

# Produced Water Sustainability in Oil and Gas Sector

Subjects: [Engineering](#), [Petroleum](#)

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Oilfield produced water (PW) is the industry's principal source of waste byproducts. Oil-producing countries, especially those with limited water resources, face significant difficulty in treating PW for recovery and reuse. Depending on its quality and content, PW can be treated using a variety of technologies. Numerous nations are currently undertaking substantial endeavors to ascertain efficacious and cost-effective treatment methodologies in order to rehabilitate their freshwater supplies. The compositions of pollutants play a major role in the selection of acceptable methods. According to the degree of contamination and the requirement for water quality, several treatment strategies can, therefore, be used. To successfully remove pollutants and/or lessen their detrimental effects on the environment, methods comprising physical, chemical, biological, and membrane treatments have been applied.

produced water

organic and inorganic components

physicochemical characteristics

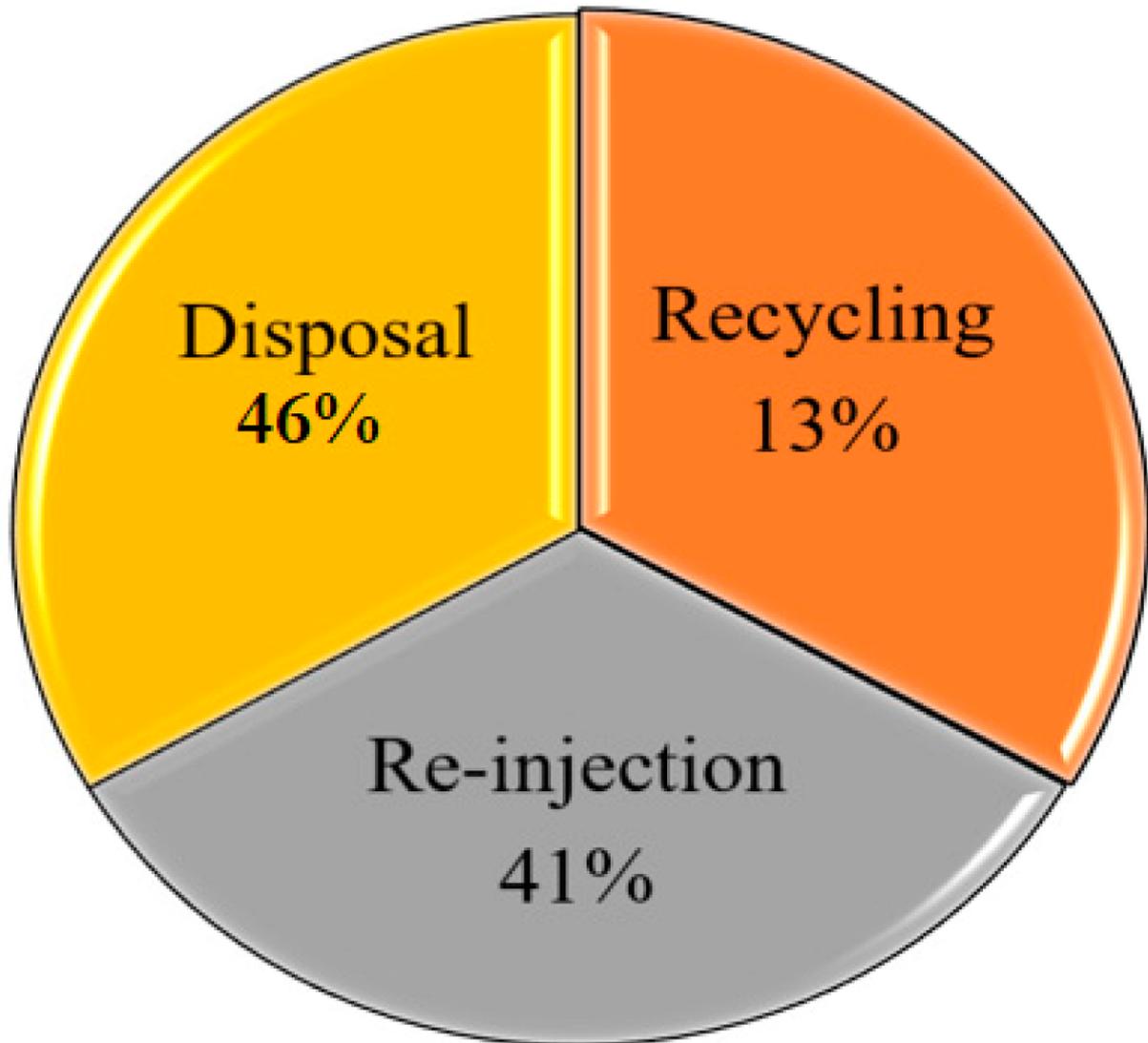
hybrid treatment

## 1. Overview of Produced Water in Oil and Gas Industry

The extraction of oil and gas supplies from shale has become feasible due to the use of horizontal drilling and hydraulic fracturing techniques <sup>[1][2]</sup>. Hydraulic fracturing is the most popular technique for recovering unconventional gas and tight oil from shale <sup>[3]</sup>. However, the exploration and production of oil and gas generates a significant amount of solid, liquid, and gas waste, with liquid waste comprising the majority <sup>[4]</sup>. Water is the main liquid effluent from oil and gas exploration activities <sup>[5]</sup>.

