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Review Article

Advancements in Digitized Workflows for Enhanced Water Management in Hydraulic Fracturing

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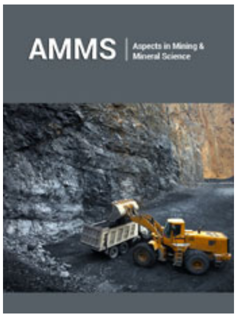
ISSN: 2578-0255



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Submission: November 28, 2024
Published: December 10, 2024

Volume 13 - Issue 1

How to cite this article: Makuachukwu Mbaegbu*. Advancements in Digitized Workflows for Enhanced Water Management in Hydraulic Fracturing. Aspects Min Miner Sci. 13(1). AMMS. 000802. 2024.
DOI: 10.31031/AMMS.2024.13.000802

Abstract

Efficient water management is a critical aspect of hydraulic fracturing due to the substantial water volumes required and the associated environmental and operational challenges. This review explores advancements in digitized workflows for water management, focusing on the development and application of a comprehensive, real-time monitoring and management system. The system integrates advanced analytics with a holistic approach to the water life cycle, encompassing sourcing, transportation, recycling, and disposal. Key functionalities include precise water-volume tracking, dynamic scheduling, leak detection, and enhanced inspection processes. The reviewed studies demonstrate significant improvements in operational efficiency, cost-effectiveness, and compliance with regulatory standards. Furthermore, the integration of machine-learning models is identified as a promising avenue for future development, offering opportunities to enhance predictive analytics, optimize recycling processes, and improve anomaly detection. These innovations underscore the potential of digitized workflows to transform water management in hydraulic fracturing, driving sustainability and operational excellence.

Keywords: Hydraulic fracturing; Water management; Digitized workflows; Real-time monitoring; Sustainability

Introduction

Hydraulic fracturing is a cornerstone of the oil and gas industry, enabling the extraction of hydrocarbons from shale formations through the high-pressure injection of water, sand, and chemicals into bedrock. This technique has unlocked substantial hydrocarbon reserves, contributing significantly to economic growth and energy security [1]. However, it is a water-intensive process, with each well consuming approximately 3 to 8 million gallons of water during its operational life. This extensive water demand presents critical challenges, particularly in water-scarce regions, where it can strain local resources and impact agriculture and communities. Addressing these concerns requires reducing reliance on fresh water and implementing effective strategies for managing produced and flowback water, often saline or brackish and requiring treatment or disposal to meet environmental regulations [2]. Together, these issues underscore the need for innovative water management approaches in hydraulic fracturing.

The scale of water usage in hydraulic fracturing highlights the pressing need for optimized water management practices (Figure 1). Presents annual and monthly total base water and non-water volumes used as carrier fluids, derived from FracFocus disclosure data for all U.S. operators. As shown in Figure 1a, the annual water volume surged to nearly 5.87 trillion gallons in 2023, a sharp increase from 667 billion gallons in 2022, reflecting a growing demand for water. Figure 1c Reveals that monthly water usage in 2023 averaged around 489 billion gallons with minimal variation. Similarly, (Figures 1b & 1d) illustrate that total base non-water volumes rose to 26.7 billion gallons in 2023 from 1.42 billion gallons in 2022, with significant monthly spikes in April, September, and October, averaging 2.23 billion gallons per month. These figures emphasize the massive volumes involved in hydraulic fracturing and the urgent need for advanced water management solutions. Recent studies have highlighted methods to optimize hydraulic fracturing operations, including fluid optimization techniques [3,4], wellbore stability analyses [5], and numerical simulations for production forecasting [6,7]. The integration of such methods with digitized water management systems could pave the way for sustainable and efficient hydraulic fracturing practices [8].

