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Chapter

Aquifer Management in Hydrocarbon Exploitation Operations

John Escobar, Darío Naranjo-Fernández, Sergio Lopera, Orlando Mauricio Quiroz, Alonso Ocampo and German Zarate

Abstract

The exploration and production of hydrocarbons require the management of associated aquifers not only because they must be intercepted and isolated during the drilling process, but also because they can be used as reservoirs for the final disposal of connate water, or as a source to maintain the energy of reservoirs and enhanced oil recovery operations. Despite the technological advances in the management of aquifers in the hydrocarbon industry, these kinds of operations have not been free of risks and opposition. Primary oil exploitation, improved oil recovery, and disposal of remaining water operations usually involve medium and deep aquifers that have physical, chemical, and geomechanical characteristics that may differ greatly from those known in shallow aquifers. Therefore, a detailed study of the porous media as well as the contained, produced, or reinjected fluids is an obligation for the regulation compliments and the safe handling of these operations. This chapter deals with issues associated with the chemical interaction of water, the problems that may arise from an incorrect evaluation or management, and the phenomena that can show a problem or evolution in injection operations. Finally, corrective, and preventive treatments and procedures that are commonly used in the hydrocarbon industry are specified.

Keywords: oil and gas industry, shallow and deep aquifers, production waters, disposal, injection, enhanced oil recovery, hydrogeochemical and isotopic analyses, microseismicity

1. Introduction

Water requirements for oil and gas extraction are often unknown to decision-makers and public opinion. Although hydrocarbon exploitation does not involve a significant overall water consumption worldwide compared to other industries, such as agriculture or municipal needs, water demands can have serious impacts on local water resources and increase disputes between water users in high-water stress areas or during the drought seasons [1].

Oil and gas production is generally accompanied by water production with several characteristics, which affect the normal balance of the water cycle, either

by water extraction or injection from and to different reservoirs. Therefore, it is required to evaluate the consequences in the water life cycle, due to water amount and source necessary for operations, water management practices, wastewater recycling, treatment, or disposal, and the impact on watersheds and the surrounding environment.

A general balance of water in industry would allow separate them into two large groups: water required for production and water resulting from extraction. These groups often have different physicochemical, geochemical, bacteriological, and isotopic features. The first one includes water with fast renewal time, low electrical conductivity, and hydrochemical and isotopic characteristics like surface water. On the other hand, the water belonging to the second group presents slow renewal times, high values of electrical conductivity, and hydrochemical facies that allow their clear differentiation from the surface water present in the region.

In most cases, water extracted together with the hydrocarbons correspond to connate water present in conventional reservoirs. They are usually a complex mixture of dissolved and dispersed organic and inorganic compounds [2]. On the other hand, production waters and return fluid consist of a formation water mixture and other fluids used during exploitation, whose composition varies spatially and temporally.

Formation waters are naturally present in all oil and gas deposits whose origin is difficult to determine in a general way. These waters are classified as endogenous and exogenous; in the first group, waters were originally present in the formation when the hydrocarbon accumulation occurred (connate waters), while in the second one, they infiltrated from the surface (absorbed) or penetrated from upper sediment accumulations or migrated by compaction of lower sediments (juvenile).

This work proposes alternatives to characterize these types of water, define the methodologies, and identify the most common risks, as well as highlight future trends in water resource management.

1.1 Approach

Typically, the oil reservoirs are developed initially by producing the wells by depleting the original pressure of the reservoir (*Natural Depletion*), and also taking advantage of the presence of an original gas cap and/or the solution gas liberation and expansion within the system as a consequence of the natural depletion (*Solution Gas Drive and Gas Cap Expansion*). Nevertheless, these mechanisms, referred to as primary depletion, render very low recovery factors (Usually less than 25% of the *Oil in Place* for medium and light oils, and less than 5% for *Heavy Oils*). This condition is different for the reservoirs where the oil column is connected to a very large and/or recharged aquifer¹ that can provide enough pressure support and displacement to the hydrocarbons, in which case recovery factors as high as 60–65% [3] can be obtained depending on the fluid type, continuity and homogeneity of the reservoir, and the size of the aquifer and recharge source. The gas reservoirs, on the other hand, are developed under natural depletion in most cases.

Once the primary recovery mechanism is exhausted, the reservoirs are subjected to the injection of water and/or gas for pressure maintenance and

¹ In reservoir engineering terminology a large aquifer refers to aquifer whose volume is a thousand times or higher than the hydrocarbon volume. While recharged aquifers which are connected to surface water bodies.

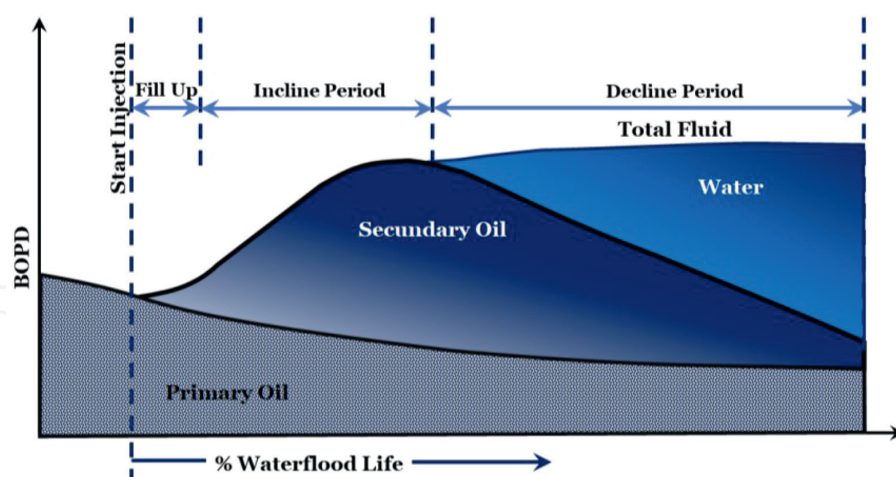


Figure 1.
Typical performance of a successful waterflooding project [5].

sometimes for displacement processes. This stage is referred to as secondary recovery and can provide additional recoveries factors between 10 and 30% over the primary recovery. Finally, some reservoirs are subjected to enhanced oil recovery processes that can be of different types: Chemical processes based on the injection of water plus specific chemicals to improve the sweep and displacement efficiency of the project, and thermal methods such as cyclic and continuous steam injection and in-situ combustion based on air injection. Other enhanced oil recovery methods include CO₂ and enriched hydrocarbon gas for injection for miscible displacement.

So far, waterflooding is the most widespread oil recovery mechanism implemented worldwide in the oil industry, due to its technical simplicity, cost-effectiveness, and the availability of the resource in most of the provinces where oil projects are developed. Most of the mature oil production development is accompanied by significant volumes of water. This condition makes the reinjection of these production waters for pressure support and displacement of hydrocarbons within the same producing horizons one of the best options, not only from the environmental side but also from the technical and economical optimization side.

Now, a water injection project for pressure maintenance and oil sweep improvement involves both surface and subsurface matters. The subsurface domain includes reservoir engineering, geology, and geophysics as well as the production technology; while the surface issues include, among other requirements, the water injection source, and the water treatment and injection infrastructure [4].

Figure 1 illustrates the performance of a successful waterflooding project. During the primary recovery stage, the oil rate declines continuously due to the pressure reduction with time, due to the fluids offtake. Once injection starts, the injected water starts restoring the pressure of the reservoir and getting the liberated gas back in solution; during this period, referred to as *Fill Up*, no incremental oil production is observed.

