REPORT

Contract: COSMA-1

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GEOLOGICAL CO_2 STORAGE AND OTHER EMERGING SUBSURFACE ACTIVITIES:

D 3.1

BEST PRACTICE: MONITORING STRATEGY & METHODS FOR GROUNDWATER RESOURCE PROTECTION

Project acronym: Cosma-1

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Title

Geological CO_2 Storage and Other Emerging Subsurface Activities – Best practice: monitoring strategy & methods for groundwater resource protection

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Un grand merci & thank you!

Executive summary

Emerging subsurface activities (ESA) describe a set of methodologies and technologies using the earths subsurface for energy production or capture and storage of carbon dioxide. The earth's heat is used as a clean source of energy (deep geothermal systems, DGS), process-related CO_2 emissions can be stored in suitable geological formations (geological CO_2 storage, GCS) and since the technique of horizontal drilling was developed, the exploitation of unconventional reserves of natural gas via hydraulic fracturing (shale gas extraction, SGE) expanded.

At the same time, 97% of global freshwater resources are stored in the earth's subsurface, too, so that exploitation interests may come into conflict with the issue of groundwater and environmental protection.

Main objective of deliverable D 3.1 of the COSMA-1 project therefore was to identify best practices of monitoring for geological carbon storage, deep geothermal systems and shale gas extraction projects with special focus on groundwater protection. Chapter 2 summarizes current groundwater monitoring standards, including monitoring network designs for emission-based (operators) and immission-based (water suppliers) monitoring. It further presents an identification of hazards related to ESA and a brief overview about the state of regulation. Finally, knowledge gaps concerning groundwater protection are identified. Chapters 3 to 5 describe for each of the above-named types of ESA the project stages and according monitoring needs and methods. Main target was to identify the key parameters and monitoring network designs ensuring reliable groundwater monitoring. As the most relevant hazards were drilling fluids, fracking fluids and brine migration as well as the mobilisation of methane, and the most likely pathways are leakages due to insufficient well integrity, for all three ESA types, pressure, temperature and TDS were recommended as key monitoring parameters. For shale gas extraction, in addition methane emission should be monitored.

Key to any monitoring is i) the baseline sampling prior to the start of subsurface activities and ii) the adequate delineation of the area of review. All further monitoring to be implemented base on site-specific considerations and the authorities' priorities. In any case, monitoring network should include the up-gradient, down-gradient and depth component. Monitoring wells and equipment should cover the full extension of horizontal bores and additional wells should be placed above potential pathways for fluid (or brine) migration as e.g. fault systems. The use of abandoned wells for monitoring is also recommended. The conception of appropriate monitoring strategies has further to be coordinated with the competent authorities, which have to control the compliance with all requirements. Therefore, site operator and water producer should report their monitoring plans and data at regular intervals to the competent authorities.

The findings were summarized by transferring them to a risk management matrix following the Water Safety Plan (WSP) approach (WHO 2009).

For shale gas extraction, deliverable D 3.2 will add specific mitigation measures to reduce the previously identified risk of negative impacts on shallow groundwater. Geological carbon storage was further investigated by means of the development of a coupled model for a theoretical case study site in the North-Eastern German Basin in the scope of work package 2 of the COSMA-project (D 2.3).

Contents

List of Abbreviations

AoR – Area of Review
AOX – Adsorbable Organic Halogens
BTEX – Benzene, Toluene, Ethylbenzene, and Xylenes
CFR – Code of Federal Regulation
CCS – Carbon Capture and Storage
CH_4 – Methane
CHC – Chlorinated HydroCarbons
CO_2 – Carbon dioxide
DGS – Deep Geothermal Systems
DIC – Dissolved Inorganic Carbon
DOC – Dissolved Organic Carbon
DVGW – Deutsche Verein des Gas- und Wasserfaches
EGR – Enhanced Gas Recovery
EGS – Enhanced Geothermal System
EOR – Enhanced Oil Recovery
EPA – Environment Protection Authority
ESA – Emerging Subsurface Activity
FMI – Formation Microscanner Imaging
GCS – Geological Carbon Storage
GWD – Groundwater Directive
GWPS – Groundwater Protection Standard
HSE – Health and Safety Executive
IEAGHG – International Energy Agency GreenHouse Gas
IGRAC – International Groundwater Resource Assessment Center
MESPOP – Maximum Extent of the Separate phase Plume or Pressure front
MIT – Mechanical Integrity Test
MVA – Monitoring, Verification and Accounting
NETL – US National Energy Technology Laboratory
NO_x – Nitrogen Oxides
PAH – Polycyclic Aromatic Hydrocarbons
PISC – Post-closure site care
PFT – Perfluorinated Tensides
SF_6 – Sulfur Hexafloride
SGE – Shale Gas Extraction
SSI – Statistically Significant Increase
SO_2 – Sulfur dioxide
TDS – Total Dissolved Solid

TOC	–	Total Organic Carbon
UIC	–	Underground Injection Control (US EPA)
USDW	–	Underground Source of Drinking Water
US EPA	–	United States Environmental Protection Agency
USGS	–	United States Geological Survey
VDL	–	Variable Density Log
WFD	–	Water Framework Directive
WHO	–	World Health Organization
WSP	–	Water Safety Plan

Chapter 1
Introduction

1.1 Background

Against the background of continuously increasing CO_2 concentrations in the atmosphere, as well as diminishing reserves of fossil fuels, finding new ways for autarkic and “climate friendly” energy production becomes more and more important. Moreover, new solutions have to be found for the mitigation of process-related CO_2 emissions.

A more extensive use of the earth’s subsurface might offer new options to tackle the mentioned challenges. The earth’s heat might be used as a clean and in human timescales endless source of energy (geothermal energy production). Process-related CO_2 emissions from steel or cement production can be stored in specific geological formations (geological CO_2 storage, GCS). Finally, since the technique of horizontal drilling was developed, the exploitation of unconventional reserves of natural gas or oil via hydraulic fracturing (fracking) poses another way for countries to become more energy self-sufficient.

Nevertheless, all these emerging subsurface activities (ESA) are related to intensive drilling activities and thus represent intrusions in the subsurface and associated groundwater, which otherwise constitutes 97% of the global freshwater (WHO 2006), support important ecosystems and supplies one-third of the world’s population with drinking-water (FALKENMARK 2005). Therefore, water suppliers are concerned that emerging activities might have negative impacts on groundwater resources and consequently on drinking water supply.

The project COSMA-1, a co-operation between the Berlin Centre of Competence for Water, the German Research Centre for Geosciences (GFZ) and the Free University of Berlin (FUB), aims at identifying and assessing potential risks associated with the named subsurface activities to groundwater with a particular focus on drinking water supply .

Subsurface activities, such as carbon capture and storage (CCS), geothermal energy production / storage and unconventional (shale) gas extraction (“hydro-fracking”, SGE), have in common that they impact parts of the subsurface and may thus potentially have an effect on fresh water aquifers. In the past, drinking water resource protection has primarily been seen as protection from superficial contamination, leading to the definition of drinking water protection zones with restriction of potentially hazardous above-ground activities. There is, however a concern by water suppliers and authorities that emerging subsurface activities may have a far larger impact radius than the hydrogeological catchment usually taken as outer limit of a water works’ drinking water protection zone.

The project target is therefore to identify hazards, known risks and knowledge gaps, and to develop a methodology to quantify / compare risks from subsurface activities in order to determine control measures and monitoring needs to reduce them.

In a first deliverable of the COSMA-1 project (SEIS et al. 2013), background information on risk analysis, including the relevant terminology and methodology, and theoretical information were given for the three considered subsurface activities. The report included a catalogue and qualitative summary of hazards and hazardous events, related to the respective subsurface activity, which might pose a risk for drinking water supply. This deliverable 1.1 therefore served as a common base for this report on the best practices for monitoring strategies and methods for groundwater resource protection with regard to deep subsurface activities.

1.2 Focus and structure of this report

The delivery of safe drinking-water requires actions to be taken throughout the water cycle from the catchment to the point of consumption. A commonly used management system that is designed to deliver safe drinking-water by meeting health-based targets is the Water Safety Plan concept (WSP) as proposed by the WHO (2006). Establishing a WSP is typically the responsibility of the water supplier, with support from and collaboration with other sectors, such as commercial, administrational or public stakeholders. Because the focus of this report is on the protection of groundwater resources, the WSP approach is not applied to the whole water supply chain, but focuses on source protection, which is the first stage in the production of safe drinking water (WHO 2004). Within the WSP approach, potential contaminations in the catchment (hazards) and measures that can be put in place to prevent, reduce or eliminate contaminants (control measures) have to be identified. Further, a system for monitoring and corrective actions to ensure that safe water is consistently supplied has to be implemented and the methods employed to control hazards have to be validated. Hazards related to emerging subsurface activities and the risk of their occurrence in a hazardous event were already outlined in COSMA D-1.1. This report continues the WSP approach by identifying strategies to monitor the various hazardous events that may occur during the realization of GCS, Hydro-Fracking and Geothermal utilization projects.

Existing monitoring strategies for groundwater, as well as available monitoring practices for each of the emerging subsurface activities serve as basis for an assessment of monitoring actions to be taken according to the WSP approach. The information and data used to identify best practices based on peer-reviewed publications, scientific reports, legislative rules and already existing guidance documents or guidelines from private or public institutions involved in the development and assessment of deep subsurface activities. Information density and degree of regulation for monitoring vary widely for the different activities and different countries. Therefore, this report summarizes monitoring strategies and methods, where they are already existing and further refines or specifies approaches, which are not implemented as best practice so far.

First of all, a summary of best practices for environmental and drinking water monitoring are presented in Chapter 2. This includes an overview of already existing directives and recommendations (from local to international level) on the design of monitoring networks, as well as on sampling parameters and strategies. Chapters 3 to 5 then give a brief description of the monitoring concepts for each of the regarded deep subsurface activities with regard to monitoring network design, key parameters and specific requirements during the different project phases. At the end of each chapter, best monitoring practices are summarized concerning the activities and monitoring packages per phase and the general key indicators. The outcome is a list of available and innovative approaches to monitor the different project phases and the identification of monitoring strategies and tools summarized in appendixes I to III.

Chapter 6 will conclude the literature review by comparing the results for the different activities and relate them to the existing groundwater monitoring strategies. In addition, the outcomes are transferred to the WSP structure.

Chapter 2
State of the art of groundwater monitoring

On a local scale, groundwater monitoring objectives can often be differentiated between environmental and drinking water safety purposes. On international or European level both approaches are combined aiming at a general approach for groundwater protection regulation. The Water Framework Directive (WFD) and other monitoring programs established by various institutions (EPA, DVGW, IGRAC), define approaches and guidelines to build and execute efficient monitoring networks for groundwater resources. Within this chapter, the state of the art concerning best practices for monitoring underground sources of drinking water (USDW) as well as a summary of hazards arising from ESAs are presented using the examples of a few regulations and guidance programs, which are considered to be of greatest relevance for the topic.

2.1 General remarks

An integrated approach to managing water as it flows through catchment, lakes, rivers and groundwater to estuaries and the sea, is defined by the WFD with the aim to protect and enhance the status of groundwater bodies, to use it sustainably and to reduce pollution hazards.

More detailed requirements for groundwater protection are given by the Groundwater Directive (GWD) (EU 2006b). It includes regulations for assessing the chemical status of groundwater, identifying significant and sustained upward trends in groundwater pollution levels, and defining countermeasures for reversing these trends. The characterization of the chemical groundwater status and the identification of trends in pollutant concentrations require sound groundwater monitoring programs as defined by Annex II (2.3) of the GWD (EU 2006b). There, three different monitoring programs are outlined:

i. Quantitative monitoring:

Quantitative monitoring is mainly conducted to determine the quantitative status of groundwater bodies by evaluating the ratio between groundwater resources and abstraction.

ii. Surveillance monitoring:

Surveillance monitoring is required to validate risk assessments, classify groundwater bodies and to assess trends. Thus, surveillance monitoring has primarily environmental purposes and provides a basis for assessing baseline conditions.

The International Groundwater Resource Assessment Center (IGRAC 2006) advises to characterize the groundwater quality in a region based on one single round of sampling. According to the IGRAC monitoring guidance, water quality (indicating water types, origin of the water and first indications of contamination), i.e. the main composition and in situ parameters (→Table 3), should be measured for a general assessment.

iii. Operational monitoring:

Operational monitoring networks are specifically designed for the observation and detection of certain hazardous events or hazards (arising e.g. from ESAs) and provide the basis for the definition of preventive or counteractive measures.

According to the GWD (EU 2006b), operational monitoring is required to establish the chemical status of all groundwater bodies or groups of bodies determined as being at risk, to identify the presence of any long term anthropogenic induced upward trend in the concentration of any pollutant and to assess the effectiveness of remediation efforts. Further, operational monitoring shall be carried out for all those groundwater bodies identified as being at risk of failing to meet WFD criteria. Usually, parameters monitored during ‘surveillance monitoring’ (baseline), are sampled.

The sampling site and parameter selection have major importance in both, surveillance and operational monitoring, because contaminants are often unevenly distributed in a groundwater body. They must give an overview of the water quality within the groundwater body/group of bodies and must represent contaminant distribution. According to the GWD, the selection process should thus cover the following steps (EU 2007):

1. Set-up of a conceptual model (hydrological/hydrogeological/hydrochemical characteristics and different type of land use).
2. Assessment of the risks (including the confidence level).
3. Assessment of practical characteristics of sampling points (access, durability,…).

2.1.1 Monitoring networks and frequency of measurement

For regular and reliable observation, it is useful to compose a "primary" monitoring network consisting of carefully selected wells and/or some newly constructed observation wells, if existing wells are not available (IGRAC 2006).Table 1 shows relative differences of the network density for aquifers of different type and depth, as a function of their response to natural influences from the surface:

Table 1: Possible differentiation of the network density in relation to depth and degree of confinement of the aquifers (IGRAC 2006).

Aquifer type	**Details**	**Spatial variation (response to recharge)**	**Required network density for spatial image**
Shallow (< 20 m)	Unconfined - Dense drainage system - Limited drainage system	Highly variable Modestly variable	High Medium-high
	(Semi)-Confined	Modestly variable	Medium-high
Medium deep (20 – 100 m)	Unconfined - Shallow water table - Deep water table	Highly variable Modestly variable	High Medium-high
	(Semi)-Confined	Modestly variable	Medium-Low
Deep (100 - >500 m)	Unconfined - Shallow water table - Deep water table	Much shallow variation Very low	Medium-high (or low) Low
	(Semi)-Confined	Extremely low	Low

An efficient monitoring network, as recommended by the DVGW providing surveillance of the vertical and horizontal components of the aquifer is shown in Figure 1. Different monitoring purposes are covered by this network (drawdown effects, early warning, etc.) as it includes early warning or up-gradient wells. These wells should be monitored twice a year in spring and autumn (DVGW 2003).

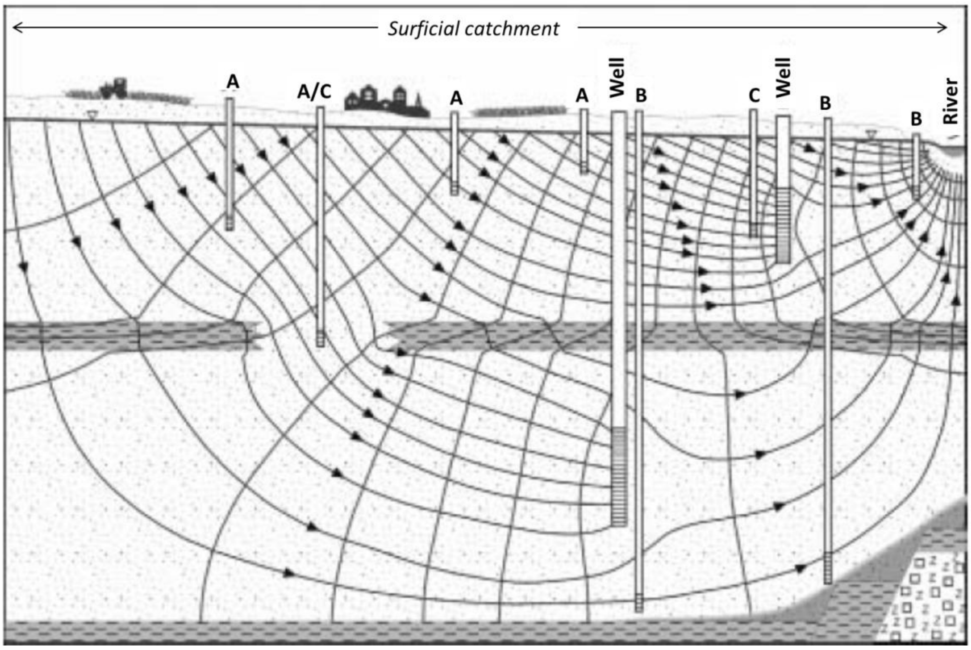


Figure 1: Principle sketch of a monitoring network including monitoring wells for contamination (A), drawdown effects (B) and early warning (C) (modified after DVGW 2003).

In karstic or fissured rocks, the assessment of flow and transport in time and space is very complicated, because flow is preferably oriented along faults and cracks or karst cavities. Moreover, the effective flow velocities are generally very high in those systems. If the required early warning time cannot be provided, a closer sampling interval or a continuous measurement of the raw water quality is needed.

The monitoring frequency must generally be based on the conceptual model and existing groundwater monitoring data. Where there is adequate knowledge of the groundwater system and a long-term monitoring program is already established, this should be used to determine an appropriate frequency for surveillance monitoring. Considering the possible time-related changes of concentration, sampling per monitoring location must be executed at the same frequency. This frequency needs to be adjusted accordingly to ensure that the information requirements are fully met. Where knowledge is inadequate and data are not available, EU (2007) suggests frequencies for surveillance monitoring that can be adopted for different aquifer types (Table 2).

Table 2: Proposed monitoring frequencies for surveillance monitoring (where information on aquifer system is sparse) (after EU 2007).

		Aquifer Flow Type				
		Confined	**Unconfined**			
			Intergranular flow		**Fracture flow**	**Karst flow**
			Significant deep flows common	**Shallow flow**		
Initial frequency – core & additional parameters		Twice per year	Quarterly	Quarterly	Quarterly	Quarterly
Long term frequency – core parameters	**Generally high transmissivity** [1]	Every 2 years	Annual	Twice per year	Twice per year	Twice per year
	Generally low transmissivity [1]	Every 6 years	Annual	Annual	Annual	Twice per year
Additional parameters (on-going validation)		Every 6 years	Every 6 years	Every 6 years	Every 6 years	-

[1] According to Krásný (1993): high transmissivity > 100m^3/day; low transmissivity < 10m^3/day

It has to be noted that in case of pollution hazards emanating from ESAs as focused on with this report, a differentiation between confined and unconfined aquifers is of minor relevance, if contaminants leak through boreholes or cap rocks. Furthermore, surveillance monitoring programs aim at identifying the risk status of groundwater bodies, but proceed from the assumption that hazards originate from surface activities. The proposed monitoring programs do not primarily take into account hazards emanating from ESAs.

2.1.1 Monitoring parameters

For parameter selection, the EU directives and IGRAC provide guidelines. Before the implementation of the WFD and the GWD on European level, surveillance monitoring was regulated on national or regional level.

An example for a surveillance monitoring program on regional level (in accordance with the WFD) is the monitoring program of the State of Brandenburg, Germany (LUGV Brandenburg 2005). The monitoring network includes 202 monitoring wells and covers 51 groundwater bodies with area sizes between 26 and 3000 km^2. Each monitoring well has to monitor an average area of > 500 m^2. The wells are sampled twice a year in spring and autumn. Some parameters (CHCs, BTEX, heavy metals and PAH) are analysed twice a year every 5 years.

Table 3 presents an overview of parameters that should be analyzed according to the above-named surveillance monitoring programs:

Table 3: Parameter of different surveillance monitoring programs

Group of Parameters	Parameter	GWD (2006)	IGRAC (2006)	LUGV Brandenburg (2005)
On-site/ in-situ parameters	Oxygen	x		x
	pH-value	x	x	x
	Electric conductivity	x	x	x
	Redox potential			x
	Turbidity			x
	Temperature	x	x	x
Main ions	Nitrate	x	x	x
	Hydro carbonate	x	x	x
	Calcium	x	x	x
	Potassium	x	x	x
	Sodium	x	x	x
	Magnesium	x	x	x
	Chloride	x	x	x
	Sulphate	x	x	x
	Ortho-Phosphate		x	x
	Fluoride		x	x
	Silica (SiO_2)		x	x
Ammonium		x	x	x
Sum parameters	AOX			x
	TOC			x
PAH	16 compounds			x
Metals	Total iron		x	x
	Manganese		x	x
	Boron		x	x
	Tin		x	x
	Aluminium			x
Pesticides				x

Group of Parameters	Parameter	GWD (2006)	IGRAC (2006)	LUGV Brandenburg (2005)
Heavy metals	Cadmium			x
	Arsenic		x	x
	Mercury			x
	Lead			x
	Copper			x
	Chrome			x
	Nickel			x
Volatile CHCs	Tri- and Tetrachlorethylen			x
	7 additional compounds			x
BTEX	5 compounds			x

2.2 Summary of hazards arising from Emerging Subsurface Activities

Table 4 gives a summary of the reported hazards related to the different subsurface activities. The drilling process is associated with all the regarded subsurface activities although to varying extents. The risk related to leakage of the drilling fluids is elevated for shale gas extraction and shallow geothermal systems due to the high number of drillings associated with them.

