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Environmental Impacts and Treatment Technologies in Hydraulic Fracturing Water Management

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INFORMATION

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ABSTRACT

This paper examines the multifaceted aspects of water management in hydraulic fracturing, focusing on both the environmental impacts and the advancements in treatment technologies. Hydraulic fracturing, a technique extensively used for extracting unconventional oil and gas resources, is notably water-intensive, leading to significant environmental concerns. The study begins with an overview of the environmental effects of fracturing, highlighting the challenges associated with large volumes of water and the potential for contamination. The review delves into various types of fracturing fluids used in the process, including slickwater fluids, gelled fluids, and linear gels, each with distinct characteristics and applications. It then explores the composition and treatment options for flowback water, which emerges post-fracturing and often contains elevated levels of pollutants. The review categorizes the treatment methods into microbial control technologies, sedimentation techniques, and electrocoagulation technologies, discussing their efficacy and limitations. The analysis emphasizes the importance of effective flowback water management to mitigate environmental impacts and improve sustainability. By examining the latest advancements in treatment technologies and their practical applications, this review provides insights into optimizing water management practices in hydraulic fracturing. The findings underline the need for continued innovation and regulatory oversight to balance resource extraction with environmental stewardship.

1. Introduction

Over the past decade, the natural gas industry in the United States—and globally—has undergone remarkable transformations. In 2005, US natural gas production hit a 20-year low of 18 TCF. By 2012, production had reached an unprecedented 24 TCF, while prices plummeted to levels not seen since the mid-1990s. This shift has been driven by the rapid growth of unconventional natural gas resources, particularly shale gas, which was once thought to be unrecoverable (U.S. Energy Information Administration, 2013).

Key technical advancements in drilling and reservoir stimulation have unlocked these shale gas resources. Modern techniques involve drilling horizontal wells and applying largescale hydraulic fracturing. The effectiveness of these technologies has led to significant increases in the estimated recoverable natural gas resources in the US. The U.S. Energy Information Administration and the Potential Gas Committee now estimate the recoverable shale gas resources to be between 800 and 1000 Tcf (23-28 Tcm), a dramatic rise from the 2003 National Petroleum Council estimate of 35 Tcf (1 Tcm).

The availability of a larger, more affordable natural gas resource in the US is reshaping the energy landscape both domestically and internationally. Within the US, the energy sector is increasingly oriented toward natural gas, particularly for power generation, which is projected to rely more heavily on gas-fired plants over the next 20-30 years. Globally, the impact of US shale gas is significant. The US has essentially exited the market for Liquefied Natural Gas (LNG) imports and is now planning to export LNG. These developments are poised to transform global gas markets and alter energy-related geopolitical dynamics, driven by the substantial influence of US shale gas.

Laalam et al. (2024) emphasize the need for accurate and reliable production forecasts to support sustainable development in unconventional reservoirs. This insight is particularly relevant to hydraulic fracturing operations, where efficient water management practices are essential for reducing environmental risks and improving operational efficiency (Laalam et al., 2024).

1.1. Environmental Effect of Fracturing

The extensive use of hydraulic fracturing technology to extract hydrocarbons from shale formations has led to several potentially harmful environmental and public health consequences. A major concern is the procurement of water for fracturing wells, which are often not located near water resources. Consequently, process water must be either piped or trucked to the well site. The increasing cost of transporting water has prompted natural gas producers to prioritize local water withdrawals. Although the volume of water used in major shale plays is relatively minor compared to the total water used in the area, the large volumes needed over short periods can compete with other local water users and create temporary stress on the water source. Rapid and concentrated water procurement can also lead to regional shortages and altered flow regimes, impacting the habitats of aquatic biota (Entrekin et al., 2011a).

The extensive water usage in hydraulic fracturing poses significant environmental challenges, including the depletion of local water resources and potential contamination of groundwater. Dehdouh et al. (2024) highlight the need for innovative drilling techniques, such as fishbone drilling, to mitigate these environmental impacts by optimizing fluid distribution and reducing overall water consumption (Dehdouh et al., 2024).

