Project Acronym and Title:

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

SUSTAINABLE WATER AND LIQUID WASTE MANAGEMENT IN SHALE GAS OPERATIONS

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Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating 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 the four main areas of potential impact: the subsurface, the surface, the atmosphere & climate, and public perceptions.

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 which may raise public concern if felt at the surface. 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 of a better European knowledge base on shale gas operations and their environmental impact 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 minimize risks and impacts of shale gas exploration and production in Europe.

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

Shale gas development can potentially impact both quantity and quality of the water resources. Water issues are one of the environmental hazards mostly covered in the literature. In addition, the management and disposal of flowback and produced water is one of the greatest challenges associated with unconventional oil and gas development. Therefore, the entire water cycle must be controlled and whatever risk assessment must consider it in a comprehensive manner. Previous deliverables from the M4ShlaeGas project have highlighted the risk scenarios regarding water and liquid waste management. All measures and recommendations in water and liquid waste management must be aimed at minimizing these risks.

The main principles of water management derive from the European Water Framework Directive. The assessment of techniques to determine best practices on liquid waste management must follow the waste hierarchy: prevention, preparing for reuse, recycling, other recovery and disposal. Furthermore, it is necessary to be consistent with precautionary principles. Recommendations about water and liquid waste management in a shale gas context need to be consistent with the "Commission recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing" (2014/70/EU).

When dealing with the need of recommendations on water and liquid waste management in the European context, several challenges have to be faced: scarcity of experiences and real data from European operators, legislative issues, different geological and geopolitical situation, great variability of the geological formations and environmental aspects, and great variability on the composition of fracturing fluids and liquid waste.

Due to these challenges, only general measures for measuring, monitoring, mitigating and managing the environmental impact of shale gas development regarding water and liquid waste management can be proposed. The determination of specific risk scenarios, and the calculation of the likelihood and the severity of the consequences for each scenario, needs to be made on a case-by-case basis. Brief recommendations to measure risks of groundwater and surface water pollution are introduced.

General recommendations are presented for comprehensive water and liquid waste management, regarding environmental assessment, risk assessment, water use and sourcing, disclosure of chemical composition, storage of chemicals, fracturing fluids and liquid waste.

Information about measures that should be implemented at the project level is also presented. In the first

instance, the accomplishment by the operator of a Water Management Plan for the specific well site is the best practice to control effectively the entire water cycle. Water Management Plans should be based on a complete hydrogeological assessment including details of the presence of groundwater and surface water and the presence of other hydrocarbon wells. In addition, details about borehole construction, fracturing fluids, naturally occurring radioactive minerals in the geological formation, water and liquid waste management and monitoring plans should be provided. Based on this information, the specific hazards and risks should be assessed and managed on a case-by-case basis.

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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. Shale gas has already proved to be a game changer in the U.S. and Canadian energy markets (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 hydraulic fracturing operations. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency 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, climate & atmosphere, and public perceptions. As the European continent is densely populated, it is most certainly of vital importance to include both technical risks and risks as perceived by the public.

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.*

1.2 Study objectives for this report

Shale gas development can potentially impact both quantity and quality of the water resources. Water issues are among the environmental hazards mostly covered in the literature. In addition, the management and disposal of flowback and produced water is

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

one of the greatest challenges associated with unconventional oil and gas development. All the water cycle within shale gas operations must be controlled.
The objective of this report is to offer an overview of the issues regarding water and liquid waste management and the applicable actions (and best practices when possible) for measuring and minimising related impacts in the European context.

1.3 Aims of this report

This report aims to summarize all the previous information about issues regarding water and liquid waste management in a shale gas context and to provide new information about assessing risks related. General recommendations about sustainable management of water, adapted to the European casuistry, are provided.

2 GENERAL OVERVIEW ABOUT WATER AND LIQUID WASTE MANAGEMENT WITHIN SHALE GAS OPERATIONS - WATER CYCLE IN HYDRAULIC FRACTURING OPERATIONS

Hydraulic fracturing is a stimulation technique used to increase oil and gas production from underground rock formations. Hydraulic fracturing involves the injection of fracturing fluids under pressures great enough to fracture the oil- and gas-producing formations. Water is a major component of fracturing fluids. It typically makes up almost 90% or more of the fluid volume injected into a well (EPA, 2015a). Water consumption typically varies from 8000 to 100000 m^3 per unconventional well, with an average of 15000 m^3 per well (Vengosh et al., 2014). Water consumption in Poland ranges between 1284 and 37849 m^3 per well (Konieczyńska et al, 2015). In UK, the estimations about water consumption range between 10000 and 30000 m^3 (CIWEM, 2012), being consistent with Polish data. Fracturing fluids typically consist of about 98 per cent water and proppant (usually sand) and 2 % additives (NYSDEC, 2011). Cuadrilla, in the UK, have stated that < 0.05 % of the fracturing fluid is made up of chemical additives (Stamford & Azapagic, 2014). The current trend is towards using a lower proportion of additives. The additives are often a mix of dilute acid, a friction reducer, biocides and an oxygen scavenger aimed to modify fluid mechanics to increase performance of the fracturing fluid or for purposes such as the prevention of corrosion of the well pipes and retardation of bacterial growth (Cuss et al., 2015). At EPA (2015b), a list of the main additives used for hydraulic fracturing purposes can be found.

After the hydraulic fracturing process is completed and pressure is released, the direction of fluid flow reverses and flows up through the wellbore to the surface (EPA, 2015b; AWWA, 2013). This fluid denominated *flowback*, generated prior to production phase, is formed by part of the injected fluids, the formation water and other components that could appear as a result of the fluid-rock interaction. Several authors estimate that 25%-75% of the injected water returns to the surface as flowback, depending on the geology and geomechanics of the formation (EPA, 2011; Pickett, 2009). The majority of the fracturing fluid is recovered in a matter of several hours to a couple of weeks (U.S. Department of Energy, 2009) recording the highest rates initially and decreasing gradually.

On the other hand, long-term produced water is generated during the production phase and continues throughout the lifetime of the well (EPA, 2015b; AWWA, 2013). Kondash et al. (2017) estimate that only 4–8% of the production water are composed of hydraulic fracturing fluids, while the remaining 92–96% is derived from naturally occurring formation brines that is extracted together with oil and gas. The total volume of liquid waste generated by a well over its lifetime depends on the site. In U.S., the estimated median volume ranges of flowback and produced water (together) is from 1700 to 14300 m^3 per well over the first 5–10 years of production (Kondash et al., 2017).

