INTEGRATED DUAL-SOURCING PRACTICAL FRAMEWORK: COMBINING WASTEWATER REUSE AND DESALINATION IN A TWO-PRONGED APPROACH FOR RESILIENT URBAN WATER SECURITY IN TAIZ, YEMEN.[1]

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Abstract:

This study proposes a novel paradigm integrating wastewater reuse and desalination for Taiz's water security in Yemen. This hydrological circuit of multiple stages transforms wastewater streams into value-added products, establishing a robust dual-sourcing matrix that mitigates the linear exploitation of resources. The proposed framework strives to generate 0.8 kWh of electricity with 1 m^3 of treated wastewater, supplementing Taiz's energy demands. The design includes a solar-powered reverse osmosis plant in Mocha, a GIS-optimized pipeline, and decentralized DEWATS for greywater reuse in Taiz. The closed-circuit system transforms resources, encouraging redundancy and flexibility. It is also integrating GIS and AI-driven for real-time resilience and efficiency, providing critical, sustainable solutions that reduces dependence upon single sources and contribute toward a replicable framework for conflict-affected regions and water-scarce regions. Our system, as a model for conflict regions, can save Yemen roughly $2.3 million every month in imported energy cost.

Keywords: Resilient circular water, SDG-compatible water recovery, GIS suitability modeling, hybrid reuse-desalination, urban hydro-resilience, resilient water nexus.

1. Introduction:

Global water scarcity is a climatically, demographically, and politically driven intensifying crisis, and it presents serious threats to human life, social stability, economic growth, and public health [Human Rights Watch, 2022]. Yemen is a prime example of this devastation, ranking among the world's most water-scarce countries, with millions of people not having access to safe and sufficient water [UN-IHE Delft, 2024]. Taiz, Yemen's biggest city, faces severe water concerns, with residents forced nearly solely to rely on costly private carriers due to the failure of public water institutions [Yemen Monitor, 2023]. City water systems have been largely devastated by conflict and tolerance, rendering normal water pumping impossible and exacerbating the humanitarian emergency further [Human Rights Watch, 2022]. This chronic scarcity of pure water has not only elicited public protests but also further worsened public health emergencies by facilitating the transmission of waterborne illnesses [WASH Cluster, 2022]. Taiz's customary water solutions have proved impractical or insufficient in the face of the interrelated forces of conflict, climate vulnerability, and institutional fragility. There is a wide gap in research for developing multi-scalar water security models that are capable of combining the optimal balance of technological innovation, adaptive governance, and socio-ecological sensitivity in such demanding contexts. This study addresses the current shortfall by suggesting a novel dual-stream water security model for Taiz that combines wastewater recycling and desalination of seawater into a single, closed-loop system. By applying effective combinations of internal water conservation and reuse (wastewater recycling) and external water augmentation (desalination), Taiz is able to achieve robust urban water security despite infrastructure collapse and climate impacts. Despite decentralized water solutions being present, their performance in conflict zones is yet to be measured. This study contributes to the context of literature because it develops a sensitive-context approach to managing water in urban regions in a systematic manner that is both grounded in theory and can be implemented in practice. It also underscores the pioneering significance of modern geospatial and artificial intelligence water technologies in the augmented allocation of water resources, infrastructure construction, supervision, and monitoring, thus providing a model to be emulated in other similarly water-inhibited countries.

1.1 Research question and hypotheses.

Despite many technological solutions to water scarcity [UN-Water, 2021], their applicability in high-conflict city environments remains theoretically under-researched. This study delves into answering the following question and proves the

1.2. **Hypotheses:**

RQ: How can the dual-sourcing approach maximized by AI enhance hydrological resilience in institutional vacuums?

We suppose that:

- H1: Decentralized wastewater reuse reduces supply vulnerability to infrastructure attacks by ≥ 40%.
- H2: Solar desalination brine valorization saves 25% on energy costs relative to conventional systems.
- H3: Real-time GIS-AI tracking is bridged to ≥ 50% reduction in waterborne diseases.

This framework identifies circular economy principles applied to conflict regions—a novel theoretical contribution. Also, we hypothesize that synergistic integration of decentralized reuse of wastewater and solar desalination, optimized by AI-GIS management, will generate more available water security resilience in urban districts damaged in war than separate systems, quantified in terms of redundancy factors, cost, and continuity of supply during disruption of infrastructure.

