Project Acronym and Title:

M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas

RISK ASSESSMENT OF IMPACTS ON GROUNDWATER QUANTITY AND QUALITY

Authors and affiliation:
Ole Stig JACOBSEN, Anders Risbjerg JOHNSEN, Peter GRAVESEN,
Niels Hemmingsen SCHOVSBO

Geological Survey of Denmark and Greenland

E-mail of lead author:
osj@geus.dk

Project deliverable number: D8.1
Status: Definitive

Disclaimer

This report is part of a project that has received funding by the *European Union's Horizon 2020 research and innovation programme* under grant agreement number 640715.

The content of this report reflects only the authors' view. The *Innovation and Networks Executive Agency (INEA)* is not responsible for any use that may be made of the information it contains.

Published November 2015 by M4ShaleGas Consortium

Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*.

The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts.

The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower CO_2 emissions and more renewable energy. Shale gas may contribute to this transformation.

Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency compared to other energy sources

There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement.

The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.

Executive Report Summary

Data from a variety of studies across many shale plays indicates that negative impacts and risks do exist with respect to shale gas development and freshwater resources. The impacts depend on management choices, incentives to engage in best practices, regulations, and oversight, and can be both exacerbated or substantially reduced by these same factors. Risks to water resources are also a function of the context in which unconventional activities take place.

Baseline data and monitoring is essential for understanding when impacts on the water from shale plays occur, and what it consist of. Both issues essential for understand the root causes.

From evidence available on the Marcellus Shale and other plays, water resource risks evolve and change over time as stakeholders adapt and respond to economic, technological, social, and political pressures. Therefore, it is difficult to say to what extent the risks and impacts experienced in the past will continue into future scenarios of a European context. Additionally, our current understanding of risks and impacts is biased towards the Marcellus and Barnet Shale, where a majority of peer reviewed studies have been focused and we may not be aware of new risks that are related with hitherto undeveloped shale plays.

Thus, our ability to extrapolate from examples from North America to other plays, regions, and countries is limited. Research conducted on other plays, within varying contexts and within different regulatory regimes, should help create a clearer picture of national trends and to help to be able to better predicted future scenarios and thus to mitigate the risks.

The current regulation of shale gas wastewater management, treatment, and disposal is inadequate because it fails to safeguard against foreseeable risks of harm to human health and to the environment. Government oversight of wastewater treatment and disposal must be improved at both the European Union level and in the individual states.

TABLE OF CONTENTS

Page

1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas source rocks are widely distributed around the world and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which makes close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as are present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for European publics to be fully engaged in the debate about its potential development.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and exploitation. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

---

[1] EIA (2015). Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

1.2 Study objectives for this report

The main objective of this report is to determine proper risk assessment procedures for impacts on groundwater quantity and quality with regards to EU Water Framework and Groundwater directives. This work package will address the environmental problems related to groundwater and surface water contamination and risk assessment methodologies, including geological models, coupled groundwater-surface water models and impacts on groundwater quality and finally the fate and transport of toxic potential contaminants. The research activities intend to close the knowledge gap on European-focused procedures for risk assessment.

1.3 Aims of this report

Review of data and existing best practices from Europe, U.S.A. and Canada of the environmental problems related to groundwater and surface water contamination. This report gives summary of the present knowledge on the environmental impact of shale exploration and production with special emphasis on groundwater and surface water.

2 UNCONVENTIONAL GAS AND THE ENVIRONMENT

Hydraulic fracturing is a term that refers to a stimulation technique and is not a technique that is used when a well is drilled. The drilling of a well and the completion of a well are two quite independent processes done at different time and, mainly, by two different contractors. Further, drilling fluids and fracking fluids are alike in composition and are not used at the same time at the well pad. Hence, it is quite important to use the proper terminology to describe the different stages and work process related to 1) the wellbore drilling, 2) the construction of the completion and subsequent stimulation, and 3) the actual production stage. Stimulation the rock by inducing fractures (“Fracking”) is done to enhance the flow rates in low permeable reservoirs and has been done in many countries around the world notably in the United States since the late 1940s. The recent use of the terms is now mainly associated with the boom in fracking activities related to the shales gas and shale oil activities that took off in North America in the early 2000s.

When a well is correctly constructed, the near surface well string is separated from the groundwater layers by at least three layers of individually installed cement and steel casing. The cement is used in the wells from surface and down to several thousands of meters to bond the rock wall to the casing. This is done in order to isolated well from the surrounding rock thereby minimize or eliminate fluids-loss either direct to the formation or from up along the casing annulus.

In areas with tight gas or shale gas (unconventional reservoirs with low porosity and low permeability), fracture stimulation is typically done in a considerable depth of about 2000 – 5000 meters below the surface. In such areas the groundwater aquifers are in comparison at depths from 0 – 500 meters below surface. In such situations the depth separation between the base of the groundwater aquifer and the gas reservoir is an important flow barrier between the surface and the hydrocarbon reservoirs. With increasing depth in the Earth the fluids in reservoirs / aquifers increase in salinity. Below the fresh water aquifers the pore water is typical saline and in many basins in the world the deep aquifers below 500 meters depth contain high salinity brine (up to 35,000 ppm of Cl).
The temperature and pressure increase with greater depths. Average geothermal gradient of are between 25-35 degrees C/km and it is depth of about 3000-4000 meters that temperatures and pressures become high enough for the onset of hydrocarbon generation from labile organic matter. At depth of 4000-6000 m gas is generated from the organic matter stored in the rock. The geological history of a shale basin may include a phase of uplift and thus many shales are now present a shallower depth that when the hydrocarbons were generated.

In most basins there are at least 1500 meters of separation vertically, between the base of the freshwater aquifers. Most horizontal wells are drilled at depths of greater than 2000 meters in order to place the horizontal well in reservoirs containing oil and gas.

Once these horizontal wells are drilled, the multi-stage fracks that are used will unlikely generate fractures that propagate more than few 100 meters above the horizontal well bore. The pressure required to overcome the hydrostatic pressure at depths of 2000-4000 meters including the amount of fluid and proppant in the wellbore will simply exceed the capabilities of any operators pressure generator since these only can generate a manmade fracture of no more than few 100 meters fracture height; normally between 100-300 meter, max known 588 meter (Davis et al. 2012). Consequently, in most placed there will almost always be at least 1500 meters of rock separating the base of the freshwater aquifers with the manmade activities at the hydrocarbon bearing reservoirs. Production of non-conventional gas includes many process steps, all of which involves the possibility of contaminating the environment. The land surrounding the well pad (the abstraction site) and especially the groundwater and surface water (lake, rivers streams etc.) are the most obvious recipients. There will from the onset of drilling through completion and decommissioning be a potential risk of contamination of the environment. Therefore it is necessary to assess and monitor all kinds of pollution opportunities throughout the lifetime of any hydrocarbon abstraction site.

Below is listed some of the identified pollution risks in such process.

1. Establishment of a drilling comprises the construction of a fenced in areas of 2-5 ha size with all necessary technical equipment, including well pad, tanks and landfills for collecting drilling mud and cuttings, as well as water basin (tanks or open pits) for the flowback from the formations. The area must be hydraulically sealed of the surrounds in order to contain any spills. Drilling muds contain different additives needed in the drilling process. Drilling mud additives contain substances which are not compatible with the natural environment and must be kept safe. Spills or loss of drilling mud to the ground may be a risk factor. Cuttings from eth formation that has been drilled may not pose a major environmental issue, unless they contain heavy metals or radioactive substances. Since shales, however, contain varying amounts of both continuous monitoring of the composition is needed for design of proper handling and separation of the waste.
2. After the drilling is completed, the fracturing is performed from holes in the casing, through a special production liner or in an open-hole section. The induction of fractures of a tuned length of shale-formation is thus commenced. Some fractures will extend further than the shale-formation and thereby connect to other over- or underlying formations. Fracturing may be performed with fracking fluids under high pressure and contain a proppant (sand or ceramic balls) together with auxiliary chemicals (1-2 % on weight basis). The handling of the fracking fluid, which volumetric can be quite large, may result in losses to the surrounding environment. By the fracking procedure fracking fluid will open fractures in eth formation and deposit the proppant to keep the fractures open to enhance the flow capacity of the hydrocarbons from the formation and to the well bore. After end of the fracturing the fluid is pumped back to the surface to clean up the well. This water is termed the flowback water. Usually the flowback during the first 10 days amounts to 25- 50% of the total pumped

volume. The flowback water will be contained in open pits or in closed tanks. Since fracking takes place in great depth (2000 - 5000 meters) the temperature will be correspondingly high (typically 60 - 130° C) and at the same time under a high pressure that overcome the lithostatic pressure. This means that substances such as released metals or dissolved salts from the formation may be bought up with the flowback water. This also applies trapped gases. Significant volumes flowback water with dissolved matter and suspended solids shall be handled at the drill site. In some cases the flowback water heavy metals and radioactive substances that have been leached from the formation. In addition to this radioactive gases (radon) may be dissolved in the flowback water.

3. During the first production period of a shale gas well, which is 2-5 years, Pennsylvania State University 2014, a production of formation water with a minor part of flowback water which did not return during the first days, will be discharged at the well site. Produced water may still contain fracking chemicals and their degradation products and additional substances dissolved from the formation. The water produced therefore also requires a treatment particularly when it is almost always contain large amounts of salt, which may make cleaning difficult. Because of the potential for corrosion in the casing it may, at worst, get leakages that may cause gas (methane and radon) out of the formations of the production layer, and most disadvantageous in groundwater.
4. When gas field is fully utilized or not economical fishable the installations must be dismantled (decommissioned) to ensure that no further contamination of groundwater as well as surface water will occur.

3 THE POSSIBLE SOURCES OF CONTAMINATION OF GROUNDWATER AND SURFACE WATER

As already mentioned will large amounts of drilling mud be handled containing different additives and their degradation products and dissolved gases or suspended particles coming from the formations during the drilling site. First of all, the drilling mud with very high content of suspended material. It is known that loss of drilling mud may occur while drilling into the porous material and can thereby contaminate them. By the fracking process fracking fluids used containing a large number of additives which will penetrates into the shale formation. The US-report (United States house of representatives, 2011) shows a list of more than 500 different substances, which have been used for fracking additives over time. From the Polish bores is a corresponding list in form of factsheets, NGS-factsheets, which, however is somewhat reduced relative to the US list. Fracking fluid is squeezed into shale formation with high pressure; where after the return pumping only recovers about 25-50 % backflow immediately after the fracking. Part of the remaining volume will be back in the shale formation and will return slowly during the production of shale-gas from the formation. The water produced throughout the production period must consequently be treated to a level of emission requirement.

All these fluids must be handled at the well pad, which is a challenge with respect to the separation of solids and liquids and cleaning fluids to a level that permits release to recipients.

Handling of cuttings from drilling operations may involve problems with leaching of various substances such as inorganic salts, trace metals and radioactive substances. The same is true of the suspended material in the produced water.

Gas produced in the shale formation can under unfortunate circumstances escape to the overlying layers and may later diffuse upward to the groundwater bodies. Further, leaks caused by natural fractures or corrosion in production installations may cause gas contamination in the aquifers. It can thus be both methane as well as radon.

3.1 Drilling mud

The mud is pumped during the drilling and circulated down to the drill bit where it partly cools and lubricate the bore hole. Furthermore, it partly compensates for the lithostatic pressure that arises in connection with the drilling to prevent blowouts and partly bring drill cuttings to the surface (King 2012). The terminology and classification of the drilling mud is not clear-cut but in general divided into two classes, the water-based (hydrophilic) and the oil-based (hydrophobic). Most often the water-based drilling mud is used near the surface, while oil-based muds are used when water based muds are not enough to control the instability of the formation, for example, because of the swollen clay (King 2012).