Table 4: Summary of hazards potentially resulting from emerging subsurface activities (see Deliverable 1.1).

Hazard (potentially affecting drinking water resources)	Resulting from			
	GCS	Fracking for shale gas exploration	Geothermal systems	
			shallow	deep
Drilling fluids	+	++ (high number of boreholes)	++ (high number of boreholes)	+
Brine / formation water	+	+		+
CO_2 – mobilization of heavy metals	+			
Additives		++ (fracking fluids)	(+)	+ (corrosion inhibitors, anti-scalants)
CH_4	+	++		(+)

Hazards present in brine or formation water are salts, heavy metals, radionuclides and natural organic contaminants like hydrocarbons and BTEX compounds. Brine or formation water may be mobilized by pressure increase in the subsurface or it is released to the surface environment from flowback (shale gas extraction > deep geothermal systems). The pathways can be improperly sealed production wells, abandoned wells without proper sealing or faults open for fluid flow.

CO_2-intrusion due to GCS might mobilize heavy metals within the aquifer matrix. Impurities of NO_x and SO_2 may enhance this effect. For the other investigated subsurface activities CO_2-intrusion is not expected.

Additives like formaldehyde or nonylphenol may be present in fracking fluids and thus represent a hazard associated with unconventional shale gas exploration. A contamination of drinking water resources has been reported to be possible and relevant risk – primarily from above ground handling of these substances (NEUTRALER EXPERTENKREIS 2012). Stimulation of deep geothermal systems has not been found to include hazardous substances, whereas additives like corrosion inhibitors or anti-scalants are used during operation and might leak into drinking water aquifers.

The mobilization of methane is the aim of unconventional shale gas extraction and has been shown also to potentially impact freshwater aquifers (NEUTRALER EXPERTENKREIS 2012). Methane may also be present in geological formations encountered during GCS or deep geothermal systems in concentrations of up to 14 % (SEIBT & WOLFGRAMM 2003). Its mobilization might therefore also be an issue for these subsurface activities.

2.3 State of the art of drinking water suppliers monitoring

For the protection of drinking water resources, water suppliers have to implement an immission-based operational monitoring (IBOM) based on the installation and operation of a monitoring network within groundwater protection zones. Immission-based operational monitoring (IBOM) is conducted to provide advance warning of the arrival of polluted water at underground sources of drinking water (USDW) and to make provision for treatment or other mitigation. It is thus impact-related.

In Germany, it is part of the self-controlling principle, after which the water supplier is responsible for (i) the quantitative and qualitative monitoring of exploited water resources and (ii) the quality assurance of their end product (DVGW 2008)

Object of observation are shallow aquifers or deeper aquifers, which are not sufficiently protected (as e.g. unconfined pore, and/or karstic aquifers). Triggers for a need of action can be trends of indicators (e.g. nitrate, sulphate) or the detection of specific contaminants (e.g. pesticides, CHCs). Any occurrence of contaminants or change of indicator parameter trends will result in a change of operation concepts and discharge volumes or may initialize measures in water treatment processes to prevent unfavourable effects on the drinking water quality.

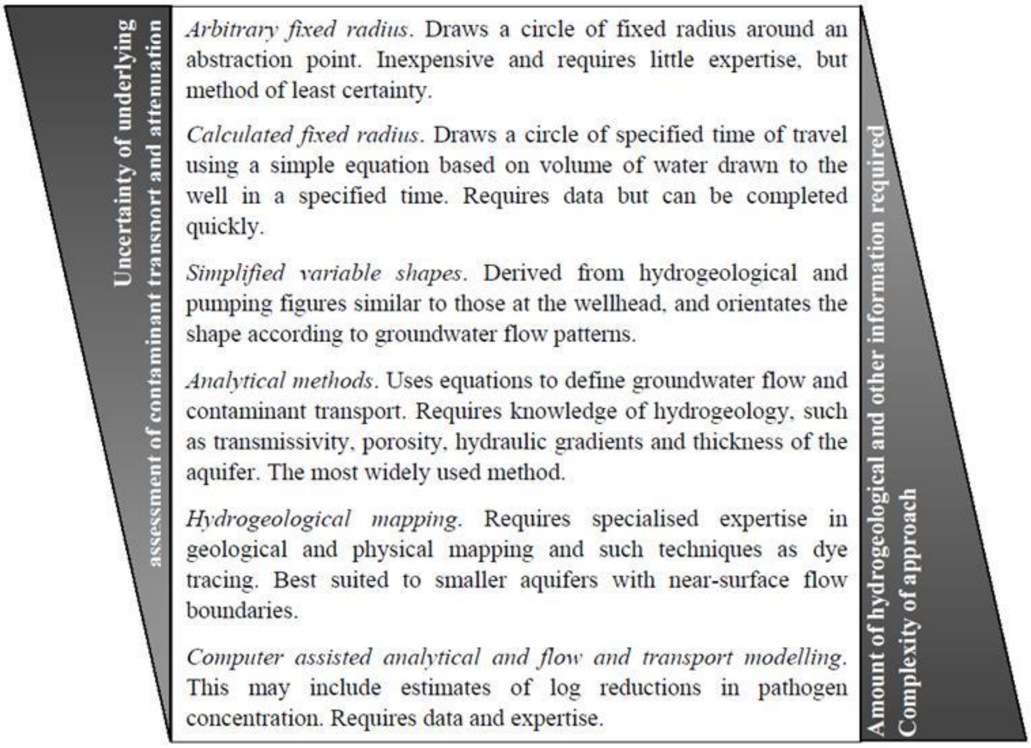
2.3.1 Delineation of groundwater protection zones

The concept of a 'zone of protection' for areas containing groundwater used for drinking water supply has been developed and adopted in a number of countries.

The delineation of groundwater protection zone is based on the distance, drawdown, travel time, the assimilative capacity and the flow boundaries (Figure 2, WHO (2006)). Several perimeters achieve the following level of protection:

- the *immediate zone* prevents rapid increase of contaminants or damage to the well head,
- the *inner protection zone*, based on the time expected to be needed for a reduction in pathogen presence (typically 50d-line),
- the *outer protection zone*, based on the time expected for the dilution and effective attenuation of slowly degrading substances,
- a larger zone that sometimes cover the whole (surficial) *catchment area*, designed to avoid long term degradation of quality.

Within these drinking water protection zones, the water suppliers and local environmental agencies are responsible for an immission-based monitoring. Early warning monitoring wells aim at detecting hazards up-gradient to the drinking water wells. The distance to the production wells must provide sufficient time between observing harmful changes in the groundwater quality and raw water production. These will then result in immediate decisions for well operation and water treatment processes.



Arbitrary fixed radius. Draws a circle of fixed radius around an abstraction point. Inexpensive and requires little expertise, but method of least certainty.

Calculated fixed radius. Draws a circle of specified time of travel using a simple equation based on volume of water drawn to the well in a specified time. Requires data but can be completed quickly.

Simplified variable shapes. Derived from hydrogeological and pumping figures similar to those at the wellhead, and orientates the shape according to groundwater flow patterns.

Analytical methods. Uses equations to define groundwater flow and contaminant transport. Requires knowledge of hydrogeology, such as transmissivity, porosity, hydraulic gradients and thickness of the aquifer. The most widely used method.

Hydrogeological mapping. Requires specialised expertise in geological and physical mapping and such techniques as dye tracing. Best suited to smaller aquifers with near-surface flow boundaries.

Computer assisted analytical and flow and transport modelling. This may include estimates of log reductions in pathogen concentration. Requires data and expertise.

Figure 2: Approaches to delineating groundwater protection zones (WHO 2006)

2.3.2 Monitoring network design, key parameters and monitoring frequencies

In Germany, design, construction, management and operation of networks monitoring groundwater characteristics in catchments of drinking water plants is standardized by the monitoring guidance document W 108 by the German Association of Gas and Water Companies (DVGW 2003). Monitoring networks must include wells designed and constructed for the monitoring of (i) existing contaminations, (ii) drawdown effects and (iii) for early warning (see also Figure 1 in chapter 2.1.1).

The distance between monitoring and production well is influenced by the early warning time, the sampling interval and the effective flow velocity as well as technical and operational boundary conditions. The early warning time should be at least one year. The monitoring screens should be installed in the depths of the flow field exploited by the production well. Further, well permeable layers should be favoured.

The list of parameters to monitor includes, in addition to surveillance monitoring parameters, specific parameters chosen for the catchment based on potential hazards to the drinking water supply. Taking Berlin as an example, parameter groups analyzed in the immission-based operational monitoring of the protection zone of a Berlin water works site include in-situ parameters, main ions, sum parameters, (heavy) metals and a wide range of organic compounds like pesticides, pharmaceuticals, hormones and hydro-carbons (SENSTADT 2001). They are measured quarterly to annually.

2.4 State of the art of ESA operators monitoring

Operators of activities that might impact groundwater resources are typically obliged to provide an early warning of the onset of groundwater pollution from a given activity (e.g. ESAs) and to allow the timely introduction of any necessary control measures by an emission-based operational monitoring (EBOM).

Thus, emission-based monitoring networks focus on specific hazards or indicators, which are typically involved in a specific hazardous event evolving from surface or subsurface activities. The overall focus is on the safe operation of the regarding activity. Environmental protection agencies (e.g US EPA) claim five types of operational monitoring:

i. *Ambient monitoring* is conducted to establish background water quality conditions (setting the baseline). The goal is to account for both, natural variation and any man-made impacts that may have influenced groundwater quality. These results will form a basis against which future monitoring results will be compared. The ambient monitoring analytes should include all those that are being generated by an existing activity or will be generated by a proposed activity.

ii. *Compliance monitoring* determines if groundwater has been impacted by an unauthorized release. Monitoring well locations should be concentrated in those areas that will first be impacted by the contaminating activity. Analytes for compliance monitoring should include, at a minimum, all those that are generated by the (emerging subsurface) activity.

iii. *Assessment monitoring* is usually initiated if compliance monitoring results indicate an unauthorized release into groundwater and to determine the cause of the groundwater impact. Analytes to be included in assessment monitoring include those that have been found to be of concern through the compliance monitoring.

iv. *Remediation monitoring* needs to be initiated when an unauthorized release has been documented through assessment monitoring. Analytes to be included in remediation monitoring are those that are being remediated, indicator parameters of such, or any parameters that may indicate physical or chemical conditions within the aquifer that could affect the remediation processes being carried out on the site (i.e. pH, Eh, dissolved oxygen, temperature).

v. *Post-closure monitoring* is conducted to determine any changes in groundwater quality after the cessation of the activity. Analytes to be included are those which were monitored during compliance and/or remediation monitoring.

2.4.1 State of regulation

A framework for evaluating and monitoring impacts from ESAs during all project stages is set by the European Environmental Impact Assessment (**EIA**) directive, for which refinements related especially to SGE are currently debated among the EU member states. So far, an EIA is mandatory for natural gas abstraction with volumes higher than 500.000 m³ per day and case-by-case for deep drillings (in particular for DGE) as well as surface industry installations for gas exploitation. During such an EIA, the effects of e.g. ESA projects on air, fauna & flora, water, human beings, landscape, cultural heritage, ... are to be evaluated.

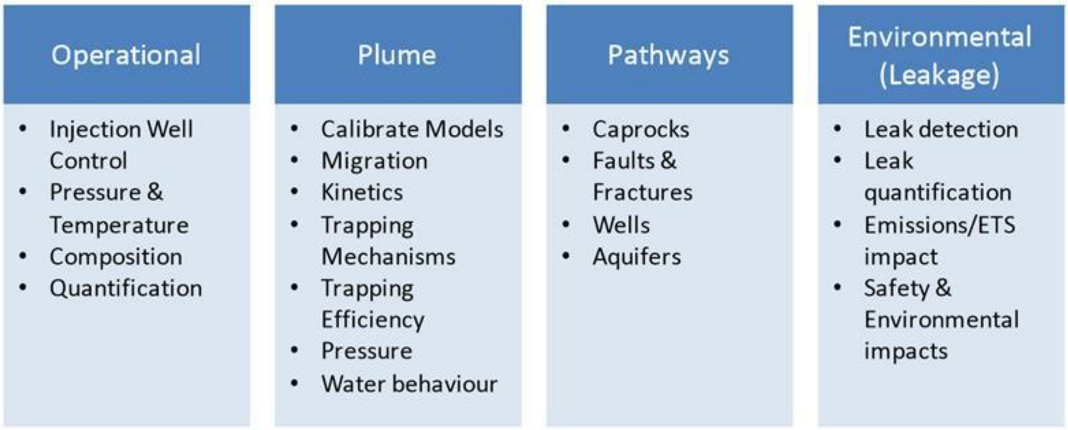
Further, EU- and international regulations were identified for carbon capture and storage (CCS/ GCS) and shale gas exploration and exploitation via fracking.

The first international **CCS Policy and regulations** were introduced within the London Convention and Protocol and followed by the OSPAR Regulation. Basic statement was the requirement of a monitoring plan and a post-closure monitoring scheme for risk assessment and management linked with geological storage.

With the frame of these regulations and the new IPCC GHG guidelines (which constitute the baseline of many CCS regulations), the European Union launched the EU CCS Directive in January 2008 that includes **mandatory monitoring plan and activities** that had to be transposed by member states before 2012. In general, the directive:

- stipulates that CO_2 may only be geologically stored once risk assessment has been carried out and exploration and storage permits have been secured, and
- instructs the member states as to the operation of CO_2 storage facilities and monitoring thereof by "a competent authority".

With respect of this new European regulation, site and operation need to comply with the CCS Directive, which evolves mandatory monitoring activities and reporting guidelines. If any leakage is suspected from monitoring activities under the CCS Directive, surveillance is triggered following the monitoring scheme described in the EU Emissions Trading System (EU ETS) Directives. Figure 3 describes the monitoring plan elements introduced within the EU CCS Directive. It has to be added that operational monitoring is stated as being mandatory.



Operational	Plume	Pathways	Environmental (Leakage)
• Injection Well Control • Pressure & Temperature • Composition • Quantification	• Calibrate Models • Migration • Kinetics • Trapping Mechanisms • Trapping Efficiency • Pressure • Water behaviour	• Caprocks • Faults & Fractures • Wells • Aquifers	• Leak detection • Leak quantification • Emissions/ETS impact • Safety & Environmental impacts

Figure 3: (Mandatory) Monitoring plan elements according to the EU CCS Directive (EU 2011b)

Further existing catalogues (databases) of monitoring techniques for GCS projects that are currently in use or in a developmental/experimental phase include NETL (2009), IEAGHG (2013), and US EPA (2013), the latter setting the same frame and objectives as the EU CCS directive in the United States.

Since **shale gas exploration and exploitation via “Fracking”** is (still) forbidden in some member states (e.g. France), there is currently no European Directive and Regulation on that topic.

In the United States, shale gas development is regulated by the government, but the **principal regulatory authority lies with the states**. Compliance with regulatory requirements for shale gas development is being accomplished in many states through additions to and modifications of existing regulations (Groat et al. 2012). Several federal laws and regulations apply to the different phase of shale gas development (e.g. Clean Water Act, Clean Air Act, Endangered Species Act,…(Groat et al. 2012)).

Since the Federal government has not enacted new regulation, each state can launch and transpose their own regulation, typically focussing on site design, drilling procedures, well design and specification, regulatory oversight/monitoring, and handling of materials and wastes. Thus, the primary responsibility for shale gas development is at the state level (Groat et al. 2012). Four components of fracking operations are generally addressed in states regulations (Alsglobal):

1. *pre-drilling regulations* primarily address site location, design, identification or inventory or materials and chemicals used, and permitting. Some states (Colorado, Ohio,…) include a pre- drill water baseline survey,
2. *groundwater and surface water impact testing* is generally not required by regulation and regulatory monitoring activities that focus on operational controls,

3. *liquid wastes and fluids* are usually treated as any other wastewater,
4. *solid wastes* that is commonly handled as any other solid or contaminated wastes.

Few states have supplemented oil and gas regulations with the requirements of shale gas exploration and exploitation. Some states (Colorado and Pennsylvania) have implemented measures to protect water supplies during shale gas operations. They do not require systematic, well-designed monitoring well programs, but operators are legally responsible if contamination occurs (GROAT et al. 2012).

For **deep geothermal systems** regulations, like the UIC Program of the US EPA (1999a, 1999b, 2007) were instituted with the specific intent of protecting groundwater resources. Thus, most geothermal applications, including all high-temperature geothermal systems, require that the water is injected back into the reservoir.

2.4.2 Delineation of the area of review

A monitoring concept aiming at the provision of a secure and environmentally acceptable realization and operation of ESAs has to consider the shape and extent of surficial as well as subsurficial zones considerably influenced by the activity (including all by drilling, stimulation, injection or abstraction activities). To describe this zone of influence, the "Area of Review" (AoR) has been introduced. Delineation of the AoR is or should be a prerequisite for permitting the ESA.

AoR concepts are already well adapted *for Geological Carbon Storage* (US EPA). There, the delineation has to consider modelled pressure fronts and CO_2 plume extensions. The AoR boundaries coincide with the expected (modelled) maximum extension of the pressure front. Additionally, the AoR must be re-evaluated at a minimum fixed frequency not to exceed five years, or when monitoring and operational conditions warrant (USEPA 2013b). An example is given in Figure 4.

AoR concepts are also applied *for Shale Gas Extraction*, in e.g. USA, but delineation criteria are not sufficiently specified to reliably protect USDW. The US EPA regulations for hydraulic fracturing activities using diesel fuels are still under development, but they recommend modifying the currently applied fixed radius approach so that it is sufficiently protecting USDW. This would imply a site-specific AoR determination to address the full extent, shape and size of the AoR caused by variations in geology, operations, and directional drilling, which typically extends beyond one-quarter mile from the wellhead (USEPA 2012b). The following criteria should be regarded, when delineating the AoR for SGE:

- AoR should be site-specific based on (hydro-)geological models considering local and regional flow systems, structural features (that might pose pathways for fluid leakages) as well as drilling and operation characteristics.
- AoR should at least cover the extent of horizontal boreholes, and of zones affected by the hydraulic stimulation.
- The delineated and site-tailored AoR should represent the zone of endangering influence for contaminating USDW.

AoR concepts are also applied *for Deep Geothermal Systems*, where the delineation is generally fixed to a quarter mile radius from the well. In addition, at least the extension of the thermal influence should be considered. Because this area strongly depends on both, reservoir conditions and the type of geothermal resource and thus the operation system, the delineation must be done site-specific.

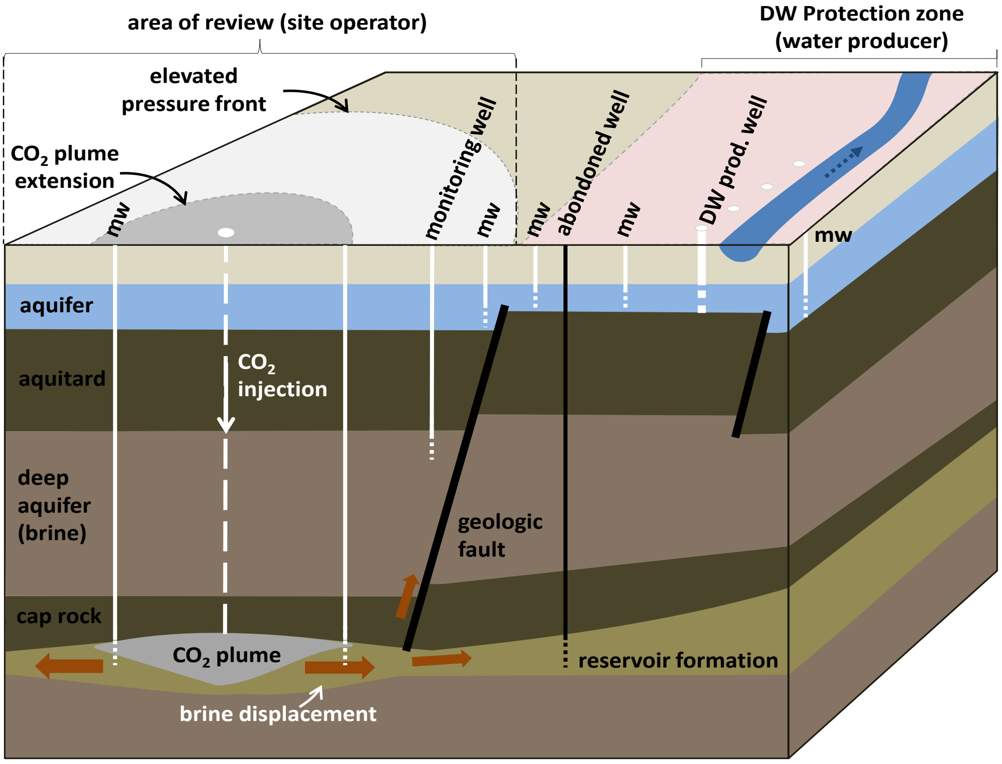


Figure 4: Monitoring network example for a GCS site (mw=monitoring well). (Modified after BIRKHOLZER et al. (2009)

2.4.3 Monitoring network design, key parameters and monitoring frequencies

The prime requirement for a successful EBOM system is to determine the "target" zones, which are the areal locations and depths that are most likely to be impacted by the activity being monitored or site being investigated. The dimensions of these target zones depend on the vertical and horizontal components of flow in the aquifers being monitored, the potential contaminants and the distance that a contamination may have travelled from the activity. The placement of monitoring wells should thus consider groundwater movement and potential contaminant pathways and distribution. The network may always include both, up- and down-gradient wells to detect potential other contaminant sources up-gradient the site (DVGW 2003).

