

Original article

Characterization and Environmental Impact of Produced Water from Oil Fields in the Sirte Basin, Libya

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Abstract

This study evaluates the characteristics and environmental implications of produced water discharged from Zaltan, Al-Lahib, and Al-Jabal oil fields in the Sirte Basin, Libya. The fields collectively produce 217,800 barrels of untreated produced water daily, containing exceptionally high levels of total dissolved solids (TDS) ranging from 40,000 ppm (Zaltan) to 160,000 ppm (Al-Lahib). Elevated concentrations of heavy metals, including mercury (100 mg/L), iron (105 mg/L), and lead (65 mg/L) in Al-Lahib, far exceed safe environmental limits. Inorganic ions such as chloride (26,658 mg/L), nitrate (10,034 mg/L), and bicarbonate (12,806 mg/L) contribute to significant salinization and groundwater contamination risks. These findings highlight the severe environmental impact of produced water discharge, including soil degradation, ecosystem disruption, and threats to public health. Implementing advanced treatment technologies, such as reverse osmosis, electrocoagulation, and constructed wetlands, is recommended to mitigate these risks and ensure sustainable water management.

Keywords. Produced Water, Heavy Metals, Total Dissolved Solids, Sirte Basin, Environmental Pollution.

Introduction

The Exploration and Production (E&P) industry is of paramount importance globally due to its role in meeting energy demands. The current global crude oil production stands at 82.44 Mbbl/day, while the refining capacity reaches 101 Mbbl/day [1]. This significant gap between crude oil supply and demand highlights the critical role of the upstream E&P industry. However, E&P operations, particularly drilling and production, pose considerable environmental risks, largely because they require substantial amounts of water and chemicals. Numerous studies since the late 1990s have documented the environmental pollution resulting from these activities in oilfields [2-7].

A significant by-product of E&P activities is Formation Water (FW), also known as Produced Water (PW) or Oilfield Produced Water (OFPW) [8]. Improper disposal of OFPW into the environment, such as surface water and soil, or during re-injection into underground formations, can lead to groundwater contamination [9-12]. Despite efforts by the E&P industry to re-inject OFPW into underground formations for disposal or reservoir pressure maintenance, a substantial portion remains on the surface, traveling to various environmental receptors and causing potential harm. The increasing volume of OFPW generation exacerbates environmental and economic challenges for the E&P industry. Between 1990 and 2015, OFPW volumes rose from less than 30 million barrels per day to nearly 100 million barrels per day [13]. This increase is linked to the maturity of oilfields, where water production rises as wells age. Secondary recovery processes, such as additional water injection for pressure maintenance, also contribute to this rise [14, 15]. Although OFPW is separated from crude oil at the surface, it retains suspended oil particles, oil and grease (O&G), and dissolved organic and inorganic compounds, including chloride (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and sulfate (SO_4^{2-}) ions [16,17]. High levels of total dissolved solids (TDS), salinity, volatile organic compounds, and heavy metals in OFPW further contribute to its environmental impact, with concentrations varying by geological formation and reservoir location [10, 18-20]. The volume and contaminant concentration of OFPW fluctuate over a reservoir's lifetime, necessitating detailed physicochemical characterization to monitor field operations, evaluate treatment efficiency, and mitigate risks to public health and the environment.

Due to the risk of formation damage, not all OFPW can be re-injected. A significant volume is discharged into the environment, often without adequate treatment, threatening ecosystems by reducing dissolved oxygen levels, forming sludge deposits, and harming aquatic and biotic life. Additionally, OFPW is typically more saline and hotter than atmospheric water, complicating its management. Meanwhile, the E&P industry's freshwater demand continues to grow for operations like drilling, production, reservoir pressure maintenance, and water flooding for secondary crude oil recovery. Reusing OFPW can alleviate freshwater demand while converting waste into usable water. Thus, addressing OFPW with effective treatment technologies is imperative. OFPW treatment must meet water quality standards set by regulatory bodies for either discharge or reuse [21].

