Project Acronym and Title:

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

# SEEPAGE SHALE GAS WASTE IN DIFFERENT GEOLOGICAL CONDITIONS


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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 hazards of waste management and waste water by shale gas operations. There is a review of the abstraction of water for hydraulic fracking and the environmental problems that can arise for the other water abstraction for household and industry. A model example is given to illustrate the influence of abstraction for shale gas operation on an ecologically acceptable level in surface water and groundwater. Further, a list of a number of waste types and waste water types with different pollution-related content that might affect both surface water and groundwater. In addition, there is mentioned a number of conditions and limitations in the use of simulation models to predict the transport of pollutants into groundwater under different geological conditions. Finally, there are given various recommendations for the establishment and operation of shale gas abstractions.

 

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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 make 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 theme of this report is a review of the knowledge that is present from the North American region with regard to the environmental problems of waste and waste from shale gas extraction. There is a review of water consumption, waste types and possibilities of contamination during different geological conditions to surface and groundwater. Further viewpoint on modelling the environmental impact from water and groundwater contamination is given.

## 1.3 Aims of this report

The report treats some of the public dissemination of coupled groundwater-surface water hydrological modelling study on waste seepage during shale gas operations. The modelling provides critical boundary conditions for seepage of waste during shale gas operations, and thereby helps establishing mitigation measures to prevent waste seepage. The report gives some immediate gap in the knowledge for a safe development of unconventional gas.

 

# 2 BACKGROUND

Thousands of shale gas wells are currently in production in North America. Through the project *M4ShaleGas* we try to compile the available knowledge on the environmental risks, especially from the United States and Canada, supplemented by knowledge from EU countries. In a number of published reports have already collected a large amount of data and experience from projects dealing Shale gas development and environmental effects; see incidentally list of quoted M4ShaleGas reports in the reference list.
Due to a considerable number of accidents and incidents, the extent and significance of environmental impact has been difficult to evaluate because the necessary research and baseline monitoring have not been done. The lack of data for characterizing and assessing the environmental impacts of shale gas development adequately are pronounced, especially regarding to potential groundwater contamination and surface water damage. In general, no vulnerability assessment and management systems are in place to identify the risks to those areas where hydraulic fracturing will be performed. Although much is known about minimizing the risks related to surface activities, there has been almost no monitoring to assess the risks of solids and fluids contaminating shallow groundwater from surface to the aquifers as a result of drilling, hydraulic fracturing, inadequate well sealing, and well decommissioning.

Depending on size and pace at which shale gas exploits, this challenges the ability to assess and manage their environmental impacts. The main concerns is the risk of contamination of groundwater and surface water taking into account the safe disposal of large quantities of wastewater and the risk of increased amounts of solid waste. Special attention should be taken to the harmful effects on communities and land and adverse effects on human health. Further, other risks include the local release to surface water. These concerns will vary from area to area because of various geological, environmental and socioeconomic conditions, and will depend on the technologies used. Several thousands of shale gas wells are currently in production in North America.

Despite a number of accidents and incidents, the extent and significance of environmental damage is difficult to evaluate because the necessary research and monitoring have not been done, see f. ex. Marcellus Drilling News 2015. Data are lacking or are sparse for characterizing and assessing the environmental impacts of shale gas development adequately, particularly in relation to potential groundwater contamination from spills and disposals of solid waste. There are no vulnerability identification and management systems in place to identify those areas in Canada where hydraulic fracturing will be so risky that it should not be undertaken.

 

# 3 WATER USE

Total water uses for shale gas operation in European countries are not expected to stress the available groundwater resource beyond sustainability even though groundwater is used as the primary water source for drilling and hydraulic fracturing. The British Geological Survey (BGS) state that water uses for shale gas operation in United Kingdom will be less than 1 % of total groundwater abstraction, in average covering 27 % of public water supply in United Kingdom (BGS 2016). Even though this seems like a manageable water use, Broderick et al. 2011 conclude that for the UK, the freshwater resource are likely to be additionally stressed by shale gas production because the resource is already under pressure in several parts of the country.

In Denmark the estimated water use for the prospected available shale gas resource with exploitation during a 20 year period, will consume less than 0.5 % of the total annual groundwater abstraction (based on results from Hansen et al. 2016). In Denmark 100 % of water used in the public and private sector is groundwater, and it is estimated that around 70 % of the available sustainable groundwater resource for abstraction, is being used. With reasonable certainty, this leaves room for additional groundwater abstraction with shale gas plays, also considering the possibility of water reuse during drilling and hydraulic fracturing. Furthermore, it can assumed that in areas of shale gas operation, the shale gas plays will take over groundwater abstraction from other sectors, for instance from farming. Therefore, even with all the uncertainties related to the estimates of water use for shale gas exploitation, and especially with unknown size European conditions for shale gas exploitation, the total water might not threaten the groundwater resource in quantitative terms. Nevertheless, local, regional, and with a European perspective, national differences of water availability and water scarcity are very significant. Even under Danish conditions, with a proportional large groundwater resource, several aquifers are already being overexploited, although this is not the national trend.

In connection with the over-exploitation of groundwater the resource, both traditional and unconventional solutions have to be used. Not all sites are groundwater resource sufficient to cover both domestic and industrial needs while hydraulic fracturing requires large amounts of water. These problems are discussed in Fernández et al. 2015 and Gómez et al. 2016. The local groundwater resource can be overexploited by shale gas operation in several ways. One is a basic resource availability issue regarding either the size of the local resource compared with demand from shale gas uses, or simply withdrawing from an already exhausted or overexploited groundwater resource. Analysis on these issues considers, for instance, yearly water availability versus total water demand from all users, including expected demand to shale gas plays. Based on such an analysis, a sustainable aquifer management plan can be formulated, and water rights to public and private consumers and industry can be given. A sustainable aquifer abstraction plan is defined in order to keep the resource renewing itself, without degrading the water quality besides the water quantity over time. Basically, this involves keeping the groundwater head steady at a specified level, in affected aquifers. Another but not less important issue is the ecological recipients depending on groundwater input or high groundwater table in contact with the deeper aquifers, where groundwater extraction occurs from. For these ecological recipients, either aquatic or

 

terrestrial, the negative effects of groundwater overexploitation are generally related to specific seasons or periods of the year where the groundwater discharge or level can determine the ecological state of the given habitat. For example, are different terrestrial ecosystems dependent on groundwater (called groundwater dependent ecosystems), or fish habitats relaying on groundwater dominated base flows.
Water use intensity is very high around the actual fracking but modest at other times. Therefore, intense water use in an area with generally adequate groundwater resources could still thread local river ecology during low flow (via decreased groundwater base flow).