Flowback contains clays, salts, rock particles, naturally occurring elements dissolved from the rock, and chemicals that were added prior to beginning the hydraulic fracturing process. Constituents of concern in flowback and produced water include total dissolved solids (TDS), total suspended solids (TSS), inorganic anions, hardess, metals, total organic carbon (TOC), dissolved organic carbon (DOC), chemical oxygen demand (COD), biochemical oxygen demand (BOD) and naturally occurring radioactive material (NORM) (Kukulska-Zając et al., 2016). Long-term produced water typically mimics the characteristics of the unconventional oil and gas formation, which often contributes, in part, to high concentrations of select naturally occurring ions (EPA, 2015b; AWWA, 2013). Long-term produced water presents a mean concentration of TDS, chloride, bromhidre, barium, benzene, Ra-226 and Ra-228 higher than flowback. On the other hand, flowback have a higher concentration of sulphate. With respects to toluene and oil and grease, both mean concentrations are similar, but extreme data are higher in long-term produced water (Shih an Olmstead, 2013). These water quality parameters vary greatly across geographies, throughout the operational life of the well (a rapid increase of the salinity associated with a decrease of liquid waste production rates during the first months is shown by Kondash et al. (2017)) and the chemicals used in fracturing (Kukulska-Zając et al., 2016). An intensive compilation of available data about quantitative and compositional aspects of flowback from U.S. and Europe can be found in Kukulska-Zając et al (2016). The authors also point out the relevant parameters to assess the harmfulness of flowback water. Flowback and produced water are usually stored temporally in tanks or pits on site. Pits were the preferred option in the past but storage in tanks has been gained momentum. Final destinations of liquid waste are (1) underground injection by deep well for final disposal -the most option in U.S. although forbidden in several states-, (2) treatment for reuse in subsequent well stimulation phases, and (3) treatment for discharge. A variety of treatment options are reported on the literature and also in several deliverables of M4ShaleGas project compilation of information about this item can be found (http://www.m4shalegas.eu/reportsp2.html).

Shale gas development can potentially impact both quantity and quality of water resources. Water issues are among the environmental hazards mostly covered in the literature. Also, the management and disposal of flowback and produced waters is one of the greatest challenges associated with unconventional oil and gas development (Kondash et al., 2017). Therefore, all the water cycle must be controlled and whatever risk assessment analysis must consider it in a comprehensive manner. The aspects involved in the water cycle within hydraulic fracturing operations (see Figure 1) are:

- Water supply: the withdrawal of groundwater or surface water needed for hydraulic fracturing fluids.
- Chemical storage and mixing: the storage of freshwater, chemicals, and proppant on the well pad and the mixing process to create the hydraulic fracturing fluid.
- Generation of liquid waste: the return of injected fluid and water produced from the formation to the surface (flowback and long-term produced water), and subsequent transport for reuse, treatment, or disposal.

- Management of liquid waste: reuse, treatment and disposal of liquid waste generated at the well pad, including produced water.

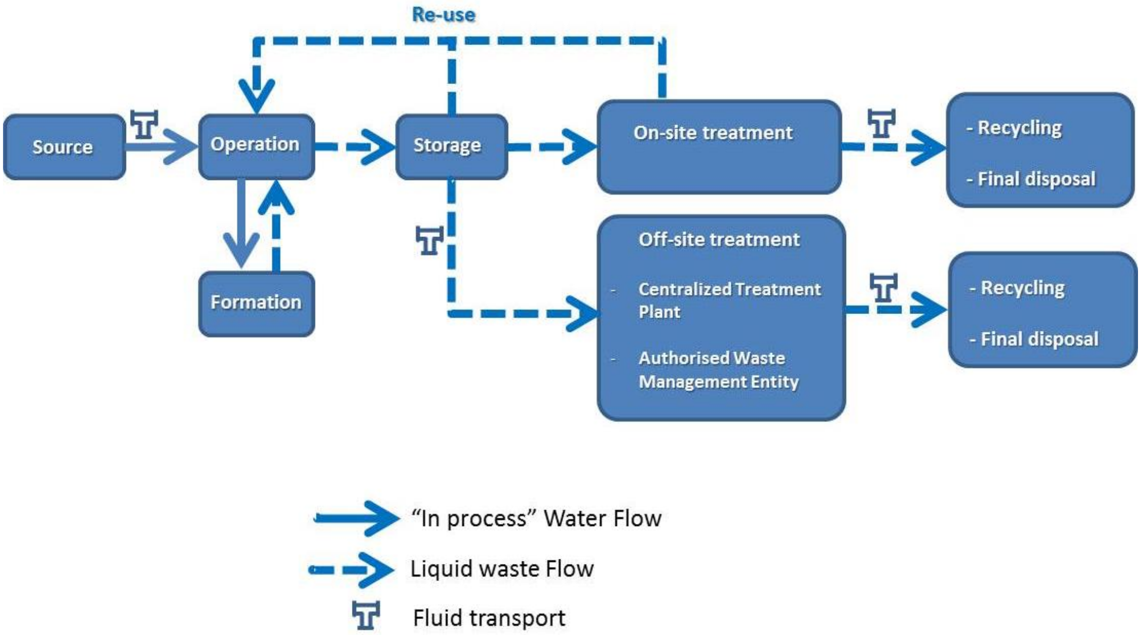

Figure 1. Flow of water in shale gas plays.

The main risks scenarios regarding water and liquid waste management within shale gas operations have been pointed out in several deliverables of M4ShaleGas project and reported widely in the literature. A brief summary of them is:

- Regarding water supply: 1) changes in the quantity and quality of drinking water available sources 2) competition with other uses of the water -especially in drought – prone areas- and 3) reduction of the ecological and quantitative status of groundwater and surface water bodies and associated ecosystems.
- Regarding handling and storage of chemicals and fracturing fluids: spills and leaks of chemicals and/or fracturing fluids that can lead into the pollution of soil, surface water and groundwater.
- Regarding on-site storage of liquid waste: 1) spills and leaks from on-site storage which can pollute soil, surface and ground water and 2) emission of gases and volatile compounds that can pose a risk for wild life (mainly birds) and human health.
- Regarding final disposal of liquid waste: contaminant reaching surface water and groundwater or accumulating in the sediment of river and lakes due to inappropriate treatment and disposal of liquid waste.

All measures and recommendation in water and liquid waste management must be aimed at minimized this risks.

3 MAIN PRINCIPLES UNDERPINNING WATER AND LIQUID WASTE MANAGEMENT IN THE EUROPEAN CONTEXT

Regarding freshwater supply, the principles underpinning water management come from the Water Framework Directive (2000/60/CE) which establishes that the first use of freshwater is the drinking water supply and the resources must be conserved.

The assessment of techniques to determine best practices on liquid waste management must follow the waste hierarchy (according to Article 4.1 of the Directive 2008/98/EC Directive on waste): prevention, preparing for reuse, recycling, other recovery and disposal, with the objective of finding the options that deliver the best overall environmental outcome. Furthermore, it is necessary to be consistent with the precautionary principle.

The current tendency to use as small amount of additives as possible connects with the first principle. Following the waste hierarchy, the most desirable option would be to reuse the flowback (usually with a prior treatment) in another well completion, but this option is limited: (1) requires other wells to be ready for hydraulic fracturing or drilling, (2) the distance between the locations where liquid waste are produced and reused (and thus the need for transport) can pose a constrain and, finally, (3) the recovered water gradually increases in TDS (being necessary larger requirement of treatment) (Rodríguez-Gómez et al., 2017). In addition, the “Water Framework Directive” (WFD) prohibits the injection of wastewater into groundwater. Although flowback is classified as a liquid mining waste, at the date there is not a specific waste classification for flowback and produced water even though it could contain hazardous substances. Konieczyńska et al. (2017) point out the need for a specific six-digit code for flowback and produced water in 01 chapter ‘*waste resulting from exploration, mining, quarrying, and physical and chemical treatment of minerals’* of the European Commission´s Decision 2014/955/EU. It is important not to classify the recovered flowback as a wastewater, since according to WFD wastewater cannot be introduced into groundwater under no circumstances, so flowback could not be reused for fracking if classified as wastewater unless one would be able to proof there was absolutely no water in target formation (which practically is not feasible) (Konieczyńska et al., 2017).

