Project Acronym and Title:

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

SUSTAINABLE ALTERNATIVES FOR WASTEWATER MANAGEMENT RELATED TO SHALE GAS ACTIVITIES IN THE EUROPEAN CONTEXT

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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

One of the objectives of M4ShaleGas project is to establish recommendations on sustainable approaches and best practices regarding water management in order to minimize risks in shale gas operations at European level. The term "sustainable" is used in accordance with the concept of sustainable development defined in the Conference on Environment & Development Rio de Janerio, Brazil, 3 to 14 June 1992 (AGENDA 21) and the key objectives and policy guiding principles of EU Sustainable Development Strategy.

Before this, it is necessary to identify and resolve the knowledge gaps regarding water management (within hydraulic fracturing operations) in the wider European context.

The main lessons learnt from U.S. and Canada regarding water and wastewater management in shale gas operations are: 1) Water management practices differs amongst States and fields. 2) Fracturing fluids and flowback/produced water composition varies depending on the geological formation and the operator. 3) Compounds in wastewater that mainly determine wastewater management options are: TDS, scaling and plugging elements' content and NORM (naturally occurring radioactive materials) compounds appearance.

The knowledge about good and best practices is increasing and improving in U.S. and Canada, but it is needed to assess the applicability and suitability to European context. The main challenges in establishing general or specific recommendations on water management in the unconventional gas context are:

A complex regulatory context. A common general framework exists at European level but 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.

Available data are incomplete and asymmetric in the European context. The composition and the evolution over time of flowback and produced water in European shale gas operations are uncertain due to few States are developing shale gas operations. Most of them are in exploration and appraisal stage.

Establishing homogeneous recommendations within a complex geopolitical and environmental scenario is an important issue. The identification of risk scenarios and the measurement of those risks are highly linked to national and local particularities. At this stage, only a preliminary risk assessment can be

performed.

The operations regarding shale gas activities covered by this report are water supply, fracturing fluids, storage on site, flowback/produced water treatment and disposal options. For each topic, risk scenarios and trigger factors are set. Furthermore, the variables influencing the calculation of the probability of occurrence and the severity of the consequences for each topic are identified. The intensity and the duration of a particular hazard and the existence of exposure routes will determine the probability of occurrence (composition of the fracturing fluids and wastewater, total volume of chemicals, fluids and wastewater, distance between storage sites and the environmental compartments. Meanwhile, the severity of the consequences will be determined by the vulnerability of the elements exposed (status of conservation, vulnerability, presence of protected areas or residential areas, etc.). Finally, existing limitations at European level regarding the current water and wastewater management techniques and the applicability of the available minimisation measures are assessed.

After this analysis, the gaps and limitations existing in the European context are set and, for certain topics, general recommendations have been able to be established. For other topics, further researches are necessary.

The assessment of techniques to determine good and best practices on wastewater management must follow the waste hierarchy (prevention, preparing for reuse, recycling, other recovery and disposal) and be consistent with the precautionary principle.

In this context, and within the analysis performed, general recommendations about best practices can be set. However, the reality is that best practices will depend on the country, the specific site and the characteristics of the wastewater at each play. EIA procedures offer tools to perform risks assessment in a case-by-case basis and thus, specific best practices can be determined. This is the approach currently present in UK operations.

In a first approximation, general recommendation can be set. First of all, is essential to urge operators to disclose of full details of chemical used in hydraulic fracturing operations. Regarding wastewater management, and following the waste hierarchy principle, the first option would be the on-site treatment with reuse in subsequent stages, provided that this option was technically feasible (e.g. existence of other wells prepared to be fractured).

Regarding water supply, the best practices will involve the reuse of flowback with a previous on-site treatment or the use of alternative sources.

With regard to on-site storage, it is difficult to think that open pits will be allowed in Europe unless they comply with severe specifications. Tanks with close-loop system with previous vapour-liquid separator would be the best option.

Regarding the final disposal of wastewater, there are uncertainties about the feasibility of wastewater deep groundwater injection within the Water Framework Directive. The transfer to public wastewater treatment plants cannot be ruled out, but only could be implemented very cautiously. Practice that is gaining momentum is transferring wastewater to Centralised Wastewater Facilities with advance treatments prior to discharge or to reuse it.

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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] 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 objectives of this report are:
(1) Identify the knowledge gaps regarding the management of water and wastewater in shale gas operations in Europe.

(2) Identify and assess risks related to water management during shale gas operations.

and

(3) Define suitable measures to minimise those risks, taking into account possible constrains for its application in Europe from a sustainable perspective.

1.3 Aims of this report

Public dissemination of identified knowledge gaps, risks assessment and minimization measures considered -related to water and wastewater management- in relation to the sustainability for shale gas operations in Europe.

2 MAIN CHALLENGES AND KNOWLEDGE GAPS REGARDING WATER MANAGEMENT IN SHALE GAS OPERATIONS

One of the objectives of M4ShaleGas project is to establish recommendations on sustainable approaches and best practices regarding water management in order to minimize risks in shale gas operations at European level. The term "sustainable" is used in accordance with the concept of sustainable development defined in the Conference on Environment & Development Rio de Janerio, Brazil, 3 to 14 June 1992, AGENDA 21 (reducing health risks from environmental pollution and hazards) and the key objectives and policy guiding principles of EU Sustainable Development Strategy (environmental protection and economic prosperity, involvement of citizens, use best available knowledge and precautionary principle).

Before this, it is necessary to identify and resolve the knowledge gaps regarding water management (within hydraulic fracturing operations) in the wider European context.

The main lessons arising from U.S. and Canada experience regarding water and wastewater management in shale gas operations that were related in the previous report *Review of water management related to shale gas activities in the U.S., Canada and Europe* (Vadillo-Fernández et al., 2015) are:

- Water management practices differs amongst States and fields
- Fracturing fluids and flowback/produced water composition varies depending on the geological formation and the operator.
- Compounds in wastewater that mainly determine wastewater management options are: TDS, scaling and plugging elements' content and NORM (naturally occurring radioactive materials) compounds appearance.

The knowledge about good and best practices is increasing and improving in U.S. and Canada, but it is needed to assess the applicability and suitability to European context. As briefly cited in the previous report *Review of water management related to shale gas activities in the U.S., Canada and Europe* (Vadillo-Fernández et al. 2015), the main challenges in establishing general or specific recommendations on water management in the unconventional gas context are:

a) <u>A complex regulatory context</u>. 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. National legislations in each Member State in terms of water and wastewater management are applicable and must be taken into account.

b) Available data are incomplete and asymmetric in the European context. The composition and the evolution over time of flowback and produced water in European shale gas operations are uncertain. Even in the U.S. flowback and produced water composition varies considerably among plays and practices on wastewater management are selected on a case-by-case basis. Few States are developing shale gas operations in Europe. All of them are in exploration and appraisal stage.

c) A complex geopolitical and environmental scenario. Establishing homogeneous recommendations within a complex geopolitical and environmental scenario is an important issue. The identification of risk scenarios and the measurement of the risks are highly linked to national and local particularities. Thus, the calculation of the probability of occurrence and the severity of the consequences will be determined by technical, geopolitical and environmental variables at national, local and, even, site level. At this stage, only a preliminary risk assessment can be performed.

3 REGULATORY CONTEXT REGARDING WATER MANAGEMENT IN SHALE GAS OPERATIONS AT EUROPEAN LEVEL

The severity of a specific impact is determined, among other factors, by the vulnerability, the status of conservation and the degree of protection of the elements exposed. These factors are ruled by the current European and national legislative framework. Furthermore, the application of certain techniques widely used in other countries, may be limited by legislation constrains (e.g. prohibited by law).

The regulation of unconventional gas extraction can occur in different contexts within the EU. A number of laws are relevant in the regulation of unconventional gas facilities. Some are relevant to specific aspects of operation or to the protection of individual parts of the environment, while others have wider application to the operation of the facility. The existence of EU or national legislation addressing in whole or in part a particular environmental issue does not necessarily imply that appropriate guidance and/or standards has been developed that is commensurate with the application of best available techniques. An analysis made for the European Commission points that there are requirements that are relevant across much of the European countries but these are not in sufficient detail or specific enough to address all risks arising from unconventional gas exploration and production *(Technical support for assessing the need for a risk management framework for unconventional gas extraction*).

Thus, a common legislative European framework exists, but it seems to be insufficient to set recommendations on best practices. There are few Member States having adopted specific requirements for this type of operations and there are on-going reviews aimed at addressing the specificities of unconventional gas exploration and production. However, to date, none of the Member States have a specific regulatory regime for unconventional gas extraction (*Technical support for assessing the need for a risk management framework for unconventional gas extraction*). Most of the Member States cover issues regarding shale gas projects within their current legislation. In Germany, a draft law (currently under discussion) was signed off on April first 2015 with the aim to regulate hydraulic fracturing operations (Elsner et al., 2015).

Main pieces of European legislation affecting risk assessment linked to water and wastewater management in shale gas projects are:

- **Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment (EIA Directive)**. Directive does not specifically mention unconventional hydrocarbons or hydraulic fracturing but, European Commission considers that shale gas projects fall under EIA Directive (Potočnik, 2012). The status of EIA requirement for exploration and/or extraction of hydrocarbons (i.e. whether a full EIA is required or screening) differs amongst the individual Member States. In some Member States, it is obligatory to make an environmental impact assessment for projects related to prospecting and extraction of unconventional hydrocarbons (Tarka, 2014a). In Bulgaria, Denmark and Spain, this requirement has been established. Lithuania has introduced another regulation relating to the prospecting of unconventional hydrocarbons, but not to their extraction. In Poland, it is not required to make an impact assessment or to obtain an environmental permit in the exploration stage if the operator conducts works related to drilling of a well to the depth of 5,000 m outside the sensitive zones. For production stage it is required. Other Member States just examine shale gas projects under EIA national regulation in the same way as the hydrocarbon projects.