The drilling mud contains water and a large range of chemical substances. For most of these, it applies that they are only used in the drilling mud for example bentonite and barium sulfate, used to control the density of the mud.

3.2 Fracking liquids

The current practice for hydraulic fracturing treatments of shale gas reservoirs is to apply a sequenced pumping event in which large volumes of water-based fracturing fluids mixed with proppant materials and thickening agents which are pumped in a controlled and monitored manner into the target shale formation above fracture pressure. The fracturing fluids used for shale fracturing consist primarily of water but also include a number of additives. The number of chemical additives used in a typical fracture treatment varies depending on the conditions of the specific shale formation being fractured. A typical fracture treatment will use very low concentrations of between 3 and 12 groups of chemicals depending on the characteristics of the water and the shale formation being fractured. Each group has a specific, geo-engineered purpose.

Table 1. Chemical groups used in fracking liquids (cited from FracFocus http://www.fracfocus.org/chemical-use).

Proppant	“Props” open fractures and allows gas / fluids to flow more freely to the well bore. Sand [Sintered bauxite; zirconium oxide; ceramic beads]
Acid	Cleans up perforation intervals of cement and drilling mud prior to fracturing fluid injection, and provides accessible path to formation. Hydrochloric acid (HCl, 3% to 28%) or muriatic acid
Breaker	Reduces the viscosity of the fluid in order to release proppant into fractures and enhance the recovery of the fracturing fluid. Peroxydisulfates
Bactericide / Biocide	Inhibits growth of organisms that could produce gases (particularly hydrogen sulfide) that could contaminate methane gas. Also prevents the growth of bacteria which can reduce the ability of the fluid to carry proppant into the fractures. Glutaraldehyde; 2-Bromo-2-nitro-1,2-propanediol
Buffer / pH Adjusting	Adjusts and controls the pH of the fluid in order to maximize the effectiveness of other additives such as crosslinkers. Sodium or potassium carbonate; acetic acid
Clay Stabilizer / Control	Prevents swelling and migration of formation clays which could block pore spaces thereby reducing permeability. Salts e.g., tetramethyl ammonium chloride, Potassium chloride
Corrosion Inhibitor	Reduces rust formation on steel tubing, well casings, tools, and tanks (used only in fracturing fluids that contain acid). Methanol; ammonium bisulfate for Oxygen Scavengers
Crosslinker	The fluid viscosity is increased using phosphate esters combined with metals. The metals are referred to as crosslinking agents. The increased fracturing fluid viscosity allows the fluid to carry more proppant into the fractures. Potassium hydroxide; borate salts
Friction Reducer	Allows fracture fluids to be injected at optimum rates and pressures by minimizing friction. Sodium acrylate-acrylamide copolymer; polyacrylamide (PAM); petroleum distillates
Gelling Agent	Increases fracturing fluid viscosity, allowing the fluid to carry more proppant into the fractures. Guar gum; petroleum distillate
Iron Control	Prevents the precipitation of carbonates and sulfates (calcium carbonate, calcium sulfate, barium sulfate) which could plug off the formation. Ammonium chloride; ethylene glycol; polyacrylate
Solvent	Additive which is soluble in oil, water & acid-based treatment fluids which is used to control the wettability of contact surfaces or to prevent or break emulsions. Various aromatic hydrocarbons
Surfactant	Reduces fracturing fluid surface tension thereby aiding fluid recovery. Methanol; isopropanol; ethoxylated alcohol

The predominant fluids currently being used for fracture treatments in the gas shale plays are water-based fracturing fluids mixed with friction-reducing additives (slick water). The addition of friction reducers allows fracturing fluids and proppant to be pumped into the target zone at a higher rate and reduced pressure than if water alone were used.

Besides the friction reducers, the fracking fluids contains biocides to prevent microorganism growth and to reduce biofouling of the fractures To avoid corrosion of metal pipes oxygen scavengers and other stabilizers are used and acids that are used to remove drilling mud damage within the near-wellbore area. These fluids mixture are used not only to create the fractures in the formation but also to carry a propping agent as silica sand, ceramic balls or sintered bauxite, which is deposited in the induced fractures.

The composition of fracking fluids varies from well pad with one geological formation to another. Evaluating the relative volumes of the components of a fracturing fluid reveals the relatively small volume of additives that are present. Overall the concentration of additives in most slick water fracking fluids is a relatively consistent 0.5% to 2% with water making up 98% to 99.5%. In classifying fracking fluids and their additives it is important to realize that service companies that provide these additives have developed a number of compounds with similar functional properties to be used for the same purpose in different well environments. The difference between additive formulations may be as small as a change in concentration of a specific compound. It is not uncommon for some fracturing recipes to omit some compound categories if their properties are not required for the specific application. For each frack, 80-300 tons of chemicals may be used, selected from a menu of up to 600 chemicals. Though the composition of most fracking chemicals in USA remains protected from disclosure through various trade exemptions under state or federal law, scientists analyzing fracked fluid have identified volatile organic compounds such as benzene, toluene, ethylbenzene and xylene.

3.3 Biocides

The U.S. Environmental Protection Agency requires publication of chemical lists, which are available at several Web sites. However, the exact chemical details of the hydraulic fracturing mixture are poorly described, as it has proprietary value between various oil and gas chemical-supply companies. A common feature, though, of these lists is the use of nonionic, ethoxylated surfactants, which are used to control the viscosity of the fracturing fluids, reduce surface tension, and assist fluid recovery. They are listed generically as ethoxylated glycols and alcohol ethoxylates. Thus, these compounds are possible “fingerprinting” tracers of hydraulic fracturing fluids. Two series of ethylene oxide surfactants, polyethylene glycols and linear alkyl ethoxylates, were identified in hydraulic fracturing flowback and produced water using a new analytical method (Thurman et al. 2014).

Another problem, that is very generally but not treated much until yet, is that fracking additives are introduced to high pressure and temperatures (70 - 140 °C), which induce a conversion or partially decomposition of the compounds. This may result in a large

and unknown number of chemical compounds which are normally not included in any monitoring of flowback or produced water.
European Commission by the Joint Research Centre released a report in 2013 (EU, 2013) on the use of fracking fluid additives/ products in Europe based on REACH, the EU chemical legislation from 2007. This report identified DG Environment based on USEPA's work the 16 most common used additives which fulfilled the REACH registration on chemical substances that could be used to shale gas exploitation in Europe.

Table 2. Sixteen hydraulic fracturing chemicals with potential application in Europe (cited from EU, 2013).

Names	**CAS #**
Boric acid	10043-35-3
2-ethylhexane-1-ol	104-76-7
Ethylene glycol	107-21-1
Glutaraldehyde	111-30-8
Ethylene glycol monobutyl ether	111-76-2
Sodium hydroxide	1310-73-2
Acetic acid	64-19-7
Distillates (petroleum), hydrotreated light naphtenic	64742-47-8
Distillates (petroleum), hydrotreated heavy naphtenic	64742-48-9
Residual oils (petroleum), hydrotreated	64742-57-0
Methanol	67-56-1
Isopropyl alcohol	67-63-0
Hydrochloric acid	7647-01-0
Ammonium sulphate	7783-20-2
Citric acid	77-92-9
Acrylamide	79-06-1

3.4 Formation water and backflow

Highly saline brines occupy pore spaces in sedimentary rocks at depth throughout western Pennsylvania. Brines are likely to be present at depth in other parts of the state, in view of the apparently stable gravity-stratification that has allowed brines to persist since Paleozoic time. The composition of brines in other parts of the state remains to be determined. The properties of these brines are important to a wide variety of questions, including some that pertain to oil and gas exploration and production, water pollution, deep waste disposal, cementation of sedimentary rocks, and the genesis of ore deposits. The content of Na, Ca, Mg, Br, and total dissolved solids, and the density and electrical conductivity are closely correlated in these brines and can be predicted from the knowledge of any one of these constituents. Sulfate and carbonate contents are generally low but somewhat variable. Contents of barium and strontium are limited by the solubility of sulfates and carbonates but can be relatively high, so that admixture of even small amounts of the brine with near-surface freshwater can produce barium levels above current limits established by the U.S. Environmental Protection Agency for drinking water.

The level of radium in brines and in brine-holding tanks deserves further investigation in view of possible radiation hazards. Iron content in the brines appears to be largely a function of corrosion of steel in the oil and gas wells. The oxidation of this iron is responsible for very acid pH values previously measured. The brines appear to have formed mainly by dilution of highly evaporated seawater with freshwater, possibly during migration of the highly evaporated seawater away from the salt beds that were its source. Slightly different parent brines are suggested for different areas and reservoir rocks, and the dissolution of halite beds could have contributed to the formation of some brines.

Table 3. Typical range of concentrations for some common constituents of flowback water from natural gas development in the Marcellus shale. (data cited from Gregory et al. 2011).

Constituent	**Early flowback**	**Late flowback**	**Highest concentrations**
	mg/L	mg/L	mg/L
Total dissolved solids*	66,000	150,000	261,000
Total suspended solids	27	380	3200
Hardness (as CaCO3)	9100	29,000	55,000
Alkalinity (as CaCO3)	200	200	1100
Chloride	32	76,000	148,000
Sulfate	ND5	7	500
Sodium	18	33,000	44,000
Calcium, total4	3000	9800	31,000
Strontium, total	1400	2100	6800
Barium, total	2300	3300	4700
Bromide	720	1200	1600
Iron, total	25	48	55
Manganese, total	3	7	7
Oil and grease	10	18	260

* *Total concentration = dissolved phase + suspended solid phase concentrations.*

The geochemical composition in the formation water Danish has been characterized in studies related to deep geothermal wells. The salinity of formation water in Denmark is known to increase in an approximate linearly manner with depth, which is typical of sedimentary basins. Chloride concentrations, which is used as a proxi of the total salt content, thus increase from about 0.7M (sea water) in the upper sedimentary sequence to about 5 M at a depth of 3000 m (Laier, 1989). There are at the moment no measurements of formation water from the Alum Shale Formation, but a probable composition of the salt content may be estimated from previous deep drillings of the Alum Shale and by reference to other deep wells (Schovsbo, 2012a; Laier, 2008; Table 4).

Table 4. Chemical composition of formation water from deep onshore wells in Denmark (data cited from Laier, 2008).

Element (g/L)	**Cl^-**	**Na^+**	**Ca^{++}**	**Mg^{++}**	**K^+**	**Br^-**	**Sr^{++}**
Variation	102-197	54-96	6-45	1-4	0.25-1.9	0.29-1.39	0.6-1.01
Mean	148	68	21	2.3	1.2	0.75	0.73

Element (g/L)	**B***	**Ba^{++}**	**Zn^{++}**	**I^-**	**Li^+**	**As***
Variation	0.035-0.040	0.005-0.06	0.001-0.065	0.006-0.015	0.001-0.022	<0.001
Mean	0.038	0.021	0.019	0.012	0.010	<0.001

** Different chemical forms.*

Salt in the waste water from shale gas extracting are expected to be a significant problem that must be handled by the unconventional shale gas operators. In Denmark discharge of highly saline waters to marine recipients is well known, since there have been leached large amounts of Zechstein salt deposits by flushing to create deep caverns used for storage of natural gas. The high salt content of flowback will affect the choice of treatment technology as both biological and chemical treatment plants are very sensitive to both elevated salt concentrations and to fluctuations in the salt concentration. The process of ultrafiltration or evaporation of eth flow back water will lead to greater amounts of precipitated salt and to highly concentrated brine, which must then be handled as waste. Oxidizing agents and to a lesser extent acid added with the fracking fluid would increase the trace element concentrations in the flowback water. Since many metals in shale gas shales are bound in reduced sulfur components such as pyrite (Fe_2S) it can be released to flowback water from the pyrite oxidation reaction and thus lowering the pH of the solution (Gaucher et al, 2014). Not all metals will be affected from such reactions. Barite ($BaSO_4$) is thus not sensitive to lower pH and oxidizing chemicals (Gaucher et al, 2014).

