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An integrated approach for produced water treatment and injection

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Abstract. During the process of the development and exploitation of oil reservoirs, a certain amount of reservoir water is produced along with hydrocarbon fluids. The volume of produced reservoir water does not remain constant over time. In the initial stages of production, relatively small amounts of water are obtained in the production. Due to a strong water drive and as time progresses the amount of produced water continuously increases. The final phase of production is often characterized by an enormous production of water, which significantly exceeds the quantity of produced oil. In highly waterflooded reservoirs, the quantity of produced water is over 90% of the total produced fluids. If well stimulations or waterflooding operations have been carried out, the properties and volume of produced water may vary even more significantly. The management of produced water is generally an expensive process, regardless of the oil price. There are usually large volumes of water to be treated, prepared and injected into the appropriate underground formations or aquifers. In this paper, the integrated approach for management of produced water will be presented, which will include constant monitoring of changes in the characteristics and volume of the produced water during the entire life cycle of the fields. Similarly, there will be a focus on the optimization of the water treatment and its disposal. Screening criteria will be presented according to the disposal formation quality and design of the water treatment system. Therefore, the decision tree will be designed according to the properties of the formation in which the treated water will be injected.

Keywords: produced water; water management; water treatment; produced water reinjection

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Introduction

Produced water is water from underground formations which is brought to surface during the oil and gas production. It is a source of many pollutants which can have negative effects on the environment. Produced water is the largest waste stream in oil and gas industry and its management presents a challenge requiring additional costs (Hagström et al., 2016). Water is present in every stage of the oilfield life cycle, from the exploration, through field development, production, and abandonment. The volume of produced water is not constant during a life cycle of the oilfield, because the water-oil ratio (WOR) increases during production (Khatib, Verbeek, 2003). The main causes of presence of produced water during the oil production are (Arnold, Burnett et al., 2004):

- Tubing, casing or packer leak,
- Channel flow behind casing,
- Raise of oil-water contact,
- High permeability layer without crossflow,
- Fractures or fissures between injectors and producers,
- Fractures or fissures from a water layer,
- Water coning or cusping,
- Poor areal sweep,
- Gravity-segregated layer,
- High permeability layer with crossflow.

Produced water is a toxic waste, and it must be properly treated and disposed according to environmental regulations. Produced water management options are (Evans, Robinson, 1999):

- Discharge to evaporation pond (deserts),
- Discharge to marine environment (offshore),
- Discharge to ground waters (onshore),
- Underground injection (underground layers, aquifers) (on/offshore).

Evaporation ponds can be used in places with high daily temperatures like deserts. For disposing into the sea or oceans, produced water must fulfill the environmental disposal standards (effluent concentration of oil in water ranges from 20-50 mg/l). Other solutions in onshore

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oilfields are injection into the underground formations or treatment of the produced water to the environmentally acceptable level, which in turn is very expensive (Evans, Robinson, 1999). Deep underground injection is safe because the treated water is far away from shallow aquifers that contain drinking and irrigation water. It is also expensive because it requires higher capacity with high injection pressures. Produced water requires appropriate technological, chemical and bacteriological processing before reinjection. It is necessary to remove all the components that adversely affect injection into underground layers. Produced water requires removal of dissolved and dispersed organic components as well as suspended solids and adjustment of the compatibility with underground waters, if needed. Since the produced water treatment and its disposal require substantial financial investment, the process of integration needs to be applied to minimize the costs of management.

The properties of produced water

Physical and chemical properties of the produced waters depend on many factors, including: geology, mineralogy, chemical reactions that have occurred during geological times, types of hydrocarbons, microorganisms, temperature and pressure (Veil et al., 2004). Produced water consists of suspended solids and different components soluble in water. These components are a mixture of organic and inorganic compounds with different levels of toxicity and biodegradability. Some of these components are naturally present in the produced water and some of them are added during the stimulations, or processing (Veil, Clark, 2011).

