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WATER MANAGEMENT IN THE MEZCAL INDUSTRY: GOVERNANCE AND COOPERATION IN SOLA DE VEGA

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ABSTRACT

The rapid expansion of the mezcal industry in Oaxaca coincides with increasing pressure on regional aquifers, as the artisanal process consumes on average 8 to 10 liters of water per liter of distillate. This study analyzes how community cooperation, local governance mechanisms and technological adoption condition water sustainability in Sola de Vega. A sequential explanatory mixed design was used. In the quantitative phase (July-August 2024) a validated 18-item Likert questionnaire was applied to 40 mezcal producers, which yielded a Cronbach's alpha $\alpha = 0.90$. An exploratory factor analysis and Dendogram with a KMO = 0.74, where four factors were extracted: Participation and Rules (PAR), Collaborative Water Planning (PLA), Technical-Environmental Management (TEC) and Cohesion-Confidence (COH), which explain 71% of the variance. A Shapiro-Wilk normality test was also performed where a p-value < 0.05 was observed, indicating that they do not follow a normal distribution, in turn the Spearman Correlations showed that TEC is negatively associated with the water footprint ($\rho = -0.64$; $p < 0.001$). The qualitative phase (September 2024) included 20 semi-structured interviews and participant observation; 148 codes and three central categories were generated: These were represented by a word map where the recurrent words "Broken trust", "Shared technology" and "Caring for the spring" were found. And a third confirmatory phase of qualitative and quantitative data in April 2025.

It is concluded that the combination of participatory governance, social cohesion and formal planning catalyzes technological adoption, significantly decreasing the water footprint. Fiscal incentives conditional on communal agreements, revolving funds managed by assemblies and itinerant intercultural training modules are recommended.

KEYWORDS: Mezcal, Water Governance, Cooperation, Sustainability.

1. INTRODUCTION

The mezcal agroindustry is experiencing its greatest boom: national production increased from 2.6 million liters in 2010 to 9.1 million liters in 2023, with a compound annual growth of 11.4% (CRM, 2024). The boost comes from the Denomination of Origin, global demand for artisanal distillates and ethnogastronomic tourism (INEGI, 2024). However, this economic progress contrasts with water availability. The Water Atlas reports that 7 of the 10 most exploited aquifers in Oaxaca are located in the Sierra Sur and Valles Centrales, mezcal regions par excellence (CONAGUA, 2023). Rainfall was reduced by 12% between 2001 and 2021 and water recharge decreased by 9% (IMTA, 2023).

Artisanal mezcal production requires between 8 and 10 liters of water per liter of distillate for cooking, fermentation, condensation and cleaning (Escamilla, Díaz, & López, 2022); palenques without recirculation can exceed 14 liters. Given this intensive consumption, water efficiency has become a critical indicator of sustainability (UNESCO-WWAP, 2020).

Water resource management in rural contexts depends on local rules and forms of cooperation (Ostrom, 1990). Latin American studies show that normative clarity, participation in assemblies and social trust increase compliance with agreements (Meinzen-Dick, 2022). In artisanal distilleries in Jalisco, community cohesion explained 38% of the variance in the adoption of saving technologies (Ramírez-López, Jiménez, & Torres, 2022). The "adaptive governance" approach argues that diverse actors, polycentric networks and social learning allow responding to hydrological variability (Folke, Biggs, & Norström, 2023).

Sola de Vega, one of the largest mezcal-producing municipalities, preserves the community tequio system for water works and spring cleaning (Martínez-Luna, 2021). Half of the palenques in this region operate on common lands and decision-making is done in agrarian assemblies. However, recent conflicts over overcharging of the "El Ocotal" spring illustrate the fragility of the agreements (García-Márquez et al., 2023). The coexistence of customary norms and federal regulations creates an ideal environment to analyze the interaction between social cooperation, water planning and technological adoption.

Despite the mezcal boom, quantitative-qualitative studies linking governance, trust and water efficiency in artisanal production contexts are lacking. Research is concentrated in regions with greater mechanization (Guanajuato, Jalisco) or is limited to life-cycle analyses without considering social variables (González-Sánchez & Leyva, 2022). Hence the need to address the question: how do community cooperation and water planning influence the adoption of water-saving technologies and, therefore, the reduction of the water footprint of mezcal.

