blue rectangle.

2.5 Groundwater Bore Samples

Registered water bores, for use as potable water sources, watering livestock and irrigation, are found across the region. Based on information supplied by Origin Energy, it is apparent that the bores in the two study regions are shallow and do not intersect any of the coal seams which are found at much deeper depths. Instantaneous contamination of the boreholes during HF is highly unlikely given the travel time required for chemicals to pass through groundwater and reach the locations. Nevertheless, some bore-water samples will be taken as confirmatory evidence in order to provide reassurance to the general public and land owners. A CSIRO groundwater specialist will oversee the groundwater sampling program and provide advice on sampling procedures when required.

Our sampling will focus on collection of bore-water samples during and post- HF operations. The same range of water quality parameters as per the surface waters will be analysed. A particular focus will be on the detection of added fluorobenzoic acid (FBA) tracer, as this provides unequivocal identification of bore-water contamination from HF operations (there are no natural sources of these compounds). Data on the water quality prior at selected bores prior to HF operations will be supplied by Origin Energy and will be used to establish baseline water quality.

At the Conadbri site, there are over 10 registered water bores located within a 5 km radius of the proposed fracturing operations and one water bore within the study area (Figure 4). Two nearby boreholes will be sampled during and on two occasions after the HF operations have ceased. Registered bores are also present at the Combabula study sites. They will be inspected during the first visit to this site and two bores selected for sampling during and after HF operations at this site (two occasions).

The water bores at greatest risk of contamination in this region are ones which intersect the coal seams that are undergoing HF and are within close proximity to one or more CSG wells. Using information available from local government sources and Origin Energy, a desktop assessment of wells across the Surat Basin will be undertaken, and, where feasible, additional water samples will be taken from the identified bores.

2.6 Soil Quality

2.6.1 Field study

Unless there is a spill of HF fluid, flowback or produced water, it is highly unlikely that soil quality will be impacted. A common practice in the industry when preparing the well-pad is to scrape the surface soils (generally to a depth of 20-30 cm) and store it for later rehabilitation of the soil. Therefore, the subsoil on the well-pad has a greater exposure to any spills during HF operations and that of the flowback water. Various post HF activities continue on the well-pad including the rehabilitation of the well-pad with surface soil.

Origin Energy does not plan to use drilling mud for rehabilitation of soils on the study sites. It is therefore best to take soil samples once the site is fully rehabilitated and is ready to be handed over to the owner. At that stage representative soil samples (e.g. using a transect of five points) will be collected with depth across the well-pad at four wells. At the same time samples from the reference soil (undisturbed by the HF and associated operations) from the study site will be taken to quantify any enhancement in contamination of soils. In the first instance, a total of 40 soil samples will be subjected to the same chemical characterisation as the water samples following suitable sample preparation/extraction of the soil. Additional soil samples from each well pad will be collected and archived for potential later analysis (if contamination is detected).

2.6.2 Impact of HF chemicals on soil quality – laboratory study

Given the difficulties of sampling soils for unpredictable spills and other contamination, a laboratory scenario-based study will also be conducted. This will involve deliberately exposing soil samples to hydraulic fracturing fluids and flowback waters. To make this study relevant to not only the study site but also to the entire Surat basin, five dominant soil types from the Basin will be collected. The representative soils selected for this study are listed in Table 1 below. Incubation studies under laboratory conditions will be carried out, with some modifications to the protocol used in a recently published by McLaughlin et al. (2016). The degradation and stability of the added contaminants will then be measured with time. Biological indices such as respiration and nitrification will also be measured, to provide key information on the consequences of chemical spills on soil health. A detailed experimental plan of the study has been presented in Appendix A.