The major components of produced water are:

• Dissolved organic compound,
• Dispersed organic compounds,
• Dissolved minerals from formations,
• Chemicals,
• Solids (formation rock particles, corrosion, scale, bacteria, asphaltenes, waxes),
• Dissolved gases (Bretz et al., 1994).

The typical produced water properties are shown in the table 1.

Produced water properties	Quantity
Concentration of oil in water	100-3000 mg/l
Total suspended solids	2-3000 mg/l
pH	5.1-7
Specific gravity at 15°C	1.03-1.15
H_2S	0-1000 mg/l
CO_2	50-2000 mg/l
Salinity	1-300 000 mg/l

Table 1. Typical produced water properties (Daniel, Bruce, Langhus, Patel, 2005)

The amount of oil that dissolves in the produced water depends on several factors: the types of hydrocarbons, the volume of produced water, artificial lift technique and production phases (Sunde et al., 1990). Dissolved organic components in the produced water are polar components and vary between low and medium range of carbon. Pressure, temperature and pH influence the dissolvability of organic components in produced water. The dissolved organic compounds include hydrocarbons (acyclic, cyclic and polycyclic hydrocarbons with two or three benzene rings), BTEX (benzene, toluene, ethyl benzene, and xylenes), poly aromatic hydrocarbons – PAH (with two or three benzene rings), nitrogen compounds (amino acids), fatty acids, naphthenic, and humic acid, and phenols (Daniel et al., 2005).

Although produced water can dissolve many compounds, most of the oil compounds remain in the dispersed phase (Ekins et al., 2007). The dispersed organic compounds include polycyclic aromatic hydrocarbons (with more than three benzene rings) and heavy alkyl phenols. Dispersed oil is in the form of oil droplets dispersed in water phase (Stephenson, 1992). The concentration of polycyclic aromatic hydrocarbons and acrylic (alkylated) phenols are proportional to the dispersed oil content in the produced water (Faksness et al., 2004). Concentration of dispersed oil in produced water is very dangerous for the environment because the dispersed components have highly toxic and carcinogenic effects on living beings. Dispersed oil droplets cannot be effectively removed by the separation (oil/water separation) (Utvik, 1999).

The produced waters from oil and gas reservoirs are often characterized by increased mineralization. The dissolved minerals from the formation are high in concentrations and include cations, anions, heavy metals and radioactive metals (Faksness et al., 2004). Cations are Na^+, K^+, Ca^{2+}, Mg^{2+}, Ba^{2+}, Sr^{2+}, Fe^{2+} and the anions Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-. Cations and anions have a major impact on the chemical composition of the produced water, mostly on salinity and scale potential (Igunnu, Chen, 2014). The salinity of produced water varies from several mg/l to more than 300 000 mg/l. The greatest influence on salinity have Na^+ and Cl^- ions and less K^+, Ca^{2+}, Mg^{2+} (Jacobs et al., 1992). Heavy metals in produced water are present in traces and include chromium, lead, cadmium, mercury, silver, nickel, zinc and many others. Concentration of heavy metals in the produced water depends on the age of the wells and on the geological properties of the formation (Utvik, 1999). The common naturally occurring radioactive elements found in produced water is radium (^{226}Ra and ^{228}Ra), which is the main source of radioactivity, that could be indicated by barium ions.

The chemicals used during the production of oil and gas and during the produced water treatment include corrosion inhibitors, scale inhibitors, emulsion breakers, biocides, antifoam agents, coagulants, de emulsifiers, solvents, etc. (Stephenson, 1992). Chemicals may be in the form of pure components or in a solution (Hansen, Davies, 1994). The concentration of these chemicals in produced water varies from field to field, depending on the operations that were applied. The presence of these chemicals depends on their solubility in water, oil, or gas (Igunnu, Chen, 2014). When these chemicals get into the produced water they can adversely affect the separation of oil and water and increase its toxicity (Hansen, Davies, 1994).

