PV Plants Water Use: Strategies for Environmental and Social Risk Management

(Beyond Water Consumption: Data Quality, Water Stewardship and Environmental & Social Risk Management in Utility-Scale Photovoltaic Projects)

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1 INTRODUCTION

1.1 BACKGROUND

The rapid deployment of utility-scale photovoltaic (PV) projects is a cornerstone of the global energy transition. Although PV technologies require substantially less operational water than conventional thermoelectric generation, water remains essential for panel cleaning and maintenance, particularly in arid environments where soiling losses are greatest (Macknick et al., 2011). Recent studies show that condition-based cleaning supported by soiling monitoring can reduce water demand while maintaining energy production and improving operational efficiency (Shahzad et al., 2025; Tsanakas et al., 2025).

However, low water intensity does not necessarily imply low environmental and social risk. The significance of water use depends on hydrogeological conditions, cumulative demand, governance capacity, and stakeholder perceptions rather than consumption volumes alone (Boeing et al., 2022). Consequently, even limited water withdrawals may become environmentally and socially significant in water-stressed regions.

Mexico provides a particularly relevant context. Utility-scale PV development has expanded across northern and central states—including Sonora, Chihuahua, Coahuila, Durango, Zacatecas, San Luis Potosí, and Aguascalientes—where exceptional solar resources coincide with arid climates, groundwater stress, and competing agricultural, industrial, and domestic water demands (ASOLMEX, 2024; CRE/CENACE, 2024; CONAGUA, 2024). National assessments indicate that 114 of Mexico's 653 aquifers are overexploited, while the WRI Aqueduct Water Risk Atlas classifies many of these regions as experiencing high to extremely high baseline water stress (CONAGUA, 2024; WRI, 2023).

Under these conditions, effective water stewardship requires more than operational efficiency. Governance quality, water-source traceability, regulatory compliance, and stakeholder engagement are equally important for strengthening Environmental and Social (E&S) performance and maintaining a project's Social Licence to Operate (IFC, 2012a; IFC, 2012b; GRI, 2021).

While previous studies have focused on water consumption and cleaning optimization (Macknick et al., 2011; Shahzad et al., 2025; Tsanakas et al., 2025), limited attention has been given to integrating Circular Water Management, environmental governance, and stakeholder engagement into Environmental and Social (E&S) Risk Management. This study addresses that gap through a qualitative comparative analysis of two utility-scale PV projects in Mexico and proposes the Integrated Circular Water Management and Water-Risk Engagement Framework (MGCR-H).

1.2 RESEARCH OBJECTIVE

The objective of this study is to evaluate how water management practices influence Environmental and Social (E&S) performance in utility-scale photovoltaic projects operating in water-stressed regions of Mexico through a qualitative comparative analysis of two operating facilities. The study examines Circular Water Management, resource efficiency, governance, stakeholder engagement, and water-source traceability to identify transferable practices and develop the Integrated Circular Water Management and Water-Risk Engagement Framework (MGCR-H), aligned with Mexican regulations, IFC Performance Standards, the World Bank Group General EHS Guidelines, and GRI 303.

2 METHODOLOGY

2.1 STUDY DESIGN

This research adopts a qualitative comparative case study approach to examine how water management practices influence Environmental and Social (E&S) performance in utility-scale photovoltaic (PV) projects operating under different hydrogeological conditions. A case study methodology was selected because it enables the investigation of complex operational and governance processes within their real-world context while integrating multiple sources of evidence (Yin, 2018).

2.2 CASE STUDY SELECTION

Two operating photovoltaic facilities monitored by RINA were selected because they represent contrasting environmental and operational conditions.

The first case study is a PV plant in Navojoa, Sonora (257 MW), located over the Fuerte–Mayo aquifer, where groundwater availability remains positive but shows a declining trend. The second case study comprises a PV Plant in Aguascalientes (290 MW). Although located within the El Llano aquifer, this facilitie operates in one of Mexico's principal PV development clusters, where cumulative groundwater deficits exceed 136 hm^3/year, creating a more restrictive regional water context.

2.3 DATA COLLECTION

Evidence was triangulated using multiple qualitative sources, including:

- ✓ Environmental and social monitoring activities conducted by RINA between 2021 and 2025;
- ✓ Site observations and technical discussions with project personnel;
- ✓ Water-consumption records, cleaning documentation, and contractor information where available;
- ✓ Public hydrogeological information from CONAGUA and other Mexican authorities;
- ✓ Mexican environmental regulations and international ESG standards, including the IFC Performance Standards (PS1 and PS3), the World Bank Group General EHS Guidelines, and GRI 303 (Water and Effluents).

The combination of documentary evidence, field observations, and stakeholder interactions strengthened the reliability of the qualitative assessment through data triangulation (Yin, 2018).

