



Recovered Water Management Study in Shale Wells

Final Report
ERM project 0243719

June 2014



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Sponsor: International Association of Oil and Gas Producers (OGP)

Prepared By: Environmental Resources Management (ERM)

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GLOSSARY

Definitions of the key terminology used in this study:

- **By-products:** residues generated during the treatment of recovered water. By-products may have different names and forms (e.g., slurry, sludge, and backwash) depending on the specific process that generated them. They may also have similar contents according to the type of constituents treated.
- **Disposal (management practice):** a recovered water management practice where treated water exits the hydraulic fracturing operation and is not subsequently used in the operation. Treated recovered water is returned to the hydrological cycle (e.g., discharged into a surface water body, evaporated into the atmosphere, or injected into a deep saline aquifer).
- **Drilling fluid:** this fluid (often referred to as “mud”) is usually a mixture of water, clay, weighing material and chemicals that is used to raise rock cuttings, made by the drill bit during the perforation of vertical/horizontal wells, to the surface for disposal.
- **Exploration and appraisal phase:** exploration typically involves the acquisition and interpretation of geological data from the potential hydrocarbon layers of interest. As part of this acquisition process, operators may decide to drill wells that are designed for logging and taking core samples to obtain further geological data on the formation. Following the data appraisal, operators may then decide to flow test the well before making any further commercial decisions. This stage may also involve carrying out hydraulic fracturing procedures, depending on the geology. The information gathered during this relatively short phase helps the operators evaluate parameters such as expected flow rates and well performance, in order to better define subsequent development phase requirements and commercial viability.
- **Flowback water:** the water that returns to the surface from the wellbore within the first months after hydraulic fracturing. Flowback water is primarily composed of fracturing fluids and sand (or other material used as proppant in the process). It may also contain some water from the formation.
- **Fracturing fluid:** fluid used to stimulate the target formation during hydraulic fracturing. It is comprised of a base liquid, a selection of additives and a proppant agent, most commonly sand. In the early days of hydraulic fracturing, freshwater was generally considered to be the only option for use as base fluid, given that the type of additives used at that time were not compatible with highly saline water. Through time, research into additives has resulted in the creation of new compounds that are capable of maintaining their properties under a broad spectrum of water quality conditions. These additives maximise the potential for recovered (or brackish) water to be used in the preparation of fracturing fluid for subsequent fracturing/drilling operations.

- **Groundwater:** as defined by the U.S. Ground Water Protection Council, groundwater refers to water contained in geological media which has been designated by a state as usable for domestic, industrial or municipal purposes¹.
- **Hydraulic fracturing:** a technique that is used by the oil and gas industry to stimulate a specific target formation that would otherwise not produce at economic rates. Fracturing is used in some hydrocarbon-bearing rocks with low permeability, such as shale, after the drilling process. The technique consists of pumping a highly pressurised fluid, primarily water containing a propping agent (“proppant”), such as sand, down the wellbore and into the formation, to create an extensive network of fractures in the hydrocarbon-bearing rock. The proppant holds the fractures open allowing fluids to be produced from the reservoir formations.
- **NORM:** an acronym for Naturally Occurring Radioactive Materials, which include radioactive elements found in the environment such as uranium, thorium and potassium, and any of their radioactive decay products, such as radium and radon. These elements have always been present in the earth’s crust and within the tissues of all living beings.
- **Pilot and development phase:** this is based on the results of the exploration and appraisal phase and is operator’s plan for the full development of the field, including the construction and operation of processing facilities, pipelines, and drilling and stimulation of wells in the areas where the oil and gas will be commercially extracted. The step before full development is a pilot project which involves the same components as full development but on a smaller scale. This helps the operator refine the design for the development. The main characteristic of a development phase is the permanency of facilities as it is associated with long term operation.
- **Produced formation water:** water that exists in subsurface formations (also known as formation water) and is brought to the surface during oil and gas extraction. Usually this water is known as produced water.
- **Proppant:** A granular substance, often sand, that is mixed with and carried by fracturing fluid pumped into a shale well. Its purpose is to keep cracks and fractures that occur during the hydraulic fracturing process open so trapped natural gas can escape
- **Recovered water:** a combination of flowback and produced water that returns to the surface from the wellbore after hydraulic fracturing.
- **Reuse (management practice):** a recovered water management practice where the treated recovered water is subsequently used in either hydraulic fracturing activities or other industrial processes.

¹ According to the Water Framework Directive (DIRECTIVE 2000/60/EC) - Article 2: groundwater means all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil. The main difference between this definition and the definition that will be used in this study is that the latter refers to water usage as a criterion to define the concept of groundwater.

- **Shale formation:** shale is a fine-grained sedimentary rock that forms from the compaction of silt and clay-size mineral particles and has a fissile (readily splitting) and laminated (made of thin layers) texture. A shale formation is an extension of this type of material that is sufficiently distinct from other surrounding geological layers to be differentiated. Most shale formations are considered source rock reservoirs for other traditional hydrocarbon reservoirs.
- **Shale Gas Play:** A set of discovered, undiscovered or possible natural gas accumulations that exhibit similar geological characteristics. Shale plays are located within basins, which are large-scale geologic depressions, often hundreds of miles across, which also may contain other oil and natural gas resources

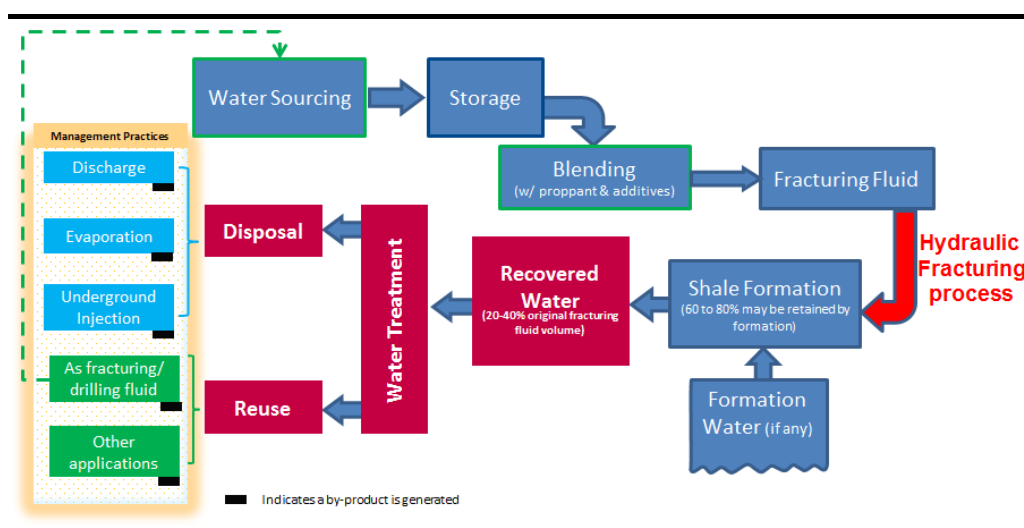
Hydraulic fracturing is a well stimulation technique that has been used in the oil and gas industry for the past 65 years to improve production from hydrocarbon containing formations. It is not exclusive to shale formations. However, because of the very low to nonporous characteristics of shale formations, hydraulic fracturing is always required as part of the oil and gas extraction.

After a shale well has been hydraulically fractured, produced and flowback water returns to the surface inside a steel pipe. For the scope of this study, all fluids (including flowback and produced water) that flow back to the surface in the first weeks to months after the fracturing of a shale well, are considered to be recovered water.

Water management is a key consideration throughout all the stages of shale play development, from an early exploration phase where only a handful of wells are stimulated to a mature development phase where there may be hundreds of wells stimulated.

A basic water management cycle showing the identified management practices is presented in *Figure 1.1*.

Figure 1.1 Water cycle overview with identified management practices



Source: prepared by ERM, 2014

This report covers only one key aspect of the entire water management cycle in shale operations: the management practices adopted in regard to the recovered water that exits from a shale oil/gas well following stimulation.

Other aspects of the water management cycle, such as the sourcing of water transport and storage, as well as related issues, such as availability and demand by other users, are not included in this report.

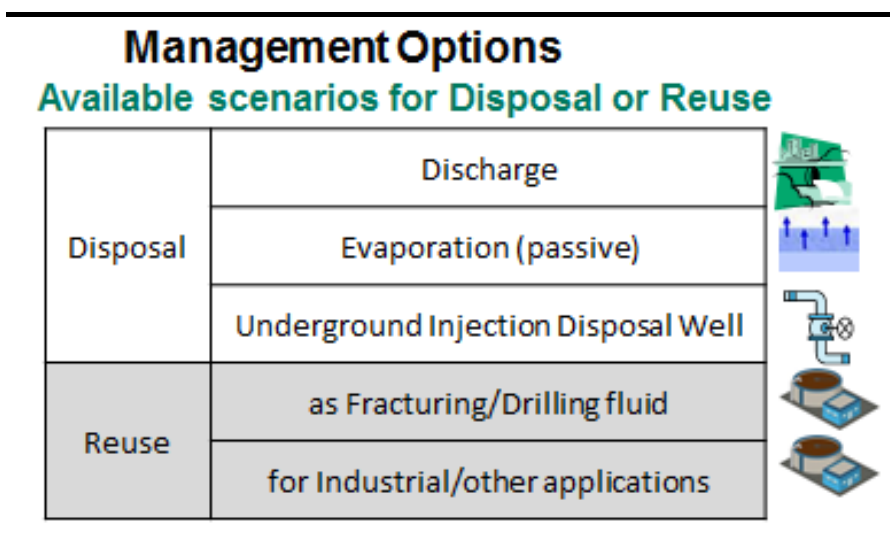
Shale plays differ widely in their geological characteristics (depth, thickness, total porosity, mineral and hydrocarbon content). The volume of water recovered after hydraulic fracturing varies in terms of quantity (e.g., volume)

and quality (e.g., concentration of heavy metals, salinity, and radionuclides), and depends a great deal on the geology of the particular shale play.

There are several proven methods for handling recovered water that have been used successfully by the industry over the past decades. The features of specific practice may vary greatly between shale plays. The final decision on which recovered water management practice to apply to a shale well is subject to a number of site-specific conditions including, but not limited to, the characteristics of the formation, existing available management options, the phase of the operations (e.g., exploration versus development), the regulatory framework, and the environmental and social conditions in the area.

Two broad management practice categories have been identified for effectively handling the recovered water once it reaches the surface: disposal and reuse. The main difference between these practices is the final end use of the recovered water. Particular management scenarios have been identified for both of these categories, as represented in *Figure 1.2*. Based on the management option and scenario selected, a fit-for-purpose treatment train must be designed to achieve the target parameters required for the water before its final disposal or reuse.

Figure 1.2 *Current Recovered Water Management Practices in Shale Wells*



Source: Prepared by ERM, 2014

If the disposal management option is selected, the recovered water will not subsequently be used in the shale operation. Within this option, three possible scenarios have been identified: i) **discharge**, where treated recovered water is usually sent to a surface water body; ii) **evaporation**, where treated recovered water evaporates into the atmosphere; and iii) **underground injection**, where treated recovered water is injected into a deep underground aquifer.

For the reuse option, two scenarios have been identified: i) reuse within the same shale operation **as fracturing/drilling fluid**, after undergoing variable levels of treatment (from basic to intermediate); and ii) **reuse in other processes** after undergoing advanced desalination treatment.

Within a single water management practice, various factors may affect otherwise equivalent scenarios. These include the choice of particular water treatment technologies, the availability of third party services and

infrastructure in the area, and the need to transport recovered water. For this reason, two individual scenarios of the same type may differ considerably in cost.

Treatment technologies vary considerably according to the target constituent(s), their underlying physical/chemical process (which mainly determines energy-input requirements), and the resultant by-product of the treatment.

From a global perspective, the majority of management practices employed are currently the disposal type (i.e., underground injection). Even so, there is a growing trend towards reuse practices, given current water supply constraints in certain areas and the limited availability of disposal wells, as this indirectly influences the running costs of an operation. The use of disposal wells is amongst the most cost-effective options, it is widely used in conventional plays, and has a low environmental impact when properly managed. For these reasons it is widespread in countries where shale activities are just starting up (e.g., China, Argentina, and Mexico), as well as in countries where a mature shale market exists (e.g., the United States).

Reuse scenarios are gradually becoming more popular, especially in the United States where more than 80% of the world's shale extraction is performed. These scenarios make more sense when used in large-scale shale development activities where there are many wells to be fractured. Also, water constraints and a lack of available underground disposal facilities further drives operators towards reuse practices as part of their water management strategy.

Considering the existing challenges for recovered water management in shale wells, three main focus areas for future developments have been identified:

- Minimisation of water volumes required in the fracturing fluid;
- Maximisation of reuse; and
- Improvement of treatment technologies.

In summary, there is no fit-all management practice/scenario that can be applied to every social, environmental, operational and/or economic setting. Management practices differ in every case and are selected based on the intended use for the recovered water.

The water management scenarios identified also have associated environmental impacts due to the various activities involved in a particular scenario. Nonetheless, since all of the management practices identified are proven and have been in use for many years, applying existing industry standards makes these practices environmentally safe when they are managed correctly.

2 INTRODUCTION

2.1 PURPOSE OF THIS STUDY

Environmental Resources Management (ERM) has been commissioned by the Oil and Gas Producers Association (OGP) to carry out this study for the purpose of developing a brief review of current and potentially viable recovered water management practices occurring in shale oil/gas wells.

2.2 SCOPE OF THIS STUDY

This report covers only one key aspect of the entire water management cycle in shale operations (*Figure 1.1*), relating to the management practices adopted in regard to the recovered water that exits from a shale oil/gas well following stimulation.

Other aspects of the water management cycle such as the sourcing of water transport and storage, as well as related issues such as availability and demand by other uses are not included in this report.

2.3 METHODOLOGY APPLIED

The present report is the result of a desktop study based on publicly available information and expert opinions on existing and potentially viable water management practices for recovered water in shale developments around the world. This desktop exercise has been validated and complemented wherever possible with first-hand information provided by different oil and gas operators by means of personal interviews. The operators that participated in this process have provided information on their own field experience in applying the identified management options in different geographies.

Furthermore, ERM has worked in collaboration with Mr. John Veil, an internationally recognised expert in this field, who has provided technical oversight in the development of this document.

2.4 MAIN LIMITATIONS

Due to the nature of the information sources used in this study, the bulk of available resources refer to shale developments in the United States, with relatively little information available on other areas such as Asia and Europe.

It is worth noting that the research focused on the most common current practices; numerous references have been found describing particular management practices in specific locations where these can no longer be considered current practice in shale operations. In view of this, the report strives to keep its findings within a limited and recent time window to properly describe the present state-of-the-art of global water management practices associated with hydraulic fracturing.

