STANDBY PAPER 3

REIMAGINING URBAN BLUEPRINTS: A NEXUS-DRIVEN FRAMEWORK FOR HYBRID WATER SUPPLY SYSTEMS IN WATER AND ENERGY-SENSITIVE SETTLEMENTS

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ABSTRACT

As South Africa pursues the African Union's Agenda 2063 goals of sustainable water availability, conventional centralised "blueprints" for water delivery are increasingly failing to meet the demands of rapid urbanisation and climate instability. In the Sekhukhune District and similar water-stressed regions, the reliance on single-source systems has led to systemic service failures.

This paper presents a reimagined framework for "Hybrid Water Supply Systems" (HWSS) that integrates decentralised options – specifically Rainwater Harvesting (RWH) and Stormwater Harvesting (SWH) – with traditional surface and groundwater sources.

The research utilises a multi-dimensional methodology: (1) A Water-Energy Nexus (WEN) analysis to quantify the energy intensity of decentralised systems; (2) A Global Warming Potential (GWP) assessment using Life Cycle Assessment (LCA) protocols to evaluate carbon footprints; and (3) A numerical simulation-optimisation model developed for the Sekhukhune District to test conjunctive use efficiency.

Findings indicate that by shifting the surface-to-groundwater reliance ratio and integrating RWH/SWH, municipalities can reduce water supply deficits to less than 1%. Furthermore, the framework identifies that gravity-fed designs in hybrid systems can reduce operational energy intensity by up to 30%, directly addressing the energy-sensitivity of South African settlements.

This research provides a "judicious blueprint" for municipal engineers to transition from reactive water management to proactive, circular, and climate-resilient utility models that harmonise water security with energy conservation.

Climate-Resilient Infrastructure; Hybrid Water Supply Systems (HWSS); Water-Energy Nexus (WEN); Conjunctive Use Efficiency; Rainwater & Stormwater Harvesting; Operational Energy Intensity.

INTRODUCTION

Rapid urbanisation, accelerating climate variability, and systemic infrastructure degradation present severe challenges to traditional centralised urban water management models. In water- and energy-sensitive regions like South Africa, these pressures are amplified by deep socio-spatial inequalities and acute power grid instability. This paper evaluates the transition from centralised linear water networks to multi-source, decentralised Hybrid Water Supply Systems (HWSS). By synthesising global techno-economic advancements, regional sub-Saharan African structural realities, and localised South African socio-technical dynamics through the lens of the Water-Energy-Infrastructure-Human Nexus (WEIHN) framework (Huang et al., 2023), we establish an urban blueprint that explicitly accommodates decentralised source realities, structural limits, and community institutional dynamics to deliver an equitable and climate-resilient framework. To enhance further understanding and applicability of the HWSS, the study presents the results of a numerical conjunctive surface and groundwater use simulation-optimisation model applied to the Sekhukhune District Municipality in South Africa to test conjunctive use efficiency.

LITERATURE REVIEW

The Failure of Centralised Paradigms

For over a century, municipal planning has relied on Centralised Water Systems (CWS) designed around a linear layout: large-scale freshwater extraction from distant reservoirs, intensive treatment at localised plants, and extensive, energy-heavy distribution piping over long distances. This structural configuration creates an inherent, vulnerable path dependency that is approaching its breaking point under contemporary conditions of rapid urbanisation and climate instability.

To address these vulnerabilities, contemporary scholarship is turning to Hybrid Water Supply Systems (HWSS). These systems integrate existing centralised components with Modular, Adaptive, and Decentralised (MAD) infrastructures. Sapkota et al. (2014) indicate that peer-reviewed empirical modelling suggests that strategic integration of these MAD systems can successfully reduce centralised mains water demand by 20% to 80%, depending directly on their level of technological sophistication, spatial distribution, and source-separation configurations (Sapkota et al., 2014). These frameworks rely on a diverse portfolio of Decentralised Water Systems (DWS), which include:

- Rainwater harvesting (RWH) and stormwater capture systems.
- Greywater reclamation and localised non-potable reuse schemes.
- Groundwater extraction via Managed Aquifer Recharge (MAR).
- Localised decentralised desalination or micro-scale purification plants.