After the *Fill Up* period is completed, the displacement process starts acting and the effect on the well producers is observed via a ramp-up in production, whose slope and summit depend upon the homogeneity of the reservoir, the mobility ratio (M), and the amount of water injected. Finally, when the water breaks through the oil production wells, the *Water/Oil Ratio* starts climbing up and the oil

rates decline until the end of the project, when the oil rate gets to its economical limit.

Therefore, it is of vital importance to have a first conceptual approach to the characteristics of the medium and the fluids contained in order to later characterize the volumes of water, its origin, its physicochemical quality, isotopic composition, risks during handling in production or injection operations and treatment alternatives according to their composition and volume. These methodologies are commonly used in the industry, but in some cases, they are not rigorously applied or with the participation of hydrogeologists with experience in medium and deep aquifers.

1.2 Methodology

To assess and manage hydrological resources in a region, the first step is to build a conceptual hydrogeological model (CHM) that includes geological, hydrodynamic, hydraulic, geochemical, and isotopic information. In this model, analyses of the fluids, inferred flow paths, and cross-connections should be included, based on a holistic understanding of the physical and chemical framework of the geological and hydrological environment. CHM should also establish the hydrochemical characteristics, isotopic signatures, and residence times of different aquifers including, besides, the possible sources of current system recharging. This will allow the establishment of the interaction between the different water reservoirs in areas where the projects are located.

Finally, CHM should serve as the basis for mathematical flow and transport models, which allow the quantification of the water volumes involved in the processes and contribute to identifying relationships not considered that may occur between the different fluid reservoirs. However, it should be clear that these mathematical representations are only expressions of current knowledge of the system and should be continuously reviewed and improved.

Beyond the initial conceptual model, the phenomena and processes that can occur at the formation level are dominated by the characteristics of the water produced or injected and the characteristics and affinity of the producing or receiving environment that, in most cases, have the conditions of a confined aquifer. A large part of the operations carried out come from hydrocarbon reservoir engineering, which has traditionally considered water as a by-product or waste; but that more recently has assumed these waters as a source of water supply or, at least, it has advanced in water consumption reduction and minimizing environmental impacts. Regardless of the above, in the management of water associated with the production of hydrocarbons, it is mandatory to characterize the volumes to be handled, physicochemical and isotopic characteristics, and consequently select the method of treatment or disposal of these fluids, as will be explained below.

2. Aquifer and water management associated with hydrocarbon operations

Interaction of hydrocarbon exploration and production operations with water present in several subsoil formations begins during the drilling process of the surface section of the exploratory or development wells. Operations interaction tends to be

controlled and, in fact, bypassed using appropriate drilling muds, clay mud cakes (which seal the flow from the well to the formation and vice versa); cementation, and steel casings (2 or 3 concentric strings). Casing and cementation play a role of double protection (protecting formation from well fluids invasion and the well from formation fluid irruption).

However, it is the operations related to the exploitation of hydrocarbons that more intensely compromise the management of large volumes of water and the formations that contain them, either because they are used as sinks for the disposal of effluents of water produced with hydrocarbons (e.g. Disposal), or because they are a source of water for enhanced recovery processes (e.g. EOR-Reuse) or because they are reinjected into the oil-bearing formations to maintain reservoir pressure (e.g. Reuse-Reinjection).

2.1 Example of magnitudes and volumes in the management of groundwater in the hydrocarbons industry

Colombia has an average daily oil production of 750,000 barrels and associated water production of close to 13 million barrels. This 1:17 ratio tends to be stable with small variations, mainly due to certain operations that may be temporarily stalled due to reconditioning works or excessive increases in water cuts in new fields.

This water production is monitored and controlled by the National Hydrocarbons Agency (ANH), through the mandatory production daily report provided by the Oil and Gas operating companies. This way, the efficiency of the operation can be controlled, as well as the compliance with the commitments contained in the environmental license, which is linked mainly to the proper disposal of these waters and the protection of aquifers. **Figure 2** shows the historical and synchronous monitoring of these volumes through the ANH Control Center, which makes it possible to determine not only the volumes by country and region, but also by field, formation, contract, and even by well.

Petroleum companies have shown adequate behavior in the management of groundwater and actively participate in the reporting of information on the quality and quantity of water used and final disposal. This behavior responds not only to compliance with the regulations but is also part of its continuous environmental improvement programs. For example, the national hydrocarbons company (ECOPETROL), which for the date exemplified in **Figure 3** produces 60% of oil and 55% of the associated water in the country, develops continuous projects that allow increasing the reuse of production waters, thus reducing the collection of surface sources and shallow aquifers, while reducing the volumes to be injected into final disposal [7].

Under the guidance of the ministries of Mines and Energy and the Ministry of Environment and Sustainable Development, initiatives are oriented so that hydrocarbon projects that can generate large impacts on the aquifer have the pertinent information on ecosystems, health, hydrology, and hydrogeology through free access WEB portals for all audiences [8]. These measures are complemented with regulatory solutions that allow government entities with greater technical strength and thematic knowledge to regulate the use (as a source or sink) of medium and deep aquifers in the hydrocarbons industry, establishing a vertical border, to determine the regulation power, to the so-called regional hydrocarbon seal, understood them as the layer of clay that regionally seals the migration of hydrocarbons to the surface [9]. **Figure 4** illustrates the