Dissolved gases that can be present in the produced water are CO_2, H_2S and O_2. They may be present naturally or may originate due to bacterial activity or due to chemical reactions in the produced water (Igunnu, Chen, 2014). The amount of dissolved gases in the produced water depends on the pressure, temperature, degree of mineralization of water and gas composition. At lower pressures, the gas solubility decreases with increasing temperature. At higher pressures, the solubility of the gas decreases with increasing temperature, and with further increase of temperature, solubility increases (Kenneth, Stewart, 2008).

Most problems during the produced water treatment and re-injection caused by solid particles that can be found in oil and gas production, especially during production from unconsolidated formations like sands. Solid particles include small pieces of reservoir rocks, precipitates, paraffin's, scales, corrosion products, stimulation products (proppant), bacteria etc. (Hansen, Davies, 1994). Microbial activity in oil and gas reservoirs can cause corrosion of equipment, precipitation of iron sulphide and contamination of natural gas (Wang et al., 2012).

The presence of H_2S in the produced water based on chemicals, mostly from methanol which is used as a solvent. Bacteria may enter in the injection wells during the drilling and other operations on the wells as well as reinjection. If there is sufficient dissolved oxygen in the produced water, the activity of bacteria can be increased (Horacek, 1992). Reservoirs with waterflooding operations are good places for the development of colonies of sulphate / reducing bacteria that can produce H_2S (Rosnes et al., 1991).

Produced water treatment technologies

The reinjection of treated produced water is more frequently applied around the world, mainly because it is the only economic way to handle large volumes of water. Generally, with the injection of produced water in aquifer, it is possible to increase the oil recovery factor.

Produced water must be properly treated before injection in underground formations. The quality of treatment must fulfill injection criteria to prevent formation damage during water injection. The main treatment techniques include (Kenneth, Stewart, 2008):

- Gravity separation,
- Coalescence,
- Gas flotation,
- Cyclones separation,
- Filtration.

Gravity separators are usually the first devices in produced water treatment. The principle of gravity separation is described by Stokes law (Powers, 1990). The most common gravity separators are API separators and skim tanks.

The API separator is one of the most common gravity separation devices for isolating the free water from the waste stream. It can remove 60-90% of free water. During the separation process, most of the suspended particles will settle to the bottom of the separator, oil will rise to the surface and free water will be in the middle (American Petroleum Institute. Division of Refining, 1990). The performance of API separators depends on the design, retention time, inlet fluid properties, operating conditions and the effects of additives (flocculants or coagulants). They are ineffective when the oil droplets have diameters smaller than 150 microns and when they are in emulsion. As the oil droplet diameter decreases, retention time must be increased to get optimal results (Daniel et al., 2005).

Skim tanks are the simplest devices for produced water treatment, which operate on the principle of gravity separation and they are used as one of the primary devices for treatment. They are designed to enable large retention times of water, which results in a gravitational separation (Kenneth, 2007). Inlet concentration of oil in water can be between 500 and 100 000 mg/l and after treatment it decreases to 250 mg/l (Arnold, Burnett et al., 2004).

Coalescers operate on the principle of coalescence of small oil droplets in large droplets and then come to surface. They are fully closed, which eliminates the release of gases and vapors and the possibility of fire. The main types of coalescers are: parallel plate interceptors (PPI), corrugated plate interceptors (CPI) and cross-flow separators, which can be used for removal of suspended particles. In that case water flow between the plates is directed to opposite direction (upflow) that the suspended particles fall. It can be applied when the concentration of oil in water is up to 3000 mg/l. After coalescence, the concentration of oil in water is approximately 150 mg/l (Kenneth, 2007).

Gas flotation units operate on the principle of creating gas bubbles which adhere to oil droplets, and raise them to the surface where they are removed. The gases used in this process are air, nitrogen or other inert gases. The gas can be introduced into the flotation cells in two ways: using pressure or induced. Gas flotation requires additives, coagulants, polyelectrolytes and de-emulsifiers which affect the flotation efficiency (Arnold, Burnett et al., 2004). Gas flotation should be used when the concentration of oil in water ranges between 250-500 mg/l. Solid particles can also be removed by gas flotation by gas bubble attachment to solid particles, reducing their weight and raising them to the surface where they are removed.