## 3.1 Potential effect on local groundwater resource

The following will exemplify how the groundwater resource could be impacted from a shale gas water use.

### 3.1.1 Sustainable water use

As previously mentioned, several factors define what sustainable groundwater uses are. Although some areas can have other important receptors affected by groundwater abstraction, the general conditions of concern are aquifer quality (which deteriorates with too high pumping relative to groundwater recharge), and groundwater dependent ecology (rivers/streams and groundwater dependent terrestrial ecology). It is obvious that the available groundwater resource for potential shale gas operation is assessed based on the total available groundwater resource for abstraction. Furthermore, it is understandable that the available groundwater resource is dependent on the amount of water that annually renews (recharges) the aquifer, as a result of precipitation and evapotranspiration (evaporation and transpiration combined). Therefore, it makes good sense to evaluate the (total) sustainable groundwater abstraction in relation to, or as a percentage of recharge (groundwater recharge).
The sustainable groundwater abstraction should be defined from the lowest of the different components, affected by the abstraction. For example, if aquifer quality can withstand an up to 30 % abstraction of groundwater recharge but river ecology can only withstand a 25 % abstraction, then the sustainable groundwater abstraction is defined as up to 25 % of groundwater recharge.

### 3.1.2 Storage of water used for shale

From North American experiences it is known that water storage is an important part of the water management in a shale gas play. The purpose of storing water is to have readily the right volume available, at a given time, were it’s applied for drilling or hydraulic fracturing, where most storage is needed for the later. The storage is utilized in different ways, for instance, as a storage facility of imported water, trucked in from non-local sources, where the process of replenishing the storage is time-consuming, and imposes a relatively high stress on the local infrastructure. Moreover, this involves a distant water source and discharge facility. When local water sources are applied the water storage facility will merely serve and be constructed as a result of the time needed to either route surface water or pump the total needed amount into the storage.

 

The storage of water is an important condition for the evaluation of a possible and sustainable groundwater abstraction for a shale gas operation. For instance, if storage facilities are undersized, abstraction of groundwater needs to be close to the time of well stimulation, e.g. at the time of high water use intensity. This could be problematic for a given groundwater dependent ecology, where the groundwater input is typically more important during some seasons than others, e.g. during summer low flows. The ability of intensive pumping is dependent on hydrogeology, and also decisive for appropriate storage facilities. In areas experiencing general water stresses, low abstraction during certain seasons are more important than for, water wise, non-stressed areas. Hence, more water storage capacity is needed in water stressed areas, regardless whether groundwater or surface waters are used for shale gas operation. Where deep aquifers are abstracted, stable and continuous pumping rates could minimize the effect on aquifer water quality and thereby setting conditions for storage. In the mentioned situation where low-flows in rivers during summer are the most critical recipient, it can be necessary to cease abstraction for the given periods of up to months, which again requires water storage to accommodate continuous shale gas operation.
Climate can affect the local water resource but also the ability of storing water, and maintaining water quality during storage. It is well known that water stresses are generally higher in arid and semi-arid regions than in humid ones, but climate, whether warm or cold, will also effect the ability to store water without degrading water quality, for instance by algae blooms in the storage basin, possibly in the time-frame of months. Generally, shale gas operators would prefer less storage capacity, and storage periods, to keep expenses for this part of the operation low on top of increased likelihood of water-storage-quality issues with longer storage periods.
The described need for storage management illustrates that management of water storage facilities should not only be done in order to secure shale gas water demand, but also in order to minimize impacts on aquifers and ecology. If these recommendations are followed, it is reasonable to evaluate water demand and sustainable groundwater abstraction on an annual basis. Looking at potential local water stresses from annual water balances require water storage facilities, designed to accommodate sub-yearly water stresses on local aquifers, and different types of groundwater dependent ecologies.

### 3.1.3 Areal shale gas water demand

The evaluation of the available water resource for shale gas can be done by calculating the water demand of the shale plays, for instance pr. square kilometer, and the water availability for the same area.
Lechtenböhmer et al. 2011 evaluated that drainage area for the US Barnett Shale are comparable with European shale gas conditions with 1.2 wells per square kilometer (0.87 $km^2$/well). Comparable drainage areas (0.49-0.81 $km^2$/well) are found by Gautier et al. 2013 for the Northern European Alum Shale. Gautiers numbers correspond to 1.2 - 2.0 wells per square kilometer. As with the water use per well, the drainage area per well, are highly dependent on local conditions, e.g. drilling depth, shale hydro-geo-chemical conditions, and environmental requirements. Hence, it is recommended that a local evaluation of well-drainage area is performed, before the drainage area is used for

 

a water resource evaluation. To find the shale gas water use per area, the drainage area per well is multiplied with the water use pr. well:
Water use per area (in volume, e.g. $m^3/km^2$) = Drainage area ($well/km^2$) * Water use ($m^3/well$)
For instance, if the estimated wells per area are 1.2 $well/km^2$, and a water use of 15,000 $m^3/well$ is expected, then the estimated water demand is 18,000 $m^3/km^2$ corresponding to 18 mm.

### 3.1.4 Areal groundwater recharge and other water uses

Groundwater recharge is very heterogeneous. Climate, soil type, area use among others affects the groundwater recharge. Therefore, an evaluation of the sustainable groundwater abstraction, rely on precise estimations of the local groundwater recharge. The estimation of groundwater recharge will always contain uncertainty, thus an estimate of the uncertainty range, e.g. in term of a confidence limits, should be included. Other water abstracted in the area should also be assessed at a local level in order to achieve a total water use evaluation of the groundwater resource. Again the uncertainty of the other abstractions should be quantified.