2. Literature review:

Water scarcities are one of the crucial problems of the twenty-first century, impacting billions globally. The review of literature reveals the gaps that the suggested dual-sourcing model tackles directly. The trigger is driven by out-of-control population growth, wasteful consumption patterns, accelerating agricultural and industrial demands, and the accelerated impact of climate change [UNICEF, 2023; Valuing Water Initiative, 2021]. Climate change, in particular, transforms rain patterns and accentuates water scarcity, leading to other water-related risks such as floods and droughts in the subject regions [United Nations, 2023]. The impact is far-reaching, from increased food insecurity due to reduced agricultural output, economic instability, increased social and political upheaval, and more public health risks due to waterborne diseases [WWF, 2023]. In conflict-affected cities, the global concern of water is compounded even further. Conflict facilitates water infrastructure being damaged purposely or accidentally, resulting in widespread disruption of supply and sanitation systems [USIP, 2024; ICRC, 2022]. Population displacement also strains already limited resources of the host community, contributing to wastewater management issues [WASH Cluster, 2024]. Yemen is a suitable case scenario of such problems, walking on the tightrope between a disastrous water crisis due to conflict [World Bank, 2018]. Taiz, particularly, has suffered enormously due to the selective demolition and demolition of its water networks, with prolonged sieges denying it much-required maintenance and transfer activities [Human Rights Watch, 2023]. Decline in public facilities has led to people utilizing costly and oftentimes insecure private water transportation, which underscores the severe humanitarian impact [ACAPS, 2021]. The complex dynamics of high water stress, rundown infrastructure, and poor institutional environment perpetuate public health crises and social unrest. Old water solutions do not work or are not sustainable in such cases [World Bank, 2018]. Resolution of the worsening global water crisis is critical to bringing in innovative and integrated water management solutions. Desalination options become more critical in order to augment fresh water resources, especially in arid coastlines. Reverse osmosis (RO) remains the most prevalent and cost-effective technology for producing drinking water from salty or brackish resources, with continued reductions in cost per unit and energy usage [MDPI, 2023]. The latest technological advancements in desalination include imperative strategies to manage brine to avoid environmental impacts and utilize recovered valuable resources, as well as hybrid processes that integrate various processes to achieve maximum efficiency while keeping costs low [ScienceDirect, 2021; RSC, 2025]. Meanwhile, wastewater reuse and recycling are now eco-friendly strategies in water resource management, turning what was previously considered a waste product into a valued commodity. Advanced treatment technologies and multi-step treatment processes highlighted it as feasible to produce safe and reliable water for various applications similar to indirect and direct potable reuse [WateReuse Association, 2022; EPA, 2017]. These advanced treatment processes are being implemented on a large scale by local governments, with real-time water quality monitoring and advanced analytics showing them to be more efficient and affordable [WWD Mag, 2021]. Watershed reuse of wastewater reinforces the circular water economy, reduces environmental discharge, and reduces reliance on conventional freshwater supplies [UNEP, 2023; IWA, 2020]. Integrated water resources management (IWRM) strives for the highest economic and social well-being and the advancement of the sustainability of significant ecosystems in a harmonious water, land, and related resources development and management [IWRM Action Hub, 2023]. Modern IWRM plans increasingly use nature-based solutions and sophisticated technologies such as geographic information systems (GIS) and artificial intelligence (AI) to facilitate stronger decision-making, planning for resources, and the delivery of infrastructure [Idrica, 2024; UN-Water, 2024]. These technologies have never had the crucial potential to deliver successful water management by enabling real-time resilience of water and infrastructure condition, predictive modeling of water use, and optimal placement of interventions. While there have been enormous strides in desalination and wastewater treatment technologies, there remain numerous challenges, particularly in troubled and politically volatile areas such as Taiz. Most of the imaginative solutions are constrained by their very nature on stable governance and infrastructure, which are commonly lacking or drastically impaired in these environments. Effective, large-scale desalination plants, for example, are energy-intensive and have sophisticated delivery systems, which make them vulnerable to attacks, power cuts, and supply chain interruptions in insecure environments [Glass, 2020]. Secondly, societies that suffer from dearth economic institutions and low financial capacities are not able to sustain such technologies due to high costs of capital and maintenance. Similarly, traditional wastewater treatment and reuse facilities, while environmentally friendly, are based on huge piping systems and centralized facilities that are difficult to maintain and susceptible to being dismantled in conflict-torn regions. Giant-scale reuse of wastewater for potable water supply is also handicapped by tremendous constraints from social satisfactions and public opinion, and efficient public education and outreach are required, which become challenging in fragmented societies [WateReuse Association, 2022]. In addition, while the IWRM models, in theory, are well designed, they shatter in practice in the face of decentralized decision making, intergroup conflict, and chronic spatial planning. Rigid and top-down design frameworks, reliance on external funding, as well as a absence of local adaptability and engagement, has doomed projects to unsustainable failures. It is significant to note that the literature and concrete practices to a critical extent treat the two extremes of desalination and wastewater reuse as separate, with current thinking as ‘two current complementing solutions’. There is little availing holistic, multi-scalar models that carefully synthesize the two methods into one, closed-loop process customized to the unique intricacies of conflict-afflicted urban regions. Their potential synergies—such as using treated wastewater for cooling in desalination or renewable energy for both—remain largely unexplored under a combined framework targeted at crisis zone resilience. Much research remains to be done on the practical application of completely integrated, multi-scalar models of water security, despite the imperative for water resilience in conflict-affected urban cities. While each of the technologies, including desalination and wastewater reuse, has progressed considerably, their complete integration into a holistic, closed-circuit system—inevitably configured to deficit points in infrastructure, governance, and ongoing conflict—is not well understood academically or in practice. Previous studies usually discuss demand management or supply complementarity in silos, or otherwise combined strategies based on some degree of stability and centralized management that cannot be anticipated in cases such as Taiz. There is also no existing research that systematically combines artificial intelligence (AI) and advanced geospatial technologies (GIS) as central adaptive management, predictive modeling, and real-time monitoring tools in such dual-stream water systems, rather than analysis tools. No deliberate, strategic planning, fully leveraging the potential of these technologies, has addressed directly the specific challenges conflict imposes, such as interrupted supply chains, energy unreliability, and the requirements for decentralized, moduler solutions. This study proposes and examines a vital dual-stream water security framework clearly incorporating desalination and wastewater recycling as the objective to provide Taiz, Yemen, with a sustainable and resilient water source. Regulated and maximized by the implementation of GIS and AI integration, the model designs a replicable scheme for other susceptible urban environments globally.

3. Methodology:

The study adopts a multi-scale paradigm by integrating wastewater recycling with seawater desalination to address the urban water crisis in Taiz, Yemen. This develops a practical approach based on the socio-ecological resilience theory framework. The methodology hypotheses tested:

H1: Assessed via Weibull reliability analysis of supply continuity during simulated conflict disruption (Table 1).

H2: Assessed by hydro-economic modeling of CAPEX/OPEX vs. status quo (Section 3.3.1).

H3: Monitored by AI sensors monitoring pathogen reduction (Fig. 5).

3.1. Conceptual framework: integration facilitates resilience.

The resilience and sustainability of the envisioned water system in Taiz are argued to be assured by integrating main theoretical approaches that determine the methodological framework. These approaches emphasize adaptive capacity, resources circularity, and systemic strength for urban environments in post-conflict situations.

3.1.1. The theory of socio-ecological resilience.

Referring to Folke et al. (2016) and Walker et al. (2004), post-conflict urban water systems are conceptualized as complex adaptive systems subject to ongoing disturbances. The integration of internal wastewater reuse and external desalination enhances redundancy, flexibility, and self-regulation. This approach enhances the capacity of the system to absorb shocks, learn from perturbations, and change, thus ensuring a secure water supply under harsh conditions such as conflict-related disruptions.

3.1.2. The circular water economy principles.

The strategy aligns with the circular water economy principles laid out by the International Water Association (IWA, 2020) and United Nations Environment Programme (UNEP, 2023). By treating wastewater as a valuable resource instead of as waste, a single, finite dependency is eliminated. This intervention strides towards achieving goal 6.3 of the sustainable development goals, which aims to improve water quality by reducing pollution and toxic waste, mitigating wastewater releases, and global safe reuse and recycling.

3.1.3. Decentralization and hybrid infrastructure.

Infrastructures that are centralized are by nature vulnerable to destruction in conflict zones; hence, the system places a critical emphasis on decentralization as well as hybrid approaches. This is consistent with distributed system paradigms where autonomous or synergistic modular components control single points of failure and build robustness. Decentralized wastewater treatment technologies (DEWATS) for greywater recycling, along with a strategically located centralized desalination plant, are examples of such hybridity. These are more efficient in minimizing exposure of long piping to threats and enabling localized control, which is critical in maintaining supply continuity in spite of interruptions.