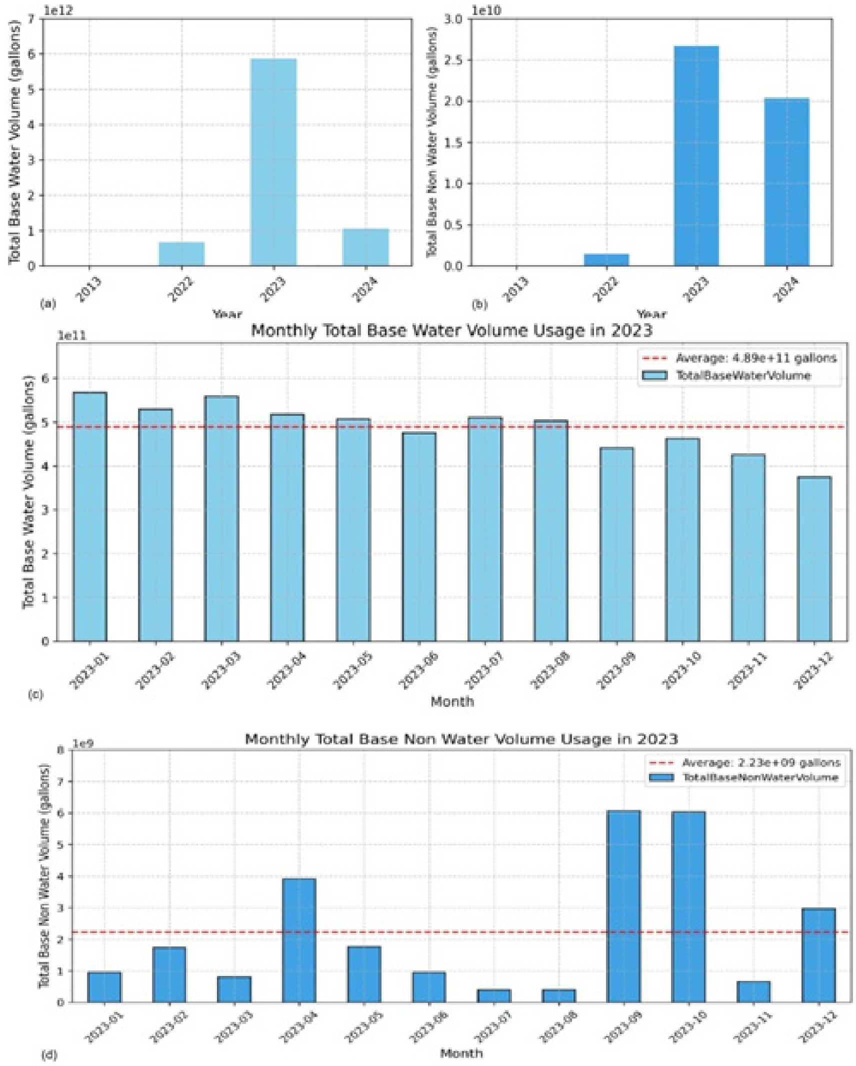

Figure 1: Water and nonwater volumes used in hydraulic fracturing. (a) Annual total base water volume used from 2013 to 2024. (b) Annual total base nonwater volume used from 2013 to 2024. (c) Monthly total base water volume in 2023. (d) Monthly total base nonwater volume in 2023 [8].

Efforts to improve water management in hydraulic fracturing within the oil and gas industry have made notable progress but continue to encounter significant limitations Liu et al. [9]. Developed systems to recycle flowback water, reducing the need for freshwater; however, these systems lack real-time monitoring and management capabilities, leading to inefficiencies and potential environmental risks. Similarly, Pajooh M et al. [10,11] introduced mobile units for on-site treatment and reuse of produced water. While effective, these units face high operational costs and logistical hurdles. Biswas [12] designed a predictive model to optimize water sourcing decisions based on regional availability and costs, but the model does not integrate operational data or adopt a holistic approach to water management. Grossmann et al. [13] proposed methods to optimize water transportation logistics during fracturing, enhancing efficiency but failing to address comprehensive water recycling and reuse. Olajire [14] explored advanced filtration technologies for treating produced water, but the study did not account for the entire water management life cycle, including storage, transportation, and regulatory compliance. Similarly, digital monitoring systems proposed by Martinez et al. [15,16] track water usage during fracturing operations but often lack real-time data integration and advanced analytics, limiting their ability to provide actionable insights and improve overall efficiency.