Evaluating these systems requires an expanded analytical paradigm. Recent studies have expanded the traditional Water-Energy Nexus (WEN) into the Water-Energy-Infrastructure-Human Nexus (WEIHN) (Huang et al., 2023). This expanded model acknowledges that physical hardware integration alone cannot succeed without explicitly co-optimising infrastructure conditions and community institutional acceptance.

Global Trajectories: Techno-Economic Optimisation & Water Microgrids

At a global scale, the core motivation for transition is the recognition of

deep resource interdependency. Globally, approximately 7% to 8% of all generated electricity is consumed directly by drinking water production, transmission, treatment, and distribution (Sharif et al., 2019). Consequently, any disruption or inefficiency in the energy sector directly threatens water delivery, and vice versa.

Drawing inspiration from decentralised electrical grids, global water research focuses on Water Microgrids (Hasnat, 2025). These localised, information and communication technology (ICT)-enabled networks coordinate multiple alternative water sources, treatment steps, and storage units close to the consumer. These systems are designed to operate in two distinct modes:

- **Grid-Connected Mode:** Interacting dynamically with the central network, shifting demands based on tariff structures and source availability.
- **Islanded / Autonomous Mode:** Disconnecting completely from the main utility network during system failures, contamination events, or electricity grid collapses to ensure baseline survival security.

Mature manifestations of this paradigm are observable globally. Driven by the legacy of the Millennium Drought, Australia pioneered the integration of large-scale seawater desalination with localised stormwater harvesting and mandatory dual-reticulation systems in new urban developments (Sapkota et al., 2014). Singapore exemplifies global best practice through its "Four National Taps" strategy, which hybridises local catchments, imported water, high-purity reclaimed wastewater (NEWater), and seawater desalination into a single digitally managed loop (Sapkota et al., 2014). In the United States and Europe, the focus centres on decentralised wastewater reuse and MAR to buffer seasonal surface variations (Sapkota et al., 2014).

To manage these multi-source networks, global research relies heavily on computational modelling and genetic algorithms (e.g., EPANET-MATLAB integrations) to minimise greenhouse gas emissions, optimise pump scheduling, and lower lifecycle costs (Sharif et al., 2019; Maxwell et al., 2023).

A typical cost-minimisation multi-objective function for a hybrid network can be framed as follows:

$$J = \min_{t=1}^{T}[\alpha \cdot E_t(P_t) + \beta \cdot C_{\text{treat}}(Q_t, S_t) + \gamma \cdot R_{\text{avail}}(S_t)] \quad \text{.....(1)}$$

Where:

- $E_t(P_t)$ represents the electrical energy cost as a function of pump power configuration P_t at time t.
- $C_{\text{treat}}(Q_t, S_t)$ represents the volumetric treatment cost for a given water flow Q_t pulled from an alternative or centralised source S_t.
- $R_{\text{avail}}(S_t)$ measures the reliability risk or penalty based on the available storage capacity of that source.
- α, β, γ are weighting parameters tailored to localised economic realities.

While these digital twins maximise performance, studies indicate that these advanced digital tools require high-fidelity telemetry, reliable grid power, and highly skilled institutional support—conditions that are frequently absent in developing regions.

Sub-Saharan African Perspective: Institutional Silos & Circular Economies

When shifting focus from global frameworks to sub-Saharan Africa, the core challenges transform from technical optimisation to overcoming institutional fragmentation, historical infrastructure deficits, and rapid, unplanned informal urban migration.