The objective of this research is to analyze how community cooperation, governance mechanisms and the adoption of water efficiency affect the water sustainability of the mezcal industry in Sola de Vega.

The research hypothesis is that community cooperation and local water governance have a significant impact on the water sustainability of mezcal communities by strengthening collective planning, technological adoption and equity in access to water resources.

2. LITERATURE REVIEW

High Water Consumption in Mezcal Production

The mezcal production process is water intensive. According to the Mezcal Regulatory Council (2020), each liter of mezcal requires between 8 and 10 liters of water, used in stages such as agave cooking, fermentation, and distillation. With annual production exceeding 6 million liters in Oaxaca and a 30% growth in exports in the last five years, the sector's water demand is significant. This increase has intensified pressure on water resources in the main producing areas.

Water scarcity in Oaxaca exacerbates this challenge. In the last two decades, rainfall has decreased by 12%, affecting the recharge of local aquifers and generating more erratic rainfall patterns due to climate change. This impacts both the availability and quality of water, increasing dependence on surface and groundwater sources. Small producers, particularly in Santiago Matatlán, face greater difficulties in accessing quality water, unlike large producers who can invest in catchment and storage infrastructure (Meinzen-Dick, 2021).

In response, the Mexican government has implemented policies such as the National Water Law and created the National Water Commission (CONAGUA) to regulate aquifer exploitation and encourage rational water use. However, these measures have shown limitations in their application, especially in regions such as the Tlacolula valley, where fragmented governance makes compliance with regulations difficult. Zeitoun et al. (2020) note that 60% of wells used by mezcal producers operate without a valid concession, reflecting institutional weaknesses in water management.

The government of Oaxaca has launched projects such as the construction of dams, rainwater harvesting systems, and watershed conservation programs. A prominent example is the Program for Conservation and Sustainable Use of Water in Mezcal Production, implemented in 2019 together with the National Water Commission, to train producers in sustainable practices such as efficient irrigation. No however, lack of funding has limited its reach to only 25% of producers in the region (Giné et al., 2020).

Challenges in Government Intervention

One of the biggest challenges in water management in Mexico is the lack of coordination between the different levels of government and local stakeholders. Although national policies establish clear guidelines on water use and conservation, their application at the local level is deficient. In Oaxaca, where mezcal production depends on community resources, decisions are often made in a decentralized manner, making it difficult to implement uniform policies (Meinzen-Dick, 2021). This decentralized model also creates tensions between producers, local governments, and federal authorities, delaying key infrastructure projects and exacerbating the water crisis.

The government has attempted to encourage producer participation through the creation of water management committees, but these efforts have had limited results due to lack of resources and adequate follow-up. Financing has also been a recurring problem, especially for small producers, who have difficulty accessing sustainability programs. The absence of significant fiscal incentives or subsidies has slowed the adoption of water-efficient technologies, perpetuating the use of traditional irrigation systems that are highly inefficient (Folke et al., 2019). Without coordinated actions and effective incentives, sustainability in mezcal production faces significant constraints.

Promoting Adaptive Governance Frameworks

A key opportunity to improve government intervention lies in promoting adaptive governance frameworks. This allows communities to adjust to fluctuating water availability through flexible decision-making systems, which is crucial in regions such as Santiago Matatlán, where climate change affects aquifer recharge and alters rainfall patterns. The establishment of watershed committees and the creation of community standards could facilitate greater participation of producers in resource management, promoting sustainable practices adapted to local conditions (Folke et al., 2019).

In addition, the government could offer tax incentives and subsidies for sustainable technologies such as rainwater harvesting and efficient irrigation systems, which would significantly reduce water consumption in mezcal production (Chen & Wang, 2020). However, access to these technologies remains limited for small producers, who rely on still insufficient financing schemes.

The water crisis in Oaxaca reflects global challenges associated with climate change, overexploitation and unequal access to water. More than 70% of the aquifers in Oaxaca are overexploited, according to the Mexican Institute of Water Technology (IMTA, 2021). Climate change has increased the frequency of extreme events, such as prolonged droughts, and reduced surface water availability, forcing an increasing dependence on groundwater (Smith & Pérez, 2020).