As the objective of EBOM is to detect specific hazards and hazardous events, the monitoring parameters depend mainly on the given activity and site-specific conditions. Table 5 indicates parameters for a list of hazardous activities and events as they were identified by various authorities (LUGV BRANDENBURG 2005, IGRAC 2006, FGG ELBE 2007):

Table 5: Exemplary emission-based operational monitoring programs (LUGV BRANDENBURG 2005, IGRAC 2006, FGG ELBE 2007, EPA 2008).

Hazardous events	Hazards	Indicators
Saltwater/brine intrusion	Main ions Total iron Manganese	In-situ parameters Sum parameters Main ions
Agriculture	Nitrate Ammonium Phosphate Pesticides	Nitrate
Lignite mining	In-situ parameters Main ions Iron(II) Sulfide Manganese	In-situ parameters Main ions
Salt mining	Main ions	Main ions
Uranium mining	Uranium Radium-226 Heavy Metals Chloride Sulphate	pH-value
Contaminated sites	PAH/ Naphthalene BTEX Petroleum hydrocarbons Phenol Chlorocarbons	-
Acidification	Main ions Aluminum	Main ions
Traffic/settlements	Main ions Boron Aluminium	In-situ parameters Main ions
Landfills	Main Ions Heavy Metals Phenols Boron Nitrate Ammonium	In-situ parameters Main Ions

Monitoring frequencies must be sufficient to detect the impacts of relevant pressures, but imply a minimum of one sampling per annum (EU 2006a). Sampling frequency and sample timing at each monitoring location should furthermore consider the requirements for trend assessment (seasonal variations), the location of the well (up-gradient/down-gradient of the pressure), short term fluctuation in pollutant concentrations and the hydrogeological properties as they reflect groundwater travel times in the subsurface. Sampling procedures must be continued until data ensure the reversal of contaminants trends or the remediation of contaminants within the aquifer. Table 6 summarized recommended monitoring frequencies depending on the aquifer flow type and main objective of monitoring:

Table 6: Operational monitoring frequency related to different aquifer types according to the GWD (EU 2006a)

	Aquifer Flow Type				
	Confined	**Unconfined**			
		Intergranular flow		**Fracture flow**	**Karst flow**
		Significant deep flows common	**Shallow flow**		
Continuous pressures	Annual	Twice per year	Twice per year	Quarterly	Quarterly
Seasonal/intermittent pressures	Annual	Annual	As appropriate	As appropriate	As appropriate
Trend assessments	Annual	Twice per year	Twice per year	Twice per year	-

2.4.4 Monitoring tools

Throughout all ESAs, some basic requirements can be applied to the different project phases. These are

- *during the pre-operation phase:*
  - Compilation of basic data for the (hydro-)geological characterization of the deep geo systems (spatial distribution of permeability, hydraulic potential, etc…)
  - Numeric modeling of deep flow systems including scenario and impact analysis
  - Hydro-chemical and pressure baseline monitoring of shallow and deep aquifers
  - (hydro-)geological exploration of surroundings (localization of abandoned wells)
  - Geophysical monitoring and characterization of fractures and fracture zones (3D-Seismic)
  - Well integrity testing (casing and cementation)
- *during the operation phase:*
  - Hydro-chemical and pressure monitoring of shallow and deep aquifers
  - Geophysical monitoring and characterization of fractures and fracture zones (3D-Seismic)
  - Well integrity testing (casing and cementation)
- *during the post-operation phase:*
  - Well abandonment testing
  - Hydro-chemical and pressure monitoring of shallow and deep aquifers.

Based on their application, function and stage of development, a classification of monitoring tools into three categories (derived from Plasynski et al. 2011) has been established, with:

i. *Primary* tools are the proven and mature techniques that provide the information required by the governmental regulations (USEPA, EU, etc.).

ii. *Secondary* tools, typically more advanced, are complementary tools to the ‘Primary’ since they can refine results. They are already established in application, but the efficiency of each tool is depending on site-specific factors.

iii. *Potential* tools can provide more advanced and detailed information and a more complex utilization. Their applicability is tested in case studies, but a commercial tool has still to be developed for the specific monitoring activity.

Potential technologies were not yet considered mature at the time this guidance was written (they had not yet been proven in commercial-scale projects), but may have some future utility as a monitoring tool after additional field testing. It is important to note that the appropriateness of certain technologies may change in the future as their deployment increases, and this should be considered when selecting the site-specific methodologies for ESA projects.

A list of all relevant monitoring techniques for the three different ESAs is given by Appendix I to Appendix III.

2.5 Identification of knowledge gaps and lack of best practices

Generally, knowledge of shallow aquifer systems is extensive. In case of water abstraction for the public water supply, exploration and monitoring standards are well defined and hydrogeological conditions and potential anthropogenic impacts are well known. Information about deep geosystems that potentially can be used as storage site or for gas or geothermal exploitation are comparatively less and information is scarce and obtained at large intervals, only. Conceptional models and scenario modelling can provide deeper insight into setup and features of these deep geosystems, but rely on the reliability of input data.

So far, existing operational monitoring programs do not or only to a minor extent consider hazards for USDW related to ESAs (except of salt water/brine intrusion). Thus, the following chapters shall provide the basis to establish an operational monitoring design including indicator parameters, frequency and location of their determination for each of the three deep subsurface activities characterized within the COSMA-project.

Currently the WFD (EU 2000) provides some indicators and practices that may supplement groundwater resources surveillance in the context of ESA deployment. However, one of the “key components”, depth, is not taken in account by current regulations. The existing directives are always considering surface contamination, but the **vertical issue** of a hazard that may arise from deeper layers is not taken in account. The delineation of groundwater protection zones is addressed in 2D with the spatial extension of the different perimeters depending on the horizontal distance between a “surface” contamination point and the wellhead. Potential risks emerging from deep layer contamination are not taken into account, so far.

Especially for shale gas development, the horizontal drilling techniques would allow operators to install the wellhead of injection wells outside a protection zone, while the production zone could even underlie a protective perimeter.

In the United States, currently regulations are implemented in response to the rapid rise of shale development and the public concern associated with it (WISEMAN & GRADIJAN 2012).

Considering fracking, the lack of standard regulation is also highlighted by the fact that water baseline testing is not required (in every state) prior to drilling and the fracturing process (WISEMAN & GRADIJAN 2012). Furthermore, although fracking is a several decades old technology (in the United States), only a few impact assessments have been done, so far. Other countries should take this US background and **implement fracking regulation** before the beginning of any shale gas operation. ESA´s regulations should be accomplished within a solid framework of laws and regulations based on the contemporary research and development works.

Chapter 3
Geological Carbon Storage

Monitoring is one of the key activities to ensure the safe realization of geological storage projects. It is essential to assess whether injected CO_2 is behaving as expected, whether any migration or leakage occurs, and whether any identified leakage is damaging the environment or human health. Thus, monitoring plans must be developed hand in hand with site characterization, modelling and risk assessment, and they must be linked to preventive and corrective measures, financial security and financial mechanisms. These monitoring, verification and accounting activities (MVA) are fundamental for a successful implementation of a geological storage project (PLASYNSKI et al. 2011). They have to be risk-based and site-specific and adaptive to changing needs that arise from the different development and implementation levels of a GCS project. Thus, existing or future monitoring guidelines can never provide fit-for-purpose monitoring plans that are applicable to any storage site (SIJACIC 2013).

3.1 General remarks

The state of the art of monitoring GCS projects during the different phases is detailed e.g. by (BENSON and MYER (2003), EU (2009), NETL (2009), PLASYNSKI et al. (2011), USEPA (2012a), IEAGHG (2013), US EPA (2013), USEPA (2013a), USEPA (2013b)).

Potential impacts to USDW arise from leakage of injected and/or formation fluids (USEPA 2013b) and above-ground handling of drilling fluids, injection additives and waste/ wastewater. Risks in the geological system include CO_2 or brine migration via faults and fractures and/ or caprock failure and risks in the technical system arise from CO_2 or brine migration via active and/or abandoned wells and surface activities.

The **site operator** is responsible for emission-based monitoring within the area of review. Primary purpose is to identify potential migration of injected CO_2 and/or formation fluid displacement from the injection zone. A monitoring plan and a post-closure monitoring scheme including risk assessment and management are mandatory requirements before start of operation (IPCC 2005, EU 2009, EU 2011a, USEPA 2013d).

Emission-based monitoring focuses on two key parameters:

1. *pressure*, and
2. *geochemical composition of groundwater.*

US EPA (2013) recommends that hydrogeochemical monitoring should be conducted in the first formation overlying the confining zone that has a sufficient permeability to support collection and analysis of ground water samples. Based on the baseline water quality determined during site characterization, the GCS operator has to control during operation and closure of the GCS site, that the concentration of these groundwater parameters is not outweighing the baseline temporal variance. Thus, sampling frequency and duration should be high enough to provide a representative temporal variance of the concentration of the analyzed parameters.

Local water suppliers are responsible for immission-based monitoring within their drinking water protection zones. For monitoring wells sited between ESA operation sites and drinking water protection zones, specific key parameters of GCS may be included in the immission-based monitoring.

3.1.1 Monitoring network design

The design of the monitoring well network is a key component of the monitoring system that serves to detect any leakage through the confining zone that may endanger USDW and supports any direct monitoring in the injection zone. Basis is the delineation of the **AoR** during site characterization (modelling of pressure front and extent of separate-phase plume) (USEPA 2013c, USEPA 2013b).

Objective of monitoring network design is to maximize the ability to detect potential leakage and track the migration of the CO_2 plume and pressure front, while minimizing the number of wells as they can serve as conduits for fluid movement (US EPA 2013).

Monitoring wells above the confining zone(s) should be preferentially placed in regions of concern for potential risk of fluid leakage and/or USDW endangerment. These regions include identified faults, fractures or abandoned wells that may represent a pathway for fluid leakage into a USDW (US EPA 2013). Additionally, regions that are predicted to overlie the maximum thickness and saturation of the CO_2 plume and/or elevated pressures constitute regions for potential concern and should be covered by the monitoring network.

The number of monitoring wells above the confining zone and their location must be determined by modelling and/or statistical analysis based on regional hydraulic gradient, flow paths, transmissivity, and baseline geochemistry (US EPA 2013). They must be located in a way that any leakage through the confining zone that may endanger a USDW will be detected in sufficient time to implement remedial measures. For projects with a separate-phase plume and/or pressure front predicted to move in a specific direction (e.g. due to formation dip), wells should be primarily placed in the predicted down-gradient direction. However, at least one up-gradient well is necessary.

3.1.2 Monitoring parameters

The specific parameters to be analyzed depend on the characteristics of the site, each formation being analyzed, and the composition of the planned carbon dioxide stream (NETL 2009, US EPA 2013). Generally, increasing **carbon dioxide concentration**, decreasing **pH**, or a change in the **geochemical signature** (main ions, TDS) of water compared to the baseline may indicate fluid migration (US EPA 2013).

Increases in **head pressure** in wells above the confining zone (if such monitoring is performed) may be indicative of fluid leakage, too and measurements should be used to complement fluid monitoring data in assessing leakage.

3.2 Best practices of monitoring during the GCS life cycle

The **life cycle** of a GCS site can be divided in four main phases: (i) site characterization, (ii) well construction, (iii) injection and (iv) site closure and post-closure. Each of the phases is characterized by different objectives and according testing and monitoring activities. On the following pages, monitoring needs, methods and key parameters are specified for the single phases of a GCS project. Constituents of interest should be the same throughout the whole GCS life cycle. All parameters for protecting groundwater from GCS activities should already be included in the baseline monitoring and may stay included during injection and PISC monitoring.

3.2.1 Site characterisation

This phase involves extensive and detailed studies of the storage site and storage complex and its surrounding by the operator to define the **geological framework** and to model it in three dimensions by static and dynamic models. Based on data collected during the preceding exploration phase (evaluation of the potential of the site to become a GCS project site), further drilling and injection testing activities may be conducted as part of the site characterization phase to reduce risks and uncertainties for the following project phases.

During site characterization, features, events and processes that could lead to leakage of CO_2 and formation fluids from the storage complex are identified and the **baseline conditions** to describe the site and complex ahead of any CO_2-injection and storage are assessed. The results of baseline monitoring are later compared to subsequent monitoring data from the injection and post-closure phases to observe time-lapse changes resulting from the injection process.

Analyses should include basic **parameters** such as pH, total dissolved solids (TDS), alkalinity, specific conductivity (SC) and major anions and cations. Other constituents may differ by formation and should be determined based on the mineralogy of the storage and confining formations. These may include: Sr^{2+}, Fe^{2+}, Fe^{3+}, Al, SiO_2, total organic carbon (TOC), CO_2(aq), and hydrogen sulfide(aq) (if the site is an oilfield) and trace metals (e.g., As, Hg, Cu, Zn, etc.). Additionally, baseline gaseous carbon dioxide should be measured in subsurface formations and all USDW within the AoR.

Methods include (refer to Appendix I):

- *Geophysical monitoring* to assess the baseline geological conditions in and around the site vicinity prior to CO2 injection. Integration of the geophysical approaches is needed to obtain the best quantitative estimate of CO_2 in place, once it is injected. Available geophysical monitoring techniques include for example seismic surveys, electromagnetic imaging, gravitational methods, well logging and **pressure and temperature** monitoring.
- *Groundwater sampling* assessing the groundwater quality and composition prior to first injection of CO_2. Available geochemical monitoring techniques include **basic groundwater quality** monitoring, i.e. analysis for inorganics and isotopes, brine composition studies, and groundwater CO_2 tracer monitoring. Groundwater sources of interest include USDW around the injection site, as well as saline formation fluids (brine) and production well water (NETL 2009).
- *Surface and atmospheric monitoring* to assess the **baseline ambient CO_2 and soil gas CO_2 concentrations** within the vicinity of the injection site. Natural and anthropogenic nonpoint sources of CO_2 in the vicinity of the site need to be addressed in order to prevent false-positive CO_2 readings once injection has commenced (NETL 2009). Available near-surface and atmospheric monitoring techniques include atmospheric CO_2 detectors, flux accumulation chambers, Advanced Leak Detection Systems, Eddy covariance tests, and soil and vadose zone gas sampling.

The baseline monitoring area should include injection facilities, the storage complex (including where possible the future extension of the CO_2 plume), and where appropriate the surrounding environment. It is the basis to define the **monitoring plan** for the whole GCS project and to delineate the **area of review** for all further monitoring activities based on the geology of the storage complex and the geological framework of the surrounding environment (EU 2011a,b).

Sampling frequency and duration must be high enough to provide a representative temporal variance of the analyzed parameters.

3.2.2 Well construction

In this phase, the infrastructure and facilities required for the storage site is constructed. New injection wells (complementary to those drilled for site characterization) are drilled and any remediation of existing wells or facilities takes place.

Basis to ensure safe operation and prevent migration pathways is to monitor and test proper well construction (USEPA 2013b). **Mechanical integrity** of the well is achieved by ensuring that each of the components of the well is constructed with appropriate materials and is functioning together as intended. Maintaining mechanical integrity helps to prevent the well and well bore from becoming conduits for fluid migration out of the injection zone.

Proper well construction should consider injecting conditions (high pressures, long injection duration) and characteristics of the injected CO_2 (potential corrosivity, lower density than most subsurface fluids). An improperly constructed well can lead to the loss of well integrity that could provoke carbon dioxide or formation fluid leakage from the well bore and into USDW (USEPA 2012a).

Methods involve

- *Borehole geophysical logging* to assess position and status of casings, screens, annulus, cement bonds etc.
- *Monitoring of* ***operational parameters*** (injection rates and volumes, well head pressure, annular pressure)

The mechanical integrity has to be tested during and after well construction and in continuous intervals during the injection phase.

3.2.3 Injection

This phase refers to the operation phase, when injection of CO_2 into the storage reservoir takes place. Primary objective of monitoring is to ensure safety with all procedures associated with fluid injection. **Operational monitoring** involves all fluid injection activities. According to the US EPA (2013), the following testing and monitoring activities are primarily required during the injection phase:

- *Analysis of the carbon dioxide stream* yielding information on the chemical composition and physical characteristics of the injected CO_2
- *Monitoring of operational parameters* injection pressure, rate and volume; well head and annulus pressure; annulus fluid volume (through the use of continuous recording devices)
- *Corrosion monitoring* of injection well materials (required on a quarterly basis)
- *Monitoring of ground water quality* and geochemical changes above the confining zone(s), at a site-specific frequency and spatial distribution
- *External mechanical integrity testing* (at least once per year)
- *Pressure fall-off testing* (at least once every five years)
- *Tracking of the extent of the carbon dioxide plume* and the presence or absence of elevated pressure (monitoring of the pressure front)
- *Surface air and/or soil gas monitoring* measuring soil gas and atmospheric CO_2 concentrations

Testing of well, cap rock and formation integrity should be applied continuously to detect potential migration pathways generated by the injection.

US EPA (2013) further recommends that all wells should be initially sampled on a (minimum) **quarterly** basis for all relevant constituents. Alternatively, a project-specific frequency can be determined based on the variability in ground water chemistry. Sampling frequency needs to be increased if the results of monitoring indicate possible fluid leakage or endangerment of USDW at a particular location. Likewise, sampling frequency can be reduced, if generally stable conditions are observed in several successive sampling rounds. Certain parameters, such as **pressure, pH** and **specific conductivity** should be monitored **continuously** using dedicated downhole sensors. The EU (2009) further demands that monitoring results must be reported annually. Furthermore, any changes with respect to the baseline values must be reported.

A potential contamination source is assessed by sampling of natural or introduced tracers (CO_2 and other hydrocarbon gases), stable isotopes of carbon and water, noble gases and perflourinated tensides (PTFs). An increase in the concentration of any impurities in the injected CO_2 (e.g., hydrogen sulfide) is indicative of injected CO_2 migration into the monitoring zone. The presence of carbon dioxide may also leach certain inorganics (e.g., lead, arsenic, iron, manganese) from the formation matrix due to lowered pH. Increasing (heavy) metals trends may thus be indicative for fluid migration, too.

3.2.4 Site-closure and post closure

Post-closure monitoring plans have to be designed before drilling and well construction. USEPA (2013a) is tentatively proposing a **post-injection site care** (PISC) period of 50 years, whereas the (EU 2011b) propose a post-closure pre-transfer phase of at least 20 years.

The primary goal in the post-injection phase is to ensure that stored CO_2 is behaving as expected and drilled wells keep their constructive integrity without any detectable leakages. Most of the injection wells and some monitoring wells can, respectively should, be plugged and abandoned to ensure that they do not serve as conduit for fluid movement into USDW. Because monitoring the reservoir is intricate once wells are abandoned, the CO_2 plume and pressure fronts should be monitored **in the aquifers close above the storage reservoir**.

At the start of the post-closure phase, the same suite of variables should be obtained as for establishing the baseline in the pre-injection phase (USEPA 2013a). While there is greater potential for leakage during the injection period due to high and possibly increasing pressure in the injection zone, it is expected that such pressures would decrease after closure, reducing the chance of leakage. Therefore, during the closure period, **monitoring of the stored CO_2** is critical for ensuring that there are no significant environmental, health and/or safety (HSE) risks. Monitoring tools and methods involve

- *3-D seismic monitoring* and *instrumented monitoring wells* to track the position of the CO_2 plume and pressure front and to identify any potential vertical leakage toward the surface.
- a *record of the pressure in the injection formation and surrounding area* as well as the pressure decay rate to confirm that the injected CO_2 is not moving beyond the specified GCS horizon.

The appropriate **frequency** of monitoring and reporting is influenced by **site-specific** conditions and will therefore change over time. During the initial stage of PISC, groundwater should be monitored at a similar frequency as during the end of the injection phase (USEPA 2013a). The frequency may then be reduced over time if a demonstration can be made that the risk of endangerment of USDW is decreasing (e.g. by pressure monitoring in the reservoir and overlying formations) and monitoring data are relatively stable. Parameters **pH and specific conductivity** should be monitored **continuously** as in previous phases.

The USEPA (2013a) recommends, that fluid sampling and pressure monitoring during PISC should use a series of monitoring wells, where some are screened within the injection zone, and others are screened in groundwater above the primary confining zone. In this way, the number of monitoring wells used will decrease over time with decreasing pressure in the reservoir and overlying formations. The last monitoring wells will then be closed in accordance with site closure.

Since the goal of GCS is the long term storage of carbon dioxide, well integrity must be maintained for the whole life of the project as wells could potentially serve as a conduit for carbon dioxide flow out of the injection zone even after injection has ceased.

3.3 Summary of best practices

Figure 5 and Table 7 summarize the monitoring activities and methods and tools for the different phases of a geological sequestration project. Table 8 lists a panel of key parameters identified to be sufficient to indicate groundwater contamination that can result from GCS operation.