Policy Fragmentation and Institutional Silos

A defining characteristic of resource governance across Africa is the entrenchment of "siloed" administrative mentalities. Regional assessments by agencies like the Southern African Development Community (SADC) show that water management, energy generation, and agricultural planning operate in isolated vertical silos (Taguta, 2026). This structural division causes major policy conflicts:

- Energy ministries may implement carbon-mitigation or power-generation plans without evaluating their localised water footprint (Taguta, 2026).
- Water departments frequently design regional transfer schemes that rely on massive, unavailable electrical inputs for pumping (Taguta, 2026).
- Cross-sectoral co-benefits are missed, compromising regional sustainability indices (Taguta, 2026).

The Continental Mandate and Informal Realities

Vast peri-urban and informal settlements have developed on the peripheries of major African cities, such as Chambishi in Zambia and Diepsloot in South Africa. Comparative assessments demonstrate that centralised infrastructure extensions are often physically or financially unviable in these environments (Sikhwivhilu, 2020). Consequently, regional scholarship strongly rejects a "one-size-fits-all" model, advocating for context-specific, decentralised interventions rather than homogeneous, top-down engineering standards.

This perspective has been formally elevated through the adoption of the *Africa Water Vision 2063* (AMCOW & AUC, 2026). This blueprint frames water as a "super-connector" linking health, food systems, energy, industry, and continental stability. The regional perspective focuses on transforming alternative water and waste streams through a Circular Sanitation Economy (CSE) to generate green jobs and recover costs (AMCOW & AUC, 2026). By framing localised rainwater harvesting, modular decentralised purification, and solar-powered groundwater extraction as formal components of an HWSS, the African perspective moves away from viewing decentralised options as temporary "survivalist" informal fixes, instead integrating them into overarching municipal master plans to achieve continental equity and security.

South African Perspective: Compounding Crises & Socio-Spatial Inequalities

South Africa represents a unique and highly complex case study for hybrid water architecture. It is an extremely semi-arid nation, ranking approximately 30th globally in rainfall, with an average annual rainfall of roughly 450 mm, compared to the global average of 990 mm (du Toit & Chilwane, 2021). This natural water scarcity intersects directly with deep socio-spatial inequalities and a protracted energy crisis.

The Load Shedding–"Water Shedding" Loop

The most critical local vulnerability in South Africa is the direct impact of power utility instability ("load shedding") on water service delivery. Rolling blackouts interrupt South Africa's metropolitan water distribution networks, which rely on steady electrical power to operate massive pumping stations, booster pumps, and water treatment works. When power drops, reservoirs cannot refill, leading directly to "water shedding" (the loss of water pressure or the complete termination of supply across entire municipal pressure zones). This feedback loop illustrates the real-world vulnerability of the water-energy nexus in a sensitive settlement.

Municipal Uptake of Water Sensitive Urban Design (WSUD)

WSUD serves as the overarching planning framework within which HWSS operates, integrating the urban water cycle—water supply, wastewater, stormwater, and groundwater management—into urban design (du Toit & Chilwane, 2021). In South Africa, the uptake of WSUD concepts varies significantly across municipalities, driven by localised water scarcity,

institutional capacity, and the constitutional realisation of the Human Right to Water (Mjadu, 2025):

- **City of Cape Town:** Following its historic "Day Zero" drought crisis, Cape Town has emerged as a national leader. The city has formalised policies for integrating Sustainable Drainage Systems (SUDS) into new property developments and is implementing extensive Managed Aquifer Recharge (MAR) initiatives in the Atlantis and Cape Flats aquifers to buffer municipal supply (du Toit & Chilwane, 2021).
- **eThekwini Metropolitan Municipality:** Globally recognised for its innovative approaches, eThekwini utilises WSUD concepts through decentralised wastewater recycling, treating industrial effluent for reuse in non-potable manufacturing processes to free up high-quality surface water for residential distribution (du Toit & Chilwane, 2021).
- **City of Johannesburg:** Implementation remains constrained by institutional fragmentation, infrastructure backlogs, and recent systemic delivery crises. WSUD efforts remain primarily focused on localised stormwater management and flood mitigation via SUDS (e.g., attenuation ponds, permeable pavements), rather than on full integration into the bulk water supply network (du Toit & Chilwane, 2021; ISS Africa, 2026).

