

Applying Fuzzy Logic to Assess Socio-Technical Transitions Shaping WASH Sustainability in Lower Omo Valley, Ethiopia

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Abstract *This study applies a fuzzy logic modelling framework within a convergent mixed-methods design to assess the socio-technical determinants of water, sanitation, and hygiene (WASH) sustainability in Dassenech Woreda, South Omo Zone, Ethiopia. Sustainable WASH access remains a critical challenge across Sub-Saharan Africa due to environmental variability, weak governance systems, and socio-cultural complexity. To address these challenges, the study integrates quantitative data from 430 household surveys with qualitative insights derived from key informant interviews, focus group discussions, and ethnographic observation. A Mamdani-type fuzzy inference system was developed to model nonlinear interactions between technology appropriateness, community engagement, and institutional support. The results demonstrate that technology appropriateness is the most influential predictor of sustainability, although optimal outcomes occur only when all socio-technical variables interact synergistically. Defuzzification outputs reveal strong threshold effects, particularly when technology appropriateness exceeds 0.6. Qualitative findings further validate these results, emphasizing the critical role of indigenous governance systems in maintaining functionality and social legitimacy. This study contributes a novel methodological framework for analysing WASH sustainability under uncertainty and provides policy-relevant insights for climate-vulnerable pastoralist systems.*

Keywords *Ethiopia, Fuzzy Logic, Mixed Methods, Pastoralist Communities, Socio-Technical Systems, WASH Sustainability.*

Introduction

Sustainable access to water, sanitation, and hygiene (WASH) services remains a persistent challenge across Sub-Saharan Africa, particularly in pastoralist regions characterized by high climatic variability, mobility patterns, and institutional fragility [2, 3]. In Dassenech Woreda, repeated failures of water supply systems highlight the limits of infrastructure-centric approaches that fail to integrate social, cultural, and governance dimensions. Environmental stressors such as droughts and floods, combined with weak service delivery systems, exacerbate the vulnerability of rural

water infrastructure [9, 16].

Existing literature shows that rural WASH systems often fail because of weak governance, limited community ownership, and inappropriate technology selection [5, 11, 15].

Behavioural and socio-cultural factors further influence the adoption and sustainability of hygiene practices [7, 8, 19]. However, most prior studies rely on linear statistical models that cannot capture the inherent complexity, feedback loops, and threshold effects in socio-technical systems. These models often fail to represent uncertainty and nonlinear interactions among sustainability determinants.

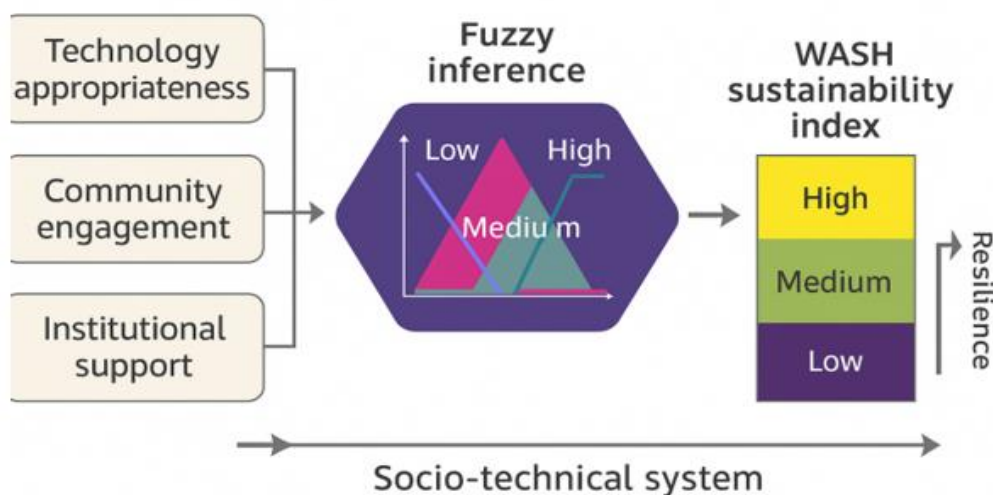


Figure 1. Sustainability Response Surface

This study addresses this methodological and empirical gap by applying fuzzy logic, originally conceptualized by Zadeh [1, 4], to model nonlinear socio-technical interactions. By integrating fuzzy logic with socio-technical systems (STS) theory [18] and a convergent mixed-methods approach, the research provides a comprehensive and context-sensitive framework for understanding WASH sustainability in pastoralist environments Figure 1. The study advances both theoretical and practical knowledge by demonstrating how adaptive, systems-based approaches can improve sustainability outcomes in resource-constrained and climate-sensitive settings.