Cyclones are devices operating on the principle of gravity separation and can separate liquids form liquids, and solid particles from liquids, on different densities basis. Depending on the design, cyclones can remove particles with diameters of 5-15 microns and suspended oil droplets with diameters up to 30 microns (Arnold, Burnett et al., 2004). Cyclones require a pumping capability of about 5 horsepower that will create sufficient pressure to operate the hydro cyclone (Bennett, 1988). With no moving parts, maintenance is not expensive.

There are two main types of hydro cyclones which are used in produced water treatment, de-oilers – to remove oil from water and de-sanders – to remove suspended solids from water. De-oilers use the centrifugal force to separate the oil from the water. Hydro cyclone rotation creates a vortex, which directs oil drops towards the vortex where they are removed (Szép, Kohlheb, 2010). Total retention time of fluid in a hydro cyclone is about 2-3 seconds. De-sanders are used in the removal of solids from liquids, which makes them very useful devices in the initial stages of elimination of particles (Bennett, 1988).

Filtration can remove the dispersed oil droplets as well as solid particles. Filter media can be: walnut shell, sand, fibers, and others. Filtration cannot remove dissolved salts and thus the effect of filtering does not affect the concentration of dissolved salts (Veil, Clarck, 2011). Sand filters are mostly used to remove metals from produced water but this requires series of pre-treatment such as pH adjustment, de-aeration and solid removal. To remove solid particles by filtration, filters with fixed or non-fixed pore structure must be used. Pressure variations in the filter can cause minor deformations or displacement of the filter media and thus potentially change the size of some pores in the medium (Bennett, 1988).

Produced water reinjection

Treatment of produced water takes special place, not only by ecological reason, but also because of being a major component of the cost of producing oil and gas. The best solution is injection of treated water in waterflooded wells, because it does not require drilling and completion which reflects on total expenses. Waterflooding has been used to maintain pressure and to improve the recovery factor of the reservoir as well as to dispose of the produced water for environmental reasons. In most cases, produced water is injected at a pressure under the fracture gradient to maintain good performance with the formation. Mechanical formation damage issues associated with fines migration may also be problematic.

The quality of the produced water is an important factor which has a high influence on this process. Produced water should not contain oxygen to avoid corrosion in the injection equipment. Solid particles can clog the pore channels and impair injectivity. Those factors can cause the damage that can limit the injection, which in turn increases the costs of injection processes (Abou-Sayed, 2005).

If the aquifers are too deep and require expensive equipment for pumping, treated produced water can be injected in shallow underground layers. It requires drilling new wells and their completion, which reflects on the total costs, and there is a possibility for pollution of fresh water sources, which is environmentally unacceptable. The large increase in pressure at the start of injection process indicates a clogging with solid particles and forming a filter cake in the near wellbore zone. Well injectivity can be improved by matrix acidizing or fracturing.

It should be mentioned, that produced water is usually treated with various types of chemicals. The precipitation of calcium carbonate is one of the biggest problems in water treatment systems, especially in high temperature and high-pressure environments where the solubility of calcium carbonate decreases with increasing temperature (Yi, Jiang, 2008). Chemicals contain carbon, nitrogen and phosphorus and can serve as substrates and/or nutrients for bacteria. As a result, the bacteria colony cans rapidly increase and cause corrosion effects. Bacteria can grow in groups and colonies, attached to the solid phase or suspended in water. Bacterial activity can cause corrosion and pore clogging. Biocides are using as additives in controlling bacteria growth (Sunde et al., 1990).

The concept of integration applied in produced water management

The main priority during the treatment of produced water should be monitoring of any changes in the properties of produced water, especially when the volume is changed. The complexity of the treatment plays a significant role in the produced water management because any significant change of the water properties must be reflected in the treatment.