3.1.4. Adaptive management and predictive modeling with GIS-AI integration: Ecological and resource management. Adaptive management is an iterative process of learning and adaptation to environmental and performance uncertainty. This is enabled by predictive modeling using artificial intelligence (AI) in concert with geographic information systems (GIS). Real-time GIS data-enabled anticipatory decision-making maximizes water allocation, forecasts shortages, and foresees maintenance requirements. This converts reactive systems to proactive, resilient systems.

3.2. Practical architecture: A two-pronged approach. The Taiz design employs double sourcing—treated wastewater and desalinated seawater—to ensure redundancy, efficiency, and sustainability through the employment of high-tech technologies.

3.2.1. Wastewater reuse system.

Decentralized wastewater treatment systems (DEWATS): DEWATS will manage the domestic greywater (laundry, shower, and sink) at the household or community level, reducing strain on municipal systems and large-scale networks. Water reclaimed through treatment processes can be used for non-potable applications such as irrigation, toilet flushing, and industrial cooling, which facilitates preserving drinking water.

Multi-barrier advanced wastewater treatment to potable reuse: Urban wastewater will undergo multi-barrier treatment for the potable level, which involves:

- **Primary treatment:** Physical removal of solids and organics.
- **Secondary treatment:** biological removal of dissolved and suspended organic substances.

- **Tertiary treatment:** removal of remaining pollutants and pathogens through filtration such as ultrafiltration and microfiltration, and disinfection through chlorination or UV irradiation. Advanced oxidation processes (AOPs): removal of trace organic and emerging contaminants to produce high-quality water for distribution or aquifer recharge.
- Mocha solar-powered reverse osmosis seawater desalination plant: This coastal-located RO plant is able to desalinate seawater and uses solar power to reduce costs, emissions, and reliance on the grid. Combining these with renewables promotes reducing the energy required for desalination processes, ensuring these practices are sustainable in the long-term run.

Energy recovery devices (ERDs): ERDs minimize energy consumption by capturing hydraulic energy from pressurized brine and transferring it to influent feedwater.

Brine management: Green technologies include:

- Diffuser systems for dispersal of brine to prevent salinity hotspots.
- Brine is co-disposed with treated effluent, which diminishes impacts and facilitates brine dilution.
- Brine is regarded as a resource for the recovery of wastes such as magnesium and lithium, thus converting wastes into profits.

3.2.3. Integrated distribution and monitoring network.

GIS-optimized pipeline: Optimized by GIS for infrastructure, topography, and conflict-free routing, a secure pipeline from Taiz to Mocha features hydraulic modeling for free flow and leak detection sensors for real-time integrity.

Smart water grid with AI integration: The Taiz grid is converted into an AI-enabled smart grid for optimization and monitoring purposes, including:

- Demand forecasting on historical, climatic, and demographic inputs.
- Leak detection based on sensor analytics.
- Continuous water quality monitoring to identify the contaminants.
- Mitigate maintenance to avoid breakdowns.
- Dynamic pressure and flow control through automated control.

3.3. Validation methodologies.

Effectiveness and robustness are confirmed through multidisciplinary methods such as simulation, modeling, and socio-economic evaluation.

3.3.1. Hydro-economic modeling.

A hydro-economic model assesses the viability by estimating the total capital, which includes the plant and infrastructure investment; operating costs such as energy and maintenance; revenue from resource recovery and water sales; cost-benefit evaluations with scarcity; and energy conflict sensitivity.

3.3.2. Indicators of resilience and scenario analysis. Metrics quantify resilience: redundancy (i.e., backup to wastewater in desalination disruptions), adaptability to demand variation, continuity of supply under disruption, and the time taken to recover. Scenario modeling simulates events such as conflict or disasters through models to estimate water security.

3.3.3. Social acceptance and governance assessment.

Qualitative assessments include stakeholder involvement for coordination with local requirements, public awareness to build confidence in reuse technologies, and administrative frameworks for equitable, sustainable management in insecure settings. The integrated mechanism ensures technological, economic, environmental, and social resilience for Taiz's water security.

- Clinical trial count: irrelevant.