Despite policies such as the National Water Law, water infrastructure projects are hampered by a lack of coordination between levels of government and insufficient funding (Vega & Pérez, 2020). To address these challenges, adaptive governance and cooperation between producers, communities and NGOs are essential. Traditional community work structures, such as the tequio, can be strengthened to address the current crisis. Collaborative management through watershed committees and community water management groups can ensure efficient use of resources, encourage the adoption of sustainable technologies, and adapt decisions to local needs (Meinzen-Dick, 2021).

Institutional and Multilevel Cooperation

The multilevel governance approach, which involves interaction between different levels of government and nongovernmental actors, is crucial to address the water crisis. However, one of the main challenges is the lack of coordination between federal, state and local levels (Zeitoun et al., 2020). To overcome this barrier, it is necessary to foster spaces for dialogue and cooperation, such as intermunicipal water management committees and watershed networks, which respect the particularities of each region and facilitate the implementation of water conservation policies.

NGOs and academic institutions play an essential role in providing technical knowledge and experience in the adoption of sustainable technologies. These organizations can act as intermediaries between local stakeholders and authorities, promoting more efficient practices and facilitating access to financing. According to Garrido et al. (2021), collaboration with NGOs has

enabled small producers in Mexico to implement low-cost technologies, such as efficient irrigation systems, improving water management in agricultural sectors.

Cooperation between producers and external actors is key to sustainable water management. Shared financing programs, in which producers and government contribute to the implementation of technologies such as rainwater harvesting and drip irrigation, could facilitate this transition (UNESCO-WWAP, 2020). Technical cooperation between NGOs, universities and farmers also ensures that these technologies are adapted to local conditions. A relevant example is the Program for Conservation and Sustainable Use of Water in Mezcal Production, implemented in 2019, where collaboration between the government of Oaxaca and NGOs trained small producers in sustainable techniques. However, lack of funding has limited its impact, highlighting the need for adequate fiscal incentives and subsidies to scale up these initiatives (Chen & Wang, 2020). The overall objective of this study is to analyze how community cooperation, local governance mechanisms and technological adoption condition water sustainability in Sola de Vega.

3. MATERIALS AND METHODS

A mixed sequential explanatory design was adopted. The initial quantitative phase was July-August 2024 where four dimensions of water governance were measured through structured surveys. The qualitative phase (September 2024) deepened emerging patterns with 20 semi-structured interviews and participant observation and a third phase of complementation and rectification of quantitative and qualitative data took place in April 2025. The sequential design allowed for the interpretation of statistical findings, discourses and local practices.

A sample size of 40 producers was calculated because, in the mezcal practice of Sola de Vega, local records range between 60 and 75 productive units depending on the season. Therefore, 40 questionnaires cover between 55% and 67% of the universe and guarantee ±10% precision at 95% confidence. Therefore, 40 questionnaires were completed. For the qualitative phase, 20 producers were selected following criteria of heterogeneity in palenque size and access to water.

The 18-item Likert questionnaire (1-5) was structured in four factors:

Participation and rules (PAR; 4 items), Collaborative water planning (PLA; 5 items), Technical-environmental management (TEC; 5 items) and Cohesion-trust (COH; 4 items).

The surveys were applied face-to-face in palenques during work days; each session lasted 18-22 minutes. Interviews (34-46 min). Three researchers conducted participant observation during milling, fermentation and distillation shifts, noting water use and reuse practices.

To evaluate the internal reliability of the applied instrument, Cronbach's Alpha coefficient was calculated, which yielded a value of $\alpha = 0.90$, indicating excellent internal consistency among the questionnaire items. This result supports the reliability of the scale to measure aspects related to water governance, community cooperation and technical water management in artisanal mezcal production contexts.

On the other hand, the Shapiro-Wilk normality test was applied. The results showed that in all cases the p-value was less than 0.05, which allows rejecting the null hypothesis of normality. This indicates that the data do not present a normal distribution, suggesting the need to use nonparametric statistical techniques.