Another significant concern is the management of post-fracturing produced fluids, known as flowback water. These fluids are highly contaminated, containing high levels of salts, scaling ions, oil and grease, other organics, and naturally occurring radioactive materials (NORMs). Managing these fluids on the surface presents handling risks, including potential spillage from vehicle accidents and contamination of freshwater sources (Entrekin et al., 2011b; Vidic et al., 2013).

Moreover, understanding the complexities involved in fluid management is critical for addressing these environmental risks. The interaction between induced and natural fractures complicates the management of flowback water, potentially exacerbating the risk of environmental contamination. Properly understanding these interactions is essential for developing effective water management strategies (Mouedden et al., 2023).

Fracking activities can also impact air quality, posing health risks to nearby residents. The primary sources of air pollution from fracking include:

- Fuel emissions from trucks, which are numerous on a well pad, transporting fluids, piping, and other materials. Completing a fracturing operation on a well pad typically requires 600-1000 truck trips (NYS DEC, 2011).

- The storage of post-fracturing fluids in open pits on-site can release volatile organic compounds into the air, which can cause respiratory problems.

- Pipeline leaks can release fugitive methane, a greenhouse gas at least 20 times more potent than CO_2 over a 100-year period.

To address these environmental challenges, various steps are being taken by industry and regulatory agencies. The Environmental Protection Agency (EPA) is studying the impacts of fracturing operations on the water lifecycle, with findings expected soon to inform a regulatory framework for hydraulic fracturing. The industry is focusing on developing fracturing additives that can tolerate high salinity water, reducing freshwater demand by enabling the use of high salinity sources. Additionally, there is an increasing emphasis on recycling or reusing flowback water for subsequent fracturing processes. While this reduces freshwater demand, the extent of flowback water reuse and recycling will depend on economic and regulatory factors. Coordinated efforts between the industry and regulatory agencies are essential to ensure that fracking operations are conducted sustainably [9].

2. Glance on Frac Fluids

Optimizing fracturing fluids is crucial for successful hydraulic fracturing operations in shale reservoirs due to their complex rock properties, such as permeability, mineral structure, and total hydrocarbon content. Anderson et al. (1982) [10] identified several issues associated with fracturing fluids, including metal corrosion, gel-residue, fluid compatibility, matrix compatibility, fluid leak-off, and fluid flow back. Therefore, the design of fracturing fluids is a vital aspect of fracturing treatments. Various types of hydraulic fracturing fluids are available, including water-based fluids, oil-based fluids, foam fluids, and energized frac fluids.

Fracturing fluids, mixed with water and proppants, are pumped into the well during the operation. The success of a fracturing treatment largely depends on the properties of the fracturing fluid. Desired properties of fracturing fluids include compatibility with formation and fluids, ability to suspend and transport proppants, ease of removal from formations, low frictional pressure, field usability, cost-effectiveness, and maintaining viscosity throughout the operation (Miskimins, 2019).

Many researchers have identified problems associated with fracturing fluid chemicals. For instance, if fracturing fluid additives cause clays to swell and trigger fines migration, the fracking operation will fail. Clay control is particularly important in formations with shale permeability on the nano-Darcy scale (Alagoz and Mengen, 2024).

Additionally, fracturing fluids should not create emulsions or deposits that could clog and plug formations. Fracturing fluids or their additives can also dissolve cementing material, leading to spalling issues. Paraffin problems caused by fracturing fluids have also been highlighted in studies (Alagoz, 2020).

Moreover, the fracturing fluid must efficiently transport proppants. An ideal fracturing fluid combines high viscosity with low fluid loss, ensuring the desired fracture volume and proper proppant transport. Most of the fracturing fluid pumped into the formation should remain in the fracture. Despite high efficiency, if the fluid is not economically viable, it cannot be used. Thus, cost-effectiveness is one of the most critical selection parameters for fracturing fluids (Alagoz and Sharma, 2021).