### 3.1.5 The available groundwater resource compared with the shale gas water demand

This section provides an example on how to estimate the available groundwater resource for shale gas operation, including all water using processes. Waste water reuse is not considered but the size of reuse should be subtracted from the total water use requirements. The quantification of the available water resource has always the two components, groundwater recharge and other sources of groundwater abstraction to be taken into account to obtain the necessary estimate. Furthermore, the water use per shale gas (stimulation) well, drainage area per well are necessary to know or estimate. The sustainable maximum abstraction, defined as previously described, should also be assessed, if not already available from local environmental authorities.
A calculation that illustrates an assessment of groundwater availability for shale gas with two hydrological conditions, one with an estimated groundwater recharge of 300 mm and another with 350 mm per year is shown in Figure 1. The availability of groundwater for shale gas operation is shown in relation to groundwater used for other purposes. Sustainable groundwater abstractions up to 30 % of the groundwater recharge are shown in Figure 1.

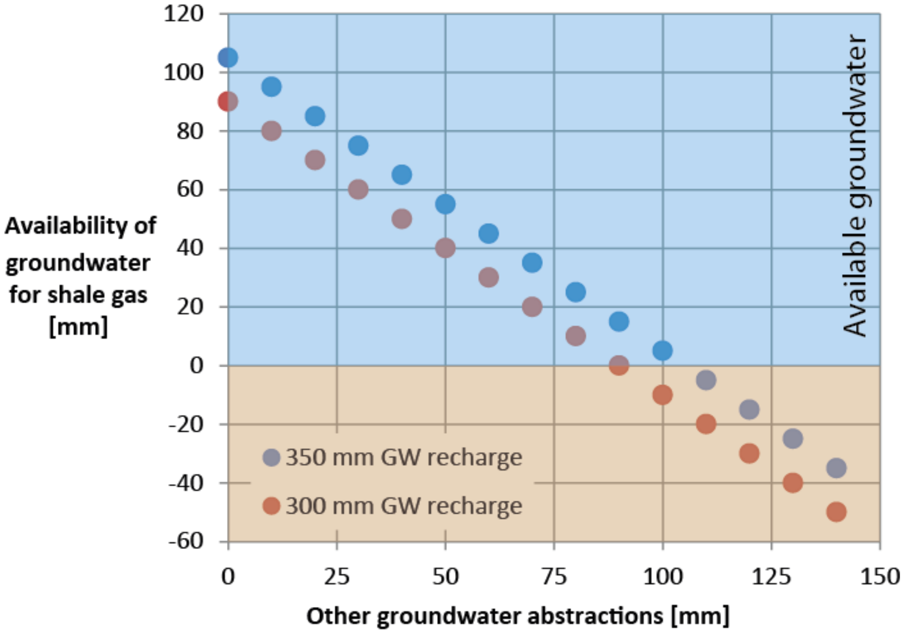


**Figure 1.** *A general applicable assessment of groundwater availability for abstraction with two hydrological conditions, with different sizes of other groundwater abstractions. The plot illustrates the limit, or maximum available abstraction for Shalegas in the relation to recharge and other abstractions.*

Together with Table 1, where the needed water is calculated, the possibility of using groundwater as the single water source for shale gas operation can be assessed. For example, if the average water use per well is 10,000 $m^3$ and there's an average of 1.6 well per $km^2$, then the areal water need is 16 mm. Figure 1. illustrates the conditions for which the shale gas water needs are acceptable according to a sustainable groundwater abstraction in relation to other groundwater abstractions and recharge. However, local conditions could likewise be used to illustrate how much other abstractions should be reduced to have a sustainable groundwater abstraction as for shale gas. Basically, if the local groundwater resource is already at the limit or maximum of sustainable groundwater abstraction, obviously the other abstractions need to be reduced by the water need of the given shale gas operation. Another situation could be a local situation, where the groundwater resource is already being overexploited. Here, reducing the other abstractions with the size of shale gas abstractions, will not lead to an overall sustainable groundwater abstraction. It is up to the local authorities, whether substituting water abstraction in an overexploited system is reasonable / allowable.

 

**Table 1.** *Shale gas water need in mm with different drainage area and water use per well.*

| Water use | Shale gas drainage area [well/km$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **[m$^3$/well]** | **1.2** | **1.3** | **1.4** | **1.5** | **1.6** | **1.7** | **1.8** | **1.9** | **2** |
| **5,000** | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 10 |
| **7,500** | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 14 | 15 |
| **10,000** | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| **12,500** | 15 | 16 | 18 | 19 | 20 | 21 | 23 | 24 | 25 |
| **15,000** | 18 | 20 | 21 | 23 | 24 | 26 | 27 | 29 | 30 |
| **17,500** | 21 | 23 | 25 | 26 | 28 | 30 | 32 | 33 | 35 |
| **20,000** | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 |
| **22,500** | 27 | 29 | 32 | 34 | 36 | 38 | 41 | 43 | 45 |
| **25,000** | 30 | 33 | 35 | 38 | 40 | 43 | 45 | 48 | 50 |

Values are given in mm and therefore calculated as [Water use * Shale gas drainage area) / 1000].

Figure 1. might also illustrate the different uncertainties of;

i) groundwater recharge, e.g. if the recharge calculated to be 350 mm but with an uncertainty of 50 mm., thus the 300 mm availability line could be used.
ii) abstractions of water for other purposes is also determined with uncertainty, e.g. 10 mm, thus the available amount for shale gas should be estimated, taken this uncertainty into account.

Similarly should uncertainty on water use per well, or drainage area, be included in the evaluation of shale gas water need and groundwater availability.
A more general calculation of the needed groundwater recharge to support both other abstractions and shale gas plays can also be done, including both drainage areas as a changing value, Figure 2.
The basic equation to calculate available groundwater for abstraction is:

$$GW_{Available} = GW_{Recharge} * L_s * 10^{-2} - GW_{Other}$$

Where GW is groundwater recharge, $L_s$ is level of sustainable groundwater abstraction in percentage, and $GW_{Other}$ is all other groundwater abstractions in the analyzed area. Based on this equation, different hydrological conditions can be evaluated in relation to the availability of groundwater for shale gas operation.