Table 1. Dominant geomorphic units and soils types in Surat Basin (after Biggs et al. 2012)

Geomorphic unit	Dominant soil type	Key features
Alluvia	Black and grey Vertosols*	Clay rich (> 35%)
Basalt	Vertosols, Ferrosols, Dermosols*	Deep clay soils Dermosol – low in free iron
Quartzose sandstones	Chromosols*	Sandy texture-contrast soils
Unweathered to moderately weathered non-quartzose sedimentary rocks	Vertosols, Texture contrast Sodosols*, Kandosols	Sodosols - Sodic B Horizon
Moderately to strongly weathered non-quartzose sedimentary rocks	Texture contrast Sodosols, Chromosols, Rudosols*, Tenosols	Rudosols – Sandy loams Chromosols – Sandy over clayey B horizon

(Soils selected for inclusion in this study

2.7 Field Sampling and Sample Analysis

CSIRO staff will make at least three site visits during the course of the study in order to undertake critical sampling (e.g. HF operations), oversee sampling conducted by contractors employed by Origin Energy, and to gain familiarity with the study sites. CSIRO will provide all sampling bottles and sampling instructions. This includes suitable preparation of collection bottles for samples following well-developed protocols, such as acid-washing for trace metals and solvent-rinsing/high temperature baking for trace organics. Water samples will be filtered/extracted on site prior to shipping to CSIRO laboratories for analysis.

The sample types and number of samples to be collected are summarised in Table 2. The water and soil quality parameters to be analysed on the samples collected is given in Table 3. This list was developed following a review of recent relevant published literature on CSG operations and interactions with stakeholders. The list covers both inorganic and organic chemicals and radionuclides that may be potential contaminants of soil and waters. Note that the list of analytes includes isomers of FBA which are deliberately added to the HF fluids by the operators to a limited number of wells in order to provide a means of tracing the progress of the injected fluids in the well for post-HF analysis of the HF operation.

All water and soil samples will be collected and analysed using internationally published (using best available among published studies) sampling and analysis protocols. Standard operating procedures will be available for each activity. Soil samples will be subjected to a range of extraction/digestion procedures prior to analysis. For the laboratory study simulating spills, fresh soil samples will be used to ensure their biological integrity.

The sampling program will include field duplicates, laboratory replicates, blanks and standard QA/QC measures. A duplicate field sample will be included in every batch of 10 samples collected. A field blank will be collected on each day of sampling. These samples are additional to the ones listed in Table 2.

Wherever possible, sample analyses will be conducted in NATA- (National Association of Testing Authorities, Australia) accredited laboratories and will be subject to rigorous quality control. All radiochemical analyses will be conducted by the Australian Nuclear Science and Technology Organisation (ANSTO) who are the lead agency in Australia for environmental radioactivity measurement.

Table 2. Summary of the proposed water and soil sampling program

Sample type	Samples to be collected	Number of samples	Notes
Surface waters			
Dogwood Creek	Water	16	Samples will be collected at 4 sites: upstream, downstream and two locations at the study site). Four sampling events: before, during (2 occasions) and after HF operations.
Farm dams	Water	12	Three farm dams sampled at Combabula study site. Four sampling events: before, during (2 occasions) and after HF operations.
Water bores	Groundwater	12	Four nearby boreholes will be sampled during and on two occasions post-HF operations
Hydraulic fracturing	HF fluid sample	6	Mixed HF fluid sample per well to be provided to CSIRO
Stimulation and flow back phase	Flowback waters	44	Two wells (12 sampling events), 4 wells (5 sampling events)
Production phase	Produced waters	24	Two wells (6 sampling events), 4 wells (3 sampling events)
Wastewater treatment facility	Incoming water	3	3 sampling events over a 6-month period
Post-treatment	RO Treated water	3	3 sampling events over a 6-month period
Membrane rejects	Brine	3	3 sampling events over a 6-month period
Soils	Soil samples from the well pad and adjacent areas	40	Soil samples (0-10 and 10-40 cm depth) will be collected at 5 points across the well pad at four wells before and after HF activities. Additional soil samples from each well pad will be collected and archived for potential later analysis (if contamination is detected). Near each well pad, paired (matching soil type) reference samples (unaffected by exploration activity) will be collected from the site.

