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# A Water Stewardship Evaluation Model for Oil and Gas Operators

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**Abstract**

The rise of the unconventional oil and gas (UOG) industry over the last two decades has transformed the domestic energy outlook but raised concerns over environmental impacts. With the evolution of Environmental Social Governance (ESG) reporting allowing for a transparent view of oilfield operations, the evaluation of corporate sustainability has become increasingly feasible. Even with increased reporting, there have been very few quantifiable metrics for sustainable water management practices in the UOG industry due to the focus being primarily on methane emissions in recent years. This study aims to provide a practical, quantitative, and concise method (two-parameter based - Quadrant Plot) to evaluate UOG operators' performance in minimizing the negative impacts of freshwater use for drilling and fracking. Parameters (%Freshwater and %Salt Water Disposal) used in this performance matrix have been optimized to gather as much information as possible and while being compatible with operators' existing data collection. This study discusses how the Quadrant Plot could quantify the water performance using private and public data from over 20 unconventional oil and gas operators. This quantitative assessment not only enables the determination of a static performance score but also allows for the depiction of changes in performance over time.

**Keywords:** water-energy nexus, water management, environmental social governance, water stewardship, sustainable water management

## 1. Introduction

The wide application of horizontal drilling and hydraulic fracturing (HF) technologies has enabled the growth of oil and gas production from unconventional reservoirs (shale and tight formations) in the U.S. (Palisch, 2010; EPA, 2015). The U.S. Energy Information Administration (EIA) natural gas production data indicates that the share of shale gas in total natural gas production has increased from 52% in 2016 to 64% in 2020 (EIA Natural Gas Production) (EIA, 2023). Being the most water-intensive step in the shale gas exploration and production, hydraulic fracturing (HF) involves significant amounts of HF fluid comprising of water, sand, chemical additives, and other components (In-Sik Rhee et al, 1995; Gregory et al, 2011) being injected into the low-permeability and deep (usually greater than 1,500 m) shale formations to release natural gas and/or crude oil (Rahm, 2011; E. Micheal Thurman, 2014). The water used for HF ranges from 8,000 to 200,000 bbl (1,300 to 32,000 $m^3$) for shale gas wells and 50,000 to 60,000 bbl (8,000 to 10,000 $m^3$) for tight oil wells (Economides & Nolte, 2000).

According to FracFocus (https://www.fracfocus.org/index.php?p=data-download), supported by the Ground Water Protection Council (GWPC) and the Interstate Oil and Gas Compact Commission (IOGCC) (https://cogcc.state.co.us/data2.html#/downloads), HF activity peaked in 2014 and slowly decreased afterward. While the total water used for HF peaked around 2019, and water used per well has steadily increased since 2011 (Scanlon, 2020). Other than HF, other activities in UOG Exploration and Production (E&P) impact the water cycle, including the treatment and disposal of produced water (PW).

In general, corporate-level water management includes water sourcing, water handling (transport and storage), and wastewater (mainly PW) management (Rodriguez & Soeder, 2015; Yang et al, 2015; Kondash, 2018; Kindash and Vengosh, 2015), illustrated in Figure 1. Typically, water used for UOG E&P comes from sources such as rivers, lakes, and aquifers. Depending on the water's quality and source, this water could be categorized as potable, non-potable, and/or reused water. Potable water is freshwater used for drinking and is usually low in total dissolved solids (WW-C in Figure 1). Non-potable water is water that cannot be used for drinking and often is high in total dissolved solids (WW NC in Figure 1). Reused water for UOG is mainly the treated produced water (PW) generated together with the production of natural gas and crude oil (PW R in Figure 1). PW often contains high concentrations of dissolved solids, dissolved organic compounds, or some radioactive materials (Li, 2013). Eventually, PW will be reused (PW R in Figure 1) or injected into Salt-Water Disposal (SWD) wells (SWD in Figure 1). Direct disposal of PW to surface waters is rare and often has more restrictions (PW D in Figure 1) (Boschee, 2012; Jiang et al, 2022). Temporary water management facilities, including oil/gas/water separators and water storage tanks, only serve as the transit points, ultimately transferring water to end use or disposal. Water use and generation do not necessarily meet the mass balance at the field or well-site level.

