Project Acronym and Title:

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

Minimizing pollution risks from drilling and production

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Disclaimer

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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

This report provides a review of the potential scenarios for minimizing pollution risks from drilling and production of fracking wells. The report emphasizes all processes in unconventional gas extraction that could cause a risk to drinking water Resources, starting from the construction of the drilling site, through drilling and hydraulic fracking, for the actual production of gas and solid waste disposal. There is the report emphasized the risks of all these processes, which until now has been reviewed in the literature, both the International reviewed papers and the many reports available from authorities and private companies. Developments in drilling techniques currently going very quickly, while legislation and environmental monitoring has been intensified, so that's why some of the previous procedure, now replaced by far more environmentally friendly. But the report points out a number of procedures that have been or are still practices which imply an increased risk of contamination of groundwater either directly or through contamination of ground or surface water.
The drilling does not seem to pose no special risks in addition to those already known, but water use by fracking is still large, though the newer techniques reduce consumption considerably. Boreholes that are not close have been a problem in terms of emissions of methane into the groundwater, but improved cementing techniques can reduce these emissions. Handling chemicals can by negligence confer an increased risk of release to the environment. Flow-back water represents a special problem if not handled in a satisfactory manner, because it contains a variety of substances that would be extremely risky to get out into nature or in the groundwater. Last, there is still a problem with storage either of produced water or of cuttings, both of which can contain high concentrations of heavy metals and other xenobiotics and beyond that in certain shales also significant amounts of radioactive elements.
Some gab in our knowledge is still waiting for more research. A large number of parameters must be considered to have an overall assessment of the landscape's vulnerability and to gain knowledge about the security of supply of water resources for drinking water and possibly for irrigation in agriculture.

There may be uncertainty about the location of drinking water resources, and especially, could deeper groundwater resources in future be a potential drinking water resource. If comprehensive data on the location of both water resources and activities in hydraulic fracturing water cycle were available, it would have been possible to more completely identify areas in the US where hydraulic fracturing activities either directly interact with water resources or have the potential to interact drinking water resources. For regions, where there are shales with either high levels of heavy metals or shales containing radioactive substances, there is a lack of more complete and better knowledge of the leaching potential from solid waste dumps and further legislation for the correct safety and environmental best placement of temporary and final disposal sites.

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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

Public dissemination of research for scenarios with minimum risks of pollution from drilling, fracking and production of exploitation shale gas. Based on the available knowledge, mainly from North America, to interpret the opportunities to reduce risk at European level.

1.3 Aims of this report

The report provides a review of scenarios that will provide less potential risk of contamination of ground water from shale gas operations. A review of the various shale gas operations with assessment of the potential risk of impacts on water quality, as well as pointing out areas that still needs more scientific work

2 BACKGROUND

Water contamination during unconventional shale gas extraction is one of the main topics that will dominate the public debate surrounding the gas industry impact on the environmental. However, the reuse of produced water for hydraulic fracturing is at present one of the topics that might diminish some of the risks. One the other hand, the concerns regarding the vast quantities of contaminants that are brought to the surface is still an indispensable issue for practice and management. As the completion of the well sites has finished and the opportunities for wastewater reuse are minor, the immediate need to use new management strategies for the wastewater will be pronounced.

One of most common problems is faulty seal with the well construction that is emplaced to prevent gas migration into shallow groundwater and is thus a considerable risk for the use to portable water. Sealing is a problem in unconventional gas wells, however relatively low, but there is still a substantial discussion whether the methane detected in groundwater in the area where extraction of unconventional gas is active is related to the gas well or is caused by natural processes. It is difficult to resolve as pre-drilling baseline data are often unavailable. At the same time, considerable concern has been payed to contamination of groundwater resources by chemicals added to the hydraulic fracturing fluid, spills/leaks, disposal of inadequately treated wastewater, or migration of hydraulic fracturing fluids or deep brines.

Simulations have suggested that transport times for shale brine and hydraulic fracturing fluid under American conditions could be decreased from geologic time scales to tens of years or in the worst cases as little as just a few years (Myers, 2012). The model used by Myers has however been heavily criticized (Saiers and Barth, 2012). Until yet, no scientific evidence of groundwater contamination due to direct migration of injected fracking fluids from gas formations due to fractures created by hydraulic fracturing into groundwater aquifers has been reported in the scientific papers. However, the number of valid studies is still limited (Gallegos et al., 2015; Mauter et al., 2014; Vidic et al., 2013), but recent publications have presented evidence of gas migration along wellbores, which were likely due to faulty well construction (Darrah et al., 2014; Vengosh et al., 2014). Detection of changes to groundwater quality in aquifers due to direct migration of fluids from the gas formations, however, is related to several factors e.g. the travel time, travel distance, preferential flow in natural and induced fractures and the ultimate dilution and detection of gas-related waters in aquifers. In some areas, however, the gas contaminated water is not likely to reach drinking water aquifers whereas in other areas, some constituents of concern simply may not have yet reached the aquifer or have been diluted to below detection limits.

After nearly 70 years of hydraulic fracking; there are reports showing that the contamination of some groundwater reservoirs have taken place and that the impact on the river's quality in some areas has deteriorated over longer periods. One must master time, noting that because of the almost lack baseline monitoring of surface and groundwater is difficult to quantify the effect size and cause of the impact.

Developments of techniques within unconventional gas exploitation are fast, especially during the last decade, and at the same time both economic requirements and environmental requirements have been strengthened. Therefore, the available scientific literature is already somewhat outdated with respect to the methods that the gas companies are currently using. Further, the monitoring of the environmental conditions has also been tightened considerably.

This report is therefore based on the three previous reports on literature review (report D8.1, D8.2 and D8.3), supplemented by the other reports within SP2. However, this report also draws on the experience of unpublished data and knowledge gained in recent years.