Despite these advancements, many existing methods focus on isolated aspects of water management without providing a holistic, digitized solution. To address these limitations, a new approach is proposed that integrates real-time data monitoring, advanced analytics, and a full life-cycle perspective on water management, from sourcing and transportation to recycling and disposal. This comprehensive software solution allows operators to continuously monitor produced and flowback water volumes, implement dynamic scheduling, and detect leaks in real time. Unlike earlier methods, this system provides a unified platform to capture and analyze data across all stages of water management, offering actionable insights to optimize water usage and reduce operational costs. Features such as historical data analysis, predictive modeling, and automated reporting ensure regulatory compliance while enhancing decision-making and strategic planning. This integrated approach supports a robust and scalable water management framework that can adapt to the diverse demands of different regions. Historically, fresh water has been critical in hydraulic fracturing because impurities reduce the efficiency of additives used in the process. Most water used in fracturing is sourced from lakes, rivers, ponds, and municipal supplies, with groundwater serving as a supplemental resource where available in adequate quantities.

In various states, the regulation of water used for hydraulic fracturing varies significantly. In some regions, local public agencies or river basin commissions govern water usage, while in others, water rights are privately owned and allocated at the discretion of the owner. Murphy Oil Corporation prioritizes the use of nonfresh water sources, such as produced water and saline groundwater, to minimize the reliance on freshwater. When alternative sources are exhausted or unavailable, and freshwater becomes necessary, Murphy aims to avoid impacting wetlands, streams, ponds, lakes, waters of the U.S., U.S. Army Corps of Engineers water bodies, and areas facing heightened water scarcity. The water use balance for three of Murphy's operational areas is presented in its 2024 Sustainability Report [17], as shown in (Figure 2). The data in (Figure 2) highlights varying water source dependencies across Murphy's operations. In the Eagle Ford Shale (Figure 2a), recycled water usage increased from 11% in 2021 to 17% in 2023, facilitated by investments in recycling infrastructure. Concurrently, surface water use declined as operations shifted to areas with limited surface water availability, leading to increased reliance on groundwater. In Tupper Montney (Figure 2b), recycled water use peaked at 71% in 2022 but decreased to 35% in 2023 due to delays in obtaining approvals for produced water conveyance. Meanwhile, in Kaybob Duvernay (Figure 2c), the company reported no recycled water use until 2022, when it rose to 41%, significantly reducing surface water reliance from 59% in 2022 to 0% in 2023. These trends reflect Murphy's ongoing efforts to adapt its water management strategies to regional conditions and regulatory frameworks.

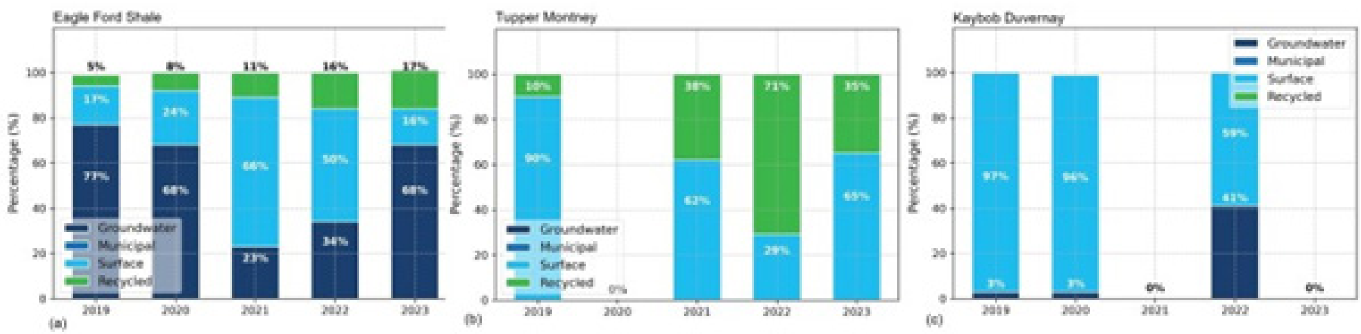

Figure 2: Water source balance for three facilities: (a) Eagle ford shale, (b) Tupper montney, (c) Kaybob duvernay [8].