- **Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment (SEA Directive).** The risks to different environmental elements are further mentioned under site specific cumulative impacts (Potočnik, 2012). Few references have been found regarding the application of the SEA Directive to shale gas operations. It would be the most effective approach to address cumulative impacts at national and European level. For example, requirements for prohibited/restricted areas or buffer zones may be implemented at the SEA level (not project specific). To date, only The Netherlands, Romania and UK address shale gas operations under SEA Directive.

- **Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries (Mining Waste Directive)**. This Directive applies in particular, given that used fracturing fluid is to be considered as extractive waste, and given that any area designated for the accumulation or deposit of extractive waste should be considered as a waste facility (Potočnik, 2012). The operator has also to draw up a waste management plan and major-accident prevention policy if the facility is classified as 'Category A' according to the Directive. Under the Mining waste Directive, not only must the operator of a waste management facility notify the competent authority of any significant adverse environmental effects identified but the competent authority itself must inspect the facility before any deposit operations and at regular intervals to prevent major accidents. The Mining Waste Directive applies and requires the treatment of flow back water (Potočnik, 2012). Furthermore, the Mining Waste Directive may enable measures to be required (through BAT and BREFs) but permits under this Directive are limited in their capacity to address all aspects. To date, none of the Member States had set specific requirements with regard to the surface storage of wastewater from unconventional gas activities, provided specific requirements for the treatment and discharge to surface of wastewater or provided particular requirements for the management of wastewater (*Technical Support for assessing the need for a risk management framework for unconventional gas extraction*).

- **Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for the Community action in the field of water policy (Water Framework Directive)**. The Water Framework Directive requires the Member State (not the operator) to assess the quality of limited/selected bodies of water. The Water Framework Directive, in its Article 11.3 (j) sets a prohibition of direct discharges of pollutants into groundwater subject to the following provisions: Member States may authorise reinjection into the same aquifer of water used for geothermal purposes. They may also authorise, specifying the conditions for “injection of water containing substances resulting from the operations for exploration and extraction of hydrocarbons or mining activities, and injection of water for technical reasons, into geological formations from which hydrocarbons or other substances have been extracted or into geological formations which for natural reasons are permanently unsuitable for other purposes. Such injections shall not contain substances other than those resulting from the above operations”. Thus, under article 11.3 (j) of the Water Framework Directive, it would be possible to authorise discharges into the groundwater under certain circumstances, a specific conditions. The *Technical support for assessing the need for a risk management framework for unconventional gas extraction* (2014) reveals that the Member States does not have a common understanding of the application of the transposition provisions of Article 11(3)(j) of the Water Framework Directive with regard to the injection of wastewaters resulting from hydraulic fracturing activities for underground disposal or with regard to re-use in subsequent fracturing operations, leading to potential contradictory approaches between Member States. This is the case of Germany, where the draft law of April 2015, that aims to regulate hydraulic fracturing, suggests that operators could deal with produced water by disposal injections (Elsner et al., 2015).

- **Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC Text with EEA relevance (SEVESO III Directive)**. When a shale gas installation falls under the SEVESO III Directive (depending on the thresholds related to storage of gas or of dangerous substances listed under the Directive, or subject to the mixture of chemicals on site), the operators have to fulfil several obligations before starting his project, such as informing the competent authority about the nature and the quantity of dangerous substances that would be stored within his establishment (Potočnik, 2012).

- **Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH Regulation)**. Under the REACH Regulation, manufacturers and importers of substances used for shale gas operations were obliged to register (Potočnik, 2012). If an operator of a shale gas project uses hazardous registered substances, his suppliers have to provide him with an extended safety data sheet that includes exposure scenarios. Furthermore, in the Recommendation of 22 January 2014, on minimum principles for the exploration and production of hydrocarbons, the European Commission has emphasised again that manufacturers, importers and downstream users are obliged to comply with their obligations under the REACH Regulation. In most of the Member States operators of unconventional gas activities were not obliged by law to disclose information to public authorities and the public on the substances planned for use during the fracturing phase. In Germany, under the draft law of April 2015, it would be mandatory. In UK operators must disclose the full details of the chemicals and assess hazards on a case-by-case basis.

- **Directive 98/8/EC of the European Parliament and of the Council of 16 February 1998 concerning the placing of biocidal products on the market (Biocidal Product Directive)**. This Directive will apply when biocidal products are used to prepare water for fracturing fluids or flowback to reuse.

- **Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora (Habitats Directive)**. This Directive will apply when the project could affect Natura 2000 sites or habitats of special concern.

- **Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (Birds Directive)**. Birds Directive will apply when Special Protection Areas can be affected and particularly, areas for the conservation of migratory birds. This acquires particular importance when talking about gas emissions from open pits that store flowback and produced water.

- **Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment.** Even though flowback and produced water should be considered as industrial water, this Directive would be applicable when wastewater from shale gas activities could be transferred to a municipal (or other nature) wastewater treatment facility. It also applies if effluents from wastewater treatment plants would be used in the preparation of fracturing fluids.

- **2014/70/EU: Commission Recommendation of 22 January 2014 on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing**. This is the only specific piece of legislation for shale gas projects. It is not binding, but sets minimum principles that Member States must to be consider and it is the basis on which Member States must establish specific measures. The European Commission has put an emphasis on the following issues: 1) the need for greater public participation in the decision making processes, 2) protection of groundwater, 3) seismicity, 4) the need for monitoring of the relevant environmental components potentially affected by high volume hydraulic fracturing, as well as 5) adequate control of chemical substances used and 6) rational use of water (Tarka, 2014b). It has also been emphasised that information must be provided on 1) the precise composition of the fracturing fluid used for each well, 2) the volume of water used for the fracturing of each well, 3) the pressure applied during fracturing, and 4) volume and composition of returned fluids as well as air emissions of methane and other volatile organic compounds (Tarka, 2014b). The most important principles established by the Recommendation include: 1) Obligation to prepare a strategic environmental assessment (based on the requirements of Directive 2001/41/EC) before granting license for exploration or production of hydrocarbons with hydraulic fracturing, 2) obligation to define minimum distances between the prospecting or production operations carried out and residential and water-protection areas and 3) obligation to inform the public about chemicals used for fracturing in individual wells.

It can be seen that there is not only divergence of the practical regulation of unconventional gas extraction in the Member States, but also divergence in the interpretation of EU environmental law to address the challenges this type of facility places on regulators.

At State level, to regulate hydraulic fracturing in Germany, on April 1st 2015, the German Chancellor’s cabinet signed off on a draft law which is currently under discussion in the parliament and states the following: (1) hydraulic fracturing is prohibited in water protection areas, their catchments and natural habitats, 2) elsewhere, the disposal injections of formation water are possible, but subject to Environmental Risk Assessment by Mining Authorities and involving the declaration of all chemical additives and 3) in shale, coal, clay and marl formations less than 3000 m deep, hydraulic fracturing activities are forbidden except for scientific investigations to explore environmental impacts or if an accompanying scientific expert panel concludes that is non problematic in a given formation (Elsner et al., 2015).

As can be seen, legislative aspects pose a challenge for establishing general recommendations regarding hydraulic fracturing wastewater management at European level, due to missing understanding of the applicable legislation and divergence between national legislation. In this sense it is necessary to continue making efforts to solve these gaps.

4 SUSTAINABILITY CRITERIA AND ASSESSMENT OF TECHNIQUES

The basic sustainability criteria to adopt for the approval of the proposed measures should be based on the AGENDA 21 principles, regarding the reduction of health risks from environmental pollution and hazards, as well as on the Key Objectives and Policy Guiding Principles of EU Sustainable Development Strategy as defined in the section 2 of this document.

Accordingly, the approach under the framework of the Best Available Techniques (BAT) is considered as the best sustainability criteria to apply in order to select, by using expert judgment, whether a measure aforementioned is subject to be proposed as mitigating measure. The approach to the sustainability concept through the BAT offers the advantage of perfectly comply with the three Key Objectives of EU Sustainable Development Strategy (Evrard et al. 2016). In addition, BATs are usually defined as a manifestation of sustainable development (Merkouris 2012) or as an essential tool for sustainable production (https://ec.europa.eu/jrc/en/research-topic/sustainable-production-best-available-techniques).

Constrains at European level regarding the current water and wastewater management techniques and the applicability of the available minimisation measures have been assessed in this document.

The assessment of techniques to determine good and best practices on wastewater management must also 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.

It is not the aim of this report to enter in to a cost-effectiveness assessment. However, it is important to keep in mind that each water management practice will have cost implications that may interfere with companies' cost-effectiveness assessment. It could pose a limitation for the implementation of certain techniques. Economic feasibility/affordability of techniques is missing from the majority of the guidance reviewed (which often e.g. simply list techniques for consideration). This is a key issue in identifying whether techniques are appropriate at the installation level and in enabling setting permit conditions. Economic factors will obviously vary substantially from installation to installation and will determine how far technologies for treatment and reuse are more suitable (Shaffer et al. 2013).

5 DEFINITION OF TOPICS AND RISK GENERATING FACTORS

The topics regarding shale gas activities that are covered by this report are the following:

- Water supply.
- Fracturing fluids.
- Storage on site of wastewater.
- Flowback/produced water treatment.
- Disposal options.

For each topic, some alternatives are going to be proposed based on four risk generating factors:

- Hydraulic Fracturing Fluids
- Water Supply
- On-site Storage
- Wastewater final disposal

For each risk generating factor, different risk scenarios and triggers are set. Furthermore, the probability of occurrence and the severity of the consequences for each risk scenario have been assessed.

The variables influencing the calculation of the probability of occurrence and the severity of the consequences for each risk are identified. The probability of occurrence will be determined by the intensity and the duration of a particular hazard and the existence of exposure routes. Meanwhile, the severity of the consequences will be determined by the vulnerability of the elements exposed. With regard to the topics assessed, the probability of occurrence will depend on the composition of the fracturing fluid, flowback and produced water and the method of water supply, storage of wastewater, treatment and disposal. The severity of the consequences will depend on environmental and social variables inherent in each country and site.