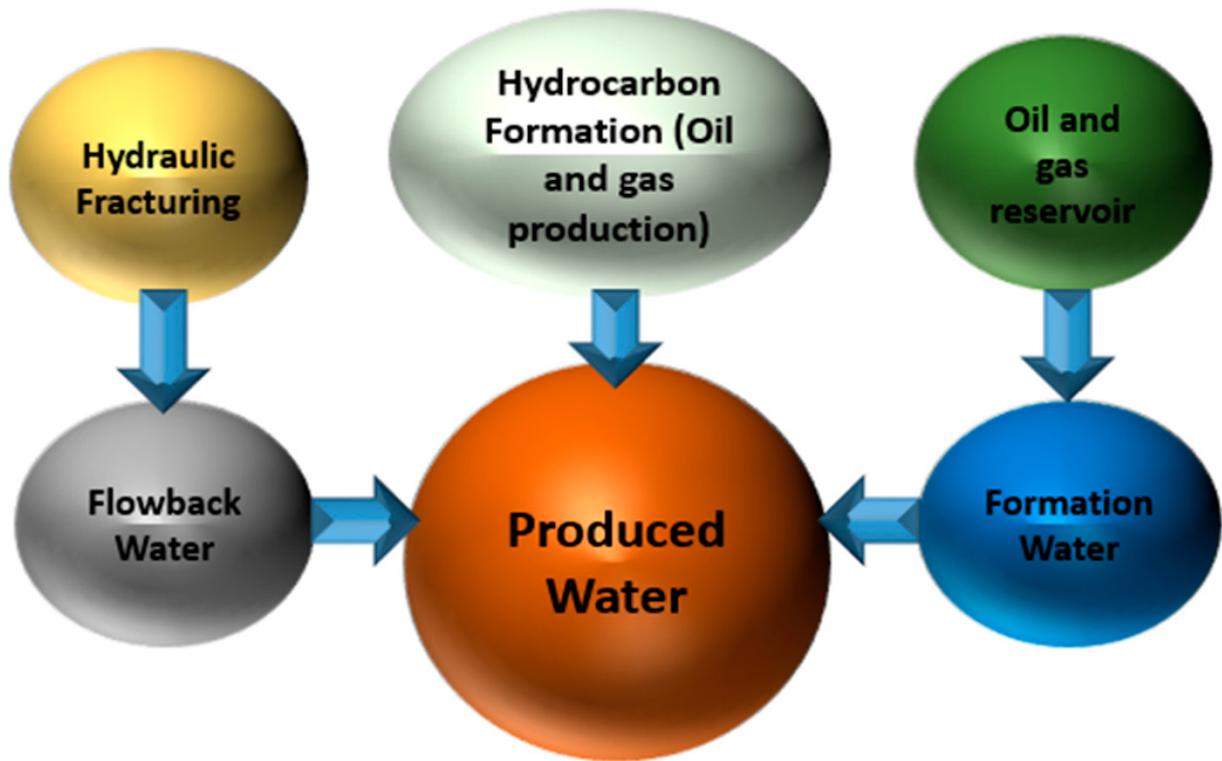
Produced water, which is composed of various organic and inorganic materials, has gained attention due to its impact on the environment <sup>[6][7][8]</sup>. The water footprint of oil and gas production, particularly in unconventional gas and tight oil recovery, has also been a focus of recent research <sup>[9][10]</sup>. The management of flowback and produced water (FPW) from shale oil and gas (SOG) exploration is a critical issue for both economic and environmental reasons <sup>[1][11]</sup>. Different techniques are used to manage extracted water, including disposal, reinjection, and recycling.

Currently, disposal accounts for 46% of produced water in the United States, followed by reinjection at 41% and recycling at 13% (**Figure 1**). However, with the expected increase in the water-to-oil ratio for crude oil resources by 2025, the market for purifying and utilizing produced water is likely to expand significantly <sup>[12][13]</sup>. The water-to-oil ratio is expected to increase by 2025, leading to a growing market for purifying and utilizing produced water <sup>[14]</sup>.



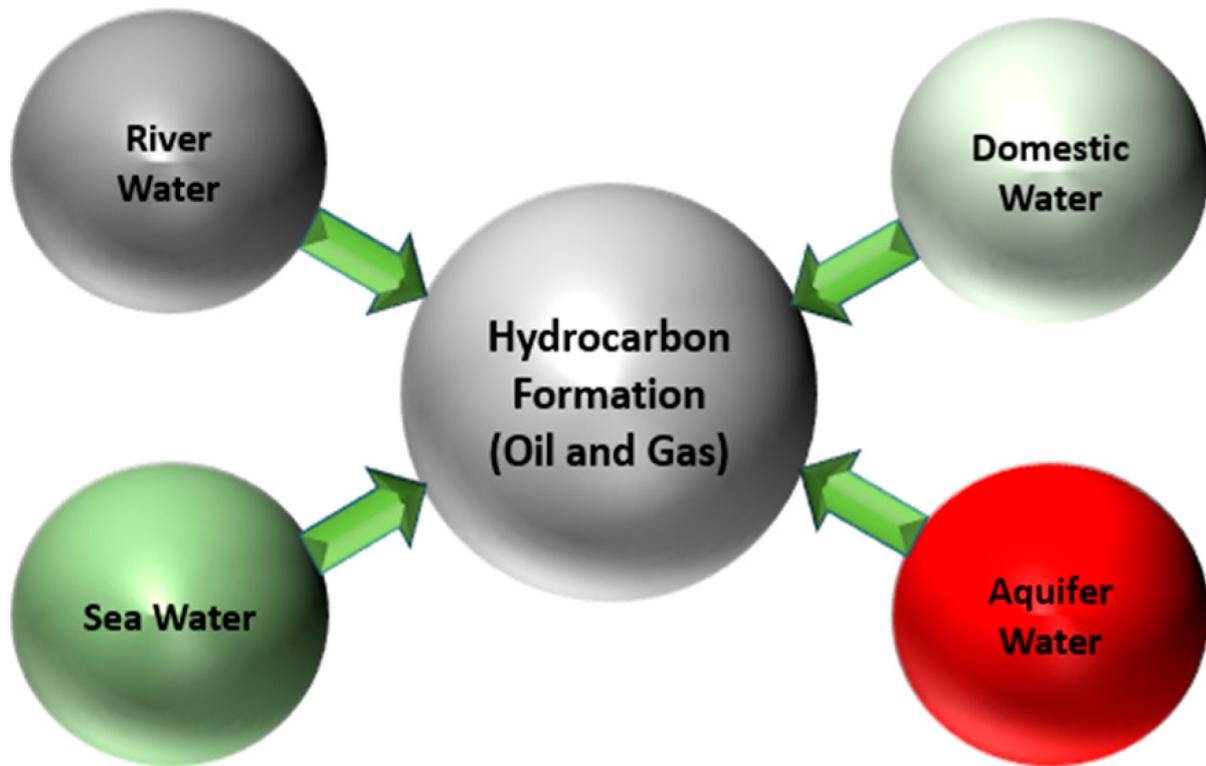
**Figure 1.** Produced water scenarios in oil and gas industry (data from [\[12\]](#)[\[13\]](#)).