In the Sirte Basin, located approximately 150 km south of Brega, Libya, produced water from oil fields is discharged directly into the desert without any treatment. This practice exacerbates soil salinization, contaminates groundwater resources, and disrupts desert ecosystems. The absence of regulatory oversight and mitigation measures further compounds these environmental challenges. This study focuses on characterizing the produced water from the Zaltan, Al-Lahib, and Al-Jabal oil fields, with an aim to provide a comprehensive assessment of its environmental hazards and propose sustainable management solutions.

Methods

Study Area

The Zaltan, Al-Lahib, and Al-Jabal oil fields are situated in the Sirte Basin (Fig. 1), a major oil-producing region in Libya. These fields collectively produce 89,200 barrels of crude oil daily, with Zaltan contributing 64,000 barrels, Al-Lahib 12,800 barrels, and Al-Jabal 12,400 barrels. The corresponding volumes of produced water are 190,000 barrels/day for Zaltan, 14,000 barrels/day for Al-Lahib, and 13,800 barrels/day for Al-Jabal.

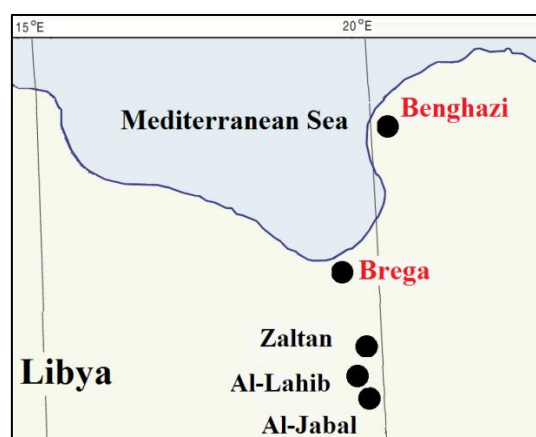


Figure 1. Geographic Map Indicating Study Sites in Libya

Analysis of Heavy Metals Using Atomic Absorption Spectroscopy (AAS)

The concentrations of heavy metals, including mercury (Hg), chromium (Cr), copper (Cu), manganese (Mn), iron (Fe), nickel (Ni), zinc (Zn), and lead (Pb), were determined using an Atomic Absorption Spectrometer AAS 320N Drawell International Technology Limited, China. Water samples were first filtered to remove any particulate matter and acidified with concentrated nitric acid to stabilize and preserve the metal ions. Calibration of the AAS was performed using certified standard solutions with known concentrations of each target metal to generate calibration curves. The analysis involved atomizing the prepared samples in a flame or graphite furnace, depending on the specific element being analyzed, and measuring the absorbance at the corresponding wavelengths for each metal. Quality control procedures, including duplicate analyses and spiked recovery tests, were conducted to ensure the accuracy and precision of the measurements.

Determination of Total Dissolved Solids (TDS)

The Total Dissolved Solids (TDS) concentration in water samples was determined using a Milwaukee TDS meter, manufactured in Romania. Before measurement, the water samples were allowed to equilibrate to room temperature. The TDS meter was calibrated using standard solutions with known TDS values, and the probe was immersed in the samples to measure the TDS concentration, expressed in parts per million (ppm). Calibration checks were performed periodically to maintain the reliability of the measurements.

Determination of Nitrite (NO_2^-) and Nitrate (NO_3^-)

Nitrite (NO_2^-) concentrations were determined using the diazotization method. A 3 mL aliquot of the sample was reacted with 0.3 mL of sulphanilamide solution (prepared by dissolving 0.5 g in 5 mL of concentrated hydrochloric acid and diluting to 30 mL with distilled water) and left for 5 minutes. Subsequently, 0.3 mL of N-(1-naphthyl)-ethylenediamine dihydrochloride solution (0.1 g dissolved in 100 mL distilled water) was added, and the mixture was left for 15 minutes to allow color development. The absorbance was measured at 543 nm using a spectrophotometer. For nitrate (NO_3^-) determination, nitrate was first reduced to nitrite using hydrazine sulfate. The total nitrite (original and reduced from nitrate) was then determined as described above. To calculate the actual nitrate concentration, the original nitrite concentration was subtracted from the total measured nitrite concentration.