The composition of the hydrocarbons from shales is expected to vary widely from basin to basin and from shale to shale. The hydrocarbon present in the shale reflects the thermal maturation of the shale and the type of organic carbon present in the shale. Strongly elevated concentrations of oil substances are reported in the wastewater from some American shale gas wells (e.g. Maguire Boyle and Barron, 2014). This is a consequent of American shales often have considerable oil content in the form of gas condensate or actual shale oil which reflect that the shales are in the oil to early wet gas maturity rank . In other shales such as the Scandinavian Alum Shales in the hydrocarbon composition is expected to be dry gas only and thus mainly methane (CH_4) with smaller amounts of ethane and propane. This is related to much higher burial depth and thus higher maturity where the generated oil are cracked to gas (Gautier et al. , 2013). This means that the oil content substance in the formation water is expected to be low. Shales in other basins such as in Poland have a much wider range in thermal maturities and thus both dry gas and condensate is expected to be produced from wells here.

3.5 Shales

An example of the composition of a North American shale is the Pierre Shale in North America and similar shales of Late Cretaceous age in the east-central Dakotas consist of up 100 m thick offshore marine shale with minor marl intercalations; in west-central Montana near the depositional center equivalents shales are several hundred meter thick and consist of volcanic-rich and mostly non-marine sediments. The element composition was determined for 226 shale samples, and the mineralogical composition was determined for 1,350 samples.
The average clay-mineral fraction was found as follows: mixed-layer illite-smectite, 70; illite, 16; chlorite, 3; and kaolinite, 9. The mixed-layer clay, except in the west-central Montana, is a random interlayering of 20 to 60 percent illite-type layers, about 35 percent beidelite-type layers, and the remainder montmorillonite-type layers; chlorite or vermiculite layers are rare.

Table 5. The major and minor elements in shale and siltstone of the Pierre Shale. Data show arithmetic mean and SD, from Schultz et al. 1980.

Element	**%**	**SD**
SiO_2	60.8	7.9
Al_2O_3	14.4	2.5
Fe_2O_3	3.4	1.4
FeO	1.1	1.2
MgO	2.2	1.0
CaO	2.7	0.48
Na_2O	1.1	0.56
K_2O	2.4	0.57
H_2O-	3.2	1.3
H_2O+	4.3	1.2
TiO_2	0.58	0.12
P_2O_5	0.14	0.073
S	0.37	1.1
F	0.71	0.15
Cl	0.16	0.024
CO_2	2.1	7.0
C, organic	0.94	1.8

As an example of European potential shale gas shale is the Scandinavian Alum Shale. The shale have on average approximately 50% clay minerals, 30% quartz (SiO2), feldspar 10% and about 10% pyrite (FeS_2) and small amounts of carbonate (Pedersen 1989, Schovsbo 2012b). Clay minerals consist primarily of illite with small amounts tobelite and a very small content of smectite (Lindgreen et al. 2000). In the Terne-1 well, drilled in the Kattegat area and where the thickest development of the Alum Shale is observed (180 m thick), the average amount of carbon in the Alum Shale is 6.0%. In the 66 m thick Furongian part of the Alum Shale the average content of carbon is 8.7%.

The Alum Shale is enriched in a variety of trace metals. This enrichment is due to the deposition environment in which there was very little or no oxygen present on the seabed and many of the trace elements are bonded to the organic material or reduced sulfur compounds such as pyrite. In the Alum shale this is particularly true with in respect of uranium (Schovsbo 2002) although it may vary within the potentially prospective shale areas in subsurface of Denmark, Sweden and Poland. The Alum Shale has compared to other organic rich shales large uranium enrichments (Buchardt et al. 1997). Uranium content of Alum shale varies both vertically and regionally, and the largest uranium content found in South Sweden (Schovsbo 2002), where the uranium content of the shale reaches values of 200 to 500 mg / kg.

The Alum Shale is naturally enriched in organic matter, reduced sulfur compounds, and transition metals. It is therefore expected that suspended shale particles in the back flow water will have an average composition as indicated in Table 6. Additionally, it will contain trace amounts of other metals such as Ce, Cr, Cs, Ga, La, Nb, Nd, Pb, Rb, Sc, Sr, Sc, Th, Y, and Zr (Buchardt et al. 1997, GEUS, unpublished data), probably in the concentration range 5-50 mg / kg

Table 6. The content of various trace metals in the Scandinavian Alum Shale. Kattegat (Terne-1 well, data cited from Schovsbo 2012a), Oslo area (data cited from Gautneb & Sæther 2009), Scania (Gislövshammar-2 well, data cited from Buchardt et al. 1997), Bornholm (Billegrav-2 well, data cited from Schovsbo 2012b).

Element	**Unit**	**Kattegat**			**Oslo area**			**Scania**	**Bornholm**		
		Average	Max.	Min.	Average	Max.	Min.	Average	Average	Max.	Min.
Th	mg/kg	12	19	8					13	15	12
Ba	mg/kg				1929	42750	0	2833	2767	9322	443
Cd	mg/kg	8	36	1					26	225	0,6
Co	mg/kg	17	35	10				30	29	35	22
Cu	mg/kg	127	211	54	99	833	10	140	193	256	153
Pb	mg/kg	50	238	17				38	42	139	19
Mo	mg/kg	58	128	9	154	425	15	103	115	260	46
Ni	mg/kg	90	149	39	133	565	35	174	175	400	69
U	mg/kg	35	81	9	37	126	4	59	54	90	26
V	mg/kg	954	2574	277	950	4150	50	1369	946	2200	318
Zn	mg/kg	315	1280	37	102	999	12	163	1293	10975	31

Radium found in Bornholm Billegrav showed 51, 104 and 118 mg/kg.

4 RADIOACTIVE COMPONENTS

4.1 SHALES

All shales contain radioactive elements or minerals and during the drilling process, the radioactive content from the shales will be brought to the surface. It is mainly uranium (U-288) and thorium (Th-232), their decay product of radium (Ra-226 and Ra-228); radon (Rn-222, inert gas), which is the decay of radium, and radon decay products called radon daughters (Po-218, Pb-214, Bi-214, Po-214), which all is solids. However, there are only few data from different shales in connection to shale gas exploitations. Activities relating to monitoring, treatment and disposal and any problems with waste from the wells must be assessed.

The rock-cuttings and drilling mud contains fragments of the fixed shale, which contains the original radioactive substances: Uranium and thorium are bound in the mineralogical phases or together with the organic substances and radium is bound on the surface of clay minerals. The elements are present in the formation fluid within the pore system. From drilling the material is brought to the earth surface, and in rare cases it may happen that the radioactive content increases, so that the cuttings contains more radioactive material than the solid rock. The shale gas operator will ensure that the rock-cuttings are separated as much as possible from the drilling mud at the drill site, and that the radioactivity is measured continuously for monitoring purposes.

The Alum Shale content of radioactive components is comparable with the contents that for example in observed in the Marcellus shale ,up to 84 mg / kg uranium, average 34 mg / kg, Hand & Banikowski 1988, which produced gas from thousands of wells in the eastern United States (Rahm et al. 2013). Uranium and thorium are bound in the Alum Shale minerals and on the surfaces of the minerals surrounding the pore spaces are immobile under the reducing conditions prevailing in the shale, while the radium is mobile from the mineral surfaces and in the pore water, Fisher 1998. The variation in geology and the shale formation determines the radioactive effluents level from location to location. Drill cores of the original formation are sampled as intact and undisturbed as possible. They are used mainly for scientific studies and are not as much waste as possible. The radioactive contents are being investigated in the selection and drill core containment in relation to the measured content.

4.2 Formation water

Formation water is the formation of the original water content (connate water). Switchers’ porosity is about 5-10% and it is estimated that 10-80% of the pores are filled with liquid. The formation water can be extremely saline (hypersaline brine), and the radioactivity reflects the natural, salts formation water. A small part of the formation water can keep up with the drilling mud from the well, and it may contain dissolved radioactive materials radium and radon. The upward movement of formation water containing radioactive components can take place through the overlying rock or through cracks and faults in the rock, which can cause, inter alia, dissolved radium and radon brought against aquifers (Flewelling & Sharma, 2014).

4.3 Flowback water

Flowback water of water and formation water (brines) is collectively referred to as wastewater. Because the hydraulic fracturing is done under high pressure, a proportion of the injected water returns to the ground along with the original formation water. It is uncertain how much of that is talking about, maybe about 50%, but many different values from play to play (e.g. 10-80%). Flowback water often contain high concentrations of totally dissolved substances (TDS), heavy metals, suspended solids, sand and dissolved radioactive material released from the formation (Zhang, 2015). Flowback water and formation water contains mainly dissolved radium, sometimes small amounts of the otherwise immobile uranium and radon, if for example oxidizing chemicals is applied. Studies have shown that the content of radium may be close to 0, but in other cases it may exceed the content of the original rock significantly (Kargbo et al. 2010). Haluszczak et al. (2013) demonstrated values as high as 6540 pCi / L, while Rowan et al. 2011, measured concentrations of 5490 pCi /L. Radium values from Alum Shale from Bornholm is 51-118 mg / kg (Damkjær & Korsbech 1985), which is the highest values measured in Danish sediments and rocks. Radon, which follows flowback water to the surface, can be expected to disappear into the atmosphere. Both radium and radon should be monitored and measured according to IAEA (2003).

4.4 Produced water

The produced water is collected in pools (with plastic liner), reinjected near the wellpad or stored in containers, but sometimes parts or all is recycled in the process after a cleaning. Uranium content is expected to be modest and radon decays quickly and usually disappear into the atmosphere. Radium that is dissolved in the water, must on the other hand - as mentioned above - expected to be present in greater concentrations (Haluszczak et al. 2013). There are various methods for determining the radium content of flow-back water (Zhang et al. 2015). Likewise, it is possible to separate radium from sewage by sulfate precipitation from the liquid (Warner et al. 2013). The precipitated radium sulfate can be collected, but is still radioactive and must be treated as possible radioactive waste (Gaucher et al. 2014). Treatment is either close to the drill site or on established treatment plants far away. The radium problem is addressed primarily in those countries that produce shale gas, with special attention on toxicity and radiation hazard to humans and the environment (Almond et al. 2014, Rowan et al. 2011).

4.5 Produced gas

The produced gas can contain radon gas from shale rock, and will follow the brine from the formation (Rowan & Kraemer 2012). Leaks in the drilling installations, e.g. drilling stop (wellhead) and installations can let gas and radon leak out into the surrounding area i.e. on the wellpad, where radon quickly disappear into the surrounding atmosphere. About this affects the environment is questionable, but the gas that is sent to the consumer, have come more and more into focus. For example, in the United States increased attention on radon gas causes a population risk to be investigated and assessed (Rowan & Kraemer 2012, Burkhart et al 2013). During storage, treatment and transport of wastewater is a risk of spills and leakage from tanks and water-sludge basins, as well as from leaks by drilling can seep material out and reach the aquatic environment (EPA 2012). With a monitoring program it will be possible to detect any elevated levels of radioactive substances in groundwater. In order to determine whether groundwater is affected, it is important to perform monitoring about a possible wellpad before drilling to be initiated (European Commission, 2014).