Produced water in the gas industry is a combination of condensed and formation water, as water injection is not used [\[15\]](#). Compared to oilfields, produced water from gas fields is more acidic and volatile [\[15\]](#). The onshore oil and gas industry disposes of produced water through the subsurface, while the offshore industry directly dumps it into the aquatic environment, causing harm to marine ecology [\[15\]](#). The composition of produced water is influenced by geological and geographical factors of the reservoir and the type of hydrocarbon formation [\[15\]](#). In shale oil and gas production, produced water includes flowback water and formation water [\[1\]](#). The flowback water rate during well extraction initially increases and then decreases over time. **Figure 2** shows the main sources of produced water, such as reservoir formation water, flowback water, and conventional and unconventional oil and gas production.



**Figure 2.** Different sources of produced water.

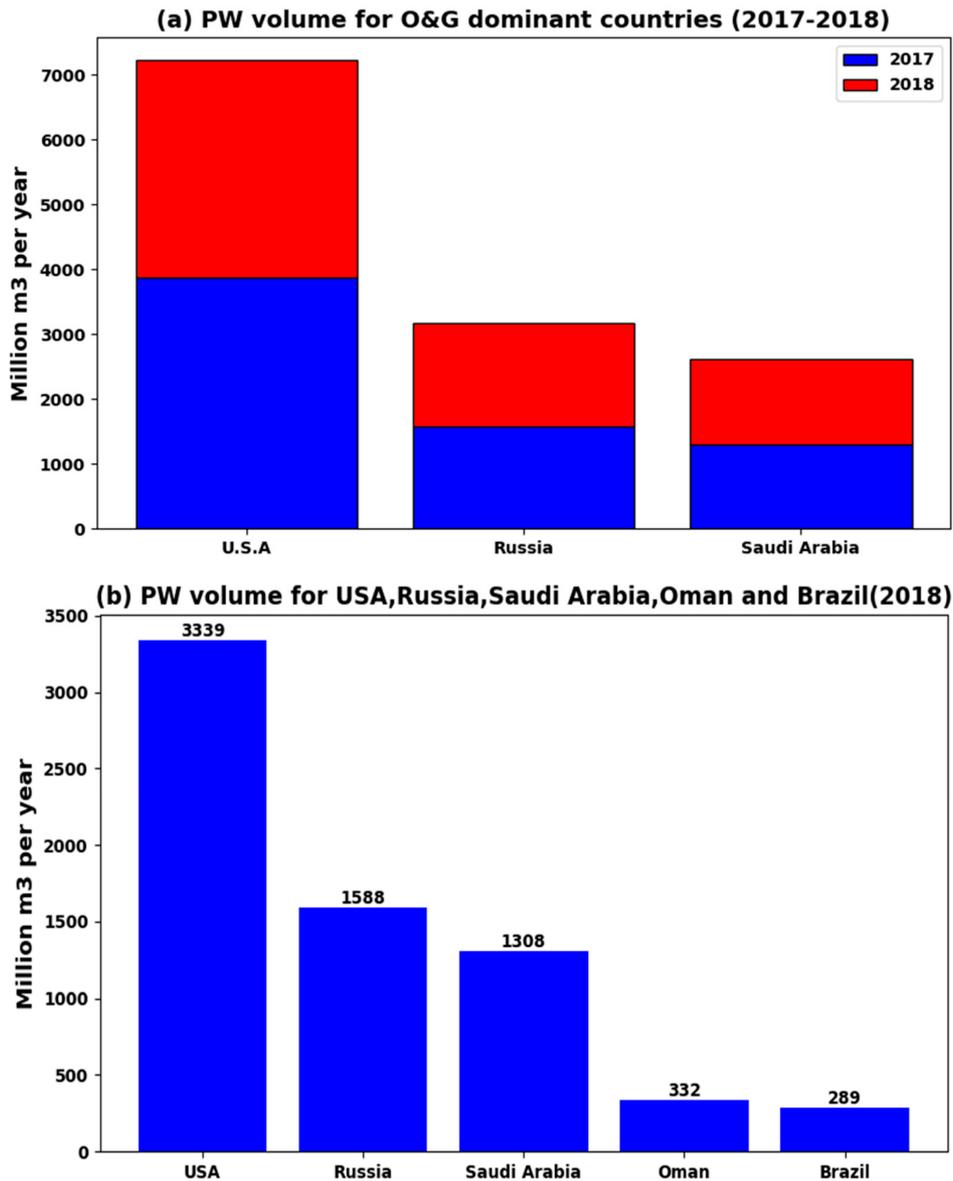
The volume of produced water from oil or natural gas production varies based on location and extraction method [16][17][18][19]. Produced water contains radioactive elements, salts, metals, and hydrocarbons [16][17][18][19]. The physical and chemical qualities of produced water also vary based on geographic location, geologic formation, and type of hydrocarbon product [20][21]. Reservoir fluid, in addition to oil, gas, and water, contains other components. When reservoir fluids are separated during the oil production process, the pressure drop leads to the formation of carbonate ions and the release of carbon dioxide. If the produced water is discharged into the sea or other bodies of water, it can contain dissolved hydrocarbons, heavy metals, CO<sub>2</sub> gas, residual oil, and water-soluble compounds, making it harmful to the environment. Water treatment is necessary to mitigate these effects [22]. **Figure 3** illustrates the water sources used in oil and gas exploration.