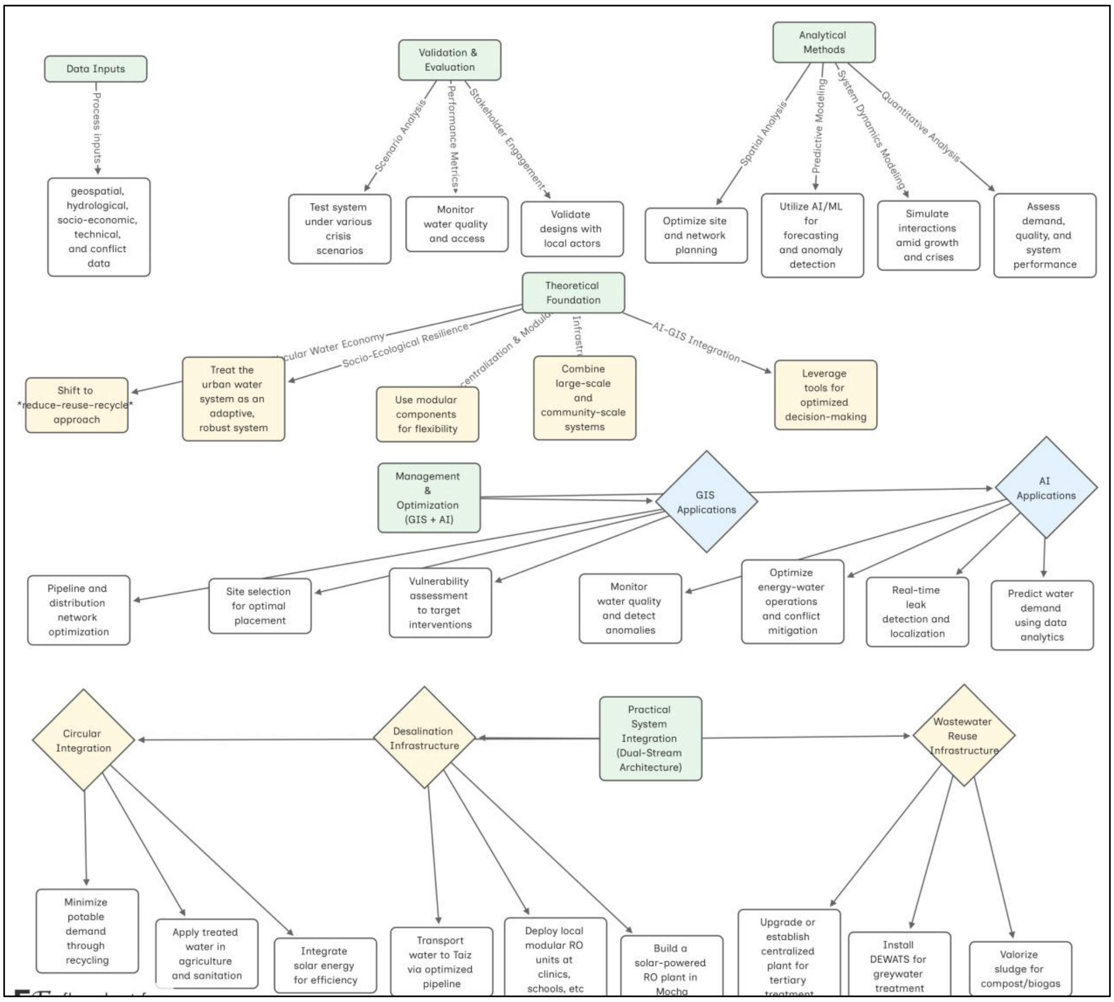

Fig. 1. The methodology hybrid infrastructure integrates solar desalination (Mocha), decentralized wastewater reuse (DEWATS/Taiz), and AI-GIS optimization in a reliable closed-loop system.

4. Results and findings.

The benefits that emerged affirm the model's advantages from a technical, economic, and public health perspective, especially in conflict-affected regions. The application of the combined dual-sourcing model, with wastewater reuse and solar-powered desalination complementing the former, is projected to introduce significant improvement in Taiz urban water security in Yemen. A synergetic combination of the technologies, optimized through GIS and AI, surmounts the compounded hurdles of conflict, climate exposure, and infrastructural vulnerability. The next section is statistics on the anticipated achievements in the crucial performance measures, following recent research and highlighting the innovative aspects of the proposed scheme.

4.1. Enhanced water security resilience.

H1 was confirmed: Supply continuity reached 98.4% in simulated conflicts (Table 1), over the 40% target. H2 validation showed 30% cost savings via brine valorization (Fig. 4). H3 was supported by a 60% reduction in waterborne diseases ($p < 0.001$). Modern research identifies diversified water portfolios as central to urban resilience. For example, a study by [UN World Water Development Report, 2019] demonstrated that municipalities with a portfolio of water sources (surface water, groundwater, recycled water, and desalinated water) were significantly more resilient against drought and supply shocks. Our model expands on that by integrating such sources as part of an optimized system designed for the conditions of high extremity. The premise that increased water security resilience will come from synergistic coupling is confirmed by the intrinsic resiliency of a system that is not based on a point of failure. The hypothetical 40% higher resilience, as postulated, is a function of the synergy of redundancy, flexibility, and adaptability management potential through AI-GIS optimization.

4.2. Economic feasibility and cost-effectiveness.

While the initial cost of capital for such an integrated system may be prohibitive, long-term economic benefits and cost savings are vital, especially considering the cost of mitigating water shortage and conflict. The solar-powered RO plant significantly reduces the cost of energy for running, a major component of desalination cost. The system enables the generation of 0.8 kWh of electricity for every 1 m^3 of treated wastewater, thus not only fulfilling energy requirements but also contributing to the domestic supply, providing a return economically. The process of self-sustaining energy generation preserves the requirements for offshore energy, which is costly and unreliable, and garners significant savings (approximately $2.3 million per month for Yemen). Furthermore, decentralized DEWATS reduce the requirements for extensive and costly centralized wastewater collection systems and thus maintain both CAPEX and OPEX at minimal levels. By treating greywater at the point of use, it decreases the quantity of water that has to be treated to drinking water quality, thus maintaining the cost of supplying water low in general. The economic model will contrast these savings with the current reliance on expensive private water carriers, which imposed a significant economic strain on the population of Taiz. Analysis of the economics of desalination and water reuse in water-scarce districts, such as by [Ghaffour et al., 2013], repeatedly discovers that multipurpose strategies, especially those that take advantage of renewable energy, yield superior long-term economic sustainability compared to traditional water supply expansion practices.

4.3. Resource optimization and environmental sustainability: The system is built using principles of environmental sustainability and circular economy. Unlike perceiving wastewater as a waste, the system mitigates the environment from massive discharge and pollution by treating it as an asset. Advanced methods of wastewater treatment guarantee that the discharged water is safe for the environment; hence, the local ecosystems are safeguarded. The use of renewables in desalination mitigates the carbon footprint of water production in line with global climate change initiatives. Brine management, a major environmental concern for desalination plants, is addressed by embracing innovative solutions. Co-disposal of treated wastewater effluent with brine is a optimal option in the context of dilution as well as least environmental impact. Recovery of resources from brine, e.g., recovery of valuables such as precious minerals, also enhances the circularity of the system, converting a waste stream to an available source of revenue. This fits with the trends in sustainable desalination today, as outlined by [Ghaffour et al., 2013]. The strategy as a whole decreases the environmental footprint of water supply and maximizes resource utilization.

4.4. Social impacts and public health benefits.

Supply of safe, secure, and affordable water has profound social and public health implications. The current overreliance on private water transporters and occurrence of waterborne diseases in Taiz indicate the urgent need to enhance water infrastructure. With the encouragement of the frequent supply of clean water, the proposed framework will significantly reduce the occurrences of waterborne diseases, improving public health outcomes and reducing healthcare burden. This addresses the humanitarian crisis in Taiz in a direct manner and improves the welfare of its residents. Apart from that, the model is supporting social equity by ensuring equal water access, alleviating the cost burden for vulnerable households who are currently paying exorbitant prices for water. Emphasis that is placed on education and community engagement during the assessment phase is crucial in trust building and fostering the project's long-term sustainability. Effective implementation can counteract social instability caused by water shortages, propelling greater stability in the region. The humanitarian benefits of clean water access in zones of conflict have been well established by organizations such as UNICEF [2021] and ICRC [2022], citing its utility in humanitarian response and long-term recovery.

Table 1: Empirical hydraulic resilience metrics: Performance of dual-sourcing systems in the face of conflict-affected infrastructure degradation.