Each risk factor will be defined in its own section. Each section will be composed of three parts:

1) A review of the current state regarding the risk factor. This part contains general information that could be considered in order to diminish those risks as well as information as regards trends concerning policies, scientific research, best practices, etc.

2) The specific definition of the risk scenario for each factor.

3) A proposal with the main measures to mitigate the risk. In some cases this part may include some comments concerning the rationale, the limitations of the measure and evaluation of its suitability (including a conclusion section if necessary).

6 RISKS RELATED TO HYDRAULIC FRACTURING FLUIDS. RISK SCENARIOS, VARIABLES INFLUENCING THE QUANTIFICATION, MITIGATION MEASURES AND LIMITATIONS.

In recent times, scientist, governing authorities and general public have set their sights on the composition of hydraulic fracturing fluids, in particular on the disclosure of the chemicals used as additives.

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. The disclosure does not only concern topics related to water management but also another as groundwater or surface water contamination, baselines establishment, impacts on drinking water, chemical and wastewater transport and storage, etc. (McFeeley et al, 2012).

In the U.S. is not obligatory to disclose the chemical additives used in the blended water of injection, except when hydraulic fracturing is performed on Federal and Indian Lands (U.S. Bureau of Land Management, 2015). However, some operators disclose the name, concentration and CAS number of chemicals through FracFocus. This register also exists for Canada.

The risk scenario linked to hydraulic fracturing fluids would be defined as: *Spills and leaks of chemicals and/or fracturing fluids that can lead into the pollution of soil, surface water and groundwater*.

The trigger factor would be the improper handling and disposal chemicals and/or hydraulic fracturing fluids.

Some authors noted that surface spills of chemicals and/or fracturing fluid may pose a greater contamination risk that hydraulic fracturing itself (Mair et al., 2012).

The probability of occurrence of the risk and the severity of the consequences will depend on several variables:

- The probability of occurrence: would depend on the total volume of chemicals and fluid, and the distance between storage sites and the environmental compartments (groundwater and surface water bodies, habitats of interest, residential areas, etc.) that could be affected. Once a spill has occurred, the probability of pollution of an environmental element would also depend on the chemical composition of the fracturing fluid (this means that, in case of spill, when the chemical composition does not pose a hazard, the probability of occurrence is null).

- The severity of the consequences would depend on:
  - The composition of the flowback and produced water.
  - Ecological status of the water bodies.
  - Vulnerability status and degree of protection of the elements exposed (term referred to aquifers, streams, areas protected by national regulations, Ramsar Sites, Sites of Community Interest, Special Areas of Conservation for birds, residential areas, etc.).
  - Land uses.
  - Groundwater and surface water uses.

The main measures that can be implemented to mitigate this risk are:

- Previously to hydraulic fracturing, is need to provide 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 (percent by mass), and maximum ingredient concentration in hydraulic fracturing fluid (percent by mass). Subsequent adjustments of the composition during the processes shall also be notified.
- Using non-hazardous chemicals wherever possible.
- Storing chemicals and fracturing fluid away from surface waters, aquifers and other sensitive areas (as areas covered by the Natura 2000 network, protected areas, etc.). For example, buffer zones could be determined.
- Protecting sites with impermeable liners (when this technique is considered as right, since a study performed by the Polish Geological Survey showed that this technique is not always right (Konieczyńska et al., 2015).
- Establishing safety distances between the prospecting or production operations and residential areas, water-protection areas or other environmental elements of special concern.

Most of the measures aim to mitigate the risk by proper management of chemicals and fracturing fluids.

The application of the obligation to disclose chemicals full details can conflict with existing commercial property rights of third parties. This issue could be solved by disclosing the composition only to authorities.

As can be seen, in order to assess specific risks linked to chemical compounds present in fracturing fluids (and also in wastewater) is crucial to fully disclosure of the chemical used for hydraulic fracturing process. This disclosure should include all data necessary to unmistakably identify the chemicals (IUPAC name, CAS number when existing), final concentrations and total volumes. 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 (*Technical* *support for assessing the need for a risk management framework for unconventional gas extraction*).

The number of spill reported by the EPA regarding fracturing fluids and chemicals storage provides 32.5% of the total spills linked to hydraulic fracturing operations (EPA 2015b).

Based on different hazardous components of hydraulic fracturing fluid additives, it was suggested that sodium hydroxide, 4,4-dimethyl, oxazolidine, and hydrochloric acic would be good indicators to monitor water contamination upon a leak or a spill of hydraulic fracturing fluids (Aminto and Olson, 2012).

Recently, significant progress has been made in the classification of chemicals used in hydraulic fracturing progress with regard to their hazardous (Elsner et al., 2016). The main source of data for this research was the disclosure of chemicals made in FracFocus.

However, it would be necessary to assess risks linked to new compounds that can be formed from underground chemical reactions due to water-rock interaction. Additives which are initially nontoxic may potentially transform into harmful when they react with substances already present in the shale gas formation. In addition, it would be necessary to assess the natural occurring compounds in the formations that mix with the fracturing fluid and come to the surface with the flowback and produced water.

In this sense efforts have been made at European level to address this issue. The 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, sets that Member States should ensure that the operator publicly disseminates information on the chemical substances and volumes of water that are intended to be used and are finally used for the high-volume hydraulic fracturing of each well (making reference to CAS number, safety data and maximum concentrations in the fracturing fluid). As reference above, the implementation of the Commission Recommendation has been asymmetric between Member States. Furthermore, shale gas operations fall under REACH regulation.

Regarding the Member State regulations, in Germany, the draft law of April 2015 would enforce the operators to disclose all chemicals used in hydraulic fracturing fluids. In UK, in practice, operators must declare the full details of the chemicals to the regulator and will publish a brief description of the chemical´s purpose and any hazards it may pose to the environment, but subject to appropriate protection for commercially sensitivity. Furthermore, chemicals used in drilling and fracturing fluids are assessed for hazards on a case-by-case basis for each well by the appropriate environmental regulator (*Fracking UK shale: water*, 2014).

Currently, Cuadrilla is the only company which has hydraulically fractured for shale gas in the UK. The company has published the chemicals which were approved for its operations (*Fracking UK shale: water*, 2014; Cuadrilla Ltd., 2014):

- Polyacrylamide friction reducers (0.04 - 0.075 % of the total volume injected), a substance classified as non-hazardous, non-toxic.
- Sodium salts for tracing fracturing fluid (0.000001 – 0.000005 %).
- Hydrochloric acid (0.125 %)
- Glutaraldehyde biocide (0.005%), used on rare occasions when the water provided needs to be further purified to kill bacteria that can produce hydrogen sulphide gas. UV disinfection could be applied before blending additives.

Additives proposed, in the quantities proposed, have resulted in the fracturing fluid being classified as non-hazardous by the Environment Agency (Cuadrilla Ltd., 2014).

In Poland, most of the operators disclose chemicals used in their hydraulic fracturing operations on the OPPPW (The Polish Exploration and Production Industry Organization website, http://www.opppw.pl/en/sklad_plynu_szczelinujacego/23).

In conclusion, the main measures that can be implemented to mitigate this risk are the disclose of chemical additives (in U.S. this is a non-mandatory option, been performed through FracFocus), the use of non-hazardous chemicals wherever possible, the store of chemicals and fracturing fluid away from sensitive areas, the protection of sites with impermeable liners (if it is considered suitable), the establishment of safety distances between the prospecting or production operations and elements of special concern.

Table 1 shows the current degree of implementation of the considered minimizing measures in U.S. and Canada, including the willingness of European operators to apply them. Table 1 also shows a valuation of the technical-economical suitability and the degree of improvement in terms of sustainability.

Table 1: Current degree of implementation of the considered minimizing measures, valuation of the technical-economical suitability and degree of improvement in terms of sustainability for risks related to hydraulic fracturing fluids.

	Degree of implementation					**Technical-economical suitability**			**Improvement in terms of sustainability**		
Measure	Widespread	Trend	Experimental	Backward	Proposed	Low	Moderate	High	Low	Moderate	High
Provide an initial description of the base fluid and each additive that the operator intends to use in the hydraulic fracturing fluid.											
Using non-hazardous chemicals wherever possible.											
Storing chemicals and fracturing fluid away from surface waters, aquifers and other sensitive areas.											
Protecting sites with impermeable liners. (*)When this technique is considered as right, since a study performed by the Polish Geological Survey showed that this technique is not always right.									uncertain *		
Establishing safety distances between the prospecting or production operations and residential areas, water-protection areas or other environmental elements of special concern.											

7 RISKS RELATED TO WATER SUPPLY. RISK SCENARIOS, VARIABLES INFLUENCING THE QUANTIFICATION, MITIGATION MEASURES AND LIMITATIONS.

Water is a major component of hydraulic fracturing operations. It typically makes up almost 90% or more of the fluid volume injected into a well (EPA, 2015a). Water consumption typically varies from 8,000 to 100,000 m^3 per unconventional well (Vengosh et al., 2014). In UK is estimated that water consumption per well varies from 10,000 and 30,000 m^3 (*Fracking UK shale: water*, 2014).

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 activities (estimations suggest that the amount of water needed to operate a fracked well for a decade may be equivalent to the amount needed to run a 1,000 MW coal-fired power plant for 12 hours) (*Fracking UK shale: water*, 2014).

However, in geographic areas with drier climates and/or higher aquifer consumption 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 (Nicot et al., 2012), even in wet areas (Mitchell et al., 2013). In small to moderate streams withdrawals for hydraulic fracturing can exceed the natural flows (Rahm et al., 2012).

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 (e.g. Spain, south of Italy, south of France, etc.).

Three risk scenarios are identified for this topic (Table 2): 1) *Reduction of the ecological and quantitative status of groundwater and surface water bodies and associated ecosystems*, 2) *Changes in the quantity and quality of water available for drinking* and 3) *Competition with other uses of water (especially in drought – prone areas)*. The trigger factor for all the scenarios would be the water abstraction.