Water treatment technologies are continuously evolving, driven by the target constituent that poses the biggest challenge for achieving a water of sufficient quality for reuse in the industry or other applications, that is, a high concentration of TDS. There are many versions of similar technologies currently being researched, and this report does not attempt to describe every possible version available, only those considered to be currently available in the marketplace.

2.5 *STRUCTURE OF THE REPORT*

This report focuses on the different characteristics of the identified water management practices, including: technical functioning, energy use, technical/practical limitations, advantages and disadvantages and the identification and management of the by-products created during the treatment of recovered water. Furthermore, it contains a general description of where the identified practices are used internationally, along with their relative importance in terms of shale gas/oil production, in order to identify which practices are currently the most commonly performed globally.

For completeness, the report describes the characteristics of the liquids involved in the hydraulic fracturing process, beginning with the water source for the base fluid, and describing the various chemical additives which may be mixed with it to form the stimulation fluid. This is followed by a description of how the fluid interacts with the underground shale formation water to ultimately produce a recovered water flow that reaches the surface through the wellbore and which must be properly managed according to various factors including its quality/quantity.

3 GENERAL DESCRIPTION OF THE HYDRAULIC FRACTURING PROCESS AND RECOVERED WATER QUALITY

3.1 OVERVIEW

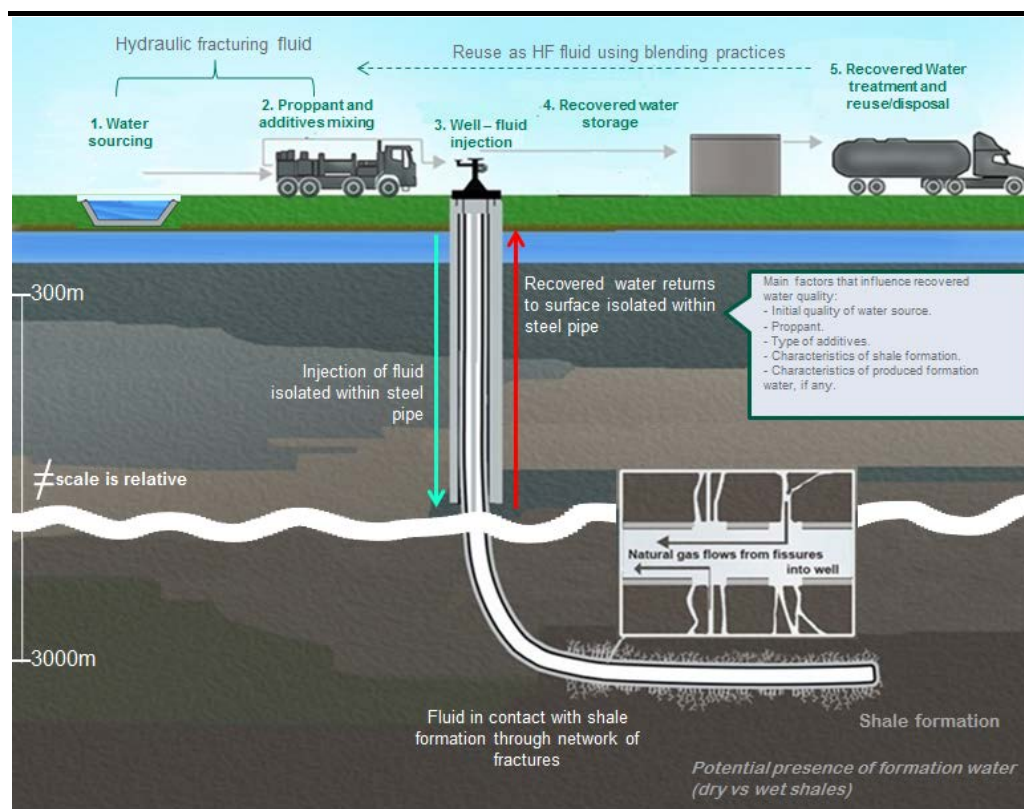
Hydraulic fracturing is a well stimulation technique that has been used in the oil and gas industry for the past 65 years to improve production from hydrocarbon-containing formations. The procedure used depends on the properties of the geological formation where the hydrocarbon deposits are. The technique is not exclusive to shale formations, but their very low to nonporous characteristics mean that hydraulic fracturing is used as part of the oil and gas extraction strategy. The recovered water is a by-product of the hydraulic fracturing technique.

Shale plays differ widely in their geological characteristics (depth, thickness, total porosity, mineral and hydrocarbon content). The geological characteristics of the shale formation at each specific site are key factors influencing both the hydraulic fracturing fluid to be used in the process and the quality of the recovered water associated to the fracturing.

3.2 DESCRIPTION OF THE HYDRAULIC FRACTURING TECHNIQUE

The general process of the hydraulic fracturing technique is represented in Figure 3.1 below.

Figure 3.1 *Water cycle overview in hydraulic fracturing operations focused on recovered water*



Source: U.S. Environmental Protection Agency. Modified by ERM, 2014

In general terms, the technique consists of pumping a hydraulic fracturing fluid (a blend of water, proppant and additives) down the wellbore through an isolated steel pipe to reach the target formation. This pumping is done under high pressure to create a network of fractures in the hydrocarbon-bearing rock. The purpose of the proppant in the fracturing fluid is to hold the fractures open creating pathways that allow oil and gas to be produced from the reservoir formations and flow up the wellbore along with the injected fluids during flowback and during the subsequent well production phase.

The fracturing process happens at different stages along the leg of the well that is in contact with the shale formation (normally a horizontal leg). The process starts with the section of the well that is farthest from the vertical portion of the well. Each stage is kept under pressure for few hours, and at the end of each stage, a plug is set to isolate that fractured interval and allow the fracturing of the next stage. This process is repeated as many times as there are stages designed for each specific well. When the well is ready to be brought into production, the plugs are drilled out.¹

Once the plugs are drilled out, the pressure is released and the direction of fluid flow reverses. The well is “cleaned up” by allowing water and excess proppant to flow up through the isolated steel pipe to the surface and the recovered water is captured and stored in closed steel tanks.

Operators strive to minimise proppant return, since the ultimate goal of a hydraulic stimulation is to convey and deposit the proppant within the fractures in the shale to maximise hydrocarbon flow.

The first water that returns to the surface is mainly known as flowback water and is basically the fracturing fluid that has been in contact with the shale formation. In some cases (depending on the retention characteristics of the formation, i.e., dry or wet formations), flowback water is mixed with formation water.

After the main volume of flowback has returned to the surface, often a low volume of produced formation water continues to exit the well. For the purpose of this study, any water that leaves the well after hydraulic fracturing is referred to as recovered water.

The recovered water is captured and stored in tanks on the surface before being sent to treatment and final disposal or reuse, which may take place onsite or offsite. In the case of offsite management, the recovered water is transported, typically by trucks, to an appropriate facility for proper management.

3.3 CHARACTERISTICS OF THE HYDRAULIC FRACTURING FLUID

The fracturing fluid is an engineered product and its final composition is defined only after the geological characteristics of the shale formation that will be stimulated have been analysed.

¹ This technique is popularly referred to as “plug-and-perf” and is one of several multi-stage techniques used.

The most common base for the hydraulic fracturing fluid is water, mixed with proppant (typically sand), and a very limited proportion of additives. As reference values, it can be estimated that around 99.5% of the fluid is a mixture of water and sand, and the remaining 0.5% is additives.

The water can be obtained from various sources including surface water bodies, groundwater, the public water supply, industrial effluent or reused water from other fracturing activities. Nowadays, operators try to reduce the water volume that is used in the hydraulic fracturing fluid as much as possible, and they often reuse water in the process where it is practical. This results from an evolution of both the hydraulic fracturing technique itself and the additives, which have been improved by increasing their compatibility with different water qualities. In addition, operators have a strong interest in employing sustainable water practices.

Additives are used in hydraulic stimulation operations to elicit certain properties and characteristics that aid and enhance the operation. Therefore they are selected based on both the specific conditions of the shale formation and the desired characteristics of the hydraulic fracturing fluid. In this way, additives are used where needed with different purposes, including as a breaker, bactericide or biocide, clay stabilizer or control, corrosion inhibitor, crosslinker, friction reducer, gelling agent, iron control, scale inhibitor, and surfactant. Developments in this area have significantly reduced the quantity and toxicity of the additives required to hydraulically stimulate target reservoirs.

While the specific composition of the stimulation fluid varies according to the geological characteristics of the reservoir and the specific needs of the project, the range of additive types generally remains the same. There are different compositions available for each additive type, although only one composition is generally used in any given shale well. In addition, not all additive types may be used in every stimulation job, typically only 3-8 different additives compatible with the shale reservoir are used to obtain the characteristics necessary for stimulation.

3.4 RECOVERED WATER QUALITY

Recovered water consists of a mixture of the hydraulic fracturing fluid, including water, additives and proppant (typically sand), dissolved material from the shale formation that was in contact with the fluid, and formation water (also known as produced water), should it exist.

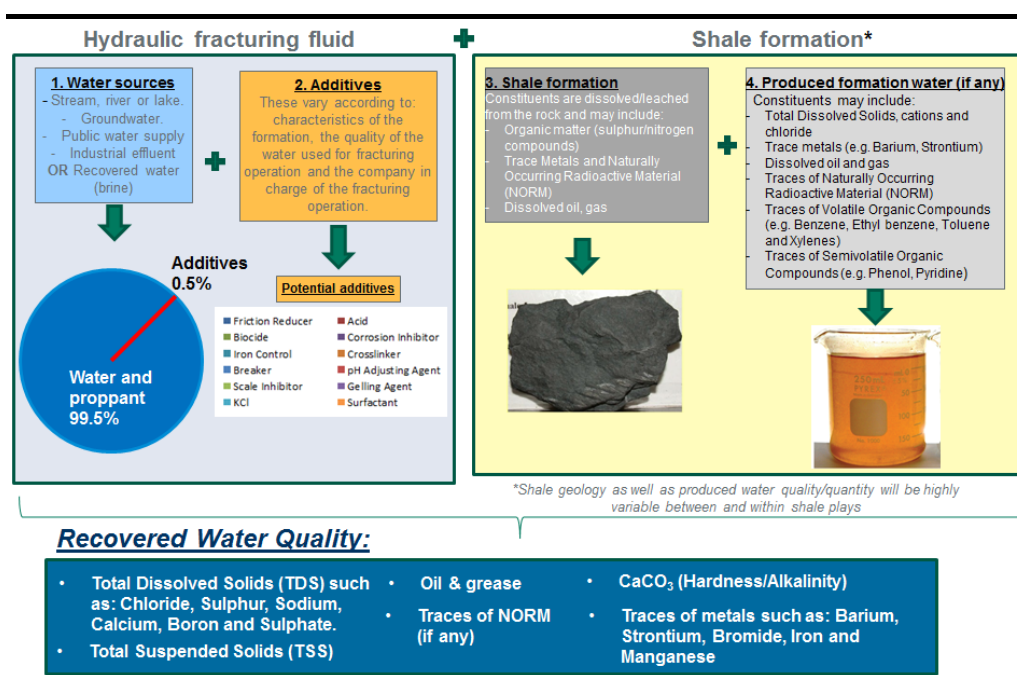
Recovered water parameters can vary widely between the different shale plays depending on the composition of the formation, but they can contain one or more of the following:

- Dissolved solids (chlorides, sulphates, and calcium), defined as total dissolved solids (TDS);
- Suspended solids – usually proppant and mineral scales (calcium carbonate and barium sulphate);
- Dispersed clay fines, colloids and silts;

- Traces of metals (calcium, magnesium, barium, strontium);
- Bacteria - acid producing bacteria and sulphate reducing bacteria,
- Iron solids (iron oxide and iron sulphide);
- Traces of oil and grease (more common if the shale formation produces primarily crude oil);
- Traces of naturally occurring radioactive material (NORM).

A summary of the different factors that influence recovered water quality is provided in *Figure 3.2*.

Figure 3.2 *Recovered water quality*



Source: Prepared by ERM, 2014

Most of the constituents of recovered water were originally part of the shale formation and the naturally occurring water that resides in it, which leaches/mixes with the flowback water while it resides in the formation during the hydraulic fracturing process. Produced formation water contains high levels of TDS on its own, and minerals leached out from the shale (e.g. barium, calcium, iron and magnesium) (Schramm, 2011); it may also contain dissolved hydrocarbons (e.g., methane, ethane, and propane) along with NORM (e.g., radium isotopes).

3.4.1 Factors influencing the volume of recovered water

One of the main factors influencing the volume of recovered water is the volume of hydraulic fracturing fluid that is used in the process, but the characteristics of the formation are also a key factor to be considered.

As previously mentioned, all shale plays are different and their geological characteristics are very site specific. For instance, each shale play has its own retention characteristics which play an important role in both the recovered water volume and quality.

Much of the water that is introduced as hydraulic fracturing fluid into a dry formation will be retained. This process is known as imbibition. Therefore the volume of water that returns to the surface as recovered water is significantly less than the volume injected as fracturing fluid. Furthermore, a dry formation does not contain much produced formation water, so the quality of the water recovered at the surface will primarily depend on the parameters of the hydraulic fracturing fluid, and the geological characteristics of the formation will have a limited influence. The opposite occurs with a wet formation, where existing produced formation water determines both the quality and volume of recovered water.

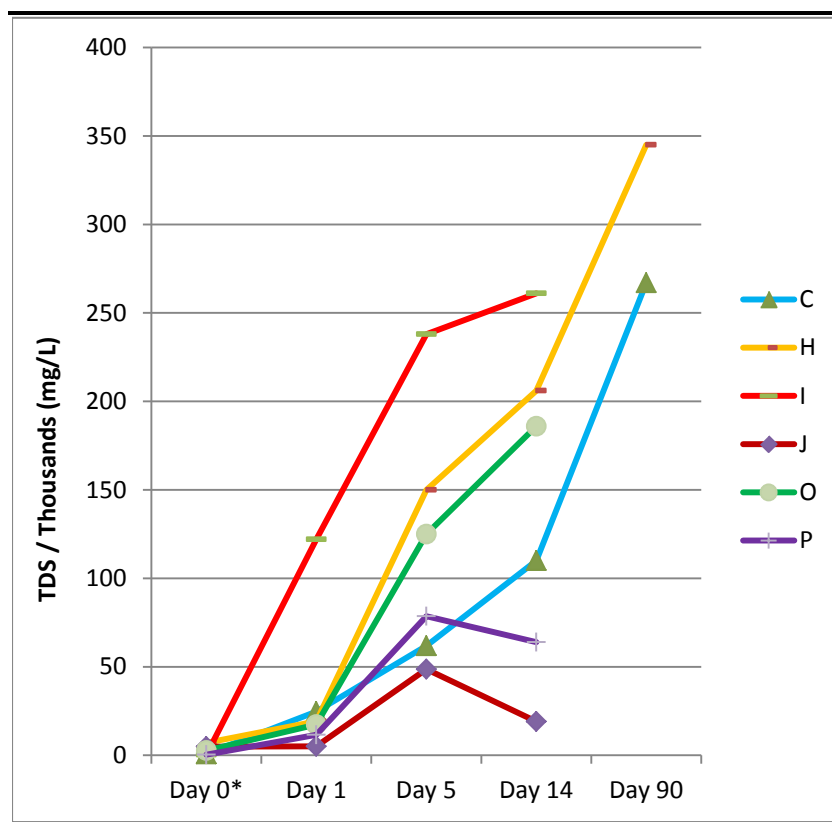
As a typical reference value, it may be expected that from 20 to 40% of the fluids pumped into the well for the hydraulic stimulation can be recovered when they flow back to surface. In some circumstances this may be as much as 100%). The additional fluids will remain trapped due to absorption and surface tension in the rock and clays of the shale formations.