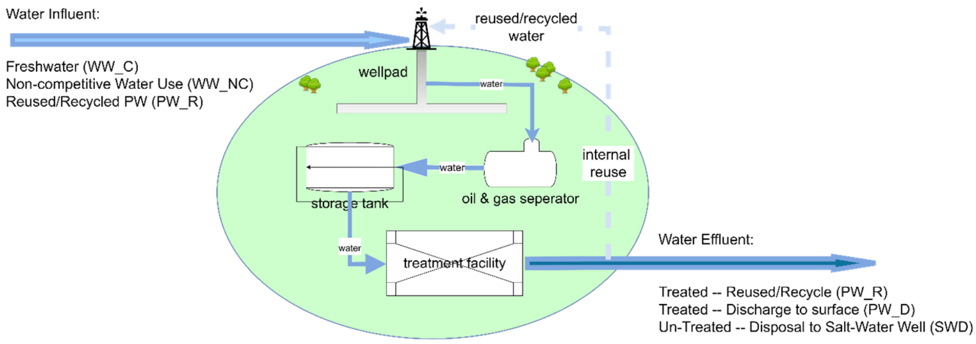


Figure 1. Water Footprint for UOG Upstream Operations

Both obtaining water and handling wastewater for UOG are significant challenges. Different geological settings are essential in determining where the UOG operators receive the required amount of water, either from surface water, groundwater, or reused water. For example, in the humid areas, such as the Marcellus-Appalachia basin, operators obtain their source water mainly from nearby surface water sources (Pollyea et al, 2020; Arthur, 2009; Allen, 2013). While in semi-arid basins, such as West Texas, operators utilize groundwater (fresh and brackish) and reused produced water as their primary sources (Lee, 2002; Snee & Zoback, 2018). Besides sourcing water, dealing with the large volume of PW is also challenging. Studies have shown that the disposal of PW in SWD wells has been related to the increased seismicity in some UOG plays (Weingarten et al, 2015; Hsi et al, 1994; Keranen et al, 2013).

Multiple metrics have been developed in the Environment, Social, and Governance (ESG) evaluation process (Li et al, 2021; Steinwinder, 2022), including water stewardship programs. Water resource managers in the UOG industry are responsible for managing and preserving water resources to ensure long-term sustainability (Hogeboom et al, 2018; Sami & Grant, 2018). Optimal environmental-friendly water management involves:

(1) Minimizing negative impacts on water quality and availability.

(2) Promoting efficient use of water resources.

(3) Addressing water-related risks and challenges.

There are an increasing number of companies and organizations that incorporate water stewardship into their ESG strategies, including The Alliance for Water Stewardship (AWS), Water Footprint Network (WFN), ISO-14046, CEO Water Mandate, Water Futures Partnership (WFP) and the Water Resources Group (WRG) (Hepworth & Orr, 2013). Deficiencies of the existing water stewardship programs include:

(1) Most of the existing water stewardship scoring systems are qualitative and there is no uniform standard across organizations. Without standards and a third-party assuring accuracy, it is difficult to compare the effectiveness of water sustainability strategies across different companies.

(2) Most current water stewardship programs have been widely adopted across various industries without specific focus, and therefore do not allow for the development of best practices.

This study aims to describe a water sustainability evaluation method (as a part of our water stewardship program) for the oil and gas industry that is easy to use and based on company data rather than objective questions. Our research seeks to offer quantitative metrics that will allow comparative analyses and the development of best practices based on company-supplied data across the many diverse UOG regions in the US. A significant obstacle to achieving this objective has been that company-supplied water data is challenging to obtain. Although many UOG operators have some degree of reporting in their annual ESG reports, the water data can be coarser than required for a spatial and temporal in-depth analysis. Therefore, instead of using a complicated data model (which needs multiple input parameters) to assess the performance of oil and gas operators, this study discusses one possible solution to fill the gap between real-world application and data-driven quantitative measurement. Our concise but practical model is based on easily obtained data sets and relatively simple metrics and analyses to maximize the information from the limited data to give a holistic evaluation of water management.