Table 3. Water and soil quality parameters to be analysed

Parameter	Description	Typical Limit of Detection (3σ) for water samples
Dissolved: Al, Ag, As, Ba, Be, Bi, Cd, Ca, Ce, Co, Cr, Cu, Cs, Dy, Er, Eu, Fe, Ga, Gd, Hf, Ho, In, Ir, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, Os, Pd, Pt, Pr, Rb, Re, Rh, Ru, S, Sb, Sc, Se, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, W, Y, Yb, V, Zn & Zr	Analysis by both inductively coupled plasma-mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectrometry (ICP-AES)	0.01-1 µg/L
Total: Al, Ag, As, Ba, Be, Bi, Cd, Ca, Ce, Co, Cr, Cu, Cs, Dy, Er, Eu, Fe, Ga, Gd, Hf, Ho, In, Ir, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, Os, Pd, Pt, Pr, Rb, Re, Rh, Ru, S, Sb, Sc, Se, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, W, Y, Yb, V, Zn & Zr	Acid digestion and analysis by both inductively coupled plasma-mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectrometry (ICP-AES)	0.01-1 µg/L
Total Hg	Cold vapour atomic fluorescence spectrometry (CV-AFS)	1 ng/L
Dissolved Organic Carbon (DOC)	Shimadzu Combustion Analyser	0.5 mg/L
Alkalinity as $CaCO_3$	Titration	5 mg/L
Sulfate and chloride	Ion chromatography	1 mg/L
Phosphate, nitrate, nitrite, ammonia	Ion chromatography	1 mg/L
Electrical conductivity	Conductivity meter	
Ra-226	Alpha counting (ANSTO - Environmental Radiochemistry)	1 mBq/L
Ra-228	Gamma counting (ANSTO - Environmental Radiochemistry)	1 mBq/L
Th-230 and Th-232	Alpha counting (ANSTO - Environmental Radiochemistry)	1 mBq/L
U-234 and U-238	Alpha counting (ANSTO - Environmental Radiochemistry)	1 mBq/L
Gross alpha and beta	Alpha & Beta counting (ANSTO - Environmental Radiochemistry)	50 mBq/L
Total suspended sediment (TSS) and pH	Gravimetry, ISE	1 mg/L
HF additives, e.g. fluorobenzoic acid tracers; butoxyethanol, biocides etc., depending on the HF fluid composition	Dissolved phase (filtration, solid phase extraction) liquid chromatography- quadrupole time of flight mass spectrometry (CSIRO Laboratory- LC-QTOF-MS)	low µg/L
Geogenic organic chemicals: Phenols (inc. phenol, methylphenols, dimethylphenols) PAHs (inc. naphthalene and substituted naphthalenes, acenaphthene, anthracene,	CSIRO Laboratory (LC-QTOF-MS) and GC-MS at NMI (NATA accredited laboratory()	low µg/L

Parameter	Description	Typical Limit of Detection (3σ) for water samples
benzopyrenes, fluoranthene, fluorene, phenanthrene) VOCs- Volatile organic carbons (including BTEX compounds) TRHs- Total recoverable hydrocarbons **T**HMs -Trihalomethanes		
Non-target compounds- unknowns (semi-quantitative)	Dissolved phase (filtration, solid phase extraction) gas chromatography-triple quadrupole mass spectrometry (GC-MSMS) full scan analysis and mass spectra library matching – at CSIRO Laboratory	low µg/L

3 Timelines and Outputs

Hydraulic fracturing operations at the Condabri site are planned to occur in July and August 2017. Operations will then occur at the Combabula site from mid to late August to late September 2017. It should be noted, however, that the schedule is subject to variation as the operations progress. This situation requires flexibility in the timing of the sampling program and, for the purposes of planning, it is only realistic to set time windows for various activities rather than fixed dates. CSIRO will liaise with Origin Energy staff on a weekly basis to keep up to date with the latest changes to the HF program.

Assuming no major delays, most of the sampling including collection of HF samples will be completed by December 2017 with the final samples (e.g. remaining produced water, surface water and groundwater samples) being collected in early 2018 and beyond (if new resources are made available).

Sample analysis will be conducted concurrently with the sampling program and is scheduled for completion by 1 June 2018 when a data report will be produced. The laboratory study on the fate of HF chemicals in soils will commence in September 2017 and conclude in June 2018. The final report on the study findings (combined with the air quality investigations) is due in December 2018.