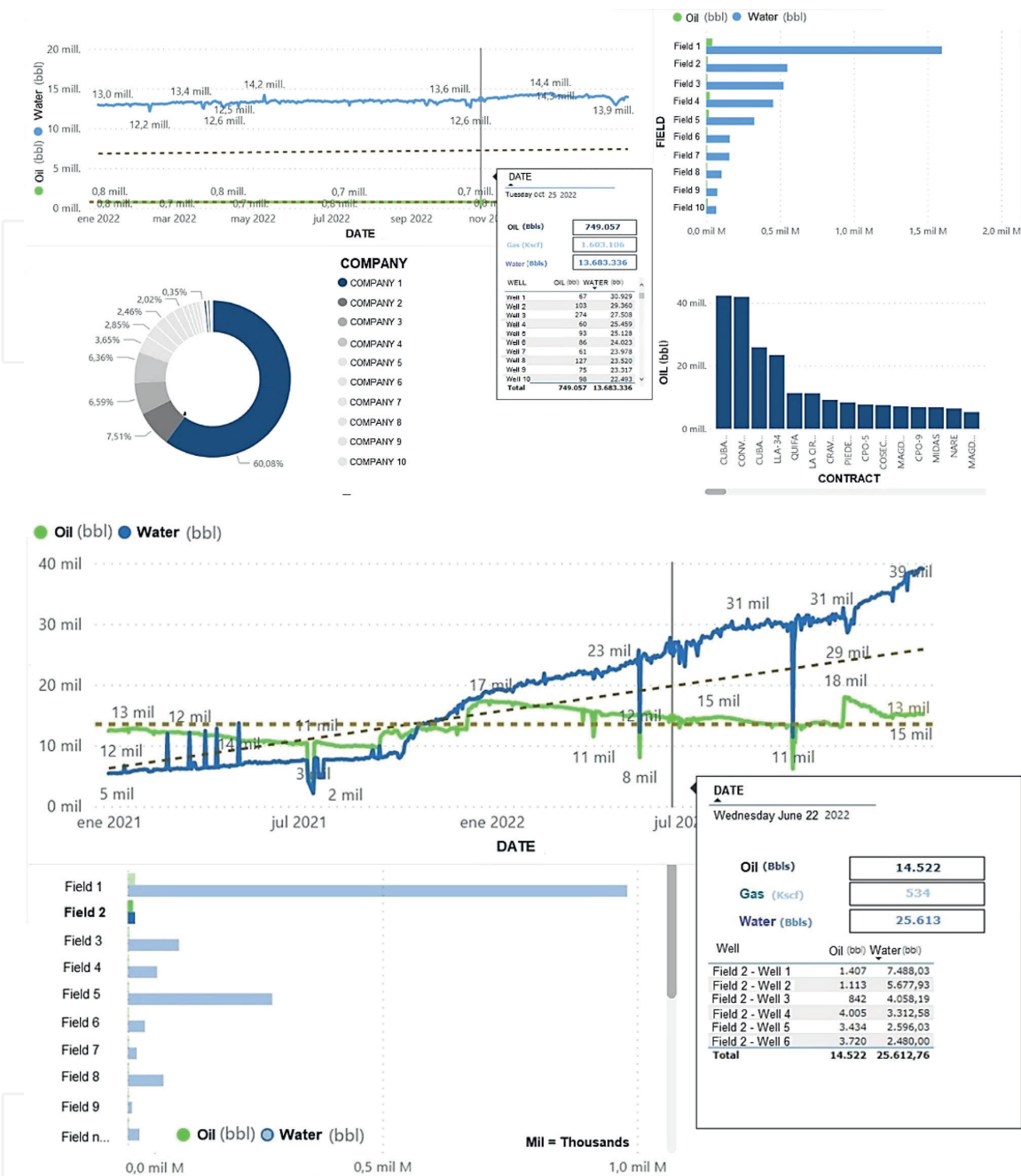


Figure 2. (Above) Typical configuration of one dashboard for monitoring the production of water associated with oil and (Below) example of the increase in water production (x8) in a specific field (Field 2) in a period of 24 months [6] (To preserve the confidentiality of the information and a better understanding, the graphs were translated and simplified using a graphic editor.).

distribution of possible contacts of the wellbore with interest formation (left), as well as components and possible geomechanical issues that could occur in a disposal or EOR project (right).

Notwithstanding the foregoing, beyond the regulations, the contingencies that may arise in these operations are largely related to the nature of the water that is managed, the physicochemical processes that may occur at the formation level, the affectations that may suffer the porous media, and the technical variables of the reinjection operation itself, as will be seen later.

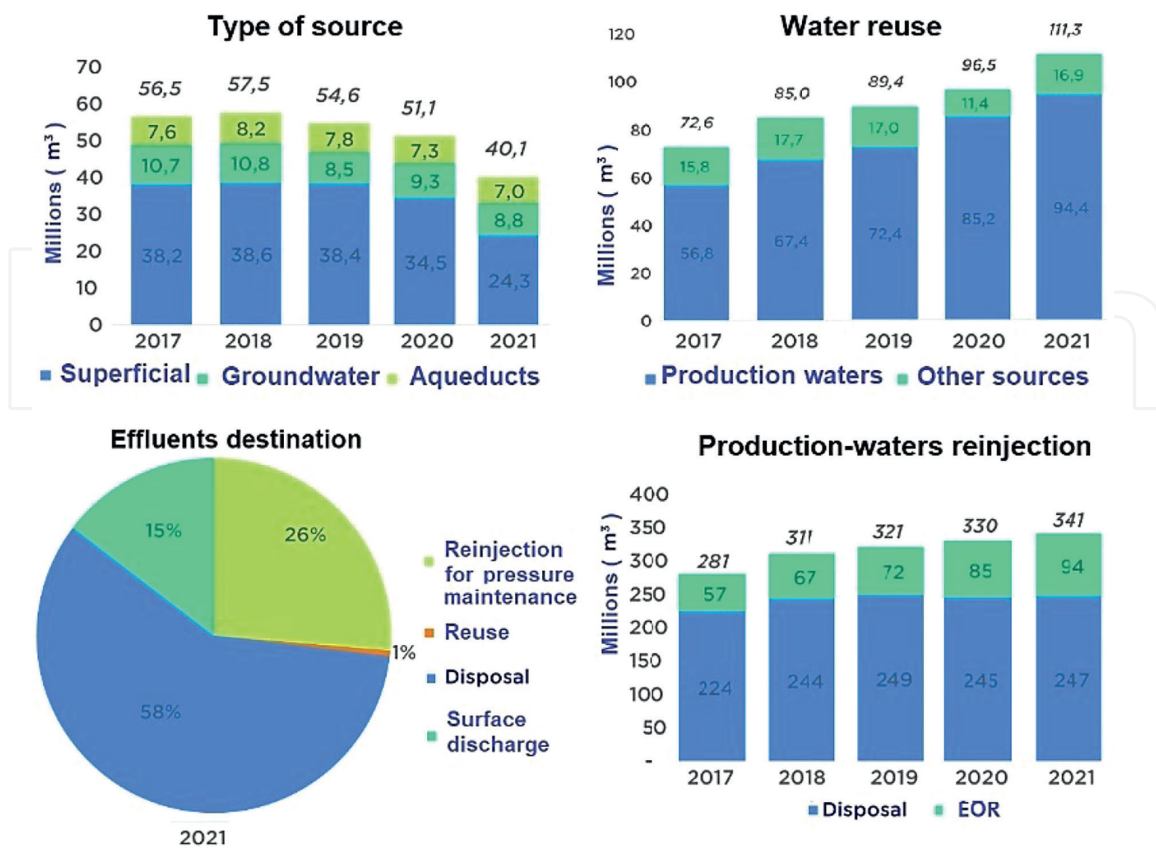


Figure 3. Achievements reported by ECOPEPETROL in the period 2017–2021 [7].

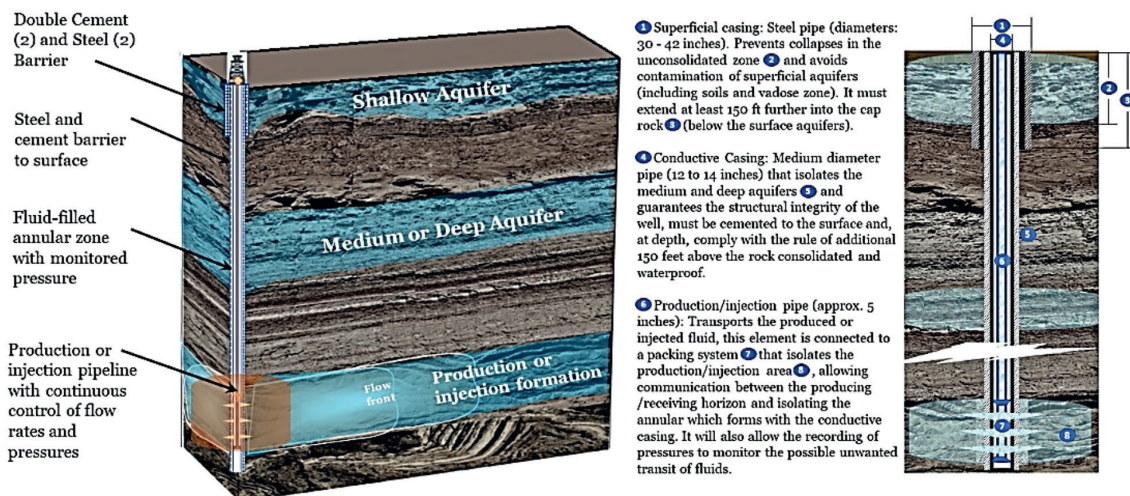


Figure 4. (Left) distribution of geomechanical elements in the wellbore, and (right) characteristics and function of this component *Vis a Vis* the saturated formations that can be intercepted [Created by authors].