Materials and Methods

Study Area and Context

The study was conducted in Dassenech Woreda, located in the South Omo Zone of southwestern Ethiopia. The region is predominantly inhabited by pastoralist and agro-pastoralist communities whose livelihoods depend on livestock mobility, seasonal water availability, and adaptive resource management strategies [3, 17]. The area experiences significant climatic variability, including recurrent droughts and flooding events, which contribute to infrastructure degradation and service disruption [9, 21].

Water supply systems in the region include boreholes, shallow wells, and river abstraction schemes. Despite ongoing development efforts, many of these systems experience frequent functionality failures due to environmental stress, inadequate maintenance capacity, and weak institutional support structures [10, 15]. Public health challenges such as diarrheal diseases and sanitation-related illnesses remain prevalent, underscoring the importance of sustainable WASH interventions [20, 22].

Study Design

A convergent parallel mixed-methods design enabled simultaneous collection and analysis of quantitative and qualitative data. This approach enables methodological triangulation, where qualitative insights contextualize and validate statistical findings. Quantitative data provide measurable relationships among key variables, while qualitative data capture the underlying social, cultural, and institutional dynamics that influence system performance.

The integration of these datasets at the interpretation stage enhances both analytical rigor and contextual validity. This design is particularly appropriate for complex socio-technical systems where purely quantitative or qualitative approaches would be insufficient to capture system behaviour.

Sampling Strategy and Sample Size

Quantitative Sampling

A total of 430 households were selected using a stratified random sampling technique to ensure representation across diverse socio-economic and geographic contexts. Stratification was based on proximity to water sources, livelihood type (pastoralist versus agro-pastoralist), and level of access to WASH infrastructure. This approach ensured statistical reliability and minimized sampling bias across heterogeneous population groups.

Qualitative Sampling

A purposive sampling strategy was employed to select participants with relevant expertise and lived experience. The sample included local government officials, water committee members, community elders, and representatives of women and youth groups. This ensured diverse perspectives, particularly from those involved in governance, system maintenance, and daily WASH practices.

Data Collection Methods

Household Survey

Quantitative data were collected through a structured questionnaire designed to assess system functionality, user satisfaction, community participation, perceived institutional support, and technology suitability. Responses were measured using Likert scales and subsequently normalized to a continuous range between 0 and 1 to ensure compatibility with fuzzy modelling techniques.

Qualitative Data Collection

Qualitative data were collected through key informant interviews, focus group discussions, and ethnographic observation. Interviews focused on governance structures, institutional challenges, and system management practices, while focus groups explored community perceptions and behavioural dynamics. Ethnographic observation provided insights into real-world usage patterns, maintenance behaviours, and informal governance mechanisms. All qualitative data were transcribed and analysed using thematic coding.

Variable Definition and Operationalization

The study examines three independent variables—technology appropriateness, community engagement, and institutional support—and one dependent variable, WASH sustainability. Technology appropriateness reflects how well infrastructure aligns with

environmental conditions, technical capacity, and user needs. Community engagement captures the extent of participation in planning, implementation, and maintenance processes. Institutional support refers to the availability of governance structures, financing mechanisms, and technical assistance.

WASH sustainability is conceptualized as a composite indicator encompassing system functionality, reliability, user satisfaction, and long-term operability. All variables were normalized to a continuous scale between 0 and 1 to facilitate integration into the fuzzy inference system.

Fuzzy Inference System Design

A Mamdani-type fuzzy inference system was developed to model nonlinear relationships among variables, consistent with established fuzzy logic methodologies [4]. Each variable was represented using triangular membership functions categorized into low, medium, and high linguistic levels. These functions were defined over the normalized interval to capture gradual transitions between states.

The rule base consisted of 12 IF–THEN rules derived from empirical data, expert knowledge, and qualitative insights. These rules capture interaction effects and conditional dependencies among variables. The inference mechanism employed the minimum operator for rule activation and the maximum operator for aggregation. Defuzzification was performed using the centroid method, producing a crisp output representing overall sustainability.