## 2. Method

### *2.1 Data*

The data used for this study comes from multiple sources, such as private data and open-source data from states or published ESG reports. Being a part of the Freshwater Friendly attribute of the Responsibly Sourced Gas certification program at Project Canary (https://www.projectcanary.com/white-paper/certification-of-freshwater-resource-use-as-part-of-a-responsibly-sourced-gas-esg-strategy/), the private data has been collected directly from the UOG operators. Therefore, we can get the quarterly water management data in specific UOG basins. Compared with this high-resolution private data, public data is raw with more extended time (annual) and coarse spatial representation (company-wide, not basin specific). As a case study, we attempted to use all available data to illustrate and test our methodology.

### *2.2 Parameter Selection*

$$\%FW = \frac{WW\_C}{WW\_C+WW\_NC+PW\_R} \tag{1}$$

(WW_C - Freshwater; WW_NC – Non-Competitive Water Use; PW_R – Reused/Recycled Produced Water)

$$\%SWD = \frac{SWD}{PW} \tag{2}$$

(SWD - Salt-water Disposal; PW- Produced Water)

%FW (%Freshwater Use) and %SWD (%Salt-water Disposal) are the few water-related data the operators track. % FW in Equation 1 is how much freshwater has been used as a percentage of the total water used. %SWD in Equation 2 is the fraction of PW (Produced Water) disposed to SWD wells.

The two figures below explain why we use the percentages not the absolute volumes. Figure 2 shows the freshwater use (left axis) and %FW (right axis) over time for 7 UOG operators. The bar plot represents the %FW, and the stepped line represents the volume of freshwater consumption. For operators 2, 3, 4, and 6, %FW positively correlates to the importance of freshwater use, but for operators 1, 5, and 7, the change of freshwater use in volume does not show the same trend for %FW. The amount of freshwater consumption broadly indicates the intensity of drilling and HF but does not reflect the effort to make water management more environmentally friendly. Therefore, to evaluate water management performance, we use the fraction of freshwater consumption of the total water used.