2.2 Typical composition of formation waters

Formation waters composition depends on factors such as endogenous waters composition in sedimentary rocks linked to depositional environments; subsequent changes due to rock-hydrocarbon-water interaction amid sediment compaction;

changes due to rock-hydrocarbon-water interaction during migration (if it occurs) and changes due to mixing with exogenous water, including younger water such as meteoric water. Among typical components of these waters are inorganic components that are present in significant quantities ranging from the order of thousands of mg/L for sodium (Na^+) and chloride (Cl^-) ions going through the order of mg/L of ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), bromide (Br^-), sulfate (SO_4^{2-}), sulfide (S^{2-}), potassium (K^+), strontium (Sr^{2+}), carbonate (CO_3^{2-}), aluminum (Al^{3+}), iron (Fe^{2+}), barium (Ba^{2+}), lithium (Li^+), ammonia (NH_4^+) and borate (BO_3^{3-}), up to the order of thousandths of mg/L for ions such as manganese (Mn^{2+}), silicate (SiO_3^{2-}), iodide (I^-), chromium (Cr^{3+}), copper (Cu^{2+}), nickel (Ni^{2+}), lead (Pb^{2+}), fluoride (F^-), phosphate (PO_4^{3-}) and arsenate (AsO_4^{3-}). Knowledge of this composition is vital to identify and evaluate mud formulation during drilling operations and potential treatments, either for disposal or reuse. This information can also be used for well-log analysis, environmental impact assessment, and geochemical exploration.

On the other hand, organic components of formation waters can be dissolved and dispersed; they are composed mainly of aliphatic and naphthenic acids with anions and, in less concentrations, amino-acids and aliphatic, cyclic, and aromatic hydrocarbons. Determination of dissolved organic compounds in formation waters is important to study hydrocarbon-associated phenomena, such as its origin and migration or its disintegration and degradation. Further, large amounts of dissolved gases, mainly hydrocarbons are contained in formation waters; however, inorganic gases such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S), associated with corrosion processes, and nitrogen (N_2) are frequently present [10].

Other physicochemical properties like the pH and the redox potential are very important. Knowledge of pH and redox potential allows the evaluation of the possible formation of scales due to its influence on the solubility of different elements and components, and the corrosion tendency of water mainly associated with hydrogen sulfide.

2.3 Typical composition production waters

Production waters is the major by-product waste associated with hydrocarbon production and usually increases as reservoir declines in hydrocarbon production. Components of produced water can be grouped into the following categories: suspended and dissolved solids, anions, metals, radionuclides, and organic compounds. Some inorganic compounds are present in production waters in substantially higher concentrations than marine waters. These compounds include sodium, chloride, barium, iron, manganese, mercury, and zinc. High concentrations of multivalent species such as iron and manganese may also be present due to low redox potential values (anaerobic conditions) in Formation waters, which favor the predominance of reduced soluble species of these ions. When extracting production waters, these reduced ions will readily precipitate as ferric hydroxide [$\text{Fe}(\text{OH})_3$] or manganese oxide (MnO_2) due to chemical oxidation caused by contact with atmospheric oxygen. Other elements, such as zinc and probably lead, could derive in part from galvanized steel structures in contact with production waters. Less common may be radioisotopes from naturally occurring radioactive material (NORM), contained mainly in formation waters, or injected marine water. The most abundant radioisotopes are radium-226 (^{226}Ra) and radium-228 (^{228}Ra), derived from the natural decay of uranium-238 (^{238}U) and thorium-232 (^{232}Th) associated with certain reservoir rocks and clays.

Organic components in production waters can appear as dissolved or dispersed [11]. Among the dissolved organic components are saturated petroleum hydrocarbons, aliphatic or aromatic, but due to the higher solubility of aromatic compared to aliphatic of the same molecular mass, dissolved aromatic hydrocarbons predominate, mainly Benzene, Toluene, Ethylbenzene, and Xylene (BTEX), and Polycyclic Aromatic Hydrocarbons (PAHs) of lower molecular mass such as naphthalene and phenanthrene (two to three benzene rings). Other dissolved organic compounds are phenols, compounds of interest due to the toxicity of some alkylphenols as endocrine disruptors. Among the dispersed organic compounds, due to their low solubility, PAHs with a higher molecular mass (more than three benzene rings) are usually found, together with saturated aliphatic hydrocarbons.

On the other hand, aliphatic and naphthenic carboxylic acids, produced by hydrated pyrolysis or by anaerobic biodegradation of saturated aliphatic and aromatic hydrocarbons, respectively, can occur as dissolved or dispersed organic components, depending on their molecular mass (solubility). Some authors [12, 13] have proposed different intervals of inorganic and organic components in production waters, however, detailing them would exceed the scope of this chapter.

Produced water may also contain other organic components that are used for three purposes: 1) to solve specific well problems, 2) to treat produced water intended for injection or discharge, or 3) to improve hydrocarbon recovery and pumping. In the first case, organic compounds are used to: protect the system against corrosion (oxygen scavengers, corrosion inhibitors, micro-biocides), prevent scale formation (scale inhibitors), dissolve paraffin deposits (solvents) and prevent the formation of methane hydrates in the production of gas (antifreeze); in the second case it is used to remove colloids (coagulants and flocculants) and facilitate the gas-crude-water separation (solvent emulsions, defoamers); while in the third case, polymers and surfactants are used [14, 15]. The concentration of these organic compounds in the production waters will be determined mainly by the doses used, the ratio division constant between the organic (hydrocarbon) and inorganic (water) phases, and the temperature.

3. Discussion

Nowadays, most of the world's oil fields produce with *Water–Oil Ratios* (WOR) greater than 90%; for this reason, the reinjection of production waters into oil-bearing formations is the most recommended way of disposing of these enormous volumes of water.

Other disposal options are the final confinement in other aquifer formations (deep or shallow); the reuse for production operations or surface disposal through total or partial evaporation (using lagoons or forced dispersion systems); agricultural irrigation, livestock, industry, civil works, and watering roads.

For reuse purposes, the following factors should be considered: 1) production waters generation rate compared to the water demand for reuse, 2) production waters quality and treatment requirements for reuse, 3) costs of produced water reuse compared to discharge alternatives, 4) availability of infrastructure and treatment alternatives, and 5) regulatory considerations [16]. Different reuse alternatives can be considered as potential options, implementing different levels of treatment depending on the quality of the wastewater and the desired reuse requirements.

On the other hand, the disposal in aquifers should receive special attention, since it can cause groundwater contamination if the injected fluid migrates, accidentally or deliberately, into an exploitable aquifer. This could be due to poor well design or construction, deteriorated pipelines, or a poor understanding of hydrogeology. In the last case, migration of reinjection water through cracks in confinement zones under induced pressures is common [17].

Figure 5 outlines the possible management alternatives (disposal or reuse) of production waters, classifying them into raw and treated production waters. For conventional reservoirs, one of the main alternatives for the reuse of produced water is the maintenance of pressure in the reservoir. Given the growing interest in the recovery of heavy oil and tar sands from oil-bearing formations, production waters can be heated to be injected as steam [15, 18]. The disposal alternative is not applicable in unconventional reservoirs because the low porosity of the formation offers a minimum pore volume to be saturated with water [19].