4. RESULTS

This section presents the main findings derived from the study, organized according to the dimensions that structured the empirical work. The aim is to offer an articulated reading of the data, making it possible to observe the local dynamics linked to water governance.

Spearman's non-parametric correlation test

Table 1 presents the Spearman correlations between the four governance factors (PAR, PLA, TEC, COH) and the dependent variable of water sustainability (SUS). A negative and significant association is observed between technical-environmental management practices (TEC) and water consumption ($\rho = -0.64$; $p < 0.001$), indicating that the adoption of efficient technologies reduces the water footprint. The relationship between collaborative water planning (CWP) and SUS is also negative ($\rho = -0.45$; $p = 0.002$). Social cohesion (COH) shows the highest positive correlation with PLA ($\rho = 0.58$; $p < 0.001$), suggesting that community trust facilitates coordination of formal agreements.

Table 1: Spearman correlations.

PAR	PLA	TEC	COH	SUS
PAR	-0.32**	0.28*	0.41**	-0.41**
PLA		-0.46**	0.58**	-0.45**
TEC			-0.39**	-0.64***
COH				-0.31*
YOUR				

*Spearman's ρ; *p* < 0.05*, < 0.01**, < 0.001***.
Source: Own elaboration performed in Python, 2025.

Exploratory Factor Analysis

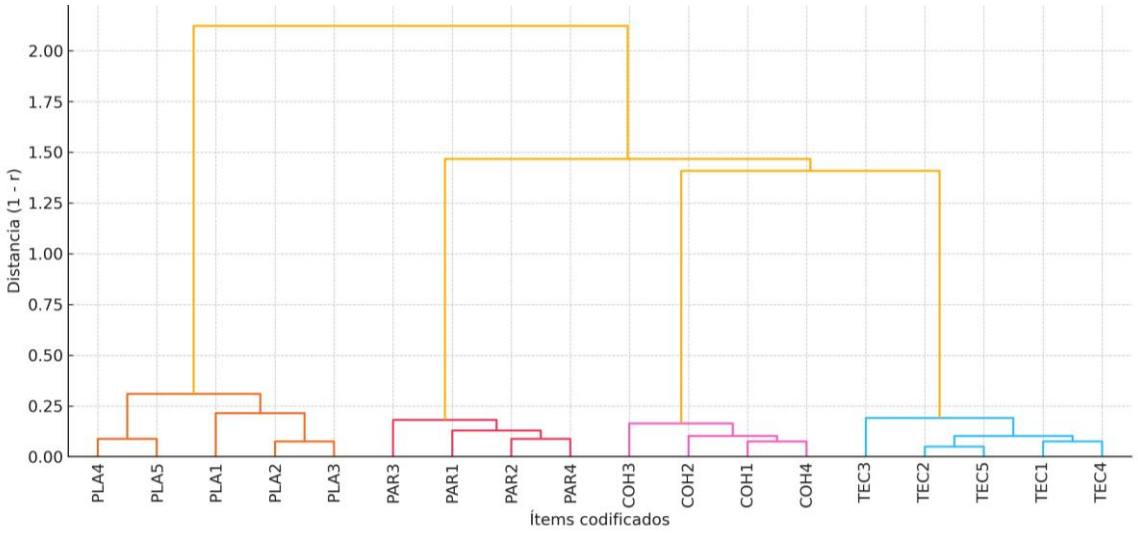
The exploratory factor analysis retained four factors with eigenvalues > 1, explaining 71 % of the total variance. Factor loadings ranged from 0.62 to 0.81 (Table 4). No cross items or communalities below 0.30 were identified. The model exceeds the recommended thresholds for sample adequacy (KMO = 0.74) and test of sphericity (χ^2 = 685.2; gl = 153; p < 0.001).

Table 2: Exploratory factor analysis.

Item	PAR	PLA	TEC	COH	Community
I1	0,78	-	-	-	0,61
I6	-	0,81	-	-	0,66
I10	-	-	0,77	-	0,63
I15	-	-	-	0,73	0,57

Source: Own elaboration performed in Python, 2025.

The factors are interpreted as: participation and rules (PAR), collaborative planning (PLA), technical-environmental management (TEC) and cohesion/ trust (COH).