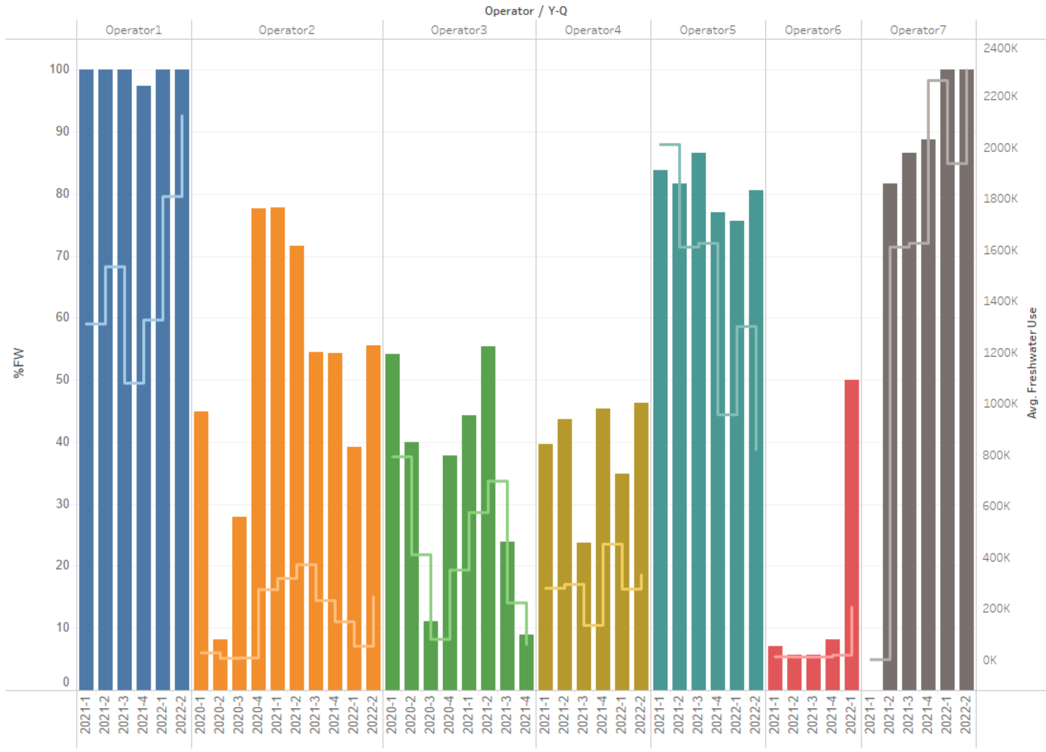


Figure 2. Freshwater use and %FW vs. time for some operators.

(Bars -- %FW; stepped line – freshwater use)

Similar to the findings in Figure 2, Figure 3 demonstrates a disparity between the amount of generated PW and the quantity of untreated PW that is disposed of (%SWD). In the case of Operator 9 (labeled as "Op9" in Figure 3), the total volume of PW (indicated by the brown line) increased between Q1 2022 and Q2 2022, while the %SWD (represented by the brown bars) decreased, implying a more efficient method of water disposal. Hence, this study employed percentages, specifically %FW and %SWD, instead of absolute quantities to evaluate water management performance.