The concept of integration in produced water management is based on integration of four main factors and shown in the Figure 1:

• Data,
• Tools,
• People,

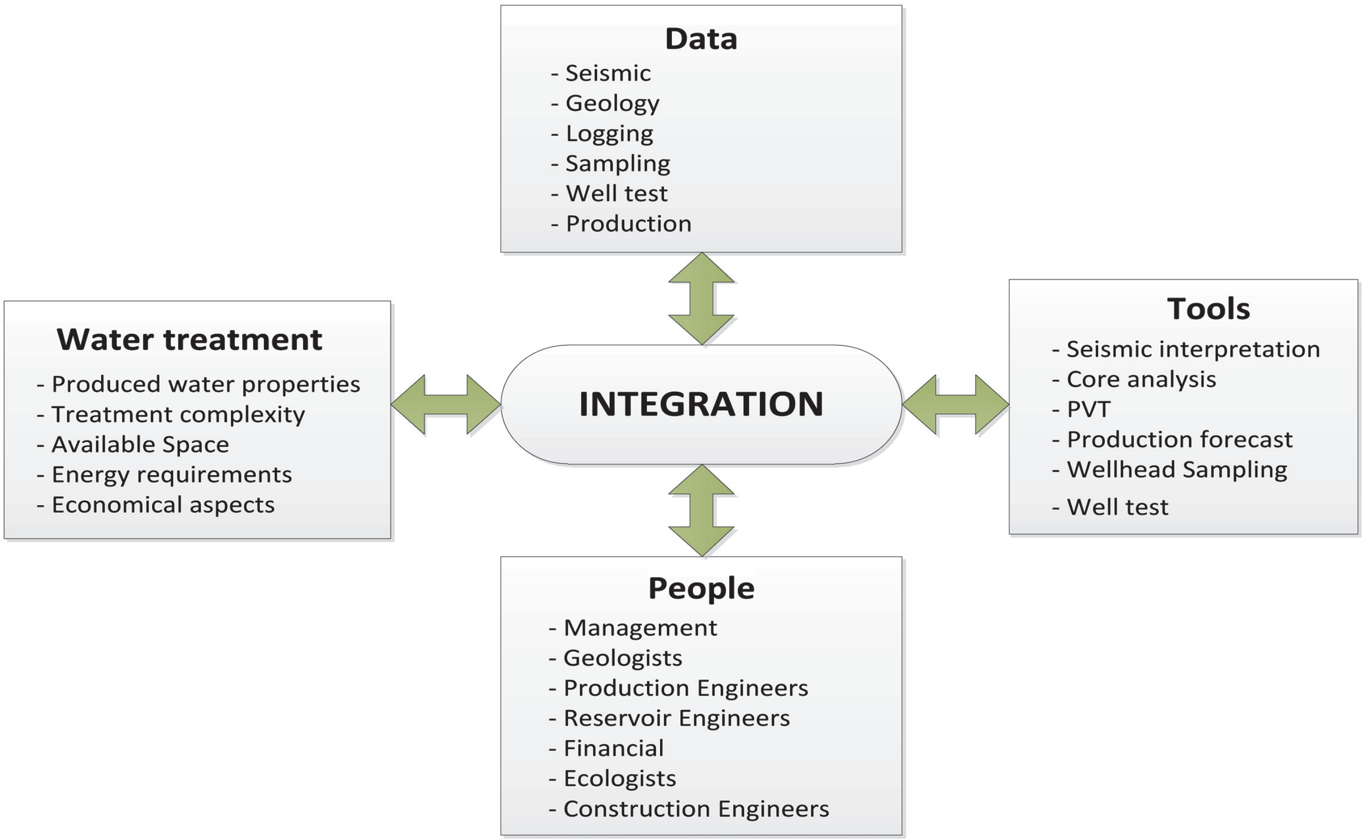

Figure 1. Integrated produced water management

• Water treatment.

Interpretation of high resolution seismic data, the presence of water zones and aquifers can be detected in the early stages of reservoir discovery. Geological data like lithology, mineralogy and depositional environment are useful in the characterization of produced water. Aquifer thickness, porosity and permeability of the aquifer, water saturation, gas-water or oil-water contacts are all useful data obtained from well logging techniques. From sample analysis, the most important parameters are chemical composition, the amount of dissolved and dispersed organic components, salinity, scaling tendency, corrosivity, the presence and the origin of suspended solids, the amount of dissolved gas in water, the density and viscosity of the produced water and its compressibility. From the well test interpretation, the most important data is the quantity of water that can be obtained in the production at various flow rates of oil or gas. During production, the quantity of water is constantly monitored by closely watching the changes in produced volumes.