For a summary of monitoring tools and techniques for GCS projects, please do also refer to Appendix I.

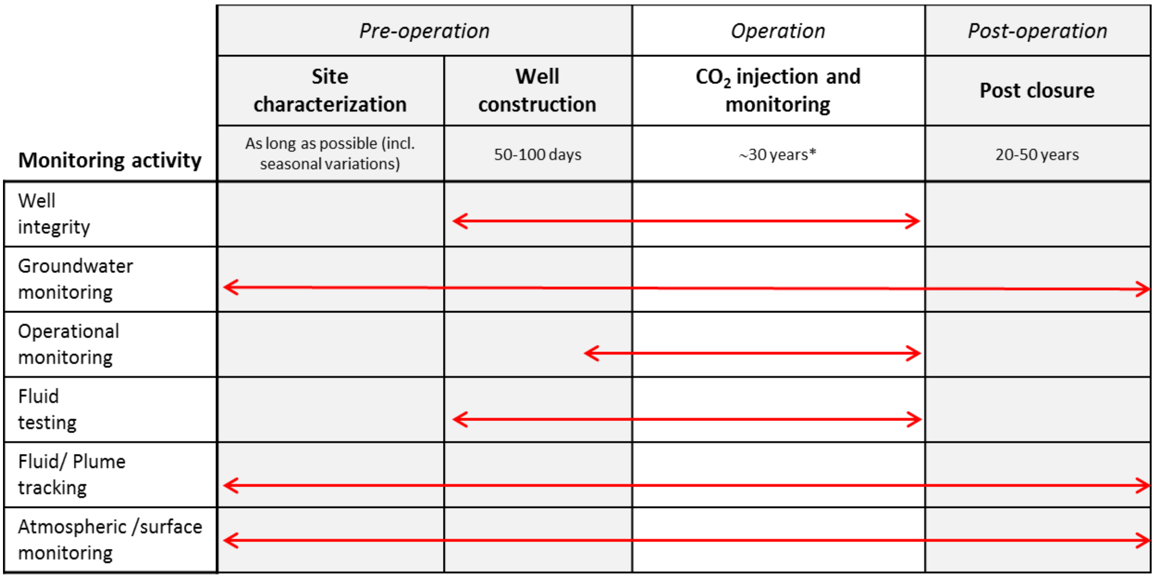


Figure 5: Testing and Monitoring Activities during phases of a GCS-Project (*Szulczewski et al. 2012)

Table 7: Basic and enhanced monitoring packages for GCS operators (modified after NETL (2009)).

Basic Monitoring Package	**Enhanced Monitoring Package**
Pre-Operational Monitoring	
Well logs Wellhead pressure Formation pressure Injection and production rate testing Seismic survey Atmospheric CO_2 monitoring Geochemical groundwater monitoring Pressure and water quality above the storage formation	Well logs Wellhead pressure, bottom hole pressure Formation pressure Injection and production rate testing Seismic survey Gravity survey Electromagnetic survey Atmospheric CO_2 monitoring CO_2 flux monitoring Pressure and water quality above the storage formation
Operational Monitoring	
Wellhead pressure Injection and production rates Wellhead atmospheric CO_2 monitoring Microseismicity Seismic surveys Pressure and water quality above the storage formation	Well logs Wellhead pressure, bottom hole pressure Injection and production rates Wellhead atmospheric CO_2 monitoring Microseismicity Seismic survey Gravity survey Electromagnetic survey Electric resistivity tomography (near-well) Continuous CO_2 flux monitoring Pressure and water quality above the storage formation
Post-Operational Monitoring	
Seismic survey Pressure and water quality above the storage formation	Seismic survey Gravity survey Electromagnetic survey CO_2 flux monitoring Pressure and water quality above the storage formation Wellhead pressure, bottom hole pressure

Table 8: Key indicators for monitoring GCS impacts on groundwater *(Benson & Myer 2003, Benson & Cook 2005, Nimz & Hudson 2005, NETL 2009, Yang et al. 2012).*

Key indicators	**Additional indicators**
pH	DOC
TDS	Stable isotopes (^{13}C, ^{14}C, ^{18}O, ^{2}H),
Pressure	Hydrocarbon gases, CO_2 and associated isotopes
	Introduced tracers (noble gases, SF_6 and PFTs)
	(heavy) metals
	Bromide
	Temperature
	Major ions
	Alkalinity
	DIC
	Chloride

Chapter 4
Shale Gas Extraction

During shale gas extraction (SGE), hazardous events concerning groundwater contamination may occur during drilling, stimulation and exploitation. Depending on the physico-chemical properties of the analytes, the interconnectedness of induced and existing fractures, the types and characteristics of geologic formations, and the distance between the fracking operation and sampled groundwater, the time frame for migration of hydrofracking-related contaminants can vary from days to many years. Establishing a reliable frac monitoring protocol is thus essential.

Regulations for oil-and-gas-related hydraulic fracturing are, if existing at all, implemented on regional level. The world's leading country in shale gas exploration, the United States of America, explicitly excludes wells used for shale gas recovery from their UIC program (except when diesel fuels are used). This highlights the status of SGE regulation and the approval and implementation needs for mandatory monitoring and verification tools in oil and gas industry. Due to this legislative gap, companies, regional authorities and NGOs have developed own approaches to monitor the integrity of SGE projects. Due to the massive quantities of water required during fracking and the various chemicals and minerals that could potentially pose significant threats to human and environmental health, monitoring plans have to include monitoring, verification and accounting (MVA) strategies (e.g. as applied for GCS projects). Several federal states and countries have lately developed recommendations and guidelines for MVA in shale gas extraction, however, regulations on national level for monitoring environmental impacts are still in development or discussion.

4.1 General remarks

The **state-of-art** in monitoring SGE projects during the different phases is described by a large number of authors and institutions (AMERICAN PETROLEUM INSTITUTE 1993, AMERICAN PETROLEUM INSTITUTE 2009, BOLANDER 2011, HETRICK 2011, SOEDER 2011, DAVIES et al. 2012, RAENG 2012, ESHLEMAN & ELMORE 2013, GWPC & IOGCC 2013, RHODES 2013). From these sources, best monitoring practices for operators were identified.

Potential impacts to USDW arise from well construction failure, migration of fracturing fluids to a drinking water aquifer, and surface spills from facilities associated with hydraulic fracturing. Additionally, migration of a carbon source (e.g., methane) for sulfate-reducing bacterial action may cause a drinking water source to be compromised. Further, gas phase transfer of the volatile hydrocarbons present in natural gas can occur, although this process will not carry the low-volatility compounds or the salts.

A statistically significant **baseline sampling program** will assist the energy company and the water suppliers, in providing that the hydraulic fracturing operation (drilling, fracking, exploitation, closure) is not interacting with water bodies (surface water or groundwater) (STEWART 2013). Since baseline sampling is however not a mandatory activity, there is only little information on the size and density of groundwater monitoring networks and sampling frequencies.

4.1.1 Monitoring network design

In the United States, SGE monitoring networks have to cover the **AoR** (USEPA 1998). The AoR must be determined by one of two methods: (1) determining the zone of endangering influence (ZEI), or (2) using a minimum one-quarter (¼) mile fixed radius around the well. Owners or operators of injection wells are required to **identify any potential conduits for fluid movement**, including artificial penetrations (e.g., abandoned well bores) within the AoR, assess the integrity of any artificial penetrations and perform corrective action where necessary to prevent fluid movement into a USDW.

The sampling locations are typically determined by federal state regulations. For example, Colorado groundwater protection rules require sampling of up to four water wells within one-half mile of a new oil and gas well (COGCC 2013a). Companies operating SGE in less regulated states perform water sampling within a two miles radius centred exploitation site (BLAKE 2011). The establishment of dedicated monitoring wells is currently not mandatory. Often, most of the wells used for the sampling procedure are residential water wells, producing some variability in the baseline water survey due to non-standardized well designs (e.g. depths and lengths of screened well sections). However, the implementation of at least **one down-gradient monitoring well in the first drinking aquifer** above fracking operations seems to constitute one of the best practices (BLAKE 2011) and should be mandatory. Additional groundwater sampling points along the planned trajectory of the horizontal borehole and **over structural features, which might provide conduits** for hydraulic fracture fluids to move out of the simulation zone, enhance considerably the efficiency of the monitoring network (SOEDER 2011).

4.1.2 Monitoring parameters

In those situations where hydraulic fracturing is suspected of contaminating groundwater, determining the source is a critical aspect for protecting drinking water resources. Approaches to identifying sources have taken several forms, including the use of salts, hydrocarbons, exclusively anthropogenic chemicals, radioactive substances, and isotope characterization. Each method, by itself, may not completely indicate the source of contamination, but used together, a presumptive determination can often be made.

Since **baseline sampling** is not a mandatory activity, some operators perform their own baseline sampling, exceeding federal states regulation standards. Table 9 presents exemplary water survey parameters as they are included in different monitoring programs established by different companies, authorities and organizations.

Table 9: Baseline water survey parameters as required, proposed or applied by an Oil and Gas company (RHODES 2013), a NGO (FracFocus) and an admission authority (Colorado Department of Natural Resources).

	Parameters		
	Shell Global Solutions (RHODES 2013)	***FracFocus (GWPC & IOGCC 2013)***	***COGCC (2013b)***
Field Screening	pH, T°, Specific Conductivity, DO, Redox	pH, Specific Conductance	pH, Specific Conductance
General Water Quality	Alkalinity, TDS, TSS, Hardness, Turbidity, MBAS/Surfactants, TOC	TDS	Alkalinity[1], TDS[1]
Anions/ Cations	Major cations and anions, As, Ba, Cr, Fe, Pb, Mn, Se, Sr	Major cations and anions. As, Ba,Cr, Se, B,	Major cations and anions[1], Ba, Sr, B, Se
Organics	BTEX, Dissolved light gases (C1-C3), glycols, $\delta^{13}C$ and $\delta^{2}H$ isotopes of Methane, $\delta^{13}C$ isotopes of Ethane, Propane+	BTEX, DRO (Diesel Range Organics), GRO (Gasoline Range Organics), Total Petroleum Hydrocarbons (TPH) or Oil & Grease (HEM), Dissolved Methane	Dissolved gases[1] (Methane, Ethane, Propane) BTEX[1], GRO, DRO, TPH[1], PHA's (including benzo(a)pyrene)
Radioactivity	Gross alpha, gross beta, ^{226}Ra, ^{228}Ra	-	-
Microbiology			iron related, sulfate reducing, slime forming

[1] Subsequent sampling analysis

Produced formation water appears to be highly variable within and between shales. Flowback waters contain some additives, salts, metals and organic compounds. In addition, the chemical composition of fracking fluid varies depending of the interaction between formation water and the chemicals used.

Understanding the exact **nature of** these **chemical streams** is important when it comes to selecting indicator parameters that can be used to trace sources or track a contamination plume (Blake 2011). Thus, flowback and produced water have to be sampled in order to identify chemicals in highest concentration (Coleman 2011). Furthermore, groundwater can be affected by substances associated with natural gas itself (Bair et al. 2010, Gorody 2012, Jackson et al. 2013a, Jackson et al. 2013b, Roy & Ryan 2013). Methane is principally the most abundant of those substances and poses relevant hazards, if released to shallow aquifers or atmosphere (USDOI 2001). Recent studies have also shown a need for isotope tracers to be included within the baseline water survey. The different isotopes signatures act as a conservative tracers in assessing contamination sources (Darrah & Poreda 2013, Revesz & Baldassare 2013, Warner et al. 2013). From their relative abundance in the produced water and flowback, the potential mobility of the indicator components in groundwater systems, as well as the ability to accurately identify and quantify the parameters in produced water and groundwater using standard approved geochemical sampling methods (Rhodes 2013), **TDS**, **chloride**, **potassium** and **sodium** have been identified as key parameters to track flowback and produced water contamination. Further indicator parameters for a 'frac fluid groundwater contamination assessment' are summarized in Figure 6:

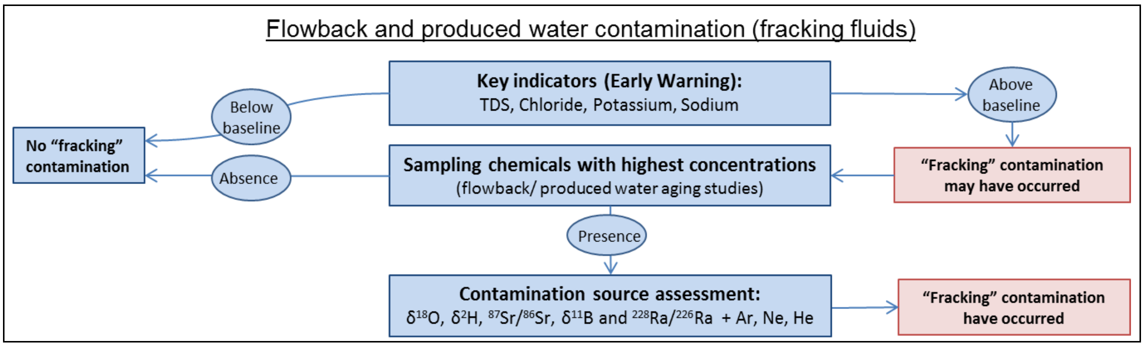


Figure 6: Groundwater monitoring regarding frac fluid contamination.

The assessment of a groundwater gas contamination in the context of fracking and shale gas operation bases on the same approach and is summarized in Figure 7. For a gas contamination, **methane** and **ethane** have proven to be the key indicators (Gorody 2012, Revesz & Baldassare 2013). If methane is above the baseline, then its carbon and hydrogen isotopes can assess the origin (microbial or thermogenic) (Coleman 1994, Baldassare & Laughrey 1997, Rowe & Muehlenbachs 1999).

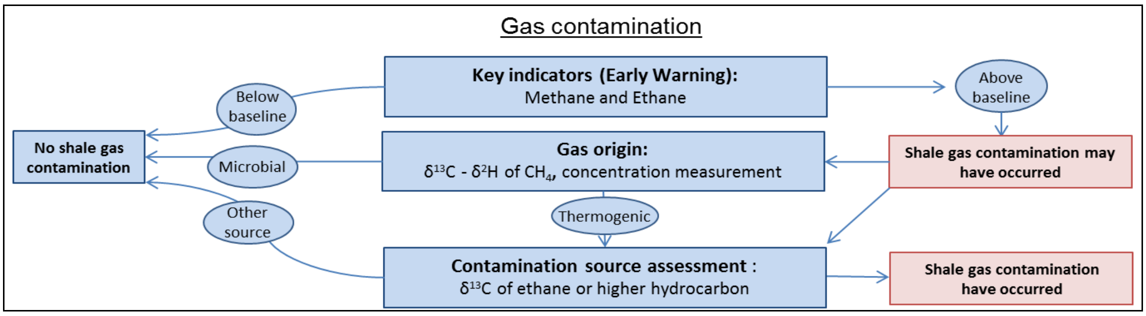


Figure 7: Groundwater monitoring regarding gas contamination.

In accordance with the emission-based operational groundwater monitoring programs (e.g. USEPA 2004, EU 2006b), a **quarterly to annual interval** (dependent on the site specifications) should be appropriate. COGCC (2013b) claims a monitoring plan comprising a baseline sampling within 12 months prior to drilling, and two more samples of each well between 6 and 12 months and again between 5 and 6 years. Concerning methane leakages, Gorody (2012) infers a repetitive sampling of source gases while drilling at the well head as well as a repetitive sampling and analysis of gas concentrations in the shallow aquifers.

4.2 Best practices of monitoring during the SGE life cycle

The life cycle of a SGE project comprises five main phases. These are (i) site characterization, (ii) well construction, (iii) fracking, (iv) the production phase and (v) site closure, including post-closure activities. Monitoring needs vary from site to site and for the different phases of a SGE project. The baseline water survey parameters need to be sampled throughout the whole SGE life cycle with special regard before, during and after the drilling and hydraulic fracturing operations (SOEDER 2011).

4.2.1 Site characterization

An integral part of understanding how wellbore construction and integrity and hydraulically induced fractures could create migration pathways to and potentially contaminate groundwater is a thorough understanding of the current **geologic and hydrologic regimes**. Site characterization and planning work thus includes detailed studies of regional and local geologic structural features from detailed pre-drill maps of the extent and chemical composition of groundwater aquifers, hydrologic flow and transport data collection as well as modelling to identify pathways for gas, drilling fluids, hydraulic fracturing fluids or formation fluids to reach the groundwater.

Methods include (Appendix II):

- *geophysical tools* to identify regional and local geologic features including faults, fractures, stress regime and rock mechanical properties by the use of seismic surveys, well logs and remote sensing technologies;
- *identification of existing wellbores*, determination of the integrity of those wellbores (i.e. casing, cement, etc.), and, where necessary, mitigation;
- *pre-drill baseline sampling* from groundwater and water supply wells to assess the chemical and isotopic groundwater composition; and
- *pre-drill baseline assessment of headspace and dissolved gas* (methane, ethane, propane).

Acting as the basis of the water quality program, a complete groundwater baseline sampling ensures the effectiveness of contamination assessment related with “fracking” activities. **Baseline groundwater quality** samples should be taken from wells near or directly over the fracturing well location (RHODES 2013).

The **design of an effective operation monitoring program** requires characterizing and understanding all the chemical variables associated with the ambient water resources and the projected gas site. This includes the characterization of additives used in hydraulic fracturing, flowback fluids and produced water. The analysis should include as many of the additive fracturing compounds as possible as well as isotope composition tracing potentially occurring contamination during the operation phase.

4.2.2 Well construction

In this phase, the infrastructure and facilities required for shale gas exploitation are constructed. Monitoring activities during the drilling phase focus mainly on the integrity of the wellbores to ensure that any hydrocarbon or non-potable water bearing formations are isolated. **Well integrity** testing include internal mechanical integrity tests to verify the appropriateness of proposed casing programs and external mechanical integrity tests to ensure the quality of the cementing job.

As for all other ESA operations, mechanical integrity of the operated wellbores (and all other wells within the AoR) has to be tested repeatedly for the whole SGE life cycle, since wells are considered as the most probable leakage pathways for aquifer contamination. Guidelines for hydraulic fracturing well construction, operation and closure are provided by the AMERICAN PETROLEUM INSTITUTE (2009).

4.2.3 Fracking

During the hydraulic fracturing phase, the permeability of the reservoir is increased by stimulating it hydraulically (fracking). The fracking process opens up existing fractures or creates new ones with lengths of up to hundreds of metres.

Fracking involves the injection of large volumes of water mixed with proppants, surfactants and biozides (fracking fluid). Fracturing fluids added during the stimulation process are recovered together with formation water as flowback during the production phase. The fluid composition varies by site and by company and fluid-rock interactions depend on the mineralogy of the shale. Thus, testing of the fracking fluid is the basis for later assessment of potential contamination events and monitoring during the fracking phase has two objectives: (1) **real-time control of treatment progression and fracture geometry**, and (2) fluid testing.

The dimensions, extent, and geometry of the induced fractures are controlled by pumping rate, pressure, volume, and viscosity of the fracturing fluid. Monitoring methods include:

- *Continuous monitoring of physical parameters*: surface injection pressure, slurry rate, proppant concentration, fluid rate, and sand or proppant rate
- *Geophysical monitoring*: Microseismic monitoring above the laterals to map the length and orientation of the induced fracture and from a nearby wellbore to get an indication of the fracture height, length, and azimuth
- *Fluid testing*: when analyzed for specific tracer substances (e.g. artificially added tracers, isotope composition), it can provide information about fracture growth

Such surveillance of the ‘frac job’ is the inevitable basis to identify any pathway between the shale layer and overlying formations (DAVIES et al. 2012). The obtained data are be used to refine simulations of the fracking process.

4.2.4 Production

In the production phase, wells abstract water containing gas, formation water and remained fracking fluids. Main objective of monitoring is to detect potential leakages. By comparing **groundwater chemistry** sampled during the operation phase with baseline groundwater data, well integrity and sound cap rock sealing can be verified to ensure safe shale gas exploitation.

Well integrity can be further verified by monitoring of changes in flowing and annular pressures, gas and fluid rates, which could indicate influx from an external source, and gas and fluid composition, which could indicate influx from an external source, too and aid in determining scaling and corrosion tendencies.

Monitoring potential leakages of **methane** or other emissions to the atmosphere by gas detectors provide data that can detect changes in the atmospheric isotope composition compared to baseline data.

4.2.5 Site-closure and post closure

The post-operation phase includes site closure and post-closure activities. Both are monitored for different purposes. Whereas appropriate well plugging and sealing is the main goal during site closure, geophysical and geochemical monitoring ensures a secure post-closure phase. Similar to well construction standards, the well plug and abandonment stage needs to respect certain procedures and guidance **to prevent vertical migration** of fluid after shale gas exploitation. Such guidance (AMERICAN PETROLEUM INSTITUTE 1993) provides information for plug location, cement quantity, quality, placement techniques, testing, and reporting (HETRICK 2011).

After site closure, the risk of (shallow) groundwater contamination is low since all produced water disposals are removed. Thus, (deep) contamination may arise from well plug failure or fracture leakages to overlying layer. A last **geophysical survey** is recommended to assess (potential) fracture connection to upper formations. Afterwards, **hydrochemical groundwater sampling** seems to be enough to predict contamination after the site has been closed. Key parameters are **TDS**, **pressure** and **methane**.