Finally, on January 2014, the European Commission dictated the document “Commission Recommendation of 22 January 2014 on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing”. Related to water and liquid waste management within the framework of shale gas operations, general recommendations are made: 1) Member States should ensure that operators carry out a characterisation and risk assessment of the potential site and surrounding surface and underground area; the risk assessment should characterise the potential exploration and production area and identify all potential exposure pathways, making possible to assess the risk of leakage or migration of drilling fluids, hydraulic fracturing fluids, naturally occurring material, hydrocarbons and gases from the well or target formation; 2) A baseline should be determined for: (a) quality and flow characteristics of surface water and groundwater, (b) water quality at drinking water abstraction points; 3) Member States should ensure that operators develop project-specific water management plans to ensure that water is used efficiently during the entire project, ensuring the traceability of water flows and taking into account seasonal variations in water availability and avoid using water sources under stress; 4) Regarding the use of chemical substances and water, Member States should ensure that a) using chemical substances in hydraulic fracturing is minimised, b) the ability to treat fluids that emerge at the surface after hydraulic fracturing is considered during the selection of the chemical substances to be used; 5) Member States should encourage operators to use fracturing techniques that minimise water consumption and waste streams and do not use hazardous chemical substances, wherever technically feasible and 6) Member States should ensure that the operator monitors the precise composition of the fracturing fluid used for each well, the volume of water used for the fracturing of each well and a characterization of the fluids that emerge at the surface: return rate, volumes, characteristics, quantities reused and/or treated for each well.

4 MAIN CHALLENGES IN MAKING RECOMMENDATIONS ABOUT BEST PRACTICES FOR WATER AND LIQUID MANAGEMENT IN THE EUROPEAN CONTEXT

The knowledge about good and best practices is increasing in U.S. and Canada, but it is necessary to identify the specific issues for the European casuistry and to assess the applicability and suitability of the North American knowledge to the European context. The main challenges to establish general or specific recommendations on water and liquid waste management in shale gas operations context are:

- Only few exploration experiences exist in Europe, thus there is a scarcity of real data from European operators.
- A common general framework exists at European level regarding shale gas operations. However, it is insufficient to establish general or particular recommendations about best practices on water management in the European context to minimise the footprint and the risks. Furthermore, certain techniques could be restricted by legislation.
- Issues about the use of freshwater differ among State Members and even between different regions. EU studies on water resources show strong regional differences. In southern Europe, for example, agriculture accounts for more than half of total national abstraction, rising to more than 80 % in some regions, while in Western Europe more than half of water abstracted goes to energy production as cooling water. Also, the pressure or stress on freshwater resources varies between Member States. Several river basins in southern Europe have extremely high water exploitation index values and a number of river basins in more northerly regions have water exploitation index values of roughly 20 %, indicating a stress on the water resource (EEA Report No 2/2009). Several regions in European countries are at risk of drought. Others, despite not being at a risk of drought, can have water issues due to the intensity of use.
- Water management practices are different among States Members. According to the Water Framework Directive, each Member state shall establish river basin management plans for each river basin district, including a programme of measures to protect and restore bodies of groundwater and surface water to achieve 'good status' (in terms of quantity and quality).
- Experience from U.S. and Canada, an also from Poland, shows that the volumes and composition of fracturing fluids and liquid waste varies considerably depending on the geological formation and the operator. Europe is a large continent with poses a great challenge due to the variety of geological and hydrogeological contexts. Even in the U.S., flowback and produced water composition varies considerably among plays and practices on liquid waste management are selected on a case-by-case basis.
- The severity of the risks related to water and liquid waste management in shale gas operations would depend on local conditions and the vulnerability of the local environment. Recommendations for a sustainable water and liquid waste management will be hardly influenced by local and regional conditions.

5 SUMMARY OF GOOD PRACTICES AND RECOMMENDATIONS IN WATER AND LIQUID WASTE MANAGEMENT

Due to the challenges reported in section 4, only general measures for measuring, monitoring, mitigating and managing the environmental impact of shale gas development regarding water and liquid waste management can be proposed. The determination of specific risk scenarios, and the calculation of the likelihood and the severity of the consequences for each scenario, needs to be made on a case-by-case basis.

Thus, general recommendations for comprehensive water and liquid waste management, regarding environmental assessment, risk assessment, water use and sourcing, disclosure of chemical composition, storage of chemicals, fracturing fluids and liquid waste are presented.

Information about the studies that should be made and about measures that should be implemented at the project level (for measuring, monitoring, mitigating and managing the environmental impact of shale gas development regarding water and liquid waste management) is also presented down below.

In the first instance, the accomplishment by the operator of a water management plan, prepared and conducted for each well-pad, becomes the best practice to control effectively the entire water cycle.

Water Management Plans should be based on a complete hydrogeological assessment wherein details of the presence of groundwater (aquifers, springs, water wells) and surface water and the presence of another hydrocarbon wells. In addition, details about borehole construction, fracturing fluids, naturally occurring radioactive minerals in the geological formation, water and liquid waste management and monitoring plan should be provided. Based on this information, the specific hazards and risks should be assessed and managed on a case-by-case basis.

5.1 Strategic Environmental Assessment

The risks of shale gas operations are further mentioned to produce cumulative impacts (Potočnik, 2012). Few references have been found regarding the application of the Directive 2001/42/EC on the assessment of the effects of certain plans and programmes on the environment (“SEA Directive”), to shale gas operations. It would be the most effective approach to address cumulative impacts at national and European level. A strategic environmental assessment is the framework wherein integral protection of water resources can be establish, for example, making possible to assess the cumulative impact on drinking water, freshwater and groundwater resources, of simultaneous shale gas projects in the same region. In addition, the establishment of prohibited/restricted areas or buffer zones may be implemented at the SEA level (not project specific).

5.2 Recommendations for measuring risks on surface water resources on a case-by-case basis.

The elements of the hydrological system which will be considered in the evaluation of the risk will be all the watercourses, all those bodies of natural water or wetlands (including the superficial ones of a seasonal nature) and reservoirs. Risks should be evaluated by means of the calculation of the probability for the generation of contaminating effluents affecting surface waters. The calculation of the severity will depend on the exposed element. Down below, general recommendations for the calculation of the severity are given.

The calculation of the probability index is a function of three factors: a proximity factor depending on the distance between the watercourses or surface water bodies and the operational sites; the toxicity or hazard of the chemicals, fracturing fluids and wastes generated (established on the basis of chemical analyses, including a study of the mobility in water) and the identification and assessment of the exposure pathways. In agreement with Turner et al., (2011), it is considered that the risk for watercourses or bodies of surface water is very high when the distance is less than 50 m. On the other hand, when the distance is greater than 500 m (300 m in the case of intermittent water courses), it is considered that the risk is very low.