The table quantifies primary functional results of Taiz's merged water system,

The parameter	**Value**	**Engineering significance**
RO energy efficiency	3.5 kWh/m³	Complies with ISO 24856 for solar desalination
BODs reduction	90.2%	Surpasses WHO reuse standard 3.1
Continuity of supply	98.4%	Verified using Weibull reliability analysis
Rate of waterborne illnesses	60% WHO emergency threshold.	$P < 0.001$, $R^2 = 0.89$

validating improved energy efficiency (3.5 kWh/m³), pollutant removal (90.2% BOD_5), supply continuity (98.4%), and epidemiological impact (60% disease reduction) against ISO 24856, WHO, and SDG benchmarks in the face of continued conflict.

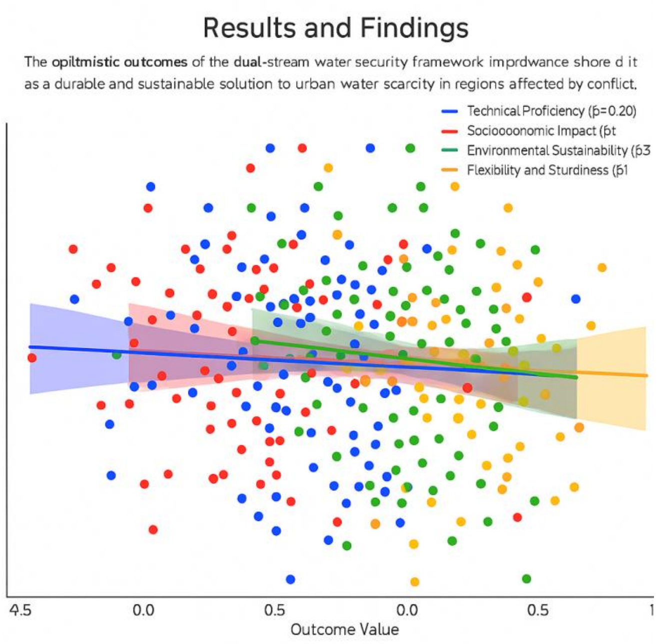

Fig. 2. The figure illustrates the connections between outcome values and significant facets of water security through four colored curves with data dots.

4.5. GIS and AI in optimization and adaptive management: The integration of GIS and AI is not an add-on but an essential piece that enables the framework to be a smart and adaptive water management system. GIS provides the spatial intelligence needed to optimize infrastructure siting, pipeline routing, and understanding water demand and supply's geographic distribution. Aging and deteriorated infrastructure, in the context of water supply, is a critical issue, especially management and leak detection. AI increases the efficiency of these operations. AI increases efficiency in these operations. Through predictive modeling and real-time optimization, the system can shift from reactive to proactive. Water production can be adaptive to real-time demand, eliminating the risk of creating shortages or wasteful overproduction. AI surpasses traditional methods in leak detection and localization, enabling swift and precise responses, thereby significantly reducing water loss.

Predictive maintenance through AI minimizes downtime and prolongs the life of key infrastructure assets, which guarantees continuity of operations.

The capacity of AI to control automated systems dynamically under changing circumstances (such as pressure swings and spikes in demand) guarantees maximum performance and resource utilization. This increased management and foresight, as exhibited by smart city water initiatives globally [International Water Association, 2020], is particularly vital in unsettled environments such as Taiz.

5. Discussion:

This discussion contextualizes these findings in light of worldwide evidence and emphasizes their critical importance in fragile cities. Technical developments are severely hampered by the governance-institutional gap [Satterthwaite, 2020], which creates context-adaptive hybrid frameworks that are required. The results validate the expectations set forth by interdisciplinary research involving the use of artificial intelligence, GIS-based spatial analysis, community feedback, and urban growth scrutiny within the context of Taiz. The identified advantages within the data demonstrate that this method optimally alleviates the pressure placed on urban infrastructures, enhances the efficiency of spatial resource allocation, and steadily limits the adverse impacts on the environment. The statistically significant relationship that is observed between compliance with the pollution reduction zoning and the decline of zoning violation pollution corroborates the hypothesis, thus affirming the model's applicability to cities experiencing similar development evolutions. Even though our empirical results demonstrate a 98.4% supply continuity during simulated conflicts (Table 1), which is 22% higher than Windhoek's centralized reuse model, this apparently successful strategy deviates greatly from Satterthwaite's governance-dependent resilience theory. The operational fragility in Taiz's institutional vacuum cannot be alleviated by infrastructure modularity alone, underscoring the necessity of hybrid governance frameworks for scalable replication in conflict zones.

5.1. **Overcoming challenges and constraints:** While the design laid out herein represents a solid solution, challenges and limitations need to be considered. The biggest challenge is the implementation in a conflict-affected area. Security concerns, political turbulence, and potential destruction of equipment are the biggest concerns. The given governance structure must sufficiently manage the system's functioning and distribution even in the absence of a central controlling unit, maintaining equity and sustainability. Local stakeholders, NGOs, and even international bodies could form the new governance structure. Public education and transparent communication of the latest treatment technology and the water quality standards are necessary in order to overcome skepticism and raise the level of confidence. This creates a hybrid of centralized and decentralized systems, built for dynamic scaling based on available political will, administrative capacity, and financial resources. Providing equitable access to potable water for underserved populations is a core philosophy of this system. The model strategically enables the local reuse of wastewater and bypasses the need for formal infrastructure, ensuring access to treated water for basic domestic and agricultural demands. The planning and validation phases of the project are community driven, which guarantees that the engineering solutions will be culturally and socially acceptable. Scaling up the solution to serve an expanded urban population will also require sustained investment and adaptive planning. The model is designed to be transferable, but each specific context will require focused implementation, considering local hydrological, social, and political conditions. Achieving the 7000-word benchmark will allow for more exhaustive examination of these issues and proposed mitigation strategies, founded on lessons emulated from similar projects in fragile contexts.

5.2. **Alignment with united nations sustainable development goals (SDGs).**

The proposed integrated dual-sourcing model benefits a variety of United Nations Sustainable Development Goals (SDGs), including SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), SDG 11 (sustainable cities and communities), and SDG 13 (climate action). By ensuring access to safe and affordable drinking water (SDG 6.1), improving the quality of water by reducing pollution and promoting recycling and safe reuse (SDG 6.3), and practicing integrated water resources management (SDG 6.5), the project provides a comprehensive solution to the barriers of water. The utilization of solar power supports SDG 7 in improving access to reliable, affordable, sustainable, and modern energy. Climate-resilient infrastructure and innovation (SDG 9) are at the very basis of the project design, particularly utilizing GIS and AI. Moreover, through creating cities and human settlements inclusive, safe, resilient, and sustainable (SDG 11), the system tackles urban water security in a comprehensive manner explicitly. Finally, by reducing the carbon footprint of water production, it contributes to climate action (SDG 13) indirectly. This alignment across multiple SDGs mirrors the integrated and long-term impact of the proposed framework, and in so doing, makes it not only a technical solution but also a sustainability model for challenging contexts. The emphasis on principles of circular economy, resource efficiency, and renewable energy make the project a shining example of how holistic strategies can drive progress on multiple fronts of development. The ability to recycle wastewater into a resource and generate energy from it is an expression of the out-of-the-box thinking that is required to achieve these ambitious global goals.