 

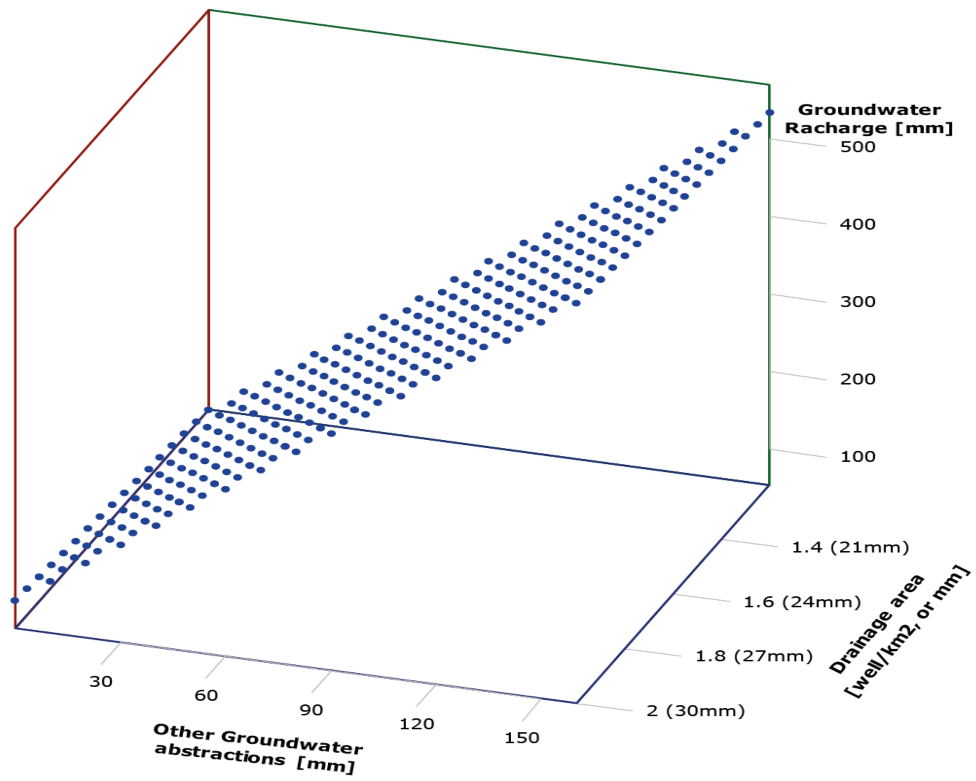


**Figure 2**. *Maximum availability of groundwater to shale gas production as a result of groundwater recharge and other groundwater abstractions. Calculated with an average water use of 15,000 m$^3$ per well and a sustainability criterion of no more than 30 % abstraction of yearly groundwater recharge is allowed.*

## 3.2 Elements taken into account for sustainable water use

The following provides a summary of important elements of the evaluation of a local groundwater resource in relation to water abstraction for shale gas operation.

1. What is a **sustainable groundwater abstraction** in relation to aquifer water quality? What is a sustainable groundwater abstraction in relation to dependent ecology, rivers/streams (1$^{st}$ to 5$^{th}$ order), or terrestrial groundwater dependent ecology. The one of those elements with the highest vulnerability determines the combined or total sustainable groundwater abstractions and is denoted the sustainable level of groundwater abstraction ($L_S$) in the groundwater availability equation (see later).

2. **Other groundwater abstractions** should be estimated. Thereby water use for shale gas is assessed as a part of a total groundwater balance. Potential restrictions, protected areas, areas where abstraction is not allowed should also be taken into account.

 

3. Shale gas **drainage area** (e.g. Lechtenbohmer et al. 2013) determines the number of wells.

4. **Water use per fracking well.** Can be used together with the average drainage area to estimate water use for an area, e.g. per square kilometer.

5. Groundwater balance for available groundwater for shale gas, including groundwater recharge, level of sustainable groundwater abstraction, and other groundwater abstractions (see embedded text for further explanation):

$$GW_{Available} = GW_{Recharge} * L_s * 10^{-2} - GW_{Other}$$

6. The **scale** of the groundwater evaluation should be based on the scale of the ecological recipient threatened by groundwater abstraction and aquifer size, and the hydrological catchment(s) feeding the aquifer and the effected ecology (aquatic and terrestrial).

7. **Uncertainty** should be evaluated on all assumptions and estimates of:
   - Groundwater recharge.
   - Water use estimates from shale gas, should include drainage area and water use per well.
   - Estimates on other groundwater abstractions.
   - Level of sustainable abstraction of groundwater recharge. Precautionary principles should be applied; considering that groundwater recharge can vary from year to year.

8. **Storage facilities** are very important because the water use in shale gas operation are intensive for some periods but not for others. Storage facilities should be able to store water for a period, long enough, to avoid groundwater abstraction during critical periods of groundwater dependent ecology (if this is the local situation). Assumptions about water storage; How long do we assume that water can be stored before water quality decreases below acceptable levels for fracking and drilling. Different kind of storage is possible, open water basins with algae growth versus closed facilities for storage. This will again be affected by climate, cold or warm temperatures will affect maximum storage times for water in the storage.

**9.** **Water reuse** is an important way to reduce impacts on local groundwater, from direct groundwater abstraction and should be an integrated part of the water resource evaluation.

 

# 4 CHARACTERIZATION OF SHALE GAS WASTE

Shale gas waste is any cuttings, refuse, sewage, fracking fluids, or any other used material that is generated during the total process from drilling, completions, hydraulic fracturing, or production operations, including drill cuttings, drilling muds, hydraulic fracture fluids, produced water including brines and flowback water. The operators are expected to take all reasonable measures to minimize the volumes of waste materials generated by their operations, and to minimize the quantity of substances of potential environmental concern contained within these waste materials. In general, no substance should be discharged or disposed to the environment unless it has been determined that the discharge or disposal is acceptable. The operators must include a complete and adequate plan to manage discharged waste material.

## 4.1 Different types of spill products

Shale gas waste might be classified as either liquid or solid. However, sometimes wastes fall between the two categories and become mixed with other wastes as they are generated and managed. From the operator view point, waste facilities and agencies and their waste management practices and regulations are based on definitions of wastes established by the industry and researchers.
The waste which by incident or accident may cause spill and leachates can be divided into different types by their origin.

### 4.1.1 Drilling mud

The production of gas wells in dense shale requires extensive drilling, which is facilitated by drilling muds. Muds can be water-based, oil-based, or synthetic, but they all contain a number of chemical additives. Because drilling muds are primarily liquid, they have to be separated from cuttings prior to disposal or reuse, and solidified and stabilized if they have to be disposal in a landfill. Due to the additives and the chemical reactions during drilling the muds might contain concentrations of contaminants that exceeded drinking water standards by leaching, including those for chlorides, benzene, and surfactants.