Determination of Chloride (Cl^-)

Chloride ion concentration was determined using a titration method with 0.21 M silver nitrate (AgNO_3) as the titrant and potassium chromate (K_2CrO_4) as the indicator. A 10 mL aliquot of the sample was mixed with 5 mL of potassium chromate solution (prepared by dissolving 3.5 g in 1 liter of distilled water). The sample was titrated with silver nitrate solution until the solution changed to an orange-red color, indicating the endpoint. The chloride concentration was calculated based on the volume of silver nitrate used.

Determination of Carbonate (CO_3^{2-}) and Bicarbonate (HCO_3^-)

Carbonate and bicarbonate concentrations were determined using an acid-base titration method. A 50 mL sample was titrated with 0.1 N hydrochloric acid (HCl) using phenolphthalein and methyl orange as indicators. Phenolphthalein was first added to the sample, and the titration was carried out until the pink color disappeared, indicating the endpoint for carbonate. Methyl orange was then added, and titration continued until the color changed from yellow to orange, indicating the endpoint for bicarbonate. The concentrations of carbonate and bicarbonate ions were calculated based on the volumes of HCl used for each endpoint.

Determination of Sulfate (SO_4^{2-})

Sulfate concentration was measured using the precipitation method with barium chloride (BaCl_2). A 50 mL aliquot of the sample was mixed with 5 mL of 10% barium chloride solution under constant stirring to ensure complete precipitation of barium sulfate (BaSO_4). The mixture was allowed to stand for a sufficient time to allow full precipitation, after which the precipitate was filtered, washed, dried, and weighed. The sulfate concentration was calculated from the mass of the barium sulfate formed.

The Methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited. Research manuscripts reporting large datasets that are deposited in a publicly available database should specify where the data have been deposited and provide the relevant accession numbers. If the accession numbers have not yet been obtained at the time of submission, please state that they will be provided during review. They must be provided prior to publication. Interventionary studies involving animals or humans, and other studies that require ethical approval, must list the authority that provided approval and the corresponding ethical approval code.

Results

Produced Water Volumes

Produced water volumes from the three fields vary significantly, with Zaltan producing the largest volume (190,000 barrels/day). Combined, these fields generate 217,800 barrels/day of untreated produced water discharged into the desert. This significant volume highlights the scale of the environmental challenge posed by its disposal.

Total Dissolved Solids (TDS)

The Total Dissolved Solids (TDS) levels vary widely among the three fields (Table 1). Al-Lahib exhibits the highest TDS concentration at 160,000 ppm, followed by Al-Jabal at 96,000 ppm, and Zaltan at 40,000 ppm.

Table 1. Total Dissolved Solids (TDS) measurements in ppm for water samples collected from Zaltan, Al-Lahib, and Al-Jabal fields

Field	TDS (ppm)
Zaltan	40000
Al-Lahib	160000
Al-Jabal	96000

Chemical Composition of OFPW

The chemical composition of Oilfield Produced Water (OPFW) contains both organic and inorganic components, with significant variability influenced by geological and operational factors. Concentrations of key inorganic components are summarized in Table 2.

Table 2. Concentration of various chemical parameters in water samples collected from Zaltan, Al-Lahib, and Al-Jabal fields, measured mg/L

Parameter	Symbol	Unit	Zaltan	Al-Lahib	Al-Jabal
Chloride	Cl ⁻	mg/L	6658	26658	15991
Nitrite	NO ₂ ⁻	mg/L	228	912	547
Nitrate	NO ₃ ⁻	mg/L	2507	10034	6020
Sulfate	SO ₄ ²⁻	mg/L	133	143	153
Carbonate	CO ₃ ²⁻	mg/L	677	2707	1624
Bicarbonate	HCO ₃ ⁻	mg/L	3202	12806	7684

Heavy Metals

Concentrations of heavy metals in the three fields are shown in Table 3. Al-Lahib exhibits the highest levels of mercury (100 mg/L), iron (105 mg/L), and lead (65 mg/L).