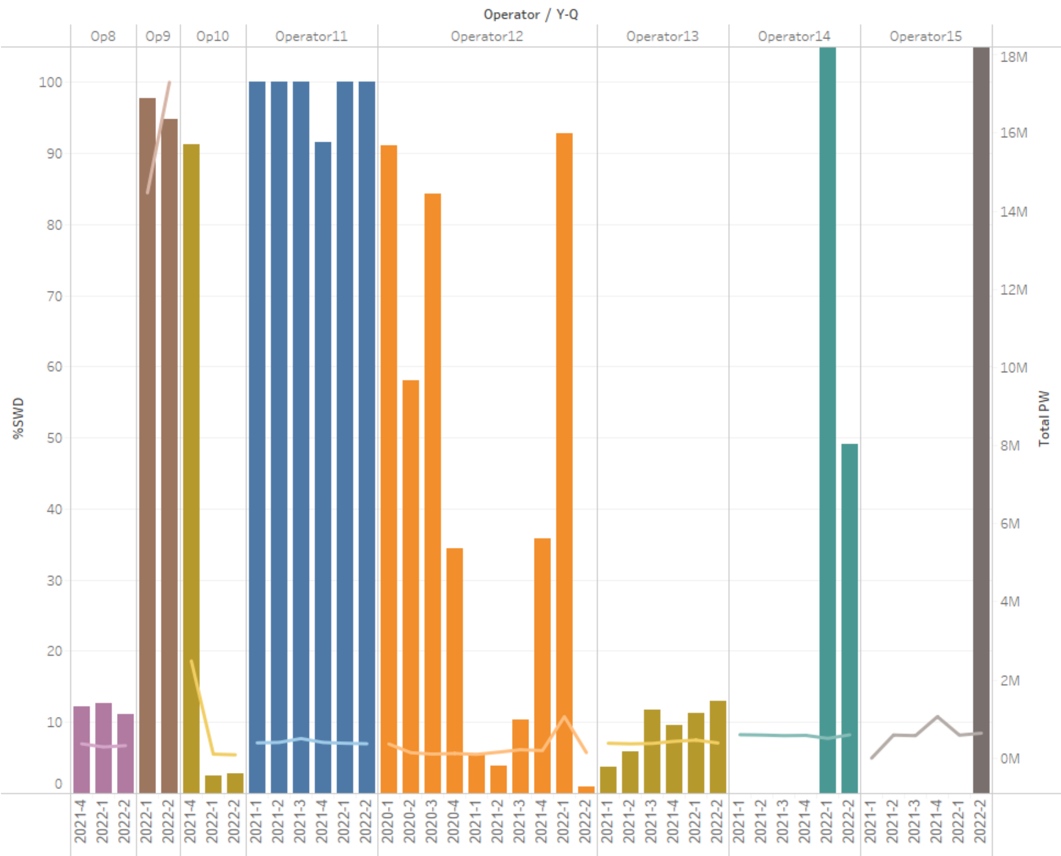


Figure 3. Total PW and %SWD vs. time for some operators.

(Bars -- %SWD; stepped line – total PW)

Additionally, %FW and % SWD could indicate the different vulnerabilities (freshwater stress and seismicity, respectfully). %FW could demonstrate the impacts on local water stress and oil and gas use crowding out other beneficial users. Because freshwater is a "limited" source and has been prioritized for drinking, irrigation and/or municipal use, the more freshwater used for UOG, the more competitive it will be for the UOG operators to obtain freshwater locally. Therefore, the less %FW is, the less influence the oil and gas activity will have on local freshwater sourcing. %SWD reflects the potential risk of induced seismicity related to wastewater disposal. Because PW (or flowback) contains high concentrations of salts, organic matter, and some other components that do not commonly exist in freshwater or drinking water, through the lifespan of a well PW will be continuously produced, and will amount to significant wastewater volumes. Dealing with PW has raised many concerns including increased seismicity due to the enormous injection into the subsurface. Some studies have shown the possible relationship between significant wastewater injection and seismic activity (Snee & Zoback, 2018; Weingarten et al, 2015; His et al, 1994; Keranen et al, 2013). Hence, the low %SWD and %FW combination will be favorable and represent optimal water management.

Performance Indicator, *D*, is the integrated parameter of %FW and %SWD, which is the Euclidean distance to the origin point. *D* represents how far away an operator's management metrics deviates from optimal water management with 0 %SWD and 0 %FW (Eq 3). Lower D values correspond to a lower risk of water stress and induced seismicity due to UOG water management.

$$D = \sqrt[2]{(\%FW)^2 + (\%SWD)^2} \quad (3)$$

*2.3 Model Visualization*

As a continuous study of a water stewardship program, we introduce the Quadrant Diagram as a tool to visualize and compare three key parameters, %FW, %SWD, and across different UOG operators. The diagram, shown in Figure 4 below, is divided into separate sections that highlight various water management features. The resulting four quadrants are labeled as follows:

(1) The lower-left quadrant, A, represents the "optimal" quadrant with minimal freshwater use and salt-water disposal.

(2) The lower-right quadrant, D, signifies the "High FW & Low SWD" quadrant, characterized by low salt-water disposal but high freshwater use.

(3) The upper-left quadrant, B, corresponds to the "Low FW & High SWD" quadrant, characterized by high salt-water disposal but low freshwater use.

(4) The upper-right quadrant, C, referred to as the "High FW & High SWD" quadrant, is the least desirable water management quadrant as it involves high freshwater use and high salt-water disposal.

The Quadrant Diagram visually represents the different water management strategies employed by UOG operators and facilitates a comparison of their respective performances.