The main tools used in the analysis of produced water include: seismic surveys; core sampling; PVT analysis; production analysis and forecast; surface sampling; well testing and reservoir simulation.

One of the most important aspects of the integrated produced water management is cooperation of various personnel involved in oil production. The board of directors must organize and raise cooperation between engineers of different profiles to exchange data and improve the common database. The team who needs to be involved in the produced water management should have petroleum engineers, reservoir engineers, geologists, production engineers, financial engineers, ecologists and civil engineers.

The availability of space on the field is a very important parameter and can have a significant impact on the treatment especially when choosing horizontal or vertical separating structures. The availability of energy is another factor to be taken in consideration when planning water treatments due to the amounts of energy used to complete the produced water treatments. Economic aspects must be justified by optimizing treatments to ensure that we have the lowest cost for the most optimal treatments.

The concept of integration in produced water management takes into account not only mentioned above aspects, but also less meaningful factors, such as: mixing of produced water, compatibility of water or type of underground formations.

Mixing produced water with different properties from various sources is not recommended, as it can lead to precipitations and deposition of different types of scales, such as: calcium carbonate, calcium sulphate, barium sulfate and strontium sulfate. Scales are formed in the tubing, pipes and the water treatment equipment, as result of changes in temperature and in pressure during the treatment. Damages in surface production facilities caused by scale precipitation could be very severe, causing reduction in diameter as well as clogging of pipes and other flowing surfaces. If the waters are incompatible, scale inhibitors must be added to prevent scale precipitation.

Compatibility of water can be determined experimentally or computationally. Several testing protocols exist for evaluating compatibility of water and scale tendency. The most common scales that are formed during the water treatment are Calcium Carbonate ($CaCO_3$), Calcium Sulfate ($CaSO_4$), Barium Sulfate ($BaSO_4$) and Strontium Sulphate ($SrSO_4$).

Type of underground formation for produced water injection. This factor presents the basis for the design of produced water treatments in this study. The types of formations for water injection considered in this study are:

- Naturally fractured formations characterized with large number of fractures and allow the injection of produced water with less quality;
- Highly permeable formations, characterized by high values of porosity (>25%) and permeability (>300 mD) as well as a high capacity storage of produced water;
- Medium permeable formations, characterized by medium values of porosity (12-25%) and permeability (100-300 mD);
- Low permeable formations, characterized by low values of porosity (<12%) and permeability (<100 mD).

In this section the produced water treatment screening process based on a formation quality is performed (Figure 2).