3.4.2 *Temporal variation in quality and volume of recovered water*

Over an extended period of time, the volume of recovered water from a given well will decrease, but during the same time period, the concentration of many of the constituents will rise (*Figure 4.3*)

Recovered water starts out with a relatively low salinity (moderate TDS, similar to the injected water), and the salinity/TDS generally increases with time. There is a lack of published data on the chemical characteristics through time of recovered water from shale wells, and very little data showing concentrations (Hayes, 2009; Acharya et al., 2011). The limited information available does suggest that the water which does not initially return to the surface remains in contact with the new rock surfaces created as a result of the stimulation process and is able to dissolve certain constituents from the shale. The longer the water remains in the fractures or pore spaces, the higher the level of dissolved constituents is likely to be, until it reaches the saturation or equilibrium point. Produced waters which have been in contact with the shale reservoir for millions of years are much less variable in quality. This variation in both volume and quality of recovered water over time (the volume of water decreases whilst the constituent concentration increases) makes treating the recovered water more challenging through time.

Figure 3.3 *Variability of TDS concentration through time in selected Marcellus shale wells*



Source: Prepared by ERM, 2014 (with data from Hayes, 2009)

4.1 OVERVIEW

The variable volume and quality of recovered water during the fracturing process at a single site and across different shale plays, makes water management a key and challenging process in shale wells. The final decision on the recovered water management practice in shale wells is subject to a number of site specific conditions including, but not limited to, the characteristics of the formation, existing available management options, phase of the operations (e.g., exploration versus development), regulatory framework, and environmental and social conditions in the area.

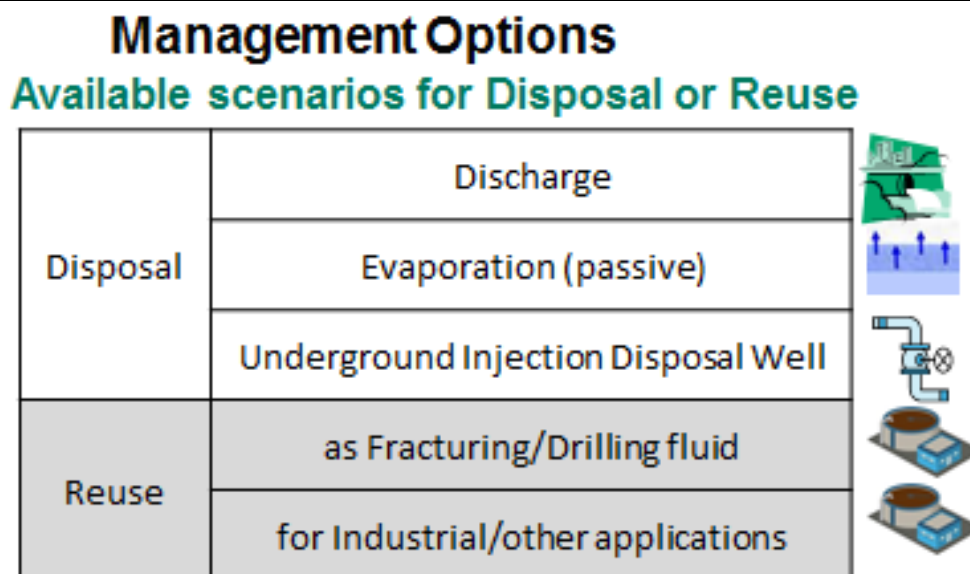
This section presents a summary of current water management practices that are used globally in shale wells and provide a general overview of the framework and factors existing behind the decision making process for selecting the most appropriate recovered water management practice for a specific site.

4.2 IDENTIFICATION OF CURRENT MANAGEMENT PRACTICES PERFORMED GLOBALLY

In order to identify the current management practices that are globally applied to shale wells, ERM has conducted a desktop review of publicly available information followed by a validation process through interviews with various operators.

As a result of these reviews, two broad management practice categories have been identified for effectively handling recovered water once it reaches the surface: disposal and reuse. The basic difference between them is the final end use of the recovered water. For each of these two broad management practices, particular scenarios have been identified, as represented in *Figure 4.1*. Based on the management option and scenario selected, a fit-for-purpose treatment train must be designed to achieve the target parameters required for the water before its final disposal or reuse.

Figure 4.1 Current Recovered Water Management Practices in Shale Wells



Source: Prepared by ERM, 2014.

Figure 4.2 presents a summary of the recovered water management practices identified as being currently applied in the field in various different countries. This figure presents the main outcomes of the review process with regard to:

- Countries in which hydraulic fracturing has recently been performed in shale wells;
- The status of the activities performed in each case to identify whether they are in the exploration and appraisal phase or the pilot and development phase;
- The recovered water management practices applied during recent hydraulic fracturing activities.

The figure also includes remarks on the management practices used in each region as a means of estimating which practices are relatively the most common.

In relative terms, the majority of shale activities currently taking place in North America. The other countries where hydraulic fracturing activities have been identified have only recently begun to perform exploration and appraisal activities in shale resources, meaning their water management practices choices are limited and influenced by the scale of their current operation.

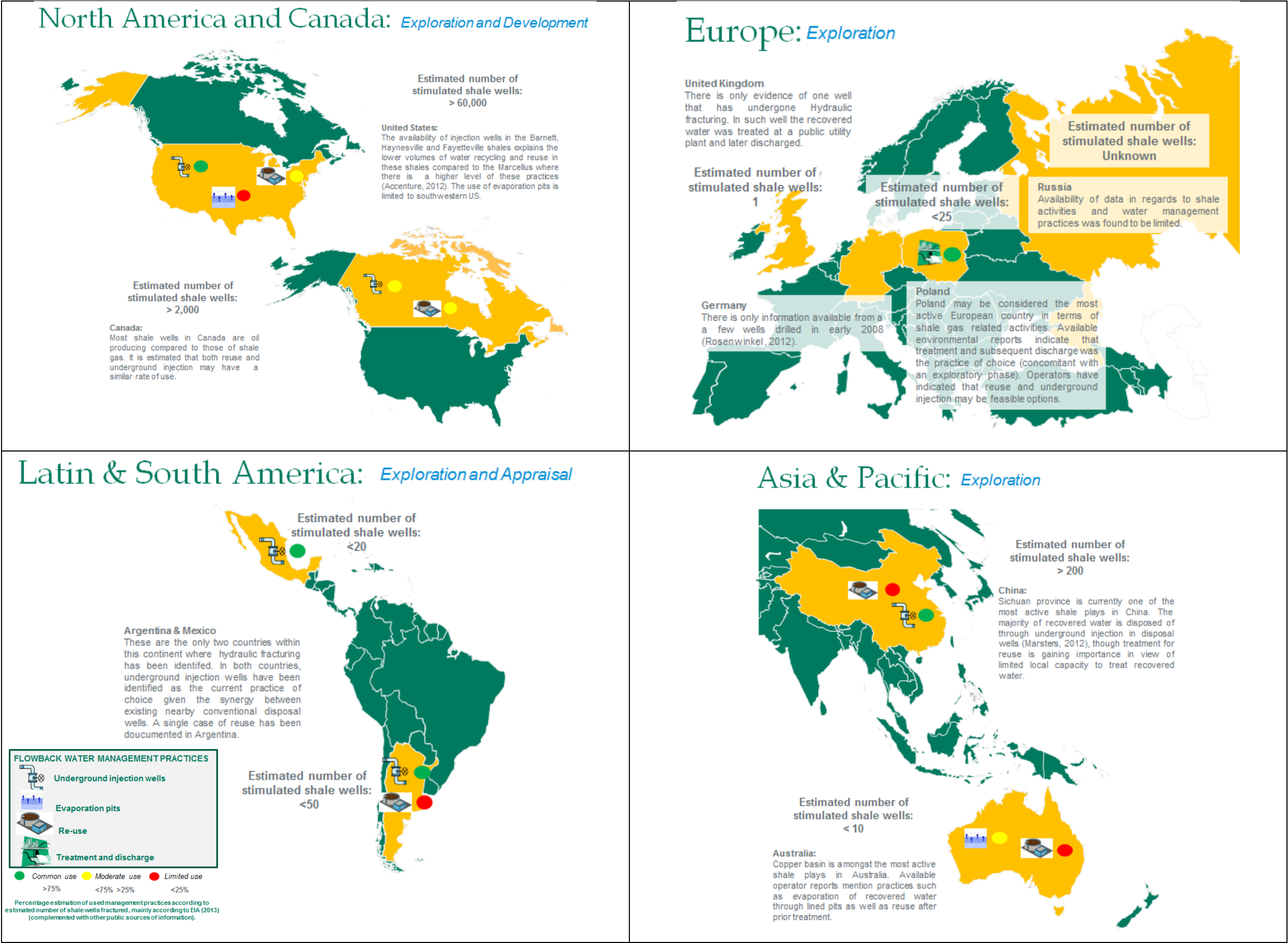
As can be seen in Figure 4.2, North America, especially the United States, is easily the country where the most shale wells have been effectively stimulated using hydraulic fracturing techniques. Here the use of underground disposal wells is the most common management practice (over 60%). Reuse is predominantly used in those shale plays where there disposal wells are limited (i.e., the Marcellus play) or where water supply constraints are critical (e.g. south-western Texas).

Most water management practices have been used for decades, mainly as a result of their historical application in conventional resources (e.g., produced water management). These practices were subsequently tailored to the quality

and volume of recovered water in shale operations. As a result, the considerable current experience (and ongoing research) in both shale and conventional resources has resulted in water management activities being conducted to high environmental and social standards, whilst still remaining economically viable.

It is not the purpose of this study to provide exhaustive country-by-country information on the management practices used, rather to give a general overview of the current status of these management options across the globe.

Figure 4.2 Summary of Current Recovered Water Management Practices in Shale Wells Worldwide



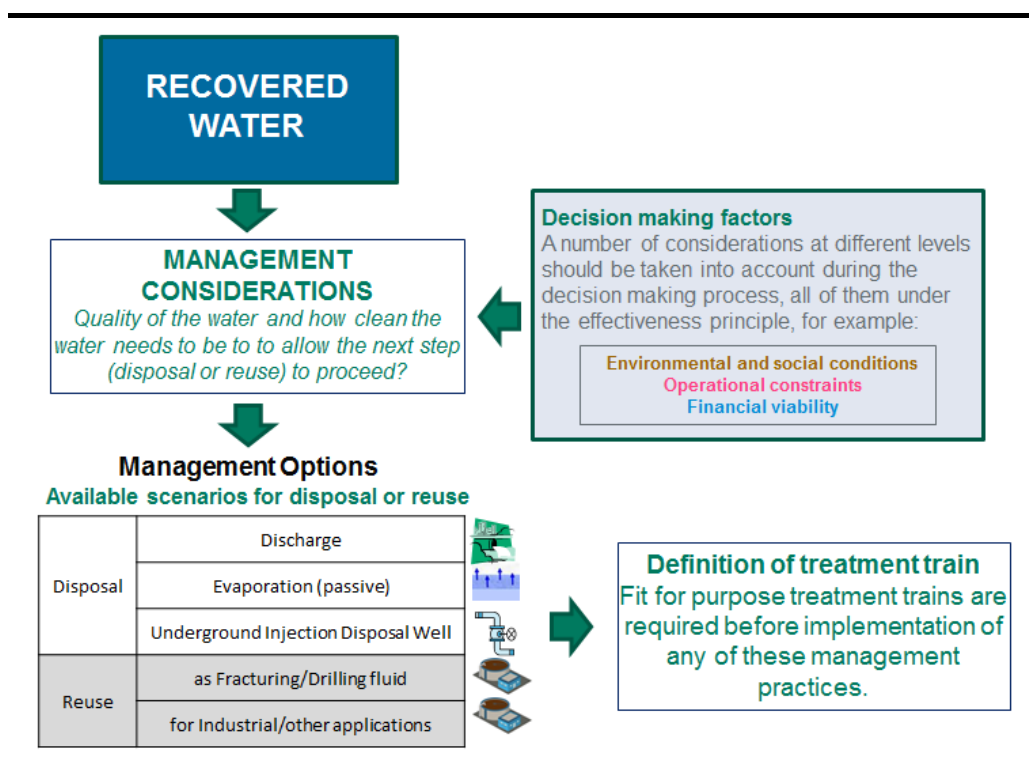
Source: Prepared by ERM, 2014

4.3 DECISION MAKING PROCESS

The choice of a water management practice is usually decided before stimulation but, as mentioned above, it is subject to a number of factors. The most important factor is how clean the water should be to enable the intended end use.

Exploratory drilling delivers key information on the shale geology, meaning the relative volumes of fracturing fluids may be calculated, as well as the expected volume of recovered water that is to be managed. Nonetheless, selecting a practice can be quite challenging as many of the influencing factors may vary within the same shale play; this is why each well must have a tailor-made water management strategy.