The severity of the effects that contaminating effluent may cause to the environment, the population and the economic activities is derived from the consideration of the water bodies (temporary or permanent) which may be affected and their use. The severity of the damage to the surface water due to effluent emission would be in accordance with the natural attenuation of the contamination load between the origin and the receiving body of surface water represents. Hudson-Edwards et al. (1996), indicated how in water systems affected by mining activities, the concentration of contaminants in water and sediments tends to decrease with the distance from the sources of contamination as a consequence of chemical and hydro-dynamic processes. There is not a single model of distribution of the contaminant load based on ranges of distances, oriented to the evaluation of the probable effects on the health and the environment. In general terms, a distance of 5 km downstream from the sites will be sufficient for the attenuation except if there is information which makes it advisable to adopt another reference distance CCME (2008).

Regarding the population, the supply of water for human consumption is the most vulnerable use in comparison with other uses of water, given that it goes hand in hand with a chronic exposure and involves a greater probability of generating systemic harm as it favours the entry into the organism, via ingestion, of dissolved toxic elements. Another important aspect in relation with this kind of use of water resources is its possible use for watering crops. The severity for the population could be assessed by evaluating the presence of a Water Protection Zone and the vulnerability of the water resources (depending on the use). Table 1 shows a general criterion for the evaluation of large use groups.

Table 1. Evaluation criteria of the exposed population vulnerability depending on the surface water use.

Assessment of the population vulnerability in the event of pollution of surface water
Water uses of very high vulnerability: Water supply for population (private water wells and human water consumption catchments, providing water to more than 50 people or population centres).
Water uses of high vulnerability: Irrigation (orchards, other crops and pastures) and farming uses (troughs). Aquaculture, fishing preserves and recreational uses (bathing areas).
Water uses of moderate vulnerability: Recreational use (sport fishing). Water for parks irrigation, etc.
Water uses of low vulnerability: Industrial use (energy generation, cooling, etc.), water for golf links irrigation, navigation and transport by water, etc.
Water uses of very low vulnerability: Other uses of low exposure.

The calculation of the severity on aquatic ecosystems should be based on the vulnerability factor of the ecosystems. It will be generally considered that the vulnerability will be inversely proportional to the degree of deterioration of the ecosystems affected. The ecological deterioration, recognised by quality standards of the surface water bodies, will depend in large part on the concentrations of toxic solutes to which the natural resources and ecosystems are exposed, and on their susceptibility to these contaminants.

As regards the surface water bodies, and according to the criteria of preservation of a natural resource or ecological conservation, are considered sensitive areas: wetlands of international importance (Ramsar Convention) or catalogued in the National Inventories of Wetlands, and protection areas of the Natura 2000 network, the conservation of which is closely linked with the surface water bodies. All these areas that are considered sensitive are registered in the Register of Protected Areas, as is set out in Art. 6 of the Water Framework Directive. Any other kind of protection of which the conservation might depend, in large part, on the surface water resources and which has not been considered in the previous register might also be included in the maximum category of evaluation. It is clear that by virtue of the value of the resource and the merit of conservation, these areas present the highest degree of vulnerability and a greater foreseeable impact in case of being affected. On the other hand, the Water Framework Directive, with regard to the protection of the surface water bodies, contemplates the evaluation and classification of the ecological status thereof as an expression of the quality of the structure and the operation of the aquatic ecosystems associated with these water bodies. Based on biological (aquatic flora, benthonic invertebrate fauna and ichthyofauna), hydro-morphological (hydrological regime and connection with ground water bodies; continuity of the river and morphological conditions) and physical and chemical indicators and the application of metrics and biological indices and those of another kind, proposes an evaluation and classification of the surface water bodies into five classes. If in the water body affected there were not any nearby station belonging to this kind of network, it is possible to get information through publications or studies carried out by universities and research organisms which make possible to evaluate this ecological condition. Table 2 shows an example of criteria for the evaluation of the vulnerability of surface water bodies.

Table 2. Criteria for the evaluation of the ecological vulnerability in accordance with the degree of protection and the ecological status of the water resource.

Assessment of the ecosystem vulnerability in the event of surface water pollution due to effluents emission
Resources and ecosystems of very high vulnerability: Sensitive areas (environmental protection of resources and ecosystems). Surface water bodies of very good ecological status.
Resources and ecosystems of high vulnerability: Well-preserved wetlands but not included in Ramsar Convention nor in national inventories. Surface water bodies of good ecological status.
Resources and ecosystems of moderate vulnerability: Surface water bodies of moderate ecological status.
Resources and ecosystems of low vulnerability: Surface water bodies of poor ecological status.
Resources and ecosystems of very low vulnerability: Surface water bodies of bad ecological status.

The degree of impact on the elements of the socio-economic environment is going to depend on the local socio-economic structure and the degree of vulnerability of the different sectors of activity, and the elements of property which might be affected. The gravity of the damage will increase according to the economic weight of the sector involved or the social value of the potentially damaged elements. The severity of the consequences of the contamination of the surface water resources may also be evaluated in terms of loss of opportunity, if this represents a limitation for the conduct of those economic activities with the greatest potential or which it is desired to develop. Let the deterioration of water quality with regard to the standards demanded for certain uses serve as an example, such as for instance the economic impact involved in agricultural areas. The severity of the effects on the economic activities should only be assessed when the socio-economic damage is great and easily noticeable.

5.3 Recommendations for measuring risks on groundwater resources on a case-by-case basis.

One of the risk scenarios identified in the shale gas context is the occurrence of spills or leaks of chemical compounds, fluids and liquid waste stored on-site, that could reach groundwater towards the subsoil and may result in a pollution event. The calculation of the probability of occurrence is a function of three factors: the intrinsic vulnerability to the contamination of the potentially affected groundwater body, the toxicity or hazard factor of the fluids and wastes and the presence of exposure pathways (possibility of infiltration).

The first question in relation with the probability of contaminating the groundwater resources is the existence of any groundwater body which might be affected. For this purpose, it is necessary to consult existing documentation which will make it possible in some way to recognise this: by means of their inclusion on geological or hydrogeological maps, the known location of wells and springs, quotation in scientific articles or the identification in studies of a more local nature. For this purpose, it will be

necessary to determine in the first instance the susceptibility of groundwater body exposed to this type of contamination (vulnerability).
The evaluation of the vulnerability of the groundwater resources to pollution starts from the premise that the physical environment offers a certain degree of natural protection. The term "vulnerability" is opposed conceptually to that of natural protection, with the result of greater vulnerability as the natural protection of these resources decreases. In any case, any aquifer exposed is vulnerable to a greater or lesser degree. The probability of an adverse effect on the groundwater bodies due to effluents or contaminating spills will be a function of (1) the capacity of attenuation of the overlying strata or the non-saturated area by processes of physical retention and chemical reactions, (2) the inaccessibility of the saturated area, from the hydraulic point of view, to the penetration of the wastes and (3) the nature, toxicity, concentration, mobility and persistence of the contaminating load and its interaction with the environment. Currently, there is a great variety of methods for evaluating the intrinsic vulnerability of the aquifers to contamination which may be sorted into three large groups: simulation models, statistical methods and methods of indexes and superposition, with the latter being the ones that have had the greatest development and application. Among the indexed methods, we should emphasise the following: DRASTIC (Aller et al., 1987), GOD (Foster, 1987), SINTACS (Civita et al., 1990), AVI (Van Stempvoort et al., 1992), EKv (Auge, 1995), BGR (BGR, 1993), DRASTIC Reduced (DGOHCA-IGME, 2002; DGOHCA-CEDEX, 2002), or in the specific case of karstic aquifers, the methods known as EPIK (Doerfliger & Zwahlen, 1997) and COP (Vías et al., 2006). All these methodologies, oriented towards the determination of the intrinsic vulnerability, might serve for the evaluation of this risk scenario. The choice of the method will depend in large part on the availability of information.