Graph 1: Dendogram.
Source: Own elaboration with Python, 2025.

The hierarchical analysis by means of a dendrogram made it possible to evaluate the internal structure of the applied instrument, confirming the consistency between the empirical grouping of the items and the proposed theoretical factors. The visualization shows, first of all, that the 18 items of the questionnaire are grouped coherently in four well-defined clusters, corresponding to the dimensions: Collaborative Water Planning (PLA), Participation and Clear Rules (PAR), Technical-Environmental Management (TEC) and Cohesion and Social Trust (COH).

At low cutoff distances (≤ 0.25), items sharing a prefix quickly integrate with each other, indicating high internal correlation and thus strong thematic homogeneity within each subscale. This characteristic supports the reliability previously observed through Cronbach's α coefficients above 0.80, and validates the relevance of keeping all items in their respective dimension.

Subsequently, the dendrogram shows an intermediate merger between the PLA and PAR clusters at a distance of approximately 1.35, suggesting moderate collinearity between the two dimensions. This relationship is conceptually consistent: the existence of clear rules tends to facilitate organizational processes of community water planning. However, this linkage does not compromise their structural independence, as both groups remain separate from the TEC and COH clusters until higher stages of clustering.

The final merging of the four large clusters occurs at the apex of the dendrogram (distance ≈ 2.1), indicating that interfactor correlations are low and that each dimension retains a sufficiently distinct statistical and conceptual identity. This clustering pattern reinforces the discriminant validity of the instrument and rules out the existence of significant thematic overlaps between factors.

In summary, the dendrogram provides solid graphic evidence of the robust factor structure and semantic consistency of the questionnaire, empirically validating its conceptual design. This representation allows not only to confirm the psychometric quality of the instrument, but also to observe structural relationships between factors that can be considered relevant for the interpretation of the findings and the development of explanatory

structural models.

Qualitative Findings

The analysis of 20 interviews generated 148 open codes. Three core categories stood out: (a) "Broken trust" accounts of distrust in government programs; (b) "Shared technology" experiences with water extraction machines; and (c) "Taking care of the spring" customary norms for cleaning water sources. The category "Shared technology" correlates with an average 34% reduction in reported water consumption.

Image 1: Word Cloud.
Source: Own elaboration with Python, 2025.

The most frequent words "Water", We organize", "system", "buy", "tank", "pump", "programs", "assembly", "rules", "sanction" clearly indicate a narrative of collective, practical and horizontal action. The repeated use suggests a sense of belonging, where collaborative work and decision making do not fall under a single authority, but are socialized.

Photo 1: Mezcal producers and researchers in an interview session.
Source: Own elaboration taken in the field, 2024.

Terms such as "pump", "system", "irrigation", "tank" show a technical-concrete register, which speaks of material appropriation of specific technologies. This technical lexicon, far from being

elitist, appears intertwined with verbs of group action such as "we installed", "we bought", "we made", which shows that the technique is not separated from the community, but is integrated in its daily practices and relational codes.

2. Semantic cohesion by thematic category

a) Shared technology: The lexicon grouped around this category denotes concrete experiences of sustainable innovation: "buy", "irrigation", "tank", "pump". What is interesting is that they do not appear in isolation, but always linked to expressions of collaboration: "between families", "we contribute", "without help, but with cooperation". This discourse naturalizes technical solidarity, which suggests an alternative modality of rural innovation that does not depend on the State or the market, but on accumulated social capital.

Photo 2: Water efficiency system in mezcal production.
Source: Own elaboration taken in the field, 2025.

a) Broken trust: Here we find terms such as "trust", "never", "programs", "government", "asked", "disappeared". This lexical constellation expresses a collective memory of institutional disappointment, which is activated in the face of unfulfilled promises or failed interventions. The verb "desaparecieron" has connotations of structural abandonment, and "pidieron papeles" refers to decontextualized bureaucratic practices that generate attrition without tangible results. This pattern explains in part the low willingness to collaborate with external agencies and reinforces the legitimacy of endogenous strategies.
b) Taking care of the spring: This category is marked by terms such as "spring", "stream", "cleaning", "rules", "assembly", "sanction", "tequio". Here the local normative framework based on uses and customs is made visible. The word "tequio" summarizes the principle of collective work without direct remuneration, while "asamblea" and "sanciona" denote legitimate mechanisms of internal surveillance. This semantic configuration supports the hypothesis that communal governance is not only normative, but operational and effective in ecological terms.