3 WELL PAD AND WELL CONSTRUCTION

The construction of the drill site includes a wide range of excavation works and arrangement of crew facilities. Work on large machines and materials for the well pad do not normally present greater risk to surface water or groundwater. Nor does lying of membranes, casting of concrete surfaces, and the construction of access roads pose any increased risk.

3.1 Water use

Data of water use is sparse for hydraulically fractured wells in Europe; however collection of data is ongoing, and may help to better understand the relative volumes of water to be used in hydraulic fracturing in different geological settings. The regional differences in geologic and hydrologic settings might show the differences in the amount of water used for hydraulic fracturing and by this the amounts of wastewater produced. In addition, with information of the local climate and the management practices, the possible potential for environmental impacts including water availability, change in water quality, wastewater disposal might be deducted.

From data available at present, the amount of water used per well in US varies from 2000 m^3 to 100,000 m^3 per well with an average of 16,000 m^3per well when averaged across seven gas provinces (Kondash andVengos, 2015). The differences in water use depend on the geological characteristics, well depth and length and fracturing methods e.g. chemicals used and fracture stimulation design (EPA, 2012, Freyman, 2014, Nicot et al. 2014). In general, 10% of the total water is used for drilling and <90% for hydraulic fracturing, and only a minor part is consumed by infrastructure (US-DOE, 2014).

Data collected in the US and Canada is based on drilling completed over several years, which means that the newer technique developed in recent years, was not taken into account. The net amounts of water used for new wells appear to be much smaller as the fracking technique has been optimized.

In US, the average annual water volumes according to FracFocus used for hydraulic fracturing operations were generally less than 1% of total water use in the area. This indicates that hydraulic fracturing operations represented a relatively small user of water. However, there are areas where the general lack of water is a problem and where at least the former water needs for hydraulic fracturing would pose an additional problem.In these areas, hydraulic fracturing operations represented a relatively large user of water. Local impacts on drinking water quantity have occurred in areas with increased hydraulic fracturing activity. Water withdrawals for hydraulic fracturing contributed to these conditions, along with other water users and the lack of precipitation. In Texas, groundwater impacts have been reported (Scanlon et al. 2014). The study showed a lowering of the groundwater table in around 6% of the area as much as 61 meters, after hydraulic fracturing activity increased in 2009.

Recent droughts in California and concerns about water use for hydraulic fracturing shows the need to inventory water use for oil and gas production (Tiedeman et al. 2016). The increasing water use has caused important implications for water management and has potentially environmental and ecological impacts. With some exceptions, hydraulic fracturing uses a relatively small percentage of water when compared to total water use and availability in general. However, hydraulic fracturing water withdrawals can affect the quantity and quality of drinking water resources by changing the balance between the demand on local water resources and the availability of those resources. Further, lowering of groundwater table may reduce discharge to the surface waters, which may cause major ecological effects. To minimize the frequency and severity of the impact on environment and on drinking water resources, public authorities should ensure that the operators develop project-specific water-management plans to ensure that water is used efficiently during the entire project. The water management plans should take into account seasonal variations in water availability and avoid using water sources under stress.

4 DRILLING

4.1 Drilling mud

The drilling mud is mostly mixed at the well pad and then pumped down in the well during the drilling and circulated down to the drill bit where it lubricates the borehole. The terminology and classification of the drilling mud is not clear-cut, but is generally divided into two classes: the water-based (hydrophilic) and the oil-based (hydrophobic). During mixing and handling at the well pad, there is a risk of unattended loss to the surroundings, and due the content of a large range of chemicals, there is consequently also a risk for contaminating soil, surface water and finally groundwater. However, it is not a high risk, as many of the previously used chemicals have been replaced by more benign chemicals and more modern techniques (King 2012).

4.2 Cementing, pumps and pipes

The most common problem in well construction is a faulty seal in the annular space around casings that is emplaced to prevent gas leakage from a well and into the aquifer (Gorody, 2012). The incidence rate of casing and cement problems in unconventional gas wells has been reported as 1 to 2 % and up to 3.4% (Considine, 2012, PA DEP, 2013). Most of the time, gas leakage is minor and can be remedied. However, in some cases attributed to leaky well casings, stray gas accumulated in private water well in Pennsylvania exploded. Other places within the Marcellus area groundwater wells showed that the maximum methane concentrations were higher when sampled from wells within 1 km of active Marcellus gas wells as compared with those farther away (Osborn et al. 2011). The presence of stray gas in some drinking water wells within one km from shale gas wells was confirmed ina later study (Jackson et al. 2013) where both isotopic signatures, methane-to-ethane ratios and noble gas ratios were analyzed.

Oil and gas wells can, however, develop gas leaks along the casing years after production has ceased (Dusseault et al. 2000). The authors of that study conclude that: “The reason is probably cement shrinkage that leads to circumferential fractures that are propagated upward by the slow accumulation of gas under pressure behind the casing.” This calls for the use of better cement formulation and strategies for long-term monitoring of gas leakage after the wells have been closed down. The problem is especially pertinent for future abandoned or “orphan” shale gas wells were the ownership will be unclear (Kang et al. 2014). Shale gas companies should therefore present long-term strategies for monitoring and remedy of abandoned shale gas wells, and the authorities should develop strategies for the long-term monitoring and handling of shale gas wells that belong to companies that go bankrupt. In comparison, the problems with drilling mud must be considered small, safe mixing of drilling mud at the wellpad can take place without problems prevent pollution if wellpad has a completely non-permeable membrane.