Statistical Analysis

Multiple linear regression analysis was conducted to estimate the relative contribution of each independent variable and to provide a baseline comparison with the fuzzy model. Regression coefficients were used to rank predictor importance and assess the consistency of findings across analytical approaches.

Data Integration and Validation

Quantitative and qualitative findings were integrated through triangulation. Statistical results identified dominant variables and threshold effects, while qualitative insights explained underlying mechanisms and contextual factors. Model validity was assessed through consistency between regression and fuzzy outputs, as well as alignment with field observations and stakeholder perspectives.

Ethical Considerations

The study adhered to established ethical standards. The study obtained informed consent from all participants, maintained confidentiality and anonymity, and allowed voluntary participation with the option to withdraw at any time.

Results

Regression Analysis

Regression analysis indicates that technology appropriateness is the strongest predictor of WASH sustainability ($\beta = 0.49$), followed by community engagement ($\beta = 0.42$) and institutional support ($\beta = 0.37$). These coefficients not only establish the relative importance of each variable but also demonstrate that sustainability outcomes are influenced by a combination of technical, social, and institutional dimensions rather than any single factor in isolation. The relatively higher coefficient for technology appropriateness suggests that the physical and operational suitability of WASH infrastructure—such as durability under climatic stress, ease of maintenance, and compatibility with local environmental conditions—plays a foundational role in determining whether systems remain functional over time.

Further interpretation of the regression model reveals that community engagement contributes significantly to improving system performance by fostering a sense of ownership,

enhancing routine maintenance practices, and facilitating collective action in resource management. However, its lower coefficient compared to technology appropriateness indicates that social participation alone cannot compensate for poorly designed or contextually inappropriate technologies. Institutional support, while ranking third, remains critical in providing technical expertise, financial resources, and governance oversight, which collectively enable system stabilization and long-term operability.

The combined explanatory power of the regression model highlights a multi-dimensional dependency structure, where improvements in one variable yield diminishing returns unless complemented by progress in others. This reinforces the premise that WASH sustainability is not linear but contingent upon balanced development across socio-technical domains.

Fuzzy Model Outputs

The fuzzy model reveals complex nonlinear dynamics that conventional regression analysis does not fully capture. Unlike linear models that assume proportional relationships, the fuzzy inference system identifies threshold effects and interaction patterns among variables, demonstrating that sustainability outcomes increase disproportionately once certain critical levels are achieved. In particular, the model shows that when technology appropriateness

exceeds a threshold value of approximately 0.6, there is a marked and accelerated improvement in sustainability outcomes.

This nonlinear behaviour reflects the presence of tipping points within the system, beyond which incremental improvements produce significantly larger impacts. For example, moderate improvements in community engagement or institutional support yield limited benefits when technology appropriateness remains low.

However, once technological suitability reaches a functional threshold, the same levels of social and institutional inputs generate substantially higher sustainability outcomes. This indicates strong interaction effects, where variables reinforce each other rather than operating independently.

Additionally, the fuzzy model captures asymmetrical relationships, suggesting that deficiencies in one variable can disproportionately undermine overall system performance. For instance, high community engagement cannot offset the negative effects of unreliable or unsuitable infrastructure, while strong institutional support may fail to produce meaningful improvements in the absence of community participation. These findings underscore the importance of coordinated interventions that address all key determinants simultaneously rather than sequentially.

Defuzzification Results

Table 1. Defuzzification Results

T	C	I	Sustainability
0.2	0.3	0.2	0.25
0.6	0.5	0.4	0.52
0.7	0.7	0.6	0.68
0.9	0.8	0.8	0.87
0.4	0.8	0.7	0.60

The defuzzification results provide concrete numerical representations of sustainability outcomes under different combinations of input

variables. These results illustrate the progressive improvement in sustainability as technology appropriateness, community

engagement, and institutional support increase. At low input levels (e.g., $T = 0.2$, $C = 0.3$, $I = 0.2$), sustainability remains minimal (0.25), reflecting fragile systems with high failure risk as mentioned Table 1.

As inputs reach moderate levels ($T = 0.6$, $C = 0.5$, $I = 0.4$), sustainability improves to 0.52, indicating partial functionality but still limited resilience. A more balanced and higher combination of inputs ($T = 0.7$, $C = 0.7$, $I = 0.6$) results in a substantial increase in sustainability (0.68), demonstrating the importance of synergy among variables. The highest observed sustainability value (0.87)

occurs when all variables are simultaneously high, confirming that optimal outcomes depend on the alignment of technical, social, and institutional factors.