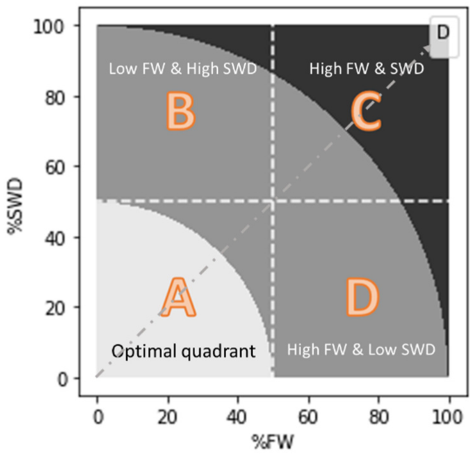


Figure 4. Quadrant Performance Plot

Depending on the different geographical locations, falling into quadrants B and D will have distinct approaches to improve water management and different priorities. For example, New Mexico produces nearly 454 million barrels of PW yearly during oil and gas production, creating water handling issues (Lee, 2022). Therefore, the oil and gas fields that produce large amounts of water may fall into quadrants B or C, depending on freshwater use, facing significant SWD challenges. For basins that have limited SWD well capacity and/or produce small amounts of water, such as parts of the Marcellus Basin, operations may reside in quadrant D resulting in a different set of challenges. And reducing the percentage of freshwater use will not be a top priority as reducing SWD in these regions. But in arid areas where freshwater is limited, optimizing %FW will be more important than optimizing %SWD.

The grey-scale colored rings on this plot represent the “Performance Indicator,” D, to compare the different operators on top of the four quadrants. The smaller the D, the better performance based on this set of metrics.

This colored contoured quad plot (Figure 4) could be used to evaluate how well an oil and gas operator manages their water and the best practices for an operator to improve their performance according to this metric. The inner white tier, “Tier 1” (D less than 50), is the most desirable area for water management (low %FW and %SWD). The outer black tier, “Tier 3” (D more significant than 100), is the least desirable area for water management.

## 3. Results

### *3.1 Case Studies of Quadrant Performance Plot*

The available data has been plotted in Figure 5. Pennsylvania (PA) has limited salt-water disposal (SWD) options due to its geological structure (Rodriguez & Soeder, 2015) and local water management policies. Consequently, operators in PA have resorted to transporting PW for disposal in neighboring states or reusing/recycling it within PA. Internal water reuse can also contribute to a reduction in the %FW utilized during operations. Moreover, external water sharing, or water reuse, among operators in the oilfield is a promising alternative. In Texas and New Mexico, some UOG operators are also exploring the limitations of reusing and/or sharing produced water to mitigate induced seismicity. These initiatives reduce the volume of water that requires disposal and contribute to a more sustainable water management approach.

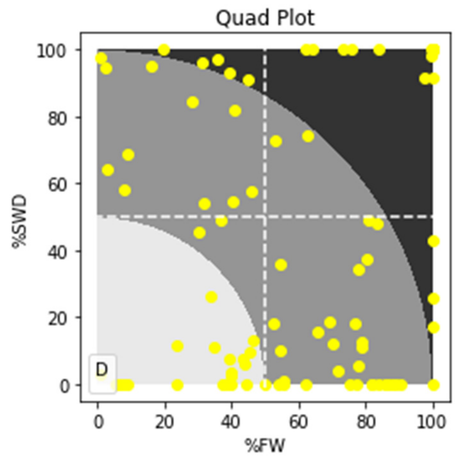


Figure 5. Example of Quadrant Performance Plot

Figures 6 and 7 illustrate quadrant performance plots for two individual operators (Operator 1 & Operator 2), using orange dots to represent quarterly data and yellow dots to represent annual aggregated data from publicly available data sources. Notably, operational planning can cause significant seasonal variations that affect the "Performance Indicator," D. To facilitate a longitudinal analysis of an operator's water management practices, we have plotted their performance paths (orange and yellow lines as well as black arrows) in chronological order, as demonstrated in Figures 6 and 7.

Figure 6 shows the water management performance for Operator 1. The data points for Operator 1 are primarily clustered in "Tier 1" and the "Optima" quadrant, characterized by low %FW and low %SWD. This suggests Operator 1 has an efficient water management system with minimal freshwater use and salt-water disposal.