Table 3. Concentrations of heavy metals in water samples from Zaltan, Al-Lahib, and Al-Jabal fields, measured in mg/L.

Field	Hg (mg/L)	Cr (mg/L)	Cu (mg/L)	Mn (mg/L)	Fe (mg/L)	Ni (mg/L)	Zn (mg/L)	Pb (mg/L)
Zaltan	7.0	0.31	7.0	0.08	0.4	4.15	0.05	5.0
Al-Lahib	100.0	2.38	5.0	0.70	105.0	20.60	20.60	65.0
Al-Jabal	45.0	2.24	2.0	0.06	11.0	15.20	15.20	20.0

Discussion

The findings of this study reveal significant environmental challenges associated with the discharge of untreated produced water (PW) from the Zaltan, Al-Lahib, and Al-Jabal oil fields in the Sirte Basin, Libya. These challenges are driven by the large volumes of PW generated, its high salinity, diverse chemical composition, and the presence of hazardous heavy metals.

The daily production of PW, particularly from Zaltan (190,000 barrels/day), contributes substantially to the combined output of 217,800 barrels/day from the three fields. This immense volume of untreated water highlights the scale of the environmental burden. When discharged into the desert without proper treatment, these volumes pose risks to soil, groundwater, and the surrounding ecosystems.

The water quality analysis underscores the variability in Total Dissolved Solids (TDS) levels across the three fields, ranging from 40,000 ppm in Zaltan to a staggering 160,000 ppm in Al-Lahib. High TDS levels can lead to severe soil salinization, rendering the land unsuitable for agriculture and compromising the region's water resources. The elevated salinity in Al-Lahib's PW, in particular, raises concerns about long-term ecological impacts, including groundwater contamination and harm to native vegetation.

Chemical analysis of Oilfield Produced Water (OFPW) further reveals a diverse array of inorganic components. Chloride concentrations, which range from 6,658 mg/L in Zaltan to 26,658 mg/L in Al-Lahib, significantly contribute to the overall salinity, posing direct threats to soil and water quality. Nitrogen compounds, including nitrite (up to 912 mg/L) and nitrate (up to 10,034 mg/L), exacerbate the risks of eutrophication when PW enters aquatic systems. These compounds can lead to excessive algal growth, reduced dissolved oxygen, and the degradation of aquatic habitats.

Carbonate (CO₃²⁻) and bicarbonate (HCO₃⁻) levels also vary widely, with maximum concentrations of 2,707 mg/L and 12,806 mg/L, respectively, observed in Al-Lahib. These elevated levels contribute to increased alkalinity, which can lead to scaling in water treatment systems and exacerbate operational challenges. The relatively low sulfate (SO₄²⁻) concentrations (133–153 mg/L) mitigate some risks, but they can still react with calcium to form solid deposits, complicating treatment processes.

The presence of heavy metals in PW adds another layer of environmental concern. Al-Lahib demonstrates the highest concentrations of mercury (100 mg/L), iron (105 mg/L), and lead (65 mg/L). These levels far exceed safe environmental thresholds and pose acute risks to soil, water, and biological health. Mercury's neurotoxic effects threaten both human and animal populations, while high lead levels contribute to soil contamination and potential entry into the food chain. Even the lower concentrations of heavy metals observed in Zaltan and Al-Jabal, such as nickel (15.20–20.60 mg/L) and zinc (15.20–20.60 mg/L), remain significant due to their potential for long-term environmental accumulation.

The environmental risks posed by untreated PW are multifaceted. High salinity can degrade soil fertility and groundwater quality, while nitrogen compounds contribute to the deterioration of water bodies. Elevated temperatures of PW compared to atmospheric water introduce thermal stress to aquatic ecosystems. The mineral-rich nature of PW, coupled with its potential to form sludge deposits, exacerbates risks to both terrestrial and aquatic environments.