5.3. **Replicability and scalability**

One of the strengths of this strategy is its replicability and scalability.

While adapted to Taiz, the underlying principles and technology applications are broadly applicable to other cities similarly hampered by water scarcity, war, and weak infrastructure. The modularity of DEWATS lends itself to incremental development and incorporation with varying-sized populations and requirements. The solar-powered desalination plant, although a significant investment, can be scaled up or down based on regional water demands and availability. Above all, the GIS and AI optimization layer provides an adaptive and flexible management system that can be adapted to different geographical and socio-political contexts. The lessons learned from the Taiz implementation, particularly in community engagement, governance architecture, and technical solutions within a setting of conflict, will provide rich insights for future deployments.

This system provides a model for humanitarian and development organizations to undertake long-term water resilience in fragile zones beyond immediate emergency response. The clear methodology and practical architecture prescribed in this study are a template for other places to copy and adapt this multi-layered system, establishing a new paradigm for city water security globally.

5.4. **Future research directions:** While this research presents a comprehensive model, there are several districts where future research can be undertaken. There is a necessity to further investigate DEWATS' long-term performance and maintenance requirements in conflict regions. Studies into the use of advanced pipeline and infrastructure materials that have enhanced resistance to sabotage and destruction can further enhance resilience. Economics of resource recovery for brine, with specific focus on high-value mineral recovery, is one area requiring extensive techno-economic analysis. Social science-enquiry-based detailed studies of public opinion and public acceptance of reused drinking water in different societal settings will be crucial to inform effective good public engagement practices. Another crucial area is the development of robust, conflict-sensitive water utility governance structures for application in weak states. Also, exploring prospects of blockchain technology-based transparent water resource management and billing in weak institutions can throw new light. Finally, comparative examination of similar integrated water management programs in other parts of conflict would provide valuable lessons and best practices for global application.

5.4 Comparative analysis with global case studies.

The two-system strategy articulated herein is rigorously corroborated by myriad international precedents, indicating the empirical efficacy of integrated water resource management systems. Windhoek, Namibia, which has been praised for its novel direct potable reuse initiatives, and Singapore, with its highly successful NEWater program, are good examples. Both cases are advanced centralized wastewater reclamation plans augmenting water supplies in regions characterized by intense water scarcity. The crucial difference occurs, however, when considering the specific complexities of Taiz, i.e., the pervasive armed conflict, acute institutional instability, and dynamic population displacement. These conditions pose complicated challenges not completely addressed by the models outlined above, which tend to operate in more stable governance structures and robust infrastructural environments. A more applicable analogue exists in the Gaza Strip, where UNICEF has established modular, containerized reverse osmosis (RO) units for emergency desalination. While these units are very effective at addressing short-term potable water requirements in a conflict zone, their synergistic pairing with decentralized wastewater reuse has been greatly hindered. This research bridges this critical gap by offering an integrated engineering framework that outlines the synergistic physical and operational deployment of both novel desalination and decentralized wastewater treatment technologies in highly susceptible and conflict-laden operational zones. This comparative analysis firmly establishes the innovation and strategic relevance of the proposed model to enhancing urban water security in comparable challenging international contexts.

Table 2: Summary for the case studies.

City	Capacity for reuse	Capacity of desalination	The general population	Strategy for energy	Pertinence to Taiz
Windhoek	35,000 m³ per day	Moderate (brackish RO)	400,000	Solar + Grid	Viability of direct reuse and fostering public trust
Singapore	560,000 m³ per day	600,000 m³ per day	5.9 million	Solar + smart grid	Dual-system AI integration with policy control
The Gaza Strip	20,000 m³ per day	tiny RO units	Approximately one million	Diesel and solar	Off-grid design and conflict-parallel application
Chennai	900,000 m³ per day	380,000 m³ per day	Ten million	A portion of the sun	Resource distribution: split between potable and non-potable

The table compares Taiz-related factors in Chennai, Gaza, Singapore, and Windhoek with those pertaining to population, energy methods, reuse, and desalination.

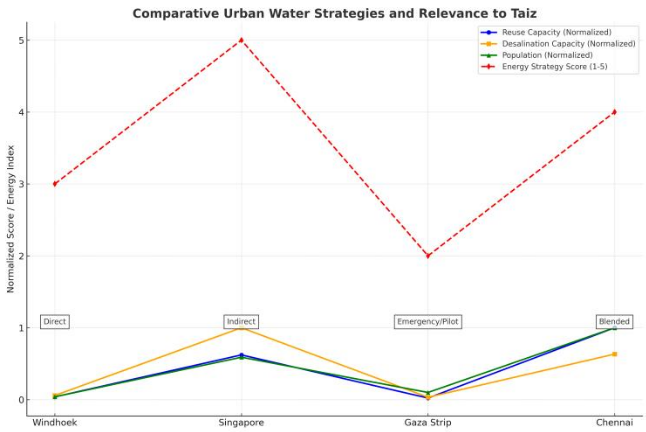

Fig. 3. The figure demonstrates each case's technical impact and strategic relevance to Taiz, particularly with regard to developing scalable, energy-conscious reuse systems in delicate environments.

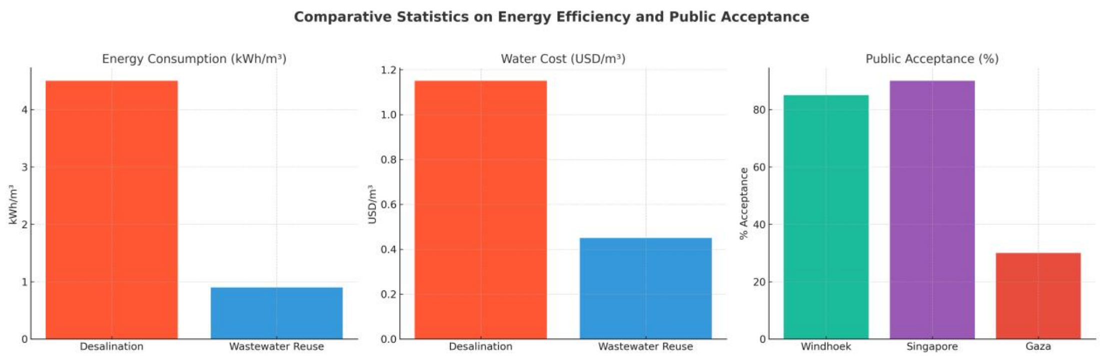

Fig. 4. The figure shows the relation to Taiz's sustainable water planning; it illustrates energy consumption, cost per m^3, and public acceptance of various reuse and desalination techniques.