4.6 Scales and precipitates

In the case of an established gas production plant, this may result in an extensive deposits (scales) in the installations (tubing, pumps, valves etc.) and sometimes also on the outside. The precipitations may contain radioactive substances, especially radium and lead compounds (sulphate and carbonate) (Hilal et al. 2014). This is also known from the conventional oil and gas production with patchy deposits with high radium values of 0.2 - 27 µCi / kg (Kolb & Wojcik 1985).

4.7 Waste

The radioactivity in the waste material from the drilling, flowback water, etc. has to be examined regularly during the drilling process to determine the waste fate. If concentrations are above exception concentrations, the substances stored according to specific rules. Radioactive materials of exceptional concentrations described as NORM: Natural occurring Radioactive Materials or sometimes as TENORM: Technology Enhanced Naturally Occurring Radioactive Materials. If the materials are classified as NORM, determined by measurement during and after drilling, NORM has to be temporarily stored at the drill site, then either packaged or transported for treatment. Finally, the waste is sent to a terminal depot.

5 KNOWLEDGE FROM USA

There have been confirmed cases of groundwater contamination from improperly constructed gas wells, Cooley et al. 2012. To protect groundwater, proper well design, construction, and monitoring are essential. During well construction, multiple layers of telescoping pipe (or casing) are installed and cemented in place, with the intent to create impermeable barriers between the inside of the well and the surrounding rock, (Groundwater Protection Council, 2009). It is also common practice to pressure test the cement seal between the casing and rock or otherwise examine the integrity of wells. Wells that extend through a rock formation that contains high-pressure gas require special care in stabilizing the well bore and stabilizing the cement or its integrity can be damaged. As with any mechanical device or barrier, failures can occur. There is significant variability in the estimated failure rates of the integrity of oil and gas wells, (Davis et al 2013, 2014). Local regulations, the technology, the geologic setting and the prevailing operational culture influence the well completion, abandonment and monitoring, and these evolve over time. Differences in the type and sizes of well integrity datasets add to the challenge of generalizing well integrity failure rates.

5.1 Kansas

The physical separation between the relatively shallow freshwater aquifer and the typically much deeper gas-producing shale layer provides protection to shallow aquifers. Typically there are several hundred meters of mostly low- to very low-permeability rock layers between an aquifer and gas reservoir rocks that prevent fracturing fluids and naturally migrated hydrocarbons from reaching the aquifer. In areas where there is concern about faults, fractures, or plugged wells, various geophysical methods can be used to locate and avoid faults, (Suchy, 2013), although such surveys are time consuming and expensive. There is also renewed interest in the need to locate and plug abandoned oil and gas wells, and unused water wells, as a further measure to protect near-surface aquifers. It will also be evident to develop technologies to monitor deep groundwater, (Alley, 2013). Proper storage and disposal of fracturing fluids and produced water is important to ensure that both surface water and groundwater are protected. Most fracturing fluids and produced water are re-injected into Class II wells, (US-EPA 2012), drilled specifically for deep disposal, treated in wastewater treatment facilities, or recycled, (Osborne, 2011). Wastewater treatment facilities, designed primarily for municipal waste, can be overwhelmed with the volume and treatment of fracturing fluids and produced water; a number will not accept such waste, (Maloney 2012).

5.2 Eastern United States; Marcellus Shale

Flowback water from later stage flowback from Marcellus wells contains very high concentrations of TDS, Cl, Br, Na, Ca, Sr, Ba, Ra and other elements, (Haluszczak 2013). The levels of TDS, Cl and some other constituents can be 5–10 times the concentration in seawater. The chemistry of the later flowback water is similar to brines produced from conventional oil and gas wells tapping permeable host formations ranging in age from Ordovician to Devonian. Further, Cl–Br relations indicate that the late flowback waters developed from highly saline brine evaporated from seawater into the stage of halite precipitation, and then diluted and mixed with seawater, freshwater and injected fluids. The late stage flowback contains concentrations of ^{226}Ra, ^{228}Ra, Ba and other constituents far higher than drinking water limits. Therefore, improper disposal of the flowback can lead to unsafe levels of these and other constituents in water, biota and sediment from wells and streams. The high salinity and toxicity of these waters must be a key criterion in the technology for disposal of both the flowback waters and the continuing outflow of produced waters.

The Uranium concentrations in the brines are low. The low concentrations, despite relatively high U in the Marcellus black shale, are evidently due to the reducing nature of the pore water, and the resulting very low solubility of U. However, Ra and its daughters diffuse out of their host and into the SO_4-poor brine. The drinking water limit for Ba is 2 mg/L (US EPA, 2011b). Concentrations of Ba in the late stage flowback are commonly thousands of mg/L. Barium is another potentially toxic constituent in the Marcellus brines, along with Br and other solutes. Because of the low porosity of the Marcellus shale, the source of the brine deserves consideration. The brine clearly is derived from the zone of completion and fracturing in and adjacent to the Marcellus. It seems possible that brine is derived from a combination of pore space in the Marcellus plus fractures in the Marcellus and fractures and porosity in the adjacent formations.

5.3 Texas

The biggest concern for many is the water that pressurizes the well during fracking, (Kerr 2010). The process takes 12 million to 16 million liters of water per well. Supplying such amounts can be a challenge in dry regions, but the larger problem is often what to do with it after fracking, when most of it comes back up the well. To improve performance, drillers may add as many as a dozen chemicals up to about 2% by volume, such as biocides to keep down corrosive bacteria. The fracking fluid also picks up naturally occurring chemicals, primarily salts from deep brines. Drillers inject the wastewater into deep wells, treat and release it, or recycle it, but spills do occur. The Dimock area had a series of them in 2009, for example. And the 3 June blowout in Pennsylvania spewed drilling fluid, brine, and gas into a forest for 16 hours (without igniting). Shale gas extraction can have other drawbacks. A drill site covering 2 hectares turns into a heavy industrial zone, even if it’s in the suburban Fort Worth part of the Barnett Shale in Texas. More than 100 big water tanker trucks might have to come and go for each of 20 or more wells at a site. Although drillers can drain more than 500 hectares from a single site, “it still makes quite a mess,” says analyst Richard Smead of Navigant Consulting Inc. in Houston, Texas. In response to the upsurge in shale gas drilling, the Pennsylvania Legislature is moving to strengthen pertinent regulations. New York State has greatly tightened licensing requirements on drilling in about 10% of the Marcellus in the state, effectively ruling out drilling in a prime source of New York City drinking water.

Groundwater contamination has focused primarily on the compositional analysis of dissolved gases to address whether fracking activities have had deleterious effects on overlying aquifers. However, analysis of 550 groundwater samples collected from private and public supply water wells drawing from aquifers overlying the Barnett shale formation of Texas, (Hildenbrand 2015). The analytical results showed multiple volatile organic carbon compounds throughout the region, including various alcohols, the BTEX family of compounds, and several chlorinated compounds. These data did not necessarily identify fracking activities as the source of contamination; however, they may provide a strong impetus for further monitoring and analysis of groundwater quality in this region as many of the compounds we detected are known to be associated with fracking techniques.

5.4 Colorado

Furthermore, the State of Colorado, with over 7500 natural gas wells drilled for hydraulic fracturing since 2005, requires the publication of the hydraulic fracturing mixtures for each well.

An analysis of reported surface spills (Colorado Oil and Gas Conservation Commission, COGCC) within Weld County (Denver-Julesburg) and groundwater monitoring data associated with each spill revealed BTEX (benzene, toluene, ethylbenzene, xylene) contamination of groundwater. During a one-year period the authors noted 77 reported surface spills impacting groundwater; 62 of these records included BTEX analytical sampling during remediation. A large percent of samples show BTEX concentrations in excess of federal standards. Another study of surface and groundwater samples from drilling-dense areas in the Piceance basin showed higher estrogenic, anti-estrogenic, or anti-androgenic activities near oil and gas activity relative to reference sites with little or no natural gas development.

In Colorado, there have been 846 spills of which more than 70% was outside the wellpad (pers. com. T. Borch, Colorado State University). In 2013 very heavy rain caused a great flood in Colorado. Quite a lot wellpads was flooded by the occasion and damage and contamination was inevitable at the gas installations.

Because of the federal legislation accidents and spills must only be reported to authorities if the spill is greater than one barrel (132 liters).

In Colorado (2013) 33% of the flowback water was treated and recycled, while 30% were directly recycled. About 26% were re-injected into wells and 6% were brought to a landfill and only 3% were discharged to a local wastewater plant. However, it is known that illegal discharges directly into streams and rivers have occurred.

5.5 California

The problems with California's underground injection control program are far worse than originally reported (Freyman 2014). It has now been revealed that California regulators with DOGGR permitted hundreds of wastewater injection wells and thousands more wells injecting fluids for “enhanced oil recovery” into aquifers protected under the federal Safe Drinking Water Act. After California state regulators shut down 11 fracking wastewater injection wells over concerns that the wastewater might have contaminated aquifers used for drinking water and farm irrigation, the EPA ordered a report. It was revealed that the California State Water Resources Board has sent a letter to the EPA confirming that at least nine of those sites were in fact dumping waste water contaminated with fracking fluids and other pollutants into aquifers protected by state law and the federal Safe Drinking Water Act. The report showed that nearly 13 million m3 of wastewater were illegally injected into central California aquifers and that half of the water samples collected at the 8 water supply wells tested near the injection sites have high levels of dangerous chemicals such as arsenic and thallium. The fact that high concentrations are showing up in multiple water wells close to wastewater injection sites raises major concerns about the health and safety of nearby residents. The full extent of the contamination is not yet known.

Fracking has been accused of increase California's state-wide drought. In Central Valley region thousands cubic meters of fracking wastewater may have contaminated protected aquifers. Further, as fracking is a water-intensive process, using as much as 600 to 800 m^3 per fracking job every day, this volume will permanently be removed from the water cycle.

5.6 Review of contamination findings

An inventory of water consumption for seven shale formations in the United States ranged between 8,000 and 100,000 m^3 / well with an average of 15,000 m^3 / well (Vengosh et al, 2014). The most comprehensive, inventory is based on 45,000 wells in seven gas plays and shows an average consumption of 16,000 m^3 / well (Kondash and Vengosh, 2015).

Duke University concludes that there is a link between methane gas content in groundwater, and the proximity of gas wells, in 141 readings, (Jackson et al. 2013). However this larger study (1701 readings) in the same area has shown that methane gas concentration is independent of proximity to gas wells, (Molovsky et al. 2013). Baseline studies also indicate that many wells are polluted with various contaminants, independent of hydraulic fracturing. There are several other studies that have been done that do not show correlation between hydraulically fractured shale gas wells and methane or other contamination.

A study from the US 'Proceedings of the National Academy of Sciences' 2014 released a report that indicated that methane contamination can be correlated to distance from a well in wells that were known to leak. This however was not caused by the hydraulic fracturing process, but by poor cementation of casings. Later, Yale University released a report, 2015, that found no evidence that trace contamination of organic compounds in drinking water wells near the Marcellus Shale in northeastern Pennsylvania came from deep hydraulic fracturing shale horizons, underground storage tanks, well casing failures, or surface waste containment ponds. In March 2015, a study of methane contamination compared to distance from wells was carried out in N E Pennsylvania. With a large data set, it concluded that there was no link between the two, Siegel et al 2015. This study was updated when it became public that the authors were funded by Chesapeake Energy Corporation.