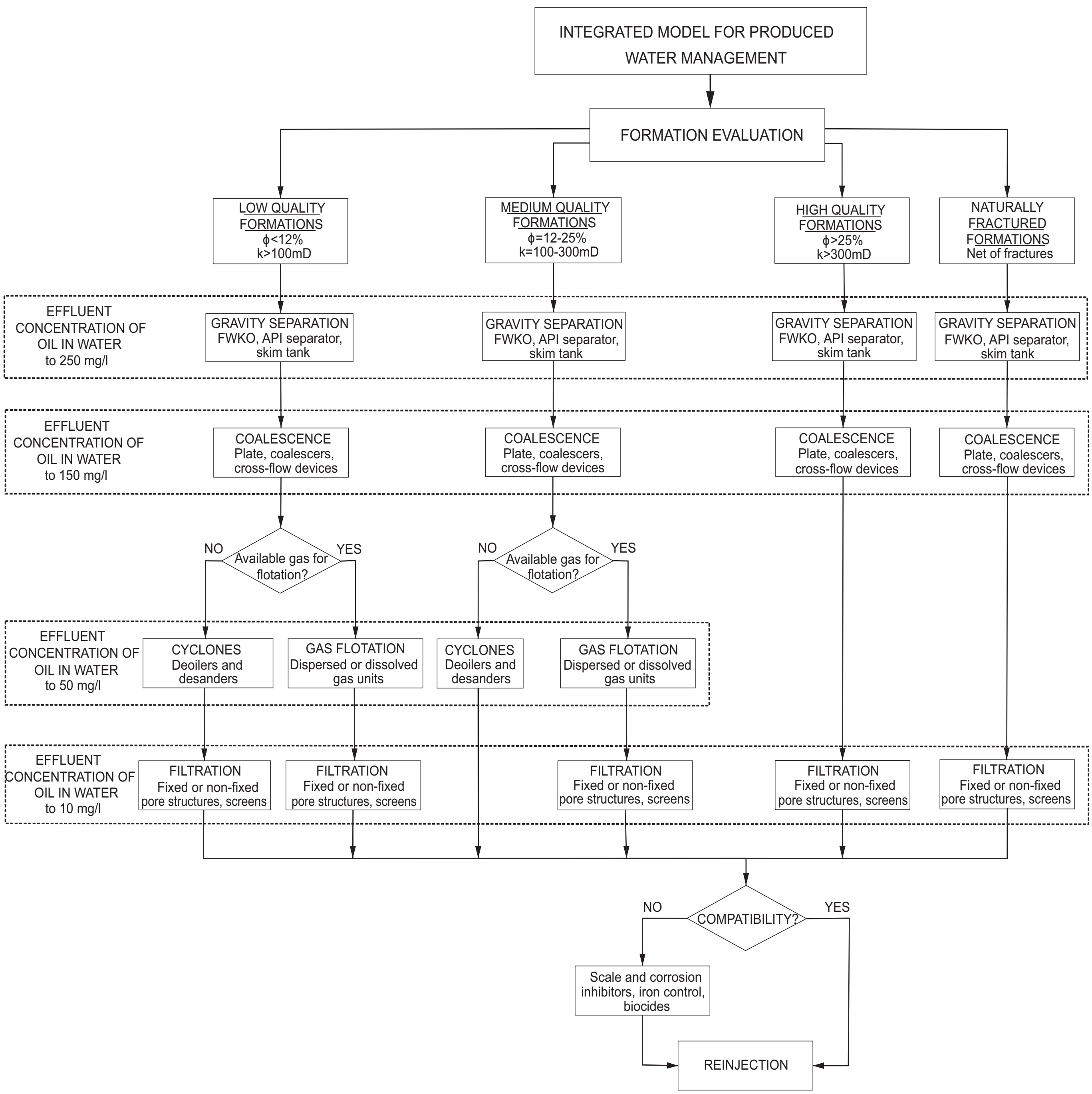

Figure 2. Flow charts for produced water treatment screening process based on a formation quality

Conclusions

Produced water management has become a major effort in the oil and gas industry. Environmental regulations about produced water treatment and disposal require more water reinjection into underground layers and aquifers. Produced water is an integral part of the production system and requires proper management to satisfy environmental regulation. The biggest problem is the injectivity decline during the reinjection processes. The main challenge is to ensure the long-term injectivity by preventing the formation impairment. This paper reviews the produced water properties, produced water treatment technologies and formations, in which the water is to be disposed. Screening criteria which suggests the proper produced water treatment process based on the quality of a different disposal formation are presented in this paper. The proposed model adapts the properties of formation to water treatment using the conventional equipment.

Proposed guidelines for water treatment are:

- Monitor the effluent oil droplets diameter; diameter must be less than the mean diameter of pore channel;
- Monitor the concentration, shape and origin of suspended solids and optimize proper filter system according to the diameter of pore channel;
- Minimize the water treatment cost by using conventional water treatment equipment;
- Monitor the scaling and corrosivity tendency;
- Monitor the compatibility of treated water with reservoir water;
- Enhance the cooperation between production and reservoir engineering departments in order to forecast produced quantities of water and plan operations accordingly.

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