2.4 ANALYTICAL FRAMEWORK

The comparative analysis assessed the technical and governance dimensions of water management using qualitative indicators related to:

- ✓ hydrogeological context;
- ✓ cleaning strategy and operational efficiency;
- ✓ water-source traceability;
- ✓ environmental data quality;
- ✓ contractor management;
- ✓ stakeholder engagement;
- ✓ governance practices; and
- ✓ resource-efficiency measures.

The findings informed the development of the Integrated Circular Water Management and Water-Risk Engagement Framework (MGCR-H), integrating adaptive management, governance, resource efficiency, and stakeholder engagement to strengthen water stewardship.

3 RESULTS AND DISCUSSION

The comparative assessment shows that effective water stewardship depends not only on reducing water consumption but also on the maturity of water management systems, environmental data quality, and governance practices (Table 1).

Table1. Comparative Summary of the Two Case Studies

Variable	Case Study 1 – Navojoa, Sonora	Case Study 2 – El Llano, Aguascalientes
Installed capacity	257 MWp (200 MW AC)	290 MW AC (150 MW + 140 MW)
Approximate PV modules	674,772 (~675,000)	~1,000,000
Climate	Arid	Semi-arid
Hydrogeological context	Fuerte–Mayo Aquifer (positive availability; declining trend)	El Llano Aquifer; regional groundwater deficit >136 hm³/year
Cleaning frequency	~9 months/year	~2 campaigns/year
Cleaning strategy	Fixed schedule	Condition-based
Soiling monitoring	Limited	Weekly
Rainfall considered in cleaning decisions	No	Yes
Water consumption records	Inconsistent (reported values ranged from approximately 1.6–3.75 L/module/year depending on the information source)	Verified (0.45–0.84 L/module/campaign)
Operational recordkeeping	Incomplete	Comprehensive
Water source traceability	Limited	Verified
Contractor supervision	Limited	Continuous monitoring
Resource Efficiency Plan	No	Yes
Operational decision-making	Reactive	Adaptive
Main E&S findings	Weak governance; limited traceability	Adaptive governance; operational resilience

Note. The groundwater deficit reported for Aguascalientes (>136 hm³/year) represents cumulative regional groundwater stress rather than conditions within the El Llano aquifer alone. The comparison focuses on differences in water management maturity and environmental data quality instead of direct quantitative comparisons of water consumption.
Source. Authors' elaboration based on RINA Environmental and Social Monitoring Reports (2021–2025), project operational documentation, field observations, stakeholder interviews, and hydrogeological information published by CONAGUA (2025).

The first case study is a 257 MWp (200 MW AC) utility-scale PV plant located in Navojoa, Sonora, over the Fuerte–Mayo aquifer, where groundwater availability remains positive but shows a declining trend according to CONAGUA. As summarized in Table 1, cleaning activities were conducted during approximately nine months of the year using water supplied mainly by third-party contractors. Reported water-consumption values ranged from approximately 1.6 to 3.75 L/module/year depending on the information source, revealing inconsistencies in operational records. Limited verification of water suppliers and extraction permits, incomplete cleaning documentation, visible water losses during cleaning, and the absence of a formal Resource Efficiency Plan reduced data reliability and constrained adaptive management. These findings indicate that the principal challenge was not the volume of water consumed itself, but the lack of reliable and traceable environmental information required to support evidence-based decision-making, responsible water stewardship, and effective Environmental and Social (E&S) Risk Management.

The second case study is located in Aguascalientes, within one of Mexico's principal PV development clusters, where cumulative groundwater deficits exceed 136 hm³/year. Condition-based cleaning supported by weekly soiling monitoring, verified water sourcing, contractor performance evaluation, and comprehensive operational records reduced cleaning frequency to approximately two campaigns per year while maintaining operational performance. Documented water consumption ranged between 0.45 and 0.84 L/module per cleaning campaign, consistent with recent studies demonstrating the effectiveness of adaptive cleaning strategies (Shahzad et al., 2025; Tsanakas et al., 2025).

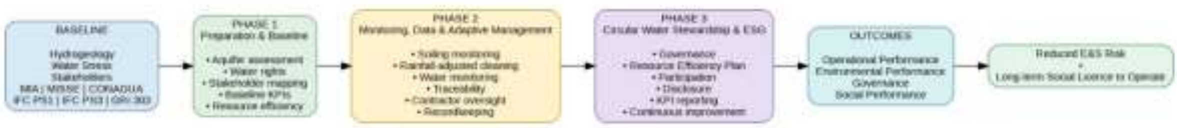
Beyond technical performance, the comparison highlights important environmental and social implications. Water-related risks were found to depend less on absolute water consumption than on water-source traceability, transparency, and governance. In the Navojoa case, limited documentation regarding third-party water suppliers and extraction permits increased uncertainty and reduced confidence in environmental performance.