To address these limits, the national perspective focuses on integrating alternative water sources into existing municipal reticulation networks to achieve systemic redundancy, aligning interventions with the National Water Act (Act 36 of 1998), SANS 241 water quality criteria, and municipal bylaws.

Socio-Spatial Realities and Disparities

Empirical field studies reveal a stark divide in the actual adoption of source-control measures across different socioeconomic demographics, as detailed in Table 1.

TABLE 1: *Adoption of WSUD Source-Control Measures Across Socioeconomic Groups in South Africa*

Aspect	Affluent Suburban Neighbourhoods	Vulnerable / Informal Settlements
Primary Alternative Sources	Automated rainwater harvesting tanks, groundwater boreholes, and private greywater systems (du Toit & Chilwane, 2021).	Informal water channels, communal standpipes, and informal shallow wells (Msimanga, 2026).
Financial & Structural Capacity	High capital availability: robust engineered roof structures are optimal for clean RWH catchments.	Low capital availability: structurally weak or crowded make-shift structures (shacks) that limit guttering and heavy tank placement.
Grid Resilience	Private backup solar photovoltaic (PV) systems or generators to keep localised pumps active.	Total reliance on communal municipal systems; complete vulnerability to localised grid outages.
Resource Disparities	High per-capita consumption, sometimes exceeding 290 litres/ capita/day in specific zones.	Severe water insecurity; strong correlation between drought periods and rapid drops in basic health indices.

Socio-Spatial Insight: Household-level Water-Energy-Food (WEF) nexus indices across South Africa's semi-arid interior confirm that housing type, gender of household heads, and localised infrastructure access are primary predictors of resource security (Msimanga, 2026). The inference thereof is that technical configurations must be highly customised to avoid exacerbating these systemic historical inequities.

Synthesis: Towards a Nexus-Driven Strategic Framework

To bridge the gap between global technical possibilities and local socio-technical constraints, urban blueprints must be reimagined around an integrated, nexus-driven framework balancing three distinct dimensions:

- **Techno-Economic Decoupling:** Integrating dedicated solar PV arrays directly into local water networks ("behind-the-meter solar") to protect decentralised infrastructure (local treatment units and small-scale booster pumps) from the unstable national electricity grid (Sharif et al., 2019).
- **Eco-Infrastructural Diversification:** Utilising localised water budgets by combining rainwater harvesting for non-potable uses, greywater treatment for irrigation, and managed aquifer recharge to provide natural, zero-evaporation storage.
- **Socio-Political Co-Design:** Transitioning from top-down planning to a collaborative co-design model, as community acceptance of alternative water sources (particularly recycled greywater) depends directly on local cultural norms, trust in testing protocols, and civic ownership (du Toit & Chilwane, 2021).

Water Crisis Metrics and Strategic Asset Management

Under non-stationary climatic conditions, the severity, frequency, and duration of localised water crises serve as primary quantitative metrics for initiating the structural transition to HWSS. By tracking indicators such as the Water Stress Index (WSI), reservoir depletion velocity, and the frequency of intermittent supply cycles, water authorities can establish precise empirical triggers for localised infrastructure deployment (Sapkota et al., 2015). This perspective shifts the paradigm from project-based thinking to system-based stewardship, directly aligning with the Strategic Asset Management (SAM) framework championed in the Africa Dialogue Series (UN OSAA, 2026). SAM emphasises lifecycle planning, governance, maintenance, and optimisation of water systems over mere infrastructure expansion. HWSS implementation is triggered when the marginal cost of expanding centralised bulk infrastructure exceeds the lifecycle cost of localised, decentralised interventions (Sapkota et al., 2014).