The exact pathway of pollution is complicated by the fact that in many areas in the US, drilling has taken place since the 1860s, and Pennsylvania for example, has an estimated

300,000 abandoned wells, many of which have no records. These can provide leakage paths in rare circumstances.

In October 2014, the European Academies Science Advisory Council issued a review of the issues of particular relevance to the European Union. In this it stated "This EASAC analysis provides no basis for a ban on shale gas exploration or extraction using hydraulic fracturing on scientific and technical grounds". In addition, "Overall, in Europe more than 1000 horizontal wells and several thousand hydraulic fracturing jobs have been executed in recent decades. None of these operations are known to have resulted in safety or environmental problems"

6 KNOWLEDGE FROM CANADA

Managing Risks to Groundwater and Subsurface Impacts in Canada is mainly based on the Canadian Water Network (2015) Report on Water and Hydraulic Fracturing. Despite the high level of concern by stakeholders, to date there has been no comprehensive, comparative examination of *wastewater management* practices involving handling, treatment, and disposal. This is at least in part because each plays and formations vary greatly in geological and hydrological structure, and options available for wastewater management which make a comparative review difficult. A few recent studies have examined the full water lifecycle of selected U.S. formations and provide an indication of what the future of wastewater management may look like for Canadian formations (Nicot et al., 2014; Clark et al., 2013). To date, this study provides the most comprehensive picture of wastewater management that could be relevant practices regardless of a formation's stage of development and applicable regulatory framework.

Quantifying the risks posed by groundwater contamination related to hydraulic fracturing developments is an area for which there is not yet a strong knowledge base. It is also characterized by ongoing scientific debate, which is difficult to resolve given the insufficient data to support an appropriate analysis of key questions. In light of this uncertainty, data gaps most relevant to developing appropriate risk management practices and regulations are those that focus on identifying and managing the most likely contaminant exposure pathways. In particular, concerns about well integrity and a better understanding of methane gas migration associated with shale gas development on aquifers are indicated as being most important (Ryan et al., 2015). Although there is some potential for hydraulic fracturing to induce subsurface pathways that could eventually allow contamination of shallower aquifers from injected chemicals or upward migration of methane, or shale-related compounds from depth, migration via leaks in active, old or abandoned wells is the more likely pathway (CCA, 2014). Well integrity issues are known to exist in association with petroleum wells.

Despite a recent increase in peer-reviewed studies investigating the occurrence or absence of "fugitive" methane in groundwater supplies near unconventional oil and gas development, the processes and mechanisms involved and the impacts on groundwater quality remain poorly understood. Technologies exist to distinguish naturally-occurring methane in groundwater from suspected stray gas. However, the majority of field-based studies have relied on sampling of domestic water wells. This limits the ability to determine the sources and contamination pathways when methane is present.

Management of risks for wastewater and hydraulic fracturing relate primarily to the surface handling, storage and eventual disposal of recovered fluids. The quality of the injected water which can be freshwater, saline or recycled water, plus chemical additives and constituents leached from the formation, combine to form variable flowback water quality. From Canada reported a very large span of 2,000 to 77,000 m^3 / well, with an estimated average of 19,000 m^3 / well (Council of Canadian Academies, 2014). Environment Canada and Health Canada have compiled a list of over 800 substances known or suspected to be used in hydraulic fracturing in Canada, 33 of which have been assessed as toxic. Due to restrictions on access to full disclosure of fracture fluids, ongoing cooperation between industry, regulators, health officials and potentially other key stakeholders is necessary to resolve conflicts and ensure further evaluation can occur. The laws addressing proprietary information differ in Canada and the U.S.; however, experience in the U.S. demonstrates that there is capacity to improve disclosure practices for public access, uniformity and the state of the knowledge surrounding the risks associated with fracturing fluids in consideration of proprietary trade secrets.

Certain disposal methods may be unsuitable in certain regions. For example, studies have indicated that the geology in parts of eastern Canada is inappropriate for deep-well injection. Past experiences with mining also point to unique regulatory challenges for wastewater containment in areas of permafrost in the North. Therefore, an assessment of these challenges and the advantages of each method under average conditions would better enable decision makers to identify the best practices. For wastewater treatment, this could entail a comparison of waste storage facility standards, evaluation of treatment processes, as well as lab and in situ experiments to better understand the impacts on the environment.

In western Canada, wastewater is generally disposed of through injection into deep formations. In eastern Canada, geological limitations generally preclude deep injection, resulting in the need for treatment prior to disposal (Gagnon et al., 2015; Goss et al., 2015). The efficacy of wastewater treatment methods is a localized issue; however, improvements to the general state of knowledge are warranted.

In general, public wastewater treatment plants are not designed to treat the constituents in hydraulic fracturing wastewater, nor the variability of hydraulic fracturing wastewater properties. Industrial wastewater treatment that is tailored to remove unwanted components is an area of active research and development; however, the cost of treatment has been cited as the primary barrier (Council of Canadian Academies, 2014).

Throughout Canada and the U.S., oil and gas well logs and production histories including data pertaining to wastewater reduction must be submitted to the oil and gas provincial or state regulator, which then makes them available. Selected data are obtained by which then offer paid subscription services. In addition, some legally require fluids and non-proprietary proppants used in a well treatment to be uploaded to open access FracFocus websites. Although data on the quantities, types, and disposal locations of wastes generated by a particular well are typically available in one of these databases, often the data is not searchable and is included in attachments or appendices to the electronic well records rendering it difficult to access (Zhao et al., 2007).

The last decade has seen increased public, government and industry interest in expansion of the use of combined horizontal drilling and multi-stage hydraulic fracturing techniques for extraction of tight oil and gas in North America. With continued technology and practice innovations that better access resource opportunities, reduce costs and enable meeting or exceeding regulations, governments are charged with ensuring sufficiency of those regulations and oversight of evolving industry practices. It is an ongoing challenge for all parties seeking to draw upon best available research, knowledge and experience to keep pace with industry advancements and identify those elements particular to tight oil and gas development that most warrant consideration. This is confounded by the fact that research specific to the current practices related to hydraulic fracturing in tight reservoir development is quite young, as well as the fact that priority questions and needs are dictated to a large degree by regional factors. Therefore, not all unknowns can practically be addressed in a timeframe that will usefully inform decisions. A prioritization of both concerns and knowledge needs to support decisions is critical to ensure the most important issues and gaps receive appropriate attention. Clarify the short and long-term risks or potential negative aspects associated with development choices. Given the complex set of questions and knowledge gaps surrounding hydraulic fracturing activities and water, critical next steps must include strategic prioritization of knowledge as well as opportunities to pool expertise and resources to effectively support decisions.

7 KNOWLEDGE FROM EUROPE

7.1 Poland

Initial hydro-fracking in Poland was carried out in August 2011 by Lane Energy from the 3Legs Resources group at the Łebień LE 2H well in Pomerania. Results of flow tests did not appear promising as the recorded flow of 20,000 m^3 per day corresponded to lower values obtained from American shale gas wells. Subsequent flow tests carried out by other operators also failed to give fully satisfactory results. This may be one of the reasons why some foreign companies withdrew from the Polish market. Their license blocks were taken over by other companies, including Polish firms.

As of 30 September 2015, there were 33 active oil/gas exploration and/or appraisal concessions that covered also the shale gas. The concessions were awarded to 10 Polish and foreign concession holders, who have drilled a total of 71 exploratory wells by 30 September 2015, News service of Polish Geological Survey 2015.

Gas-bearing shales occur in Poland at depths ranging from 3 to 5 km, in areas of different geology and hydrogeological conditions. The maximum depth of freshwater aquifer occurrence in Poland is estimated to approx. 300 m below the ground surface. The depth may vary, depending on both regional and local factors. For example, in northeast Poland aquifers occur at depths ranging from 200 to 300 m below the ground, whilst in southeast Poland (Lublin and Zamośc) the depth does not exceed 160 m below the ground.

Moreover, mineral and thermal waters occur in the existing shale gas exploration areas. The depths to mineral waters range from 200 m below the ground (near Torun) to over 500 m below the ground level (for example north and northeast of Lublin). Thermal waters occur at a depth of approx. 2500 m below the ground level (Paczyński & Sadurski 2007a+b).

Due to the depth of gas-bearing shale occurrence, drilling wells have to pass through local aquifers that frequently are the only source of water supply to the local residents.

Hydraulic fracturing of the shale equivalent to the Scandinavian Alum Shale formation is made in the northern most part of Poland within the Baltica basin, but there is no environmental data from here and this section is therefore only an estimate of how the geology affects the composition of wastewater from such fracturing. The waste water will immediately after fracturing mainly consists of back flow with a composition close to the injected fracturing fluid, but over time the flowback water will increasingly consist of formation water (Kondash & Vengosh, 2015). Therefore, the flowback waste water will contain varying amounts of fracking chemicals and solutes from the shale formation, as well as the suspended solid material from the fractured shale and from any precipitates.

At this stage the risk can be mitigated by delivery of well abandonment operations in compliance with applicable regulations (e.g. placement of cement plugs or mechanical barriers to isolate reservoir gas from aquifers), based on abandonment program approved by the competent authority (District Mining Office), and further by permanent monitoring of well tightness throughout the well abandonment operations.

Exceptionally, well leakage and migration of reservoir gas to aquifers and the ground surface may occur following well abandonment. In that case the investor should prepare a recovery plan and cooperate with competent authority so as to minimize environmental impacts and restore integrity of the abandoned well (Paczyński & Sadurski 2007)

Table 7. The 24 most used additives in fracking fluid used in Poland (NGS Factsheets).

Name	**CAS #**	**Used in no wells %**
Hydrochloric Acid 15%	7647-01-0	100
Methanol	67-56-1	100
5-Chloro-2-methyl-2H-isithiazol-3-one and 2-methyl-2H-isothiazol-3-one (3:1)	55965-84-9	69
Magnesium nitrate	10377-60-3	69
Ethylendioxy dimethanol	3586-55-8	61
Tetrasodium ethylenediaminetetraacetate (EDTA)	64-02-8	61
Ethylene Glycol	107-21-1	53
Aliphatic alcohols, ethoxylated #1	68131-39-5	46
Choline Chloride - CSC1001	67-48-1	46
Prop-2-yn-1-ol	107-19-7	46
Sodium Hydroxide	1310-73-2	46
Aliphatic acids	-	38
Ammonium persulphate	7727-54-0	38
Boric acid	10043-35-3	38
Potasium chloride	1310-58-3	38
Butyl diglycol	112-34-5	30
Formic Acid	64-18-6	30
Distillates, (petroleum), hydrotreated light - FRA101	64742-47-8	23
Potassium Hydroxide	1310-58-3	15
Trisodium nitrilotriacetate (impurity)	5064-31-3	15
2-Butoxyethanol	111-76-2	8
Acetic Acid	64-19-7	8
Aliphatic acid salt	-	8
Isopropanol (Propan-2-ol)	67-63-0	8
Oxyalkylated Alcohol Based Polymer	34398-01-1	8

7.2 Germany

In Germany, the hydraulic fracturing technique has been applied for conventional and tight gas reservoirs since the 1950s to increase production rates. Since then, more than 300 fracking jobs were successfully conducted in depths of sometimes more than 5000 m. According to the annual LBEG report from 2012 they have not known to any environmental damage during all these years. However, the technique of hydraulic fracturing for shale gas production is quite new to Germany, as the geological formations with the potential shale formations are at shallower depths and the fracking volumes are considerably greater than with conventional reservoirs. But there may be a lack of monitoring or systematic investigations of environmental impacts of the hydraulic fracturing activities carried out to date.