5 HYDRAULIC FRACKING

5.1 Fracking liquids and chemicals

Chemical additives in the fracking fluids used for hydraulic fracturing may include friction reducers, scale inhibitors, and biocides. Formerly many chemical were applied in U.S. and Canada, but several local authorities currently require that all chemicals must be published online, and many companies are voluntarily disclosing this information (FracFocus). On the other hand, many chemicals added for fracturing are still not regulated by the U.S. Safe Drinking Water Act, raising concerns about contamination of surface water and drinking water supply.

However, during the last decade a high number of the 1200 chemicals and other components that were used in hydraulic fracturing, has been replaced or omitted as additives. Recent developments in fracking techniques has led to the current use of far fewer additives during the entire fracking procedure in the US / Canada, which has resulted in an immediate reduction in the risk of groundwater and surface water contamination. A review of possible or used additives and chemicals and their properties and hazards are presented in the report D10.1 and D10.2. Some of the remaining additives presently used, can cause environmental problems when they return to the surfarce in the backflow water. Consequently, special care must be taken in the disposal of these. Four commonly used options for disposal include storage in open air pits for evaporation, underground injection, treatment and then discharge or recycling the fluid for additional fracking operation.

Due to different operators and different geological settings the variability of additives, both in their purpose and chemical composition, means that a large number of different chemicals have been used for hydraulic fracturing. The US-EPA has identified more than 1200 chemicals, which have been used in hydraulic fracturing fluids from 2005 to 2013 (US-EPA, 2015a+b).

Fracking fluid may have harmful effects to the soil and groundwater, and this is important to be addressed. Selecting the proper sites and high-quality cementing of well casings will diminish the risk of groundwater contamination.

As impacts on surface water and groundwater resources have been documented, studies on site-specific factors that could be used to describe the frequency or severity of impacts are not available. Because these factors influence whether spilled fluids reach groundwater and surface water resources, they affect the frequency and severity of contamination of drinking water resources from spills during the chemical mixing stage of the hydraulic fracturing liquid.

It has to be emphasized that the proper management of injecting, hauling and disposing of these fluids is maintained and that the most serious of chemical in the fluid is always designed to be kept from contaminating groundwater.

Hydraulic fracturing fluids and additives have reached surface water in some cases during the chemical mixing stage and have the potential by infiltration to reach groundwater resources. Small spills of various volumes have reached surface water, whereas large volume spills may travel longer distances to groundwater or surface waters, which increase the frequency of impacts on drinking water resources. In addition, concentrated additives may result in more severe contamination of drinking water resources than small volume spills. Impacts on groundwater resources must be classified as more severe than impacts on surface water resources because of the much longer renewal time of groundwater and the difficulties to remediate.

Consequently, spill prevention and immediate response activities has to be designed as a standby to prevent spilled fluids from reaching groundwater or surface water resources and minimize contamination from spilled fluids or chemicals.

In many phases of hydraulic fracturing is the aqueous environment exposed to dangers targeting effects on drinking water resources. This depends in part on the composition and amount of the chemicals, that enters the environment, as well as the properties of the chemical substances and the effect on the surroundings, and finally, how they move and are converted in the environment. Therefore, some chemicals in hydraulic fracturing liquids are of more concern than others, because they are more likely to move with the water by spills to the drinking water, and may proceed in the environment for long periods if they are not degraded.

5.2 Fracturing fluid storage

Since the start of the first oil and gas wells were drilled, impoundments or pits have been used to store drilling fluids and wastes. Pits as excavated holes in the ground are used for storage of produced water, for emergency overflow, or for temporary storage of the fluids used to complete and treat the well. Instead of impoundments, above ground container or tank systems such as steel tanks can be used.

The storage of fluids within impoundments is the most risky element in the prevention of contamination of shallow ground water due to the volume size. The failure of a tank, or a pit liner, can result in a release of contaminated liquids directly into surface water or shallow ground water. Normally, liners are constructed of compacted clay or synthetic materials like polyethylene or treated fabric. Environmental remediation of these accidentally released fluids will be a costly and time-consuming process and most of all technical difficult. Therefore, prevention of releases is vitally important. In a number of states in US, the use of impoundments has been banned (Pittsburgh Post-Gazette, 2015). Depending on the state, there are a number of other rules regarding pits and the protection of surface and groundwater (FracFocus).

New systems have been developed that avoid the use of pits. One technology that is becoming more common is closed loop fluid handling systems. These systems avoid the use of pits by keeping fluids within a series of pipes and tanks throughout the entire fluid storage process. Since fluid is never placed into contact with the ground, the likelihood of groundwater contamination is minimized, although pipes might leak if not maintained and monitored properly. Such systems are highly recommended.

5.3 Flowback handling and disposition

After hydraulic fracturing has been performed, fracking fluids will return to the surface over a period of time. Depending of the geology, fracturing practice and production launching, the flowback volume may be highly variable of the total amount of injected water. Recent estimates from the US are in the low end with only an average of 2% of the injected fluid returning to the surface for the Barnett formation, 3% for the Eagle Ford formation and 4% for the Haynessville formation. Thus, most of the injected hydraulic fracturing and drilling fluids may be imbibed into the shale formations within 3 months after fracturing (Kondash et al, 2017; Birdsell et al., 2016). Estimates calculated by Birdsell et al., (2016) indicate that: "significant fractions of injected fluid volumes (15–95%) can be imbibed in shale gas systems". This has led to the conclusion that "Imbibition of hydraulic fracturing fluids into partially saturated shale is an important mechanism that restricts their migration, thus reducing the risk of groundwater contamination" (Birdsell et al., 2016).

The original fluid used for fracturing may furthermore have changed during the process due to reactions at high temperature and pressure. Besides this the flowback can also contain brine and suspended matter from the fractured shale formation. It is therefore essential that flowback water should be managed in a proper manner.