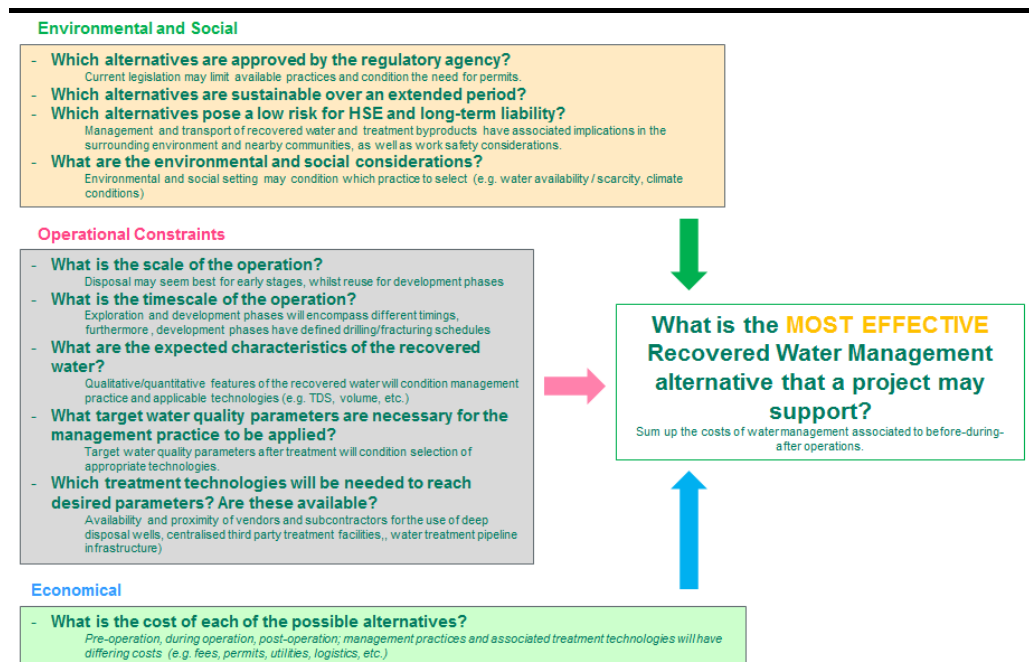
Figure 4.3 *Decision Making Process for Recovered Water Management in Shale Wells*



Source: Prepared by ERM, 2014

A summary of some of the main decision making factors involved is presented in Figure 4.4.

Figure 4.4 *Basic Decision Making Factors Involved In Selecting a Recovered Water Management Option in Shale Wells*



Source: Prepared by ERM, 2014

5 DESCRIPTION OF DISPOSAL/END USE OPTIONS AND TREATMENT TECHNOLOGIES FOR RECOVERED WATER

5.1 OVERVIEW

This section presents a more detailed description of each of the existing recovered water management practices mentioned in the previous sections. The description includes details on technical functioning and energy use, technical and practical limitations, and advantages, as well as the identification and management of any by-products created during the treatment and management of recovered water.

This section also provides a general overview of viable technologies that are applied in the field for treating recovered water associated to shale wells. For reference purposes, information on the most common treatment technologies associated to each management practice has been provided.

As many factors influence the decision of which water management practices are used, there is intrinsic variation. Two situations where the same management practice is applied may vary in terms of actual costs (e.g., using an existing facility versus constructing a new one), energy requirements, limitations, and so on, determined by the factors outlined in *Figure 4.4*.

5.2 RECOVERED WATER MANAGEMENT PRACTICES AND TREATMENT TECHNOLOGIES

As mentioned in previous sections, two broad management practice categories for effectively handling recovered water once it reaches the surface have been identified: disposal and reuse. Within each of these practices, different scenarios have been identified including discharge to surface water, underground injection into disposal wells, passive evaporation ponds, and reuse in fracturing/drilling fluids or other industries.

According to the end use of the recovered water, applicable regulatory/industry considerations will condition both its suitability and the treatment technologies required for selected management practice.

The process by which recovered water attains these parameters is commonly known as a treatment train, and this can range from simple treatments, such as the basic settling of suspended solids, to highly specialised processes that are able to produce clean fresh water.

Figure 5.1 presents a summary of the most common treatment technologies used for recovered water. They have been grouped by main target parameters.

Figure 5.1 *Main Treatment Technologies Available for Recovered Water in Shale Wells*

Group Parameters	Treatment technology	Main function
Suspended Solids (TSS) and Metals	Media filters or bag/sock filters	Removal of large solids like sand and scales
	pH adjustment, flocculation, and clarification	Removal of metals from flowback and produced water
	Oxidation*	Organics and metals removal
	Electrocoagulation	Removal of suspended, emulsified or dissolved contaminants
Suspended Solids (TSS) and Oil	Oil/Water separators	De-oiler
	Hydrocyclone	De-oiler
	Flotation with or without chemical addition	De-oiler
	Micro-, Ultra-, Nano-FILTRATION	Removal of 10 to 0.0005 micron sized constituents
Desalination* (TDS)	Reverse Osmosis	Removal of low level TDS
	Thermal distillation/Evaporation	Removal of high level TDS
	Crystallization	Removal of high level TDS

*: NORM presence is usually in the form of salts, and as such may be removed by a combination of oxidation (precipitate) and desalination treatments, by-products from these treatments will have to be monitored for NORM before disposal.

Source: Prepared by ERM, 2014

Section 5.6 further details the listed treatment technologies along with their main features, categorised by the main target constituents that are found in recovered water.

For each of the identified scenarios, there will usually be a basic treatment train related to the constituents that are to be dealt with. Even though several treatment technologies have been described, not all of them are commonly used.

The following sections provide a description of each management practice and the basic treatment trains associated to each management practice scenario. Where more than one treatment technology for any given constituent is available, the most commonly used technology associated to that specific scenario is marked in bold and underlined. Furthermore, specific by-products from the treatment are also identified.

5.3 DESCRIPTION OF DISPOSAL OPTIONS

There are a limited number of disposal options for water recovered from shale wells. Disposal options are effective when applied in the early phases of the project (during the exploration and appraisal phase) where the volumes of recovered water are relatively low or moderate when compared to other advanced phases of the project (e.g., full development phase) and where reuse is not a feasible option.

5.3.1 Disposal: Discharge to Surface Water

Discharge to surface water typically refers to treated recovered water being released into a surface water body that is normally also used as a source for domestic or industrial purposes. This input may also influence the current environmental conditions of the water body (e.g., it could support minimum

river flows or wetlands), especially in areas where water may be scarce. Discharge is not a common management option for recovered water in shale wells, and it is not allowed in the US. In areas where discharge is allowed and is chosen by the operator, an extensive treatment process is necessary to remove any oil and grease, TSS, metals, and TDS to achieve water quality that complies with the applicable standards. One of the major limitations in the application of this management practice in shale wells is the high salinity of the recovered water. The cost of treating the recovered water (pre-treatment and desalination) in treatment plants to achieve the desired water quality involves a high energy demand, meaning this practice less sustainable when the whole process is reviewed. If discharge was permitted to a saline water body, like a sea or a saline aquifer, the requirement for reaching an acceptable level TDS may be less than for a fresh water body. The other requirements would not change. The discharge of recovered water into a saline water body is not currently practiced.

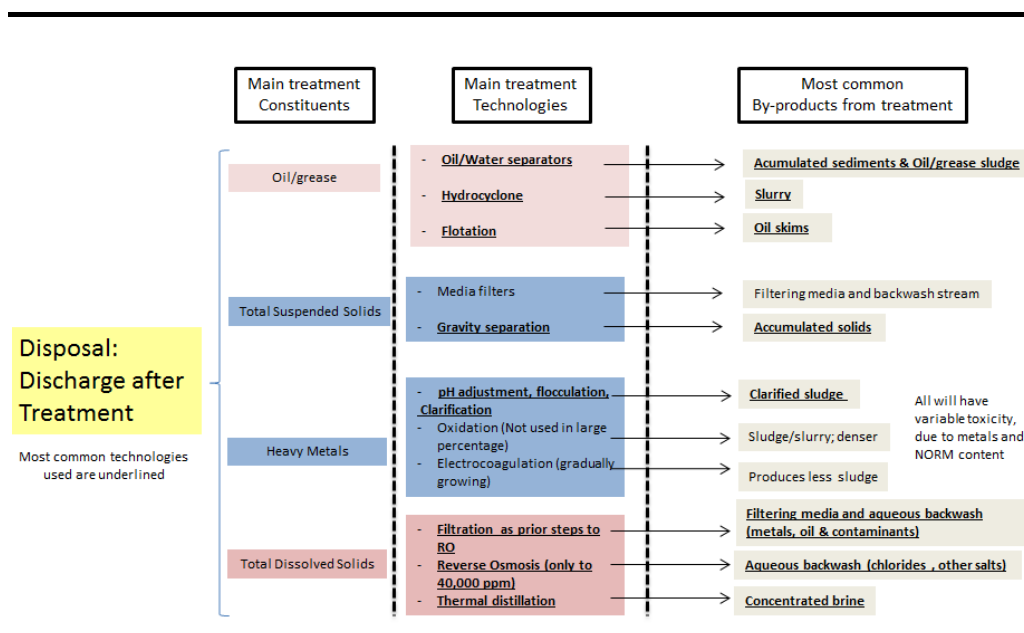
So far, discharge to surface water has only been the method of choice in a small number of sites, and where it has been applied, it has mainly been for early stimulations in the exploration and appraisal phases (e.g., in the UK, Poland, and Australia). This is mostly because of the combined conditions of restrictions in use or non-availability of underground disposal wells and no practical subsequent reuse of the recovered water. It can be concluded that this is by far the least practical and sustainable option for managing recovered water.

Treatment train for disposal: discharge to surface water

In order to use discharge as a disposal option for highly saline water (as is the case of the recovered water), treatment plants must remove the salt from the water. Before the water is desalinated, it must be pre-treated to remove solids, oil and grease, and often metals.

Figure 5.2 shows the common/potential treatment train for discharging treated recovered water to a surface water body. The final design of the treatment train is subject to both the quality of the recovered water (site specific) and the standard limits for discharge into surface water bodies defined in each country.

Figure 5.2 Common potential treatment train for Disposal: Discharge Scenario



Source: Prepared by ERM, 2014

Technical Description of Disposal: Discharge to Surface Water

A comprehensive description of this management scenario and its technical diagram is presented in Factsheet 1 below.

DISPOSAL –Discharge

Practice Description :

Recovered water is discharged to a surface water body, usually after being sent to a certified wastewater treatment facility to attain water quality parameters within applicable discharge limits.

Energy Use:

Moderate to high, depending on technologies used to condition water properties to applicable discharge limits.

Targeted Water Quality Parameters:

Will ultimately depend on existing regulations for discharge, which may require high standards in terms of TDS/chemical concentrations. May require anything from basic settling/filtration to more advanced desalination treatments.

Treatment by-product(s):

Will depend on treatment train; typically a combination of sludge, other solids, and concentrated brine; all these may be of variable toxicity, with considerable concentrations of metals and radionuclides.



Outfall pipe. Source: courtesy of OGP members, 2014

General Notes

Outside the U.S. discharge is usually the preferred option during exploration phases, provided there are no subsequent fracturing activities and/or absence of other management options.

Main Associated Impacts

(S/H: Social /Health; E: Environmental)

Type	Description	Value
S/H	Limited pollution risk to domestic/ industrial surfacewater users	Low
E	Water is discharged according to applicable legislation	Low

Advantages:

- Minimal permitting costs when dealing with low volumes of recovered water
- Use of existing facilities
- Although not common practice, discharging to the sea would require less intensive TDS (salinity) treatment, and hence would probably be of lower cost.

Disadvantages:

- May require treatment to a relatively high standard with associated high costs (e.g. high TDS water)
- It is possible that existing treatment facilities may struggle to handle certain volumes/qualities of recovered water.



Water transport truck. Source: courtesy of OGP members, 2014

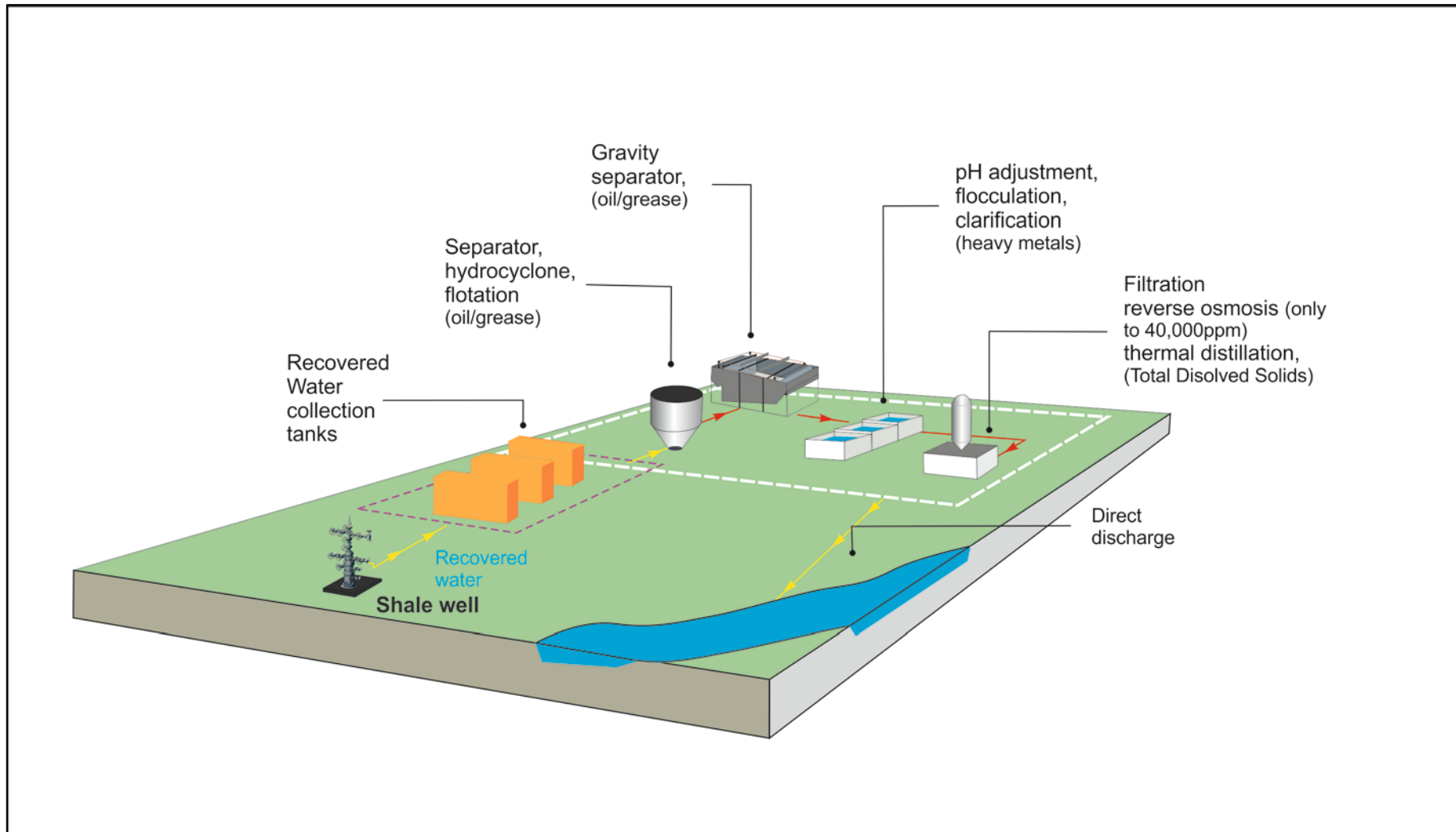
Cost

Phase	Description	Value
Prior to Operation:	Related to obtaining permits.	Low
During Operation:	Will depend mostly on fees related to applied treatment technologies which can be costly (depending on quality needs of environment for discharge).	Moderate - High
After Operation:	Negligible costs	Low

Main Considerations for Selection

- Distance/volume of water transport to a treatment facility.
- It is probable that water may need desalination before discharge with associated high running costs given expensive technology needed to treat this parameter.