The Water-Energy Nexus & Lifecycle Assessments (LCA)

From an Energy Intensity (EI) perspective, every alternative water asset within an HWSS possesses a distinct operational energy profile, quantified as the cumulative electrical energy required to treat and distribute a cubic meter of water(kWh/m^3) (Behzadian & Kapelan, 2015). Conventional gravity-fed surface water schemes maintain a low EI profile (0.3 to 0.5 kWh/m^3). In contrast, advanced decentralised configurations exhibit exponentially higher energy demands: advanced wastewater reclamation utilising MBR systems coupled with reverse osmosis loops scales to 1.0 – 1.5 kWh/m^3, while decentralised seawater desalination plants demand 3.0 – 4.5 kWh/m^3 (Behzadian & Kapelan, 2015).

WEN optimisation within an HWSS, therefore, requires a delicate trade-off analysis: while MAD systems minimise volumetric demand on centralised water systems, they simultaneously increase localised electricity demand. In energy-constrained systems like South Africa, this increased EI must be mitigated by decoupling hybrid facilities through co-located renewable microgrids (Sharif et al., 2019).

To thoroughly validate these configurations, recent scholarship relies on comprehensive Life Cycle Assessments (LCA) isolating two core metrics (Ghimire et al., 2017):

- **Global Warming Potential (GWP):** Quantified in $CO_2.\text{eq}/m^3$
- **Energy Use Potential (EUP):** Quantified in MJ/m^3.

LCA sensitivities show that while systems like Rainwater Harvesting

(RWHS) drastically reduce mains water stress, their net GWP and EUP can eclipse conventional surface supply systems if poorly optimised (Ghimire et al., 2017). The embodied environmental burdens within the storage infrastructure (e.g., concrete vs high-density polyethene tanks) constitute a massive spike in upfront GWP and EUP. Furthermore, during the operational phase, frequent cycling of low-efficiency, downscaled pumps to maintain hydraulic pressure across dual-reticulation grids can increase operational EUP. To maximise the benefits of an HWSS, an immediate balance between the volumetric savings and the long-term, cradle-to-grave carbon and energy footprints, as determined by LCA metrics, is required.

METHODOLOGY

(a) The Rainwater-Energy Nexus (RWEN) Framework

- *Conceptual Basis*: The RWEN framework addresses the strong interdependence between water and energy within the urban water cycle, explicitly treating rainwater harvesting systems (RWHS) as energy consumers within the broader service delivery cycle.
- *Key Metric*: Energy Intensity (EI), defined as the unit of energy consumed per unit of water, serves as the primary parameter to evaluate the environmental and economic feasibility of distinct RWHS configurations.
- *Analytical Approach*: The framework integrates both top-down and bottom-up approaches to comprehensively quantify and compare the energy flows of conventional urban networks alongside alternative rainwater harvesting systems.

(b) LCA and GWP Analysis Protocol for an RWHS

- *Emission Quantification*: Global Warming Potential (GWP, measured in $kgCO_2/kWh$) is evaluated based on the established correlation between a system's energy intensity (EI) and its greenhouse gas (GHG) emissions.
- *Protocol & Emission Factors*: In the absence of updated local data, the protocol adopts the International Financial Institutions Technical Working Group on Greenhouse Gas Accounting (IFI TWG) Default Emission Factors.
- *System Customisation*: The default values—originally established for conventional water sourcing, conveyance, treatment, and distribution—are customised and calibrated for domestic RWHS environments to map lifecycle impacts.

(c) Socio-Economic Acceptance Index () for RWHS Selection

- *Objective*: The *S-el* quantification evaluates the social perception, public willingness, and institutional viability of implementing domestic RWHS at scale.
- *Index Development*: The index is compiled via data analysis from structured surveys addressing critical socio-economic parameters, including:
  - Public perception of rainwater as a necessary or secondary resource.
  - Perceived dignity and quality trust in rainwater versus municipal piped water.
  - Individual and community willingness to adopt harvesting technologies.
  - Institutional governance, including political will, public awareness campaigns, and multi-tier government guidelines to mainstream RWHS into official water delivery portfolios.