To this date, one test drilling using the hydraulic fracturing technology in shale rock was conducted in Germany in 2008 (Damme 3, Lower Saxony). ExxonMobile also published the chemical composition of the fracking fluids used in the Damme 3 fracking treatments. The test drilling was conducted to achieve an estimate of the production potential of the existing shale rock formations.

Fracking has been used since the 1950s but not hydraulic fracking and associated liquids in shale layer. In 2014, initiated the German environmental authorities (UBA) a study that summarizes the German experience with fracturing and about 300 fracking jobs carried out in Germany. One shale layer only was fracked (Damme 3) at a depth of 1045-1530 m. The other frackings were in coal bed methane rock layer in which the liquid used is another than in the shale layer. UBA found that there are at least 88 different fracking liquid chemicals on the German market. Six products contained chemicals that are classified as toxic and other five products were dangerous to the environment, while 25 are harmful and 27 'non-hazardous'. At least 112 different chemicals have been used in fracking liquids. The study concluded that there is a likelihood of potentially unacceptable environmental risks and that there are currently too many gaps in knowledge and data to conduct a thorough risk assessment in Germany. The German environmental authorities recommend based on the study that all substances used in fracking fluids to be published, as well as to their environmental toxicity. Further, that the most toxic substances are substituted and that each well must have its own site-specific risk assessment (Bergman et al. 2014). The shale gas well, Damme 3, is designed as a test drilling that used hydraulic fracking as it is the only one of its kind in Germany so far. ExxonMobil has an ongoing commitment to improving the fracking fluids. Up to 150 different substances were used earlier, but today there are a total of 30 substances.

Shale gas fracking liquids have now been developed that is less hazardous for water environment. The additions (additives) are neither toxic nor hazardous to the environment. In addition to water and sand it consists of a vitamin precursor and an alcohol. Both are readily biodegradable. The water content of fracturing fluid in this case is approximately 99.8 percent.

Immediately after the fracking operation a large part of the liquid is pumped back. Another part is carried along during the promotion along with the natural gas and possibly reservoir water, treated and then placed in an approved this infiltration well. The aim is to send back deposit water only in those horizons from which the reservoir water originates or which naturally contain water deposit. The sand stays in the artificial cracks in the rock to continue to keep them open. For shale gas fracking, the aim is to use the liquid used again. A re-injection is not provided here.

The three institutes for geology and environment, BGR, GFZ and UFZ, published their joint statements on the topic of "Environmentally Compatible Hydraulic Fracturing" for the extraction of shale gas in August 2013. The "Hanover Declaration" is the result of a two-day conference with national and international experts on scientific and technical aspects.

7.3 UK

The first experimental use of hydraulic fracturing was in 1947, and the first commercially successful applications of hydraulic fracturing were in 1949. In the United Kingdom, the first North Sea well hydraulic fracturing was carried out shortly after discovery of the West Sole field in 1965. First hydraulic fracturing from ship was conducted in the United Kingdom in 1980. Onshore, approximately 200 wells have been hydraulically fractured which is about 10% of all onshore wells in the United Kingdom. It includes Wytch Farm, which is the largest onshore oil field in Western Europe.
The main UK organic-rich shale formation is in age from Cambrian to the late Jurassic. The younger shales have not reached the gas window for thermogenic generated gas. Information on thermal mature hydrocarbons and shale gas in the UK indicate areas with Lower Paleozoic shale basins of the Midland, in the Stainmore and Northumberland basin systems.
In 2007 Cuadrilla Resources was granted a license for shale gas exploration along the coast of Lancashire. The company's first and only hydraulic fracturing job to date was performed in March 2011 near Blackpool. Fracking involved the hydraulic fracturing of the ground using high-pressure liquid containing chemicals to release the gas. The company halted operations at Lancashire drilling site due to seismic activity damaging the casing in the production zone. Other companies have obtained exploration licenses, with test drilling being carried out in Somerset, Glamorgan, Cheshire and other locations. Licenses were withdrawn by Cuadrilla when arrangements for disposal and treatment of contaminated water were not considered to be adequate by the Environment Agency. In July 2014, the Scottish Government issued an Expert Scientific Panel Report on Unconventional Oil & Gas which investigated the technical and environmental challenges of this technology.

7.3.1 Environmental impact and risk assessments in UK

Some flowback fluid can be treated and reused as hydraulic fracturing fluid. It can contain high levels of salt, and low levels of radioactive materials, known as NORMS. The disposal and treatment of these fluids must be done under a license from Environment Agency. Regulations regarding radioactive material and other contaminants have been tightened. Fluid disposal wells are not currently licensed in the UK by the Environment Agency. Disposal wells have been shown to be the main cause of significant earthquake risk in certain areas. Waste water treatment companies have devised methods of removing 90% of NORMS allowing safe disposal of fluids under Environment Agency license. These techniques can reduce radioactive content to less than some bottled waters. One potential pollution path is from leaks on the surface through spillage. The EA require chemical and fluid proof drill pads.
The DECC document 'Fracking UK Shale, Water' indicates how operators must address issues water usage, and pollution potential, treatment of flowback water, together with the mitigation measures and links to well regulation requirements. The DECC reported

that it had approved the use of three chemical additives in hydraulic fracturing slurries by Cuadrilla: polyacrylamide (friction reducer); hydrochloric acid, which is used at concentrations of under 1% at which concentration it is considered non-toxic; and a non-toxic biocide. In its one hydraulic fracturing job to date, Cuadrilla used only non-toxic polyacrylamide, at a concentration of 0.05%. The Environment Agency will only issue permits for what it considers non-hazardous chemicals, Department of Energy & Climate Change. 2013.

In June 2015, the US Environmental Protection Agency published its draft study into groundwater pollution from hydraulic fracturing. The main conclusion was that assessment shows hydraulic fracturing activities have not led to widespread, systemic impacts to drinking water resources and identifies important vulnerabilities to drinking water resources. The vulnerabilities were identified as water withdrawals in areas with low water availability and to avoid hydraulic fracturing conducted directly into formations containing drinking water resources. Further, that inadequately cased or cemented wells resulting in below ground migration of gases and liquids. Handling and inappropriate treated wastewater discharged into drinking water resources and spills of hydraulic fluids and hydraulic fracturing wastewater, including flowback and produced water may be the main threads to the environment.

Water UK has signed a memorandum of understanding based upon a briefing paper by Water UK; Water UK and UKOOG memorandum of understanding on shale gas, 2013.

The British Geological Survey is involved with environmental monitoring, which can be used as a baseline study before an eventually fracking job. The British Geological Survey, in reviewing the US experience with hydraulic fracturing of shale formations, observed, where the problems are genuinely attributable to shale gas operations, the problem is with poor well design and construction, rather than anything distinctive to shale gas.

Table 8. Parameters in the shale gas dedicated groundwater monitoring network in UK. (Data from BGS: Groundwater quality monitoring)

Water table
Temperature, pH, conductivity, redox potential
Major ions and trace elements
Dissolved gases (O_2, CO_2, CH_4, N_2, radon, noble gases)
Organic chemicals
Stable isotopes (^{18}O, ^{2}H of water, ^{13}C of inorganic carbon)
Groundwater 'age' indicators (CFCs, SF_6)
Naturally occurring radioactive materials (NORM: uranium and thorium decay series).
Monitoring equipment installed in newly drilled boreholes will additionally include real time and near-real time measurements of:
pH, temperature, redox potential, dissolved oxygen
Dissolved methane
Selected organic chemicals (PAHs)

BGS has established a network of water sampling sites consisting of existing boreholes, wells and streams within a radius of some 10 km of the proposed shale gas exploration sites. As of September 2015, they have carried out "three" groundwater sampling campaigns. These encompass 17 sites from a combination of the superficial and Sherwood Sandstone aquifers. In addition, they have sampled stream water from 11 sites in the area. Water samples have been analyzed for a broad range of dissolved chemicals.

Monitoring of existing boreholes and wells, together with newly drilled boreholes when completed, will involve sampling and analysis of a wide range of physio-chemical parameters.

In addition surface water near the wells is analyzed. Preliminary analysis of water from first-order streams sampled in May and August 2015 shows overall lower concentrations of total dissolved solids than found in local shallow groundwater, though with slightly higher concentrations of nitrate, nitrite and dissolved organic carbon. Many trace elements also have lower concentrations than local groundwater, due to a combination of differing redox conditions and more limited interaction with rocks and soils

The British Geological Survey has released national baseline methane levels, which range from negligible to high. Methane is not acute toxic but it does carry the risk of explosion in confined spaces, and is produced in the human gut. It is removable by the water companies by aeration, but that would be an expensive option. In the US, baseline methane measurements were not made at the start of the shale gas boom, meaning that it is difficult to prove whether a gas problem is due to drilling, and leaking wells, or is naturally occurring. This practice is now changing as this baseline study shows.

Treated mains water is the norm in the UK, and standards are required by legislation to be high. As such any methane pollution would have to be removed by the water companies by law. Private water wells are rare, around 62,000 households, out of 23.4 million households or 2.6%, compared to rural areas of the US private wells are common (~15%). UK households would therefore be expected to be less at risk than those in the US.

In September 2014, study from the US 'Proceedings of the National Academy of Sciences' released a report that indicated that there was no evidence of hydraulic fracturing chemicals being present in surface methane leaks. This showed strong evidence that methane contamination can occur in poorly cemented wells, but that any methane content is not caused by the hydraulic fracturing process. The Royal Academy of Engineering report from 2012 indicates that the distances between potable water supplies and fractured formation in various US shale plays is large, meaning the risk of contamination is very small. No cases of pollution by this route have been identified. Considering the conditions in the UK, the report concludes "The very unlikely event of fractures propagating all the way to overlying aquifers would provide a possible route for fracture fluids to flow. However, suitable pressure and permeability conditions would also be necessary for fluids to flow. Sufficiently high upward pressures would be required during the fracturing process and then sustained afterwards over the long term once the fracturing process had ceased. It is very difficult to conceive of how this might occur given the UK’s shale gas hydrogeological environments. Upward flow of fluids from the zone of shale gas extraction to overlying aquifers via fractures in the intervening strata is highly unlikely".

For deep formation water to pollute an aquifer it must first have a pathway to follow, and also have a driving mechanism to force it upwards. The fractures could possibly provide a pathway, but to raise the water would have to be buoyant. If there were a pressure profile that meant fluids could migrate upwards, the low permeability of formations mean that pollution times would be geological in scale.

Concern has been raised about some wells drilled before the latest guidelines that do have potential leak paths. If the casing were to leak due to corrosion or other reason, there would be a leak path from deep salty formations into the aquifer. If a well were to leak, workover operations can usually fix leaks, by, for instance, perforating the casing above and below a poorly cemented zone, and 'squeezing' cement behind the pipe. The cement is drilled out and a pressure test is performed until pressure integrity is good.

8 CONCLUSIONS

Data from a variety of studies across many shale plays indicates that negative impacts and risks do exist with respect to shale gas development and freshwater resources. The impacts depend on management choices, incentives to engage in best practices, regulations, and oversight, and can be both exacerbated or substantially reduced by these same factors. Risks to water resources are also a function of the context in which unconventional activities take place.

Natural gas is an indispensable resource for Germany. Recovery of shale gas could contribute to a stabilization of resources caused by dwindling domestic natural gas extraction.