Technical Diagram of Disposal: Discharge to Surface Water



Source: Prepared by ERM, 2014

5.3.2 *Disposal: Passive Evaporation*

Evaporation is used in some arid locations as a disposal practice for recovered water from shale wells. It consists of isolated, lined, shallow ponds where water is stored and evaporated from using the natural energy of the sun and the wind.

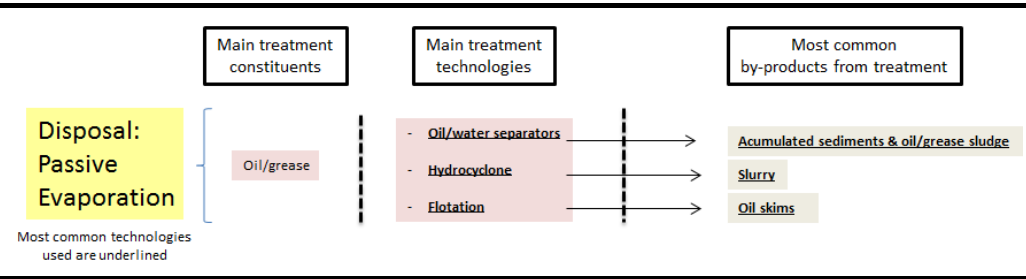
This practice has been identified mainly in the western United States and Australia. Typically it is used in remote areas and places that have significant open spaces where shallow evaporation ponds can be located. There are several third-party commercial waste disposal companies in the United States that use evaporation as their primary method of managing water. Unless the air is dry and there are local winds, evaporation does not occur quickly enough to be an economical practice.

Treatment train for disposal: passive evaporation

Evaporation does not require pre-treatment to remove contaminants. Nevertheless, if the recovered water contains any free oil, it should be removed before the water is sent to the pond. Any oil floating on a pond surface will necessitate the entire pond being covered with netting to protect migratory birds.

Figure 5.3 shows the common/potential treatment train for the passive evaporation of recovered water.

Figure 5.3 *Common potential treatment train for Disposal: Passive Evaporation Scenario*



Source: Prepared by ERM, 2014

Technical description of disposal: Passive evaporation

A comprehensive description of this management scenario and its technical diagram is presented in Factsheet 2.

DISPOSAL – Evaporation

Practice Description :

Passive evaporation from permitted lined evaporation ponds. These are relatively shallow and recovered water will typically need oil/grease pre-treatment (requiring use of additional lined sludge/settlement ponds).

Energy Use:

Low, associated to pre-treatment; low energy requirements for basic oil/water separation (acceptance pits, gun barrel tanks or other).

Targeted Water Quality Parameters:

Low hydrocarbon content of flowback water (non-sheen producing) for better evaporation results.

Treatment by-product(s):

Oil/grease sludge from pre-treatment (sludge/settlement ponds) and sediments (the latter associated to pond liner disposal and pond closure).



Evaporation pond in Australia. Source: courtesy of OGP members

General Notes

This option is used primarily in a few western U.S. states and Australia with large open land areas and dry climates, but it represents only a small percentage of the total water management practices currently in use worldwide.

Main Associated Impacts

(S/H: Social /Health; E: Environmental)

Type	Description	Value
S/H	Volatile organic compounds (VOCs) may cause air pollution issues in the immediate surroundings.	Moderate
E	Covering of water/sludge pits will prevent avifaunal contact.	Low

Advantages:

- Relatively low cost in comparison to other practices;
- In arid climates, takes advantage of natural conditions of humidity, sun, and wind;
- Typically located in remote areas.

Disadvantages:

- Not practicable in humid climates;
- May create air quality and salt deposition problems (excessive buildup of sediments);
- NORM control.

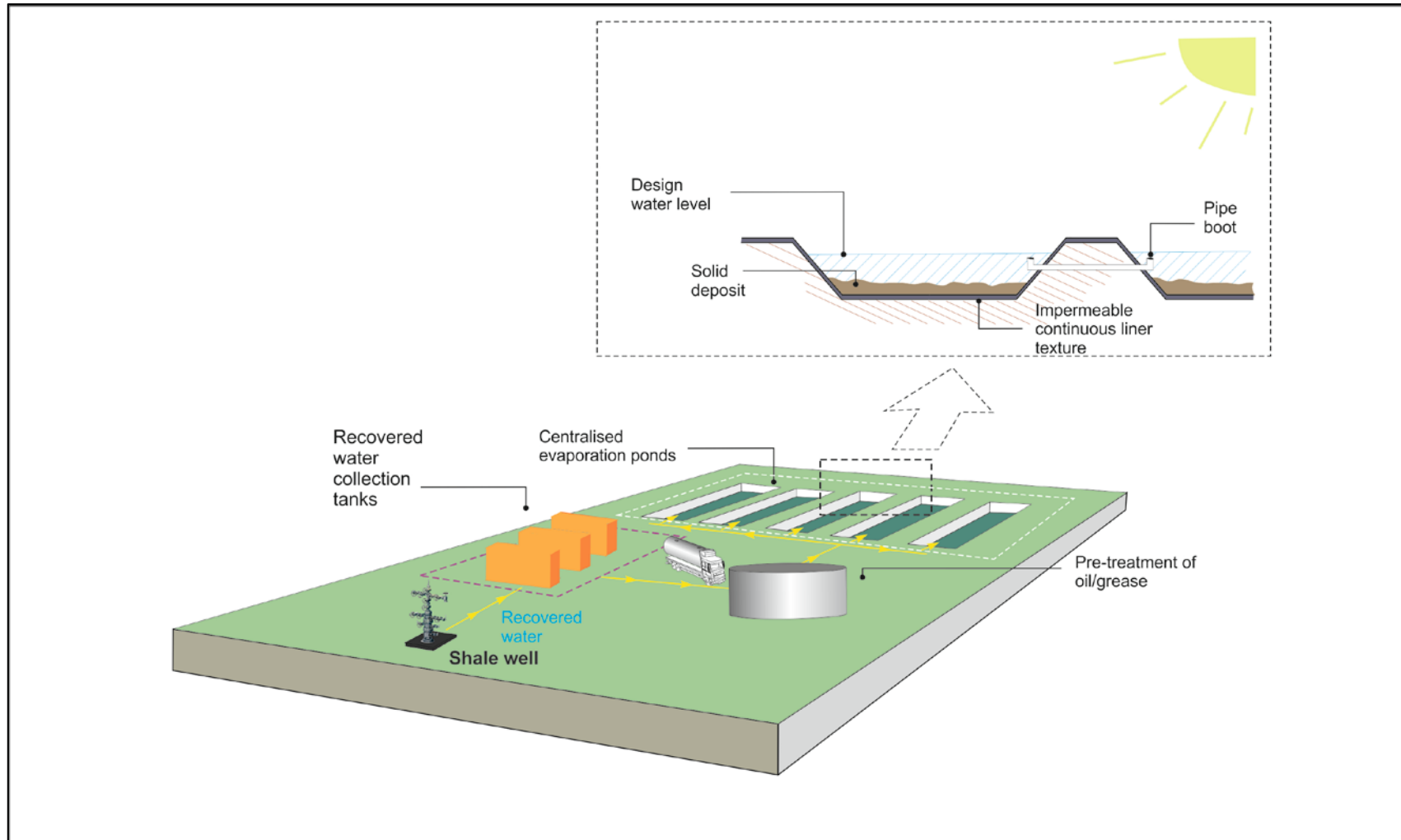
Cost

Phase	Description	Value
Prior to Operation:	Related to pit permitting and construction.	Moderate
During Operation:	Related to operational features of selected pre-treatment for oil/water separation .	Low
After Operation:	Related to pit closure and restoration	Low

Main Considerations for Selection

- Geographical location of the pits, being only practicable in areas with an arid climate.

Technical Diagram of Disposal by Passive Evaporation



Source: Prepared by ERM, 2014

5.3.3 Disposal: Underground Injection Disposal Wells

Underground injection into disposal wells is the most commonly used practice for disposing of recovered water from shale wells. This practice is actually very common for disposing of water not only from shale wells but also other common types of hydrocarbon formations. Clark and Veil (2009) showed that 98% of the produced water from all types of onshore wells in the U.S. is managed through this practice. In the specific case of recovered water from shale wells in the U.S., nearly all of it is sent to disposal wells.

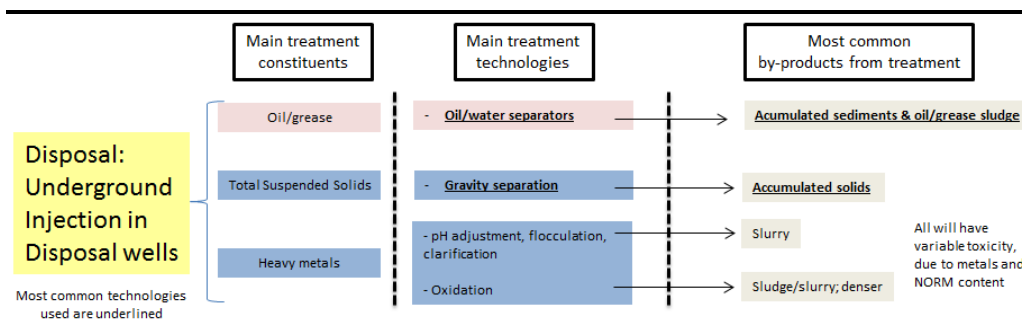
Underground injection consists of sending recovered water into isolated formations. This may be done by either using old wells that are technically modified to become disposal wells, or the third party commercial wells that are drilled specifically for this purpose. Not all wells can be used as disposal wells. The well site must be studied in order to guarantee the technical feasibility of converting it into a disposal well. Disposal wells are monitored and controlled and have to comply with the existing regulatory framework applicable to them.

Treatment train for disposal: underground injection disposal wells

When water is injected into a disposal well only minimal pre-treatment is needed, in order to prevent the formation from plugging.

Figure 5.4 shows the common/potential treatment train for underground injection of recovered water into disposal wells.

Figure 5.4 *Common potential treatment train for Disposal: Underground Injection Disposal Well Scenario*



Source: Prepared by ERM, 2014

The pre-treatment will typically involve passing the recovered water through an oil/water separator so free oil can rise to the top and be skimmed off. This way, solids can fall to the bottom and can be captured and removed later as sludge. Very few if any chemical additives are used but this depends on the quality of the recovered water and the characteristics of the disposal well.

Considering that the existing regulations relating to the management of disposal wells vary widely between countries, additional treatments may be required, for instance to remove metals or microbes, as happens in Argentina.

Technical description of disposal: underground injection in disposal wells

A comprehensive description of this management scenario and its technical diagram is presented in Factsheet 3.

DISPOSAL -Injection in Disposal Well

Practice Description :

This management practice involves injecting liquids into an isolated reservoir through the use of a permitted well that is specifically designed for the disposal of produced & flowback water associated to conventional and shale exploration.

Energy Use:

Low-Moderate, associated with pre-treatment energy requirements and high volume pumps for injection.

Targeted Water Quality Parameters:

Basically pre-treatment for TSS (e.g. by gravity settling or filtration), oil/grease (e.g. separators) and in some cases microbes (e.g. biocides) is needed prior to disposal, but may require further treatment depending on disposal well management practices.

Treatment by-product(s):

Only by-products of pre-treatment, where necessary, usually sludge which is normally managed as industrial waste and may contain metals and NORM.



Injection well at Commercial Disposal Facility in Texas.

Source: courtesy of OGP members, 2014

General Notes

In the US, EPA and state agencies recognise this as a safe, widely used, proven, and effective method for disposing of wastewater. Disposal wells can be permitted either by operators for their own use or by third-party commercial waste management companies.

Advantages:

- This type of well is commonly available in conventional oil and gas producing plays;
- Abandoned O&G wells can be converted to disposal wells (subject to prior technical studies and modifications);
- Can handle large volumes of waste;
- Tend to have relatively low cost (if using existing wells or supporting a large number of shale activities (e.g. stimulated wells)

Disadvantages:

- Pre-treatment often required to prevent formation plugging;
- Trucking will be often required to reach disposal site;
- Formation permeability, storage capacity and pressure can be limiting factors for disposal well locations;
- Few cases of low magnitude seismic events have been linked to improperly sited/managed disposal wells

Cost

Phase	Description	Value
Prior to Operation:	Related to obtaining injection permits ; or conversion of old well if non existent	Low* (if using an existing well)
During Operation:	Related to pre-treatment, and additional costs of commercial disposal.	Low
After Operation:	Related to plugging and abandonment of the well.	Low

Main Considerations for Selection

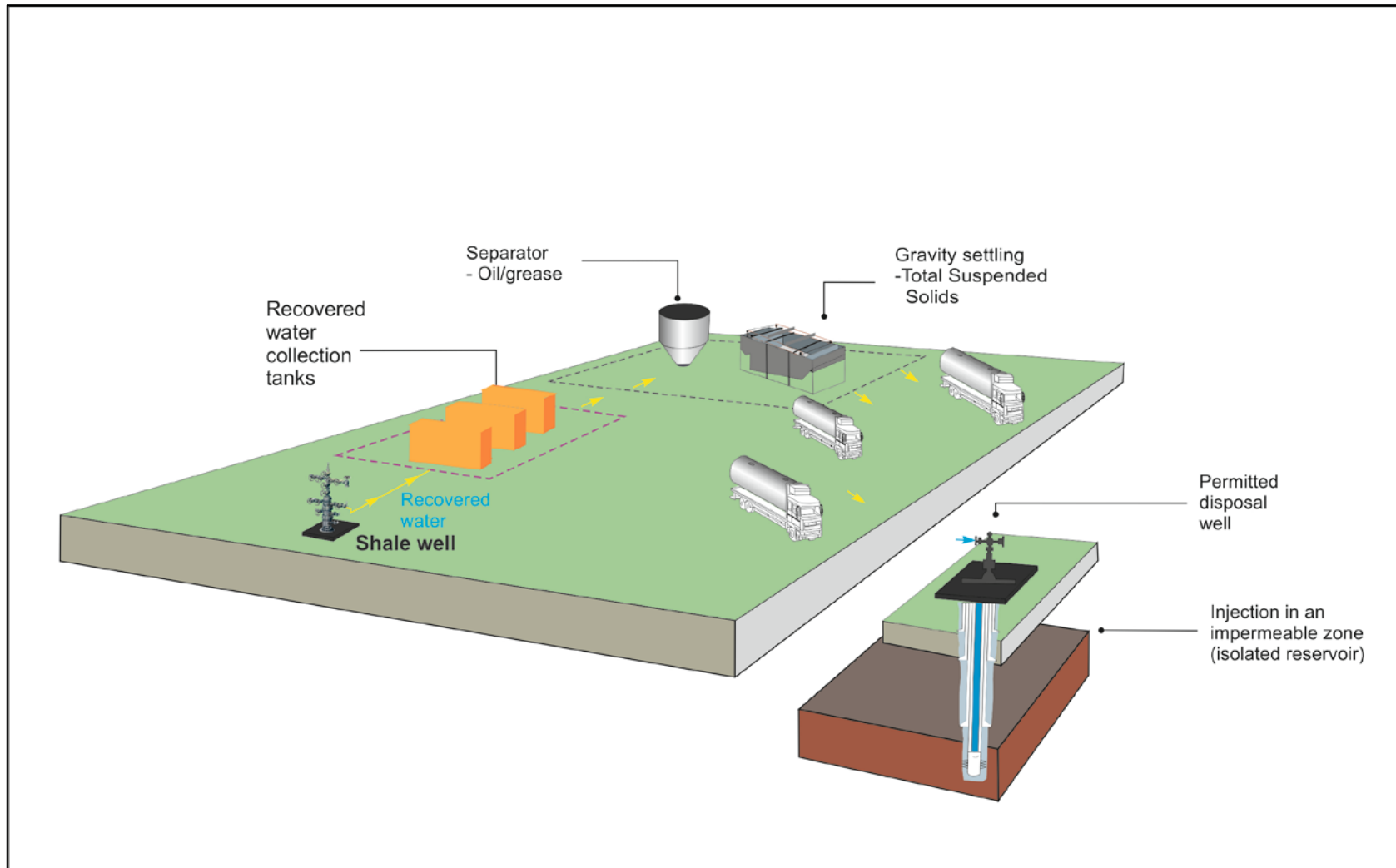
- Regulatory framework may limit the applicability of this practice;
- Availability of geological features that support injection will limit locations where this type of well may be drilled
- Target water quality parameters before disposal are dictated by regulators