**Figure 3.** Water injection sources for hydrocarbon formation.

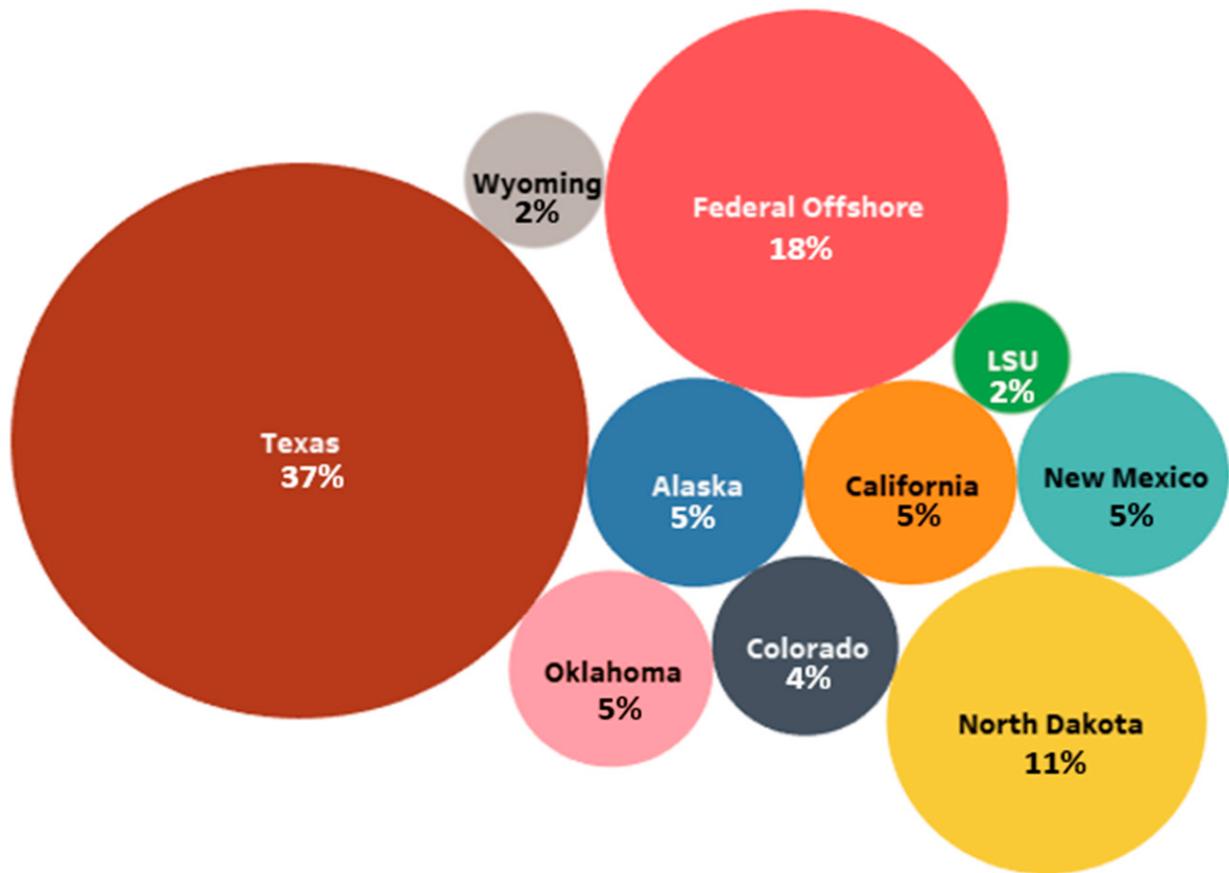
The United States, Russia, and Saudi Arabia are the world's three largest producers in terms of crude oil output. The United States has nearly one million wells that produce approximately 3.8 billion cubic meters of produced water annually [23][24][25][26]. Russia's annual oil equivalent production of 285 million metric tons results in a production of 1.5 billion cubic meters of produced water [26][27].

According to **Figure 4a**, the volume of produced water generated in 2017 and 2018 by the United States, Russia, and Saudi Arabia, the three largest oil and gas-producing nations, is compared. Additionally, **Figure 4b** includes data from Brazil and Oman, allowing for a comparison of their 2018 output as well.



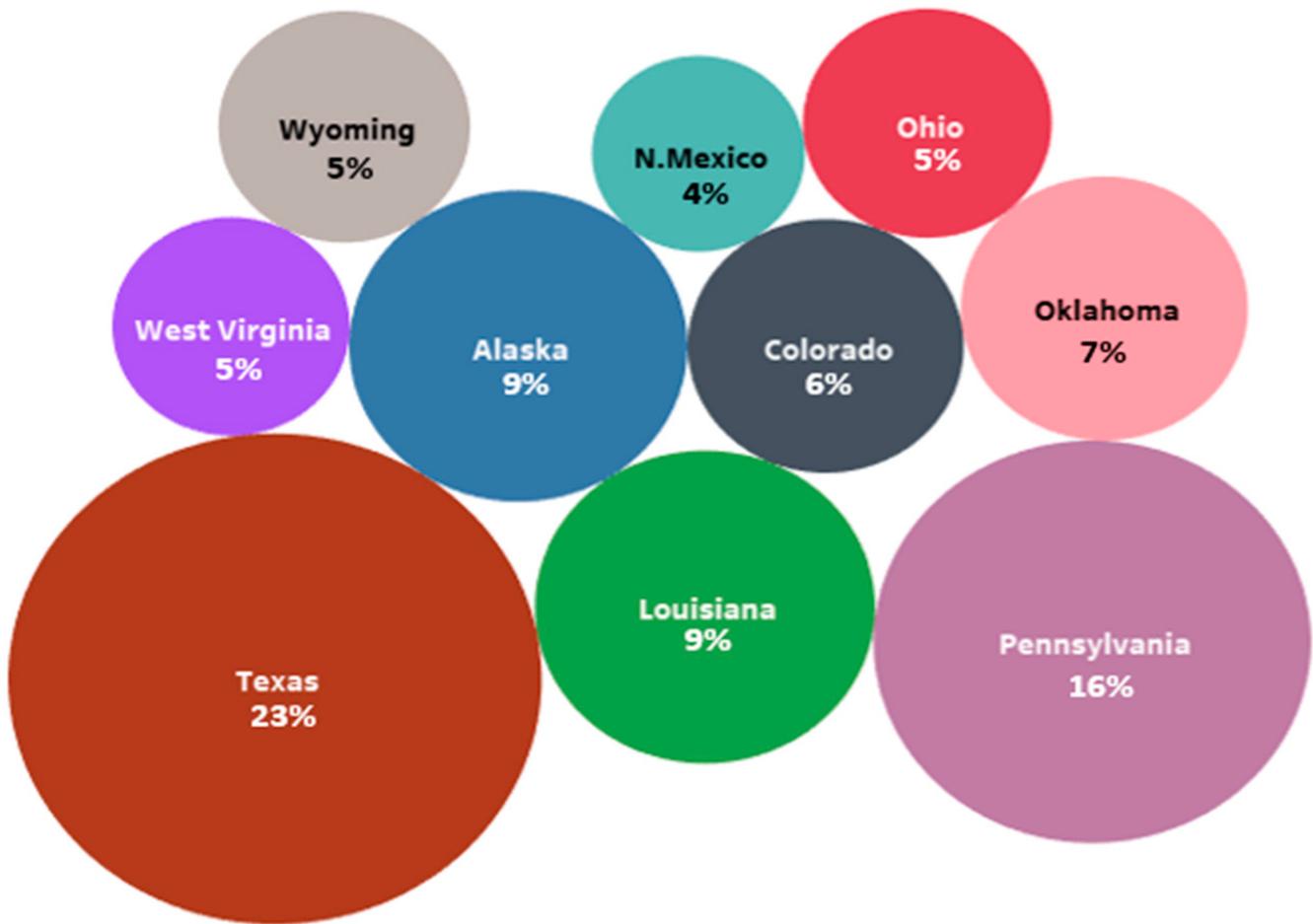
**Figure 4.** (a) PW volume for dominant oil- and gas-producing countries (USA, Russia, and Saudi Arabia) for 2017 and 2018; (b) PW volume for USA, Russia, Saudi Arabia, Oman, and Brazil in 2018 (data from [\[25\]](#)[\[26\]](#)[\[27\]](#)[\[28\]](#)[\[29\]](#)[\[30\]](#)[\[31\]](#)[\[32\]](#)).