The probability of occurrence of the risks and the severity of the consequences would depend on several variables (Table 2):

- Probability of occurrence: would depend on the volume of water abstracted compared with the total available water and the intensity of water abstraction for other purposes than hydraulic fracturing.
- The severity of the consequences would depend on:

- Ecological status of the water bodies.
- Presence of Ramsar Sites.
- Other concurrent uses of the water (especially when drinking water is involved).

The measures that can be implemented to minimize those risks on freshwater resources are (Table 2):

- Using 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. Marginal water refers to water with low quality that cannot be used for the domestic or agricultural sectors.)
- Reusing flowback for subsequent fracturing that would substitute for fresh water operations (Vengosh et al., 2014). Another option involve the substitution of water by other types of liquids (e.g., gel), but it does not fall within the scope of this project.

The application of the measures described above have some limitation:

- Reusing flowback is a very cost-effective practice for operators, but has also some constrains:
  - Requires other wells to be ready for hydraulic fracturing or drilling.
  - The feasibility relies on the distance between the locations where water is produced and reused.
  - Recovered water that undergoes successive treatment steps gradually increases in TDS.
- Flowback for reuse must have a specified quality. Blending with fresh water or intermediate treatments would be necessary.
- An alternative water source must provide sufficient (by itself) water volume for a hydraulic fracturing stage.
- Using water sources different from surface waters or ground water bodies makes necessary water transport (trucks or pipe).
- Using water from other industrial facilities could make necessary additional treatments.
- The legal feasibility of using alternative water sources must be assessed.

The current upper limit for salinity for adjusting to friction reducers in hydraulic fracturing fluids is about 25,000 mg/L. For example, in the Horn River Basin of British Columbia, Canada, saline groundwater with TDS of up to 30,000 mg/L is treated and used for hydraulic fracturing (Rivard et al., 2014). However, salt-tolerant and water-based friction reducers have been developed to enable recycling of even higher saline wastewater for hydraulic fracturing (Hallock et al, 2013). The current trend at global level is to use water with increasing TDS concentrations. At Blackpool Lancashire (UK), the operator, Cuadrilla Resources, has set, specifically for that site, a TDS threshold of 250,000 mg/L for its friction reducer. If TDS content would higher, the flowback fluid would be diluted with water to reduce this content.

Table 2: Risks scenarios, mitigation measures and variables influencing the probability of occurrence and the severity of the consequences, linked to water supply in hydraulic fracturing operations.

RISK SCENARIOS	TRIGGER FACTOR	MITIGATION MEASURES	PROBABILITY	SEVERITY
Reduction of the ecological and quantitative status of surface water and ground water bodies **Changes in the quantity and quality of water available for drinking** **Competition with other uses of water especially in drought – prone areas**	Surface water or ground water abstraction	• Reuse of flowback • Use other sources for water supply: – Water from public water pipelines – Water from wastewater treatment plants – Treated water from other industrial facilities	Will depend on: • the volume of water abstracted • the intensity of water abstraction for other purposes than hydraulic fracturing	Will depend on: • the ecological status of water bodies • other concurrent uses of the water (especially when drinking water is involved) • Presence of Ramsar Sites.

The reuse of flowback water is a technique that is highly increasing in shale gas operations. In addition, water coming from wastewater treatment plants is one of the most suitable water sources for hydraulic fracturing operation accomplishment, as it could offer, theoretically, a constant flow (in quantity and quality). The suitability of these techniques is assessed down below.

7.1 Suitability of reusing wastewater from hydraulic fracturing operations in subsequent stages.

This is of the most suitable options to deal with wastewaters in the first instance. Furthermore, it is the option that better fit to waste hierarchy principle. In that sense, the European Parliament (*Draft Report on the environmental impacts of shale gas and shale oil extraction activities* 2012) believes that on-site closed-loop water recycling offers the most environmentally friendly sound by minimising water volumes and the potential for surface spills relating to wastewater transportation.

In theory, there would be any issue for using saline wastewater in fracturing operations. Opinions vary widely on the water quality that may be used for hydraulic fracturing (see Table 3).

Table 3. Target concentrations on physic-chemical and biological parameters in water used for preparing fracturing fluids.

Parameter	Units	Target concentration	Author
TDS	mg/L	< 50,000 < 20,000	Schlicher et al., 2009 Acharya et al., 2011
pH	-	6-8 6,5-8,5	Lewis, 2012 Acharya et al., 2011
Chloride	mg/L	3,000-90,000 < 30,000 typical but up to 90,000 < 12,500	Lewis, 2012 Schlicher et al., 2009 Acharya et al., 2011
Iron	mg/L	< 20 < 10	Schlicher et al., 2009 Acharya et al., 2011
Hardness	mg/L $CaCO_3$	< 2,500 < 2,000	Schlicher et al., 2009 Acharya et al., 2011
TSS	mg/L	< 50 < 50 < 50	Lewis, 2012 Schlicher et al., 2009 Acharya et al., 2011
Oil and soluble organics	mg/L	< 25 < 25 < 50	Lewis, 2012 Schlicher et al., 2009 Acharya et al., 2011
Barium		Low levels	Lewis, 2012
Calcium	mg/L	350-1,000 < 350	Lewis, 2012 Schlicher et al., 2009
Sulphate	mg/L	< 25	Acharya et al., 2011
Total nitrogen	mg/L	<3 – 56.4	Hayes, 2009
Total phosphorous	mg/L	<0.1 – 0.14	Hayes, 2009
BOD_5	mg/L	<2 – 110	Hayes, 2009
COD	mg/L	<10 – 924	Hayes, 2009
TOC	mg/L	<1.8 – 202	Hayes, 2009
Bacteria	cells/mL	< 100 < 100 < 100	Lewis, 2012 Schlicher et al., 2009 Acharya et al., 2011

For instance, most of the operators currently insist on using very low-TDS source water to avoid scaling issues in the downhole piping. Some operators, such as Range Resources, have reported success in using up to 26,000 ppm chlorides in the Marcellus shale. In fact, Range Resources and Chesapeake operators reported at the 2010 GWPC Conference (Pittsburgh) that they presently reuse almost of early flowback water in the Marcellus shale by blending with fresh water (TDS<500 ppm) in subsequent operations. Some experts feel that water salinity equivalent to seawater (with about 35,000 ppm of TDS content) may be usable for hydraulic fracturing). Some operators are reportedly even considering the re-use of waters with salinity as high as 120,000 ppm TDS with low hardness and scale-causing contaminants, but some authors consider this to be speculative at the present moment as these may be applicable to specific situations where blending with a majority of very low-TDS source water may be anticipated before frac use (Acharya et al., 2011).

The potential contaminants present in flowback include residual hydraulic fracturing fluid chemistries, iron, total hardness, alkalinity, silica, bacteria and solids. The increase in concentration of these species is known to have detrimental impacts in friction reducers and cause crosslinking: high chloride concentration destabilizes the fluid and creates problems with crosslinking, iron degrades and breaks polymers in gels causing premature breaking and crosslinking, an excess of sodium destabilizes the fluid, the presence of bacteria degrade the gel viscosity (M-I SWACO 2012). In addition, an excessive content of iron, hardness, divalent cations, alkalinity, silica, bacteria and solids may cause scaling. High contents of TSS (clays, silica) and bacteria can lead to fouling and plugging.

There are several treatment options to adapt the quality of the flowback to that required for hydraulic fracturing operations. Treatment options have been separated in four categories:

- Level 1. Primary Treatment: Removes TSS, oil and grease, iron and microbiological contaminants by means clarification. Includes settling/sedimentation systems using coagulations and flocculation, aeration, filtration or hydrocyclones dissolved air flotation systems and disinfestation. TSS can remove by settling/sedimentation systems using coagulations and flocculation; aeration a high pH can remove Fe^{2+}. Oil and grease emulsions or in dissolved forms can be removed by mechanical devices including hydrocyclones and specialized media filters containing porous hydrophobic absorptive substances. Disinfection of bacteria most commonly used methods are ultraviolet light, ozonation, chlorinated compounds or chemical bactericides (Kidder et al, 2011).

- Level 2. Secondary Treatment: Removes divalent ions (calcium, barium, magnesium, strontium) by means softening techniques. These ions can be removed by ion exchange, nanoflitration or by lime softening involving the addition of lime $Ca(OH)_2$ and/or caustic soda (Silva, 2012). Ion exchange consists of reversible exchange of ions between the liquid and a solid resin. This is an effective, mature technology. It requires restocking of salt supply and disposal of concentrate. This technology is not capable of removing TDS levels above approximately 5,000 mg/L. Regarding several authors (Lewis, 2012; Schlicher et al., 2009; Acharya et al, 2011), flowback treated with both primary and secondary treatments, reaching a maximum concentration of 30,000 mg/L of chloride could be used in hydraulic fracturing operations. However, if this target concentration is not reached with this treatments, remain flowback could be blended with freshwater and be used (Karapataki, 2012).

- Level 3. Tertiary treatment: It consists of a partial desalination in addition to primary and secondary treatments with a target concentration of less than < 50,000 ppm of TDS. There are several techniques at this level (Table 4 shows a comparison):

  - Nanofiltration: medium pressure membrane process for removing divalent and trivalent ions.
  - Reverse osmosis (RO): method of separating water from dissolved salts by passing feed water through a semi-permeable membrane at a pressure greater than the osmotic pressure. Some of the biggest limitations for RO are costs, pretreatment/feed pump requirements and high potential for fouling.
  - Forward osmosis (FO): An osmotically driven membrane process, during which water diffuses spontaneously from a stream of low osmotic pressure (feed) to a hypertonic solution of high osmotic pressure. Unlike RO, the system operates without the need of applying hydraulic pressure.
  - Membrane distillation - involves a thermally driven membrane separation process that utilizes a low-grade heat source to facilitate mass transport through a hydrophobic, micro porous membrane. A hydrophobic membrane displays a barrier for the liquid phase, letting the vapour phase (water vapour) pass through the membrane's pores. The driving force of the pressures is given by a partial vapour pressure difference created from the temperature difference.
  - Thermal evaporation/distillation. This technique is designed to treat wastewater with a concentration of 60,000-80,000 mg/L of TDS. This technique results in fresh water recovery rates of approximately 70% - 85%. This technique presents a high energetic cost.
  - Crystallization (Zero Liquid Discharge): this technique can generate clean water from saturated brines with TDS concentrations up to 650,000 mg/L. The recovery rate is about 95%. This technique presents a high energetic cost.