Main Associated Impacts

(S/H: Social /Health; E: Environmental)

Type	Description	Value
S/H	Social/health impacts are very low, or even negligible for a properly managed disposal well	Low
E	Injection of recovered water in isolated formations limits any environmental incidence	Low

Technical Diagram of Disposal: Underground Injection in Disposal Wells



Source: Prepared by ERM, 2014

5.4 DESCRIPTION OF REUSE SCENARIOS

There are many factors that may favour water reuse practices as opposed to disposal. The volumes of water needed to perform a well stimulation may be a critical constraint in areas where this resource is scarce, or disposal practices, which are generally reckoned to be very cost effective, may not be so in a particular situation. Important features of the recovered water itself that influence this decision include:

- 1) The volume of recovered water: wells that produce significant and continuous volumes of recovered water are preferred for reuse due to the logistics involved in storing and transporting the water.
- 2) The quality of recovered water: salt content, total suspended solids and hardness of the recovered water may affect possible reuse. Nevertheless, recent technological developments have increased the possibilities for reusing recovered water in fracturing and drilling processes.

Depending on the quality, a reuse scenario may be an effective recovered water management strategy, but there are a number of limitations that may not be fully applicable to shale wells. Reuse is considered a sustainable and practical option for pilot or development phases, and of more limited application in exploration and appraisal phases.

The main reuse scenarios associated to recovered water are described in terms of the level/intensity of treatment (e.g., from basic filtration, through chemical processes, up to intensive desalination technologies) required to achieve particular end-uses, either within shale operations or other industrial processes.

5.4.1 Reuse in Fracturing or Drilling Fluids

Following a basic or intermediate treatment, recovered water from shale wells can be reused either in fracturing fluids or even as drilling fluid for other shale wells. This is a very cost-effective practice as it reduces an operator's expenses in both water sourcing and recovered water management.

The main limitation in the application of this management practice is that it requires other wells to be ready for hydraulic fracturing or drilling at the time when the recovered water is produced in another location. In addition, the feasibility of this practice also relies on the distance between the locations where recovered water is produced and reused, as well as the question of whether there is sufficient recovered water for subsequent operations.

Treatment train for reuse: fracturing or drilling fluid

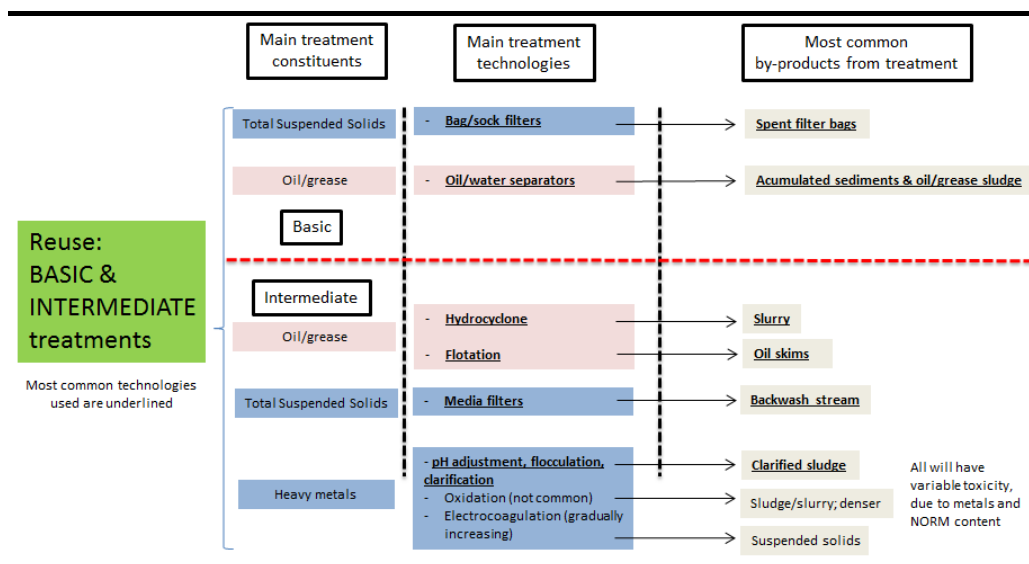
The treatment train for this scenario depends on the quality of the recovered water that is collected and on the quality of water required where it will be reused. Therefore, two general treatment trains have been defined: basic treatment and intermediate treatment.

In basic treatment, the recovered water is passed through simple filtration devices (often bag/sock/cartridge filters and oil/water separators) to remove large solid particles and oil/grease. The filtered water is blended with other water sources to make up the drilling or fracturing fluid for future wells in the same field. This simple process is performed onsite with water easily transferred to nearby wells for reuse. This basic treatment does not remove oil, metals, or compounds other than large solid particles.

The intermediate treatment is more comprehensive than the basic level. The endpoint in this case is clean brine. This means that the treatment is designed to remove finely dispersed oil, metals, and scale-causing compounds, but no TDS are removed.

Figure 5.5 shows the common/potential treatment train for the basic and intermediate treatment of recovered water for reuse as fracturing/drilling fluid.

Figure 5.5 Common potential treatment train for Reuse in fracturing and drilling fluid: (Basic and intermediate treatment)



Source: prepared by ERM, 2014

Technical description reuse: basic and intermediate water treatment

A comprehensive description of this management scenario and its technical diagram is presented in Factsheet 4.

REUSE – Fracturing/Drilling fluid (Basic & Intermediate)

Practice Description :

Storage of recovered water in a permitted lined reservoir or sealed tanks and reuse for the subsequent stimulation/drilling of another well after BASIC (e.g. filtration, separation) and/or INTERMEDIATE (e.g. clarification, oxidation) treatment steps.

Energy Use:

Low-Moderate: Basic treatment is usually not energy intensive, but intermediate level may be energy intensive

Targeted Water Quality Parameters:

Brine water can be as effective as freshwater. Parameters such as: pH, iron, bicarbonate, calcium, magnesium, boron, sulphate, TDS, sodium, chloride, potassium and bacteria can limit reuse.

By-product(s) of treatment:

Accumulated solids; sludge with high concentrations of metals and NORM



Recovered water may undergo settling in sealed tanks for later reuse. Source: courtesy of OGP members, 2014

Advantages:

- Minimises costs of operators having to source water and later treatment of recovered water;
- Sustainable approach that conserves water resource;

Disadvantages:

- Requires storage facilities;
- Lined pits or tanks may be required;
- Water can only be recycled a finite number of times before quality forces disposal or further ADVANCED treatment;
- Must have a new well waiting to be stimulated so long-term water storage is avoided.



Discharge of recovered water to a centralised pit for reuse

Source: courtesy of OGP members, 2014

Cost

Phase	Description	Value
Prior to Operation:	Related to permitting and reservoir construction; or Low in case of tanks.	Low-Moderate
During Operation:	Assumes no trucking and/or minimum pre-treatment.	Low
After Operation:	Related to size of pit and closure requirements; or Low in case of tanks.	Low - Moderate

Main Considerations for Selection

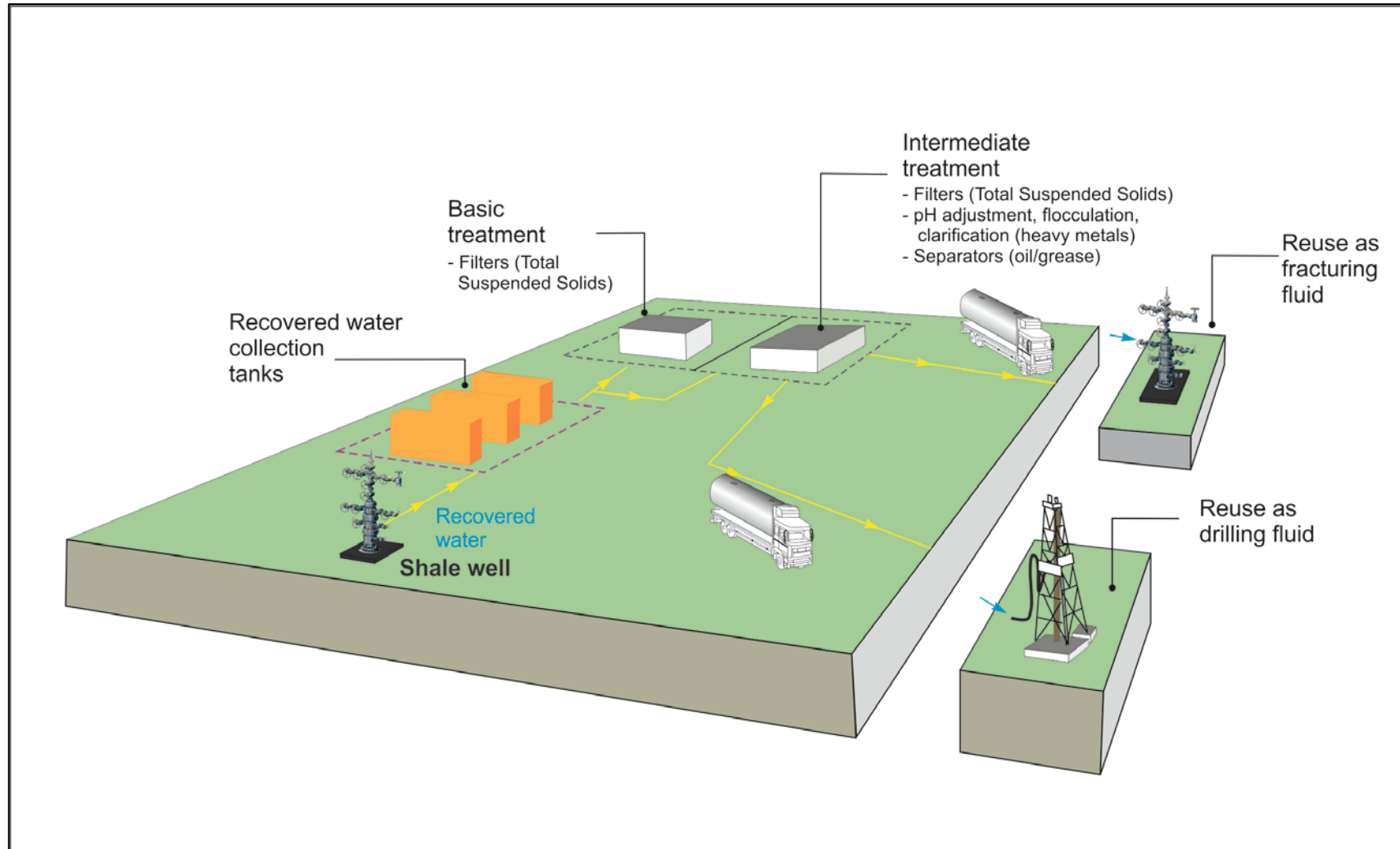
- Dilution (practice also called "Blending"), can be a practical and cost effective method of treatment before reuse;
- Volume of water recovered should be large enough to limit water intake from other sources;
- Other drilling/fracturing activities must be performed in the vicinity to take full advantage of this management option;
- Higher levels of parameters such as TDS and metals after every subsequent fracturing will warrant further treatment to make reuse compatible

Main Associated Impacts

(S/H: Social /Health; E: Environmental)

Type	Description	Value
S/H	Potential for exposure to VOCs if pits are used, will be significantly lower using tanks	Low
E	Reuse scenarios minimise impact, by products from pre-treatment are manageable	Low

Technical Diagram Reuse: Basic and intermediate water treatment



Source: Prepared by ERM, 2014

5.4.2 Reuse in other industrial activities

In order to reuse water in other industrial activities advanced treatment is required and the endpoint is clean fresh water with low TDS. Currently, not very much recovered water is treated to this level and reused in oil and gas operations or in other industries. It is applied in locations with no other lower-cost water treatment options as well as in areas with water shortages.