From 2012 to 2017, oil production in the US increased by 50.4% to 3.4 billion barrels per day, a 94% increase from 2007–2017 (**Figure 5**). Texas was the leading producer, accounting for 37% of hydrocarbon production. The federal offshore enterprise was the second largest hydrocarbon producer. North Dakota produced 11% of crude oil in 2017. Alaska, New Mexico, California, Oklahoma, Colorado, Wyoming, and Louisiana were among the top ten oil-producing states in 2017 [\[25\]](#).



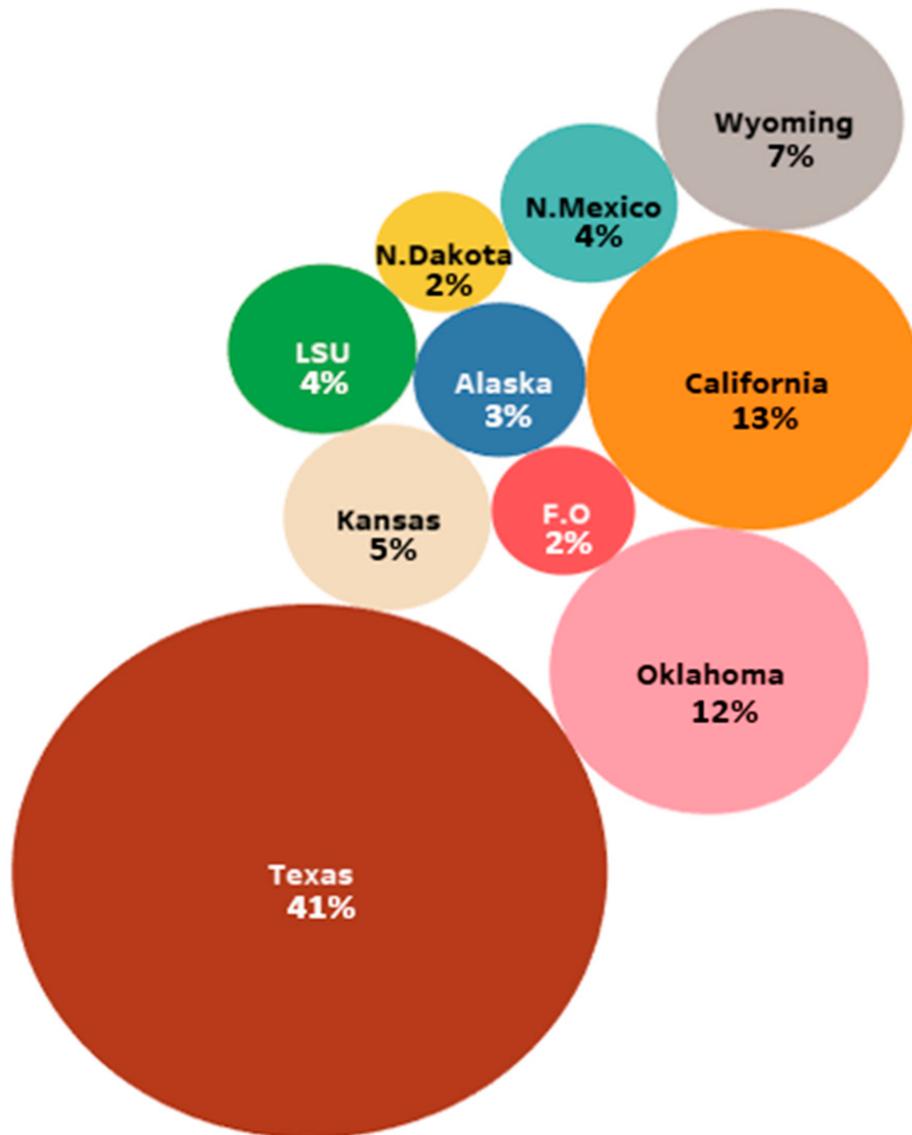
**Figure 5.** Top ten oil-producing states in the US. (data from [\[25\]](#)).

According to **Figure 6**, Texas was the leading producer of natural gas in the United States in 2017, accounting for 23.0% of the total output. Pennsylvania followed in second place with a proportion of approximately 16%. Louisiana and Alaska both contributed 9% each, while Oklahoma and Colorado contributed 7% and 6%, respectively. New Mexico produced more natural gas than Wyoming, Ohio, and West Virginia combined, with a 5% share compared to their combined 4%. According to John Veil's report in 2020, gas production in the United States experienced a significant increase of 17.7% from 2012 to 2017, reaching a total of 35 billion Mmcf [\[25\]](#).