To advance the goal of increasing the use of recycled produced water, updates to water management monitoring tools became necessary. Previously, pond water volumes were tracked using spreadsheets, a method prone to numerous limitations. These included susceptibility to human error, reliance on manual calculations, challenges with remote access, absence of real-time data updates, and risks of data loss or deletion. To address these issues and introduce enhanced functionalities, the Operations and Data Science teams collaborated to create a dedicated water management software application. This application enables operators to input key data, such as the total measured volume of the pond, the "water in" volume, and the "water out" volume for specific dates. Additionally, it provides access to historical data, streamlining the review of past records. The app also supports daily and monthly inspections through an integrated inspection checklist, making monitoring more systematic and efficient. Ongoing development aims to incorporate leak-detection monitoring, further expanding the application's utility in ensuring comprehensive and accurate water management.

Water Management Application

The app is divided into three key modules: Water Management, Inspection, and Water Leak Detection. The Water Management module allows users to monitor pond water volumes, categorize water sources, and log daily activities. The Inspection module facilitates tracking daily and monthly maintenance checks. The Water Leak Detection module, currently under development, will provide real-time alerts for leaks using a digital twin model, enhancing the system's efficiency and sustainability in hydraulic fracturing operations. In the Water Management module, the Pond List screen (Figure 3a) offers an overview of pond volumes categorized by water sources like produced, surface, and rainwater. Users can filter ponds, search by name or ID, and track actions such as measuring, adding, or removing water. Activities are logged via a calendar interface, allowing for easy input and review of historical data. The Production Date screen (Figure 3b) provides a detailed calendar to log and review daily water management tasks, including inflow, outflow, and volume measurements. The Water Management screen (Figure 3c) enables users to input specific measurements and classify water transfers by source type, ensuring comprehensive tracking.

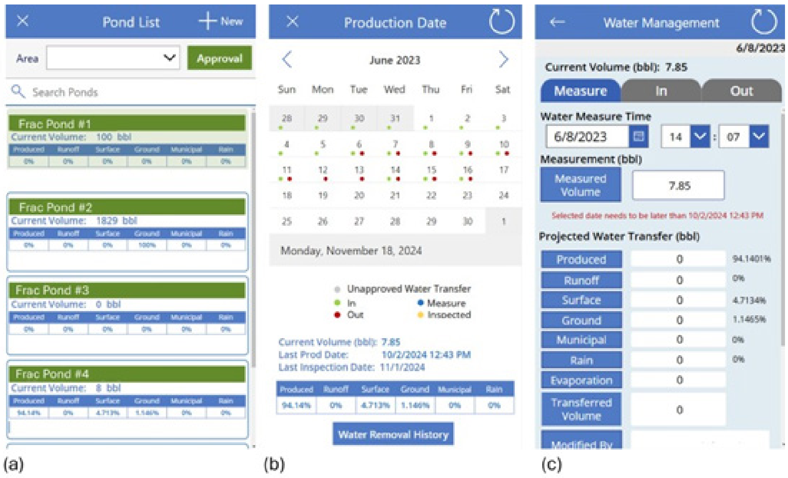

Figure 3: Water management application pond and production screens: (a) Pond list screen, (b) Production date screen, (c) Water management screen [8].

A pond can have three primary actions: Measure, In, and Out.

For Measure, users input the measured volume and comments. If the measured volume is less than the existing volume, water is deducted proportionally across categories. If it exceeds the current volume, users choose between "Produced" or "Rain." Selecting "Produced" records the additional water as "In," while selecting "Rain" adjusts the rain percentage upward, reducing other categories proportionally. Category percentages are calculated based on the ratio of each category's volume to the total pond volume. The In action records water transferred into the pond. Users input the amount for five categories-produced, runoff, surface, ground, and municipal-and add comments. This action also determines initial category ratios, which update dynamically with subsequent entries. The Out-action logs water transferred out, along with its destination. If the destination is another pond, the transfer updates the receiving ponds "In" data accordingly (Figure 4).