Just as what happens with surface water, the processes of contamination of groundwater take place if there are contaminating or toxic materials, which evaluation could be performed in the same way that in the case of surface water.

The severity of the damage, in the case of contamination of the water resources, is closely linked with a probable loss of the current or potential use due to the deterioration in the quality of the water. The gravity of the effects will be greater when these resources are scarce and with priority protection, such as those used for drinking water supply, or when the degree of contamination makes its use in economic activities of importance for local development non-viable, or when it becomes a serious threat due to its toxicity to the health of the population exposed and of the ecosystems depending on them. In the specific case of groundwater, the severity of the damage may be aggravated, even further, due to the high economic and technical cost involved in the recovery of a contaminated aquifer with the result that this kind of impact may in practice be considered irreversible.

Regarding the effects on the population, the route of exposure of persons to contamination, is mainly due to ingestion of water and agricultural produce irrigated with water from contaminated wells or springs, and, to a lesser extent, due to contact and dermal absorption through the domestic use of the water (personal hygiene) or with recreational purposes (swimming-pools etc.).

Shale gas operations can constitute specific sources of contamination of groundwater resources. The concentrations of contaminants may be very high in the recharging area, moving slowly in the saturated area, and in the direction of the flow of water, undergoing, at the same time, a process of attenuation due to dilution and dispersion. From all of this, it can be deduced that the "concentrations of exposure" will decrease with distance from the sites. For the calculation of the distance of the final extent of the contaminating plume, from which it is considered that its potential capacity for contamination is very limited, it is necessary to make a hydrodynamic and hydrogeological analysis of the behaviour of the underground flow and of the contaminants, which requires deep and detailed knowledge of transit times, which will affect the distance in metres according to the particular case. In the literature and among the different methodologies which have dealt with the evaluation of risk in abandoned mine workings or soil contamination, there is no consensus for pre-setting this distance, in such a manner as to serve as a spatial framework of reference for all the process of evaluation of the damage. For example, an arbitrary distance of 1 km has been adopted by the Irish Environmental Protection Agency in the case of mining activities.
As occurred with the effects deriving from the contamination of surface water, there is no unanimity in establishing a model of distribution of the contaminating load based on ranges of distances in metres, oriented to the evaluation of the probable effects on health or the environment. The distances which are used for the delimitation of protection perimeters around points of extraction of drinking water might serve as references but, in general, they generally refer to transit times (one day for the immediate area, 50 days for the nearby area, and ten years for the distant area (Martínez and García, 2003). Taking into consideration some of the criteria followed in methodologies of risk analysis applied to contaminated soils (Alberruche et al., 2014), a theoretical and qualitative model of distribution of the contaminating load is proposed in which the contamination plume has its maximum concentrations at between 0 and 100 m, diminishing in directly proportional manner with distance up to 1 km.

Just as the matter was set out in the analysis of the severity of the consequences associated with the contamination of surface water, one of the factors involved in the calculation of the severity is the population exposed, through the ingestion of contaminated water taken from the subsoil. For this purpose, it is necessary to know the number of wells and springs devoted to the water supply of the population (water for human consumption) within a radius of 1km, or alternatively, in the direction of the predominant flow of groundwater up to that reference distance, if this is known through piezometric maps or hydrogeological research. The existence of a “protected zone for taking water for human consumption, which supplies over 50 persons” (Register of Protected Zones), in the spatial area of reference, will make it possible to assign directly the maximum value of this factor.

The vulnerability factor of the population is closely linked with the type of use which is made of the groundwater resource. Associated with it, and implicit from the point of view of the risk to the health of persons, there is a duration of exposure and a dose, both of which are dependent on the characteristics of the use of the water. Considering the exposure and the potential dose, and by way of a guiding criterion, in Table 3, the evaluations of the vulnerability of the population are set out with an attempt being made to reflect the large groups of uses. This is a non-exhaustive list which makes possible the inclusion of new water uses in the groups already defined by the evaluator. Extraction of water for supplying human consumption is emphasised and those which supply an average volume of at least 10 m^3/day, as well as, if applicable, the corresponding protection perimeters; and future extractions of water for supply declared to be of special protection. Likewise, areas of withdrawal and their protection perimeters of mineral and thermal waters are emphasised.

Table 3. Criteria to evaluate the exposed population vulnerability depending on the groundwater use.

Assessment of the population vulnerability in the event of ingestion or direct contact with polluted groundwater
Water uses of very high vulnerability: Water supply for population (private water wells and human water consumption catchments, providing water to more than 50 people or population centres), mineral water for human consumption, etc.
Water uses of high vulnerability: Irrigation (orchards, other crops and pastures) and farming uses (troughs), recreational uses (bathing areas), thermal waters (health resorts), etc.
Water uses of moderate vulnerability: Water for parks irrigation, etc.
Water uses of low vulnerability: Industrial use (energy generation, cooling, etc.), water for golf links irrigation, etc.
Water uses of very low vulnerability: Other uses of low exposure.

Regarding the severity of the effects on the natural environment deriving from the generation of contaminating effluents affecting groundwater resources, groundwater is, in itself, a non-renewable natural resource. On the other hand, there are many ecosystems (mainly wetlands and river systems) which present a close and dependent interrelationship with underground water resources, which makes clear their ecological value and the effects that deterioration in quality would cause to the environment. The severity index of the effects on the natural environment deriving from the generation of contaminating effluents affecting underground water resources will be a function of the vulnerability factors of the ecosystems and exposure to contaminated underground water. The exposure factor or concentration of the contaminating load to which the different ecosystems or elements of the environment are exposed can be valued as a function of the distance, in accordance with the same theoretical model used to evaluate the effects on the population.
With a view to the definition of the ecological vulnerability of the ecosystems, sensitive areas (which are the object of environmental protection) are considered: groundwater bodies: wetlands of national importance (Ramsar Convention) or those catalogued in National Wetlands Inventories and areas under the Natura 2000 network, the conservation of which is closely linked to groundwater bodies. All these areas that are considered sensitive are registered in the Register of Protected Areas and are

contemplated in the corresponding hydrological plans. Any other kind of protection where conservation might depend, to a large extent, on groundwater resources and where they were not considered in the previous register will also be included in this category. It is evident that, by virtue of the value of the resource and the merits of conservation, these areas present the greatest vulnerability and a greater foreseeable impact in case of being affected. In addition, those wetlands whose ecosystems present good conservation despite not having been included in any of the previous types of protection are also considered highly vulnerable.