Communication of the results of the project to stakeholders (including industry, government and community) will be managed in accordance with GISERA's communication strategy. This may include presentations at community and industry meetings, conferences and publication of reports, scientific articles and fact sheets and a knowledge transfer session. It is anticipated that there will be a number of conference presentations and publications in international journals arising from the study

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Appendix A: Impact of HF chemicals on soil quality: soil contamination experiments

Background

A recent assessment of potential exposure pathways for contamination of soils with chemicals (Patterson et al., 2017) established that spills of HF fluids and flow back water are among the most polluting and plausible pathways of exposure (Table A1). It was recognised that spills, however, are unpredictable and are very site- and event-specific and therefore conducting a field-based soil contamination study may not yield meaningful information that can be extrapolated to other locations.

Considering the above, a scenario based assessment, mimicking the exposure via spills of HF and flowback water (under controlled conditions) was proposed to be a more appropriate approach as it would generate useful information on the potential fate of HF chemicals in soils that could be used to inform future management of chemicals.

The objectives of the study are:

(i) To establish the likely fate of key organic chemicals that may be accidently introduced to soil via spill of hydraulic fracturing fluids and flowback waters.
(ii) To assess the sorption of compounds, as an indicator of mobility of selected suite of high-risk chemicals through the soils
(iii) To better understand the potential impacts of soil contamination with HF and flowback waters on soil health (through microbial assays) and potential groundwater contamination.

To cover the exposure and impact pathways as a result of spill of HF and flowback water on soils and groundwaters, three aspects will be covered in this study, namely:

(i) degradation (persistence) of chemicals in HF and flowback water in soils;
(ii) mobility of HF and geogenic organic chemicals through soils to shallow groundwater, and.
(iii) potential impacts of a spill on soil microbial health.

Table A1. Common sources of soil contamination and their relevance/ controls to the current study site

Contamination source	Relevance and control	Relative importance
Drill cutting piled on site or reused for rehabilitation	Not stored on site Not used for rehabilitation	Not likely to be a significant source
HF fluid is prepared on site	Some chemical blending and handling occurs during the HF process	Spill of the chemicals could be an important source
Flowback water stored in pits	Flowback water goes into tanks or to wastewater plant via pipeline	Leakage from pits is not relevant Spills from tanks or leakage from pipe can contaminate soil
Chemical stored on site	Chemicals not stored on site	Not likely to be significant source
Disposal of solids from flowback water	Proppants and sediments are not buried or stockpiled on site	Not likely to be significant source
Untreated flowback or produced water reuse	Only treated water (RO) is reused	Not likely to be a contamination source. Untreated flowback water will represent a greater risk
Transport of chemicals to and from the site	Transport is essential but carried out under great care	Accidental spill can be an important source. May be similar to those in HF fluid.
Spills, flowline failure, equipment failure	Relevant to the site, unpredictable	Can be a significant source – spills is a key source specific to hydraulic fracturing

Methodology

Chemical sources

Two types of fluids are seen as the main contributor to the potential contamination of soil via spills during various operations including transport, namely the HF fluid and the flowback water. The main difference between the two sources is that the flowback water is likely to be highly saline and contain geogenic chemicals (both organic and inorganic) in addition to those present in the HF fluid. While some chemicals present in HF fluid may have been attenuated during the HF process, others may remain largely unchanged and in similar concentrations in the flowback water. The chemical composition of the source waters will be characterised.

Soil types

Five soils types chosen from different geomorphic units occurring in Surat Basin were selected to represent diversity of soil type in the region. These are listed in Table A2.