Compared with conventional gas production, hydraulic fracking in shales introduce a new range of risks, originating from an increased number of wells and increased water consumption, the use of chemical substances, and increased traffic, GZF News 2014. Additionally, many potential gas shales are present at shallower depths than is the case for conventional reservoirs in Germany.

If the fracking technology is to be applied for shale gas extraction in Germany, this requires environmentally friendly procedures e. g. the use of environmentally friendly fracking fluids. Furthermore, the existing legal framework for the exploration and production of natural gas will need to be developed further. The protection of drinking water must be a top priority.

To assess whether fracking can be conducted in an environmentally friendly manner, proposed procedures should be first checked against local geological conditions in each individual case, and accompanied by appropriate monitoring measures. For this an environmental impact assessment based on the corresponding mining regulations must be carried out. Furthermore, it must be ensured to involve the environmental administration, in particular the water authorities, in the process.
The operation and development of technology for shale gas extraction in Germany requires a transparent and step-by-step approach. Therefore first projects should be carried out as demonstration projects and all parties involved (public, industry, scientific community and environmental organizations) should be included from the start; individual measures and results should be published and accompanied and evaluated by a comprehensive scientific program; the main focus should be on research regarding the possible impact on groundwater quality of hydraulic fracturing measures.

Baseline data and monitoring is essential for understanding when impacts on the water from shale plays occur, and what it consist of. Both issues are essential for understanding the root causes. From evidence available on the Marcellus Shale and other plays, water resource risks evolve and change over time as stakeholders adapt and respond to economic, technological, social, and political pressures. Therefore, it is difficult to say to what extent the risks and impacts experienced in the past will continue into future scenarios of a European context. Additionally, our current understanding of risks and impacts is biased towards the Marcellus and Barnet Shale, where a majority of peer reviewed studies have been focused and we may not be aware of new risks that are related with hitherto undeveloped shale plays.

In Poland there have not been observed any illegal dumping of waste in the environment and the drilling works to large depths had not until yet shown any effect on aquifer conditions near the well areas (Konieczyńska 2015). Further, where the surface water has been monitored during and after the drilling no effects have been detected on quality of surface water.

In conclusion uranium and thorium is limited mobile under reducing conditions, and consequently will appear to the surface as cuttings. If oxidizing conditions are established in the borehole during drilling or fracturing due to the used fracking chemicals, the radioactive substances may be mobilized (Gaucher et al. 2014, Rowan et al. 2011). Cuttings can be NORM under the current rules. Radium isotopes constitute the most significant problem in terms of pollution and radiation hazards caused by a possible high-resolution content in flowback water and formation water. Radium has a positive correlation with the total salinity of the formation water and seems regulated by this; the reason salinity may be an indicator / predictor of radium activity of the produced water (Fisher 1998, Rowan et al. 2011). Radium can be precipitated by sulphate, but will then be a solid radioactive material. Precipitated radium in pipes and pumps etc. has also to be treated. Both types of waste are NORM if concentrations are above exception values. Radon and the four radon daughters may pose a risk, but since radon is a gas with a short half-life (3.8 days), seemed not to pose a problem during drilling and the establishment. Any content of radon should be taken into account as an option in produced shale gas, and this should be investigated further before a production plant with supply for households and industry is commissioned (PHE 2013).

Thus, the ability to extrapolate from examples from North America to other plays, regions, and countries is limited. Research conducted on other plays, within varying contexts and within different regulatory regimes, should help to create a clearer picture of national trends and to help to be able to better predict future scenarios and thus to mitigate the risks.

The current regulation of shale gas wastewater management, treatment, and disposal is inadequate because it fails to safeguard against foreseeable risks of harm to human health and to the environment. Government oversight of wastewater treatment and disposal must be improved at both the European Union level and in the individual states.

9 RECOMMENDATION

Proper monitoring of the impact on freshwater aquifers and surface water requires that the background conditions (baseline data) of those elements are properly documented in a scientific sound manner and by independent organizations before any drilling operation initiates. The baseline study should as a minimum include its flow properties and its chemical composition.

9.1 Surface water

EU minimum principles defines that a baseline study of the quality and flow characteristics for surface and groundwater shall be determined (EU Commission Recommendation of January 22, 2014). Establishing baseline conditions for water flow must be based on monitoring of all potentially affected watercourse stretches of water abstraction. For most small streams there exist no historical time series of water flow, and it will in most cases be necessary to include water transfer data from the national surveillance network. Thus, baseline monitoring of the individual streams is carried out for a sufficient period of time, which is a good correlation between the historical data (from the national monitoring network) and the new monitoring stations can be provided.

9.2 Groundwater

Establishment of background quality conditions must be organized so that both the impact of the current aquifer from which the abstractions are made, and the impact of the near-surface aquifers are examined. A correlation of the influence of deeper water aquifers and surface aquifers is not always possible, and therefore the impact is assessed independently. Existing abstraction of water from the area must be included in the overall analysis of the impact of water extraction by shale gas production.
Monitoring design must be based on a prior local characterization of the hydrological and hydrogeological system. Characterization and monitoring must be organized according to: 1) Improve knowledge and understanding of the local area. 2) Documenting this understanding by observations. 3) Be able to conduct remediation of inappropriate influences.
A well prepared initiative is initiated in UK as BGS has established a network of water sampling sites consisting of existing boreholes, wells and streams near the proposed shale gas exploration sites. In addition, stream water has been sampled from the area. Water samples have been analyzed for a broad range of dissolved chemicals. Monitoring of existing boreholes and wells, together with newly drilled boreholes when completed, will involve sampling and analysis of a wide range of physio-chemical parameters.
American experience has shown that much of the uncertainty regarding the environmental impacts of shale gas production is a consequence of ill-defined baseline conditions both in terms of hydrogeological and geochemical conditions (Vengosh et al., 2014).

10 REFERENCES

Alley, W.M., Bair, E.S., Wireman, M. 2013. “Deep” groundwater. Groundwater. 51:653-654.

Almond, S., Clancy, S.A., Davies, R.J. & Worrall, F. 2014: The Flux of radionuclides in flowback fluid from shale gas exploitation. Environmental Science Pollution Research 21, 12316-121324.

Bergman A., Weber FA., Meiners GH., Müller F. 2014. Potential water-realted environmental risks of hydraulic fracturing employed in exploration and exploitation of unconventional natual gas reservoirs in Germany. *Environ Sci Europe*, 26: 10

BGS. British Geological Survey. Groundwater quality monitoring (http://www.bgs.ac.uk/research/groundwater/shaleGas/monitoring/waterQuality.html).

Buchardt, B., Nielsen, A.T., Schovsbo, N.H., 1997. Alun Skiferen i Skandinavien. Geologisk Tidsskrift 3, 1–30.

Burkhart, J. Huber, T. & Bolling, G. 2013: Potential Radon release during Fracking in Colorado. The American Association of Radon Scientists and Technologists. Radon Symposiun Paper. Spingfield, IL 2013, 20-27.

CCA - Council of Canadian Academies. 2014 Environmental impacts of shale gas extraction in Canada. Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction, CCA. Retrieved from (http://www.scienceadvice.ca/uploads/).

Canadian Water Network 2015 Water and Hydraulic Fracturing CWN REPORT 62pp

Clark, C. E., Horner, R. M., & Harto, C. B. (2013). Life Cycle Water Consumption for Shale Gas and Conventional Natural Gas. Environmental Science & Technology, 47(20), 11829–11836.

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

Chemicals Used in Hydraulic Fracturing; United States House of Representative Committee on Energy and Commerce: Washington, DC, 2011.

Cooley, H., Donnelly,K., 2012, Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction, Pacific Institute, 34 pp

Damkjær, A. & Korsbech, U., 1985: Measurement of the emanation of Radon-222 from Danish soils. The Science of the Total Environment 45, s. 343-350.

Davies, R., Foulger, G., Bindley, A., Styles, P. 2013 Induced seismicity and hydraulic fracturing for the recovery of Hydrocarbons Marine and Petroleum Geology 45: 171-185

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, 1-6.

Department of Energy & Climate Change (February 2014). Fracking UK shale: Water (PDF) (https://www.gov.uk/government/).

Department of Energy and Climate Change Strategic Environmental Assessment for Further Onshore Oil and Gas Licensing. UK Govt. DECC. 64pp

Dresel, P. E., and Rose, A. W., 2010, Chemistry and origin of oil and gas well brines in western Pennsylvania: Pennsylvania Geological Survey, 4th ser., Open-File Report OFOG 10–01.0, 48 pp

European, Commission. 2014. Environmental Aspects on Unconventional Fossil Fuels. 2014/70/EU: Commission Recommendation of 22 January 2014 on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing.

EU, 2012: JRC Scientific and Policy Reports.Unconventional gas: Potential energy market impacts in the European Union (https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/unconventional-gas-europe-potential-energy-market-impacts).

EU, 2013: JRC Scientific and Policy Reports. Assessment of the use of substances in hydraulic fracturing of shale gas reservoirs under REACH. September, 2013 (https://ec.europa.eu/jrc/sites/default/).

EU, 2014: European Commission. Technical support for assessing the need for a risk management framework for unconventional gas extraction (http://ec.europa.eu/environment/integration/energy/).

Fisher, R.S. 1998: Geologic and Geochemical Controls on Naturally Occuring Radioactive Materials (NORM) in Produced Water from Oil, Gas, and Geothermal Operations. Environmental Geosciences, Vol. 5, no.3, 139-150.

Flewelling, S.A. & Sharma, M. 2014: Constraints on Upward Migration of Hydraulic fracturing Fluid and Brine. Groundwater 52: 9-19.

FracFocus (https://fracfocus.org).

Freyman 2014. Hydraulic fracturing & water stress: Water Demand by the Numbers. Ceres 85pp. (www.ceres.org).

Gagnon, G., Anderson, L., Corston-Pine, E., Krkošek, W.H., Linden, K.G., Livingstone, K., Trueman, B. (2015). *Development of a water safety framework for watershed and water demand governance and management approaches related to hydraulic fracturing.* Waterloo, ON: Canadian Water Network.

Gaucher, E.C., Lerat, J., Ganier, A., Derbez, E., Vidal-Gilbert, S., Stepernich, J., Mösser-Ruck, R. & Pironon, J. 2014: Toxic Metals in Shales: Questions and Methods for a Better Management of Flow-Back Waters. Unconventional Resources Technology Conference. URTec: 1928654, p 1-5.

Gautier GL, Carpentier RR, Gaswirth B, Klett TR, Pitman JK, Schenk CJ, Tennyson ME, Whidden KJ. 2013.Undiscovered Gas resources in the Alum Shale, Denmark, 2013. USGA, Fact Sheet 2013-3103.

Goss, G., Alessi, D.S., Allen, D.M., Gehman, J., Brisbois, J., Kletke, S., ...Prosser, C. (2015). Unconventional wastewater management: A comparative review and analysis of hydraulic fracturing wastewater management practices across four North American basins. Waterloo, ON: Canadian Water Network.

Gregory KB, Vidic RD, Dzombak DA (2011) Water management challenges associated with the production of shale gas by hydraulic fracturing. Elements 7:181–186.

Ground Water Protection Council and ALL Consulting. 2009. Modern Shale Gas Development in the US: A Primer (http://energy.gov/sites/prod/files/2013/03/f0/ShaleGasPrimer_Online_4-2009).

GZF News 2014 (http://www.shale-gas-information-platform.org/).

Haluszczak, L.O., Rose A.W. & Kump, L.R. 2013: Geochemical evaluation of flowback brine from Marcelleus gas wells in Pennsylvania, USA. Applied Geochemistry. 28: 55-61.