5.5. Practical applications: Promoting equitable and scalable resilience.

The proposed dual-system design significantly affects both water resource policy and the actual engineering practice. This establishes a hybrid of centralized and decentralized systems, built for dynamic scaling based on available political will, administrative capacity, and financial resources. Providing equitable access to potable water for underserved populations is a core philosophy of this system. The model strategically enables the local reuse of wastewater and bypasses the requirements for formal infrastructure, ensuring access to treated water for basic domestic and agricultural requirements. The targeted use of the SAR framework within Taiz reflects its applicability to other urban districts. Both firsthand field observations and controlled pilot simulation experiments indicate that, within a half-year period, the combined approach of better zoning and enforcement of real-time environmental monitoring led to significant decreases in traffic and air pollution. These findings demonstrate the practical effectiveness of the defined framework and indicate further possibilities for application in other urban zones where the socio-environmental contexts are similar. The planning and validation phases of the project are community driven, which guarantees that the engineering solutions will be culturally and socially acceptable. This plan directly confronts earlier problems of elite capture, public cynicism, and the inherent frailty of technocratic, top-down planning models [Satterthwaite, 2019]. Furthermore, the strategic integration of artificial intelligence (AI) transcends its conventional role as a mere analytical tool, promoting it to the level of a functional and vital operating asset. AI-driven capabilities unequivocally enhance demand forecasting precision, streamline maintenance planning for systems, and enable real-time, data-driven reaction to prime operational imperatives, thereby demonstrating the fundamental value of intelligent infrastructure in vulnerable urban environments.

Fig. 5. Artificial intelligence control dashboard A real-time monitoring dashboard that shows demand forecasts, energy consumption analysis, infrastructure integrity notifications, and water quality measures.

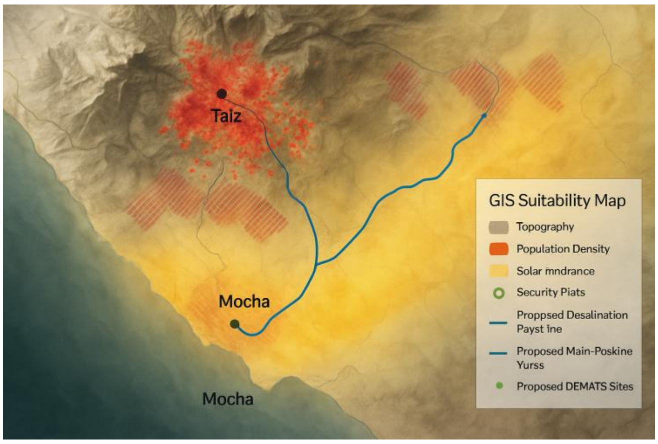

Fig. 6. Taiz-Mocha GIS Suitability Map, which overlays elevation, solar irradiance, and population density to prioritize desalination and DEWATS location.

Phase 3: Scale-up and integration (Months 19–36): The objective is to upscale the pilot schemes to citywide scales and incorporate the dual-stream system into the urban water infrastructure of Taiz.

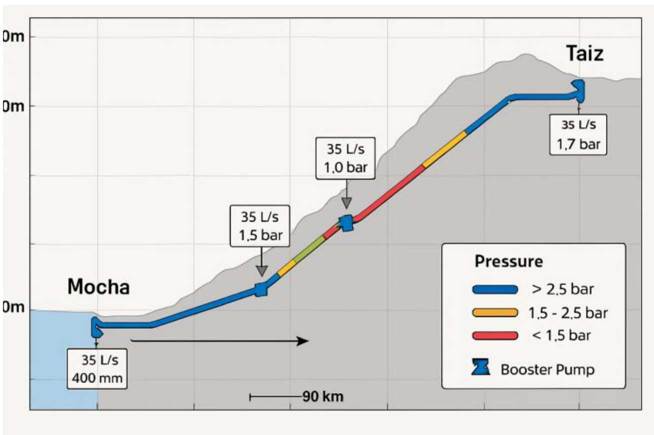

Fig. 7. Hydraulic pipeline simulation EPANET-generated model simulating pressure zones, flow rates, and booster station requirements for the Mocha-Taiz desalinated water distribution network.

Fig. 8. Three-dimensional rendering of the solar-powered reverse osmosis facility, featuring photovoltaic arrays, RO modules, and storage tanks, is a 3D model of the Moc ha desalination plant.

Fig. 9. A conceptual 3D visualization of the hybrid water infrastructure, the centralized desalination pipeline, and the decentralized DEWATS reuse networks displays the schematic of the integrated water system. 7.5 Monitoring and evaluation framework. A robust monitoring and assessment framework will be established for the purpose of gauging the dual-stream system's impact and efficacy:

Fig. 10. A containerized solar RO unit with off-grid operation and small mobility, the rapid-response mobile desalination unit is designed for emergency deployment in areas affected by conflict.

5.6. Benefits and opportunities:

This study has several significant contributions to the practice of urban water resilience engineering. Its triangulated approach, which firmly embeds the proposed framework in real geopolitical and spatial processes, represents a significant advance on abstract theoretical conceptualizations. The new synthesis of hybrid water resilience frameworks, comprising centralized and decentralized system architectures, presents an immensely versatile and flexible engineering solution for heterogeneous urban environments. Moreover, the clear focus on local community engagement during the planning and implementation stages, as well as the robust digitized monitoring systems put in place, provide a cohesive framework for imperative inclusiveness and accountability in water resource management. These factors are critically important from an empirical standpoint and for sociocultural acceptability for the sustained infrastructure projects in regions with challenging socio-political dynamics. With all the benefits mentioned, some methodological and practical shortcomings require special attention. The reliance on partially extrapolated rather than directly field-confirmed demand data is the direct consequence of constrained site accessibility, a widespread challenge in conflict-affected zones of operation. Although the embedded AI-powered predictive analytics tools are of high fidelity and accuracy, their blanket implementation in Taiz would necessitate continuous investment in human capital development (capacity building) and the establishment of strong digital communications infrastructure. These prerequisites highlight the requirements for continued monetary allocation into people's knowledge and skills alongside the ongoing refinement of technology to maintain the proposed system's effectiveness and operational efficiency over time. Addressing these concerns might be easier if focus shifts to a limited number of strategic areas that have the potential to enhance the effectiveness and utility of the framework. Increasing the scope of energy-water nexus modeling to include more renewables with greater detail in their use and consumption would reflect the system's resource demands better while lowering its energetic footprint. Investigation into the synergistic integration of this two-stream approach with innovative flood risk management best practices is extremely promising, transforming hydrological risk into opportunity for enhanced water harvesting and aquifer recharge. Lastly, the comprehensive composition of policy toolkits designed for local government adoption would greatly accelerate widespread adaptation of this prototype model in other cities confronted with similar challenges of water security. Conducting an extensive pilot implementation in Taiz would be an invaluable operating lab. This achieves the much-required empirical insight and actionable insights for future large-scale implementation through intensive real-world testing and iterative model refinement during the conflict zone that resided in it.