**Figure 6.** Top ten gas-producing states in the US (data from [\[25\]](#)).

In 2017, 24.4 billion barrels of water were produced from oil and gas production, equivalent to one trillion gallons of water annually. This represents a 15.2% increase from 2012 and a 16.2% increase from 2007 to 2017 as shown in **Figure 7**. The top ten states in the US in terms of generated water production in 2017 include Texas, which contributed to the highest discharge (41% in 2017), followed by California and Oklahoma, North Dakota, Wyoming, Kansas, Louisiana, New Mexico, Alaska, and the federal offshore. The volume of produced water has increased by 16.2% in the past decade [\[25\]](#).



**Figure 7.** Top ten states in the US regarding produced water production (data from [\[25\]](#)).

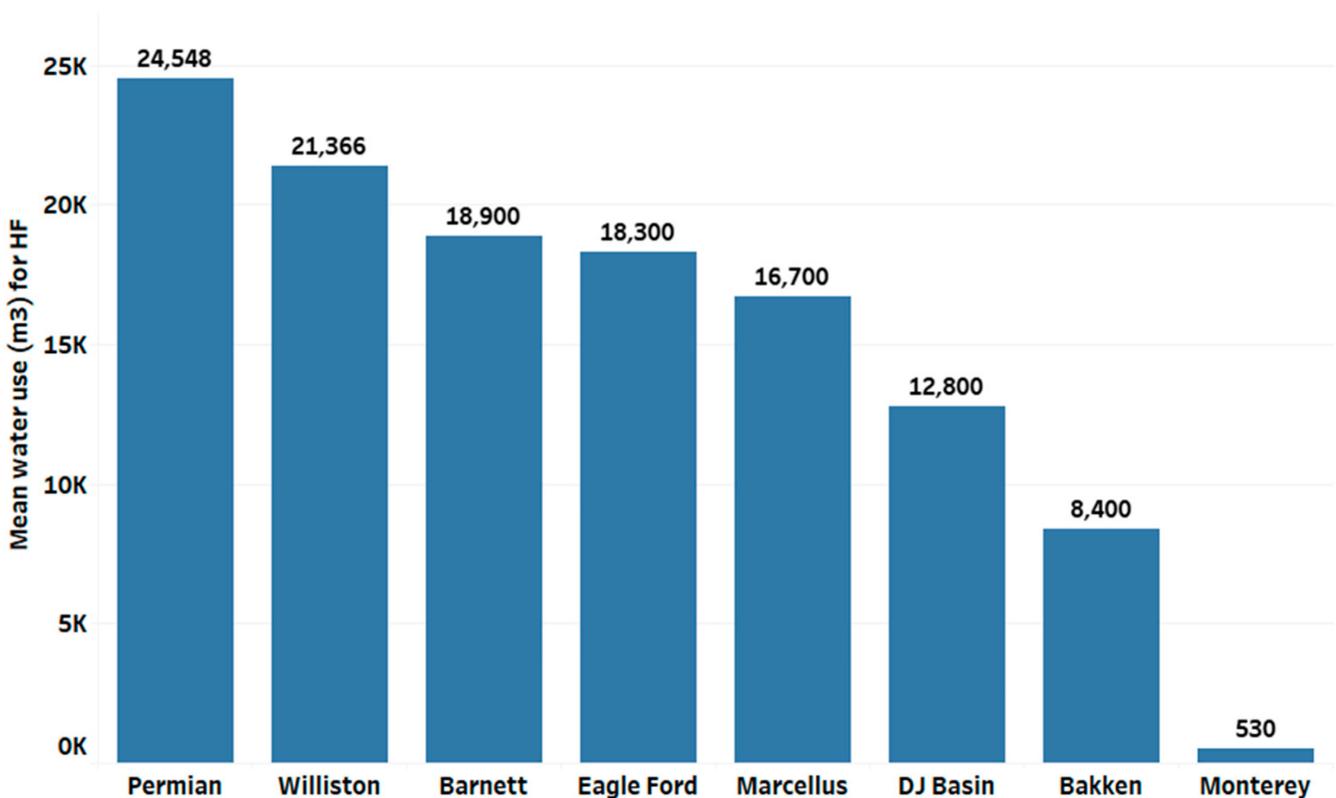
Oil and gas production generates significant wastewater, necessitating effective management without harming the economy or environment. Effective treatment requires a comprehensive understanding of the effluent's features and properties and the consequences to the ecosystem in each country, as highlighted by [\[33\]](#).

Unconventional gas and tight oil reservoirs have low permeability compared to conventional oil and gas reservoirs (1–1000 mD). Hydrocarbon recovery is more challenging in these formations [\[34\]](#). Hydraulic fracturing operations use hydraulic fracturing fluid, composed of water and proppant, with chemical additives accounting for less than 20% of the total volume. These additives can include friction-reducing polymers, liner gels, biocides, surfactants, and corrosion inhibitors. The use of hydraulic fracturing fluid is crucial for efficient oil and gas production [\[35\]\[36\]\[37\]\[38\]\[39\]\[40\]](#).

Hydraulic fracturing, a process used in oil and gas production, consumes a significant amount of water, which is problematic in semi-arid basins where water availability is often stressed to meet demand. From 2000 to 2011, total freshwater consumption for shale gas HF activities in Texas ranged from  $6.5 \times 10^6 \text{ m}^3$  to  $18 \times 10^6 \text{ m}^3$  and up to  $145 \times$

$10^6 \text{ m}^3$  [41]. Between 2005 and 2014, the total hydraulic fracturing water volume for ten of the biggest US formations was around  $940 \times 10^6 \text{ m}^3$  [42][43]. Nearly half of the hydraulically fractured wells in the United States were in areas of severe or extreme water stress, with 97% of wells in Colorado falling into this category [44][45]. The median yearly water use for horizontal wells increased from  $700 \text{ m}^3$  per well to more than 15,200 and  $19,400 \text{ m}^3$  per well.

**Figure 8** represents the average water use ( $\text{m}^3$ ) for hydraulic fracturing of horizontal wells in major shale plays in the US. Huge volumes of water are needed for hydraulic fracturing of horizontal wells. For example, Eagle Ford ( $18,300 \text{ m}^3$ ), Barnett ( $18,900 \text{ m}^3$ ), DJ Basin ( $12,800 \text{ m}^3$ ), Bakken ( $8,400 \text{ m}^3$ ), Marcellus ( $16,700 \text{ m}^3$ ), and Monterey ( $530 \text{ m}^3$ ) require high volumes of water [46]. The annual average water usages for the Permian and Williston basins regarding hydraulic fracturing operations account for  $24,548 \text{ m}^3$  and  $21,366 \text{ m}^3$ , respectively [47].