4.3 Summary of best practices

An overview of the different monitoring activities involved in a SGE project is presented in Figure 8. Table 10 provides an overview of the basic and enhanced monitoring methods applied during the different phases of a shale gas extraction project and Table 11 summarizes the key indicators to monitor SGE impacts on groundwater.

A full and comprehensive list of methods to monitor SGE operations (including a short description, availability, benefits and challenges of each method) can be found in Appendix II.

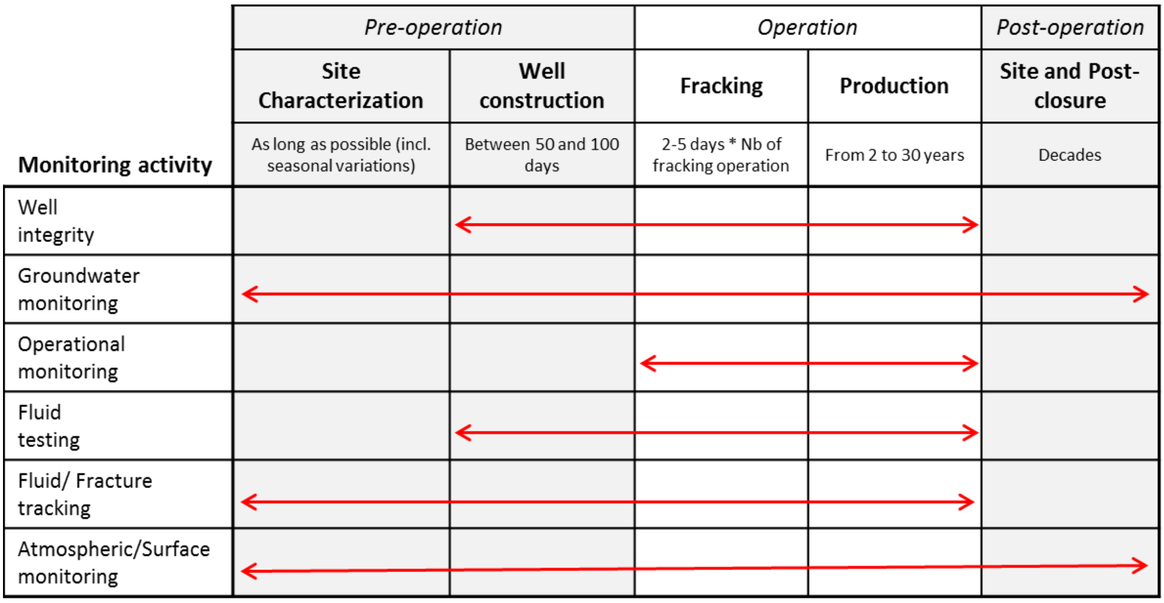


Figure 8: Monitoring activities during the different project phases of shale gas extraction.

Table 10: Basic and Enhanced Monitoring packages for the different phases of shale gas extraction operations.

Basic Monitoring Package	**Enhanced Monitoring Package**
Pre-Operational Monitoring	
Well logs	Well logs
Wellhead pressure	Wellhead pressure
Formation pressure	Formation pressure
Injection and production rate testing	Injection and production rate testing
Seismic survey	Seismic survey
Atmospheric CH_4 monitoring	Gravity survey
Soil gas monitoring	Electromagnetic survey
Geochemical groundwater monitoring	Ground deformation
	Atmospheric CH4 monitoring
	Soil gas monitoring
	Geochemical groundwater monitoring
	CH_4 flux monitoring
	Pressure above the storage formation

Operational Monitoring	
Wellhead pressure and flow rates Frac fluid testing Seismic survey (3-D) Microseismic survey Tomographic survey Tiltmeter Atmospheric CH_4 monitoring Soil gas monitoring Geochemical groundwater monitoring Well integrity (SBT, MWD, LWD, USIT, RHOB, CBL, GRL)	Wellhead pressure and flow rates Well logs Frac fluid testing Seismic survey (3-D, 2-D, VSP) Microseismic survey Tomographic survey Tiltmeter Gravity survey Electromagnetic survey Ground deformation CH_4 flux monitoring Atmospheric CH_4 monitoring Soil gas monitoring Geochemical groundwater monitoring Tracer monitoring Pressure above the storage formation Well integrity (SBT, MWD, LWD, USIT, RHOB, CBL, GRL)
Post-Operational Monitoring	
Formation pressure Seismic survey (3-D) Microseismic survey Tomographic survey Atmospheric CH_4 monitoring Soil gas monitoring Geochemical groundwater monitoring	Formation pressure Seismic survey (3-D, 2-D, VSP) Microseismic survey Tomographic survey Gravity survey Electromagnetic survey CH_4 flux monitoring Atmospheric CH_4 monitoring Soil gas monitoring Geochemical groundwater monitoring Tracer monitoring

Table 11: Key indicators to monitor SGE impacts on groundwater.

1 Key indicators	2 Additional indicators
TDS	Fracking fluids
Sodium	Noble gases
Potassium	Isotopes (O, H, Sr, B, Ra)
Chloride	
Methane/ Ethane	
Pressure	

Chapter 5
Deep Geothermal Systems

Geothermal energy is produced by the utilization of different geothermal sources and different operation systems. Monitoring geothermal operation systems therefore require site-specific monitoring plans.

A classification can be made in different ways. It is either based on the depth (deep > 400m > shallow) or on the temperature (low – medium - high enthalpy) of the utilized geothermal field. Deep geothermal systems (DGS) can further be divided into hydrothermal and petrothermal reservoirs. Hydrothermal systems produce hot formation fluids, whereas petrothermal systems are used as heat exchanger by injecting fluids into the hot rock (hot-dry-rock). The necessary permeability needed for a circulation is produced by stimulating the reservoir hydraulically or chemically. These 'Enhanced Geothermal Systems' (EGS) become more and more important in geothermal energy production by exploiting high enthalpy reservoirs, but require a more sophisticated monitoring. Within this report, only approaches to monitor deep geothermal systems (>400m) with medium to high enthalpy are specified.

5.1 General remarks

Because of the variable boundary conditions and the lower pressure compared to other ESAs, monitoring of geothermal utilization projects and here especially EGS is far less regulated and developed than for GCS or SGE. Recently, the monitoring of EGS has become a main subject of research due to rapid implementation of projects (TESTER et al. 2006, ZIMMERMANN et al. 2012) and a related occurrence of induced seismicity events (MAJER et al. 2007, U.S DEPARTEMENT OF ENERGY & ENERGY EFFICIENCY AND RENEWABLE ENERGY 2008, MAJER et al. 2012).

While groundwater contamination has been a problem in the past (USGS 1994) or in areas less regulated than e.g. Europe or U.S., today every effort is made by the geothermal industry to minimize the effects of geothermal development on local water regime and surface features. Therefore, no significant contamination of groundwater as a result of geothermal activity was reported during the last decade. Geothermal brines, which may contain compounds harmful to environment and humans (e.g. salts, heavy metals, etc.) are usually required to be injected back into the geothermal reservoirs.

Geothermal operations are typically evaluated for their environmental impacts regarding geology and soils, air quality, noise, ecology, land use, waste management and water resources including groundwater and surface water. Compared to other potential impacts, **impacts of DGS operations on groundwater** are nowadays considered to be of minor concern in the literature (GFZ 1999, KRISTMANNSDÓTTIR & ÁRMANNSSON 2003, KAGEL et al. 2007, FRICK & KALTSCHMITT 2008). But, once a contamination of USDW occurred, counter and mitigation measures can be much more time and cost-intensive than those, which have to be implemented for other environmental impacts. Primarily, drilling through USDW and into the geothermal reservoir can create pathways for geothermal fluids (which are usually under high pressure) to rise and mix with shallower groundwater (compare COSMA-1 Deliverables D1.1 (SEIS et al. 2013) and D1.2 (THOMAS et al. 2013)). Impacts may include

- the alteration of natural circulation of geothermal fluids and thus the usefulness of the USDW resource.
- the degradation of the quality of shallow aquifers by geothermal fluids (when leaking),.
- drawdowns in connected shallower aquifers, potentially affecting connected springs or streams (SANJUAN et al. 2010).

Tracer tests are therefore recommended to characterize the connections between different wells, in particular between the reinjection and production wells, and to study the **flow-patterns** in the geothermal system. They are most often used to determine the feasibility of proposed long-term reinjection schemes in resource management and further provide information of lateral movement rate of the invasion front.

Temperature effects from DGS operations on shallow groundwater are considered as very unlikely in literature (KRISTMANNSDÓTTIR & ÁRMANNSSON 2003, KAGEL et al. 2007, FRICK & KALTSCHMITT 2008).

5.1.1 Monitoring network design

In the United States, the USEPA (1998) demands the delineation of an **area of review** (AoR) for geothermal wells used for direct heat return flow or electric power for all underground injection wells. Monitoring wells should be chosen and placed in a way that they provide full coverage of the AoR, of which the radius should be minimum a quarter mile from the well. The AoR should further at least cover the extension of thermal influence. Thus, it is site-specific and strongly dependent on reservoir conditions (e.g. fluids, geology, flow conditions, etc.) and on the type of geothermal resource, and thus on the operation system (e.g. duplette, hot-dry-rock, etc.).

The monitoring network should be able to detect potential groundwater contaminations both from well casing leakage as well as from cap rock leakage through extended or opened fractures. Therefore, monitoring wells should be placed down-gradient from the facility in shallow groundwater and above zones with known or assumed fractures or zones, which might potentially be affected by geothermal operation. For an early warning of migrating and up-coning brines, the monitoring network can be extended by placing well(s) below the cap rock in zones with high permeability and suspected pathways for the fluids.

5.1.2 Monitoring parameters

Pressure measurements can indicate relevant changes in the hydraulic flow field at a geothermal system site. Especially, when reservoirs are stimulated to enhance flow circulation, pathways in the cap rock can be opened or widened resulting in ascending formation fluids and consequently pressure increases in overlying aquifers. Pressure should be monitored in those aquifers and areas, where changes in groundwater table as effect of fluid withdrawal could potentially occur. Pressure changes may also change fluid mixing ratios or fluid-fluid interactions and therefore may have an impact on groundwater chemistry.

To determine impacts of contaminants (when discharged to the environment) or brines (when ascended from deeper aquifers) on shallow groundwater, total dissolved solids (**TDS**), **chloride/magnesium ratio** and **temperature** can be used as key indicators. Noticeable changes in these parameters (compared to baseline conditions) may indicate groundwater alteration or contamination emanated from geothermal system operation. Determining the source of impact or identifying involved fluids once contamination has occurred, **stable isotopes** such as ^{18}O and ^{2}H can be used to trace the origin and age of geothermal water/ groundwater and to indicate mixing processes (IAEA 2000).

Based on information presented by USEPA (1999a), the following **constituents** were found to routinely or frequently **exceeding health-based standards** in one or more geothermal reservoirs and should therefore be monitored regularly: antimony, arsenic, barium, boron, cadmium, copper, fluoride, lead, mercury, strontium, sulfate, zinc, and total coliform. Aluminum, copper, iron, manganese and pH also have been measured above secondary drinking water standards at some sites. Further parameters of interest are CO_2 and H_2S. With their help, changes in the hydrochemical composition of the sampled groundwater can be detected early. **Additives** in the injected fluid inhibiting the corrosion of well components should be also sampled and analyzed in groundwater.

5.2 Best practices of monitoring during the DGS life cycle

All monitoring activities should cover the full life cycle of a deep geothermal energy project and should be adapted to the different needs during the project phases. The life cycle of geothermal energy project includes five main phases. During the first phase, (i) site exploration and characterization takes place, followed by (ii) well and facility construction. The operational stage may include, depending on the type of geothermal systems, (iii) a stimulation phase and (iv) the production phase. Finally, during (v) post-operation the site is closed, including well plugging, facility reconstruction and post-closure care. Monitoring objectives, methods, parameters and sample frequencies for these phases are detailed below.

5.2.1 Site characterization

Main objective of the design and siting phase is the detailed mapping of the resource area and a broad assessment of the impacts of the proposed well on the surrounding area. Detailed **mapping** of the potential geothermal resource areas covers tectonic and stratigraphic features, surface petrology, mineralogy, and lithology of the resource area. Features of particular interest are fracture zones, which may provide flow paths for the geothermal fluid.

Methods involve (Appendix III):

- *geological mapping* aiming mainly at information about the reservoir rock (temperature, stress field, lithology, and structure)
- *geochemical monitoring* establishing the baseline chemical composition of groundwater and emerging fluids in the area of interest. It includes the collection and analysis of samples of geothermal steam and water, diffuse soil degassing surveys, hydrogeological studies and hydrochemical surveys of natural surface waters in geothermal fields.
- *geophysical techniques* including resistivity surveying (TEM/MT and 1D/3D inversion), micro seismicity, gravity and geodetic surveying, magnetic surveying and active seismic methods.

During the pre-operational phase, these **baseline** surveys provide the data required i) for well siting, well design and environmental monitoring and ii) to assess changes due to the geothermal operation, which might include effects on aquifer quantity and quality, the stability of bedrock and the effect of increased groundwater movement, aquifer drawdown and well interference.

5.2.2 Well construction

Once preliminary characterization activities have been completed, reservoir development can proceed with drilling of the injection/production well.

According to USEPA (1999a), geothermal wells must be sited in such a way that they inject into a formation separated from any USDW by a confining zone free of known open faults or fractures within the area of review (AoR). Further ensuring the integrity of the USDW, geothermal wells should be sited beyond an area that extends at least one-quarter mile from any part of a drinking water source, including not only the surface expression of the water supply well, tunnel, or spring, but also all portions of the subsurface collection system.

During drilling, **downhole monitoring data** can yield reservoir conditions or drilling performance or both or possibly even preventive measures that can avert a disastrous loss of well control. Mud logging can provide information about downhole stratigraphy, intrusions, geothermal alteration and geological relations of aquifers. Mechanical integrity of the wells has to be assessed before the well is put into service the first time.

Monitoring of geothermal drilling and well testing activities rely mostly on technology used in the oil and gas industry modified for high temperature applications and larger well diameters. The type of monitoring performed is highly variable depending on site-specific characteristics. Especially the temperature could be a limiting factor for tools developed for the application in low temperature settings of gas and oil exploitation. Methods and parameters include:

- *drilling logs* with record of **lithology**, **water levels**, etc.
- *Borehole geophysical logging* of **temperatures**, **stress fields** and **mechanical integrity** of the well construction (CBL, annular pressure, etc.)

As for the other ESAs, leakage via well casings is one of the most likely pathways for contamination of shallow aquifers. Thus, the well integrity must be tested and maintained during the whole DGS life cycle.

5.2.3 Stimulation

In EGS operations, the reservoir is stimulated before production starts. In the absence of an aquifer, pathways have to be generated between the injection and the extraction wells by geological stimulation. The stimulation can involve cold water injection, thermal cycling, airlift (often at high flow-rates aimed at high-pressure and/or thermal stimulation) as well as chemical stimulation methods. All these methods aim at opening up and cleaning out existing fractures and forming new ones This can change **stress patterns** in the rock, resulting in seismic events (MAJER et al. 2007).

Routine seismic monitoring is the basic diagnostic tool to gather data on seismicity in the vicinity of the EGS area to forecast **induced seismic activity**, and understand induced seismicity for mitigation and reservoir management purposes.

5.2.4 Production

The production phase involves injection and recovery of (geothermal) fluids. Monitoring should provide both, data for managing the geothermal reservoir and for checking the proper operation of the well. Therefore an on-going **operational monitoring** includes (CROCKETT & ENEDY 1990, HALLIBURTON ENERGY INSTITUTE 1996, USEPA 1999a):

- *wellhead flow, rate and injection metering* to avoid consequences of an excessively large flow volume,
- (in combination with) *pressure monitoring*, providing an indication of casing integrity and avoiding excessive pressure, thereby minimizing the likelihood of injection-induced seismic activity from increased subsurface pressure
- *fluid sampling* to identify changes in fluid and groundwater composition caused by its geothermal utilization,
- *biochemical monitoring* to anticipate undesired bacterial growth, which might enhance e.g. scaling processes in the well and at related equipment and thus reduce the DGS capacity,
- *geochemical monitoring* to identify corrosion or clogging of the wells caused by changed saturation states of the fluid constituents (oxygen, carbon and carbon oxides, sulphur-containing gases, hydrogen, and metal halides), and
- *well integrity testing* to ensure that injected fluid is reaching the intended injection zone and is not being released to shallower formations (e.g. USDW)..

During the production phase, the same set of geochemical and geophysical tools and parameters as during site characterisation (baseline) should be used. **Pressure** and **temperature** should be measured **continuously** through downhole pressure sensors and fiber optic temperature sensors placed in the (injection, production and monitoring) wells.

Periodic geophysical logging of surface soil thermometry, broadband seismology, microgravity and SAR interferometry can detect mass transfers or changes in the geothermal reservoir during its exploitation as well as vertical surface ground deformations (SANJUAN et al. 2010).

Because geothermal injection wells are sometimes located in areas of seismic activity, casing integrity can be compromised by ground movement and monitoring is essentially for secure operation. Monitoring of **annulus pressure** to detect leakage of either the casing or the injection tubing should be carried out **continuously**. Periodic mechanical integrity tests (MIT), including wireline logging and sonic and radiation techniques, might be performed before a well returned to service after workover or repairs, and at established intervals during normal operations (USEPA 1999a).

Fluid sampling should include the geothermal wells and neighbouring wells or thermal springs to control the evolution of the fluid geochemistry and the gas/steam ratio. Natural occurring isotopes might additionally be used to trace fluids and the hydrochemical composition of **shallow groundwater** should be monitored continuously for **pressure** and total dissolved solids (**TDS**) or electric conductivity (EC) and **sampled semi-annually to annually**.

5.2.5 Site-closure and post closure

During the post-operation phase, the operation site is closed, wells are plugged and facilities are deconstructed. In general, there is no mandatory requirement to monitor reservoir conditions, but impacts on groundwater and surface water bodies might occur at later times and monitoring should thus be extended to a post-closure period (decades). Key parameters should be, as during site characterisation and production, **pressure** and **temperature** logging by downhole sensors for the injection and production wells, and **pressure** and **TDS** (or EC) in shallow groundwater aquifers (monitoring wells).

5.3 Summary of best practices

A summary of monitoring activities during the different project phases is given in Figure 9. Table 12 summarizes the (basic and enhanced) monitoring methods and Table 13 the key parameters. A list of available and potential monitoring techniques is presented in Appendix III.

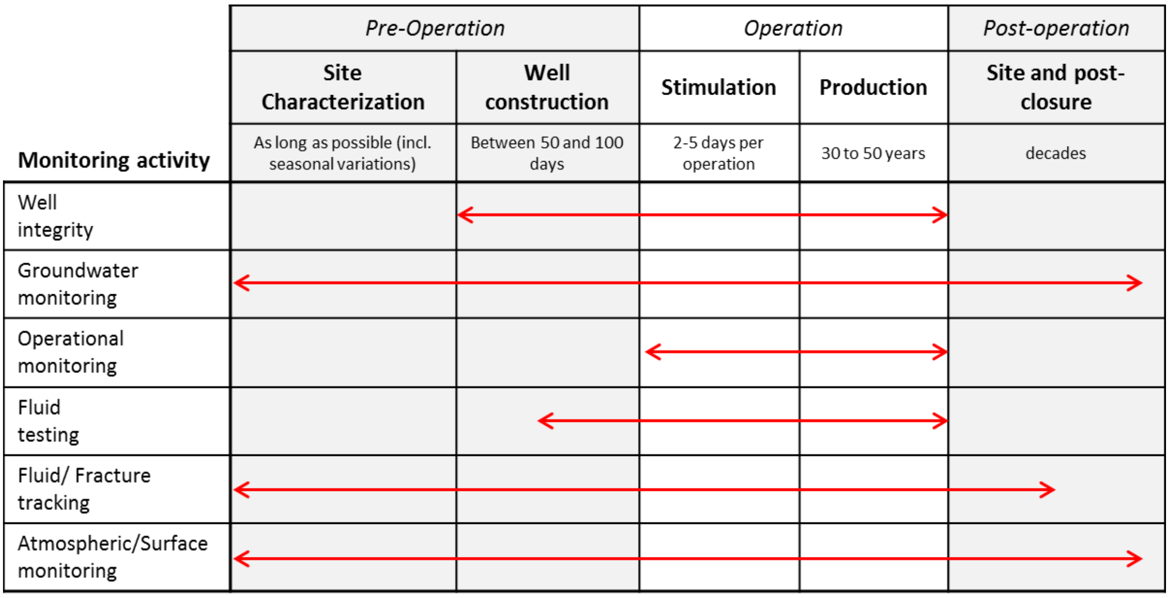


Figure 9: Monitoring activities during the different phases of a deep geothermal energy project.

Table 12: Basic and enhanced programs for monitoring DGS operations.