### 4.1.2 Drill cuttings and fracturing sand

After a hole is drilled into shale to develop a gas well, large amounts of drill cuttings come back out. The actual volume of drill cuttings generated will vary depending on the depth of a well and length of the laterals in horizontal drilling. Various estimates have been estimated. Anderson 2013 reports 500 tons for a deep Marcellus Shale well, whereas Darrah et al. (2014) give 34 to 750 tons for an average Marcellus well and 35 to 1000 tons for an average Marcellus well in West Virginia.
Regulatory agencies generally consider drill cuttings to be a natural material that can be disposed in landfills. However, cuttings are coated with drilling fluids and amounts of fracking liquid used in hydraulic fracturing. The cuttings might also consist of minerals, which have high leachability of heavy metals or radioactive components, salts, and hydrocarbons.

 

Hydraulic fracturing opens up the shale deposits so that gas can be extracted from shale or mudstone. The fractures have to be kept open by the use of fine silica sand treated with chemicals. Thousands of tons of sand are used per well. But a significant amount returns to the surface after the fracturing process by the first flowback water. Very little information is available about the specific chemical constituents or concentrations in fracturing sand waste before its final disposal.

### 4.1.3 Fracturing liquids

Fracking fluid consists of multiple chemicals. Industry has used up to 600 different components. Typically, 5 to 10 chemicals are used in a single fracturing job, but a well may be fracked multiple times. Many fracking chemicals in USA have been protected from disclosure under trade secret exemptions. However, lists of fracking chemical used during the last decades have been published, which provided a better view on the environmental impacts. Studies of fracking waste have identified formaldehyde, acetic acids, and boric acids, among hundreds of others. For more detail see Jacobsen et al. 2015, Jacobsen and Gravesen 2016, Vieth-Hillebrand and Schmid 2015.

### 4.1.4 Flowback

When the fracturing process is completed and drilling pressure is released, the injected water and fluids return as flowback. In many states that track flowback require that operators report the volumes created in the initial period after fracturing ranging typically from 2-10 million liters used to hydraulically fracture a well. The proportion of fracturing fluid injected into a well that returns as flowback varies. In general, 10 – 40 % of the injected fracking fluid will return to the surface during the first 10 days, while a recent review of data reported by operators put recovery at 8% in West Virginia and 6% in Pennsylvania, (DiGiulio et al, 2011). The contaminants present in flowback water and concentrations vary depending on the chemicals used for the hydraulic fracturing and the acids added to the fracturing fluid to reduce friction, eliminate bacteria, or prevent corrosion of pipes, (Vieth-Hillebrand et al 2015 and 2016, Kukulska-Zajac et al. 2016). In addition, the formation water and constituents leached from the shale and rocks have shown consistently high levels of sodium, chloride, strontium, barium, and bromide (Gregory et al. 2011, Barbot et al. 2013, Haluszczak et al 2013). In addition, flowback water can contain substances originating from the fractured formation, such as hydrogen sulfide and various volatile organic compounds (Gaucher et al, 2014).

### 4.1.5 Brine

Brine refers to interstitial water resulting from deep drilling and production that has a high saline content. Brines normally will flow to the surface in a mixture with fracking liquid as flowback water and later as produced water. The constituents in brines vary from formation to formation and may contain salts, metals, hydrocarbons and gases.

 

### 4.1.6 Produced water

Geological formations that contain gas also often store large amounts of water, which is released to the surface during gas production. The amount of produced water or formation water that is generated per well by gas production varies from play to play. The concentrations of minerals, metals, oil and grease, and radiological materials vary also depending on the formation being drilled. Shale gas wells produce in the range from 400-5000 liters per day. Produced water from the Marcellus Shale is the second saltiest and most radioactive of all sedimentary basins in the U.S. where large-scale oil and gas development is underway (US-EPA, 2012a). Produced water from the Marcellus and Utica Shale regions are estimated to contain up to10 times more salt than seawater, requiring considerable treatment before it can be reused or properly disposed. Produced water may continue to flow over the entire life of a well but the proportion of water relative to hydrocarbon increases with time.

### 4.1.7 Radioactivity

A majority of the contaminants from shale gas waste have not yet been identified, while the risks of others are only partially understood. However, this is not the case with radioactive components, which are found in many shale formations, and to which exposure is known to increase the risk of human health. In general, radium can be soluble in water or adsorbed to organic materials or clay. Due to the long half-lives of the two isotopes, Ra-226 and Ra-228 (approx. 1,600 and 5.75 years, respectively), they might be persistent environmental contaminants that will accumulate gradually over time. The concentration of radioactivity varies from shale to shale and also within the shale formations depending on depth and origin. By drilling and afterwards production of gas the radioactive components are brought to the surface through produced water, drill cuttings, and drilling muds, which result in radioactive deposits in sludge and scale (Pb-210) that accumulate on pipes and equipment, ( US-EPA 2015b , Jacobsen et al. 2015). The high level radioactivity in drilling waste have been primarily documented with regard to produced water and flowback, whereas minor attention have been payed to the solid waste and the possibility of leaching. Some studies have found that treatment plants for waste water have often a low removal of radium and other contaminants such as barium and strontium, likely due to the high salinity of the wastewater (Warner et al., 2013).

# 5 CONTAMINATION OF GROUNDWATER AND SURFACE WATER

The different potential pathways for contamination of groundwater and surface water with waste from fracturing activity include surface spills prior to injection, fluid migration once injected, and surface spills of flowback and produced water. Further, deposit of solid waste is often neglected but due to leaching of component in the solid waste it may be a threat to surface water by drainage or to groundwater by infiltration. As fracturing fluids are injected into the subsurface under high pressure, this mixture could move through the well bore or fractures created in the reservoir rock by hydraulic pressure and enter shallow formations that are freshwater aquifers, (US-EPA 2012b).