The ecosystems associated with river segments inter-related with groundwater bodies by diffuse connection, such as is the case of those effluent flows which run over highly permeable detrital alluvial sediments, or by specific connection through springs, show also a high ecological vulnerability, especially, if they present good conservation or a very good or good ecological state, in accordance with the Water Framework Directive. In Table 4, some criteria for the evaluation of the vulnerability of ecosystems are proposed.

Table 4. Ecological vulnerability assessment according to the value of the resource and the groundwater ecological status.

Assessment of the ecosystem vulnerability in the event of groundwater pollution
Resources and ecosystems of very high vulnerability: Sensitive areas (environmental protection of resources and ecosystems).
Resources and ecosystems of high vulnerability: Well-preserved, hypogenic and mixed wetlands not included in Ramsar Convention or in national inventories; well-preserved riparian ecosystems interconnected with groundwater bodies.
Resources and ecosystems of moderate vulnerability: Surface water bodies of moderate ecological status. Slightly disturbed riparian ecosystems interconnected with groundwater bodies of moderate ecological status. Slightly disturbed hypogenic and mixed wetlands. Water for irrigation of woody and herbaceous crops and pastures.
Resources and ecosystems of low vulnerability: Disturbed riparian ecosystems interconnected with groundwater bodies of poor ecological status. Disturbed hypogenic wetlands.
Resources and ecosystems of very low vulnerability: Highly disturbed riparian ecosystems interconnected with groundwater bodies of bad ecological status. Disturbed mixed wetlands.

The severity of the effects on the socio-economic environment will depend on the local socio-economic structure and the degree of vulnerability of the different sectors of activity and property elements which might be affected; the seriousness of the damage will increase according to the economic weight of the sector involved. The severity of the consequences of groundwater resources contamination may also be evaluated in terms of loss of opportunity, if the contamination may mean a limitation on the development of those economic activities with the greatest potential for development or which it is desired to promote. In areas with scarce water resources, strongly dependent on groundwater for supply, which have experienced significant urban and tourist growth, lack of water which satisfies the standards of quality for human consumption has exercised and exercises a restrictive role. In those agricultural areas specialising in intensive irrigated agriculture, the deterioration in quality of water, with regard to the demands of its use, may cause serious damage or limit the development of the sector.

5.4 Water use and water sourcing

Total water use of shale gas development overall is relatively low compared to other water withdrawal sources, such as cooling water for thermoelectric-power generation (Vengosh et al., 2014). In U.S. the water consumed for hydraulic fracturing is generally less than 1% of total annual water use and consumption (EPA, 2015a). The Department of Energy & Climate Change of UK consider that the amount of water used in fracking is not exceptional compared with other industrial uses (representing less than 1 % of total groundwater abstraction). According to Vandecasteele et al (2015), in Poland between 0.03 and 0.86 % of the total water withdrawals for all sectors could be attributed to shale gas exploitation.

However, in geographic areas with dry climates and/or high consumption of groundwater resources, water withdrawals could potentially impact the quantity and quality of drinking water resources at more local scales (EPA, 2015a). Groundwater exploitation for hydraulic fracturing can lead to local water shortages, even in wet areas (Nicot et al., 2012, Mitchell et al., 2013). In small to moderate streams, withdrawals for hydraulic fracturing can exceed the natural flows (Rahm et al., 2012). As a result of a significant withdrawal within in a short period of time can cause a cumulative impact on water abstraction and promoting excessive water depletion. Furthermore, the use of fresh water in hydraulic fracturing operations may engage in competition with current customary practices, especially in countries experiencing cyclical droughts or in the near future may suffer droughts due to climate change.

Several measures can be implemented to minimise risks on freshwater resources:

- Reuse flowback for subsequent fracturing operations would substitute fresh water consumption (Vengosh et al., 2014). This practice is gaining moment in U.S., but it presents some constrains: it would be necessary the existence of nearby wells prepared to be fractured and flowback probably will need some kind of treatment before it use. The current upper limit for salinity for adjusting to friction reducers in hydraulic fracturing fluids is about 25000 to 30000 mg/L (Rivard et al., 2014) or even higher (Hallock et al, 2013). Cuadrilla Resources has set, for Blackpol site, a TDS threshold of 250000 mg/L for its friction reducer. If TDS content would higher, the flowback fluid would be diluted with water to reduce this content. According to current researches, the flowback could be used with a primary and secondary treatment used in conjunction with the mixture with fresh water.
- Use of alternative water resources (e.g. water from the local water system, water from wastewater treatment plants, treated water from other industrial facilities or marginal water). An alternative water source must provide sufficient (by itself) water volume for a hydraulic fracturing stage. In deliverable 9.2., an assessment of the suitability of using treated effluents from wastewater treatment plants in hydraulic fracturing operations was made, concluding that this practice would be

feasible (Rodríguez-Gómez et al., 2017). Also, water from brackish aquifers has been use for fracturing purposes with a previous treatment to remove sulphates, magnesium, iron, bacteria, and large solids that can damage pipelines and pumping equipment. The effect of the need for transportation (trucks or pipe) must be also assessed in a case-by-case basis.

- Substitution of water by non-water fluids (e.g., gel).
- Share sources of water in multiple operations or with other operators.

In the particular case of using treated wastewater from municipal treatment plants, it is important to point out that this source would be sufficient (in quantity) to be a successful source of water for hydraulic fracturing purposes. Data from Eurostat related to the volume and number of wastewater treatment facilities in several EU countries, for year 2012, has been collected and classified (Table 5).

Table 5. Data of number of facilities and volume of wastewater generated for year 2012 in several EU countries (Source: http://ec.europa.eu/eurostat/web/environment/water/database). The calculus of the medium value of discharge for each facility in last column has been included.

	Number of wastewater facilities	**Generation and discharge of wastewater (Mm^3) in 2012**	**Calculated medium value of discharge of wastewater (m^3) per day in 2012 for each facility**
Bulgaria	87	446.7	14,067
Czech Republic	2,562	1,195.6	1,279
Estonia	593	359.8	1,662
Spain	2,041	8,717.4	11,702
Croatia	112	398.7	9,753
Latvia	650	234.3	988
Lithuania	561	256.4	1,252
Malta	4	21.2	14,521
Austria	1,842	2,358.9	3,509
Poland	3,191	2,199.3	1,888
Romania	464	4,982.9	29,422
Slovenia	318	107	922
Slovakia	254	599	6,461

Theoretically, based on these data, wastewater treatment facilities should provide enough water resources for the smallest and medium shale gas plays. Nevertheless, considering that most of the wastewater treatment plants are designed for flow rates under the range of the 1000 m^3 per day, the treated wastewater does not seem likely a good primary resource of water for hydraulic fracturing. A large wastewater facility (or a set of them) maybe may provide enough resource for smallest and intermediate plays but it could imply to solve some additional problems (transportation services and facilities, proximity to large populations, etc.).

At the level of project, the water management plans, regarding water sourcing, should include the following information (for measuring and mitigating the impact on fresh water resources, in terms of quantity and quality):

- The total volume of freshwater that it is necessary to perform hydraulic fracturing (in m^3/year) per well and/or well pad.
- Yearly water availability versus total water demand from all users, including expected demand to shale gas plays.
- A study about the availability of alternative water sources (in terms of quantity and quality).