Basic Monitoring Package	Enhanced Monitoring Package
Pre-Operational Monitoring	
Fluid sampling Wellhead pressure and flow MITs (PTS, CBL, GRL, CL) Seismic surveys	Fluid sampling Groundwater monitoring Reservoir geochemistry Wellhead pressure and flow MITs (PTS, CBL, GRL, CL) Annulus pressure tests Resistivity logs Seismic surveys Gravity surveys Ground temperature/deformation Biochemical monitoring Tracer tests
Operational Monitoring	
Fluid sampling Wellhead pressure and flow MITs (PTS, CBL, GRL, CL)	Groundwater monitoring Reservoir geochemistry Fluid sampling Wellhead pressure and flow MITs (PTS, CBL, GRL, CL) Annulus pressure tests Resistivity logs Seismic survey Gravity survey Ground deformation Biochemical monitoring Tracer tests
Post-Operational Monitoring	
	Groundwater monitoring Reservoir geochemistry Tracer tests Seismic survey

Table 13: Key indicators to monitor DGS impacts on groundwater.

Key indicators	Additional indicators
Pressure Temperature TDS pH	Geothermal fluid composition CO_2 H_2S Natural isotope composition (^{18}O, ^{2}H) (Heavy) Metals Additives

Chapter 6
Summary and conclusions

This report aimed at identifying current best practices and monitoring tools and methods that have already proven their applicability for emerging subsurface activities monitoring. Best monitoring practices provide increased protection of USDW and improved safety and cost performance for deep subsurface operations. Each case requires certain best monitoring practices to be installed and maintained based on the authorities' priorities and site-specific considerations, and knowledge and experience in operating and monitoring ESAs is growing with every new site characterized and established and with every measurement taken and analyzed.

Emission-based operational groundwater monitoring (EBOM) conducted by the ESA operartor is focusing on the integrity of operation facilities (borehole, casing, fractures) to ensure safe implementation and establishement of ESA operations. Main objective is to detect potential impacts on hydraulic and/or hydrochemical conditions in formations overlying the reservoir, used as storage, heat or gas source, before pollutants may contaminate drinking water aquifers. Immission-based operational groundwater monitoring (IBOM) conducted by drinking water producers is providing early-warning to prevent pollutants from entering drinking water resources. Monitoring networks need to be designed in a way allowing the detection of contaminants before they are abstracted by wells and before they reach the supply net. In case of detected impacts, operation should be stopped or adjusted and countermeasures should be initiated to prevent an intrusion of pollutants into USDW.

As outlined in the previous chapters, independent of the type of subsurface activities, the following steps were however recognized as being inevitable parts of best practice:

1. geological, geophysical and hydrochemical site characterization
2. 3D modelling
3. determination of the Area of Review (AoR)
4. baseline sampling (of groundwater chemistry, fluids used during operation, gas emission, ...)
5. well siting and monitoring network design based on geological features
6. securing well integrity
7. development of site-specific monitoring plans developed prior to start of operation and continuous operational monitoring.

A sound groundwater monitoring network with a relevant radius around the projected site (as e.g. horizontal well bores may extend over hundreds of meters), is a substantial part of best practices. Hydrogeological information is important for predicting the flow field changes due to operation. Understanding existing flow rate, direction, and volumes gives insight into how discharged and injected fluids behave and travel in the formation. Techniques such as injectivity, transmissivity, and tracer testing should therefore be used to acquire information beneficial to siting decisions (USEPA 1999b). Geophysical methods have to be run during the site characterization in order to assess the integrity of existing wellbore, and also to characterize the hydrologic/ hydrogeologic site parameters and seasonal baseline testing is one of the most important early warning actions to be carried out before drilling and operation start. Testing water quality and chemical concentration of a panel of relevant contaminants prior to and during the operational phase provide evidence in case of future issues.

Monitoring networks should cover the full extent of the site-specific AoR. The site-tailored monitoring network should always feature observation wells (i) monitoring the impact of injection or abstraction on the reservoir formation itself or on overlying formations below the cap rock and (ii) on USDW.

Reservoir and overlying formations should be monitored two-dimensional, appropriately in down- and up-gradient direction (at a minimum of two wells). Considering a proper groundwater protection, it is further recommended to monitor freshwater aquifers overlying the cap rock at a minimum of four wells. Above the cap rock, respectively in USDW, monitoring wells should be placed above the zones with the highest predicted impact potential and above zones with potential pathways (faults, fractures or abandoned wells) for fluid and/or gas migration. Because every drilling penetrates the confining layers (which isolates the reservoir formation from USDW) and boreholes might then constitute a potential leakage for migrating contaminants, the increase of information provided by the well needs to be balanced against the risk of contamination.

For SGE operations, and with certain qualifications for DGS (stimulated and deviated boreholes), the highest impact potential can be expected along the trajectory of the horizontal borehole. For GCS operations, this potential is highest above the zone with maximum thickness of the CO_2 plume or with maximum elevated pressures.

The identified key indicators (TDS, pressure and temperature) should be monitored continuously in shallow and deep aquifers throughout the whole ESA life cycle. Indicators for gas migration, like carbon dioxide (pH) or methane should be sampled quarterly. Table 14 summarizes the identified best practises (parameters, network design, sampling frequencies) of emission- and immission-based monitoring for the three discussed ESA types.

Currently, *drinking water protection zones* (DWPZ) are particularly effective to control groundwater pollution from diffuse and point sources emanating from anthropogenic surface activities (DVGW 2003). Their attention is however directed to contaminations coming from above or the same depth (2D). They are not delineated and designed to control hazards emanating from deep subsurface activities ascending towards USDW. ESA operators, on the other hand, have to warrant, that the range of the pressure front or fluid migration stays within the delineated AoR and that the AoR is not overlapping with DWPZ. Thus, according to the actual state of knowledge, siting and operation of ESAs should not be allowed within DWPZ. Because drilling is not only vertically directed in most site cases, the designation of protection zones should in future include both, the horizontal as well as the vertical dimension. If hazards, having their origin hundreds to thousands meters below the protection zone surface, cannot be excluded from polluting the groundwater, it might then as well be appropriate to extend the spatial dimensions of the protected zones.

In Germany, deep drillings for storage or exploitation purposes in protection zones are very unlikely at the moment. To eliminate influences from construction and operation of ESA on public water supply, e.g. by perforating several multi-aquifer formations, drilling for geothermal water utilization is already forbidden in certain drinking water protection zones (e.g. in the German-Austrian Molasse Basin) (EXPERTENGRUPPE THERMALWASSER 2012). But current groundwater protection zone rules do not forbid such activities in external protection zone (zone III covering the surficial water catchment area) as long as risks to the groundwater can be excluded. Similar regulations were found in the United States, where delineated buffer zones in surface water supply areas are only applied for surface and not for subsurface activities.

With their experience in groundwater monitoring, drinking water producers are seen to be able to advice and support ESA operators during the conception and implementation of appropriate monitoring strategies as a safe and environmentally acceptable realization of deep subsurface activities is of mutual interest for both, the water producer and the site operator. The conception of appropriate monitoring strategies has further to be coordinated with the competent authorities, which have to control the compliance with all requirements. Therefore, site operator and water producer should report their monitoring plans and data at regular intervals to the competent authorities.

Table 14: Summary of best practices monitoring types including parameters, key indicators, area of interests, monitoring network and sampling frequency for monitoring ESA. / Emission-based operational groundwater monitoring (EBOM) should be conducted by the site operator, immission-based operational groundwater monitoring (IBOM) by the water producer.

ESA type		GCS	SGE	DGS
EBOM	Parameters	pH, TDS, alkalinity, EC, main ions, Sr2+, Fe2+, Fe3+, Al, SiO2, TOC, CO2, H2S, trace metals, pft	pH, EC, DS, alkalinity, DO, Redox, TOC, main ions, Ba, Sr, B, Se, fracking additives, stable isotopes of C, H, O, methane, ethane, noble gases,	Sb, As, Ba, Bo, Cu, F, Pb, Mg, Sr, SO4, Zn, Al, Fe, Mn, TDS, pH, CO2, H2S, Cl, Br, corrosion inhibitors, 18O, 2H
	Key indicators	TDS, pressure, CO2, pH	TDS, methane, Cl, Na, K, pressure	TDS, pressure, T°, Br, Cl/Mg-ratio
	Area of Review	- Site-specific based on modeling - Cover the expected maximum extension of pressure front	- site-specfic based on modeling - Cover extent of horizontal boreholes and fractured zones	- Site specific based on modeling (resource, system) - Cover thermal influence extension
	Monitoring network	- Up and down gradient in the storage reservoir - Regions predicted to overlie maximum thickness of CO2 plume or maximum pressure above cap rock - Regions with identified faults, fractures, abondoned wells above cap rock	- Up and down gradient in the first aquifer formation above fracking operations - Along planned trajectory of horizontal boreholes in USDW - Above faults, fractures, abondoned wells in USDW - At least four wells within the AoR	- Down gradient below the cap rock - Up and down gradient in USDW - Above faults and fractures in USDW
	Sampling frequency	- Quarterly for at least 1 year as baseline - Quarterly during injection and initial PISC - Continuous monitoring of pressure and TDS throughout the project	- Quarterly for at least 1 year as baseline - Quarterly to annually during operation - TDS and pressure continuously	- semi-annually to annually - T°, TDS and pressure continuously
IBOM	Key indicators	TDS, pressure, T°, Br, methane (SGE)		
	Protection zones	- Surface and subsurface catchment - 3-dimensional (horizontal and vertical)		
	Monitoring network	- Basis of drinking water aquifer within DWPZ - Above faults and potential pathways in DWPZ - Up gradient according to predicted flow paths in DWPZ - (Up gradient between DWPZ and potential contamination source) - (In the first aquifer below the drinking water aquifer basis)		
	Sampling frequency	Continuously with permanently installed devices		

The results of this study were additionally transferred and implemented to the WSP risk management approach. Accordingly, the strategies developed to monitor hazards related to the different ESAs are summarized in Table 15.

Table 15: Integration of Monitoring Activities related to hazardous events emanating from ESAs in the Water Safety Plan Approach.

Operation	**Hazardous event**	**Cause**	**Risk**	**Monitoring**				
				What?	*How?*	*Where?*	*When?*	*Who?*
GCS	CO_2 intrusion	- Free CO2 leaks into upper aquifer - CO2 escapes through gap in cap rock into higher aquifer - Injected CO2 migrates up dip, increases reservoir pressure and permeability of fault. - CO2 escapes via poorly plugged abandoned well.		- CO_2 plume front - Water chemistry (pH, heavy metals), - Hydrostatic pressure	- Seismic surveys - Hydrochemical sampling and analysis - Pressure logger	- CO_2 plume front within AoR - Hydrochemistry and pressure in wells within AoR, above cap rock and in freshwater aquifer, above known faults and fractures	- CO_2 plume front occasionally - Hydochemistry at least quarterly - Pressure continuously	Site operator (and water supplier)
	Brine Intrusion	Pressure build-up in deep saline aquifers		- Water chemistry (TDS, main ion composition) - Hydrostatic pressure	- Hydrochemical sampling and analysis - Pressure logger	Within AoR, above cap rock and in freshwater aquifer, above known faults and fractures	Continuously to quarterly	Site operator (and water supplier)
SGE	Spillage of chemicals (fracking fluids, natural gas,…) and formation water	- Borehole and pipeline leakages - Blow-outs - Accidents during transport and storage of chemical additives		Water chemistry: - TDS, main ions - Frac fluids - Stable isotopes - Noble gases	Hydrochemical sampling and analysis	- Wells in shallow groundwater - Soil	Occasionally	Environmental Agencies
	Upward migration of fracking fluid, formation water and flow back.	- Upward migration of fracking fluids along faults and fractures - Presence of an artesian aquifer		- Water chemistry: - TDS, main ions - Frac fluids - Stable isotopes - Noble gases - Hydrostatic pressure	- Hydrochemical sampling and analysis - Pressure probes	Within AoR, above cap rock and in freshwater aquifer, above known faults and fractures	- Quarterly to at least annually - Pressure continuously	Site operator (and water supplier)
	Upward migration of natural gas	- Presence of a continuous open fault - Fractures propagate beyond expected dimensions		Water chemistry: - CH4, C_2H_6 - Hydrocarbon isotopes	Hydrochemical sampling and analysis	Within AoR, above cap rock and in freshwater aquifer, above known faults and fractures	Quarterly to at least annually	Site operator (and water supplier)
DGS	Water scarcity/ surplus	Change in groundwater quantity by pressure changes		Ground and surface water level	Aerial photography, water level measurements, spring flow	Wells, surface waters, springs	According to need in intervals	Environmental Agencies
	Fluid Intrusion	- Presence of faults and fractures - Presence of an artesian aquifer		- Water chemistry (TDS, main ion composition) - Hydrostatic pressure	- Hydrochemical sampling and analysis - Pressure logger	Within AoR, above cap rock and in freshwater aquifer, above known faults and fractures	- Quarterly to at least annually - Pressure continuously	Site operator (and water supplier)
	Water pollution	Discharge of brine to surface or groundwater bodies		Water quality (T, pH, CO2, H2S, EC, SS, TDS, main ions, heavy metals, B, F, 2H, 18O)	Water sampling	At sources and in ground/ surface water in drilling and plant surroundings	At least annually	Site operator
		Corrosion of the casing by brine		Fluid chemistry	Hydrochemical sampling	At sources	Continuously	Site operator

References

ALSGLOBAL State Fracking Regulations. Retrieved 23.01.2014, http://www.alsglobal.com/en/Our-Services/Life-Sciences/Environmental/Capabilities/North-America-Capabilities/USA/Oil-and-Gasoline-Testing/Oil-and-Gas-Production-and-Midstream-Support/Fracking-Regulations-by-State

AMERICAN PETROLEUM INSTITUTE (1993): Well abandonment and inactive well practices for U.S.: exploration and production operations. . Environmental guidance document, American Petroleum Institute,

AMERICAN PETROLEUM INSTITUTE (2009): Hydraulic fracturing operations - well construction and integrity guidelines: 36

BAIR, E. S.; FREEMAN, D. C. & SENKO, J. M. (2010): Subsurface Gas Invasion, Bainbridge Township, Geauga County, Ohio Expert Panel Technical Report, Ohio Department of Natural Resources - Division of Mineral Resources Management

BALDASSARE, F. J. & LAUGHREY, C. D. (1997): Identifying the Sources of Stray Methane by Using Geochemical and Isotopic Fingerprinting. Environmental Geosciences 4(2): 85-94, http://dx.doi.org/10.1111/j.1526-0984.1997.00005.pp.x

BENSON, S. & COOK, P. (2005): Underground Geological Storage. In: Change, I. P. O. C.: IPCC Special Report on Carbon Dioxide Capture and Storage. 5, Cambridge, U.K, Cambridge University Press

BENSON, S. M. & MYER, L. (2003): Monitoring to ensure safe and effective geologic sequestration of carbon dioxide, Netherlands, ECN, Petten (Netherlands); Working Group III, Mitigation of Climate Change, Intergovernmental Panel on Climate Change IPCC, c/o National Institute of Public Health and the Environment RIVM, Bilthoven (Netherlands)

BIRKHOLZER, J. T.; ZHOU, Q. & TSANG, C.-F. (2009): Large-scale impact of CO2 storage in deep saline aquifers: A sensitivity study on pressure response in stratified systems. International Journal of Greenhouse Gas Control 3(2): 181-194, http://www.sciencedirect.com/science/article/pii/S1750583608000753

BLAKE, U. (2011): Designing a Water Quality Program for Shale Exploration. Technical Workshop for the Hydraulic Fracturing Study: Chemical & Analytical Methods, US EPA: 18

BOLANDER, J. (2011): Assessment Methods for Well Integrity during the Hydraulic Fracturing Cycle (Ed.): Technical Workshop for the Hydraulic Fracturing Study: Well Construction and Operation, Arlington, VA, USA, U.S. Environmental Protection Agency, 21

COGCC (2013a): COGCC approves pioneering new groundwater protections Colorado Department of Natural Resources

COGCC (2013b): Drilling, Development, Production and Abandonment

COLEMAN, D. D. (1994): Advances in the Use of Geochemical Fingerprinting for Gas Indentification (Ed.): American Gas Association Operations Conference, San Francisco, CA, USA, 10

COLEMAN, N. P. (2011): Produced Formation Water Sample Results from Shale Plays. Technical Workshops for the Hydraulic Fracturing Study: Chemical & Analytical Methods. Arlington, Virginia, US EPA: 20

CROCKETT, C. L. & ENEDY, K. L. (1990): A Walk Through Time: Injection in the Southeast Geysers (Ed.): Proceedings of the Symposium on Subsurface Injection of Geothermal Fluids, Santa Rosa, CA, USA, Underground Injection Practices Council Research Foundation

DARRAH, T. H. & POREDA, R. J. (2013): Method for Determining the Genetic Fingerpring of Hydrocarbons and Other Geological Fluids using Noble Gas Geochemistry, US Patent 20,130,091,925

DAVIES, R. J.; MATHIAS, S. A.; MOSS, J.; HUSTOFT, S. & NEWPORT, L. (2012): Hydraulic fractures: How far can they go? Marine and Petroleum Geology 37(1): 1-6, http://www.sciencedirect.com/science/article/pii/S0264817212000852

DVGW (2003): Messnetze zur Überwachung der Grundwasserbeschaffenheit in Wassergewinnungsgebieten. 15

DVGW (2008): Safe and secure drinking water supply - risk management under normal operating conditions. 20

EPA (2008): Guidelines for groundwater investigation and monitoring for landfills. Authority, E. P., Draft Version Environment Protection Authority, 53

ESHLEMAN, K. N. & ELMORE, A. (2013): Recommended Best Management Practices for Marcellus Shale Gas Development in Maryland. Appalachian Laboratory - University of Maryland Center for Environmental Science, 172

EU (2000): European Water Framework Directive - Council Directive 2000/60/EC of 23 October 2000. Enacted: 22.12.2000,

EU (2006a): Directive 2006/118/EC of the European Parliament and of the council of 12 december 2006 on the protection of groundwater against pollution and deterioration. 42

EU (2006b): Groundwater Directive 2006/118/EC on the protection of groundwater against pollution and deterioration.

EU (2007): Common implementation strategy for the Water Framework Directive (2000/60/EC) - Guidance document N°15 - Guidance on groundwater monitoring. European Commission. Brussels. 15: 54

EU (2009): DIRECTIVE 2009/31/EC on the geological storage of carbon dioxide.

EU (2011a): Characterisation of the Storage Complex, CO2 Stream Composition, Monitoring and Corrective Measures. Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide: 155

EU (2011b): Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide: Criteria for Transfer of Responsibility to the Competent Authority. Guidance Document 3, EXPERTENGRUPPE THERMALWASSER (2012): Grundsatzpapiere zur Thermalwassernutzung im niederbayerisch-oberösterreichischen Molassebecken. Büttner, W. & Kolmer, C., im Auftrag der Ständigen Gewässerkommission nach dem Regensburger Vertrag,

FALKENMARK, M. (2005): Water Usability Degradation. Water International 30(2): 136-146, http://dx.doi.org/10.1080/02508060508691854

FGG ELBE (2007): Bericht der Flussgebietsgemeinschaft Elbe zum Überwachungsprogramm nach Artikel 8 EG-WRRL. Flussgebietsgemeinschaft Elbe, 21

FRICK, S. & KALTSCHMITT, M. (2008): Ökologische Aspekte der tiefen Erdwärmenutzung - Analyse und Bewertung lokaler Umwelteffekte. Erdöl, Erdgas, Kohle 124(7/8): 323-328

GFZ (1999): Evaluierung geowissenschaftlicher und wirtschaftlicher Bedingungen für die Nutzung hydrogeothermaler Ressourcen. Abschlussbericht zum BMBF-Projekt BEO 0326969, GeoForschungsZentrum Potsdam,

GORODY, A. W. (2012): Factors affecting the variability of stray gas concentration and composition in groundwater. Environmental Geosciences 19(1): 17-31, http://eg.geoscienceworld.org/content/19/1/17.abstract

GROAT, C. G.; GRIMSHAW, T. W. & THE ENERGY INSTITUTE (2012): Fact-Based Regulation for Environmental Protection in Shale Gas Development.

GWPC & IOGCC (2013): FracFocus - Chemical Disclosure Registry. http://fracfocus.org/, Ground Water Protection Council
Interstate Oil and Gas Compact Commission: 1

HALLIBURTON ENERGY INSTITUTE (1996): Oilfield Environmental Engineering and Management.

HETRICK, L. H. (2011): Case study for well integrity over a full life cycle (Ed.): Technical Workshop for the Hydraulic Fracturing Study: Well Construction and Operation, Arlington, VA, USA, U.S. Environmental Protection Agency, 122-135

IAEA (2000): Isotopic and chemical techniques in geothermal exploration, development and use. Arnórsson, S., International Atomic Energy Agency,, 351

IEAGHG (2013): Interactive Design of Monitoring Programmes for the Geological Storage of CO2. http://www.ieaghg.org/index.php?/Monitoring-Selection-Tool.html

IGRAC (2006): Guideline on: Groundwater monitoring for general reference purposes. Jousma, G., IGRAC, 165

IPCC (2005): The IPCC Special Report on Carbon dioxide Capture and Storage. Intergovernmental Panel on Climate Change,

JACKSON, R. B.; VENGOSH, A.; DARRAH, T. H.; WARNER, N. R.; DOWN, A.; POREDA, R. J.; OSBORN, S. G.; ZHAO, K. & KARR, J. D. (2013a): Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proceedings of the National Academy of Sciences 110(28): 11250-11255

JACKSON, R. E.; GORODY, A. W.; MAYER, B.; ROY, J. W.; RYAN, M. C. & VAN STEMPVOORT, D. R. (2013b): Groundwater Protection and Unconventional Gas Extraction: The Critical Need for Field-Based Hydrogeological Research. Groundwater 51(4): 488-510, http://dx.doi.org/10.1111/gwat.12074

KAGEL, A.; BATES, D. & GAWELL, K. (2007): A Guide to Geothermal Energy and the Environment Geothermal Energy Association,

KRÁSNÝ, J. (1993): Classification of Transmissivity Magnitude and Variation. Groundwater 31(2): 7

KRISTMANNSDÓTTIR, H. & ÁRMANNSSON, H. (2003): Environmental aspects of geothermal energy utilization. Geothermics 32(4–6): 451-461, http://www.sciencedirect.com/science/article/pii/S037565050300052X

LUGV BRANDENBURG (2005): Umweltdaten aus Brandenburg.