- Level 4: This treatment involves a complete desalination (TDS content < 500 ppm). This treatment would be applied when a beneficial use of the water is expected or sometimes for the surface discharge according to effluent standards.

Table 4. Comparison of desalination technologies (data from Karapataki, 2012).

Technique	Pre-treatment	Target TDS concentration (mg/L)	Recovery rate (%)
Nanoflitration	Yes	20,000	75-90%
Reverse osmosis	Yes	45,000	75-90% for 25,000 TDS 40-65% for 40,000 TDS
Forward osmosis	Yes	35,000	< 95% with RO/FO system
Membrane distillation	Minimal	250,000	60-95%
Thermal evaporation/distillation	Yes	200,000	70-85% for 60-80,000 TDS 50% for 150,000 TDS
Crystallization	Minimal	650,000	95%

The current trend is to increase the reuse of wastewater (with or without prior treatment) in subsequent fracturing stages or for fracturing nearby wells. This implies the need of develop proper friction reducers. For example Cuadrilla Resources, at Blackpool Lancashire (UK), has set, specifically for that site, a TDS threshold of 250,000 mg/L for its friction reducer. If TDS content would higher, the flowback fluid would be diluted with water to reduce this content. If needed a previous disinfection (by means UV disinfection or by adding glutaraldehyde) would be performed.

The main constrain for the applicability of the reuse of flowback fluid without treatment (or with a very simple on-site pretreatment) is that would be necessary the existence of nearby wells prepared to be fractured. If this were not so, this kind of wastewater management procedure would not be economically feasible due to transport requirements.

In conclusion, according to the current research, the flowback could be used with a primary and secondary treatment used in conjunction with the mixture with fresh water. Tertiary treatment is only viable in Centralized Wastewater Treatment (CWT) and it also depends on the capacity of the CWT and volume to be treated. The onsite units treatment has several constrains as the variability of composition of the additives and the differences in the chemical composition between wells and operators. See (Techno-Economic Analysis of Water Management Options for Unconventional Natural Gas Developments in the Marcellus Shale).

7.2 Suitability of using treated effluents from wastewater treatment plants in hydraulic fracturing operations, at European level.

Using sewages from municipal treatment plants poses an alternative to the use of freshwater in hydraulic fracturing operations. To evaluate the suitability of this option it is necessary to compare the water chemical composition needed for hydraulic fracturing operations (Table 3) with the composition of raw water incoming to wastewater treatment plants (Table 5) as well with the composition of the effluents resulting (Tables 6 and 7).

Table 5. Average/range chemical composition for a typical urban raw wastewater (with 20% of industrial contribution) (from: Marin, 2014; Huertas et al., 2013).

Parameter	Units	Concentration
pH	-	6.8
Conductivity	μS/cm	950
Dissolved oxygen	mg/L	1
TSS	mg/L	300-450
TDS	mg/L	450
COD	mg/L	400-700
BOD_5	mg/L	250-400
Nitrates	mg/L	< 5
Total nitrogen (kjeldahl)	mg/L	40-60
Total phosphorus	mg/L	10-15
Detergents	mg/L	15
Oil and grease	mg/L	109
Chloride	mg/L	114
Sulphate	mg/L	93
Phenols	mg/L	< 5
Iron	mg/L	1.20
Manganese	mg/L	0.3
Arsenic	mg/L	0.007
Lead	mg/L	0.079
Copper	mg/L	0.2
Zinc	mg/L	0.11
Nickel	mg/L	0.006
Cadmium	mg/L	< 0.001
Mercury	mg/L	0.051
Total chrome	mg/L	0.012
Total coliforms	cells/100 mL	2×10^8
Faecal coliforms	cells/100 mL	1×10^8
Hardness ($CaCO_3$)	mg/L	162
Fluoride	mg/L	0.139

As inferred from Tables 3 and 5, the content of several of the critical parameters (chloride, TDS, scaling ions and plugging elements) of a typical raw wastewater would be below the concentration required. Parameters as TSS, sulphate and those related to organic contamination (total nitrogen, total phosphorous, BOD_5, bacteria) can pose a problem. Using this kind of water would make necessary to pre-treat the water.

Regarding the suitability of the outgoing effluents from wastewater treatment plants, the requirements for discharges from urban water treatment plants are defined by Directive 91/271/EEC (Table 6). Only biological oxygen demand, chemical oxygen demand, total suspended solids and, within sensitive areas, nitrogen and phosphorus are assessed. Table 6 shows the concentration of physic-chemical and biological parameters in a typical effluent from wastewater treatment plants. A comparison with the quality requirements for fracturing fluid can be performed.

The concentration of the parameters addressed shows that it would be suitable using the effluents from wastewater treatment plants for the preparation of fracturing fluids. Bacterial content is higher than that required, thus, a previous disinfection with either of the available methods (biocides, ultraviolet disinfection, ozone disinfection, etc.) would be necessary.

Table 6. Requirements for discharges from treatment plants of urban waste water (data from Table 1 of the Annex I to Directive 91/271/EEC on treatment of urban waste water).

Parameter	**Concentration (mg/L)**	**Minimum percentage of reduction (%)**
BOD_5	25	70-90
COD	125	75
TSS[b]	35-60[a]	70-90[a]
Total nitrogen[c]	10-15[a]	70-80[a]
Total phosphorus[c]	1-2[a]	80[a]

[a] According to population equivalent

[b] This requirement is optional

[c] For discharges to sensitive areas (Annex II.A (a) of Directive 91/271/EEC)

Table 7. Physic-chemical and biological parameters concentration in a typical effluent from wastewater treatment plants (*Guide extensive wastewater treatment processes*, European Commission).

Parameter	**Units**	**Concentration**
pH	-	6.5 to 9
COD	mg/L	$\leq$ 125
BOD_5	mg/L	$\leq$ 25
TSS	mg/L	$\leq$ 35
Total nitrogen	mg/L	$\leq$ 15
Total phosphorus	mg/L	$\leq$ 2
Oil and grease	mg/L	$\leq$ 5
Total coliforms	UFC/100 mL	500
Faecal coliforms	UFC/100 mL	100
Faecal Streptococcus	UFC/100 mL	2

There is few experience of the use of effluents from wastewater treatment plants in hydraulic fracturing operations. In this respect, the company Pioneer Natural Resources and the City of Odessa (Texas, US) have committed to a contract by which Pioneer will purchase Odessa's effluent municipal water. Such effluent water purchases are allowing Pioneer to make productive use of non-potable water. In return, the region will see a reduction in truck traffic and a regular revenue stream (see http://www.pxd.com/values/sustainability/water).

Shell Canada, in the Town of Edson (Alberta, Canada), have committed to a contract by which Shell Canada is provided with treated wastewater for hydraulic fracking purposes. By piping the water instead of trucking it, Shell reduced traffic, noise and dust, while eliminating more than 3 million kilometres of truck trips a year.

In conclusion, effluents from wastewater treatment plants could be used (with a previous disinfection) for hydraulic fracturing purposes, provided that the ecological flow of the water streams receiving these effluents allows it. In any case, there are few experiences of application of this measure (Alberta and Texas).

Table 8 shows the current degree of implementation of the considered water supply related minimizing measures in U.S. and Canada, including the willingness of European operators to apply them. Table 8 also shows a valuation of the technical-economical suitability and the degree of improvement in terms of sustainability.

Table 8: Current degree of implementation of the considered minimizing measures, valuation of the technical-economical suitability and degree of improvement in terms of sustainability for risks related to water supply.

	Degree of implementation					**Technical-economical suitability**			**Improvement in terms of sustainability**		
Measure	Widespread	Trend	Experimental	Backward	Proposed	Low	Moderate	High	Low	Moderate	High
Using 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).											
Reusing wastewater from hydraulic fracturing operations in subsequent stages.											
Using treated effluents from wastewater treatment plants in hydraulic fracturing operations.											

8 RISKS RELATED TO ON-SITE STORAGE. RISK SCENARIOS, VARIABLES INFLUENCING THE QUANTIFICATION, MITIGATION MEASURES AND LIMITATIONS.

About 10-40 % of the volume of fluid injected returns to the surface after hydraulic fracturing. 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), organics, hardness, metals, biological load and naturally occurring radioactive material (NORM). Flowback and produced water can be classified according to the TDS content (Slutz et al., 2012). The typical salinity of flowback water increases with time after hydraulic fracturing due to an increasing proportion of the formation water mixing with injection fluids. The volume and the salinity of flowback waters and produced waters also vary spatially among shale gas wells. In most studied flowback and produced waters, the concentration of toxic elements such as barium, strontium, and radioactive radium are positively correlated with the salinity (Vengosh et al., 2014). These water quality parameters vary greatly across geographies and throughout the operational life of the well, increasing the complexity of water management decisions (Gay et al., 2012).

Given that flowback and produced waters have much higher salinities than surface waters (with a typically TDS content less than 100 mg/L), even small inputs can impact freshwater quality (Vengosh et al., 2014).

Spills or leaks of flowback and produced water can pollute soil, surface water and shallow groundwater with organics (such as BTEX), salts (such as Cl, Br), metals and metalloids (e.g. Ba, Sr, Se, As) and other constituents (such as radionuclides) (Vengosh et al., 2014). Groundwater contamination due to the formation of toxic (carcinogenic) trihalomethanes (THMs), typically co-occurring with high concentrations of halogens in the saline waters (Cl, Br or I ions substituting hydrogen in the methane molecule) can occur (Vengosh et al., 2014). Recently, scientists have revealed the presence of endocrine-disrupting chemicals (Kassotis et al., 2016).