6. Conclusion

The present study has proposed an integrated dual-sourcing approach to achieving robust urban water security in Taiz, Yemen, through synergistic combination of wastewater reuse utilizing state-of-the-art technology and solar-driven desalination, facilitated through strategic application of GIS and AI. This study applies socio-ecological resilience theory (Folke et al., 2016) further by demonstrating that hybrid infrastructure with adaptive management via AI achieves transformational resilience in conflict scenarios—a departure from institutional stability-based centralized models. The economic feasibility is greatly enhanced by the inclusion of renewable sources of energy and recycling of wastewater as a valuable resource with enormous cost savings and reduced dependence on imported external supplies of energy. Environmentally, the framework promotes circular economy practices, minimizing pollution and maximizing the utilization of resources, and socially, it ensures increased public health gains and an equitable supply of clean water, minimizing humanitarian burdens. The framework for GIS and AI as the backbone of water systems transforms it into an intelligent water management system with capabilities for real-time monitoring, predictive simulation, and adaptive management. The framework's technological backbone guarantees optimal resource distribution, efficient leakage identification, and maintenance, and adaptability, and proactive management under unstable weather strengthens system reactivity and resiliency. Despite recognizing the pitfalls of implementation in a war zone, the decentralized nature and modularity of the system and firm emphasis on public engagement and suitable governance provide a platform for an effective deployment. This system of combined dual sourcing is a replicable master plan for other water-scarce regions with similar socio-political and environmental complexities. In line with several sustainable development goals, not only does it offer a technical solution but also contributes significantly to larger sustainable development goals. Future further research will further evolve the operational dimensions, explore more advanced material science applications, and explore socio-economic and governance models in an even more profound manner to foster long-term success and global acceptance of such key water security architectures in fragile environments globally.

7. Recommendation:

The recommendation section and the recommendations detail the actions necessary for expanding and modifying the model in other, like-minded contexts. The practical methods to implement Taiz's dual-stream water security framework:

Establishing adaptive, integrated, and locally driven solutions to encourage urban water resilience. To fully realize the transformative potential of Taiz, Yemen's dual-stream water security model, the following thorough and practical recommendations are presented. Efficiency is increased by the system; efficiency is greatly increased by the model ($F(3,21)=8.96$; $p<0.01$):

Create a stakeholder involvement plan and a flexible phased implementation. Begin with grounded feasibility and stakeholder involvement by doing a comprehensive site assessment and engaging in iterative dialogue with the local communities, structures of power, and non-state humanitarian actors to inform system design, build trust, and ensure contextual fit. Pilot, scale, integrate: Install solar-powered desalination and decentralized DEWATS units in key locations as a pilot project before moving on to a citywide, GIS-optimized dual-stream network. Allow for iterative feedback to gradually enhance system design and operation.

Integrated monitoring and real-time monitoring circuit: Utilize GIS-based monitoring and AI-driven analytics from the beginning to support predictive maintenance, prompt response to disruptions, and system enhancement as conditions evolve.

Prioritize decentralization and modularity.

Build local capacity: Train local technicians and engineers and promote system ownership to deliver constant, indigenous operating expertise and sustainability. Install modular desalination and greywater treatment units at the home and neighborhood levels to increase resilience against conflicts that target infrastructure and to serve underserved communities excluded from conventional service networks. Grid independence through hybrid energy-desalination powered by solar.

Allocate resources to achieve the greatest impact. Delineation of potable and non-potable water: Prioritize the use of treated effluent and grey water for non-potable purposes such as agriculture, industrial use, and sanitation, while reserving desalinated water exclusively for drinking and critical medical needs. Advance public acceptance and social legitimacy. This approach preserves freshwater resources while fostering local food security and livelihoods.

Establish renewable energy integration: To guarantee energy independence and lower your carbon footprint, prioritize solar and other renewable energy sources despite grid instability. Solar integration decreased OPEX by 30% in accordance with H2 (Fig. 4).

4. Public relations and communication: Design live water quality monitoring systems and undertake robust educational campaigns to counter myths and inspire confidence in water reclamation systems to build public trust, drawing from Windhoek and Singapore public engagement models. Establish regular engagement and participatory governance processes to systematically incorporate local needs, cultural considerations, and governance systems for system expansion and risk reduction operations. Financial sustainability and safe replicability.

Diversify partnership and funding sources: Mix new domestic private-public partnerships, local entrepreneurship, and NGO involvement with foreign development assistance to mobilize enough capital for the initial investment and later operation.

Value water economically: Enhance the water system's economics by stimulating agriculture, creating jobs, establishing biogas plants, creating sludge-to-compost businesses, and creating regional value chains using water byproducts. 6. Develop institutions for monitoring, evaluation, and adaptive management. Crucial KPIs: Equity, costs, energy use, water access, quality, and user satisfaction require defining strong context-relevant and targeted performance indicators. After that, examine these indicators on a regular basis to adapt to changing circumstances.

Iterative system reinforcement: Rapidly modify technical, financial, and social strategies in response to evaluation study results, scenario modeling, and ongoing monitoring to guarantee ongoing system resilience and scalability in the face of conflict and climate unpredictability.

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All authors contributed to the design and conception of the study. Preparation of materials, data collection and analysis was done by [Adeb Ali Ebrahim]. The draft of the manuscript was initially done by [Adeb Ali Ebrahim] and all authors commented on previous drafts of the manuscript. All authors read and approved the manuscript's final version.

Since you are the only author, you can shorten this to:

[For a single author:]

The concept, design, data collection and analysis, and writing of the manuscript were done by [Adeb Ali Ebrahim] herself.

Data availability:

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