Interestingly, the scenario where community engagement and institutional support are relatively high ($C = 0.8$, $I = 0.7$) but technology appropriateness remains moderate ($T = 0.4$) yields only moderate sustainability (0.60). This further reinforces the dominant role of technology appropriateness and highlights the limitations of relying solely on social and institutional interventions without addressing technical suitability Figure 2.

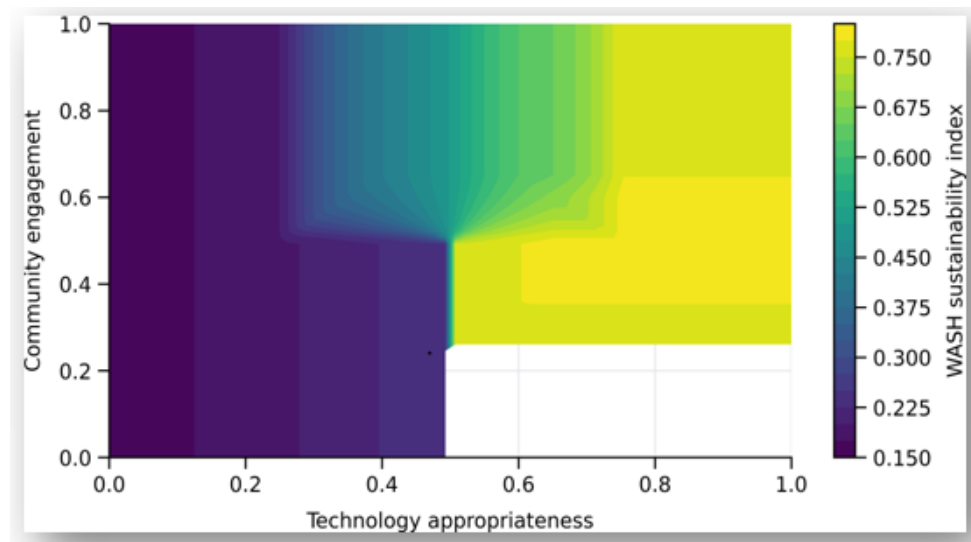


Figure 2. Sustainability Response Surface Showing the Interaction between Technology Appropriateness and Community Engagement at Institutional Support $I = 0.6$

Discussion

This study demonstrates that WASH sustainability in pastoralist systems is inherently nonlinear and context-dependent, reinforcing socio-technical systems theory [18]. The integration of regression and fuzzy modelling provides a more comprehensive understanding of system behaviour by capturing both linear trends and nonlinear interaction effects. The findings confirm that sustainability outcomes emerge from the interplay between technological, social, and institutional dimensions rather than from isolated interventions.

The dominance of technology appropriateness aligns with global evidence identifying inappropriate technologies as a major cause of rural water system failure [5, 6]. However, this study extends existing knowledge by showing that technological suitability alone is insufficient unless it is embedded within socially legitimate and contextually relevant governance systems. Technologies that fail to align with local capacities, environmental conditions, and user preferences are unlikely to be maintained, regardless of their technical sophistication.

Community engagement emerges as a necessary but insufficient condition for

sustainability. While active participation enhances ownership, accountability, and routine maintenance, it cannot compensate for fundamentally flawed infrastructure. This challenges widely held assumptions in development practice that community mobilization alone can ensure long-term system functionality [11, 12]. Instead, engagement must be complemented by appropriate technological design and institutional backing.

Institutional support functions as a critical enabling factor that stabilizes system performance under conditions of environmental and socio-economic stress. By providing technical expertise, regulatory oversight, and financial resources, institutions enhance the resilience and adaptability of WASH systems. Importantly, the fuzzy model demonstrates that institutional support amplifies the positive effects of both technology and community engagement rather than acting independently.

Qualitative findings further emphasize the importance of indigenous governance systems, particularly elder-based institutions, in regulating access, resolving conflicts, and ensuring compliance with maintenance norms. These culturally embedded structures provide legitimacy and continuity that formal institutions often lack, making them indispensable for sustainable WASH service delivery in pastoralist contexts [16, 17].