In US the regulating of wastes such as flowback fluid lies on the state regulatory agencies, which means that there can be quite different jurisdiction over waste management. The vast majority of flowback fluids are disposed of in underground injection wells, which must be conducted in a Class II injection well as described in the US-EPA-report (US-EPA, 2016). While proper disposal of flowback fluids into permitted and monitored injection wells may be the most effective means of safely isolating these fluids from the near-surface environment, the specific geological settings required for such wells do not exist in all areas.

In areas where injection in deep underground is not possible or legal, there are other methods of handling flowback fluids such as treatment and discharge or reuse. Treatment of flowback can be conducted on-site or transported to centralized treatment facilities. Depending on the treated water discharge may be allowed in US under state or federal law, under strict controls from a state or the federal environmental protection agency.

5.4 Recycling

Treated flowback fluid may be recycled for other purposes, instead of simply disposing of it. Technologies as filtration, reverse osmosis, decomposition in constructed wetlands, ion exchange and others may eventually result in the widespread practice of recycling flowback fluids for hydraulic fracturing to reduce water consumption. Due to advanced technology this practice has been used by an increasing numbers of companies.

5.5 Hydraulic fracturing and the risk

Flowback water may, as described in the reports D8.1-D8.3, contain many compounds or minerals originating from the fractured shale. In addition, some of the chemicals used for the fracking procedure may have been transformed into other components. Minerals and cuttings may contain components which could be a risk if disposed directly to the environment, for example concentrated brine, heavy metals or radioactive elements. The potential risk from chemicals in the hydraulic fracturing water may vary from site to site and at the same time the characteristics of flowback water are influenced by the geochemistry of the fractured shale. To understand whether specific compounds or chemicals can affect human health through their presence in drinking water, data on concentrations in drinking water would be needed. This is rarely the case, and as mentioned earlier, new components may be present in the flowback due to transformation processes during fracking. However, as the high numbers of formerly used chemicals has been reduced during the last decade, the risk from the added chemicals might be minor when applying modern, state-of-the-art technology. But still data might not be available in all cases. Data alone, however, are not sufficient to determine which chemicals have the highest potential to contaminate groundwater and drinking water resources.

6 GAS PRODUCTION

During the actual gas production, the amount of produced water can be very different. This is partly due to the geological conditions in and around the gas producing shale and partly the way the hydraulic fracking has been going on. Some shale can be very dry and not of producing as much water while others shales may be more fractured and therefore more watery. Produced water is very different than flowback with respect to water quality, typically with a higher TDS, chloride, barium, and in some areas also radium-228 concentrations.

According to a recent summary of flowback and produced waters from unconventional oil and gas exploration in USA (Kondash et al. 2017), the estimated median volumes of wastewater ranged from 1700 to14,300 m^3 per well over a 5-10 year's period. The gas-producing shales showed considerable variation with a low median production of wastewater for the Marcellus formation (17000 m^3 per well) and higher production volumes for the Barnett (9000 m^3 per well), Eagle Ford (6100 m^3 per well) and Haynesville (11.6000 m^3 per well) formations. This study also demonstrated that 20-50% of the wastewater was produced during the first six months, and that the fracturing liquid constituted only 4-8% of the total wastewater, while the rest was formation brine. A clear distinction between the initial flowback water and produced water, i.e., when flowback stops and produced water starts to flow, is not practically possible as there will be a gradual transition where the brine content increases during the first months after fracturing. For instance, the average content of formation brine in seven wells from the Marcellus and Barnett formations, reached 70% after 30 days and 85% after 60 days (Kondash et al. 2017).

High concentrations of various other chemicals have been observed in produced water before treatment. The knowledge of the chemical composition of produced water is based on analysis of produced water samples, and requires advanced laboratory equipment and techniques that can detect and quantify chemicals in produced water, for example, organic polymers or naturally-occurring organic compounds, or benzene, toluene, ethylbenzene, xylenes, oil and grease. But produced water may also contain many constituents, as chloride, bromide, sulfate, sodium, magnesium, and calcium, metals, or radioactive materials, including radium. During the first period of production there might be remains of fracturing chemicals and their chemical transformation products and finally the total TDS content is very high in many cases several times higher than seawater. The high content of TDS in produced water is mostly due to salinity. USGS report that TDS ranges are up to 632 g/L in the Bakken, up to 476 g/L in the Marcellus, and up to 300 g/L in the Barnett, and 317 g/L in the Eagle Ford (USGS, 2016). This has implications for developing water recycling and reuses methods, including strategies handling the amount of water to recycle and the technology to use for recycling. However, some wastewater is transported over very long distances to wastewater treatment facilities increasing the risk for spill or accidents, which imply that on-site wastewater disposal methods deserve further research.

As the volume of produced water generally decreases with time, so that the volumes handled on site immediately after hydraulic fracturing and the start of gas production can be much larger than the volumes to be handled. The volume of produced water may vary from site to site, due to geology, and time after hydraulic fracturing. In dry shales produced water might count for less than the injected fracking liquid, while in shales with fractures connected to adjacent formations, the volume could excess the injected volume many times.

Reports on spills of produced water in the United States have been collected by US-EPA in a large database (US-EPA, 2015c). A risk assessment of contamination of the environment showed that the most common causes of produced water spills are related to human error, leaks from pipelines or valves or technical failures like storage leaks. The identified hydraulic fracturing-related spills have been characterized by numerous low volume spills of a few m^3 or less, and relatively few large-volume spills of 50 m^3or more. Some of the spills of produced water have reached groundwater and surface water resources. About 13% were reported to have reached different surface water habitats and only one has reached groundwater so far. Fisher and Sublette (2005) counted spills in Oklahoma between 1993 and 2005. More than 16,000 were identified and of these was 75% identified as exploration- and production-related releases of oil or saltwater. The primary origins the releases were leaks from lines, tanks, wellheads, surface equipment, and pits and 34% of these releases resulted in reported impacts to environmental recipients. Similar studies from Pennsylvania confirm these trends.