Economically, the contaminants in PW impose significant treatment costs on the exploration and production

(E&P) industry. Advanced technologies such as reverse osmosis, membrane filtration, and electrocoagulation are required to meet environmental standards. However, these challenges also present opportunities for resource recovery. Treated PW could be repurposed for secondary oil recovery, industrial applications, or irrigation in arid regions, reducing reliance on freshwater resources and transforming an environmental liability into a sustainable resource.

In summary, the study highlights the urgent need for comprehensive PW management strategies. Addressing the environmental risks associated with high TDS, diverse chemical compositions, and hazardous heavy metals requires innovative treatment technologies and stringent regulatory enforcement. These interventions will not only mitigate environmental harm but also pave the way for sustainable reuse of PW, contributing to resource conservation and environmental protection in the Sirte Basin.

Conclusion

This study highlights the significant environmental risks associated with the direct discharge of untreated produced water from the Zaltan, Al-Lahib, and Al-Jabal oil fields in the Sirte Basin, Libya. The high levels of total dissolved solids (up to 160,000 ppm) and elevated concentrations of heavy metals, including mercury (100 mg/L), iron (105 mg/L), and lead (65 mg/L), far exceed safe environmental limits, posing severe risks to soil quality, groundwater resources, and local ecosystems. The substantial presence of chloride (26,658 mg/L), nitrate (10,034 mg/L), and bicarbonate (12,806 mg/L) exacerbates salinity and alkalinity, threatening vegetation and promoting scaling issues.

Immediate interventions, such as advanced treatment technologies—reverse osmosis, electrocoagulation, and constructed wetlands—are crucial for mitigating these impacts. These approaches not only reduce salinity and heavy metal concentrations but also enable the sustainable reuse of treated water for industrial and agricultural applications, transforming an environmental challenge into a resource management opportunity.

Conflicts of Interest

The authors declare no conflicts of interest related to this research. The study was conducted independently, and no financial, personal, or professional relationships influenced the outcomes or interpretation of the results presented in this paper.

References

- Rajbongshi A, Gogoi SB. A review on oilfield produced water and its treatment technologies. *Petroleum Research*. 2024;9(4):640-56.
- Gallup DL, Isacoff EG, Smith DN III. Use of Ambersorb® carbonaceous adsorbent for removal of BTEX compounds from oil-field produced water. *Environmental Progress*. 1996;15(3):197-203.
- Henderson SB, Clarke RJ, Wilson J, Tait RD. Potential impact of production chemicals on the toxicity of produced water discharges from North Sea oil platforms. *Marine Pollution Bulletin*. 1999;38(12):1141-51.
- McCormack P, Jones P, Hetheridge MJ, Rowland SJ. Analysis of oilfield produced waters and production chemicals by electrospray ionisation multi-stage mass spectrometry (ESI-MSn). *Water Research*. 2001;35(15):3567-78.
- Obire O, Amusan FO. The environmental impact of oilfield formation water on a freshwater stream in Nigeria. *Journal of Applied Sciences and Environmental Management*. 2003;7:61-6.
- Horner JE, Castle JW, Rodgers JH. A risk assessment approach to identifying constituents in oilfield produced water for treatment prior to beneficial use. *Ecotoxicology and Environmental Safety*. 2011;74(4):989-99.
- Gogoi SB, Sharma BK, Tamuli AK, Borah A, Goswami P, Saikia PH. Characterization of oil field produced waters of Upper Assam Basin, India. *International Journal of New Technology and Science Engineering*. 2015;2(1):2349-0780.
- Goswami M, Tamuli AK, Sharma BK, Gogoi SB. Environment friendly treatment of petroleum hydrocarbon contaminated formation water: Mechanisms and consequences for degradation and adsorption. *Water Resources and Industry*. 2023;30:100224.
- Li H. Produced water quality characterization and prediction for Wattenberg field [dissertation]. Colorado State University; 2013.
- Dos Santos EV, Aquino Neto S, Botelho Junior AB, Magriotis ZM, Silva DR. Decontamination of produced water containing petroleum hydrocarbons by electrochemical methods: A minireview. *Environmental Science and Pollution Research*. 2014;21:8432-41.
- Pichtel J. Oil and gas production wastewater: Soil contamination and pollution prevention. *Applied and Environmental Soil Science*. 2016;2016(1):2707989.
- Yazdan MMS, Ahmed A, Fares M, Zhang Y, Moghaddam AD. Review on the evaluation of the impacts of wastewater disposal in hydraulic fracturing industry in the United States. *Technologies*. 2020;8(4):67.
- Liu Y, Zhang R, Meng X, Ye S, Zheng Y. A review of treatment technologies for produced water in offshore oil and gas fields. *Science of the Total Environment*. 2021;775:145485.
- Sahoo B. Effect of formation water disposal on ground water in the oilfields of Dibrugarh and Tinsukia districts of Assam [dissertation]. 2011.
- Muggeridge A, Cockin A, Webb K, Frampton H, Collins I, Moulds T, et al. Recovery rates, enhanced oil recovery and technological limits. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. 2014;372(2006):20120320.