For unconventional reservoirs, production water can be reused in other hydraulic fracturing operations. In these reservoirs, the main sources for the formulation of the hydraulic stimulation fluid are superficial freshwater bodies and aquifers [20, 21]. For this reason, the reuse of production waters for hydraulic stimulation is considered

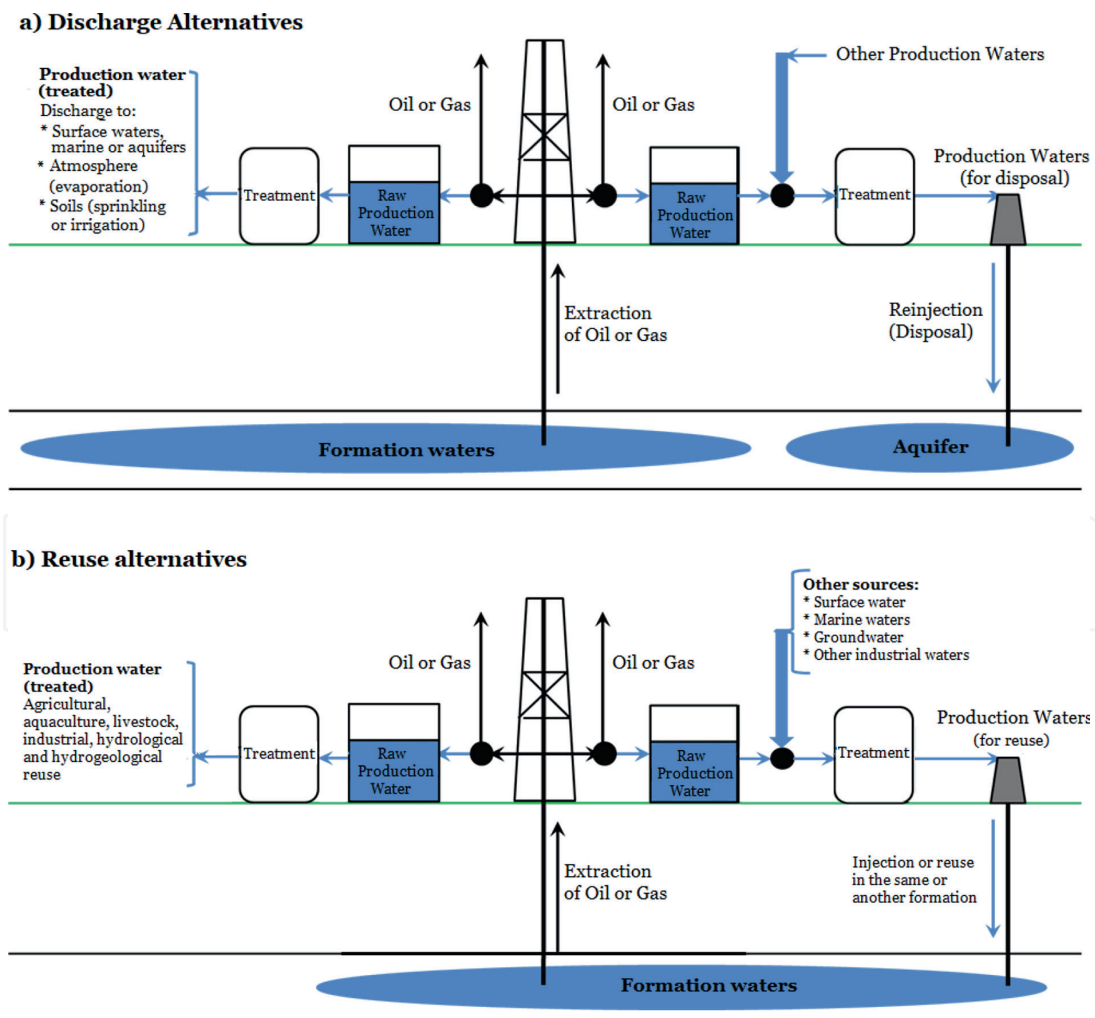


Figure 5. Origin and possible destinations of production waters for: a) discharge (as disposal) or b) reuse (mainly in pressure maintenance operations). [Created by authors].

an alternative that allows for reducing the pressure on the water resource [14, 22]. Additionally, this practice can result in economic benefits by reducing the costs associated with the acquisition and transport of water for stimulation, and transport and reinjection in injection wells [20, 23].

In pressure maintenance, enhanced recovery, or in hydraulic fracturing operations, the production waters without treatment (raw water) needs to achieve the physicochemical characteristics of compatibility with formation waters, therefore it is possible to mix them with surface, marine, underground or production waters from other wells. However, in the event of disposal, and to reach that compatibility, the only recommended mixing is with production waters from other wells.

In spite of the above considerations, there always exists the possibility of affecting negatively the aquifers surrounding the operations of reuse and disposal of hydrocarbon-associated waters. It is important to clarify that the disposal of water is done in specific formations, i.e. geological strata which have enough porosity and permeability to produce or receive fluids through wells drilled across them. The system is comprised of wells in a spatial distribution, production facilities, and other surface flows and components that form what is called an *Oil or Gas Field*.

Although the number of wells drilled in some formations can be counted by dozens or thousands, not all of them are dedicated to water injection; nevertheless, their number and integrity status could be considered as an indirect vulnerability indicator. Despite the magnitude of the number of wells drilled worldwide, just a few cases of massive or regional affectation of aquifers are reported in the literature. The reported events are mainly associated with fluids migration to shallow aquifers, loss of integrity due to seismic events, and geomechanical or structural failures in some fields.

These unwanted events can be attributed to poor or sub-standard practices in some hydrocarbon exploitation operations, which lead to loss of integrity and structural or geomechanical failures; causing the unwanted arrival of fluids to shallow aquifers used for human activities, and subsidence with the affectation of surface infrastructure. A great deal of these unwanted consequences happened because of seismic events from a different origin, as discussed below.

3.1 Issues associated to water injection for disposal

The injection in deep aquifers is a widely spread practice for the disposal of waters associated with oil or gas production. It is accepted in most of the countries where hydrocarbon exploitations take place if the regulatory restrictions are fulfilled. It can be considered a safe practice if all the technical and environmental measures are considered in the planning and execution of the disposal operations.

In this scenario, the aquifer may be confined or could be connected to recharge zones on the surface. In the cases of confined aquifers, the injection volumes are restricted due to the extremely low compressibility of the water (3×10^{-6} /psi), which is in the same order as the rock compressibility [24]. In these cases, extremely large aquifers are required for a commercial-scale disposal project. In most of the cases, where this disposal process is implemented massively, the aquifers have some sort of communication with surface water sources but with renewal times long enough to avoid the injected water coming to the surface. The main challenges faced by these projects include:

- Lack of enough injectivity in the target reservoirs where the water disposal will take place due to low permeability rock or the effect of formation damage mechanisms.

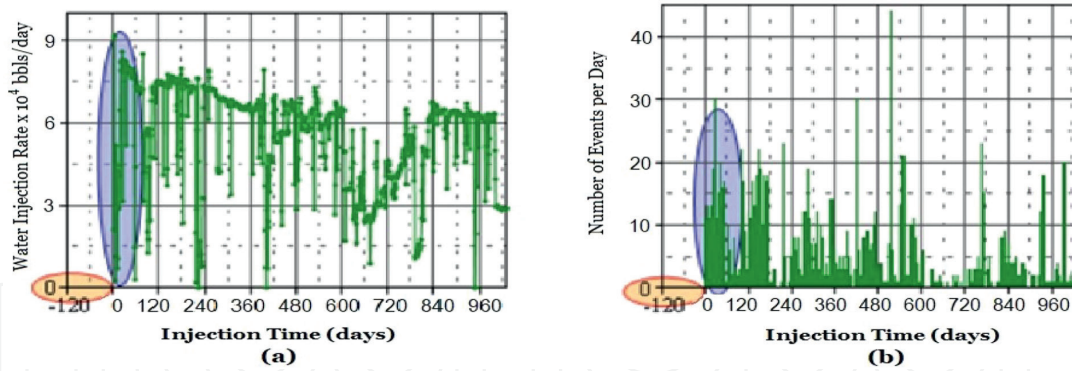


Figure 6. Correlation between water rate injection and number of microseismicity events for the Mirador formation in the Cusiana field in Colombia [25].