6.1 Produced water handling and reuse

As mentioned above, produced water volumes are highly variable making a simple decision difficult to find the best treatment and disposal practices. There are many technical and legal issues that must also be taken into account. For companies and operators, there are also economic considerations, which should be compared with the environmental risks, which can be crucial to which option to choose. Many technical solutions may be taken into account and has been for many years. The produced water has in America been managed using some of these techniques: evaporation ponds, deep-well injection, on-site treatment, or centralized treatment plants. A part of these techniques are less use at present due to changes in legislation or environmental protection and in some case also the impact on humans.

In many cases, storage in tanks or open pits is practiced even this step may increase the possibility of leakage or spills. In some states, collecting pits for produced water storage are allowed before disposal; however, the practice of the latter varies throughout the state (Torres et al 2016). In warm areas, evaporation from the pit is allowed because the rates of evaporation are favorable. The on-site treatment, which occurs within the proximity of the well pad, is applied in less frequently in the Barnett (Nicot et al. 2014), whereas in Pennsylvania impoundments have been banned. Some states have due to lack of disposal possibility exported produced water to neighboring states, which also increases the risk of spills and accidents (Detrow, 2012). Such inter-state transport of waste water should be reduced to a minimum within EU. In Pennsylvania about 75 % of the total produced water was treated in industrial wastewater treatment plants (Rozell and Reaven, 2012). However, the Pennsylvania Department of Environmental Protection has now requested companies to reduce disposal through wastewater treatment plants in order to protect surface waters, resulting in a present wastewater reuse of 70% (Ferrar et al., 2013, PADEP, 2014).

Exploration and production companies are under pressure to reduce the amount of fresh water used in dry areas like Texas or California, and to cut the high cost of pumping water to gas wells for later having to find methods of disposal in an environmentally sound manner. Until recently, many companies considered recycling too expensive or worried that using anything other than freshwater would reduce well output. But the companies are increasingly treating and reusing flowback water from wells, which unlike freshwater is very high in salt, with good results. However, the practice scales down the amount of freshwater used for fracking, but still concerns about groundwater contamination have not been eliminated. Increased industry comfort with recycling comes as regulators are moving to require more recycling of water used in fracking. But many documented cases of surface water and groundwater impacts from produced water spills provide information of the types of impacts that can occur. In most of the cases reviewed for this report, documented impacts included elevated levels of salinity in groundwater and/or surface water resources. As Pennsylvania has completely eliminated the use of surface impoundments for wastewater storage the risk for contamination of the environment has been diminished.

Wastewater sent to centralized treatment of is emerging in many states in US as a solution for long-term efficiency in managing wastewater treatment and in handle both the flowback and produced wastewater within a region, up to 75 km in radius with pipelines connecting all well pad directly.

Initiatives similar to those from the Pennsylvania Department of Environmental Protection stresses, that future trend in water consumption for gas drilling should represent more recycling of water for fracking, and perhaps a greater use of other types of water, such as treated wastewater. There is a need for an industrial initiative to develop and manage these water-related issues, if unconventional gas producers should be able to effectively manage their operations environmentally sound and maximize profits. Centralized water management permits sewage treatment must be carried out on economies of scale, reducing capital costs for treatment and distribution systems, and reduces operating costs.

Impacts on groundwater from shallow disposal of hydraulic fracturing waste water have been documented (Llewellyn et al. 2015). For example, leaching and discharge have contributed to elevated levels of total dissolved solids and especially bromide and chloride which has been related to increases of hazardous and toxic brominated disinfection byproducts found in surface water and drinking water.

Past disposal of waste water (flowback and produced water) has affected groundwater quality, as shown in Ohio and Texas (Kell, 2011). Other cases of impacts have been identified in several states with influence on groundwater included detection of volatile organic compounds. Based on documented effects on groundwater resources from unlined pits, many States have introduced rules banning seepage pits or unlined storage pits to either hydraulic fracturing waste water or waste in general.

As the fracking fluid, and especially the formation brine, has high salt contents, pollution of groundwater and surface water would lead to increased electric conductivity. Mandatory, continuous monitoring of electric conductivity in groundwater and nearby surface waters during hydraulic fracturing and the following years of production would therefore be an efficient means of early warning when a pollution event is taking place.

The presence of salts, heavy metals and radio-nuclides in the large volumes of formation brine, that are produced over the life-span of a well, may pose a greater risk than the added fracturing chemicals. The authorities should therefore ensure that the operators develop adequate strategies for the produced water. Operators should ensure the traceability of water flows, estimation of wastewater volumes, as well as proper treatment strategies for wastewater contaminants in, before licenses are granted for large-scale exploration of shale gas.

6.2 Radioactivity

A special problem for unconventional gas extraction is that shale and mudstone may contain varying levels of naturally occurring radioactive material (NORM) such as thorium and uranium. The material in question is low to medium level, naturally occurring radioactive material present in the brine and shales that comes from the ground during the drilling process. In USA, the low-level radioactive material is regulated by the single states, giving them jurisdiction over how such things are disposed of. However, there are two classifications of radioactive material come from drilling: NORM and TENORM; NORM (Naturally Occurring Radioactive Material) and TENORM (Technically Enhanced NORM). That means its natural radiation has been concentrated by human activity, like recycling drilling mud during fracking operations, which imply that TENORM has to be disposed of in specially built landfills. In some states NORM waste may be deposit in normal landfills, whereas TENORM cannot.

These elements (Uranium and Thorium) will decay over time. Daughter products include radium-226/228 may form radium salts, which are relative soluble in water and can be transferred to unconventional gas flowback and produced water (Vidic *et al.*, 2013).