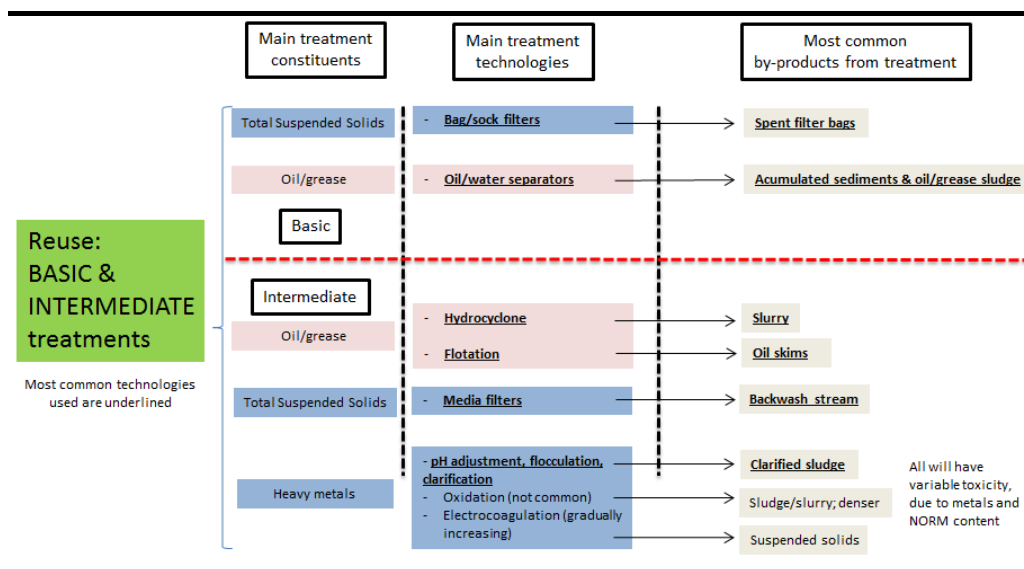
In very dry locations, with long-term water shortages like west Texas, some operators use advanced treatment processes in order to generate their own dedicated water supply. Recovered water that undergoes successive basic/intermediate treatment steps gradually increases in TDS to the point where it can no longer be used in the shale operation. For this reason, if water is going to be continuously reused, it is necessary to desalinate it

Treatment train for reuse: other industrial activities

For advanced treatment, the basic and intermediate procedures explained above are applied followed by desalination technologies, such as thermal distillation, which are expensive. It is important to note that most recovered water has TDS higher than 40,000 mg/L (Veil, 2012), and therefore reverse osmosis is not a practical option.

Figure 5.6 shows the common/potential treatment train for the advanced treatment of recovered water for reuse in other industrial activities.

Figure 5.6 Common potential treatment train for Reuse in other industrial activities



Source: Prepared by ERM, 2014

Technical description for reuse: other industrial sectors

A comprehensive description of this management scenario is presented in Factsheet 5.

REUSE – Fracturing/drilling fluid; or other applications (Advanced)

Practice Description :

Storage of recovered water in a permitted surface storage site or sealed tanks and reuse for subsequent well stimulation or other compatible use after being subjected to additional ADVANCED treatment.

Energy Use:

Moderate to high, depending on type of technology and number/types of treatment stages.

Targeted Water Quality Parameters:

Brine can be as effective as freshwater, but parameters such as: pH, iron, bicarbonate, calcium, magnesium, boron, sulphate, TDS, sodium, chloride, potassium and bacteria can limit reuse. Secondary use of treated water will have specific water quality requirements depending on its intended use.

Treatment by-product(s):

Will depend on treatment train, typically being a combination of sludge, other solids, and concentrated brine; all these may contain considerable concentrations of metals and NORM with variable toxicity.



Advanced Treatment Facility : Crystallizer (Separation / Evaporation System)

Source: courtesy of OGP members, 2014.

Main Associated Impacts

(S/H: Social /Health; E: Environmental)

Type	Description	Value
S/H	Potential for exposure to vapor; assumes reused water does not pose a threat to human health.	Low
E	Reuse scenarios minimise environmental impact; assumes reused water does not pose a threat to ecology.	Low

Advantages:

- Byproducts include clean water and concentrated brine. The latter can be reused in stimulation/drilling operations;
- Waste heat from nearby natural gas compressor stations or gas directly from the wellhead can be used to power advanced treatment systems.
- Saves money on disposal and water supply;
- Sustainable approach that conserves water resource;
- Can be a good supplemental water supply in arid areas.

Disadvantages:

- Cost and energy requirements are high for thermal treatment;
- Operational challenges with scale buildup;
- Management of brine can be an issue.
- May need associated storage facilities (for by-products e.g. salts)

General Notes

Several types of thermal distillation and evaporation systems have been used to treat flowback which usually has high TDS levels.

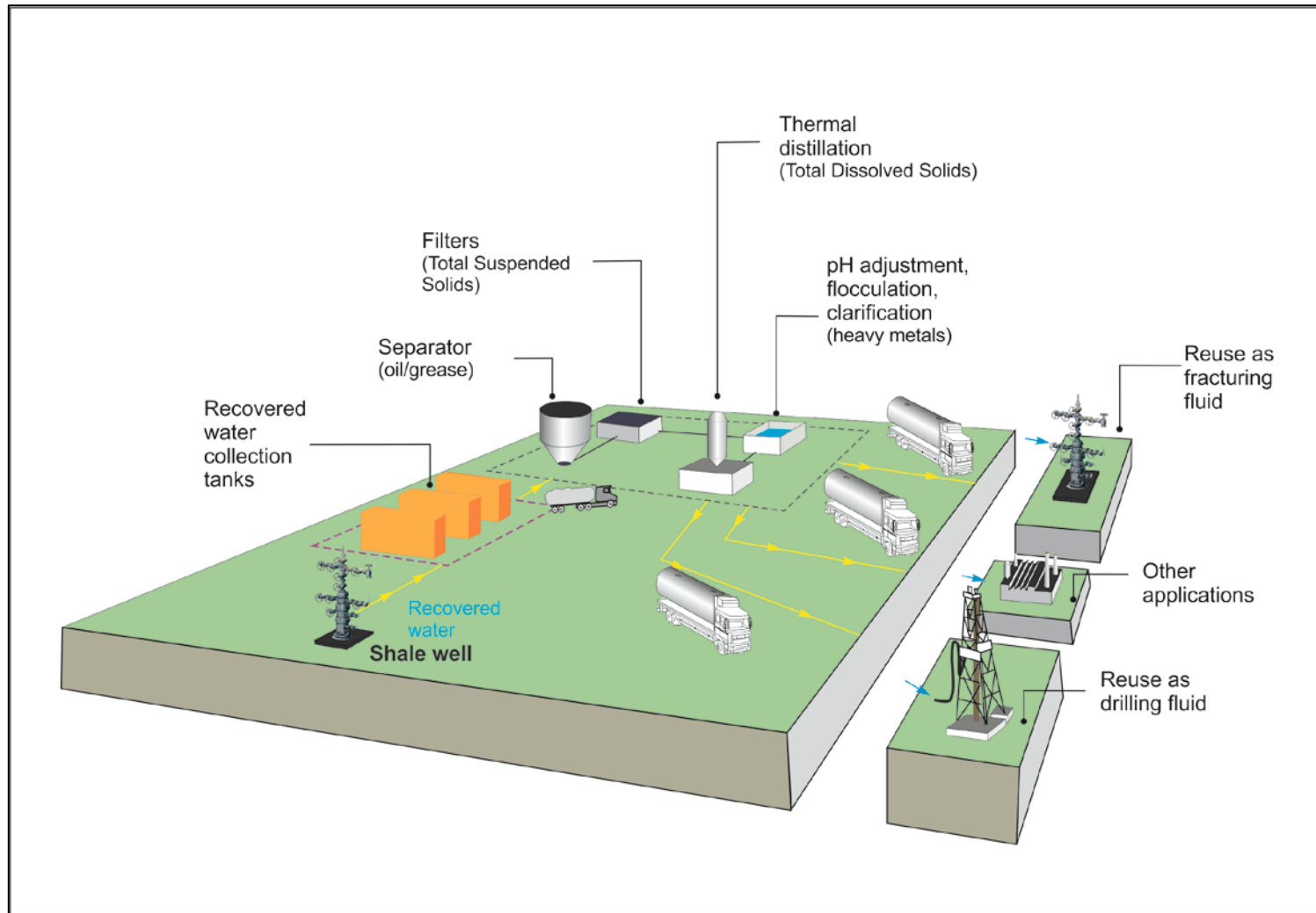
Cost

Phase	Description	Value
Prior to Operation:	Depending on treatment technology capital costs, permitting and reservoir construction.	Moderate-High
During Operation:	Related to energy consumption, fees and maintenance of selected treatment technologies.	High
After Operation:	Related to size of pit and closure requirements; and associated facilities if needed	Low-Moderate

Main Considerations for Selection

- Recovered water may have varying degrees of salinity, energy intensive processes may require high energy input devices (e.g. Crystalliser, Mechanical Vapor Recompression); while less saline water may be treated through basic membrane technologies.
- Some water chemistry may be difficult to treat, resulting in higher costs.

Technical Description for Reuse in other Industrial Sectors



Source: Prepared by ERM, 2014

5.5 SUMMARY OF THE MAIN MANAGEMENT OPTIONS

Table 5.1 presents a summary of the identified water management practices, along with a brief explanation of their main attributes, for comparative purposes.

Based on a qualitative assessment of aspects such as energy use, financial cost, and environmental and social impacts, it can be concluded that both reuse of recovered water, either in fracturing or drilling fluids (i.e., only basic-intermediate treatment required), and underground injection into disposal wells constitute effective recovered water management scenarios from an economic/environmental perspective.

On the other hand, practices that may be considered less financially viable or environmentally effective, according to the criteria used, are discharge into surface water bodies and reuse in other industrial activities, given the advanced treatment technologies required, especially for TDS removal. Although the described impacts may be very similar and relatively low (green in Table 5.1) due to the industry's ability to mitigate them, the energy/cost factors can vary greatly. However, in practice, when a management practice is being selected, the other factors mentioned in previous sections are also considered. These include the different operational conditions of the exploration versus development phase, and social setting.

Table 5.1 Summary of Key Aspects of Identified Management practices

Factsheet	Management Category	Type	Description	Energy Use	Cost*	Main Associated Social/Health Impacts	Main Associated Environmental Impacts
1	Disposal	Discharge	Recovered water is discharged to a surface water body, usually after being sent to a certified wastewater treatment facility to attain parameters within acceptable discharge limits.	High standard discharge parameters may necessitate intensive treatment	Will depend mostly on fees related to applied treatment technologies which can be expensive, unless discharged to sea which would limit level of TDS removal	Limited pollution risk to domestic/industrial surfacewater users	Impact is low since water is treated to applicable standards
2	Disposal	Evaporation	Passive evaporation from permitted lined evaporation ponds constructed specifically for this use. These are only valid in arid climates	Limited pre-treatment energy requirements will have a relatively low power consumption	Ponds require a large surface area to handle large volumes of recovered water	Volatile organic compounds (VOCs) may cause localised air pollution issues	Impact is low as water/sludge pits are covered with nets to prevent contact with avifauna
3	Disposal	Underground injection well	Injection into permitted disposal wells. This is a popular option where it is permitted, especially during development phases, but specific geological requirements limit locations where these wells can be drilled.	Related to pre-treatment energy requirements and use of high volume pumps for injection	Relatively low pre-treatment costs and fees	Limited risk of groundwater pollution from wells that are managed correctly	Impact is low due to injection in deep isolated formations
4	Reuse	as fracturing/drilling fluid	Recovered water treated to basic/intermediate level is stored in permitted reservoirs/tanks and reused in subsequent stimulation/drilling. Brine can be reused for successive fracturing, but will have limited reuse cycles until further treatment is applied	Basic treatment is usually not energy intensive, but intermediate level may be so	Site pre-treatment and use of ponds/tanks that need associated permits and construction	Potential exposure to vapours if pits are used, negligible exposure with tanks	Reuse scenarios minimise environmental risks/impacts, limited number/volume of by products from pre-treatment
5	Reuse	as fracturing/drilling fluid; other industrial uses	Recovered water treated to advanced level is stored in permitted reservoirs/tanks and reused in subsequent stimulation/drilling or other compatible use. Creates a pure water stream that can have a wider variety of uses, as well as significant dry deposits.	Desalination technologies are generally energy intensive	Usually requires a comprehensive treatment train (basic, intermediate and advanced) with associated fees for treatment	Potential exposure to vapours if pits are used, negligible with tanks; reused water does not pose a threat to human health	Reuse scenarios minimise environmental risks/impacts; reused water does not pose a threat to ecology

*: Transport issues have not been considered since these may apply to varying degrees to all management practices
Source: Prepared by ERM, 2014.

5.6 *DESCRIPTION OF TREATMENT TECHNOLOGIES*

The preceding sections have described the different management practices that have been identified and their associated treatment trains. This section further describes each of the treatment technologies involved including:

- A basic description of how the technology works (including a photo of typical equipment used);
- The main target constituents to be treated (note that certain technologies may be able to further treat other constituents);
- The relative costs and energy use;
- Advantages and disadvantages of the technology; and
- Treatment by-products.

For completeness, microbe removal technologies have been included, although these are not considered to be treatment for recovered water, as they are usually used in the development of new fracturing fluid.

5.6.1 Treatment technologies focused on Total Suspended Solids and Heavy Metal removal

Mechanism/Process: Filtration		
Description: Removal of large solids like sand and mineral scales through simple media filters or bag/sock filters.		 Granular Activated Carbon media filter Source: OGP, 2014
Target parameters: -Total Suspended Solids (TSS)	Cost/Energy use: Running costs and energy use are relatively low.	
Advantages: - Low cost, low energy use - Effective TSS removal for pre-treatment	Disadvantages: - Grain size and distribution affects hydraulic performance of filtration process and efficiency of particle removal; - Time: slow head-loss accumulation plus high capacity for accumulating solids will produce long filter runs - Filter maintenance	By-product of treatment: - Used bag/sock filters - Used media - Backwash of media filters
Mechanism/Process: pH adjustment, coagulation/flocculation, sedimentation, and clarification		
Description: Designed to remove metals from flowback and produced water; lime or another chemical is added to raise the pH. This supports formation of metal sludges (metal hydroxides when lime is used). Coagulants are added to promote flocculation/settling, and then the wastewater is sent to a clarifier. The sludge is often dewatered in a filter press.		 pH adjustment equipment Source: OGP, 2014
Target parameters: -Total Suspended Solids -Heavy Metals	Cost/Energy use: Relatively low in terms of equipment & energy costs	
Advantages: - Straightforward process that has been used for years. - Efficient removal of metals	Disadvantages: Waste handling/disposal	By-product of treatment: Sludge with variable content of heavy metals; a filterpress can dewater sludge to form a cake like by-product.

Mechanism/Process: Oxidation			
Description: Organics and metal removal; may include ozone, peroxide or oxygen; strong oxidizer reacts with organic or inorganic material and precipitates to be removed from solution. May include cavitation and electrochemical decomposition.			Mobile treatment system that uses various oxidation processes Source: Hydrozonix, 2014
Target parameters: -Total Suspended Solids -Heavy metals -Free oil -Microbes	Cost/Energy use: - Moderate cost of oxidizer materials - Low energy use		
Advantages: - Efficient with high throughput for primary treatment of soluble constituents - Treats ionic constituents as well as organics - Mobile technology available	Disadvantages: - Handling and storage of oxidizer - Relatively high maintenance and waste disposal costs		
By-product of treatment: Precipitate slurry			
Mechanism/Process: Electrocoagulation (EC)			
Description: Electrocoagulation is a process for destabilising suspended, emulsified or dissolved contaminants in an aqueous medium by introducing an electrical current into it. The electrical current provides the electromotive force that causes the chemical reactions. The current is introduced into the water via parallel electrodes made of various metals generally selected to optimise the removal process.			Electrocoagulation equipment Source: OGP, 2014
Target parameters: - Total Suspended solids - Heavy metals	Cost/Energy use: Moderate cost & energy use		
Advantages: - Lower sludge production than competing technologies - Simple equipment, easy to operate - Chemical-free procedure. The sludge formed by EC tends to settle readily and is easy to de-water, because it is composed of mainly metallic oxides/hydroxides.	Disadvantages: - The electrodes dissolve into the wastewater streams as a result of oxidation, and need to be replaced regularly - The use of electricity may be expensive; - In some EC systems an impermeable oxide film can form on the cathode, leading efficiency loss in the EC unit		
By-product of treatment: Small volumes of suspended solids and sludges.			