Finally it is necessary to point out that the reuse of the flowback water and the use of alternative sources are in accordance with the hierarchy principle of the Waste Directive, but both can run in to legal issues within the Water Framework Directive, that should be solved.

5.5 Public disclosure of chemicals used in hydraulic fracturing fluids

The public disclosure of the chemicals used in hydraulic fracturing and the details of how and where fracturing was completed, is essential to assess, mitigate and correct, risks linked directly to fracturing fluids and also to liquid waste. Surface spills of chemicals and/or fracturing fluid may pose a greater contamination risk that hydraulic fracturing itself (e.g. Mair et al., 2012; Clancy and Worral, 2016). The likelihood of contamination risks would depend on the total volume of chemicals and fluid, the chemical composition of the substances stored and the specific composition of the fracturing fluid, the distance between storage sites and the environmental compartments that could be affected and the probability of spreading depending of the receiving medium (presence of preferential runoffs, soil permeability and infiltration capacity, etc.).

The hazards linked to the chemicals used in drilling and fracturing fluids must be assessed on a case-by-case basis for each well or well-pad. Thus, at the project level, providing an initial description of the base fluid and each additive that the operator intends to use in the hydraulic fracturing fluid, including the trade name, supplier, purpose, ingredients, CAS Fact Sheet, maximum ingredient concentration in additive, and maximum ingredient concentration in hydraulic fracturing fluid is an essential question when risks are aimed to be measured, minimised or mitigated. Also, total volumes must be assessed. This measure is considered, by the European Commission, as a measure of high level of ambition to reduce likelihood and the reduction of damage of the risks linked to unconventional gas extraction.

In accordance with the Commission Recommendation of 22 January 2014 and following the current trends (in U.S, Canada and U.K.), the principle of rationalization of chemical compounds must be implemented by means of using non-hazardous chemicals wherever possible and using the fewest number of compounds (and concentration).

5.6 Chemical storage and chemical mixing

Although additives usually do not exceed 2% of the fracturing fluids, the total amount of chemicals used may be significant. Consequently, special care must be taken in their storage. Chemicals used in hydraulic fracturing and drilling are usually transported to the well pad in tankers, stored and mixed on site. These are other possible points of risk due to the possibility of chemical spills. The EPA found that 31% of chemical spills on or near the well pad related to hydraulic fracturing resulted from equipment failure. Equipment used in hydraulic fracturing operations typically consists of chemical storage trucks, oil storage tanks/tanker trucks, a slurry blender, one or more high-pressure, high-volume fracturing pumps, the main manifold, surface lines and hoses, and a central control unit (EPA, 2016).

The age and the technological advancement of the equipment is other factor to consider potential spills. It should be taken into account that uncontrolled spills could damage other storage units and equipment, which could result in additional spills. Base fluids used in hydraulic fracturing are typically stored on-site in large volume tanks. Non-water-based fluids may be stored in specialized containment units designed to prevent or minimize releases. Fresh water used as a base fluid is generally not a source of concern for spills. Reused wastewater, brine, and non-aqueous base fluids have the potential to adversely impact drinking water resources in the event of a spill, but it should be covered in the paragraph focused on produced water handling (EPA, 2016). Additives are usually stored on-site in the containers in which they were transported and delivered. Certain additives require specialized containment units with added spill prevention measures. (EPA, 2016).

Hoses and lines are used to transfer hydraulic fracturing fluids from storage units to specialized mixing and pumping equipment and ultimately to the wellhead. Incomplete or damaged seals or improperly fitted seals in the connections, as well as wears or tears in the hoses/lines can cause leaks or spills. Discharge hoses transfer additives from containment vessels or totes to the blender. It is particularly important that these hoses are in good condition and that connector seals or washers fit properly and are undamaged. High-pressure flow lines are subject to erosion caused by the high-velocity movement of abrasive, proppant-laden fluid. Curved sections of flow lines are particularly susceptible to erosion and are more likely to develop stress cracks or other defects that can result in a leak or spill (Malone & Ellly, 2007).

There are some other elements in the circuit to consider to asses possible points of failure: 1) the blender is the central piece of equipment used to create the fracturing fluid for injection. The blending process is monitored to ensure that a uniform mixture is maintained regardless of injection rates and volumes. Excessive or reduced rates of flow during treatment can cause malfunction which can result in spills; 2) a manifold (usually a trailer-mounted manifold) works as a central transfer station for all fluids used in the hydraulic fracturing operation. The manifold is a collection of low- and high-pressure pipes equipped with multiple fittings for connector hoses. Manifold and pump system components require varying amounts of manual assembly, so there may be more opportunities for human error, leading to a spill. 3) high-pressure fracturing pumps take the fracturing fluid mixture from the blender, pressurize it, and propel it down the well. Typically, multiple high-pressure, high-volume fracturing pumps are needed for hydraulic fracturing. Such pumps come in a variety of sizes; 4) the wellhead assembly allows high volumes of high pressure proppant-laden fluid to be injected into the formation. As with all components of hydraulic fracturing operations, repeated and prolonged stress from highly pressurized, abrasive fluids may lead to equipment damage, and in addition, surface blowouts or uncontrolled fluid releases may occur at the wellhead because of valve failure or failure of other components of the assembly (Malone & Ellly, 2007, EPA, 2016).

In EPA (2016) a total of 36,000 spills along 6 years (from January 2006 to April 2012) were recorded and statistically treated. Of these spills, the EPA identified 457 spills that occurred on or near the well pad and definitively related to hydraulic fracturing. Of these 457 spills, 151 were related to the chemical mixing process. The spills associated with chemical mixing ranged in volume from 19 L to 73,130 L, with a median volume of 1,600 L. The source of largest spills was storage containers, which released approximately 314,000 L of spilled fluid. Environmental receptors (i.e., surface water, groundwater, soil) were identified in 101 of the 151 chemical mixing-related spills, or 67% of all chemical and fracturing fluid spills in the analysis. Soil was by far the dominant environmental receptor, with 97 spills reaching soil; reported spill volumes ranged from 19 L to 31,000 L. Thirteen spill reports indicated that the spilled fluid had reached surface water; reported spill volumes ranged from 105 L to 27,800 L. Nine spill reports identified both soil and surface water as a receptor; spill volumes ranged from 106 L to 10,800 L. Groundwater was not identified as a receptor from spills of chemicals or hydraulic fracturing fluid in any of the spill reports. Due to the lack of observations, it is often unclear if there was impact on groundwater. Storage units were the predominant sources of spills that reached an environmental receptor. 6 spills from storage containers reached a surface water receptor. 38 of the spills from storage units reached a soil receptor. Regarding spills of hydraulic fluids and chemicals from storage containers, 16 spills were due to failure of container integrity, which includes holes and cracks in containers, and overflowing containers as a result of human error or equipment malfunctions (EPA, 2016).