Flowback and produced water from hydraulic fracturing operations has formerly been disposed to wastewater and processed by public sewage treatment plants, which in most cases are incapable of removing the radioactive components, which often has led to release into major rivers. The other problem is that the two radium isotopes have relative long half-lives. The longest lived, and most common, isotope of radium is ^{226}Ra with a half-life of 1,600 years.

Several studies had shown that water sampled downstream from wastewater treatment plants found the creek sediment contained levels of radium 200 times background levels and that river water also has content of radioactive elements (Warner et al 2013).

Because of the long half-life of radium isotopes will a spill be critical since leaching into the groundwater could do this useless for many years as drinking water. Measurements of radioactivity in flowback and produced water in Marcellus Shale have shown concentrations of total radium between 73 and 6,540 pCi/L (Haluszczak *et al*. 2013), with a highest concentration of 10.000 pCi/L (Acharya, *et al*. 2011). These figures are far beyond the permitted level for drinking water in US. The concentration limit for drinking water is 5 pCi/L, (Rowan *et al*., 2011).

Brine water that flows back from a number of hydraulic fracturing sites in Pennsylvania and Virginia in the Marcellus Shale region after hydraulic fracturing is many times more salty than seawater, with high contents of various elements, including radium and barium.

To reduce the risk of contamination of the environment in the areas where shale contains high concentrations of radioactive Uranium and Thorium, the handling of fracking water as well as produced water should be under tighter control. Specifically, it would be advisable, that fracking water and produced water were pre-treated on site to reduce the content of radioactive elements in the effluent. During pre-treatment, radioactive waste will be transformed from a dissolved state into a precipitated solid state. This means that strategies should be developed for the treatment and storage of a concentrated solid waste of radionuclides. In addition to dissolved radium salts in the wastewater, there will also be significant amounts of dissolved radon gas that may escape to the atmosphere or decay into the "radon daughters", who can accumulate on the surface of pipes, valves, fittings etc.

6.3 Risks of spreading fracking waste on roads

In the US, waste from fracking operations is exempt from federal hazardous waste regulations (US- Environmental Protection Agency). Generally, the individual states which authorize the produced brine to be spread on roads to ice or dust control. A risk for contaminating is the practice of road spreading of wastewater for deicing purposes. US EPA emphasize that produced water may still contain chemicals from the fracking process and may also have high concentrations of natural contaminants. US-EPA notes that produced water (brines) may still contain chemicals that have been used in fracking process and, therefore, also have higher concentrations of natural contaminants, due to its prolonged contact with the shale formation.

As mentioned above wastewater from some shale contains considerable amounts of naturally occurring radioactive material (NORM) which is not acceptable for spreading on roads. Besides NORM material other chemicals may be present as heavy metals, organic substances and alike. Spreading of wastewater on roads increases the risk that pollutants will leach into surface water or groundwater and must as such be avoided, (Poole, 2013).

6.4 Wastewater Disposal

Many threats against groundwater quality are obvious during the whole process of extracting unconventional gas. The surficial disposal of hydraulic fracturing wastewater has impacted the quality of groundwater and surface water many places. In particular, discharges of insufficient treated wastewater lead or leached to surface water have contributed to elevated levels of toxic chemicals both river systems as well as groundwater.

Effects to surface and groundwater depend on the geological conditions, environmental vulnerability, chemical properties, and the volume of spills (Schwarzenbach et al., 2006). These parameters may have weight in different situations so a small volume spill of a toxic chemical into a small water body may have a more serious impact on the water quality. Additionally, the chemical composition of a spill can affect the ability of spilled fluids to move to the groundwater and therefore it is important to evaluate the potential for spill to influence surface and groundwater quality.

The major risk for spill of wastewater may be attributed to four main processes during shale gas development:

- Leakage from lined and unlined pits for the storage or disposal
- Overflow from lined and unlined pits for the storage or disposal
- Breakage or failure of pipelines and valves
- Accidents in transporting wastewater from well pad

Spill prevention and immediate response may prevent spilled fluids from reaching groundwater or surface water resources and minimize impacts from spilled fluids. If spills happens outside the well pad the soil property and the sediment below might influence the flow either towards the groundwater or in absence of permeable subsurface more likely to surface water or wetlands.

In conclusion, spills from surface impoundments/pits and wrecked trucks leaking pipelines or infiltration directly to groundwater though broken liners are potential risk for surface water and groundwater contamination.

7 SOLID WASTE

Solid waste from shale gas drilling can in general terms have three sources, dewatered drilling mud, cuttings from the well and finally TDS from flowback and produced water. In this regard, we ignore the wastewater and solid waste from the crew.

Drilling muds, which contains the rock cuttings, are brought to the surface where the liquids and solids are separated on a shale shaker or by other methods. The cuttings are generally dried and left as a solid waste, and the mud is reused and sent back down the well. After drilling is completed in a well, muds must be reused or properly disposed.

Drilling muds contain a base fluid of water- or oil based compounds; a high density agent as barite, clay; and a stabilizer, which could be CMC, lignosulfonate, lignite a.o. During the drilling operation the drilling mud come into contact with mineral salts and organic matter in the various geological strata drilled, which means that drilling mud changes its chemical composition and, therefore, may contain environmentally hazardous substances when it returns to the surface. Shales naturally contain salts, metals, organic matter and sometimes also NORM material. After final use the drill fluid has to be dewatered or dried and due to the content of quite a lot xenobiotic compounds it has to be treated as industrial waste. In case of radioactive elements analyses must determine if the waste is TENORM and consequently must be disposed as such due to legislation.