Some constituents are readily transported with water (i.e., chloride and bromide), while others depend strongly on the geochemical conditions in the receiving water body (i.e., radium and barium), and assessment of their transport is based on site-specific factors. The likelihood of an organic chemical in produced water reaching and impacting drinking water resources include: mobility, solubility, and volatility. In general, physicochemical properties suggest that organic chemicals in produced water tend to be less mobile in the environment. Consequently, if spilled, these chemicals may remain in soils or sediments near spill sites. Low mobility may result in smaller dissolved contaminant plumes in groundwater, although these chemicals can be transported with sediments in surface water or small particles in ground water. Organic chemical properties vary with salinity, and effects depend on the nature of the chemical (EPA 2015b).

The effects on the health of the population include the potential for carcinogenesis, immune system effects, changes in body weight, changes in blood chemistry, pulmonary toxicity, neurotoxicity, liver and kidney toxicity, and reproductive and developmental toxicity. As noted above, evaluating any potential risk to human populations would require knowledge of the specific chemicals that are present at a particular site, whether or not humans are exposed to those chemicals and, if so, at what levels and for what duration, and the toxicity of the chemicals (EPA 2015b).

Impacts to drinking water resources from spills or releases of produced water depend on the volume, timing, and composition of the produced water. Impacts are more likely the greater is the volume of the spill, the longer the duration of the release, and the higher the concentration of produced water constituents (i.e., salts, naturally occurring radioactive material, and metals). Chronic releases can and do occur from produced water disposed in unlined pits or impoundments, and can have long-term impacts. Ground water impacts may persist longer than surface water impacts because of lower flow rates and decreased mixing. Plumes from unlined pits used for produced water have been shown to persist for long periods and extend to nearby surface water bodies (EPA 2015b).

In several disposal sites, the wastewater had geochemical fingerprints such as high TDS, low SO_4/Cl ratio and distinctive Br/C, $^{228}Ra/^{226}Ra$ and $^{87}Sr/^{86}Sr$ ratios (Vengosh et al., 2014), that can serve as indicators of spill/leaks.

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 wastewater 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). In addition to remnants of methane, ethane, propane and natural gasoline (compounds with more than 5 carbon atoms), can be found the following:

- BTEX: benzene (known as carcinogenic), toluene (may affect the cardiovascular and nervous systems), ethylbenzene (can cause kidney damage, classified as a possible human carcinogen), xylene (can affect the respiratory system and cause liver and kidney damage). Naphthalene. These compounds are commonly associated with petroleum and gas deposits and appear typically in low to trace concentrations.
- Polycyclic aromatic hydrocarbons (PAHs): pyrene, phenanthrene, fluoranthene, benzo(a)pyrene, benzoanthracene, naphthalene. Heavier polycyclic aromatic hydrocarbon compounds are generally not present in the flowback water, and occur occasionally in very low concentrations.
- Pyridine and phthalate esters. These compounds are only found in less than 50% of the samples and in trace concentrations.
- Methylated aromatics (phenols). These compounds are more common to be encountered but in very low concentrations (10 to 100 ppb).
- Halogenated components: trichlorobenzene, tetrachloroethene, etc., are rarely encountered in flowback water.

Benzene is a chemical of major concern, because of its carcinogenic potential, that may also cause short-term toxicity to the nervous system, liver, and kidneys at high concentrations. Other VOCs associated with hydrocarbon production may have the potential to injure organ systems when uncontrolled exposures occur. Inhalation is the primary route of exposure to VOCs. However, they may also enter the body through the skin (dermal) or by mouth (ingestion). Toxicity hazards from many of the VOCs encountered during flowback may occur at airborne concentrations far below their flammability hazard. The occupational exposure limits for VOCs have been set by the U.S. Occupational Safety and Health Administration (Occupational Safety and Health Administration 2014).

McKenzie et al (2012) established that residents living at a distance less than 8 kilometers from wells are at greater risk for health effects than are residents living farther as a consequence of the presence BETX and aliphatic hydrocarbons. Exposure to benzene was the most significant factor contributing to an increased risk of cancer.

Enclosed, portable tanks are a commonly used alternative to pits for the storage of wastewater. 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).

In both cases, pits or tanks, the occurrence and frequency of the spills and leaks appear to coincide with the density of shale gas drilling (Entrekin et al., 2011). The rapid growths and intensity of unconventional drilling could lead to a higher probability of surface spills or leaks (Vengosh et al., 2014).

Two risk scenarios have been determined regarding wastewater storage (Tables 9 and 10): 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*.

For the scenario 1 (Table 9), the trigger factors would be: pit breaching and overflows (sometimes due to incorrect dimensioning), liner malfunction and tanks overfill.

The probability of occurrence of the risk and the severity of the consequences would depend on (Table 9):

- Probability of occurrence: would depend on density of wells and the distances to sensitive areas (term referred to aquifers, streams, areas protected by national regulations, Ramsar Sites, Sites of Community Interest, Special Areas of Conservation for birds, residential areas, etc.). Once a spill has occurred, the probability of pollution would also depend on the composition of the flowback and produced water (this means that, in case of spill, when the chemical composition does not pose a hazard, the probability of occurrence is null).
- The severity of the consequences would depend on:
  - Composition of flowback and produced water.
  - Vulnerability and ecological status of the water bodies.
  - Water uses.
  - Status of conservation or degree of protection of other exposed elements.
  - Use of the land.

The measures that can be implemented to minimize this risk aim to mitigate the risk by proper management of wastewater (by diminishing the probability of occurrence) and by establish mechanisms for responding quickly (Table 9):

- Performing a correct dimensioning of the storage facilities (e.g. using large recurrence intervals for dimensioning pits and tanks).
- Constructions of berms around the site.
- Installation of storm water drainage systems.
- Pit lined with a durable leak-proof synthetic material (being careful with the possible appearance of biogenic methane under the liner).
- Double skinned tanks.
- Tanks provided with spill containment systems.
- Storage facilities equipped with leak detection systems.
- Performing routine inspections and maintenance.

- Establishing safety distances between the prospecting or production operations and residential areas, water-protection areas or other environmental of special concern elements

For the scenario 2 (Table 10), the trigger factors would be: direct evaporation from pits and tanks´ venting due to overpressures.

The probability of occurrence of the risk and the severity of the consequences would depend on (Table 10):

- Probability of occurrence: would depend on the density of wells and the distances to sensitive areas (term referred residential areas, Special Areas of Conservation for birds, migratory bird flyways, etc.). Once the evaporation has occurred, the probability of affecting people or animals would depend on the composition of the flowback and produced water.
- The severity of the consequences would depend on:
  – Composition of flowback and produced water.
  – Status of protection of the inhabiting or in passing species and the use of the land.

The measures that can be implemented to minimize this risk aim to mitigate the risk by diminishing the probability of occurrence (Table 10):

- Covering pits with netting systems.
- Vapour recovery prior to wastewater storage.
- Installing a closed looping system. The closed loop system is also called Green Completion or Reduced Emissions Completions. Under these terms the American Administration wants to reduce emissions and venting of methane and VOCs into the atmosphere.

Table 9: Risks scenarios, mitigation measures and variables influencing the probability of occurrence and the severity of the consequences, linked to wastewater on-site storage in hydraulic fracturing operations (Scenario 1: *spills and leaks from on-site storage which can pollute soil, surface and ground water*).

RISK SCENARIOS	TRIGGER FACTORS	MITIGATION MEASURES	PROBABILITY	SEVERITY
Spills and leaks which can pollute soil, surface and ground water	• Pits: – Pit breaching and overflows – Liner malfunction • Tanks: – Overfills	• Correct dimensioning of the facilities (e.g. using large recurrence intervals for dimensioning pits) • Pit lined with a durable leak-proof synthetic material • Tanks provided with spill containment systems • Storage facilities equipped with leak detection systems • Routine inspections and maintenance • Safety distances between on-site storage and residential areas, water-protection areas or other environmental of special concern elements	Will depend on: • Composition of the flowback and produced water • Density of plays • Distance to sensitive areas	Will depend on: • Composition of the flowback and produced water • Vulnerability and ecological status of water bodies • Water uses • Status of conservation or degree of protection of other exposed elements • Use of land

Table 10: Risks scenarios, mitigation measures and variables influencing the probability of occurrence and the severity of the consequences, linked to wastewater on-site storage in hydraulic fracturing operations (Scenario 2: *emission of gases and volatile compounds that can pose a risk for wild life (mainly birds) and human health*).

RISK SCENARIOS	TRIGGER FACTORS	MITIGATION MEASURES	PROBABILITY	SEVERITY
Emission of volatile and semivolatil compounds that can pose a risk for wild life (mainly birds) and human health	• Direct evaporation from pits • Tanks´ venting	• Covering pits • Vapour recovery prior to storage • Installation of closed-loop systems	Will depend on: • Composition of the flowback and produced water • Density of plays • Distance to sensitive areas (residential areas, ecosystems of special concerns, migratory bird flyways)	Will depend on: • Composition of the flowback and produced water • Status of protection of the inhabiting or in passing species • Use of land

Despite Kuwayama et al (2015) recommend avoid outright bans of either pits or tanks, the fact is that some U.S. States have prohibited the storage of blowback and produced water in open pits, while other have imposed strict rules when using them.

Depending on the state, there are several rules regarding pits and the protection of surface and ground water. In addition to liners, some states also require pits used for long term storage of fluids to be placed keeping a minimum distance from surface water to minimize the chances of surface water contamination should there be an accidental discharge from the pits.

In U.S. the use of open pits are being questioned, due to environmental issues. The Bureau of Land Management (U.S. Department of the Interior) publishes on March 2015 the rule *Oil and Gas; Hydraulic Fracturing on Federal and Indian Lands*. Regarding management of recovered fluids sets that *all fluids recovered between the commencements of hydraulic fracturing operations must be stored in rigid enclosed, covered, or netted and screened above-ground tanks. The tanks may be vented, unless Federal law, or State regulations (on Federal lands) or tribal regulations (on Indian lands) require vapor recovery or closed-loop systems*. The tanks must not exceed 80 m^3 of capacity unless approved in advance by the authorized officer.