## 5.1 Waste spill

### 5.1.1 Surface Spills and Infiltration of waste waters

During the development and production period a proper storage and disposal of fracturing fluids and produced water is important to ensure that both surface water and groundwater are protected. After storage or treatment most fracturing fluids and produced water may be re-injected into Class II wells drilled specifically for disposal. In other cases the stored waste water is treated in wastewater treatment facilities, or recycled. During transport to the treatment plant, leakage may occur and spill to surface water or soil might cause contamination.
Contamination risks to surface water or aquifers during development of shale gas plays have led to increased regulations in some U.S. states. Potential pathways for contamination include surface spills, waste disposal, and surface spreading of well cuttings or road spreading. A study of the shale gas development in Pennsylvania showed a documented increase in chloride downstream of the waste treatment plant and also elevated total suspended solids downstream of shale gas wells (Olmstead et al., 2013).
Over the past decades the major causes of gas well induced groundwater pollution was caused by surface spills of wastewater. Leakage from surface storage has been a significant cause of groundwater contamination in the past, including saline contamination of freshwater aquifers nearby well site brine-holding impoundments (Pettyjohn, 1982) and water wells (Novak and Eckstein, 1988). The storage and management of flowback water may also present risks from heavy metals, radioactive materials and fracturing chemicals.
The impoundments for storage are typically constructed of clayey till and often liners and membranes to yield an expected impermeable condition. These liners may in some situation get damaged making a saturated flow possible through the unsaturated zone below, due to clay shrinkage and fissuring in the underlying clay till (Folkes, 1982). The impoundments are also susceptible to overflow due to extreme precipitation events or to the management failure to empty the impoundment over periods of several years. As a consequence of these problems, storage tanks are increasingly required by regulatory agencies to replace such storage impoundments and reduce the potential for overflow

 

due to extreme precipitation events, to minimize the risk for liner leakage or to the failure to empty the impoundment over periods of several years.
There are many pathways by which a spill might contaminate the aquifer below and by this the drinking water resources. US-EPA recorded spills between January 2006 and April 2012 from nine states, (US-EPA 2015a). The collected data showed more than 36,000 spill events, of these was a minority directly related to the hydraulic fracturing process. However, spill from logistics reloading and similar processes must also be taken into account with regards to the protection of groundwater and surface waters. Only 457 spill events corresponding to 1% was related to hydraulic fracturing. Among these are overland flow to adjacent surface waters, soil contamination and eventual transport to surface water by ditches or drain, or by infiltration through the unsaturated zone to underlying ground water. US-EPA has characterized 151 spills, and found that waste water reached surface water in 9% of all cases and soil in 64% of all cases, (US-EPA 2015a). During the investigation none of the spills of hydraulic fracturing fluid were reported to have reached groundwater. However, infiltration may take several years so, it may not be immediately apparent whether a spill will reach groundwater or not.
Depending on the geological and pedological conditions impacts of spill may occur very fast. Papoulias and Velasco (2013) reported a spill in Kentucky that had contaminated the surface water relatively quickly when hydraulic fracturing fluid entered a creek, significantly reducing the pH in water and increased the conductivity severely.

## 5.2 Road spreading

During many years a widespread discharge method for shale gas waste water was the spreading of brines on roads for dust control and de-icing. However, the environmental concern with that practice was the high levels of salt, chloride, and chemical contaminants (e.g., metals, organic solvents a.o.) in the brine, which can harm human health, aquatic life, and vegetation**.** During thaw periods the melting snow and rain will transport the brine into soil, streams, rivers, and groundwater. Besides this, the different states have different regulations for the road-spreading of brine, with special reference to the chemical content; limits of total dissolved solids, calcium, chloride, and other contaminants; and the methods used and rate of application. One major problem still remains on radioactive components, concentration and radiation levels.

## 5.3 Pits and impoundments

For many decades, well operators have used open pits or impoundments to store waste products at well sites until further treatment or disposal. However, with the growth of shale gas recovery in North America, many operators have changed to raised impoundments to store both large amount of freshwater needed for hydraulic fracturing, as well as the waste water. Some states have recently changed laws required the operators to use the tank system above ground. But in recent decades is the growth in drilling activity has increased and the number of such storage facilities also increased, which has led to increased concerns about the risk of groundwater contamination that could be caused by leaking or overflowing pits and impoundments.

 

## 5.4 Solid waste

At the well sites, pits are situated to store solid waste from the drilling or precipitate from the production. They are either dug into the ground or placed above with embankments. The temporary storage is used for solid waste, drill cuttings, drilling mud and fracturing sand. The construction of these pits is regulated according to guidelines and restrictions. However, liners might be broken and untighten by accident with a following leakage of fluid into springs, ponds, and streams or infiltration to groundwater by saturated flow.
A comprehensive investigation of groundwater contamination from wells in Ohio found that improper construction or maintenance of production pits was the primary cause, accounting for nearly 44% of all documented contamination incidents (Scott, 2011).
After the temporary storage in the pit on the well site, the solid waste will be transported to more permanent repositories. Both drilling mud and cuttings can contain large amounts of salts, metals and also radioactive materials and under certain conditions can leach into either surface water or infiltrate through the unsaturated zone to the groundwater. Depending on soil and sediment types the different substances will move at various velocities towards the recipients.

 

# 6 MODELLING THE SEEPAGE TO GROUNDWATER AND SURFACE WATER

A very important feature in modelling seepage is to replicate the actual physical flow at the given locality of a potential surface spill from shale gas activity. Even with a known physical system, e.g. geology and climate, variation of seepage can be significant. For instance, if the surface geology through which seepage to the groundwater or surface water will occur is sand, then a typical value of (saturated) hydraulic conductivity can vary between $10^{-4}$ and 1 cm/s (Freeze and Cherry, 1979). If the distance between source and recipient (e.g. river) occurs as saturated flow along a 100 m distance with a head gradient (drop in groundwater table) of 1 m resulting in a gradient of 0.01, the specific discharge is between 0.01 cm/s and $10^{-6}$ cm/s. In average, the time of arrival of a conservative and dissolved tracer will be between 3 days and 94 years (calculated with an effective porosity of 0.3, equations can be found in e.g. Fitts, 2002). The example shows that even with a known geology the variation in average travel time varies significantly and a precise description of the physical flow system is crucial if modelling of seepage from source (a potential shale gas spill on the surface) to surface water or a specific groundwater aquifer recipient shall be successful.