The word cloud represents not only frequencies, but tense relations between the communal and the institutional, the technical and the symbolic. On the one hand, an organizational discourse appears: "we

made", "we bought", "we cooperated", "we cleaned". On the other, markers of institutional exclusion are activated: "I don't trust", "they never came back", "they disappeared", "they asked". This duality reflects a form of organizational resilience that emerges not by alignment with public policies, but in spite of them.

This has important implications for theories of water governance: it validates models of co-production of innovation (Ostrom, 1996), where communities design, implement and maintain solutions without delegating external authority. At the same time, it forces us to rethink the role of the State: not as a provider of technical solutions, but as a facilitator of existing collaborative processes.

The results obtained in this study not only confirm the hypothesis, but allow us to reconfigure it under a more complex perspective: water efficiency in mezcal production depends less on individual technical factors and more on social relations mediated by rules, formal agreements and degrees of internal cohesion. In statistical terms, community cooperation does not have a strong direct effect on the reduction of water consumption, but it does exert significant indirect effects through inter-institutional planning (PLA) and collective adoption of technologies (TEC).

This dual mediation should not be interpreted as a weakness, but as evidence of the importance of organizational mechanisms that operate between symbolic commitment and technical change. That is, sustainability does not occur by participation, but by the institutionalization of such participation in planned, collective and sustained actions.

5. DISCUSSION

Several studies have addressed the relationship between cooperation and water management in rural contexts, but few have attempted to quantify this link within an artisanal agroindustrial chain such as mezcal. In Mexico, recent studies have documented technological adoption in palenques in Guanajuato and Jalisco, attributing it to individual innovations incentivized by the export market (Ramírez-López et al., 2022). However, those contexts operate under entrepreneurial logic with less reliance on customary norms and without a community fabric as dense as in Sola de Vega.

This study better aligns with Andean research (Meinzen-Dick, 2022; Boelens et al., 2015) that identifies social capital as a key predictor in the management of canals, intakes and saving devices. For example, in Bolivian irrigation systems, it has been shown that the existence of formal assemblies and water rotation agreements (shifts) has a greater impact on the rational use of the resource than the availability of technology.

Likewise, the qualitative results presented here reinforce Sabatini's (2021) thesis of "broken trust": when the State imposes solutions without recognition of local rules, legitimacy is eroded and technological adoption becomes superficial. This is reflected in our emerging category where women producers in Sola de Vega expressed distrust towards public programs, despite having potential access to them.

6. CONCLUSION

This study analyzed the relationship between community cooperation, local governance and technological adoption in the water management of the mezcal industry in Sola de Vega, Oaxaca. Through a mixed sequential explanatory design, it became evident that water sustainability does not depend exclusively on technology or external financing, but on the articulation of endogenous social mechanisms.

1. Community cooperation, articulated through formal agreements and collective strategies, indirectly but significantly influences water efficiency. The structural model confirmed that such cooperation acts through collaborative water planning and joint technological adoption, reducing water consumption by up to 34% per liter of mezcal.
2. Social cohesion functions as a structuring factor. Communities with high levels of internal trust have better planning and technical adoption capabilities. This finding reinforces that social capital produces not only legitimacy, but also concrete environmental results.
3. Participation alone is insufficient. Attendance at assemblies or tequios does not guarantee better water practices if there are no clear rules, written agreements and evaluation mechanisms. Institutional planning emerges as a bridge between regulations and effective operation.
4. The most sustainable innovations were those generated by the community. Mistrust of official programs justifies the fact that many technological solutions have been implemented through solidarity contributions or informal revolving funds, without direct governmental intermediation.
5. This research reinforces theories such as the commons and adaptive governance in rural contexts. Water management in productive

systems such as mezcal should be analyzed as a technical, organizational and cultural web, where the traditional and the modern converge in new forms of hybrid governance.

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