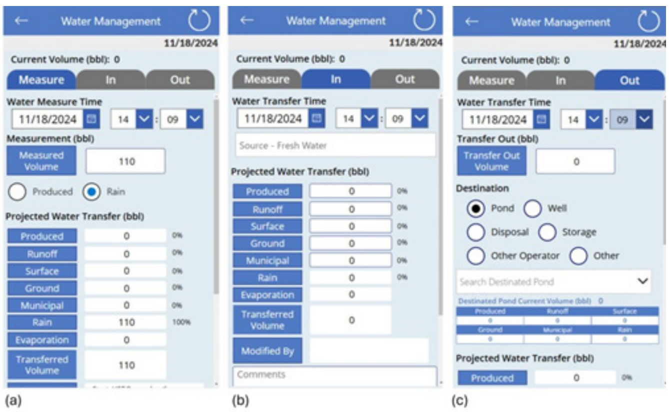

Figure 4: Detailed entry and classification of water transfer activities in the water management application: (a) Water management, measure; (b) Water management, In; (c) Water management, Out [8]

Module 2-Inspection: The Inspection Calendar (Figure 5a) enables users to log, edit, and track inspections. The Yard Site Inspection screen (Figure 5b) includes questions requiring comments and photos for "Inadequate" responses. The Daily Inspection screen (Figure 5c) allows users to complete predefined questions and submit daily inspection reports, ensuring consistent monitoring and maintenance. Ponds must undergo daily and monthly inspections to ensure they meet operational standards. These inspections cover categories like structural integrity, water quality, and equipment functionality. Inspectors must complete all categories before submitting the report. In the Inspection Module, users select a pond from the list and access the inspection calendar. They can add a new inspection by choosing a date without a yellow spot or edit an existing one by selecting a date with a yellow spot. Users answer multiple questions under headings such as Structural Condition, Water Quality, and Operational Safety. If any answer is marked as "Inadequate," users must provide comments or photos. The inspection report, organized by question type, helps ensure thorough documentation and necessary follow-up actions.

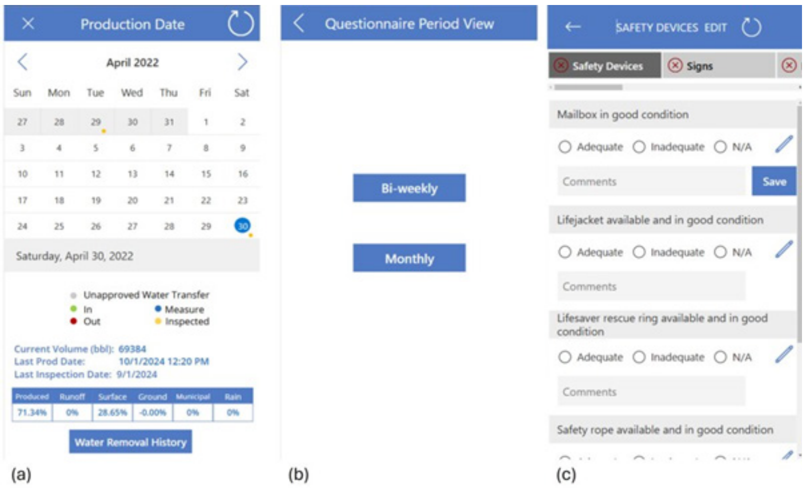

Figure 5: Inspection screens in the water management application: (a) Inspection calendar, (b) Questionnaire period view, (c) Safety device inspection [8].