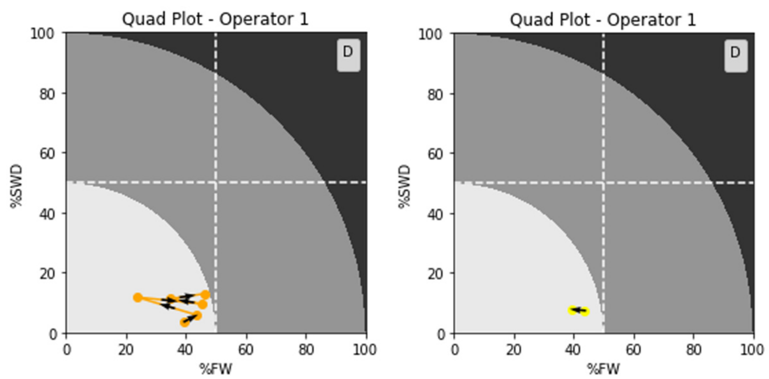


Figure 6. Water management performance for Operator 1

(left – quarterly data, right – annual aggregated data

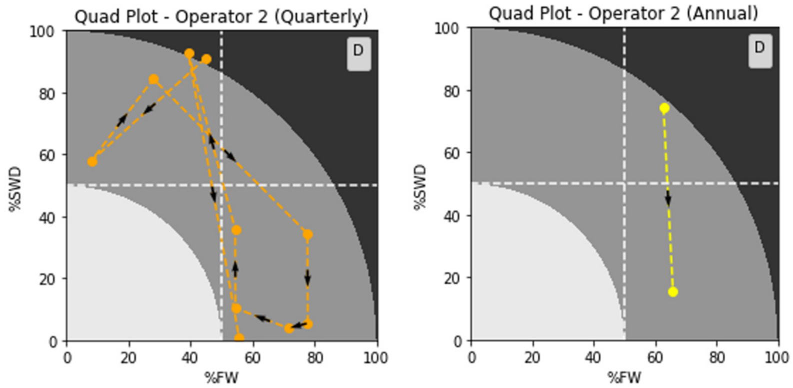


Figure 7. Water management performance for Operator 2
(left – quarterly data, right – annual aggregated data)

By analyzing the data presented in Figures 6 and 7, we can track an operator's performance over time and identify the factors that contribute to their water management practices. Figure 7 shows the performance of Operator 7. Most of the quarterly data points for Operator 2 fall into "Tier 2", with two exceptions in Tier 3 for 2020 Q1 and 2022 Q1, during which there were fewer drilling and fracturing activities, and more than 90% of the wastewater was sent to SWD. The starting point for Operator 2 is in quadrant B & Tier 3 but experiences a significant improvement in the next quarter. The operator shifted from high SWD operations to high FW operations, oscillating between the two over time. The annual data shows a clear improvement from 2020 to 2021, with a 30% reduction in D and a 78% reduction in %SWD. This Quadrant Performance plot is an effective tool for visualizing an operator's performance in terms of %FW, %SWD, and D. These insights can be used to inform future decision-making and improve the overall sustainability of UOG operations.

### *3.2 Relationship between the Performance Indicator D and Freshwater Replacement Ratio FR^2*

As a continuous study of the development of quantitative methodologies of the water stewardship (Carlson et al, 2022), "Freshwater Replacement Ratio", FR2, has been introduced to quantify the stress of the UOG operations on local water supplies. The equation used to calculate FR2 is shown below,

$$FR\hat{}2 = \frac{WW\_NC + PW\_R + CC + PW\_D}{WW\_C} \tag{4}$$

(Numerator: WW_NC – Non-Competitive Water; PW_R – Reused/Recycled Produced Water; PW_D – Produced Water treated and discharge to surface; Denominator: WW_C -- Freshwater)

Since CC (Conservation Credit) is incorporated into the calculation of FR2 but has not been included in the calculation for D, this parameter would be a key factor impacting the relationship between FR2 and D. While for most of the cases, CC is close to zero, the inverse of D square would be positively related to FR2. The larger the D, the smaller the FR^2.

$$\frac{1}{D^2} \propto FR\hat{}2 \tag{5}$$

Figure 8 illustrates the relationship between D and FR2. The colors in figure 8 represent the ratio of PW and total Water Use (WW). Ratio of PW and WW, PW/WW, could indicate whether this is a wet play/basin or a dry play/basin. Green data points represent the ratio of PW/WW less than 1, meaning that less PW has been generated than the total WW, and blue data points have the ratio of PW/WW greater than 1, with the maximum value of 188 (a "wet" or high PW field).