16. Fontenot BE, Hunt LR, Hildenbrand ZL, Carlton DD Jr, Oka H, Walton JL, et al. An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett Shale Formation. *Environmental Science & Technology*. 2013;47(17):10032-40.
17. Harkness JS, Dwyer GS, Warner NR, Parker KM, Mitch WA, Vengosh A. Iodide, bromide, and ammonium in hydraulic fracturing and oil and gas wastewaters: Environmental implications. *Environmental Science & Technology*. 2015;49(3):1955-63.
18. Veil JA, Puder MG, Elcock D, Redweik RJ. A white paper describing produced water from production of crude oil, natural gas, and coal bed methane [Internet]. Argonne National Laboratory; 2004. Available from: <https://www.osti.gov>.
19. Olajire AA. Recent advances on the treatment technology of oil and gas produced water for sustainable energy industry—mechanistic aspects and process chemistry perspectives. *Chemical Engineering Journal Advances*. 2020;4:100049.
20. Jiang W, Zhang H, Zuo W, Li J, Yuan C. A critical review of analytical methods for comprehensive characterization of produced water. *Water*. 2021;13(2):183.
Klemz AC, Andrade JH, Pacheco EBG, Da Silva LT, Benachour M, Vieira MGA, et al. Oilfield produced water treatment by liquid-liquid extraction: A review. *Journal of Petroleum Science and Engineering*. 2021;199:108282.

الملخص

تُقيّم هذه الدراسة خصائص المياه المصاحبة المنبعثة من حقول النفط زلطن، واللهيب، والجبل في حوض سرت بليبيا، وتأثيراتها البيئية. تنتج هذه الحقول معًا حوالي 217,800 برميل يوميًا من المياه المصاحبة غير المعالجة، والتي تحتوي على مستويات عالية جدًا من المواد الصلبة الذائبة الكلية (TDS) تتراوح بين 40,000 جزء في المليون (زلطن) و160,000 جزء في المليون (اللهيب). كما تم تسجيل تركيزات مرتفعة للمعادن الثقيلة، بما في ذلك الزئبق (100 ملغ/لتر)، والحديد (105 ملغ/لتر)، والرصاص (65 ملغ/لتر) في حقل اللهيب، وهي تفوق بكثير الحدود البيئية الآمنة. تسهم الأيونات غير العضوية، مثل الكلوريد (26,658 ملغ/لتر)، والنترات (10,034 ملغ/لتر)، والبيكربونات (12,806 ملغ/لتر)، في زيادة ملوحة التربة ومخاطر تلوث المياه الجوفية. تُبرز هذه النتائج التأثير البيئي الخطير لانبعاث المياه المصاحبة، بما في ذلك تدهور التربة، واضطراب الأنظمة البيئية، والتهديدات للصحة العامة. توصي الدراسة بتطبيق تقنيات معالجة متقدمة، مثل التناضح العكسي، والتخثر الكهربائي، والأراضي الرطبة المُنشأة، للتخفيف من هذه المخاطر وضمان إدارة مستدامة للمياه.