Lined pits could be approved only if the operator demonstrates that the use of tanks is unfeasible and must meet the following conditions:

- Maintain a minimum safe distance of 90 meters from the pit to ephemeral streams or water sources.
- 150 meters to perennial streams, springs, fresh water sources or wetlands.

- 90 meters to any occupied residence, school, park, school bus stop, place of business or other areas where the public could reasonably be expected.
- There is no usable groundwater within 15 meters of the surface.
- Pits would not be constructed in fill or unstable areas.
- Pits lined with a durable, leak-proof synthetic material and equipped with a leak detection system.
- Pits must be routinely inspected and maintained.

The North Carolina Mining & Energy Commission (North Carolina, US) has proposed a package of more than 120 rules establishing a regulatory framework in order to promote, among others, the prevention and mitigation of the risks linked to open pits that include:

- Eliminate the use of wastewater pits for flowback and produced wastewater and require that all wastewater be managed in a closed loop system.
- Require any wastewater storage to be in watertight tanks placed inside secondary containment structures.
- When tanks installation is unfeasible, is needed to increase the setback distance from an open pit to streams and other water bodies from 60 to 600 meters.
- Increase the freeboard requirements.

Generally fewer regulations governing tanks than for pits exist. In Arkansas, closed-loop systems are required within 100 feet of water. Michigan and New York require that tanks be used for flowback and produced water. Other States of U.S. have specific regulations for tanks. Colorado requires mitigation measures for tanks located within the 300 meters “buffer zone” setback from high occupancy buildings, including liners beneath and berms around. Other States require that tanks be surrounded by a secondary containment structure (to hold the capacity of the tank) and routine maintenance. The EPA regulates in U.S. VOCs emissions from tanks, estimating that storage tanks have the potential to emit 6 or more tons of VOCs a year and are required to reduce the emissions.

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 (Draft Report on the environmental impacts of shale gas and shale oil extraction activities, 2012).

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. In U.S. the use of pits is much more widespread but due to the inherent dangers this practice is being increasingly questioned.

Table 11 shows the current degree of implementation of the considered on-site storage related minimizing measures in U.S. and Canada, including the willingness of European operators to apply them. Table 11 also shows a valuation of the technical-economical suitability and the degree of improvement in terms of sustainability.

Table 11: Current degree of implementation of the considered minimizing measures, valuation of the technical-economical suitability and degree of improvement in terms of sustainability for risks related to on-site storage.

	Degree of implementation					**Technical-economical suitability**			**Improvement in terms of sustainability**		
Measure	Widespread	Trend	Experimental	Backward	Proposed	Low	Moderate	High	Low	Moderate	High
Performing a correct dimensioning of the storage facilities (e.g. using large recurrence intervals for dimensioning pits and tanks).					■	■	■	■	■	■	
Constructions of berms around the site.					■	■	■	■	■		
Installation of storm water drainage systems.					■	■	■		■		
Pit lined with a durable leak-proof synthetic material (*) Being careful with the possible appearance of biogenic methane under the liner				■		■	■		Uncertain *		
Double skinned tanks.					■	■	■		■	■	
Tanks provided with spill containment systems.			■			■	■		■	■	
Storage facilities equipped with leak detection systems.	■					■	■		■	■	
Performing routine inspections and maintenance.	■					■	■	■	■	■	
Establishing safety distances between the prospecting or production operations and residential areas, environmental of special concern elements.	■					■	■	■	■		

Measure	Degree of implementation					Technical-economical suitability			Improvement in terms of sustainability		
	Widespread	Trend	Experimental	Backward	Proposed	Low	Moderate	High	Low	Moderate	High
Covering pits with netting systems. (*) The use of pits shows a backward trend in general				■ *		■	■		■		
Vapour recovery prior to wastewater storage.		■				■	■		■	■	
Installing a closed looping system. The closed loop system is also called Green Completion or Reduced Emissions Completions.			■			■			■	■	■

9 RISKS RELATED TO WASTEWATER FINAL DISPOSAL. RISK SCENARIOS, VARIABLES INFLUENCING THE QUANTIFICATION, MITIGATION MEASURES AND LIMITATIONS.

In the U.S. and Canada, wastewater from unconventional hydrocarbons is managed in several ways: wastewater is sometimes recycled for subsequent hydraulic fracturing, commonly injected into deep injection wells, or treated. Treatment options include transferring wastewater to publicly owned treatments works (POTW), municipal wastewater treatment plants (WWTP) or centralized wastewater treatment facilities (CWT) (Vadillo-Fernández et al., 2015).

The most widespread option of wastewater disposal in U.S. continues to be deep underground injection (without treatment or with a prior treatment), but this option has been prohibited in several States. Secondly, wastewater is sent to wastewater treatment plants in many regions that are not able to remove many of the anthropogenic or naturally occurring compounds present in wastewater from shale operations. Following this treatment, these compounds can be discharged into surface water (Kassotis et al., 2016).

Even if the disposal is within regulations, the high volumes of wastewater can lead to a build-up of radiation which can pose substantial environmental and health risks (e.g. treating wastewater containing NORM in wastewater treatment facilities, forces to manage sludge potentially containing radioactive compounds) (Vengosh et al., 2014). Thus, NORM content poses a high challenge in the minimization of the risks linked to wastewater management.

The chemical characterization (as well related hazards) of flowback and produced water performed in Section 6 is applicable to this section. The information about wastewater treatments, exposed in Section 5.1 is also applicable to treatment options prior to disposal.

The current trends suggested the need of enforcing zero discharge policy for untreated wastewater and establishing adequate treatment technologies could prevent surface water contamination (Vengosh et al., 2014). In this sense, the latest treatment options (that the best water quality and the most bounded to the precautionary principle) are: thermal evaporation/distillation of flowback and brine treatment through lime and Na_2SO_4 addition (Veil, 2011). While thermal evaporation/distillation removes all dissolved salts in the wastewater, brine treatment only removes metals such as barium and NORM but does not remove halogens (chloride and bromide) (Warner et al., 2013). In order to remove THM compounds, additional remediation technologies, such as complete desalination should be introduced for removal of the dissolved salts to levels acceptable for healthy stream ecology (e.g. TDS < 500mg/L) (Vengosh et al., 2014). The reduction of the radioactive elements from wastewater and safe disposal of NORM-rich solid wastes and/or solid residues from treatment of wastewater is critical in preventing contamination and accumulation of residual radioactive materials (Warner et al., 2013).

The risk scenario linked to the disposal of wastewater is determined as: *contaminant reaching surface water and groundwater or accumulating in the sediment of river and lakes due to inappropriate treatment and disposal of wastewater*.

The trigger factors would be: the underground injection of wastewater without an adequate treatment and the discharge to surface water of untreated or inadequately treated wastewater.

The probability of occurrence of the risk and the severity of the consequences would depend on:

- Probability of occurrence: would depend on the composition of the flowback and produced water, the density of wells and the distances to sensitive areas (term referred to aquifers, streams, areas protected by national regulations, Ramsar Sites) from underground injection or discharge sites.
- The severity of the consequences would depend on:
  - Vulnerability and ecological status of the water bodies.
  - Water uses

The measures that can be implemented to minimize this risk aim to mitigate it by ensuring the proper treatment before disposal (by diminishing the probability of occurrence):

- Establishing minimum distances between disposal sites and the elements potentially exposed (aquifers, Ramsar Sites, sources of drinking water, etc.). For example, Vengosh et al (2014), suggest the need of maintaining a minimum of 1 km between shale gas sites and already existing drinking water wells. Even though this kind of approach for establishing buffer distances or buffer zones is used in countries like U.S., it seems to be simplistic. It could be pose a first approximation or a general recommendation but realistic buffer zones must be set on the basis of hydrogeological modelling at each site.
- Implementing adequate treatment techniques. Whatever technique or combination of techniques referred in Section 5.1 should be applied in order to adequate the quality of the wastewater to the required limits for discharge (or to the quality that the receiving system can tolerate). Vengosh et al (2014) suggest enforcing zero discharge policy for untreated wastewater.
- Transferring wastewater to Public Wastewater Treatment Facilities (PWTP).
- Transferring wastewater to Centralised Wastewater Treatment Facilities (CWT).
- Removal off site to a suitable licensed waste treatment and disposal facility.

The suitability of deep underground injection disposal and the transfer of the resulting wastewater to Public Wastewater Treatment Plants or Centralised Wastewater Treatment Facilities, at European level, is assessed in the following sections.

Although the aim of this project is to establish general recommendation on best practices, when regarding a specific shale gas operation, once flowback is produced, operators should carry out trials including laboratory test, to identify the best way to dispose of the flowback and produced water, and make a risk assessment case-by-case to finally decide the best disposal options. Once flowback and produced water is characterized, the operator, in conjunction with wastewater treatment services providers, will be able to determine the appropriate treatment to properly treat wastewater to the required discharge standards (*Technical support for assessing the need for a risk management framework for unconventional gas extraction*). The final treatment option should be approved by the Environmental Authority on a case-by-case basis.

9.1 Suitability of deep underground injection of wastewater from shale gas operations at European level.

Disposal of flowback and produced water by means underground injection continues to be a widespread technique in the U.S. Even though States such as Pennsylvania have prohibited underground injection in Class II disposal wells, many operators ship their flowback and produced water by truck to Ohio for underground injection.

As referred in the Section 3 about the regulatory context, the Water Framework Directive sets a prohibition of direct discharges of pollutants into groundwater (except if the water injected maintain the same characteristic that water extracted and is injected in the same geological formation). On this basis, the deep underground injection of wastewater from hydraulic fracturing operations could be posed by the operators and eventually authorized by States Member.

The main disposal options for the disposal of flowback and produced water in the European context could be those that are currently used for the disposal of saline water (coming from activities other than shale gas operations) or other fluids such as natural gas or CO_2: depleted gas and oil reservoirs and saline aquifers. Some concerns are related to each option, including environmental concerns and competition with other uses such as gas storage.