As a result of the large geological heterogeneity, often observed even within a given geological unit, the estimate of travel times of solutes is very uncertain. Without very detailed knowledge on hydrogeology, a modelling exercise to conceptualize possible flow paths and times is not reasonable.

The relevance of studying impacts of surface spills and modelling are exemplified by Brantley et al (2014), who investigated spills, other than methane, for unconventional shale gas development in Pennsylvania between 2008 and 2013 to water bodies (major spills larger than 400 gal, 1.5 $m^3$). Of the 32 reported incidents, 9 were drilling muds/fluids, 9 were brine (flowback or produced water), 7 were gel or fracking fluids, 5 were hydrostatic test waters or sediments, 2 were of unknown quality, and 1 was diesel. This study shows a wide range of chemical spills to water bodies but in relation to the 4000 completed wells, the incident rate is low.

## 6.1 Physical processes affecting seepage of waste to the groundwater

Seepage of pollutants from the surface through the unsaturated zone, saturated zone and to a groundwater or surface water source is a result of a number of processes. First, and possible most important parameter, is the local geological setup. The mobile part of the porosity (effective porosity), the permeability or vertical/horizontal hydraulic conductivity is a result of the geological conditions and this is true for both the unsaturated and saturated zone. Most shallow strata, from the surface and a few meter downward, anthropogenic effects, e.g. from agriculture, typically down to one meter below surface, urban geology, typically down to 4-6 meter, will also have a significant effect on possible seepage through the unsaturated to the saturated groundwater zone. However, under most European conditions it is not likely to have shale gas operation in

 

urban areas as seen e.g. in Colorado, USA, thus the anthropogenic geological zone will not have a larger extent than the normal soil type with typically 3-4 soil-horizons.
The degree of saturation (in the unsaturated zone) and depth of the unsaturated zone is very important for a possible transport of pollutant to a groundwater recipient or through groundwater to a surface water recipient (e.g., a lake or river). In the unsaturated zone the hydraulic conductivity depends on the degree of saturation. The unsaturated hydraulic conductivity changes between values of the saturated hydraulic conductivity to almost zero at the driest state of the sediment (where soil moisture is still present but the surface attraction from sediment grains is too high to allow flow of water through the sediment). When the degree of saturation increases a possible pollutant travels faster through the unsaturated zone. The depth of the unsaturated zone is obviously important for the travel time.
The volumetric size of the surface spill is also important in the recognition of travel times. During a large spill, the unsaturated hydraulic conductivity becomes close to the saturated hydraulic conductivity, which is relatively high compared to a hydraulic conductivity with low water content in the unsaturated zone. In the opposite situation, soil moisture or water content will be low and result in a relatively low hydraulic conductivity, and in longer travel times.
The climate, and the season of the year where the spill occurs, will affect the travel time of a pollutant in several ways, especially if a rapid seepage occurs with travel times of days. In the unsaturated zone, the amount of recharge will determine whether a minor spill will percolate through the unsaturated zone, e.g. during a dry season.
Multiple-porosity, e.g. in fractured clay, where the volumetric mean of hydraulic conductivity are low, can have a significant effect on mass transport, because most flow, as well as mass transport, occurs along high permeable fractures or zones.

# 7 RECOMMENDATIONS

## 7.1 Recommendations for research and monitoring programs

It has been known for a long time that methane might migrate from the subsurface to the upper freshwater aquifers and also that the ability to ignite methane in groundwater from drinking water wells has been reported. Consequently, baseline monitoring of groundwater for methane concentrations and its carbon isotope ratios is becoming standard practice in areas where unconventional gas development occurs. However, in the absence of reliable baseline information about other parameters, it may be difficult to discover surface spills which have reached the groundwater. Such incidents on gas extraction activities is therefore critical to establish baseline conditions before drilling and to use multiple lines of evidence to better understand pathways to the groundwater. The increasing reuse of flowback and produced water for hydraulic fracturing has growing concerns regarding the vast salt quantities that are brought to the surface from each well during flowback and produced water periods. Hence, there is a mandatory need for intensive risk assessment and regulatory oversight for spills and other accidental discharges of wastewater to the environment. Further, in order to minimize the risk there is a need to find alternative management strategies for this wastewater from the shale gas wells.

## 7.2 Baseline Groundwater Quality Mapping

A general monitoring useful for screening the water quality is valuable information, which could assist in rapid resolution in any incident or accident that could occur. The aim is to determine a baseline of water quality screening parameters from which any raised changes induced by the drilling or stimulation of wells for unconventional gas extractions can be compared. Further regulatory requirements to collect such data are principally used to address complaints and to minimize the ecological effects. However, the present baseline surveys tend to include existing water wells only, without a detection of spatial variability in chemical parameters, and usually fail to assess natural variations in concentrations and isotopic fingerprint, and how these are affected by geography and geology, and supplemented by differences in aquifer properties. More comprehensive geochemical mapping could involve a time series of an expanded suite of parameters, ideally in a network of dedicated groundwater monitoring wells.
As minimum, multiple time monitoring of water wells within a radius of influence from potential contaminant point sources is most easily accomplished by collecting pre- and post-drilling sample sets. The monitoring program has to initiate at least 1-2 years before the drill operation starts in order to measure the natural variation in the different parameters to be measured. Minimum screening parameters needed to discover the occurrence and source of a contamination must include, besides the different hydrocarbons with isotopic fingerprint, a set of inorganic parameters as anions, metals and depending of the shale composition also radioactivity.

## 7.3 Future research

A total understanding of the amount groundwater is used for hydraulic fracturing is hindered largely by information lack, where the information is either missing or difficult to record and compile. Regulation has not kept up to date with shale gas development, which has resulted in insufficient or lacking data reporting regarding the source of water used in hydraulic fracturing. Moreover, those data that are available are often difficult to interpret, and several sources may be necessary to supply the needed information, such as the conditions of surface water and groundwater. In general, baseline monitoring is missing in the majority of regions.