- Risk of contaminating shallow aquifers that could be used for human activities, due to integrity failures in wells completion.
- Chemical shock fronts are created in the cases of significant differences in salinity between the injection and in-situ waters in the target injection reservoir.
- Generation of excessive or out-of-norm micro-seismicity due to high well-head injection pressures over injection. **Figure 6** below is an example of the correlation between water rate injection and number and microseismicity events.

To overcome or mitigate the above issues, careful analysis and evaluation of the water quality and its compatibility with the reservoir fluid should be done. These studies should include physicochemical and isotopic analyses, and local and regional hydrogeology studies to understand the size and lateral extension of the target reservoirs, and its possible connection with surrounding aquifers and/or surface water bodies.

To avoid excessive induced seismicity, both the volumes and the wellhead pressures should be controlled and closely monitored, in order to prevent injecting the water very closed to or above the fracture pressure of the reservoir. For projects that inject large volumes of water, it is advisable to install local microseismicity networks to monitor this activity.

3.2 Issues associated to water injection for reuse and EOR operations

Operations that require the use of large volumes of water combined with chemical mixtures, recirculation, injection, pressure management, and effluent treatment, among many others, are not exempt from contingencies that may influence the entire project, including the receiving or producing formations, the mechanical assemblies or even the surrounding environment at different scales and compartments.

Usually, it is common to find problems associated with the loss of injectivity, corrosion of mechanical elements, induced seismicity, and regional management of aquifers, including possible alterations of neighboring formations, either due to a possible intercommunication between different aquifers or between the oil-bearing formations and aquifers or due to aquifers use as a water source for EOR processes. Also, the channeling of the fluids due to reservoir heterogeneities, unwanted fracturing of the

reservoir, and loss of containment capacity of the seal rock due to high injection pressures; may affect the technical, environmental, or financial viability of these projects.

3.2.1 Channeling and induced seismicity

One of the issues of special interest is the channeling of the fluids due to reservoir heterogeneities rendering early and fast water breakthrough at the producing wells, and generation of microseismicity events higher than allowed due to high well-head injection pressures and/or over-injection., **Figure 7**.

Higher energy-induced seismicity, derived from the injection of large volumes of waste fluids, is generated by two main causes: 1) an increase in pore fluid pressure, and 2) a change in stress state that can cause the reactivation of existing faults or fractures [26, 27]. Recent numerical models suggest that fluids travel up to hundreds of meters, while pore pressure extends to distances on the order of kilometers [28].

The occurrence of induced seismic events during residual water injection operations seems to be an inevitable process. Therefore, efforts to reduce the magnitudes of the most significant events should be aimed at replacing them with a cloud of many smaller events with equivalent total energy [29].

3.2.2 Loss of injectivity of the formation

The waters that are injected into the subsol can interact, at the pore level, with the receiving formation, blocking the flow or reducing it. The most common phenomenon, which tends to occur at this scale, is plugging by particles penetrating into the rock, caused mainly by (a) External particles carried into the formation by injected fluids, including drilling muds, used in the completion and well repair and recovery processes; (b) Particle mobilization in situ due to drag forces and rock-fluid interactions; and (c) Appearance of particles in the formation by chemical reactions that cause organic and inorganic precipitations.

From the point of view of water chemistry, these phenomena can be grouped into:

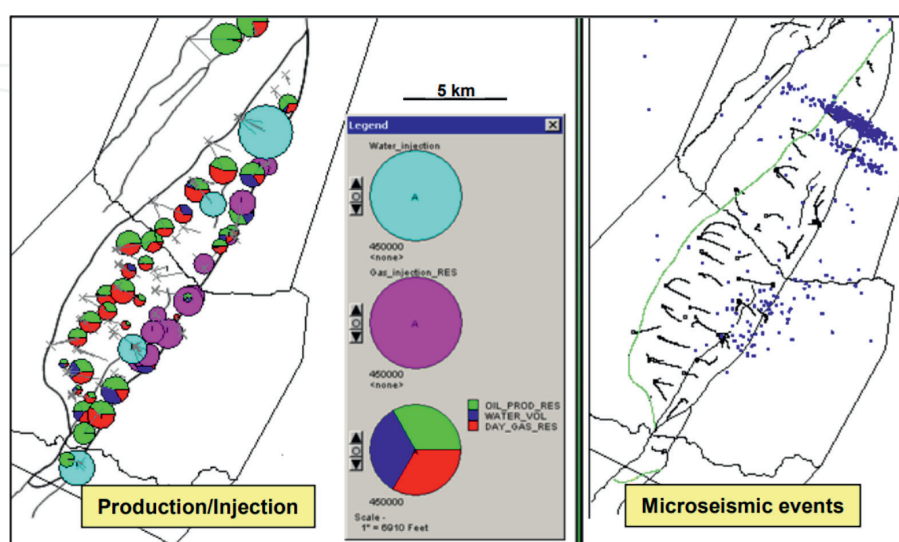


Figure 7. Correlation between water injection wells and rates to the microseismicity and density of events in the Cusiana field in Colombia. There is also a strong alignment of the events with the direction of the maximum horizontal stress (NW-SE) [25].

Formation of precipitates (flakes and scales). Scale can reduce the permeability of producing formations, clog hydrocarbon-producing wells (in primary or secondary recovery), or injection wells. These scales are produced by some of the most common ions in formation waters that generate precipitates in case the reinjection and formation waters are not compatible. The most common scales are calcium sulfate (anhydrite), calcium carbonate (calcite), strontium sulfate (celestite), barium sulfate (barite), and iron hydroxides. The appearance of these scales depends on factors such as: pH, temperature, type, and concentration of ions, the composition of the formations, and partial pressure of the gases (for example, partial pressure of carbon dioxide in the formation of calcite). A special case is dolomite, which can be produced by the reaction of magnesium present in the formation of water in contact with calcite or by the interaction between magnesium sulfate and calcite.

On the other hand, the release of divalent ions such as calcium, magnesium, strontium, and barium into solution can cause a decrease in formation permeability due to the precipitation of chemical agents present in the “enhanced” waters used in some reinjection processes (such as polymers and surfactants). The formation of these precipitates can be controlled using inhibitors.

Dispersion and hydration of clays. The clays present in the formations, especially smectites, and illites, can decrease the permeability due to their dispersion (migration) or hydration (swelling) caused by the disposition of non-compatible waters with high pH, due to the disposition of non-compatible waters with high pH, this causes an increase in the negative surface charge and the consequent increase in the electrostatic repulsion forces. Thus, for example, the exposure of a consolidated clayey sandstone to a fluid with a high pH can reduce its permeability one hundred times in a short period of time [30]. This effect can be minimized by making the pH compatible between the reinjection and formation waters.

For its part, hydration produces a decrease in permeability due to swelling caused by the adsorption of water on the surfaces and inside the clayey structures. This originates from the disposal of waters that are not compatible with low salinities. In the case of smectites, for example, water can penetrate between the layers that compose it and cause the sheets to separate and swell. This effect can be minimized by increasing the salinity of the reinjection water (usually with sodium chloride) or by preparing the reinjection water with mixtures of water from different formations.