2.1. Slickwater Fluids

Creating complex fractures in very low permeability shale reservoirs is achievable by pumping large quantities of water at high rates with small concentrations of proppant, resulting in partial proppant monolayer fractures. The renewed interest in using non-gelled water, or slickwater, as a fracturing fluid for shale gas reservoirs has highlighted the necessity for friction reducers. Since viscosity is less crucial for proppant transport under these turbulent conditions, slickwater fracturing can be more cost-effective and create better conductive fractures compared to crosslinked or foamed fluids. Friction reducers decrease friction and the associated horsepower requirements for pumping, and they also protect equipment from the wear and tear caused by high-rate operations. Although surfactants might seem like the obvious choice for friction reducers, they are ineffective in the highly turbulent regimes of high-injection-rate jobs. Instead, non-damaging viscoelastic surfactant-based systems have gained attention. For example, Teot et al. (1981) added an organic electrolyte to associate with the surfactant, incorporated low-molecular-weight polyethylene oxide into a viscoelastic surfactant system to reduce friction in turbulent flow.

2.2. Gelled Fluids

Gelled fluids are composed of water-soluble polymer compounds that increase the viscosity of the base fluid at borehole temperatures. The first water-soluble polymer used in water-based fluids was guar gum or galactomannan. Guar gum is a naturally occurring polysaccharide made up of galactose and mannose units. The mannose (M) units are connected via β-1,4-glycosidic linkages, while the galactose (G) units are bonded to mannose via α-1,4-glycosidic linkages. The M/G ratio is crucial for the polymer's solubility in water; a high ratio indicates low solubility. For example, guar derived from locust bean has a low galactose content and is sparingly soluble in water (Aqualon, 2007).

The performance of natural guar is influenced by pH, temperature, shear, and salinity. Chemically modified guar derivatives, such as hydroxypropyl guar and carboxymethyl hydroxypropyl guar (CMHPG), offer improved performance and greater chemical and thermal stability in fracturing operations. Fluids that use low molecular weight guar and its derivatives are also known as "linear gels" (Weaver et al., 2003).

2.3. Linear Gels

Linear gels are used to achieve low viscosity in hydraulic fracturing fluids. They employ guar or guar derivatives, such as hydroxypropyl guar (HPG), carboxymethyl guar (CMG), or carboxymethylhydroxypropyl guar (CMHPG), as viscosifying agents. The industry typically uses natural polymers like guar, starches, and cellulose derivatives to viscosify water. These natural polymers hydrate or swell in water, providing the base gel's viscosity. Often, the base gel offers sufficient viscosity for limited proppant transport and fluid loss control.

These polymers can be crosslinked to enhance performance, thermal stability, and reduce costs by using lower polymer loading. Guar is the most common natural polymer used as a gelling agent for fracturing applications due to its availability, cost-effectiveness, and ease of derivatization. Guar gum, also known as guaran, is derived from the ground endosperm of the seeds from Cyamopsis tetragonolobus (L.) Taub. The seeds are dehusked, milled, and screened to obtain guar gum, which is typically produced as a free-flowing, pale off-white powder, ranging from coarse to fine ground.

3. Flowback Water Characteristics and Treatment Options

3.1. Flowback Water Composition

In the days immediately following a hydraulic fracturing treatment, a substantial volume of fluid, known as "flowback water," returns to the surface, typically amounting to 10-20% of the initially injected volume. The chemical makeup of flowback water varies greatly due to water-rock interactions, the chemicals used in the fracturing fluid, and the specific timing of sampling during the flowback period. Generally, flowback water can contain elevated levels of salts, scaling ions, oil, grease, other organics, naturally occurring radioactive materials (NORM), and derivatives of the original additives. Due to the large volume and high pollutant concentration, flowback water presents significant environmental challenges in terms of management, treatment, and disposal.