Spill prevention, containment, and mitigation influence the frequency and severity of the impacts of spills. There are several factors to take into account including regulations, company practices, employee training, equipment maintenance, etc.
The first measure to assess is the containment systems. EPA investigated in this regard and found that of the approximately 25% of reports that included information on containment in activities related, the most common types of containment systems referenced in the hydraulic fracturing-related spill records included berms, booms, dikes, liners, although many of the spill reports did not indicate specific containment measures. In cases where secondary containment systems were not present or were inadequate, operators sometimes built emergency containment systems. The most common were berms, dikes, and booms, but there were also examples where ditches, pits, or absorbent materials were used. There was not enough information to detail the use of emergency containment systems or their effectiveness.

According to the above information about the functional features of the different elements of the chemical mixing process and taking into account the statistics of spills previously exposed it is possible to establish several measures in order to ensure the maintain low operational risk levels.

- Protect sites with impermeable liners or even with the construction of a watertight compartment (in the case of hazardous chemicals), locating the containers inside, with enough volume to retain whatever accidental spill.

- Store chemicals and fracturing fluids away from surface waters, aquifers and other sensitive areas (as areas covered by the Natura 2000 network, protected areas, etc.). Buffer zones could be determined after a thorough case-by-case examination. Regarding surface water, and in agreement with Turner et al., (2011), it is considered that the risk for watercourses or bodies of surface water is very high when the distance is less than 50 m. On the other hand, when the distance is greater than 500 m (300 m in the case of intermittent water courses), it is considered that the risk is very low.

- To ensure an adequate formation for the human resources as well as a correct maintenance conditions for the equipment and facilities are two essential measures to avoid spill and leakages related to the machinery involved in the transportation and storage of the hydraulic fracturing fluids.

- Designing a plan for the detection of spills, which include periodical inspections of the site and the definition of the measures applicable in the case of spill.

5.7 Storage of liquid waste

The number of spills reported by the EPA regarding flowback and produced water provides 48.5% of the total spills linked to hydraulic fracturing operations (EPA 2015b). The most widespread use in the U.S. to store flowback and produced water are open pits. In many cases, pits serve as disposal system by means evaporation (sometimes spraying flowback and produced water to speed up the process). Pits are excavated into the ground and isolated by polyethylene liner or compacted clay to prevent infiltration. Water overflows and failure of the waterproof layer can result in the release of contaminated materials directly into soil, surface water and shallow groundwater. For example, in the U.S. shallow groundwater contamination has been linked in part to surface pits used for the storage of flowback and produced water (DiGiulio et al., 2011). Environmental clean-up of these accidentally released materials can be a costly and time consuming process. Therefore, prevention of releases is vitally important. In addition, pits can lead to odors issues and gas emission, posing a hazard for birds and wildlife. The emissions could include volatile and semivolatile components (VOCs) (Hayes, et al, 2012).

Enclosed, portable tanks are a commonly used alternative to pits for the storage of liquid waste. A typical tank in a shale gas operation consists of about 80 m^3. Hoses can be used to connect several tanks together, allowing for variable capacity (Kuwayama et al., 2015). The use of tanks as a wastewater storage solution has been increasing in the gas industry and has been a target for new regulations. Kuwayama et al (2015) concluded that tanks are associated with fewer and smaller spills than pits, but they are not infallible and, when fail, they can pose more catastrophic damages. The use of tanks diminishes the appearance of VOCs emission, linked to eventual venting (needed to address overpressures). Despite Kuwayama et al (2015) recommend avoid outright bans of either pits or tanks, the fact is that some States in U.S. have prohibited the storage of flowback and produced water in open pits, while other have imposed strict rules when using them. In the European context, pits could be approved within the Mining Waste Directive but, due to the high environmental footprint and the difficulty to control damages linked to pits, as early as 2011, the European Parliament considered that on-site closed-loop water recycling, using steel storage tanks, offers the most environmentally sound way to treating flow-back water, minimizing the potential for surface spills. In UK, open pits are forbidden for flowback and produced water storage (*Fracking UK shale: water*, 2014).

In conclusion, despite open pits are feasible, it is considered that, at European level, storage flowback and produced water in tanks (provided with closed-loop systems) would be considered as a best practice.

Measures applicable to the storage of chemicals and fracturing fluids are directly applicable to tanks containing flowback.

5.8 Flowback and produced water composition

Operators must provide information about the volumes and composition of the flowback and the produced water. This information is essential not only for the assessment of the risk of the theoretical spills, but also for the identification of the best way to manage these fluids and to ensure the traceability of these fluids in the case of spill. At the early stages of flowback production, when the greatest volumes are recovered, this information needs to be provided more systematically, dilating the frequency as the volume decrease.

At the project level, the operators must specify the frequency and methodology of the sample taking as well as the laboratory tests (and its methodology) that will be performed. In Kukulska-Zając et al. (2016) relevant parameters to assess the harmfulness of flowback water are pointed out. In addition, Garcia and Rouchon (2017) propose geochemical species to monitor in a shale gas exploitation context.

5.9 Establishment of safeguard zones

The calculation of the likelihood of risks related to surface and groundwater contamination is based on the vulnerability strongly depends on the distance between the source of pollution and the receiving environment. In this connection, there are several references in the literature about the establishment of safeguard zones to protect the drinking water resources, water protection areas and vulnerable surface or groundwater bodies. In sections 5.2 and 5.3, general recommendations on the calculation of safeguard distances and the evaluation of the vulnerability of the exposed elements have been made and can serve as the basis for the establishment of safeguard zones in a case-by-case basis.

6 CONCLUSIONS

Europe poses a complex legislative, environmental and social scenario in to which good and best practices regarding water and liquid waste management in the shale gas context must be set. The knowledge about good and best practices is increasing and improving in U.S. and Canada, but there are several challenges in order to establish general or specific recommendations on water management in the unconventional gas context mainly due to the complex regulatory framework, the scarcity and asymmetry of real European data and the complex geopolitical and environmental scenario.

The recommendations have been established through the identification of several risk scenarios in which the impacts of the shale gas activities regarding water and liquid waste management have been noted. In this context, only general measures for measuring and mitigating the environmental impact of shale gas development have been proposed. The determination of specific risk scenarios as well as the calculation of the likelihood and the severity of the consequences for each scenario needs to be made on a case-by-case basis. Key points for the evaluation of the probability of occurrence for risks linked to surface and groundwater pollution scenarios and the evaluation of the severity (based on the vulnerability of exposed elements) have been highlighted in this deliverable.

In the first instance, the accomplishment of a water management plan for the each well or well-pad becomes the best practice to control effectively the entire water cycle. It is important to point out that the presence of NORM (normal occurring radioactive materials) in the geological formation is a critical issue that could determine specific measures.

Regarding water sourcing, other general recommendation is the application of the guidelines of the Water Framework Directive by minimising the total volume of water and the hierarchy principle of the Waste Framework Directive (reusing flowback, using alternatives to freshwater sources, as treated wastewater from municipal treatment plants or brackish water). It is important to point that the use of alternative water sources can run into legal issues within the Water Framework Directive so this point must be solved in the future.

Ensuring proper procedures on each well site, strictly following health safety and environmental standards and developing specific measures to the prevention of spills and leakages (developing of prevention plans, introducing quick measures for the detection and remedy actions, protecting sites with impermeable liners), and ensuring the specific training of workers will minimise risks linked to spills and leakages.

Finally, transparency (by means of public disclosure of data) should be a guideline principle in order to improve public acceptance.

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