**Figure 8.** Average water use ( $\text{m}^3$ ) for HF (hydraulic fracturing) of horizontal wells in major shale plays in USA (data from [46][47]).

## 2. Sustainable Produced Water Management

Sustainable oilfield water management is essential for responsible oil and gas exploitation, environmental protection, and water conservation. Every day, millions of barrels of PW are produced all over the world. Apart from providing a risk of water resource contamination, these effluents are directly linked to corrosion and scale in refinery pipelines [6]. The sort of treatment and disposal strategy chosen is determined by the technical feasibility, price, and availability of technology and facilities, as well as current legislation [48]. A typical produced water management workflow is shown in **Figure 9**.

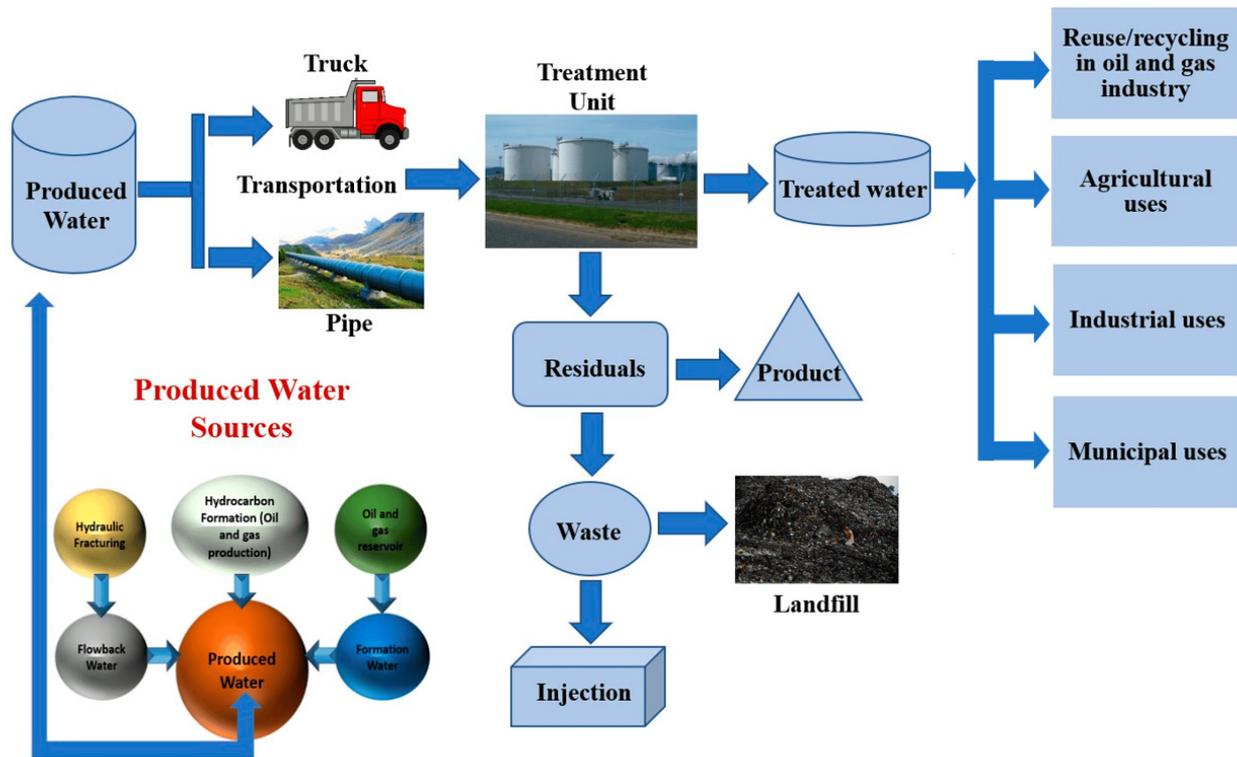


Figure 9. Typical produced water management strategies.

## 2.1. Treatment Aspects

Primary, secondary, and tertiary treatments can address PW effluent and management limits [49]. The primary operation usually removes free O&G, solids, and particles. Secondary treatment removes oil droplets and particulates. Tertiary treatment removes residual contaminants, improving water quality estimates for disposal or reuse [6]. Technology that reduces PW production, reuse and recycling of effluent, and, if required, disposal in the environment are the main methods for controlling PW onshore and offshore. Recovery, reuse, and recycling can control PW when process reduction fails. Injection, industrial, irrigation, and beneficial usage are choices [50].

Adsorption, membrane filtration, advanced oxidative processes (AOP), and biodegradation have been studied for PW treatment [26]. Physical and chemical therapy can address many instances of PW. Flotation, filtration, electrodialysis, cyclones, sand filters, evaporation, DAP, and adsorption are physical treatments. Chemical treatment methods use precipitation, chemical oxidation, photocatalysis, the Fenton reaction, demulsifiers, ozone, and electrochemical technologies. Active sludge, biological aerated filters (BAF), novel micro-capacitive desalination cell (MCDC), and microalgae-based treatments are biological treatments. Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis membranes are examples of membrane technology [6][51][52].

Future technologies include electrochemical water purification. They are low-cost, environmentally benign, and do not require chemicals or generate secondary waste, making them better than other treatment systems. They also remove organic pollutants, generate and store energy, and recover vital elements from produced water without damaging the environment [53]. PW treatment efficiency and convenience depend on chemical agents. Bactericides, descalers, and corrosion inhibitors stabilize systems.

Water purification agents, which demulsify, flocculate, and modify water quality, are the most significant chemicals for effective PW treatment. Offshore PW purification can use quaternary ammonium, carboxylate, sulfonate, or polyphosphate ester demulsifiers. Stabilization corrosion inhibitors used in offshore PW treatment include borate, organic amine, mercaptan, sulfonate, polyphosphate, molybdate, and tungstate [54].