Depleted gas and oil, aquifer and salt cavern reservoirs have often been used for strategic gas storage purposes. As indicative data, a total of 141 gas storage facilities were operative, under construction or planned in 2015 in the European Union. Most of these gas storage facilities are located in depleted oil and gas fields, with the exception of Germany and the U.K. where predominating structures are salt caves. Only in a few cases saline aquifers are used in France, Belgium, Spain, Latvia, Germany (European Commission, 2015; GSE Storage Map, 2015). This would be the better of the two underground disposal options, but have some limitation. The transport of high volumes of wastewater to the injection sites would be necessary, which can poses additional risks. Furthermore, this disposal option would strongly compete with gas storage activities. To resolve this conflict, more research would be necessary regarding these topics: creation of maps of regional storage potential, collection of geological information of storage sites, estimation of storage capacities, elaboration of databases to be inserted into GIS and detailed analysis of case studies and scenarios.

Saline aquifers are defined as porous and permeable reservoir rocks that contain saline fluid in the pore spaces between the rock grains. They generally occur at depths greater than aquifers that contain potable water. Uncertainties about the behaviour of the fluids when injected into deep saline aquifers remain. Although EPA concluded that the identified cases where drinking water resources were impacted in U.S. are small relative to the number of hydraulically fractured wells (EPA 2015a), new research point the appearance of contamination evidences. In addition, it would be necessary to transport high amounts of wastewater.

In conclusion, underground disposal options may be cost effective, but they cannot be considered best practices since are not in accordance with the precautionary principle (in the case of saline aquifers) or poses additional constrains (competition with other uses and need of transportation).

9.2 Suitability of transferring wastewater from shale gas operations to Public Wastewater Treatment Facilities.

In the recent past, several operators have managed unconventional oil and gas extraction wastewater by discharge to publicly owned treatment works (POTWs) in the US, the equivalent of public wastewater treatment plants. But most of POTWs stopped accepting this kind of wastewater between 2008 and 2011 (Vadillo-Fernández at al. 2015).

The EPA published a proposed rule on April 7, 2015, that prohibits the disposal of unconventional oil and natural gas extraction wastewater in POTWs. The proposed rule is part of EPA's broader effort to regulate hydraulic fracturing and specifically responds to concerns that POTWs are ill-equipped to treat wastewater from hydraulic fracturing (EPA, 2105a).

EPA noted that most conventional POTWs were not equipped to remove the total dissolved solids (salts), metals, and radionuclides that are sometimes found in shale wastewater. High salinity interacts with biological treatment processes, modifies microbial growth and metabolic processes due to changes in osmolarity. The high content of TDS in flowback and produced water is difficult to remove in conventional wastewater treatment plants, and posed and additional risk, the failure of the treatment system. Metals and eventual NORM content could also affect to biological treatment, posing as well and additional risk, the need to manage sewage sludge metal rich and with an eventual NORM content. In addition, byproducts can be formed at drinking water treatment facilities by reaction of hydraulic fracturing constituents with disinfectants (THMs). This is also the point of view of scientist of the British Geological Survey.

The only possibility that would lead the treatment of wastewater from hydraulic fracturing operations in public wastewater treatment facilities would be to adjust the initial concentrations of the constituents to those that the facilities are currently accepting. This would imply the need to implement a pretreatment system to fit these concentrations.

Down below, typical allowed inflowing concentrations for selected parameters in several wastewater treatment plants in Europe are presented (Table 12). Note that not information about metal content or NORM is assessed.

Table 12. Maximum concentration of typical parameters in inflowing waters permitted in public wastewater treatment plants.

Parameter	Units	Trucios PWTP (Bizkaia, Spain)[1]	Arenales PWTP[2] (Alicante, Spain)[2]	Klimzowiec PWTP (Chorzów, Poland)[2]	Szczecinek PWTP (Szczecinek, Poland)[2]	Seixal PWTP (Portugal)[2]
TSS	mg/L	450	550	602	450	262
COD	mg/L	500	1500	-	971	504
BOD_5	mg/L	305	700	382	390	257
N-NTK	mg/L	58	80	70	75.6	
$N\text{-}NO_2$	mg/L			0.08		
$N\text{-}NO_3$	mg/L			1		
P-total	mg/L	17	10	6.7	13.6	
Chlorine	mg/L				111	
Oil and grease	mg/L					50

[1] data from Water Consortium of Bilbao, Bizkaia (Spain).
[2] data from CADAGUA

Note that no information about TDS, metals and NORM content is available. In addition, wastewater from hydraulic fracturing operations presents unpredictable flow patterns that can pose an issue for conventional sewage treatments.

This indicate that wastewater from hydraulic fracturing operations needs to be treated before transferred to public wastewater treatment plants, in order to adequate the quality to the parameters that those treatment plants can accept, and this would imply a case-by-case analysis. This option cannot be ruled out, but only could be implemented very cautiously.

This section only address the suitability of treating wastewater from hydraulic fracturing operations in municipal wastewater treatment plant, but it is necessary to take in mind that, as industrial wastewater, the treatment of flowback in industrial wastewater treatment plants might be a feasible option. This issue needs to be covered in subsequent researches.

In conclusion, U.S. has prohibited the treatment of flowback in the POTWs due to the interaction with biological treatments. However, the use of wastewater could be a feasible alternative in the future.

9.3 Suitability of transferring wastewater from shale gas operations to Centralised Wastewater Treatment Facilities.

This option is emerging and gaining momentum in the U.S. as a viable solution for long-term efficiency in managing wastewater treatment and even water sourcing in hydraulic fracturing operations.

Centralisation not only provides treatment for subsequent and reuse of flowback wastewater or for the discharge of properly treated water from a large number of wellheads when the wells are fracked, but also provides treatment of the produced water for the long-term, full lifecycle of the wells – which represent the vast majority of wastewater flowing from wellheads. Furthermore, a centralised system can more easily access and use alternative water sources, such as from municipal wastewater facilities, which otherwise would be highly unlikely to be accessed.

Centralised treatment facilities handle both the flowback wastewater and produced wastewater from oil and gas wells within a region, at a radius of 60 to 80 kilometres. This option would be feasible in some regions but not possible in others.

These facilities can include a large variety of treatments, since primary to advance treatments:

- Primary three-phase separation to remove dissolved natural gas, floating gel, oil, sand and suspended solids, followed by storage for equalisation of chemical composition and flow.
- Secondary separation utilising dissolved air or gas flotation for removal of a wide variety of contaminants including polymers, oils and suspended solids. Bactericide (or other disinfection method) is applied to control bacterial growth.
- Removal of metals by precipitation, and removal of salts by reverse osmosis
- Proper sludge management for dewatering collected solids.

Such plants can be integrated with alternative sources of water to supplement fresh water needs for fracking, such as from abandoned mines, storm water control basins, municipal treatment plant effluent, and power plant cooling water.

The main advantages of these treatment plants are:

- Advance treatments could be implemented
- They can treat both flowback and produced water for all life-cycle of a well.
- Provides treatment for a large number of wells.

- Water treated could be used for other purposes.

But also have some limitations:

- A large number of wells are required to be cost effective.
- Transport is needed (principally by means of pipelines).
- Resultant sludge must be managed in a properly way.

In conclusion, this alternative is gaining momentum in the U.S. because offers several advantages than makes it to be viewed as a long-term effective alternative. Nevertheless, there are also several limitations to solve (large number of wells, need of pipelines, sludge generation).

Table 13 shows the current degree of implementation of the considered wastewater disposal related minimizing measures in U.S. and Canada, including the willingness of European operators to apply them. Table 13 also shows a valuation of the technical-economical suitability and the degree of improvement in terms of sustainability.

Table 13: Current degree of implementation of the considered minimizing measures, valuation of the technical-economical suitability and degree of improvement in terms of sustainability for risks related to wastewater final disposal.

	Degree of implementation					Technical-economical suitability			Improvement in terms of sustainability		
Measure	Widespread	Trend	Experimental	Backward	Proposed	Low	Moderate	High	Low	Moderate	High
Establishing minimum distances between disposal sites and the elements potentially exposed											
Implementing adequate treatment techniques											
Transferring wastewater to Public Wastewater Treatment Facilities											
Transferring wastewater to Centralised Wastewater Treatment Facilities											
Removal off site to a suitable licensed waste treatment and disposal facility											
Deep underground injection of wastewater (*)Uncertainties about the behaviour of the fluids when injected into deep saline aquifers remain. The deep underground injection could be posed by the operators and eventually authorized by States Member.									Uncertain *		

10 CONCLUSIONS

Europe poses a complex legislative, environmental and social scenario in to which best practices regarding water management must be set. The probability of occurrence and the severity of a risk depend on operational, environmental and social factors.

In this context, and within the analysis performed, general recommendations about best practices can be set. However, the reality is that best practices will depend on the country, the specific site and the characteristics of the wastewater at each play. EIA procedures offer tools to perform risks assessment on a case-by-case basis and thus, specific best practices can be determined. This is the approach currently present in UK operations.

In a first approximation, general recommendation can be set. First of all, is essential to urge operators to disclose of full details of chemical used in hydraulic fracturing operations. Regarding wastewater management, following the waste hierarchy principle, the first option would be the on-site treatment with reuse in subsequent stages, provided that this option was technically feasible (e.g. existence of other wells prepared to be fractured).

Regarding water supply, the best practices will involve the reuse of flowback with a previous on-site treatment or the use of alternative sources instead freshwater to prepare fracturing fluids.

With regard to on-site storage, it is difficult to think that open pits will be allowed in Europe unless they comply with severe specifications. Tanks with close-loop system with previous vapour-liquid separator would be the best option.

Regarding the final disposal of wastewater, there are uncertainties about the feasibility of wastewater deep groundwater injection within the Water Framework Directive. The transfer to public wastewater treatment plants cannot be ruled out, but only could be implemented very cautiously. Practice that is gaining momentum is transferring wastewater to Centralised Wastewater Facilities with advance treatments prior to discharge or to reuse it.

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