Cuttings will come from the drilled rocks from the surface to slate and from shale itself. Although the composition of such cuttings is generally not of concern, the amount of cuttings from the shale may be quite large depending on the total length of each well. The drill cuttings reflect the geology the drill has passed during drilling. Therefore, cuttings from the shales have a quite different composition than the ones that came from the overlying strata. This is essential for the composition of cutting from the organic rocks such as these will have a high content of labile organics. Most shale formations were formed from the middle of the Cambrian and the late Jurassic. The deposits of organic matter and clay and silt minerals occurred in marine or limnic anoxic environments and especially in epi-continental marine basins and were limited to estuaries. In areas close to the bedrock shields erosion could cause that large quantities of uranium and thorium was washed out, after which they were bound to the organic matter in the sediment. There are in these areas with a high organic production also high content of radioactive elements, (Mykowska et al. 2015, Fisher, 1998). These organic rocks will typical also be those containing the high amounts of NORM components that can be present as a result of uranium and thorium decay products, which is associated with the organic content of the shale. The amount of NORM cuttings from a modern well pad might exceed 2000 tons (20 wells and 2400 meter horizontal drilling). Besides radioactive components the cuttings may contain heavy metals, arsenic and organic material, which in open pits or deposits is leachable.

Materials that contain trace amounts of TENORM are present in the rocks and minerals of the earth’s crust and sometimes in the shales (black shales), and has very high concentrations of radionuclides that can result in elevated human exposure to radiation. There is different legislation between US-states of how to dispose cuttings. The U.S. EPA, National Academy of Sciences, and American National Standards Institute all recognize drill cuttings as TENORM upper sit to the situation in Ohio. At the same time US EPA recommend radioactive shale materials that exceed the safe level of 5 pCi/g not intended for disposal in solid waste landfills nor a hazardous waste landfills. Radioactive materials exceeding this level should instead be disposed of by shipping the waste to licensed low-level radioactive waste landfills.

Improper handling, storage, or transport of shale gas waste can lead to leaching and other releases of pollutants that contaminate land and water with toxic material or just improper concentrations of ionic compounds. The authorities should therefore require regular testing of shale waste to assess whether waste from any given source, through a given period of time, possesses contamination characteristics of surface water and groundwater. This would makes it possible for operators and regulators to treat non-TENORM waste by using existing treatment and disposal systems.

The authorities within the EU countries should ensure that adequate strategies are developed for monitoring of leachate content, for reducing pollution of groundwater and surface water by leachate, and for the long-term handling of leachate before granting licenses for large scale shale gas exploitation.

8 FINAL REMARKS

In order to minimize the risk of unconventional gas production it is essential to collect data to perform risk assessment and reduce uncertainties. During decades the extraction of gas has been a water-consuming process, which in some regions has been a challenge with regard to the need for drinking water and for the environmental standard in rivers and wetlands. However, new techniques have slightly diminished the need for water for the fracking process. Moreover, the extended use of chemicals required in the procedure has also been minimized.

The risk of spills that is still present in different phases of the process can be avoided with proper handling and management techniques. At the same time, this is encouraged by the increased attention from citizens and a change in legislation and monitoring of the aquatic environment. Improved understanding of the fate and transport of contaminants of concern and increased long-term monitoring will help effectively manage water-quality risks associated with unconventional gas companies in the future.

The increasing awareness during well injection, hydraulic fracking and the chances of well failure and leakage at present are always required. In spite of a minor usage of natural water resources and increasing reuse of water the management of produced water can be improved by applying proper handling techniques, less transportation, and increasing improvement of storage tanks, impoundments, and pipes. The fast-growing international shale gas development has to gain experience from the US and Canada to develop their own strategy for water consumption and waste water management. However, it should be recognized that there are differences in EU legislation compared to that of USA.

Confidentiality requirements dictated by legal niceties coupled with the prevailing desire for sustainable economic development while the limited funds for research are major obstacles to peer-reviewed research on the possible environmental impacts. It is therefore time to work with these environmental issues to avoid a negative environmental legacy that could be likened to the situation of the abandoned coal mines in North America.

The amount and quality of waste water associated with shale operations varies as a function of the geological formation and operators in the art. It can vary even within the same shale play and perhaps over time.

Until recently, drilling companies wanted to use only freshwater to their shale gas operations, but the use of alternative water sources and reuse / recycling of wastewater has been increasing growing. But because fracturing fluids require very specific quality requirements for composition, technologies for wastewater treatment has been developed in the last few years, which means that operators can use water sources with a much higher content of TDS. These trends in the development means that the risk of contamination of the environment has significantly been reduced and the amount of waste to be disposed were significantly less.

Although deep injection wells have been the most common treatment option in the USA, the advanced wastewater treatment has become more common. Some places in the United States, operators of unconventional gas extraction have transported sewage to central treatment plants for later either discharged or returned to the operator for reuse/recycle in fracturing. Decisions on wastewater treatment is primarily based on the TDS content in the US, while NORM waste has become a major challenge which unfortunately is not resolved.

8.1 Contingency plan for accidents and spill

No matter how well you can organize and carry out drilling work and subsequent maintenance of the production of shale gas, there will always be a potential for either technical or human accidents that can cause spills. Therefore, it is imperative that a spill contingency plan should provide emergency procedures to mitigate environmental and safety impacts from unplanned or accidental releases into the environment. Such a plan must include action against emissions, both for situations where emissions occur from authorized operations or activities where there is exceeding the allowable discharge limits. Contingency plans for spills must provide enough detailed instructions for efficient systems, processes, procedures as are necessary to minimize the impact on the natural environment from unauthorized or accidental releases; while protecting crews and residents around the accident site.

The main concerns is the risk of deterioration in the quality of groundwater and surface water and how safe disposal of large amounts of sewage and waste can be done without adverse effects on communities and ecosystems These concerns will vary from area to area because of various geological, environmental and socioeconomic conditions, and will depend on the technologies used.