5.6.2 Treatment technologies focused on Total Suspended Solids and Oil removal.

Mechanism/Process: Oil/Water separators			
Description: De-oiler; separation of phase-separated oil under gravity effects (e.g., inclined/corrugated plate separators)			Oil/Water separator Source: OGP, 2014
Target parameters: <u>- Oil</u> - Total Suspended Solids	Cost/Energy use: Relatively low in terms of equipment & energy costs		
Advantages: -Minimal energy required (only for pumps) -Effective for removing bulk oil and suspended solids. Equipment resistant to breakdowns	Disadvantages: -Works well for free oil, but not as effective on dispersed and soluble oil. Performance can be improved by adding flocculants	By-product of treatment: - Oil sludge	
Mechanism/Process: Hydrocyclone (liquid/liquid type)			
Description: De-oiler; separation of phase-separated oil under centrifugal force generated by pressurised, tangential input of influent stream			Hidrocyclone unit Source: OGP, 2014
Target parameters: <u>- Oil</u> - Total Suspended Solids	Cost/Energy use: Moderate: maintenance & energy costs Low energy use		
Advantages: -Equipment is compact -High efficiency and throughput for fine oil particles -Most commonly employed mobile technology	Disadvantages: - No solid separation - Too many solids (sand) in the inflow can damage the metal surfaces of the hydrocyclone.	By-product of treatment: Slurry	

<u>Mechanism/Process:</u> Flotation (Dissolved Gas flotation / Induced Gas Flotation) with or without addition of chemicals		
<u>Description:</u> Flotation technologies introduce bubbles of air or other gas into the bottom of a sealed tank. As the bubbles rise, they attach to oil droplets and solid particles and lift them to the surface where they can be skimmed off.		 Dissolved Air flotation Source: OGP, 2014
<u>Target parameters:</u> - <u>Total Suspended Solids</u> - <u>Oil</u>	<u>Cost/Energy use:</u> Moderate cost & energy use	
<u>Advantages:</u> - Few moving parts - Efficiency due to coalescence - Simple operation	<u>Disadvantages:</u> - Maintenance of pumps and skimmers - Does not remove soluble oil	<u>By-product of treatment:</u> Oil skim

5.6.3 Treatment technologies focused on Total Dissolved Solids (desalination)

Mechanism/Process: Reverse Osmosis		
Description: Membrane filtration technology that uses pressurised water to remove 0.0005 - 0.00005 micron sized constituents. The common upper limit for TDS removal using this technology is approximately 40,000 mg/L		 Reverse Osmosis units Source: J. Veil, 2014
Target parameters: - Total Dissolved Solids (salinity) - Heavy Metals - Microbes	Cost/Energy use: High cost & energy use	
Advantages: - Can remove very small ions like chlorides as well as metals and microbes	Disadvantages: - Moderate to high costs - Requires extensive pre-treatment to remove suspended solids to avoid membranes fouling	By-product of treatment: Concentrated brine
Mechanism/Process: Membrane technology: Micro-, Ultra-, Nano-FILTRATION (from larger to smaller pore diameter)		
Description: Membrane filtration; water under pressure to remove constituents: micro = 10 - 0.1 micron mesh; ultra= 0.05 - 0.005 micron mesh; nano = 0.005 - 0.0005 micron mesh. As the membrane pore size decreases, the pressure (and hence energy) required to push the water solution through the membrane increases. In addition, the tendency to foul the membrane increases as the pore size decreases. For this reason, membrane filtration is often conducted in stages		 Membrane filter Source: J. Veil, 2014
Target parameters: -Total Dissolved Solids (salinity) -Total Suspended solids -Heavy Metals -Microbes	Cost/Energy use: High; due to the energy & pressure required	
Advantages: - Compact - Mobile technology available - High levels of fresh water recovered - The smaller the pores, the smaller the molecules that can be removed	Disadvantages: - Relatively high energy/pressure requirement - The smaller the pores, the greater the potential for fouling and greater the need for pre-filtration.	By-product of treatment: Concentrated residues during membrane cleaning

Mechanism/Process: Thermal distillation/Evaporation		
Description: Desalinisation; using heat to turn water containing high levels of TDS to steam; the steam is then condensed to create clean water, leaving behind a smaller volume of highly concentrated brine. Common technologies include mechanical vapour recompression (MVR), capable of treating TDS in excess of 40,000 mg/L. Historically, thermal distillation has not been cost-effective for treating produced water, but with relatively small volumes of high salinity flowback water the technology has been applied, particularly when the operator wants good water for reuse.		Evaporator Source: J. Veil, 2014 
Target parameters: -Total Dissolved Solids (salinity)	Cost/Energy use: - High cost/energy requirements.	
Advantages: - Mobile technology available; - Creates high quality clean water	Disadvantages: - High energy requirement - Requires pre-treatment (e.g. flocculation, filtration, settling) to avoid fouling and corrosion.	
		By-product of treatment: Concentrated brine
Mechanism/Process: Crystallisation		
Description: Crystallisation essentially involves evaporating all the water to generate a solid by-product. Cost considerations for this treatment technology include: feed water quality versus target TDS concentrations, zero liquid discharge objectives, high energy input, limited non-mobile facilities, and disposal of solid waste. Depending on the number of evaporation steps, this technology can evaporate up to 95% of the water content, and is therefore considered a disposal technology.		Crystalliser Source: J. Veil, 2014 
Target parameters: -Total Dissolved Solids (salinity)	Cost/Energy use: Very high, given the large energy requirement.	
Advantages: - Eliminates the need for any wastewater to leave the site. - Potential to be a zero liquid discharge (ZLD) system.	Disadvantages: - Extremely high energy requirements often make this not cost-effective.	
		By-product of treatment: Dry solids and/or dense sludge.

5.6.4 Treatment technologies focused on Microbe removal

Mechanism/Process: Chemical biocides		
Description: Disinfection; kills many microbes that may cause biofouling. A commonly used biocide is chloride.		 Biocide injection skid Source: OGP, 2014
Target parameters: - Microbe removal	Cost/Energy use: Low; material costs	
Advantages: - Cheap - Simple - Helps protect piping and surface equipment from fouling - Mobile technology available	Disadvantages: - Not effective on all microbes - Does not affect a wide range of constituents; - Handling and storage of biocide	By-product of treatment: Small volumes of suspended solids
Mechanism/Process: UV light		
Description: Usually takes place prior to adding biocides.		 Ultraviolet injection Source: OGP, 2014
Target parameters: - Microbe removal	Cost/Energy use: Low cost & energy use	
Advantages: - Reduces volume of biocide required to kill or inhibit microbe growth; - No disinfection by-product	Disadvantages: - No residual kill capacity - Pre-treatment required to filter suspended solids, TDS, soluble molecules, humic acids, and minerals - Reuse practices may be incompatible with the process unless the fluid has low levels of TDS	By-product of treatment: None

<u>Mechanism/Process: Ozone</u>			
<u>Description:</u> Destroys bacteria and other microorganisms through an infusion of ozone.			Mobile treatment system that uses ozone, among other oxidation processes Source: Hydrozonix, 2014
<u>Target parameters:</u> - Microbe removal	<u>Cost/Energy use:</u> Moderate cost Low energy use		
<u>Advantages:</u> - Capable of removing bacteria without producing residual by-products - Treatment equipment is small	<u>Disadvantages:</u> - Moderate operational cost - Does not inhibit re-growth like biocides - Toxicity issues associated with ozone generation - Long-term disinfectant power of ozone is directly related to COD (Chemical Oxygen Demand)	<u>By-product of treatment:</u> None	

6 *FUTURE DEVELOPMENTS IN RECOVERED WATER MANAGEMENT FOR SHALE WELLS*

6.1 *OVERVIEW*

The preceding chapters describe the currently viable recovered water management practices and the most common treatment technologies used in shale wells. This section presents an overview of potential future trends expected in management practices.

As previously explained, recovered water is one of the final elements of the water cycle in shale activities and is preceded by water sourcing and the preparation of fracturing fluids. Therefore, any future developments in these other elements will also impact the development or evolution of recovered water management practices.

6.2 *FUTURE DEVELOPMENTS*

Considering the challenges for the recovered water management in shale wells, three main focus areas for future developments have been identified:

- Minimisation of the freshwater volumes required in the fracturing fluid;
- Maximisation of reuse; and
- Improvement of treatment technologies.

6.3 *MINIMISATION OF FRESHWATER IN THE HYDRAULIC FRACTURING FLUID*

One of the challenges for recovered water management is the volume of water required, especially in locations where water sources are limited. It is therefore expected that future developments in fracturing technologies will focus on minimising the volume of water necessary for the fracturing fluids. New developments are evolving towards the use of non-freshwater sources (e.g., water from other industrial processes or brackish water), as well as the use of other media (i.e., not water) that can be used for hydraulic fracturing operations (e.g., waterless fracturing fluids). However, these are not used nearly as often as water; examples include liquid carbon dioxide, liquid propane, nitrogen gas foams and gels. Nevertheless, the use of other types of fluids may present other challenges such as safety risks (e.g., due to toxicity) which must be properly addressed (Zhu & Tomson, 2013).

6.4 *MAXIMISATION OF REUSE*

In the early days of hydraulic fracturing, freshwater was generally considered the only option for use as base fluid, given that the type of additives used at that time were not compatible with highly saline water. Over time, research into additives led to the creation of new compounds (e.g., scale control additives, gelling/viscosity agents such as cross-linkers) capable of maintaining their properties under a broad spectrum of water quality conditions (e.g., high TDS content), thus maximising the potential recovered

(or brackish) water to be used to prepare fracturing fluid for subsequent fracturing/drilling operations.

There are many proven treatment solutions for recovered water from shale wells, but the methods for applying these treatment approaches are usually decided on a well-by-well basis, given the drastic fluctuations in the rate of water flow, as well as the concentration of contaminants (Thakre & Shenkar, 2011). Nonetheless, factors such as water stress and scarcity at specific locations will undoubtedly favour those technologies that allow high volumes of recovered water to be reused. For these reasons it is expected that large scale fracturing operations where water is not abundant will continue to focus on the recycling of recovered water for reuse.

6.5 IMPROVEMENT OF TREATMENT TECHNOLOGIES

Treatment technologies have been shown to be widely applicable according to the target parameters, with different implications for energy costs, treatment of by-products and practical limitations when they are used in on-site scenarios; in view of this, future water management technologies are likely to focus on the following questions:

- How does the technology work? Novel treatments may either rely on proven principles such as membrane separation treatments (e.g., forward osmosis which reduces fouling, increases energy efficiency and lowers capital costs (Coday et al. 2014)) or other principles like dewvaporation, carrier gas extraction (CGE) and directional solvent extraction (DSE) (Narayan, 2014). It is expected that ongoing research and continuously changing economic and technological conditions will broaden the current limited use in shale development.
- What inputs are needed? (e.g., energy, chemicals) reducing energy consumption affects both cost and environmental impact; the same applies to minimising transportation (e.g., onsite treatment).
- What by-products are generated? Also including their management and/or disposal.
- How to reduce treatment costs? A lower cost structure should be attained with practices remaining sustainable.
- What are the water quality limits for the treatment technology? Technology is shifting towards a wide range of water qualities being treated with the same technology or group of technologies.
- How can solutions be applied to a variety of reservoir conditions? Technical solutions will have to be rugged enough to move from one well to another and withstand both the harsh environment on a pad and transportation across the terrain.

Water management is a promising business, with a wide variety of vendors offering different solutions for recovered water treatment. The need for reliable, safe, and cost-effective solutions for treating recovered water has begun to drive forward innovation and development in this market sector, with oil and gas exploration companies, vendors and universities involved in looking for innovations specific to deployment in a particular shale play. Nowadays, water management is a lucrative and competitive environment that is generating products that will change the face of water management throughout the water industry (Thakre & Shenkar, 2011).

- Hydraulic fracturing is a well stimulation technique that has been used in the oil and gas industry for the past 65 years to improve production from hydrocarbon-containing formations.
- After a shale well has been hydraulically fractured, water flows back to the surface (recovered water) throughout the following weeks to months.
- The volume and quality of the recovered water is highly variable and depends on the particular shale play geology. The total dissolved solids (i.e., salinity) are one of the most important parameters to take into consideration when selecting a treatment technology and considering the overall cost effectiveness of a management practice.
- Recovered water management is a key aspect of shale development, and there are a variety of proven and environmentally manageable disposal-reuse scenarios.
- There are many factors involved in the selection of a recovered water management option. These range from environmental aspects (e.g., physical, social, and regulatory issues) to operational and economical considerations. Choosing a management option is part of a process linked to evolving knowledge of the shale play gained through exploration activities.
- The aforementioned factors may differ greatly between shale plays across the globe. They include, but are not limited to, recovered water chemistry, the availability of disposal options, and the availability of source water. It is therefore expected that no single water management strategy predominates and the most likely scenario involves a combination of disposal-reuse strategies that evolve throughout the development of a particular shale play.
- The current international management practices tend towards disposal scenarios through the use of underground injection wells. The popularity of this strategy stems from the fact that it is commonly used in conventional resources and also that wells for injection are readily available in shale plays located where other conventional activities have already taken place.
- In locations with no existing or prior oil & gas development activities, disposal strategies are usually more typical during the early development of a shale play, due to the limited extent of fracturing operations (i.e., there is no other well waiting to be fractured so reuse of fluids is not needed). As a shale play develops, reuse strategies become more important if there are no economic options for disposal or water is scarce.
- Treatment technologies are a common feature of water management practices, and they are selected according to the intended end use of the treated recovered water. Most treatment technologies are not stand-alone; multiple treatment types/stages are needed to address the target constituents of recovered water, including salt content, metals, naturally occurring radioactive material, and hydrocarbons/organics. Treatment

technologies have distinct energy requirements and chemical inputs, and produce by-products which may need further management.

- Future developments in recovered water management will focus on minimising the volume of water required (e.g., through the use of other media to carry proppant, such as gels, foam, and gases), maximising reuse (e.g., by developing fracturing fluid additives that are robust enough to be used in a broad variety of water qualities), and improving treatment technologies (e.g., through research on technologies that are more efficient, capable of handling large volumes of variable quality recovered water, and which are readily deployable in the field, as well as being cheaper).

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