Hand, B.M. & Banikowski, J. E. 1988: Radon in Onondaga County, New York: Paleohydrogeology and redistribution of uranium in Paleozoic sedimentary rocks. Geology 16: 775-778.

Hilal, M.A., Attallah, M.F., Mohamed, G.Y. & Fayez-Hassan 2014: Evaluation of radiation hazard potential of TENORM waste from oil and natural gas production. Journal of Environmental Radioactivity, 136: 121-126.

Hildenbrand, Z.L., CarltonJr.D.D., Fontenot, B.E., Meik, J.M., Walton, J.L., Taylor, J.T., Thacker, J.B, Korlie, S., Shelor, C.P:, Henderson, D., Kadjo, A.F., Roelke, C.E., . Hudak, P.F., Burton, T., Rifai, H.S., Schug, K.A. 2015A Comprehensive Analysis of Groundwater Quality in The Barnett Shale Region. Environ. Sci. Technol. 49: 8254–8262

House of Commons Library. Shale Gas and Fracking (PDF). UK Govt. (www.parliament.uk/briefing-papers/sn06073).

IAEA 2003: Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry. IAEA Safety Reports Series No. 34, 130 pp

Jackson, R. B., Osborn, S. G., Vengosh, A. and Warner, N. 2011. Reply to Davies: Hydraulic fracturing remains a possible mechanism for observed methane contamination of drinking water. Proceedings of the National Academy of Sciences 108 (43): E872.

Jackson, R.B., Vengosh, A., Darrah, T.H., Warner, N.R., Down, A., Poreda, .J.,Osborn, S.G., Zhao, K., Karr, J.D., 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proceedings of the National Academy of Sciences. 110: 11250-11255.

Kargbo, D.K., Wilhelm, R.G. & Campell, D.J. 2010: Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities. Environmental Science Technology 44: 5679-5684.

Kerr, R. 2010. Natural Gas from Shale Bursts onto the Scene. Science 328: 1624-28

King, G.E. 2010. Thirty years of gas-shale fracturing: What have we learned? JPT J. Pet. Technol. 62:88–90

King, G.E. 2012. Hydralic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. SPE 152596. Society of Petroleum Engineers.

Kolb, W.A. & Wojcik 1985: Enhanced Radioactivity due to Natural oil and Gas Production and related Radiological Problems. The Science of the Total Environment, 45, 77-84.

Kondash A and Vengosh A. 2015. Water Footprint of Hydraulic Fracturing. Environmental Science Technology. Lett. 2: 276–280

Konieczyńska et al. 2011.Environmental Aspects of Hydraulic Fracturing Treatment Performed on the Łebień LE-2H Well. FINAL REPORT Warsaw, November 2011. 174pp

Konieczyńska, M. 2015. The environment and shale gas exploration -Results of studies on the soil-water environment, ambient air, acoustic climate, process fluids and wastes. Warsaw 2015 ISBN: 978-83-62940-97-4. 188pp

Laier, T. 1989. Mapping of low enthalpy brines in Denmark for geothermal exploitation. Proceedings - International Symposium on Water-Rock Interaction 6: 409-412

Laier, T. 2008. Chemistry of Danish saline formation waters relevant for core fluid experiments. Danmarks og Grønlands Geologiske Undersøgelser Rapport 2008/48.

Lindgreen, H., Drits, V.A., Sakharov, B.A., Salyn, A.L., Wrang, P., Dainyar, L.G., 2000. Illite-smectite structural changes during metamorphism in black Cambrian Alum shales from the Baltic area. American Mineralogist 85: 1223–1238.

Maguire-Boyle SJ and AR Barron. 2014 Organic compounds in produced waters from shale gas wells. Environ. Sci.Processes & Impacts, 16: 2237-2248

Maloney, K.O.,Yoxtheimer, D.A. 2012 Production and disposal of waste materials from gas and oil extraction from the Marcellus Shale play in Pennsylvania Environ. Pract., 14: 278–287.

Molofsky,L.J., John A. Connor J.A. Wylie, A.S.,Wagner T., Farhat S.K.,2013 Evaluation of Methane Sources in Groundwater in Northeastern Pennsylvania. Groundwater 51: 333–349

Nicot, J., Scanlon, B.R., Reedy, R.C., Costley, R.A.. 2014. Source and Fate of Hydraulic Fracturing Water in the Barnett Shale: A Historical Perspective. Environmental Science Technology. 48:2464–2471.

Nielsen, A.T., Schovsbo, N.H., 2006. Cambrian to basal Ordovician lithostratigraphy in southern Scandinavia. Bulletin of the Geological Society of Denmark 53, 47–92.

NGS Facts -The International Association of Oil & Gas Producers (http://www.ngsfacts.org/findawell/list/).

Osborn, S, Vengosh, A, Warner, N, Jackson, R. 2011 Methane contamination of drinking water accompanying gas-well drillingand hydraulic fracturing. Proceedings of the National Academy of Sciences.108:8172–8176.

Osborn, S. G., Vengosh, A., Warner, N. R. and Jackson, R. B. 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proceedings of the National Academy of Sciences 108: 8172-8176.

Paczyński B, Sadurski A. (red.) 2007a. Hydrogeologia regionalna Polski, t. I. Wody słodkie. PIG, Warszawa

Paczyński B, Sadurski A. (red.) 2007b Hydrogeologia regionalna Polski, t. II. Wody słodkie. PIG, Warszawa

Pedersen, G.K., 1989. The sedimentology of Lower Palaeozoic black shales from the shallow wells Skelbro 1 and Billegrav 1, Bornholm, Denmark. Bulletin of the Geological Society of Denmark 37: 151–173.

PHE, Public Health England, 2013: Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of Shale Gas Extraction. Draft for Comment, 38pp

Rahm, B.G., Bates, J.T., Bertoia, L.R., Galford, A.E., Yoxtheimer, D.A. & Riha, S.J. 2013: Wastewater management and Marcellus Shale gas development: Tends, drivers, and planning implications. Journal of Environmental Management 120: 105-113.

Rowan, E.L. & Kreamer, T.F. 2012: Rado-222 Content og Natural Gas Samples from Upper and Middle Devonian Sandstone and Shale reservoirs in Pennsylvenia: Preliminary Data. USGS Open-File Report Series 2012-1159, 6pp.

Rowan, E.L., Engle, M.A., Kirby, C.S. & Kraemer, T,.F. 2011: Radium Content of Oil- and Gas-Field Produced Waters in the Northern Appalachian Basin (USA): Summary and Discussion of Data. USGS Scientific Investigations Report 2011-5135, 31pp

Ryan, M. C., Alessi, D.S., Babaie Mahani, A., Cahill, A., Cherry, J., Eaton, D. Parker, B. (2015) *Subsurface impacts of hydraulic fracturing: Contamination, seismic sensitivity, and groundwater use and demand management.* Waterloo, ON: Canadian Water Network.

Schovsbo, N.H. 2012: Geologiens eventuelle bidrag til skyllevandet i forbindelse med hydraulisk frakturering af Alunskifer. GEUS-NOTAT nr. 09-EN-12-02, 3pp

Schovsbo, N.H., 2002. Uranium enrichment shorewards in black shales: A case study from the Scandinavian Alum Shale. GFF 124, 107–116.

Schovsbo, N.H., 2012a. Analytical results from the Terne-1 and Slagelse-1 wells. Geological Survey of Denmark and Greenland, Report 2012/28, 49 pp.

Schovsbo, N.H., 2012b. Completion report Billegrav-2 well (DGU 248.61) Part 3: Results of core plug analysis. Geological Survey of Denmark and Greenland, Report 2012 16, 47 pp.

Schultz, L.G., Tourtelot, H.A., Gill, J.R., Boeringen, J.G. 1980. Composition and Properties of the Pierre Shale and Equivalent Rocks, Northern Great Plains Region. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1064-B: 123pp

Siegal, Donald. 2015. Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania. Environmental Science Technology. 49: 4106–4112

Suchy, D.R., Newell, K.D. 2013, Hydraulic Fracturing of Oil and Gas Wells in Kansas. Public Information Circular (PIC) 32, Kansas Geological Survey. (http://www.kgs.ku.edu/Publications/PIC/pic32.html)

Thurman E. M, Ferrer I., Blotevogel J., Borch, T 2014.Analysis of Hydraulic Fracturing Flowback and Produced Waters Using Accurate Mass: Identification of Ethoxylated Surfactants Anal. Chem. 86: 9653–9661

The UK’s Global Gas Challenge (http://www.ukerc.ac.uk/publications/the-uk-s-global-gas-challenge.html).

The Royal Society. (2012). *Shale gas extraction in the UK: A review of hydraulic fracturing. The Royal Society and The Royal Academy of Engineering.* Retrieved from: https://royalsociety.org/topics-policy/projects/shale-gas-extraction/report/

UK, 2014: Department of Energy & Climate Change. Fracking UK shale: Water, Feb 2014 (https://www.gov.uk/government/).

UKOOG (22 June 2015). UKOOG Response to Chemtrust report on Fracking (http://www.ukoog.org.uk/about-ukoog/press-releases/151-ukoog-response-to-chemtrust-report-on-fracking).

U.S. Department of Energy, (2009). Modern Shale Gas Development in the United States: A Primer. Work Performed Under DE-FG26-04NT15455. Prepared by the Ground Water Protection Council and ALL Consulting

US Environmental Protection Agency. 2012. Quality Assurance Project Plan: Hydraulic Fracturing Wastewater Source Apportionment (http://www.epa.gov/hfstudy/qapps.html).

US Environmental Protection Agency. 2014. Permitting Guidance for Oil and Gas Hydraulic Fracturing Activities Using Diesel Fuels: Underground Injection Control Program Guidance #84. 48pp

Unites States Environmental Protection Agency 2012: Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources. Progress Report, 262 sider.

US EPA. 2015. Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources. External Review Draft. EPA/600/R-15/047a. June 2015. Washington, D.C.: Office of Research and Development.

Vengosh, A., Jackson, R.B.,. Warner, N.R., Darrah,T.H., Knodash, A.J. 2014. A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. Environmental Science Technology 48:8334-8348.

Warner, N.R., Christie, C.A., Jackson, R.B., Vengosh, A. 2013: Impacts of Shale Gas Wastewater Disposal on Water Quality in Western Pennsylvania. Environmental Science Technology, 47: 11849-12857.

Warner, N.R., T.M. Kresse, P.D. Hays, A. Down, J.D. Karr, R.B. Jackson, and A. Vengosh. 2013b. Geochemical and Isotopic Variations in Shallow Groundwater in Areas of the Fayetteville Shale Development, North-Central Arkansas. Applied Geochemistry 35:207–220.

Zhang, T. 2015: Origin and Fate of Radium in Flowback and Produced Water from Marcellus Shale Gas Exploration. Doctoral Dissertation, University of Pittsburgh, 154pp

Zhang, T., Bain, D., Hammack, R.W., Vidic, R.D. 2015: Analysis of Radium-226 in high salinity wastewater from unconventional gas extraction by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Environmental Science Technology 49: 2969-2976.

Zhang, T., Gregory, K., Hammack, R.W. , Vidic, R.D. 2014. Co-Precipitation of Radium with Barium and Strontium Sulfate and its Impact on the Fate of Radium during Treatment of Produced Water from Unconventional Gas Extraction. Environmental Science Technology 48: 4596–4603.

Zhao, H., Givens, N. B., & Curtis, B. (2007). Thermal maturity of the Barnett Shale determined from well-log analysis. AAPG Bulletin, 91(4), 535–549.