A thorough understanding of the chemical and physical composition of flowback water is essential for predicting the potential environmental impacts of its mismanagement. For example, a typical chemical profile of flowback water from the Marcellus shale region is shown in Table 1 (Hayes and Severin, 2012). Analyzing the quality parameters of flowback water is challenging and necessitates insight into how different chemical interferences can affect the accuracy of standard testing and analysis methods.

Table 1. An Example of Flowback Water Specs (Hayes and Severin, 2012)

		Flow Back (mg/L)	
Parameters	**Fracture Fluid (mg/L)**	**Day 5**	**Day 14**
pH	7.2	6.6	6.2
Total alkalinity	–	138	85.2
Total suspended solids	–	99	209
Total hardness as $CaCO_3$	130	17,700	34,000
Total dissolved solids	735	67,300	120,000
Total organic carbon	226	62.8	38.7
Chemical oxygen demand (COD)	1730	4870	8530
Biochemical oxygen demand (BOD)	<2–2220	144	39.8
Oil and gas	–	6.3	ND
Calcium	–	4950	ND
Barium	–	686	ND
Strontium	–	1080	ND
Sulfate	–	–	–

For successful recycling of flowback water, it is essential that the water quality is compatible with fracturing additives.

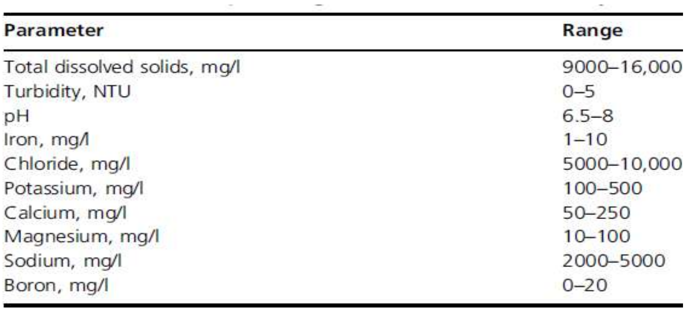
High concentrations of mineral scales, dissolved salts, and colloidal particles can render the fracture fluid ineffective by precipitating the polymeric gel and causing it to collapse (Minnich, 2011).

To remove scales before reusing flowback water, lime softening, ion exchange, and membrane filtration are commonly used. However, these processes generate potentially hazardous sludge, creating another management issue for disposal. Some companies address scales in flowback water by mixing it with sulfate-rich water, such as acid mine drainage (AMD), which causes divalent ions to rapidly combine with sulfate and precipitate. Similarly, mixing barium-rich flowback water with freshwater and using barium seeding can precipitate barite (Keister, 2013).

The salt tolerance of gelling agents and other fracturing additives has significantly improved over the years. Some fracturing treatments have successfully used saline water with total dissolved salts (TDS) as high as 270,000 ppm. The selection of a high saline-based fracture fluid formulation is tailored to the geology of the formation and the overall economics of the fracture treatment (Lebas et al., 2013).

Ideal reusable flowback water should have low levels of hardness, salinity, and suspended solids, regardless of the recycling method used. The current standard for recycled flowback water quality varies due to different fracture fluid formulations employed by operators. For example, flowback water from the Marcellus shale has high barium content, which must be removed before recycling, whereas Barnett shale flowback water has low barium levels but high dissolved organic content and suspended solids. Consequently, water quality guidelines for recycled water differ by region. A general guideline for baseline wastewater treatment system design includes maintaining dissolved solids in treated flowback water between 9,000 and 16,000 ppm and hardness levels between 125 and 625 mg/l as $CaCO_3$ (Lee and Neff, 2011).