Results

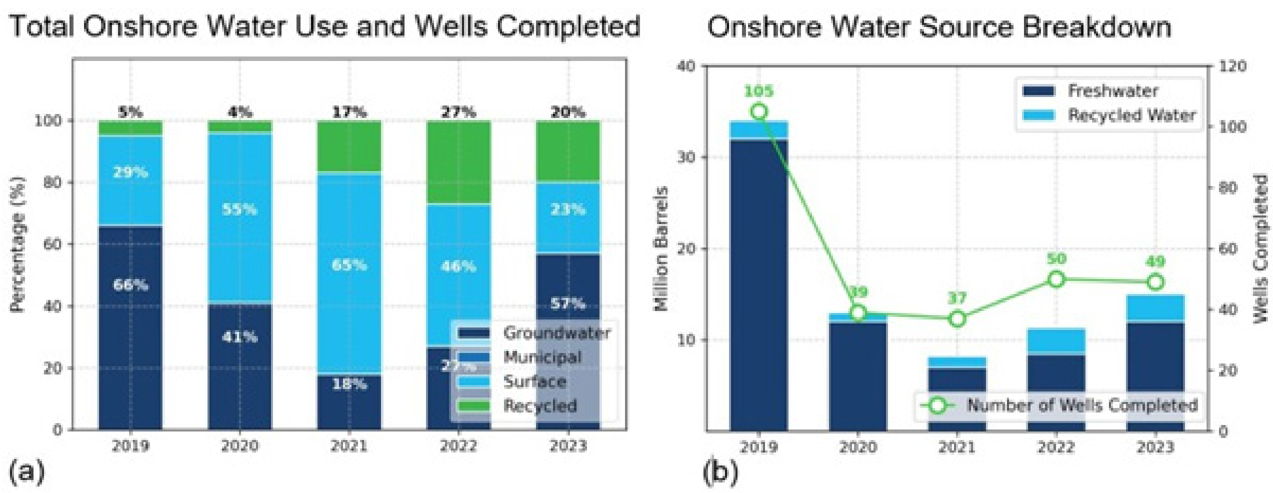

Figure 6: Overview of (a) Onshore water use and (b) Source breakdown from 2019 to 2023 [8].

To comply with legislative requirements and internal best practices, water metrics are tracked across all onshore business units. These metrics include freshwater and alternative water consumption, water sharing volumes, and freshwater use intensity (barrels per lateral length and per fracture stage). Figs. 6a and b display key water metrics, highlighting trends in freshwater and recycled water usage alongside the number of wells completed from 2019 to 2023. Figure 6a shows a decline in freshwater use from approximately 30 million barrels in 2019 to 25 million barrels in 2023, alongside fluctuations in the number of wells completed. The number of wells peaked at 105 in 2019, dropped to 39 in 2020, and gradually recovered, reaching 49 wells in 2023. This decline in freshwater usage, despite the stable well count, suggests improved efficiency and increased use of recycled water. Figure 6b Illustrates a shift in water sources over time. Groundwater use decreased from 66% in 2019 to 57% in 2023, while recycled water usage grew from 5% to 20%. The produced water recycling ratio peaked at 27% in 2022 before slightly dropping to 20% in 2023, due to the larger volumes and longer laterals required for operations. These trends reflect a focus on reducing freshwater usage and increasing reliance on recycled water. The application helps operators optimize water sourcing, usage, and recycling, ensuring sustainability, compliance, and cost efficiency.

The results highlight a steady decline in freshwater usage from approximately 30 million barrels in 2019 to 25 million barrels in 2023, alongside increased integration of recycled water, demonstrating enhanced efficiency in water management practices. These findings are consistent with advancements in proppant optimization and hydraulic fracturing techniques, which emphasize improved resource utilization and reduced environmental impact [18]. Furthermore, innovative methods, such as Fishbone Drilling, have showcased their potential to maximize hydrocarbon extraction while promoting sustainability by leveraging natural fractures and minimizing the operational footprint [19]. These trends underscore the importance of integrating advanced technologies to achieve operational efficiency and sustainability in hydraulic fracturing practices.

Conclusion

This study addresses the significant challenge of managing water resources in hydraulic fracturing, a process that consumes large volumes of water and poses environmental and operational risks. The primary issue identified was the inefficiency in managing these water resources sustainably throughout their life cycle while ensuring compliance with regulatory standards. To tackle this, a comprehensive, digitized water management application was developed. This solution integrates real-time data monitoring, with meters feeding data into the system, advanced analytics, and a complete view of the water life cycle, including sourcing, transportation, recycling, and disposal. The application allows for precise tracking of water volumes by source, dynamic scheduling, leak detection, and comprehensive inspections, all of which contribute to improved operational efficiency and reduced environmental impact. Insights gained through this system include optimized water usage, higher recycling rates, and consistent regulatory compliance. Ultimately, the digitized platform provides a robust, scalable solution for enhancing the efficiency, sustainability, and regulatory compliance of water management in hydraulic fracturing operations.

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