Anhydrite hydration. Anhydrite can be present in sandstone formations as a cementing agent between the grains of sand; if this anhydrite encounters water, it can be transformed into gypsum. In contact with high salinity solutions (such as many formation waters), the anhydrite remains unchanged, but if the reinjection waters gradually decrease the salinity of the formation, the anhydrite is hydrated, transforms into gypsum and the mineral volume increases to 1.5 times.

Presence of microorganisms. Reinjection waters may contain heterotrophic and autotrophic bacteria; Examples of the latter are the genera *Crenothrix*, *Gallionella*, and *Sphaerotilus* [10], which use the oxidation of ferrous iron, to ferric iron with oxygen, as an energy source and the carbon dioxide as a carbon source.

Among the heterotrophic bacteria are bacteria of the genera *Aerobacter*, *Bacillus*, *Escherichia*, *Flavobacterium*, and *Pseudomonas*, which use oxygen oxidation of various organic compounds to carbon dioxide as a source of carbon and energy. Additionally, other microorganisms such as copepods, diatoms, and dinoflagellates are present in reinjection waters when seawater is used for pressure maintenance or enhanced recovery. All this biomass can generate pore blockage either due to its detrital nature and/or due to the production of exopolymers as a consequence of its biological activity.

Fine particle migration. Because of the processes that occur in the porous media, one of the phenomena that require the greatest attention in modern fluid injection operations for EOR or disposal is triggered, this phenomenon is known as “particle migration”, in Ref. to the movement of particles between 0.5 and 40 microns (range traditionally reported by specialized literature). The flow of these “fine” elements includes a diverse group of mineralogies that must be determined with specialized laboratory core analysis [31].

Particle flow processes can be classified into two groups: internal and external processes. The external correspond to those that occur on the face of the formation; while the internal occur in the porous medium; In turn, each group can be divided into three types of processes [32]: (i) those that occur on the pore surface (deposition and removal); (ii) in the throat of the pore (plugging and unblocking) and/or (iii) that affect the total volume of the pore, such as formation and disappearance in situ of crusts; migration, appearance and disintegration of particles, with or without chemical reactions; release of fine particles by chemical dissolution of the cement, coagulation or disintegration, among many others.

The most common phenomenon that tends to occur at this scale is plugging by particles penetrating the rock, caused mainly by external particles carried into the formation by injected fluids. As fine particles move along tortuous channels, they are eventually captured, retained, and deposited in the porous matrix, resulting in changes in porosity and permeability. **Figure 8** illustrates some of these processes.

These particles can be stabilized by applying chemicals that modify the forces that act between the particles and the rock. Particle stabilization studies are based on the design and implementation of displacement tests to evaluate the effectiveness of certain treatments to control the mobilization, dispersion, and generation of fine particles in consolidated cores and sand packs.

Corrosion of conduction tubes, liners, and lines. The wear and eventual rupture of the pipes due to corrosion can generate an increase in injectivity, not related to formation, but to the leakage of reinjection water towards layers of greater permeability such as superficial aquifers.

Electrochemical corrosion is a common phenomenon in injection and producer wells. This corrosion is generated by the presence of dissolved gases in the formation waters such as hydrogen sulfide (H_2S), carbon dioxide (CO_2), and oxygen (O_2), the latter present in the reinjection waters due to the contact of the production waters with the atmosphere during the crude oil separation processes. These gases are electron acceptors that solubilize the elemental iron (Fe) present in the steel, acting as an electron donor, and oxidizing it to ferrous iron (Fe^{2+}). Among the dissolved corrosive

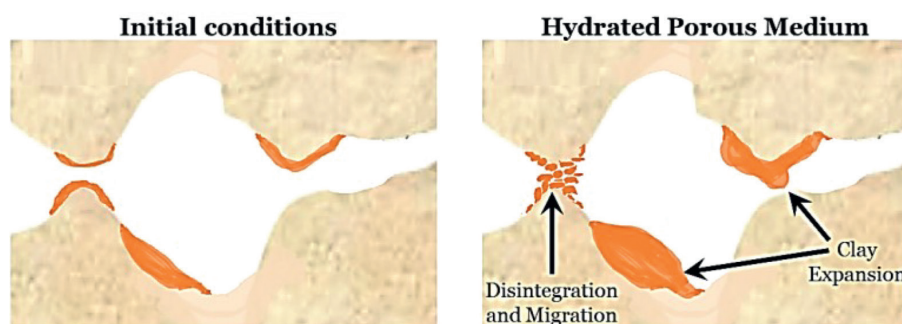


Figure 8. Illustration of some processes that can take place at the pore level and have a direct influence on injectivity. [Created by authors].

gases, oxygen has the worst consequences since concentrations as low as 1 mg/L can cause severe corrosion [10].

On the other hand, the carbon dioxide in the solution increases as the pH decreases, due to the displacement of the carbonate system, increasing the corrosivity of the water. It must also be taken into account that with the increase in pH, the formation of calcite incrustations is favored due to the displacement of the equilibrium towards the formation of carbonate ions, and ferrous carbonate may appear, which is an incrustation that, on the one hand, can obstruct the formation, but on the other, in conditions of rapid and uniform nucleation of the crystals on the metallic surface, can constitute an additional protective layer against corrosion in pipes and conduction lines.

Solution salinity (dissolved solids concentration) has adverse effects on corrosion. On the one hand, because water acts as an electrolyte (electron conductor), corrosion is favored by increased salinity. However, the increase in salinity decreases the concentration of dissolved gases, in turn reducing the corrosion caused by them. Other factors of interest that act on this phenomenon are temperature and pressure, since the increase in temperature decreases the concentration of dissolved gases, while the increase in pressure favors it.

Microbiologically mediated corrosion can also occur. For example, the presence of hydrogen sulfide in formation and reinjection waters is of biogenic origin, produced by the metabolism of sulfate-reducing bacteria (heterotrophic anaerobic) such as *Desulfovibrio desulfuricans*, which use various organic compounds as carbon and energy sources. Because of them, ferrous sulfide (triolite) can be produced, which is an incrustation that can cause the plugging of the formation. However, under proper pH conditions, it can be deposited as a protective layer on the metal surface. Another scale that can form is ferric sulfide which is produced by the reaction of ferric oxide with hydrogen sulfide.

Finally, changes in temperature, such as those that can occur in injected formation, significantly influence all equilibria, whether chemical, precipitation/dissolution, or oxidation/reduction; or physical equilibria such as hydration with anhydrite.

4. Conclusions and recommendations

Management alternatives for water produced in oil projects include dumping or reuse. In this frame, the predominant alternatives are disposal in aquifers through injection wells (reinjection water) and reuse for improved recovery in oil-bearing reservoirs, therefore, it is essential to have a list of physicochemical parameters that allow the characterization of formation and reinjection water (**Table 1**).

Likewise, it is advisable to have a physicochemical characterization of the different aquifers present prior to the start of oil production projects.

The selection of the treatment alternative for production waters will depend, among other factors, on its physicochemical characteristics and the volume of discharge or reuse, these aspects will make it possible to determine the levels of contaminant removal, which must be within the limits established in the local environmental regulations.