Global Comparison

Evidence from other pastoralist and semi-arid regions strongly supports and contextualizes these findings. In northern Kenya, sustainability outcomes improve significantly when water technologies are adapted to pastoral mobility patterns and supported by reliable supply chains, although externally imposed governance systems often lead to system breakdowns [6]. In Tanzania, community-managed water schemes demonstrate higher functionality when governance structures are embedded within customary institutions, highlighting the

importance of aligning formal interventions with local socio-cultural systems [12].

Across the Sahel region, including countries such as Niger and Mali, climate variability exacerbates infrastructure failure risks, particularly in areas with weak institutional capacity. Programs that integrate climate-resilient technologies with strong local governance mechanisms consistently outperform infrastructure-focused interventions [13, 14]. Compared to these contexts, the Lower Omo case exhibits more pronounced threshold effects, likely due to extreme environmental variability and higher dependence on mobility-based livelihoods. These cross-regional comparisons reinforce the conclusion that sustainable WASH outcomes depend on the alignment of technology, governance, and community systems.

Policy Implications

The findings indicate that WASH interventions must move beyond linear and sector-specific planning models toward adaptive, systems-based approaches that account for complexity and uncertainty. Policymakers should prioritize achieving minimum thresholds of technology appropriateness before scaling up interventions, as suboptimal technologies significantly limit the effectiveness of social and institutional investments.

Investment strategies should emphasize climate-resilient, durable, and locally maintainable systems that align with the environmental and socio-economic realities of pastoralist communities. Strengthening linkages between indigenous governance structures and formal institutions is essential for improving accountability, legitimacy, and long-term sustainability. Furthermore, integrated socio-technical planning frameworks should be adopted to ensure that interventions simultaneously address technical, social, and institutional dimensions rather than treating them as separate components.

Methodological Contribution

This study demonstrates the practical applicability of fuzzy logic as an analytical tool in public health and development research, particularly in contexts characterized by uncertainty, data limitations, and complex system interactions. By integrating fuzzy modelling with conventional regression analysis, the study enhances both explanatory depth and analytical robustness.

The approach allows for the identification of nonlinear relationships, threshold effects, and interaction dynamics that are often overlooked in traditional statistical models. As such, it provides a more realistic representation of socio-technical systems and offers valuable insights for evidence-based policymaking and intervention design.

Limitations and Future Research

Despite its contributions, the study has several limitations. The use of simplified triangular membership functions may not fully capture the complexity and variability of real-world conditions. Additionally, the finite rule base limits the ability of the model to represent all possible interaction scenarios. The cross-sectional nature of the data also restricts the analysis of temporal dynamics and long-term system evolution.

Future research should incorporate sensitivity analysis to assess the robustness of model outputs under varying assumptions. Exploring alternative membership functions, such as Gaussian or trapezoidal forms, could improve model precision. Longitudinal datasets would enable the analysis of system dynamics over time, while integration with system dynamics or agent-based modelling approaches could further enhance predictive capability and policy relevance.

Conclusion

WASH sustainability in pastoralist systems is driven by complex and nonlinear interactions among socio-technical variables. This study

demonstrates that fuzzy logic provides a robust and flexible framework for capturing these dynamics and translating them into actionable policy insights. The findings highlight that sustainable outcomes cannot be achieved through isolated interventions but require the coordinated alignment of appropriate technology, strong community engagement, and supportive institutional frameworks.

By advancing both methodological and empirical understanding, this research contributes to the development of more effective and context-sensitive strategies for improving WASH sustainability in climate-vulnerable and resource-constrained environments.

Conflict of Interest

The author declares no conflict of interest regarding the research, authorship, and/or publication of this article.

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Ethical Approval

This study was conducted in accordance with established ethical standards for research involving human participants. Ethical approval was obtained from the relevant institutional review board prior to data collection. Permission to conduct the study was also secured from the Dassenech Woreda administrative and sectoral offices, including the Water and Health Offices. Informed consent was obtained from all participants before their inclusion in the study, and respondents were assured of confidentiality, anonymity, and their right to withdraw at any stage without consequence.

Author Contributions

The author was solely responsible for the conception and design of the study, data collection, analysis and interpretation of results, and manuscript preparation. The author also approved the final version of the manuscript for publication.

Data Availability

The datasets generated and/or analysed during the current study are not publicly available due to confidentiality agreements

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with participants and local authorities but are available from the corresponding author on reasonable request. Qualitative data, including interview transcripts and focus group discussions, have been anonymized to protect participant identity.

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