MAJER, E.; NELSON, J.; ROBERTSON-TAIT, A.; SAVY, J. & WONG, I. (2012): GEOTHERMAL TECHNOLOGIES PROGRAM - Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems. Nathwani, J., U.S. Department of Energy, 52

MAJER, E. L.; BARIA, R.; STARK, M.; OATES, S.; BOMMER, J. J.; SMITH, B. & ASANUMA, H. (2007): Induced seismicity associated with Enhanced Geothermal Systems. Geothermics 36(3): 185-222, http://www.sciencedirect.com/science/article/pii/S0375650507000387

NETL (2009): Best practices for: Monitoring, Verification, and Accounting of CO2 Stored in Deep Geologic Formations. U. S. Department of Energy, 132

NEUTRALER EXPERTENKREIS (2012): Sicherheit und Umweltverträglichkeit der Fracking-Technologie für die Erdgasgewinnung aus unkonventionellen Quellen. Risikostudie Fracking, 75

NIMZ, G. J. & HUDSON, G. B. (2005): The Use of Noble Gas Isotopes for Monitoring Leakage of Geologically Stored CO2. In: Benson, S. M.: Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO2 Capture Project Geologic Storage of Carbon Dioxide with Monitoring and Verification. 24, London, Elsevier Science. 2: 1113–1130

PLASYNSKI, S. I.; LITYNSKI, J. T.; MCILVRIED, H. G.; VIKARA, D. M. & SRIVASTAVA, R. D. (2011): The critical role of monitoring, verification, and accounting for geologic carbon dioxide storage projects. Environmental Geosciences 18(1): 19-34, http://eg.geoscienceworld.org/content/18/1/19.abstract

RAENG (2012): Shale gas extraction in the UK: a review of hydraulic fracturing. The Royal Society and The Royal Academy of Engineering, 76

REVESZ, K. & BALDASSARE, A. (2013): Important considerations in the use of carbon and hydrogen stable isotopes to determine the origin of hydrocarbons in groundwater- A case study from pre-shale gas Tioga County (Ed.): Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Technical Workshop on Analytical Methods US EPA

RHODES, I. (2013): Indicator Parameters: Pre-drill Baseline Groundwater Surveys, Post-drill Groundwater Monitoring, and Gas Analysis (Ed.): Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Technical Workshop on Analytical Methods U.S. Environmental Protection Agency

ROWE, D. & MUEHLENBACHS, A. (1999): Low-temperature thermal generation of hydrocarbon gases in shallow shales. Nature 398(6722): 61-63, http://dx.doi.org/10.1038/18007

ROY, J. W. & RYAN, M. C. (2013): Effects of Unconventional Gas Development on Groundwater: A Call for Total Dissolved Gas Pressure Field Measurements. Groundwater 51(4): 480-482, http://dx.doi.org/10.1111/gwat.12065

SANJUAN, B.; JOUSSET, P.; PAJOT, G.; DEBEGLIA, N.; DE MICHELE, M.; BRACH, M.; DUPONT, F.; BRAIBANT, G.; LASNE, E. & DURÉ, F. (2010): Monitoring of the Bouillante Geothermal Exploitation (Guadeloupe, French West Indies) and the Impact on Its Immediate Environment (Ed.): World Geothermal Congress 2010, Bali, Indonesia, 11

SEIBT, A. & WOLFGRAMM, M. (2003): Stimulation tests in a deep Rotliegend sandstone formation - Geochemical aspects (Ed.): International Geothermal Conference, Reykjavik, Iceland

SEIS, W.; STAUB, M.; MASSAT, L. & GRUETZMACHER, G. (2013): Geological CO2 storage and other emerging subsurface activities - Catalogue of potential impacts on drinking water production. Berlin Centre of Competence for Water, 39

SENSTADT (2001): Bewilligung zur Förderung von Grundwasser im Wasserwerk Wuhlheide für die öffentliche Trinkwasserversorgung des Landes Berlin

SIJACIC, D. (2013): CATO2: Design of Monitoring Systems & Remediation - Technical report describing the design of monitoring systems, and remediation. CATO 2 33

SOEDER, D. (2011): Design and Rationale for a Field Experiment using Tracers in Hydraulic Fracture Fluid (Ed.): Technical Workshop for the Hydraulic Fracturing Study: Well Construction and Operation, Arlington, VA, USA, US EPA

STEWART, D. (2013): Analytical Testing for Hydraulic Fracturing Fluids Water Recovery and Reuse (Ed.): EPA’s Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Technical Workshop on Analytical Methods US EPA

SZULCZEWSKI, M. L.; MACMINN, C. W.; HERZOG, H. J. & JUANES, R. (2012): Lifetime of carbon capture and storage as a climate-change mitigation technology. Proceedings of the National Academy of Sciences 109(14): 5185-5189, http://www.pnas.org/content/109/14/5185.abstract

TESTER, J. W.; ANDERSON, B. J.; BATCHELOR, A. S.; BLACKWELL, D. D.; DIPIPPO, R.; DRAKE, E. M.; GARNISH, J.; LIVESAY, B.; MOORE, M. C.; NICHOLS, K.; PETTY, S.; TOKSÖZ, M. N. & VEATCH, R. W. J. (2006): The Future of Geothermal Energy. Laboratory, I. N., Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, Massachusetts Institute of Technology, 372

THOMAS, L.; TAUTE, T.; SCHNEIDER, M.; KEMPKA, T. & KUEHN, M. (2013): Report on risk analysis, best practices and lessons learned from existing geothermal projects in Germany. Geological CO2 storage and other emerging subsurface activities, Berlin Center of Competence for Water,

U.S DEPARTEMENT OF ENERGY & ENERGY EFFICIENCY AND RENEWABLE ENERGY (2008): Geothermal Technologies Program - An Evaluation of Enhanced Geothermal Systems Technology Energy, U. S. D. O., U.S Departement of Energy, US EPA (2013): Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Testing and Monitoring Guidance. Water, O. O., U. S. Environmental Protection Agency

USDOI (2001): Technical Measures for the investigation and mitigation of fugitive methane hazards in areas of coal mining. Office of Surface Mining Reclamation and Enforcement, United States Department of the Interior,

USEPA (1998): Part 146 - Underground injection control program: Criteria and standards.

USEPA (1999a): The Class V Underground Injection Control Study - Electric Power Geothermal Injection Wells. 17 United States Environmental Protection Agency - Office of Ground Water and Drinking Water

USEPA (1999b): The Class V Underground Injection Control Study - Geothermal Direct Heat Return Flow Wells. 18 United States Environmental Protection Agency - Office of Ground Water and Drinking Water,

USEPA (2004): Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action. United States Environmental Protection Agency,

USEPA (2007): Underground Injection Control Individual permit Class V Injection Permit No, HI596002. Epa, U.,

USEPA (2012a): Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Construction Guidance. Water, O. O., US EPA,, 52

USEPA (2012b): Permitting Guidance for Oil and Gas Hydraulic Fracturing Activities Using Diesel Fuels – Draft: Underground Injection Control Program Guidance #84. Office of Water,

USEPA (2013a): Geologic Sequestration of Carbon Dioxide - Draft Underground Injection Control (UIC) Program Guidance on Class VI Well Plugging, Post-Injection Site Care, and Site Closure. Water, O. O., US EPA,,

USEPA (2013b): Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Area of Review Evaluation and Corrective Action Guidance. Water, O. O., US EPA,, 96

USEPA (2013c): Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Site Characterization Guidance. Office of Water, US EPA,, 192

USEPA (2013d): Geologic Sequestration of Carbon Dioxide - Underground Injection Control (UIC) Program Class VI Well Testing and Monitoring Guidance. Water, O. O., US EPA,,

USGS (1994): Potential Effects of the Hawaii Geothermal Project on Ground-Water Resources on the Island of Hawaii. Report No. 94-4028 U. S. Geological Survey,,

WARNER, N.; JACKSON, R.; DARRAH, T.; DWYER, G. & VENGOSH, A. (2013): New Isotopic Tracers for Shale Gas and Hydraulic Fracturing Fluids (Ed.): Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Technical Workshop on Analytical Chemical Methods, US EPA

WHO (2004): Guidelines for Drinking-Water Quality: Recommendations. Geneva, WHO

WHO (2006): Protecting Groundwater for Health – Managing the Quality of Drinking-water Sources. London, IWA Publishing, 678

WHO (2009): Water safety plan manual : step-by-step risk management for drinking-water suppliers. Geneva, World Health Organization, 101 p, http://whqlibdoc.who.int/publications/2009/9789241562638_eng.pdf

WISEMAN, H. & GRADIJAN, F. (2012): Regulation of Shale Gas Development, Including Hydraulic Fracturing.

YANG, C.; ROMANAK, K.; HOLT, R. M.; LINDNER, J.; SMITH, L.; TREVINO, R.; ROECKER, F.; XIA, Y.; RICKERTS, J. & HORVORKA, S. (2012): Large Volume of CO2 Injection at the Cranfield, Early Field Test of the SECARB Phase III: Near-Surface Monitoring (Ed.): Carbon Management Technology Conference, Orlando, Florida, USA, Carbon Management Technology Conference

ZIMMERMANN, G.; BLÖCHER, G. & HUENGES, E. (2012): Enhanced Geothermal Systems (EGS) - Potential and Stimulation treatments. In: Bruhns, H. (Ed.): Energiewende - Aspekte, Optionen, Herausforderungen, Berlin, Arbeitskreis Energie in der Deutschen Physikalischen Gesellschaft 12

Appendix I - Monitoring techniques Geological Carbon Storage

Monitoring Techniques		Technology Type	Project Phase			Description	Benefits	Challenges
			Pre	Op	Post			
Surface and Atmospheric Monitoring	CO2 detectors	Secondary	x	x	x	Sensors for monitoring CO_2 either intermittently or continuously in air.	Relatively inexpensive and portable. Mature and new technologies represented.	Detect leakage above ambient CO_2 emissions (signal to noise).
	Laser systems and LIDAR	Secondary	x	x	x	Open-path device that uses a laser to shine a beam, with a wavelength that CO_2 absorbs over many meters. Used to assess CO_2 fluxes over large spatial scales.	Highly accurate technique with large spatial range. Non-intrusive method of data collection over a large area in a short timeframe.	Needs favorable weather conditions. Interference from vegetation, requires time laps Signal to noise.
	Ecosystem stress monitoring	Secondary	x	x	x	Satellite or airplane-based optical method that can be used in a time-lapse manner to assess changes in vegetation integrity that could signify a CO_2 leakage location.	Easy and effective reconnaissance method.	Detection only after emission has occurred. Quantification of leakage rates difficult. Changes not related to CCS lead to false positives. Not all ecosystems equally sensitive to CO_2.
	Flux accumulation chamber	Secondary	x	x	x	Quantifies the CO_2 flux from the soil, but only from a small, predetermined area.	Technology that can quickly and effectively determine CO_2 fluxes from the soil at a predetermined area.	Only provides instantaneous measurements in a limited area.
	Soil and vadose zone gas monitoring	Secondary	x	x	x	Sampling of gas in vadose zone/soil (near surface) for CO_2.	CO_2 retained in soil gasses provides a longer residence time. Detection of elevated CO_2 concentrations well above background levels provides indication of leak and migration from the target reservoir.	Significant effort for null result (no CO_2 leakage). Relatively late detection of leakage.
	Eddy covariance	Potential	x	x	x	Atmospheric flux measurement technique to measure atmospheric CO_2 concentrations at a height above the ground surface.	Mature technology that can provide accurate data under continuous operation.	Very specialized equipment and robust data processing required. Signal to noise
	Advanced leak detection systems	Potential	x	x	x	Sensitive multigas detector (CH_4, total HC, and CO_2) with a GPS mapping system carried by aircraft or terrestrial vehicles. Technology being evaluated by DOE.	Good for quantification of CO_2 fluxes from the soil.	Null result if no CO_2.
	Tracers (isotopes)	Potential	x	x	x	Natural isotopic composition and/or compounds injected into the target formation along with the CO2 that allows for detection of leakage and provides indication of plume flow direction.	Used to determine the flow direction and early leak detection.	Samples need analyzed offsite of project team does not have the proper analytical equipment.
Geochemical Monitoring	Groundwater monitoring	Primary	x	x	x	Sampling of water or vadose zone/soil (near surface) for basic chemical analysis.	Mature technology, easier detection than atmospheric. Early detection prior to large emissions.	Significant effort for null result (no CO2 leakage). Relatively late detection of leakage.
	Aqueous geochemistry	Primary	x	x	x	Chemical measurement of saline brine in or above the target storage reservoir.	Coupled with repeat analyses during and after CO_2 injection can provide massbalance and dissolution/mineral trapping information.	Cannot image CO_2 migration and leakage directly. Only near-well fluids are measured.

	Tracers	Secondary		x	x	CO_2 soluble compounds injected along with the CO_2 into the target formation used to determine hydrologic properties, flow direction, and low-mass leak detection.	Used to determine the hydrologic properties, flow direction and low-mass leak detection.	Many of the tested CO_2-soluble tracers are GHGs, and therefore, add to risk profile.
Operational Monitoring	Carbon dioxide stream analysis	Primary		x		Chemical analysis to evaluate the potential interactions of CO_2 and/or other constituents of the injectate with formation solids and fluids.	Provision of continuous stream analysis by the application of CEM systems.	Only limited set of parameter (CEM systems) or no continuous monitoring (Laboratory analysis).
	Wellhead flow and rate metering	Primary		x		Continuous recording devices to monitor injection rate and volume and/or mass	Verification of compliance	Determination of the cumulative volume of injected CO_2 needs density corrections
	Pressure fall-off tests	Primary		x		Monitoring pressure decay at the well after ceasing injection for a period of time to measure formation properties in the vicinity of the injection well.		Multiple injection wells within the same zone as injection at one well will influence the pressure fall-off curve at other wells.
	Corrosion monitoring	Primary		x		Detection of deterioration of well components using coupons, a flow loop or alternative methods	Early detection of deterioration of well components that may cause loss of mechanical integrity	Corrosion inhibitors or corrosion-resistant alloys are additional options to provide protection from corrosion
Well integrity tests	Injection well logging (wireline logging)	Primary	x	x	x	Wellbore measurement using a rock parameter, such as resistivity or temperature, to monitor fluid composition in wellbore and to assess geologic characteristics as a function of well depth.	Easily deployed technology and very useful for wellbore leakage.	Area of investigation limited to immediate wellbore. Sensitivity of tool to fluid change.
	Annulus pressure monitoring	Primary	x	x	x	A mechanical integrity test on the annular volume of a well to detect leakage from the casing, packer, or tubing. Can be done permanently.	Reliable test with simple equipment. Engineered components are known to be areas of high frequency.	Periodic mechanical integrity testing requires stopping the injection process during testing. Limited to constructed system.
	Pulsed neutron capture	Primary	x	x	x	A wireline tool capable of depicting oil saturation, lithology, porosity, oil, gas, and water by implementing pulsed neutron techniques.	High resolution tool for identifying specific geologic parameters around the well casing. Most quantitative to CO_2 saturation in time-lapse.	Geologic characteristics identified only in the vicinity of the wellbore. Not sensitive to dissolution trapped and mineral trapped CO_2. Sensitive to borehole conditions, fluid invasion because of workover. Decreased sensitivity in lower salinity water, at low saturation.
	Sonic (acoustic) logging	Primary	x	x	x	A wireline tool capable of depicting oil saturation, lithology, porosity, oil, gas, and water by implementing pulsed neutron techniques.	Oil field technology that provides high resolution. Can be used to time seismic sections.	Does not yield data on hydraulic seal. May have to make slight corrects for borehole eccentricity. Not a “stand alone” technology. Should be used in conjunction with other techniques.
	Density logging (RHOB log)	Primary	x	x	x	Continuous record of a formation bulk density as a function of depth by accounting for both the density of matrix and density of liquid in the pore space. Allows for assessment of formation density and porosity at varying depths.	Effective technology that can estimate formation density and porosity at varying depths.	Lower resolution log compared to other wireline methods.
	Cement bond log (ultrasonic well logging)	Primary	x	x	x	Implements sonic attenuation and travel time to determine whether casing is cemented or free. The more cement which is bonded to casing, the greater will be the attenuation of sounds transmitted along the casing. Used to evaluate the integrity of the casing cement and assessing	Evaluation of quality of engineered well system prior to leakage, allows for proactive remediation of engineered system. Indicates top of cement, free pipe, and gives an indication of well cemented pipe.	Good centralization is important for meaningful and repeatable cement bond logs. Cement bond logs should not be relied on for a quantitative evaluation of zonal isolation or hydraulic integrity. The cement should be allowed to cure for at

						the possibility of flow outside of casing.	Authorized as an MIT tool for the demonstration of external integrity of injection wells.	least 72 hours before logging.
	Gamma-ray logging	Primary	x	x	x	Use of natural gamma radiation to characterize the rock or sediment in a borehole.	Common and inexpensive measurement of the natural emission of gamma rays by a formation.	Subject to error when a large proportion of the gamma ray radioactivity originates from the sand-sized detrital fraction of the rock. Limited to site characterization phase.
Geophysical approaches	Multicomponent 3-D surface seismic time-lapse survey	Secondary	x	x	x	Surface 3-D seismic surveys covering the CCS reservoir that can provide high-quality information on distribution and migration of CO_2 and identification of subsurface features. Best technique for map view coverage. Can be used in multicomponent form (e.g., three, four, or nine components) to account for both compression waves (P-waves) and shear waves (S-waves).	Mature technology that can provide high-quality information on distribution and migration of CO_2. Best technique for map view coverage. Can be used in multi-component form (ex. three, four, or nine component), to account for both compressional waves (P-waves) and shear waves (S-waves).	Semi-quantitative. Cannot be used for mass-balance CO_2 dissolved or trapped as/mineral not monitored. Signal to noise, not sensitive to concentration. Thin plumes or low CO_2 concentration may not be detectable.
	Vertical seismic profil	Secondary	x	x	x	Repeated seismic surveys source in a wellbore, receiver at surface. Can be implemented in a “walk-away” manner to monitor the footprint of the plume as it migrates away from the injection well and in time-lapse application. VSP provides a very detailed survey because of the close spacing of the geophones.	Mature technology that can provide robust information on CO_2 concentration and migration. More resolution than surface seismic by use of a single wellbore. Can be used for calibration of a 2-D or 3-D seismic.	Application limited by geometry surrounding a wellbore.
	2-D seismic survey	Secondary	x	x	x	Acoustic energy, delivered by explosive charges or vibroseis trucks (at the surface) is reflected back to a straight line of recorders (geophones). After processing, the reflected acoustic signature of various lithologies is presented as a 2-D graphical display.	Can be used to monitor “bright spots” of CO_2 in the subsurface. Excellent for shallow plumes as resolution decreases with depth.	Coverage limited to lines.
	Optical logging	Secondary	x	x	x	Device equipped with optical imaging tools is lowered down the length of the wellbore to provide detailed digital images of the well casing.	Simple and cheap technology that provides qualitative well integrity verification at depth.	Does not provide information beyond what is visible inside the well casing.
	Shallow 2-D seismic	Secondary	x	x	x	Closely spaced geophones along a 2-D seismic line that can provide high-resolution images of the subsurface, including changes in lithology and the location of CO_2 plumes.	Mature technology that can provide high resolution images of the presence of gas phase CO_2. Can be used to locate “bright spots” that might indicate gas, also/ used in time lapse.	Semi-quantitative. Cannot be used for mass-balance CO_2 dissolved or trapped as/mineral not monitored. Out of plane migration not monitored.
	Magnetotelluric sounding	Potential	x	x	x	Changes in electromagnetic field resulting from variations in electrical properties of CO_2 and formation fluids.	Can probe the Earth to depths of several tens of kilometers.	Immature technology for monitoring of CO_2 movement. Relatively low resolution.
	Electromagnetic resistivity	Potential	x	x	x	Measures the electrical conductivity of the subsurface including soil, groundwater, and rock.	Rapid data collection.	Strong response to metal. Sensitivity to CO_2.
	Electromagnetic induction tomography	Potential	x	x	x	Uses differences in how electromagnetic fields are induced within various materials as a means to identify subsurface lithology and geologic features.	Provides greater resolution and petrophysical information than ERT.	Difficult to execute. Requires non-conductive casing downhole to obtain high–frequency data. Esoteric technique, not proven for GS.