The major gaps in our knowledge should be incorporated in future research programs to support both sustainable development of unconventional gas and protection of groundwater resources.
Some of these gaps concerning waste spill is to identify the characterization of the background or baseline conditions, groundwater flow, geochemical and isotopic characterization in shallow groundwater.
Secondly to set up field experiments for studies of the processes by which natural gas, saline formation waters and fracturing chemicals may infiltrate and contaminate shallow aquifers both by measurements and by modeling the transport mechanisms.
Thirdly to set up laboratory experiments to study the leaching from the solid waste from the shale gas activity. Drilling mud and drill cuttings has shown to contain large amounts of environmental harmful compounds.
Fourthly, to set up studies of the reactions in the shale formation between the fracking chemicals and the minerals and organic matter in the shale itself to identify the numerous compounds produced which will be brought to the surface by the flowback water or produced water. Further, an identification of the Eco toxicological effects of these compounds should be taken into account.

## 7.4 Immediate actions

After reviewing numerous reports and scientific papers, there are some quite obvious actions that can lead to minimizing the risk of contamination of aquifers and drinking water resources. Among these actions, both administrative as well as technical are tools that can immediately be put into use.
Many European countries have already obliged well operators to specify which landfill sites have been or will be used to deposit shale gas waste. This means that there is always an overview of possibly problematic waste.
Further, the authorities could oblige the operators to always perform tests at independent laboratories of the waste before disposing of it to ensure that environmental impacts can be minimized.
It will also be adequate to require operators to hold a basic monitoring around the potential drilling sites.
Especially supervision should be mandatory if the operators or logistics are to manage and dispose of radioactive material to avoid the spread of nature and groundwater.

## 7.5 Constraints and limitations in modelling

Monitoring of groundwater directed towards impact from unconventional gas development seldom exists (Council of Canadian Academies 2014) and this is a general problem in modelling as well as for simple identification of whether a possible contamination has occurred. A review of the present European water monitoring with comparison with the North American practices is given in Fajfer et al. (2015). Modelling without information and observations of the possible spill cannot answer questions regarding transport to a recipient without empirical data to setup and calibrate the applied and chosen model. Modelling of the potential transport of a possible spill (before it happens) should be supported by, for instance, data from tracer tests or by analyses of naturel occurring geo-chemical tracers. In modelling without supporting data, local evidence is often meaningless because a small misassumption can lead to significant errors in estimation of, for example, travel times. Calibration of applied models should be done with data relevant for the predictions the model later is used for. For instance, setting up and calibrating a model against hydraulic heads do not necessarily make the model suitable for predictions of solute transport because hydraulic head do not effect vertical/longitudinal or transverse dispersivity, that are important for dilution of the solute.
As a minimum, all modelling should be supported by an uncertainty analysis. An uncertainty description or analysis in relation to modelling transport of contaminants, consist of a test of all the assumptions the model is built on.

Important model predictive uncertainties to be analysed are:

- Input/data uncertainty (e.g. uncertainty in observations)
- Geological uncertainty (e.g. layer boundaries, clay/sand fraction, assumptions of homogeneity versus heterogeneity)
- Structural/Conceptual uncertainty and model boundaries (e.g. if flow and transport are dominated by multiple porosities but simulated as one geometric unit, then travel time from source to recipient will be wrongly estimated. Model boundaries, assumptions are not correct resulting in wrong flow paths)
- Parameter uncertainty (e.g. errors in simulated dispersion (dispersivity) will lead to wrong travel times)

There are many other ways to categorize uncertainties in hydrological modelling, e.g. following Renard et al. (2010) into i) input, ii) output, iii) structural and iv) parameter uncertainties, but the above mentioned bullets illustrate areas of modelling associated with large predictive uncertainties. An analysis of the different sources of uncertainty, accordingly to the predictive entity, is a necessary element of modelling seepage from source to recipient.

 

# 8 CONCLUSIONS

A lack of sound scientific hydrogeological field observations and a scarcity of published peer-reviewed articles on the effects of unconventional gas activities with special reference to waste handling on shallow groundwater make it difficult to address these issues. On the other hand numerous reports from governmental institutes, from universities, or from operators are available. But the framework of data and statements can be threshold for quality verification and interpretation.

The potential role of the hydrogeology and geochemistry in identifying, characterizing, and monitoring aquifer vulnerability to contamination by chemicals and waste and spill are mandatory for a safe development of shale gas. These topics will require a tight collaboration of engineers and geoscientists from both industry and research community. The major gaps in knowledge about the environmental impact are a draw back to the safe development of natural gas resources and the protection of groundwater as drinking water resource and not least to the social perception of shale gas industry.

As mentioned, an extensive scientific investigation into the potential for groundwater contamination from unconventional gas activities is necessary. For a safe development a numbers of projects have to be initiated. Among these could one project be a review of analysis of existing cases of unconventional gas development and the environmental problems with waste handling. Another could be a potential classification of both liquid and solid wastes as industrial or hazardous, thereby subjecting them to additional testing and disposal requirements. And further, testing of solid waste and clear risk-based numerical standards indicating which levels of NORM in waste would prompt more stringent waste management practices. Last but not least a number of controlled experiments to understand processes that are believed to be responsible for or may result in groundwater contamination from surface spills.

If hydraulic fracking was just a new-and simple method of tapping natural gas sources, it would be welcomed by most the public as a cheaper, less contaminating alternative to oil and coal. The problems are the method of extraction. In order to extract the gas a broad numbers of more or less toxic chemicals have been used for the fracking. As flowback and produced water brings back the majority of these chemicals and their transformation products in a mixture with the deep brine a problem arise. If these fluids stayed far underground, they might not damage the environment, but due to the fracking process the large amounts of liquid has to be handled on the surface. And all handling contains risks for spill and accidents. Although the gas development has been in action for nearly half a century it would have been expected that a country as the US would have laws to protect the environment from toxic pollutants like these, but unfortunately the current laws are full of loopholes when it comes to fracking. The Safe Drinking Water Act has an exception for toxic chemicals injected into wells during hydraulic fracturing. And also the Clean Water Act permits temporarily stored waste water from fracking facilities to go untreated in many states.

The public debate and the many opinions that prevail around the exploitation of shale gas have generally been directed at the actual fracking and especially if methane could migrate to the drinking water resource. Similarly, there has been much discussion about the amounts of surface water and groundwater as needed for the hydraulic fracking. Very few have dealt with the waste and wastewater problems. Quite a few scientific articles dealing leaching to groundwater, while there are made several studies of waste water into streams and rivers. As regards the model works to simulate the impacts on groundwater and surface water both quantitatively and qualitatively, has not to our knowledge been any kind of debate.

 

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