Table 2. Target reuse water quality example (Lee and Neff, 2011)



Parameter	Range
Total dissolved solids, mg/l	9000–16,000
Turbidity, NTU	0–5
pH	6.5–8
Iron, mg/l	1–10
Chloride, mg/l	5000–10,000
Potassium, mg/l	100–500
Calcium, mg/l	50–250
Magnesium, mg/l	10–100
Sodium, mg/l	2000–5000
Boron, mg/l	0–20

3.2. Treatment of the Flowback Water

Effective management of wastewater generated during shale gas production is crucial to mitigate the associated human health and environmental risks. The treatment of hydraulic fracturing fluid involves several critical processes aimed at addressing various contaminants and pollutants. A key aspect is microbial control, which prevents the growth of harmful bacteria and microorganisms that can degrade water quality and cause biofouling in equipment. This is typically achieved through the use of biocides and other microbial control methods to inhibit or eliminate microbial activity in the wastewater.

Another important process is the removal of suspended solids, which eliminates particulate matter that can clog equipment, reduce water quality, and pose disposal challenges. Sedimentation and filtration techniques are commonly employed to settle and remove these solids. Additionally, the removal of heavy metals is essential due to the toxic nature of elements like arsenic, lead, mercury, and cadmium, which pose serious environmental and health hazards. Adsorption techniques, using materials such as activated carbon or specialized resins, and electrocoagulation methods are used to capture and separate heavy metals from the water. Desalination is also a critical component, aimed at removing dissolved salts and minerals that contribute to high salinity levels in flowback and produced water. Technologies such as reverse osmosis and distillation are utilized to desalinate the water, making it suitable for discharge or reuse. Through these comprehensive treatment processes, wastewater can be safely managed, minimizing the environmental footprint of shale gas production and safeguarding human health.

3.3. Microbial Control Technology

Bacteria can lead to reservoir souring and microbial-induced corrosion, which are significant issues in shale gas production. Source water for hydraulic fracturing often contains various microorganisms, and the polysaccharides present in fracturing fluids can act as energy sources for bacterial growth (Struchtemeyer and Elshahed, 2012). Consequently, both surface equipment and downhole pipelines are susceptible to microbial-induced corrosion.

Recent studies have identified sulfate-reducing bacteria (SRB) and acid-producing bacteria (APB) as key contributors to microbial-induced corrosion (Moore and Cripps, 2012). SRB are anaerobic bacteria known for reducing sulfate to hydrogen sulfide (H_2S) or ferrous sulfide, which can directly cause corrosion (Moore and Cripps, 2012). The activity of SRB can result in pitting, stress corrosion cracking, and blistering of carbon steel (Little et al., 2000). APB, on the other hand, produce organic or inorganic acids as metabolic by-products, which lower the local pH and exacerbate SRB-induced corrosion. These acids also serve as nutrients for SRB growth, further intensifying the corrosion process (Hubert and Voordouw, 2007).

Disinfection of hydraulic fracturing flowback fluid can be achieved using ozonation, chlorine compounds, or chemical biocides. Ozonation and chlorine dioxide are commonly employed as they can be generated on-site. Ozonators use corona discharge to convert air oxygen into ozone, with doses as low as 0.5% to 3% effective for achieving a treatment goal of 1,000 CFU/mL bacteria (Kidder et al., 2011). Additionally, ozonation helps reduce iron, manganese, and sulfide concentrations. The Ozonix system, patented by Ecosphere Technologies Inc., combines advanced oxidation processes, including ozonation, hydrodynamic and acoustic cavitation, and electrochemical oxidation (Kidder et al., 2011). This microbial control technology has been extensively utilized in China for treating fracturing flowback fluid, offering high efficiency and low cost.

3.4. Sedimentation Technology

Basic separation processes focus on removing suspended particulates and oils from wastewater. In the oil and gas industry, several conventional separation technologies have been successfully employed for many years and are also used in treating fracturing flowback fluid in shale gas production. Often, after basic separation, the produced water can be recycled, mixed with freshwater and chemicals, and used to create fracturing fluid for subsequent operations (Smith, 2013).