	Time-lapse gravity	Potential	x	x	x	Use of gravity to monitor changes in density of fluid resulting from injection of CO_2.	Effective technology.	Limited detection and resolution unless gravimeters are located just above reservoir, which significantly increases cost. Sensitivity.
	Microseismic (passive) survey	Potential	x	x	x	Provides real-time information on hydraulic and geomechanical processes taking place within the reservoir in the interwell region, remote from wellbores by implementing surface or subsurface geophones to monitor earth movement.	Technology with broad area of investigation that can provide provides high-quality, high resolution subsurface characterization data and can provide effects of subsurface injection on geologic processes.	Dependence on secondary reactions from CO_2 injection, such as fracturing and faulting. Difficult to interpret low rate processes (e.g., dissolution/mineral trapping and slow leakage). Extensive data analysis required.
	Crosswell seismic survey	Potential	x	x	x	Seismic survey between two wellbores in which transmitters and receivers are placed in opposite wells. Enables subsurface characterization between those wells. Can be used for time-lapse studies.	Crosswell seismic profiling provides higher resolution than surface methods, but sample a smaller volume.	Mass-balance and dissolution/mineral trapping difficult to monitor.
	Resistivity log	Potential	x	x		Log of the resistivity of the formation, expressed in ohm meter, to characterize the fluids and rock or sediment in a borehole.	Used for characterization, also sensitive to changes in fluids.	Resistivity can only be measured in open hole or non-conducive casing.
	Thermal hyperspectral imaging	Potential	x	x		An aerial remote-sensing approach primarily for enhanced coal bed methane recovery and sequestration as a means to detect surface deformation changes resulting from CO2 injection.	Covers large areas; detects CO_2 and CH_4.	Not a great deal of experience with this technique in GS.
	Synthetic aperture radar (SAR and InSAR)	Potential	x	x		A satellite-based technology in which radar waves are sent to the ground to detect surface deformation.	Large-scale monitoring (100 km x 100 km).	Best used in environments with minimal topography, minimal vegetation, and minimal land use. Only useful in time-lapse.
	Color infrared transparency films	Potential		x	x	A vegetative stress technology deployed on satellites or aerially that can be an indicator of CO_2 or brine leakage.	Good indicator of vegetative health, which can be an indicator of CO2 or brine leakage.	Detection only post-leakage. Need for deployment mechanism (i.e. aircraft).
	Tiltmeter	Potential		x		Measures small changes in elevation via mapping tilt, either on the surface or in subsurface.	Mature oil field technology for monitoring stream or water injection, CO2 flooding and hydrofracturing.	Access to surface and subsurface. Measurements are typically collected remotely.
	Induced polarization	Potential	x	x	x	Geophysical imaging technology commonly used in conjunction with DC resistivity to distinguish metallic minerals and conductive aquifers from clay minerals in subsurface materials.	Detecting metallic materials in the subsurface with fair ability to distinguish between different types of mineralization. Also a useful technique in clays.	Does not accurately depict non-metallic based materials. Typically used only for characterization.
	Spontaneous (self) potential	Potential	x	x	x	Measurement of natural potential differences resulting from electrochemical reactions in the subsurface. Typically used in groundwater investigations and in geotechnical engineering applications for seepage studies.	Fast and inexpensive method for detecting metal in the near subsurface. Useful in rapid reconnaissance for base metal deposits when used in tandem with EM and geochemical techniques.	Should be used in conjunction with other technologies. Qualitative only.

Appendix II – Monitoring techniques Shale Gas Extraction

Monitoring Techniques		Technology Type	Project Phase			Description	Benefits	Challenges
			Pre	Op	Post			
Surface and Atmospheric Monitoring	CH4 detectors	Primary	x	x	x	Portable/Fixe sensors for monitoring CH4 either intermittently or continuously in air.	Relatively inexpensive and portable. Mature and new technologies represented.	Detect leakage above ambient CH4 emissions (signal to noise).
	Soil and vadose zone gas monitoring	Primary	x	x	x	Sampling of gas in vadose zone/soil (near surface) for CH4 and other higher hydrocarbons (ethane).	Information about CH4 concentration and origin (after isotopic characterization).	Significant effort for null result (no CH4 leakage) or microbial origin.
	Flux accumulation chamber	Secondary	x	x	x	Quantifies the CH4 flux from the soil, but only from a small, predetermined area.	Technology that can quickly and effectively determine CH4 fluxes from the soil at a predetermined area.	Only provides instantaneous measurements in a limited area.
	Ecosystem stress monitoring	Potential	x	x	x	Currently research program in USA IBGN calculation?		Detection only after emission has occurred. Quantification of leakage rates difficult. Changes not related to fracking lead to false positives.
	Eddy covariance	Potential	x	x	x	Atmospheric flux measurement technique to measure atmospheric CH4 concentrations at a height above the ground surface.	Mature technology that can provide accurate data under continuous operation. Detection of CH4 leakage above shale gas site (GHG effect).	Very specialized equipment and robust data processing required. Signal to noise
	Advanced leak detection systems	Potential	x	x	x	Sensitive multigas detector (CH4, total HC, and CO2) with a GPS mapping system carried by aircraft or terrestrial vehicles. Technology being evaluated by DOE.	Good for quantification of CH4 fluxes from the soil.	Null result if no CH4.
Geochemical	Groundwater monitoring	Primary	x	x	x	Sampling of water or vadose zone/soil (near surface) for basic chemical analysis.	Mature technology, easier detection than atmospheric. Early detection prior to large contamination.	Significant effort for null result (fracking contamination). Relatively late detection of leakage.
	Tracers	Secondary		x	x	Natural (isotopes characterization) or added tracers (PFTs).	Used to determine the origin of the contamination.	Many of PFTs are GHGs, and therefore, add to risk profile.
Operational Monitoring	Frac fluid analysis	Primary		x		Chemical analysis of the frac fluid (flowback, produced water).	Reliable contamination assessment due to unique fluid fingerprint for each fracking site.	Huge amount of additives to analyze.
	Wellhead pressure and flow rates	Primary	x	x		Gauge reading wellhead pressure	Ensuring that the pressure applied is not exceeding the permitted one (materials).	
	Annulus pressure tests	Secondary	x	x				
Well Integrity	SBT (Segmented Bond Tool)	Primary	x	x		Radial cement bond device, which measures the quality of cement effectiveness, both vertically and laterally around the circumference of the casing.	Evaluation of quality of engineered well system prior to leakage, allows for proactive remediation of engineered system. Indicates top of cement, free pipe, and gives an indication of well cemented pipe.	SBT is usually run with a VDL (variable density log). Results are affected by fast formation.

	USIT (UltraSonic Imaging Tool)	Primary	x	x		Continuously rotating pulse echo with nearly 100% coverage of the casing wall.	The USIT tool is 3 3/8” in diameter and by changing the rotating transducer subassemblies can operate in casing sizes from 4 ½’ to 13 3/8”	It is very sensitive to the condition of the borehole and is preferably run along with a CBL to provide best overall picture of well integrity
	MWD (Measurements While Drilling) & LWD (Logging While Drilling)	Primary	x	x		LWD tools work with its Measurement While Drilling (MWD) system to transmit partial or complete measurement results to the surface via typically a drilling mud pulser or other improved techniques.	MWD records values like direction, inclination, tool face etc, which all are values needed to achieve a successful drilling. LWD services acquire high-quality data for geosteering and formation evaluation. Combine different logging activities (Porosity, permeability, lithology, pressure, resistivity…). Tools are encompassed in a single module in the steering tool of the drill string, at the end of the drilling apparatus (or the bottom hole assembly). Now, video is even available to help in the process.	
	Density logging (RHOB log)	Primary	x	x		Continuous record of a formation bulk density as a function of depth by accounting for both the density of matrix and density of liquid in the pore space. Allows for assessment of formation density and porosity at varying depths.	Effective technology that can estimate formation density and porosity at varying depths. Help to identify gas bearing formation and other geological features prior to drilling. Reservoir characterization.	Lower resolution log compared to other wireline methods.
	Cement bond log (CBL - ultrasonic well logging)	Primary	x	x		Implements sonic attenuation and travel time to determine whether casing is cemented or free. The more cement which is bonded to casing, the greater will be the attenuation of sounds transmitted along the casing. Used to evaluate the integrity of the casing cement and assessing the possibility of flow outside of casing.	Evaluation of quality of engineered well system prior to leakage, allows for proactive remediation of engineered system. Indicates top of cement, free pipe, and gives an indication of well cemented pipe.	Good centralization is important for meaningful and repeatable cement bond logs. Cement bond logs should not be relied on for a quantitative evaluation of zonal isolation or hydraulic integrity. The cement should be allowed to cure for at least 72 hours before logging, 48 hours for API.
	Gamma-ray logging (GRL)	Primary	x	x		Use of natural gamma radiation to characterize the rock or sediment in a borehole.	Common and inexpensive measurement of the natural emission of gamma rays by a formation. Calculate lithology, total and effective porosity saturations and kerogen content.	Subject to error when a large proportion of the gamma ray radioactivity originates from the sand-sized detrital fraction of the rock. Limited to site characterization phase.
	Optical logging	Secondary	x	x		Device equipped with optical imaging tools is lowered down the length of the wellbore to provide detailed digital images of the well casing.	Simple and cheap technology that provides qualitative well integrity verification at depth. Allows real time production logging.	Does not provide information beyond what is visible inside the well casing.

Geophysical approaches	Multicomponent 3-D surface seismic time-lapse survey	Primary	x	x	x	Surface 3-D seismic surveys covering the shale layer reservoir and fracture extension that can provide high-quality the location of seismic events and identification of subsurface features. Best technique for map view coverage. Can be used in multicomponent form (e.g., three, four, or nine components) to account for both compression waves (P-waves) and shear waves (S-waves).	Mature technology that can provide high-quality information on fracture and shale layer. Best technique for map view and fracture extension coverage. Can be used in multi-component form (ex. three, four, or nine component), to account for both compressional waves (P-waves) and shear waves (S-waves).	Semi-quantitative. Signal to noise, not sensitive to concentration. Thin fractures can’t be identified. Carbonate layer and sophisticated geology give less resolution data.
	Tomographic Fracture Imaging	Primary	x	x	x	Method that uses Seismic Emission Tomography (SET) in combination with empirical data on fracture geometry. Image directly both natural fracture network and those induced by fracking.	Proved very robust and has achieved independently documented accuracy and precision of +/- 5 meters. TFI has been used to verify that the reservoir permeability field is bounded by the reservoir seal and that fracing activity did not compromise this important boundary.	
	Microseismic (passive) survey	Primary	x	x	x	Provides real-time information on hydraulic and geomechanical processes taking place within the reservoir in the interwell region, remote from wellbores by implementing surface or subsurface geophones to monitor earth movement.	Technology with broad area of investigation that can provide provides high-quality, high resolution subsurface characterization data and can efficiently provide extensive diagnostic information on fracture development and geometry.	Extensive data analysis required.
	Crosswell seismic tomography survey	Primary	x	x	x	A survey technique that measures the seismic signal transmitted from a source, located in one well, to a receiver array in a neighboring well. The resulting data are processed to create a reflection image or to map the acoustic velocity or other properties (velocities of P- and S-waves, for example) of the area between wells. Placement of the source and receiver array in adjacent wells not only enables the formation between wells to be surveyed, it also avoids seismic signal propagation through attenuative near-surface formations.	Better resolution than is possible with conventional surface seismic surveys. This technique is often used for high-resolution reservoir characterization when surface seismic or vertical seismic profile (VSP) data lack resolution, or for time-lapse monitoring of fluid movements in the reservoir.	
	Tiltmeter	Primary		x		Measures small changes in elevation via mapping tilt, either on the surface (surface tilt) or in subsurface (offset well tilt).	Mature oil field technology for monitoring stream or water injection, CO2 flooding and hydrofracturing. Map of fracture extension and orientation	Access to surface and subsurface. Measurements are typically collected remotely.

	Vertical seismic profile (VSP)	Secondary	x	x	x	Repeated seismic surveys source in a wellbore, receiver at surface. Can be implemented in a "walk-away" manner to monitor the footprint of the plume as it migrates away from the injection well and in time-lapse application. VSP provides a very detailed survey because of the close spacing of the geophones.	Combined with vertical-force seismic provide a seismic 'log' of natural and induced fracture orientation and density in unconventional reservoir. Can be used for calibration of a 2-D or 3-D seismic.	Application limited by geometry surrounding a wellbore.
	2-D seismic survey	Secondary	x	x	x	Acoustic energy, delivered by explosive charges or vibroseis trucks (at the surface) is reflected back to a straight line of recorders (geophones). After processing, the reflected acoustic signature of various lithologies is presented as a 2-D graphical display.	High quality fracture extension monitoring.	Coverage limited to lines. Resolution decrease with depth. Only shows a single slice of the formation
	Controllled Source Electromagnetic (CSEM) 1D	Potential	x	x	x	CSEM survey can indicate the presence of oil and gas in offshore situations.	Potential to identify high gas saturation zones in shale reservoir	Better resolution for shallower formation
	Resistivity log	Potential	x	x		Log of the resistivity of the formation, expressed in ohm meter, to characterize the fluids and rock or sediment in a borehole.	Used for characterization, also sensitive to changes in fluids.	Resistivity can only be measured in open hole or non-conducive casing.
	Synthetic aperture radar (SAR and InSAR)	Potential	x	x		A satellite-based technology in which radar waves are sent to the ground to detect surface deformation.	Large-scale monitoring (100 km x 100 km).	Best used in environments with minimal topography, minimal vegetation, and minimal land use. Only useful in time-lapse.
	Color infrared transparency films	Potential		x	x	A vegetative stress technology deployed on satellites or aerially that can be an indicator of CH4 or brine leakage.	Good indicator of vegetative health, which can be an indicator of CH4 or brine leakage.	Detection only post-leakage. Need for deployment mechanism (i.e. aircraft).

Appendix III– Monitoring techniques Geothermal Energy

Monitoring Techniques		Technology Type	Project Phase			Description	Benefits	Challenges
			Pre	Op	Post			
Surface monitori	Ground temperature measurements	Potential	x	x		Temperature measurements within soil in the Vadose zone with a thermocouple in a grid pattern or at specific intervals along profile lines	Low cost because no sophisticated equipment is required and provision of quick results	Seasonal and weather effects limit reoccupation of site measured, permanent installation needed, but data points are limited.
	Soil and vadose zone gas monitoring	Secondary	x	x		Sampling of gas in vadose zone/soil (near surface).		Only appropriate at geothermal sites with vulcanism
	Surface water monitoring	Secondary	x	x		Sampling of surface water chemistry		
Geochemical	Groundwater monitoring	Secondary	x	x	x	Sampling of water or vadose zone/soil (near surface) for basic chemical analysis.	Mature technology, easier detection than atmospheric. Early detection prior to large emissions.	
	Tracers	Potential	x	x		Isotope ratios of δ18O, δ2H, and tritium	Established method of validating reservoir models	Smart tracers has still to be developed.
Operational Monitoring	Fluid sampling	Primary	x	x		Obtains samples of formation and recharge fluids to determine mixing ratios and processes	Can provide information about the rate of lateral movement of the invasion front	Real-time detection technology has limited scope and poor accuracy.
	Wellhead pressure & flow monitoring	Primary	x	x		Continuous recording devices to monitor injection rate and volume and/or mass and pressure	Verification of compliance	
	Biochemical monitoring	Primary	x	x		Microbial screening to identify impacts of bacteria community on geothermal operation and capacity	Identification of bacteria community essential for countermeasures to prevent biofouling or adapt operation	
	PTS log	Secondary	x	x		Combined measurement of the relative velocity of fluid, pressure and temperature during production flow tests	High temperature spinners already available from several sources	
Well integrity	Wireline logging	Secondary	x	x		A sensor package (temperature, sending back signals in real time as it traverses the wellbore	Real-time information about downhole condition, e.g. pressure, lost circulation, bit dysfunctions	Tools and sensors are available for operation up to 150°C, higher temperature versions have limited lifetimes or require shielding
	Annulus pressure monitoring	Secondary	x	x		A mechanical integrity test on the annular volume of a well to detect leakage from the casing, packer, or tubing. Can be done constantly.	Reliable test with simple equipment. Engineered components are known to be areas of high frequency.	Periodic mechanical integrity testing requires stopping the injection process during testing. Limited to constructed system.
	Acoustic televiewer (ATV)	Secondary	x	x		Continuously imaging the wellbore wall with a televiewer, which uses the travel time of acoustic pulses to measure the distance from the rotating transducer to the wellbore wall (fracture density)	Detect shape, formation, fractures, casing damage, and other irregularities in the well and its surroundings.	Fractures which have been filled with material of similar physical properties and are not broken off during drilling operation will not be seen by the ATV.
	Caliper log (CL)	Secondary	x	x		Measure in real time the borehole diameter from bottom to top to show cavities, scaling, etc.	High temperature calipers are readily available	
	Gamma-ray logging (GRL]	Secondary	x	x		Use of natural gamma radiation to characterize the rock or sediment in a borehole (presence of	Can also be used for depth correlation between multiple log.	Spectral gamma tools not available for high temperature applications

						radioactive elements often signals fractures)		
	Cement bond log (CBL)	Secondary	x	x		Implements sonic attenuation and travel time to determine whether casing is cemented or free. The more cement which is bonded to casing, the greater will be the attenuation of sounds transmitted along the casing. Used to evaluate the integrity of the casing cement and assessing the possibility of flow outside of casing.	Evaluation of quality of engineered well system prior to leakage, allows for proactive remediation of engineered system. Indicates top of cement, free pipe, and gives an indication of well cemented pipe. Authorized as an MIT tool for the demonstration of external integrity of injection wells.	Good centralization is important for meaningful and repeatable cement bond logs. Cement bond logs should not be relied on for a quantitative evaluation of zonal isolation or hydraulic integrity. The cement should be allowed to cure for at least 72 hours before logging.
	Collar Casing Locator (CCL)	Potential	x	x		Detect variations in the amount of iron in the vicinity of the tool	Locate casing joints and damages	Low temperature application
	Downhole camera inspection (TV)	Potential	x	x		A camera is lowered in the borehole shooting pictures sideways or downwards	Useful for studying fractures, scaling and casing damage	Limited to low temperatures and depths
	3-D Seismic	Secondary	x	x		Acoustic energy, delivered by explosive charges or vibroseis trucks (at the surface) is reflected back to a straight line of recorders (geophones).	Best technique for map view coverage; provide high-quality information on subsurface features. Localization of drilling sites.	Limited spacious coverage compared to 2-D
	2-D Seismic	Secondary	x	x		Acoustic energy, delivered by explosive charges or vibroseis trucks (at the surface) is reflected back to a straight line of recorders (geophones).	Exploration of large geological structures, suitable for localization of project sites	Coverage limited to lines. Less resolution compared to 3-D.
	Thermal infra-red (TIR) imaging	Secondary	x	x		Aircraft or satellite-based technology to monitor ground temperature.	Complete coverage of a field or thermal areas can be acquired	Weather and ground conditions may be unsuitable for long periods of time resulting in logistic and scheduling delays.
	Neutron log	Potential	x	x		A neutron source sends out high energy neutrons	Useful for estimation of porosity	Low temperature application
	Resistivity logs	Potential	x	x		Measures the electric resistivity of the rock around wells based on porosity of the rock along with salinity and temperature of the fluid	Used to delineate the boundaries of geothermal fields.	Low temperature application
	Microgravity surveying	Potential	x	x		Measurement of pressure drawdown, saturation and temperature changes give a picture of the mass movements during exploitation and tracks reinjected fluids	Confirm or refute models derived from well-bore measurements which may be confined to only a small part of the field.	require high-precision instrumentation and need to be accompanied by ground subsidence and water level monitoring
	Borehole gravimetry	Potential	x	x		Borehole gravity logs to measure mass changes.	Amplitude of gravity changes greater if measured within the regions of mass change	High-temperature devices needed for geothermal field operation, resolution may be insufficient for EGS.
	Microseismic (passive) survey	Potential	x	x		Provides real-time information on hydraulic and geomechanical processes taking place within the reservoir in the interwell region, remote from wellbores by implementing surface or subsurface geophones to monitor earth movement.	Technology with broad area of investigation that can provide provides high-quality, high resolution subsurface characterization data and can provide effects of subsurface injection on geologic processes.	Extensive data analysis required. Resolution may be insufficient for EGS,; not hardened fo downhole use.
	Magnetic survey	Potential	x			Measurements of the earth's magnetic field that are then mapped and used to determine subsurface geology.	Technically acceptable for site characterisation	

	Magnetotelluric survey	Potential	x			An electromagnetic method of determining structures below the earth's surface using electrical currents and the magnetic field.		Improvement potential for application in site characterisation
	Self-potential	Potential		x		Self-potential in geothermal systems measures currents induced in the subsurface because of the flow of fluids.		Not proven for imaging and mapping fractures
	Tiltmeter	Potential		x		Device able to measure extremely small changes in its rotation from horizontal.	The "tilt" measured by an array of tiltmeters emplaced over a stimulation allow delineation of inflation and fracturing caused by the stimulation.	Difficult to interpret in zones of multiple fractures.
	Synthetic aperture radar (SAR and InSAR)	Potential	x	x		A satellite-based technology in which radar waves are sent to the ground to detect surface deformation.	Large-scale monitoring (100 km x 100 km).	Best used in environments with minimal topography, minimal vegetation, and minimal land use. Only useful in time-lapse.