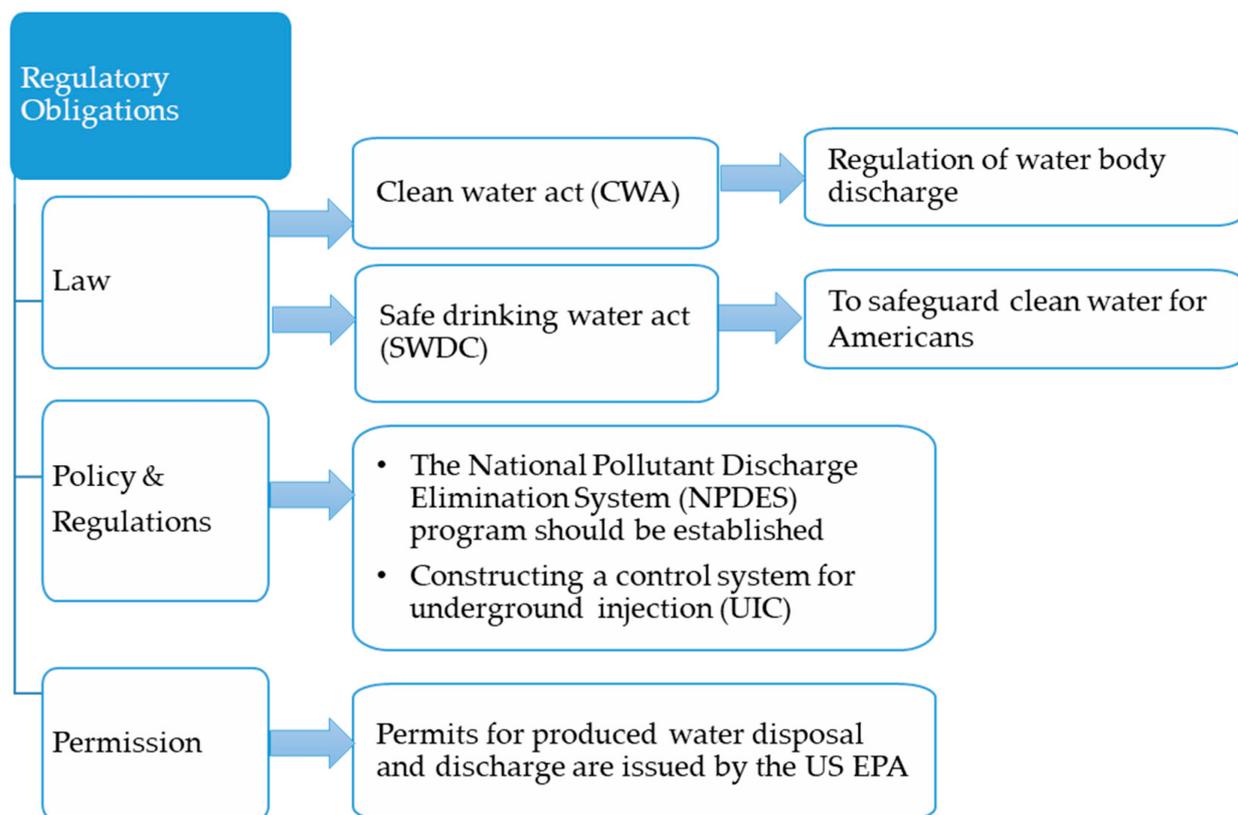
## 2.2. Regulatory Aspects

To make sure that oil and gas businesses follow ethical environmental standards, regulatory requirements are essential for sustainable management of produced water from oilfields. Federal, state, and municipal governments, as well as other organizations, often establish these policies. Regulatory responsibilities [55] may consist of the following:

- Comply with the reporting obligations specified by the appropriate environmental agencies and obtain permits prior to discharging, injecting, or storing produced water. These include NPDES (National Pollutant Discharge Elimination System) and state-issued licenses, as well as UIC (Underground Injection Control) well permits;
- Conform with the criteria and standards for water quality that have been established by state and federal regulatory agencies. These standards establish the maximum allowable concentrations of various pollutants in the produced water and the bodies of water it may contaminate;
- Comply with standards governing the disposal and transportation of hazardous and non-hazardous waste generated during the treatment and handling of produced water. This may include following the Resource Conservation and Recovery Act (RCRA) regulations;
- Create and implement spill prevention and response plans to avoid inadvertent leaks of produced water or other contaminants. It is crucial to adhere to the regulations outlined in the Clean Water Act (CWA) and the Oil Pollution Act (OPA);
- Consistently monitor and provide regulatory authorities with reports on the quantity and quality of produced water, emissions, and discharges; frequently use electronic reporting systems. It is imperative to acquire the appropriate permits for UIC wells and adhere to the prescribed guidelines for injection wells, which may encompass pressure monitoring, mechanical integrity testing, and wellbore integrity assessments;
- In order to mitigate soil erosion and sediment discharge into water bodies, it is imperative to enforce erosion and sediment control measures mandated by regulatory agencies throughout the construction and operation phases. It is imperative to adhere to regulations pertaining to environmentally friendly completions and emission control, such as the Clean Air Act (CAA) and the implementation of best available control technology (BACT), to mitigate emissions;
- Ensure adherence to regulations pertaining to concentrated brine disposal and Zero Liquid Discharge (ZLD) systems, which may encompass standards for permits and disposal;
- Ensure that activities that have the potential to affect the environment or public health are duly communicated to the public and involve local stakeholders and communities in a manner consistent with regulatory requirements;

- Adhere to the stipulations placed forth by specific regulatory authorities with regard to the financing of research and development initiatives that seek to enhance technologies for water treatment and management;
- As required by federal and state agencies, conduct environmental impact assessments to determine the potential environmental effects of oilfield activities, such as produced water management;
- In order to verify compliance with relevant environmental regulations, regulatory authorities should conduct routine inspections and compliance assessments of the oilfield;
- Comply with standards governing the closure and remediation of oilfields, including produced water management facilities, to avoid long-term environmental damage.

Depending on where they operate, oil and gas businesses may be governed by different laws and authorities in different areas. Companies must maintain a sustainable and environmentally responsible approach to produced water management in oilfields by collaborating closely with regulatory bodies and ensuring stringent adherence to all applicable obligations. Noncompliance can result in fines, legal action, and damage to a company's reputation. Typical regulatory aspects are summarized in **Figure 10**.



**Figure 10.** Regulatory obligations for PW management.

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