Table A2. Dominant geomorphic units and soils types in Surat Basin (after Biggs et al. 2012)

Geomorphic unit	Dominant soil type	Key features
Alluvia	Black and grey Vertosols*	Clay rich (> 35%)
Basalt	Vertosols, Ferrosols, Dermosols*	Deep clay soils Dermosol – low in free iron
Quartzose sandstones	Chromosols*	Sandy texture contrast soils
Unweathered to moderately weathered non-quartzose sedimentary rocks	Vertosols, Texture contrast Sodosols*, Kandosols	Sodosols - Sodic B Horizon
Moderately to strongly weathered non-quartzose sedimentary rocks	Texture contrast Sodosols, Chromosols, Rudosols*, Tenosols	Rudosols – Sandy loams Chromosols – Sandy over clayey B horizon

* - Soils selected for inclusion in this study

Experimental procedure

All experiments will be conducted under controlled laboratory conditions to avoid any confounding factors that may occur in the field. Homogenised soil samples will be subjected to a known volume of chemical sources (two types of fluids) as well clean water. The volume will be determined to amount required to saturate the soil with the fluid to represent a scenario where the spill was adequate to fully saturate the soil and any excess fluid either leached through to deeper layers or migrated through surface runoff. The saturated soil will be allowed to dry and reach a moisture content that is equivalent to 60-70% of maximum water holding capacity before the commencement of experiment. For the mobility study, uncontaminated soils will be used.

Experimental details

Degradation study: The experimental conditions will be based on published relevant studies (e.g. McLaughlin et al., 2016). Soil will be incubated under constant temperature and moisture conditions representative of Surat Basin. The soils containers will kept open to atmosphere, as is the case under field conditions.

Mobility study: The study on mobility of selected organic chemicals in soils will be carried out using a batch method of sorption. It is noteworthy that intact cores are very site specific (due to presence of biopores and soil structure) and hence do not allow extrapolation to other sites. Hence a batch method that will result in more generic assessment is preferred here. The chemicals will be selected based on their persistence and their equilibrium sorption coefficients (Kd values) will be measured. This will provide an assessment of their mobility (i.e. retardation factor) in comparison with water flow. This information together with degradation will allow an assessment of their potential of contaminating groundwater as a result of a spill.

Microbial health of soil: The soils exposed to HF and flowback water will be tested for a number of microbial functions. Tests will be conducted to represent carbon turnover (microbial respiration), nitrogen cycling (nitrification) and general microbial diversity. Three standard tests will be carried out. These are OECD 307 Substrate Induced Respiration Test (to establish if the general diverse range of bacteria are functioning well), OECD 216 Substrate Induced Nitrification Test (to assess if the specialist bacteria involved in nitrification are affected) and terminal restriction fragment length polymorphism (tRFLP) test to establish any effect on the bacterial diversity of soils.

Chemical analysis: The fate of key chemicals present in source waters will be established by a time series of soil analysis. Three HF and 3 geogenic chemicals will be included in the study. The sampling times will be 0, 1, 3, 7, 14, 28, 56 and 90 days following commencement of experiment. The choice of chemicals will depend on the chemicals added to HF fluids and geogenic chemicals expected to be in the flowback water at these sites.

Number of treatments: (number of soil samples involved in assays)

Chemical sources: n = 3 (HF and flowback water) + control (RO Water)

Soil types: n= 10 (Vertosol, Dermosol, Sodosol, Chromosol and Rudosol) – 5 surface and subsurface soils (B Horizon)

Number of chemicals:

For residue analysis – broad suite depending of what is in HF fluid and in flowback waters.

For sorption study - n= 6 chemicals (to be selected based on HF fluid composition and flowback water).

Sampling times – n= 8 (0, 3, 7, 14, 30, 60 and 90 days) – the last sampling events may depend on earlier results from the experiment.

Number of replicates: 3

Total number of samples:

For the degradation study: 3 sources x 10 soils x 7 times x 3 replicates = 630 samples (90 samples each time)

For the microbial health study: 3 sources x 10 soils x 5 times x 3 replicates = 450 samples (90 samples each time)

For the mobility study: 10 soils x 6 chemicals x 8 concentrations = 480 samples (80 samples for each chemical)

Output

The study will provide the following:

- Quantification of how rapidly the chemicals in spills are degraded in soils
- Prediction of how the chemicals in spills are likely to move through soil to groundwater.
- Identification of contaminants that may persist and potentially pose impact on soil microbial health.
- Data and information that is useful for management of spills to avoid contamination.

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