All the data follow a power relation between D and FR2. The quarterly data shown implies a positive relationship between FR2 and $1/_{D^2}$. Points above the trendline indicate "good" water managements (better than expected) with higher FR2 than expected. Points below the trendline indicate a "bad" water management with lower FR2 than expected.

The PW/WW ratio is greater than 1 for most of the outliers above the power trendline (better performance than expected). The large quantity of PW could make water reuse and recycling more economical and practical. Therefore, those operations have higher FR^2 than expected.

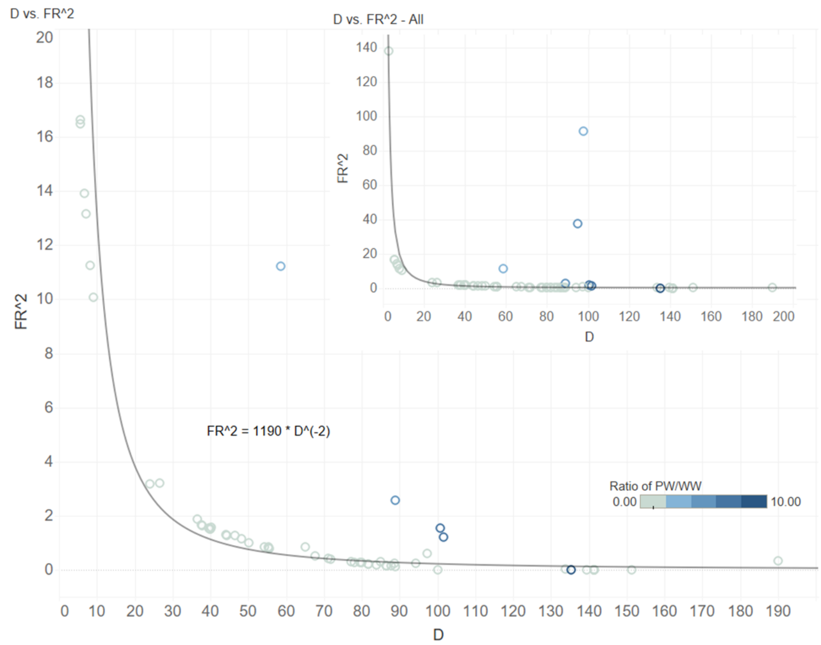


Figure 8. Correlation between D and FR^2 for different data sources

The two most important scoring criteria of our water stewardship metrics, FR^2 and *D* have different approaches to evaluate the water management for an oil and gas operator. FR^2 focuses on the effort to replace freshwater with other "non-competitive" waters, such as brackish water and reused water. D is an integrated score to evaluate the impact on local freshwater resources and potential for induced seismicity.

## 4. Conclusion

The oil and gas industry has garnered increased attention on its water management as part of Environmental, Social, and Governance (ESG) considerations, given the spatially inhomogeneous distribution of freshwater, water stress, water use, and induced seismicity due to wastewater injection. In this study, we have developed a quantitative evaluation methodology to assess UOG water management as one part of a water stewardship program. Our approach utilizes real-world data to evaluate UOG operators' strategies in managing freshwater and wastewater, focusing on %FW, %SWD and performance indicator "D" as critical parameters. The Performance Quadrant Plot, which integrates these three parameters, can assign UOG operators to different quadrants and track their progress over time, offering suggestions for improvement based on data. By assessing localized vulnerability to freshwater stress and human-induced earthquakes, we can establish a more sustainable water management reference for the UOG industry. While there are some limitations due to the early stage of data collection, we are confident that with the continued development of this program with UOG operators, we will gain comprehensive data-driven insights that can inform sustainable water management practices in the industry.

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