(d) Hydrological and Conjunctive Use Modelling

- *Model Structure*: To optimise multi-source urban water use, a coupled simulation-optimisation model was developed. The architecture binds a groundwater simulation model to a multi-objective optimisation program, thereby creating a unified supply-demand conjunctive-use framework.
- *System Parameters:*
  - *Surface Water:* Characterised by streamflow distribution and local reservoir storage capacities.
  - *Groundwater:* Accounts for subsurface geology, aquifer safe yield, transmissivity, response recovery times, and hydraulic interactions with existing wells.
- **Optimisation Goal:** The model operates under the core objective function of *minimising total water deficiency* across the designated command area while fully satisfying baseline water demands. A key boundary condition assumes that the initial water supply infrastructure remains fixed over time.
- **Case Study Validation:** The framework was operationalised using institutional and hydrological data from the Elias Motsoaledi Local Municipality (EMLM) within the Sekhukhune District Municipality to establish realistic water allocation rules.

The Conjunctive Use Model

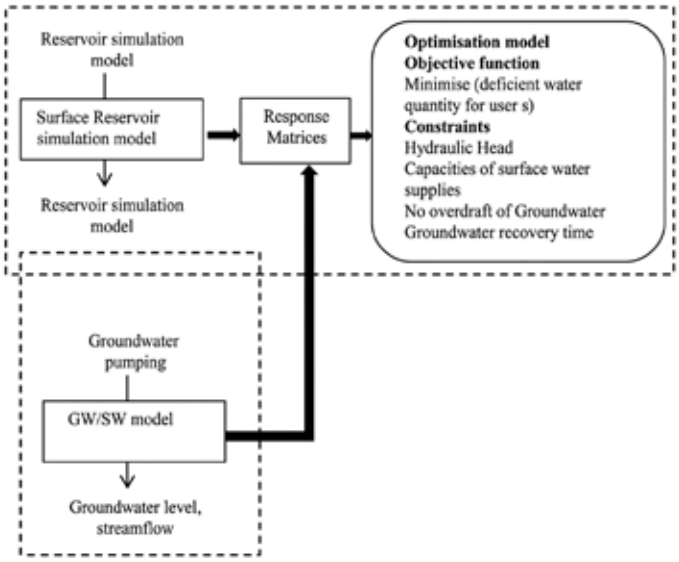


FIGURE 1: *Conjunctive use simulation-optimisation framework. (Source: Ochieng et al., 2023)*

In optimisation, a model with the objective function to minimisation of total deficiency was applied. The model assumed the initial facilities for water supply are fixed and do not change with time. The objective function minimises the total water deficiency while satisfying all water demands in the command area. Equations 2-7 provide the numerical expressions (models) used to build the final model.

$$Min.\, x_m = \sum_{i=1}^{n} Q_{D,i,m} \quad \ldots\ldots (2)$$

$$i = 1,2,3, \ldots\ldots n$$

Where: $Q_{D,i,m}$ =Total water demand of user *i* in the command area, m, [L^3]

To prevent groundwater resources from being depleted through well-sustained pumping, contamination, and well degradation, a weighting factor is included in Equation 2. Thus, the final objective function is given as:

$$Min.\, x_m = \sum_{i=1}^{n} \beta_i Q_{D,i,m} \quad \ldots\ldots (3)$$

Where: β_i = weighting factor for groundwater depletion objective function for *i*