In many fracturing sites in China, particularly in Sichuan and Xinjiang, fracturing flowback liquid is commonly stored in holding ponds or tanks. This temporary storage method buffers the varying water quality and flow rates before further treatment, reuse, or disposal. Holding ponds effectively separate large particulates and free oils from the aqueous phase and allow for water evaporation, which reduces the volume of stored wastewater. The separation process relies on gravity, making it most effective when the densities of particles and oils are significantly different from that of water, but it requires a long retention time and occupies a large footprint.

Holding ponds are often constructed and lined to contain the flowback liquid, and mobile storage tanks may also be utilized as part of the on-site treatment system. Although holding ponds were widely used during the early development of shale gas, their use has declined due to environmental concerns. These ponds need careful inspection and maintenance to prevent overflow and leaks, which could contaminate surface and groundwater. While this technology is cost-effective and straightforward to implement, its drawbacks include the extended retention time, large footprint, and the potential risk of leakage.

3.5. Electrocoagulation Technology

In electrocoagulation (EC), sacrificial anodes corrode to release cations, typically aluminum or iron, while the cathode releases gases such as hydrogen bubbles. This technology combines electrochemistry, flotation, and coagulation to target a broad spectrum of contaminants, including suspended particles, oils, and bacteria. EC is favored for its simplicity in equipment, ease of operation and maintenance, and minimal sludge production. Importantly, no chemicals are added during the EC process. Its modular and adaptable design is particularly suited for shale gas wastewater treatment, and it can even be powered by solar panels if required. However, because the sacrificial electrodes gradually dissolve to release cations, they need to be replaced regularly. Additionally, electrode passivation—where an impermeable oxide film forms on the cathode—can reduce reactor performance. Energy costs are also a concern, and the gases generated, hydrogen and oxygen, pose flammability and explosion risks.

Several commercial electrocoagulation systems are available for treating produced water. For example, Halliburton's mobile Clean Wave system, powered by a diesel generator and housed in two containers, has a throughput of 57 m^3/hr. This system can treat water with total dissolved solids (TDS) ranging from 10 to 300,000 mg/L. It is reported to achieve 95- 99% removal of total petroleum hydrocarbons, total suspended solids, and total iron and heavy metals, while also coagulating particles larger than 1 µm. Additionally, it reduces water turbidity to less than 10 NTU and can break emulsions, with an expected average sludge generation of less than 5% (Lebas et al., 2013).

A recent field test of an electrocoagulation system in the Brushy Canyon formation, New Mexico, demonstrated its effectiveness in treating flowback water with a TDS of 267,588 ppm. The system removed over 99% of total suspended solids and iron, 18.28% of boron, 27.58% of magnesium, and 8.39% of strontium, though it did not affect the TDS levels. The treated water was then mixed with various additives to form a gel fracturing fluid used in fracturing seven wells across 97 stages. Despite its "green" credentials, due to the absence of chemical additives and ease of maintenance, electrocoagulation faces challenges such as high energy costs and safety issues related to gas generation.

4. Conclusion

In conclusion, the advancements in hydraulic fracturing have significantly boosted the production of unconventional oil and gas resources, yet they bring substantial environmental and operational challenges. The intensive water use associated with modern hydraulic fracturing, coupled with the high volumes and variable composition of flowback water, poses serious concerns. Effective management of flowback water is crucial to mitigate its environmental impacts, especially given the risks of releasing inadequately treated wastewater and the variability in its chemical profile due to geological and operational factors.

The integration of technological and regulatory frameworks for managing flowback water is essential to address these challenges. Advances in multilateral drilling and well refracturing amplify the need for a comprehensive flowback management strategy that considers the temporal and spatial variations in fluid composition and quantity, the economics of treatment technologies, and the sustainability of local water resources. Implementing a holistic approach through system dynamics can offer a tailored strategy that balances the diverse interests of stakeholders, ensuring responsible shale gas development while securing long-term water and energy resources. The emphasis on developing robust, adaptable management practices will be key to addressing the environmental and logistical challenges associated with hydraulic fracturing.

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