In North America, several thousands of shale gas wells currently are in production and new come every year. Despite a number of accidents and incidents, it is still very difficult to scientifically assess the extent and significance of environmental damage because the necessary research and monitoring has not been done. Especially lacking in many places a baseline monitoring, this could provide an opportunity to identify changes in surface water and groundwater.

Data is missing or sparse for the characterization and assessment of environmental impacts of shale gas development adequately, especially in relation to potential groundwater contamination from spills and disposal of solid waste. There is no vulnerability mapping and systems in place to identify the areas in Canada and the United States, where hydraulic fracturing will be so risky that it would not be appropriate. Although much is known about minimizing risks associated with surface activities, there has been almost no monitoring to assess the risk of solids and liquids polluting shallow groundwater from the surface to the aquifers as a result of drilling, hydraulic fracturing, insufficient proof seal and good shutdown.

8.2 The knowledge gaps and data uncertainty

The radical land-use, which is characteristic of shale gas extraction, poses an unquestionable need to coordinate a variety of information about the area. This should be made within the concession approved. However, this has not always been the practice during the many years where mining has taken place.

A large number of parameters must be considered to have an overall assessment of the landscape's vulnerability and to gain knowledge about the security of supply of water resources for drinking water and possibly for irrigation in agriculture.
There may be uncertainty about the location of drinking water resources, and especially could be deep groundwater resources in the future be potentially used for drinking water are not always known. If comprehensive data on the location of both water resources and activities in hydraulic fracturing water cycle were available, it would have been possible to more completely identify areas in the US where hydraulic fracturing activities either directly interact with water resources or have the potential to interact drinking water resources.

For regions, where there are shales with either high levels of heavy metals or shales containing radioactive substances, there is a lack of more complete and better knowledge of the leaching potential from solid waste dumps and further legislation for the correct safety and environmental best placement of temporary and final disposal sites.

In areas where we know the activities in hydraulic fracturing has taken place or occur, data that could be used to characterize the presence, migration or transformation of hydraulic fracturing-related chemicals in the environment before, during and after hydraulic fracturing. These data are rarely present and even more rarely are a complete set of the data necessary for a holistic assessment of the impact. Specifically, local water quality, that is necessary to compare before and after the hydraulic fracturing conditions are not normally collected or easily accessible.

Because of the significant gaps and uncertainties of the available data, it is rarely possible to fully assess the groundwater risks of a particular production activity. Thus, it may not possible for local decision to calculate or estimate the impact on the level of resources of drinking water due to activities in unconventional gas production based on hydraulic fracturing.

There is therefore a need for procedure and legislation in order to collect all the data necessary for a holistic assessment of the impact on the water cycle, both quantitatively and qualitatively.

9 CONCLUSIONS

The unconventional shale gas production is a highly water-intensive process at each location requires large amount of data to perform an adequate risk assessment to reduce uncertainties. The problem is that to date there are very few risk of non-conventional onshore gas production, comprising a holistic assessment. The public information on the chemicals used and effects on groundwater are incomplete because some of them are considered confidential in North America. A holistic assessment of risk should be conducted to fully understand the implications involved in the process and at the same time drawing up strategies for risk reduction action plans for accidents to improve safety.

The risk of spills and accidents that are present in several stages of the process can be minimized with proper handling and management techniques. Produced water management can be improved by using safe handling techniques, reducing transport and increasing the inspection of storage tanks and pipes, and to avoid impoundments. Further, a zero discharge of wastewater minimizes the risk of contamination of groundwater and surface water. The many water problems that are identified in the United States caused by unconventional shale gas production demonstrate the need for the development of strategies to minimize water shortages and pollution.

When drilling companies seeking authorization from a national or local authority to investigate shale gas, companies must provide comprehensive information on for example environmental and geological consequences of their activities. Baseline monitoring gives the authorities the data of chemical groundwater status before and after shale gas operations and is usually performed as part of an impact assessment environment.

i. Drilling operations is the first process in connection with the extraction process. The right casing of shale gas wells is crucial for the safety of the following operations. Good practices bring several layers of impermeable cement and steel casing to isolate the well. In particular, it is important that the annulus is sealed so that nothing may be able to migrate outside of the borehole. In addition, all wells are pressure tested to ensure integrity before hydraulic fracturing takes place.

ii. The hydraulic fracturing involves pumping liquid at high pressure into the shale rock to open the fractures. It does not seem like this pose any real risk of groundwater contamination as shale formations typically found between one and four kilometers below freshwater aquifers with potable water supply.

iii. After the hydraulic fracturing, an estimated volume of two to 22 % of the fracturing fluid (Vengosh et al., 2017) will be recovered in the first few weeks of production. At the same time, depending on the geological formation, the brine from the formation when the production of gas begins. In this connection, storage of flowback and produced water in open pits is inadequate, which also reflects in the US as this storage method is being phased out and the steel tank containers are increasingly used to store water before it is then processed or recycled. At the same time it is recommended that flowback increasingly should be reused for future hydraulic fracturing operations as profitability of recycling flowback water is increasingly viable.

iv. Use of waste from the wells to be restricted and only be reused if the material is thoroughly checked for hazardous substances, to meet the same standards as all other fixed or residual waste is considered beneficial uses. In particular, organic solvents, heavy metals and radioactive substances, which are substances which are not dealt in nature, but remains to be a threat to groundwater quality, and thus the drinking water utility. Further, it is recommended to establish a general rule of prohibition against burial and land-spreading of waste. Further, all waste shall safely be removed from the well pad within established time frames, and that the decommissioning of the plant will occur after the guidelines have been concluded for restoration and remediation.

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