The physicochemical characterization of the waters intervenes in the oil project and the geological knowledge of the formation provides indications about different

	Parameter	Unit	Problem
Generals	pH	—	Scale formation, electrochemical corrosion, clay dispersion, solution compatibility.
	Temperature	°C	
	Relative density	—	Compatibility of solutions.
	Redox potential -Eh- Total Suspended Solids (TSS)	mV	Scale formation, electrochemical corrosion
	Conductivity	μS/cm	Scale formation, electrochemical corrosion, hydration of clays and anhydrites.compatibility of solutions.
	Salinity	mg/L	
	Total Dissolved Solids (TDS)	mg/L	
	Total Suspended Solids (TSS)	mg/L	Migration of fine particles
Organic matter	Total Organic Carbon (TOC)	mg/L	Growth of aerobic and anaerobic heterotrophic microorganisms
	Chemical Oxygen Demand (COD)	mgO ₂ /L	
	Total Hydrocarbons (HTP)	mg/L	
	Greases and oils	mg/L	
Cations	Aluminum (Al ³⁺)	mg/L	Scale formation
	Calcium (Ca ²⁺)	mg/L	
	Barium (Ba ²⁺)	mg/L	
	Strontium (Sr ²⁺)	mg/L	
	Magnesium (Mg ²⁺)	mg/L	
	Manganese (Mn)	mg/L	
	Iron (Fe)	mg/L	Scale formation, electrochemical corrosion, aerobic autotrophic microorganisms, microbiologically mediated corrosion.
Anions	Bicarbonate (HCO ₃ ⁻)	mg/L	Scale formation
	Carbonate (CO ₃ ⁻)	mg/L	
	Sulfate (SO ₄ ²⁻)	mg/L	Anaerobic heterotrophic microorganisms, microbiologically mediated corrosion.
	Sulfite (S ²⁻)	mg/L	Scale formation, microbiologically mediated corrosion.
Other Ions	Zinc (Zn ²⁺)	mg/L	Scale formation
	Copper (Cu ²⁺)	mg/L	
	Chromium (Cr)	mg/L	
	Nickel (Ni ²⁺)	mg/L	

	Parameter	Unit	Problem
Nutrients	Nitrate (N-NO ₃ ⁻)	mg/L	Growth of autotrophic and heterotrophic microorganisms
	Ammonia nitrogen(N-NH ₃)	mg/L	
	Orthophosphates (P-PO ₄ ³⁻)	mg/L	
Dissolved gases	Carbon dioxide (CO ₂)	mg/L	Scale formation, electrochemical corrosion, growth of aerobic autotrophic microorganisms
	Hydrogen Sulfide (H ₂ S)	mg/L	Scale formation, microbiologically mediated corrosion.
	Dissolved Oxygen (OD) (O ₂)	mg/L	Scale formation, electrochemical corrosion, growth of aerobic autotrophic and aerobic heterotrophic microorganisms

Table 1. Possible physicochemical parameters for the characterization of formation waters reuse or disposal. [Created by authors].

problems associated with water injection for reuse and EOR operations. This knowledge is also considered a starting point in preventing the risks of contamination of aquifers and soils, induced seismicity, and corrosion at the conduction lines. For a more complete characterization, it may be included a measurement of components used for the formulation of the hydraulic stimulation fluid that can cause problems in the pipelines.

Compatibility tests must be performed between the formation and the reinjection waters. These tests allow preventing future problems such as scale formations. Chemical speciation using these waters can be an initial step to determine possible affectations.

When production waters do not comply with the established maximum permissible limits of contaminants for discharge or reuse, according to local environmental regulations or operational parameters, it is necessary to select a set of processes to allow the removal of compounds to reach the water quality requirements. The removal levels will depend on the alternative use or reuse of the treated production waters. For example, for reuse in enhanced oil recovery or hydraulic fracturing, treatment requires low levels of removal of some contaminants at a relatively low cost, whereas, for reuse in crop irrigation, treatment requires high levels of removal of many contaminants, which have a high cost (Up to 7 times).

The expected results of produced water treatment processes in terms of the removal of specific contaminants vary depending on the process used. **Table 2** compiles quantitative information on the application intervals and expected removal percentages for fats and oils, suspended solids, and dissolved solids through different treatment processes.

The discharge or reuse standards, together with the characteristics of the production waters, define the processes that must be implemented to structure a treatment technology. In most applications, the main treatment needs will include one or more of the following levels: 1) remove greases and oils, 2) remove dissolved solids, 3) decrease BTEX concentrations, 4) decrease the biological oxygen demand of soluble organic compounds, 5) control elevated levels of volatile organic acids, 6) control suspended solids, 7) reduce brine volumes that require disposal, 8) control total and fecal

	Process	Application interval (mg/L)	Removal (%)
Greases & oil	Separators		
	API	500–20.000	90
	Corrugated Plate Interceptor	500–10.000	90
	Induced Gas Flotation (IGF)	500–1.000	96
	Hydrocyclone	300–500	95–99
	Centrifuge	100–10.000	93
	Filters		
	Porous media (walnut shell)	50–100	98
	Microfiltration (MF)	50–180	99
	Thermal (distillation)		
	Multi-effect	< 20	99
	Vapor compression	< 20	98
	Alternatives		
	Evaporation-crystallization	< 20	99
Total Suspended Solids (TSS)	Separators		
	API	< 1.000	50–75
	Corrugated Plate Interceptor	< 400	80
	Induced Gas Flotation (IGF)	< 200	85
	Hydrocyclone	< 200	65–80
	Centrifuge	30–300	65–80
	Filters		
	Porous media (walnut shell)	< 30	99
	Microfiltration (MF)	< 20	98
	Thermal (distillation)		
	Multi effect	< 10	100
	Vapor compression	< 10	100
	Alternatives		
	Evaporation-crystallization	< 10	100
Total Dissolved Solids (TDS)	Membranes		
	Reverse osmosis (RO)	1.000–45.000	> 99
	Electrodialysis-Reverse electrodialysis	500–40.000	99.5
	Thermal (distillation)		
	Multistage flash	5.000–50.000	> 99.9
	Multi-effect	1.500–100.000	> 99.9
	Vapor compression	1.500–200.000	> 99.9
	Membranes	500–250.000	> 99.5
	Freeze–thaw	> 5.000	> 94
	Alternatives		
	Ion exchange	< 750	95
	Capacitive deionization	500–5.000	99
	Evaporation-crystallization	300.000	> 99.9

Table 2. Application intervals and removal percentages for some parameters through different production waters treatment processes. [Created by authors].

coliforms, 9) remove constituents of special interest (e.g. boron, which restricts the final use in, for example, irrigation), and 10) adjust the rate of sodium adsorption to avoid its retention (only for irrigation or shallow aquifer recharge). In recent decades, technologies have been developed for different levels of treatment of production waters that allow discharge or reuse standards to be achieved.

Finally, in operations that handle the extraction, reinjection, treatment, and recirculation of large volumes of water through porous media of high pressure and, in some cases, high temperatures, induced seismicity and the appearance of microseismic nests are inevitable.

In these cases, it is essential to manage events through holistic knowledge of the intervened porous medium and the main parameters of the technical operation, requiring at least 1) defining and accurately mapping the proximity of the crystalline basement, the geomechanical properties, and faults in the formations subject to injection; 2) design and adjust, when necessary, the well geometric arrangement and disposal rate of fluids, and 3) monitor the accumulated volume of such fluids.

Author details

John Escobar¹, Darío Naranjo-Fernández^{1*}, Sergio Lopera²,
Orlando Mauricio Quiroz³, Alonso Ocampo⁴ and German Zarate⁵

1 University of Antioquia, Medellín, Colombia

2 National University of Colombia, Medellín, Colombia


3 National University of Mar del Plata, Mar del Plata, Argentina

4 Gastim Technologies, Bogotá, Colombia

5 National Hydrocarbons Agency, Bogotá, Colombia

*Address all correspondence to: dario.naranjo@udea.edu.co

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