From a social perspective, the study indicates that conflicts surrounding water use are often driven by perceptions of inequity rather than by actual water demand. In water-stressed regions, the use of third-party water tankers without verified permits or documented sources may generate institutional distrust and weaken the project's Social Licence to Operate, even when operational water consumption remains relatively low. These findings highlight the importance of integrating technical efficiency with stakeholder engagement, transparent disclosure, and accountable water supply chains (IFC, 2012a; IFC, 2012b; Boeing et al., 2022).

Adaptive cleaning supported by environmental monitoring improves operational resilience while generating reliable information for evidence-based Environmental and Social Risk Management.

Based on these findings, this study proposes the Integrated Circular Water Management and Water-Risk Engagement Framework (MGCR-H) (Figure 1), which integrates adaptive monitoring, Circular Water Management, governance, stakeholder engagement, and continuous improvement into a practical approach for utility-scale photovoltaic projects. Rather than focusing exclusively on water consumption, the framework emphasizes that effective water stewardship depends on reliable environmental information, water-source traceability, transparent governance, and stakeholder trust. By combining these elements within Environmental and Social (E&S) Management Systems, the MGCR-H framework strengthens evidence-based decision-making, operational resilience, and long-term Social Licence to Operate.

Figure 1. Integrated Circular Water Management and Water-Risk Engagement Framework (MGCR-H) for Utility-Scale Photovoltaic Projects



Operationalizing the MGCR-H Framework

To operationalize the Integrated Circular Water Management and Water-Risk Engagement Framework (MGCR-H), this study proposes a concise set of Key Performance Indicators (KPIs) integrating technical performance with Environmental and Social (E&S) governance. Beyond measuring water consumption, the KPIs support adaptive management by evaluating operational efficiency, water-source traceability, regulatory compliance, and social legitimacy, consistent with IFC Performance Standards 1 and 3 and GRI 303: Water and Effluents (IFC, 2012a; IFC, 2012b; GRI, 2021).
The KPIs address three complementary dimensions: (i) traceability, including verified water suppliers and documented water origin; (ii) social performance, including reported water shortages and a Social Legitimacy and Trust Index; and (iii) operational performance, including water intensity (m^3/MW/year), condition-based cleaning, and water savings achieved through soiling monitoring (IFC, 2012a; Boeing et al., 2022; Shahzad et al., 2025; Tsanakas et al., 2025).
Together, these KPIs support Circular Water Management, adaptive decision-making, transparent governance, and long-term Social Licence to Operate (IFC, 2012a; Boeing et al., 2022).

Study Limitations and Future Research

The findings should be interpreted within the scope of a qualitative comparative case-study approach, which seeks analytical rather than statistical generalization (Yin, 2018). The analysis was limited to two operating facilities and the availability of environmental monitoring data, particularly historical water-consumption records and third-party water-source traceability. These limitations highlight the importance of reliable environmental information for adaptive water management and Environmental and Social (E&S) Risk Management.
Future research should validate the MGCR-H framework across a broader portfolio of photovoltaic projects monitored by RINA. Combining these datasets with stochastic approaches, including Monte Carlo simulations, would enable quantitative assessment of uncertainty associated with soiling, rainfall variability, groundwater availability, cleaning strategies, and climate change, providing stronger decision-support tools for evidence-based water stewardship.

4 CONCLUSIONS

This study demonstrates that effective water stewardship in utility-scale photovoltaic (PV) projects depends not only on minimizing water consumption but also on integrating Circular Water Management, resource efficiency, environmental governance, and stakeholder engagement into Environmental and Social (E&S) Management Systems. The qualitative comparison of two operating PV facilities in Mexico showed that environmental and social performance is influenced primarily by the maturity of water management systems, environmental data quality, governance practices, and water-source traceability rather than by hydrogeological conditions alone. While the Navojoa case highlighted the consequences of limited environmental information and weak supply-chain traceability, the Aguascalientes case demonstrated how adaptive, monitoring-based management can improve operational resilience and water stewardship even under greater regional groundwater stress.

The proposed Integrated Circular Water Management and Water-Risk Engagement Framework (MGCR-H) provides a practical approach for integrating hydrogeological assessment, adaptive monitoring, transparent governance, stakeholder engagement, and continuous improvement into utility-scale PV operations. By shifting the emphasis from measuring water consumption alone to managing water-related environmental and social risks, the framework supports evidence-based decision-making, strengthens Environmental and Social Risk Management, and reinforces long-term Social Licence to Operate.

The findings establish a foundation for future quantitative validation using RINA's broader portfolio of monitored photovoltaic projects, where stochastic approaches such as Monte Carlo simulations can be applied to evaluate uncertainty associated with climate variability, groundwater availability, cleaning strategies, and operational performance, thereby supporting more robust decision-making for Environmental and Social Risk Management.

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