The objective function in the optimisation problem was subject to the following set of constraints linking the hydraulic heads of the unconfined and confined aquifers (Equations 4-5), the capacities of the surface reservoir

water supplies (Equation 6), and the prevention of overdraft of groundwater resources (Equation 7). This is achieved by:

$$K_{i,H,min} \leq K_H - K_s \leq K_{H,max} \quad (4)$$

Where: $K_{i,H,min}$ is the allowable minimum hydraulic head at i [L], $K_{i,H,max}$ is the allowable maximum hydraulic head at i [L], $K_{i,H}$ is hydraulic head at i [L], K_s is drawdown at i [L]. At the pumping wells, the drawdown must not exceed the desired values for all time steps. Using the transient functions, these constraints can be expressed as:

$$I_s = \sum_{i=1}^{n} \gamma_i Q_{g,i,m} \quad (5)$$

Where: I_s is the drawdown at cell i, γ_i, is an objective weighting factor for groundwater yield from i. and $Q_{g,i,m}$ is pumped groundwater from cell i in command area m [L³].

$$\sum_{r=1}^{m} \sum_{i=1}^{n} Q_{r,i,m} \leq \sum_{i=1}^{n} W_r \quad (6)$$

Where: $Q_{r,i,m}$ = surface water from source r to command area m, W_r= surface water reservoir capacity [L³].

$$\sum_{r=1}^{m} \sum_{i=1}^{n} Q_{g,i,m}^{j} + \sum_{i=1}^{n} Q_{g,i} \leq Q_{g,n} \quad (7)$$

Where: $Q_{g,i}^{j}$ groundwater pumped from aquifer i for user j in command area m [L³].

$Q_{g,i}$ Groundwater pumped from cell i [L³]

Overall, natural groundwater recharges in part [L³]

Elias Motsoaledi Local Municipality (EMLM) Surface Water Data

Given the use, a 30-day decision interval is selected for the case study. In a year, 12 decisions are taken, with an interval of 30 days between each decision in a wet year. A wet year is considered to begin from June 1 and end May 31. The mean annual rainfall in the command area is 620 mm based on 10 years of historical records from January 2006 to December 2016. Based on the Mean Annual Precipitation (MAP) in the surrounding area, assuming recharge being 2% of MAP, the rainfall recharge is approximately 702 m³/a. Table 2 presents the average inflow to the reservoir, pipeline losses, consumption, and average rainfall in the command area for each of the 12 decision intervals for the whole year. The first period, starting from June, is taken as the beginning of the wet year.

TABLE 2: *Inflow from WTP, pipeline loss, and consumption statistics*

Decision interval	Inflow (m³)	Pipeline loss (m³)	Consumption (m³)	Rainfall Ave (mm)
1	283.950	15.67	268.28	5.69
2	233.660	15.13	218.53	5.87
3	221.150	12.64	208.51	7.47
4	263.979	24.136	239.843	10.12
5	296.757	24.265	272.492	49.45
6	266.795	27.324	239.471	83.23
7	258.596	24.477	234.119	105.09
8	315.941	31.856	284.085	124.89
9	267.737	10.125	257.612	101.62
10	310.651	0.39	310.261	69.41
11	192.760	6.94	185.82	53.12
12	288.990	38.7	250.29	18.73

Table 3 presents the outcome of the Water Services Assessment by DWS and a summary of the quaternary of Water Resources in Elias Motsoaledi. The outcome of the Water Services Assessment Model (WSAM) for quaternary water resources indicates a total surplus of 255.9 m3/a. This demonstrates the potential of exporting and developing water resources.

TABLE 3: *Elias Motsoaledi Local Municipality quaternary water resources (Source: WSAM, 2019; Ochieng et al., 2023)*

Summary of Water Resources			
Water Resources		Water Requirements	
	million M³/a		million M³/a
Surface	545	Irrigation	199.1
Groundwater	54.6	Urban	10.6
Return Flows	18.2	Rural	23.3
Transfer IN	50.9	Mining & Bulk Industrial	5.3
		Ecological Reserve	123.6
		Transfer OU	50.9
TOTAL	668.7		412.8

RESULTS

The RWEN Framework

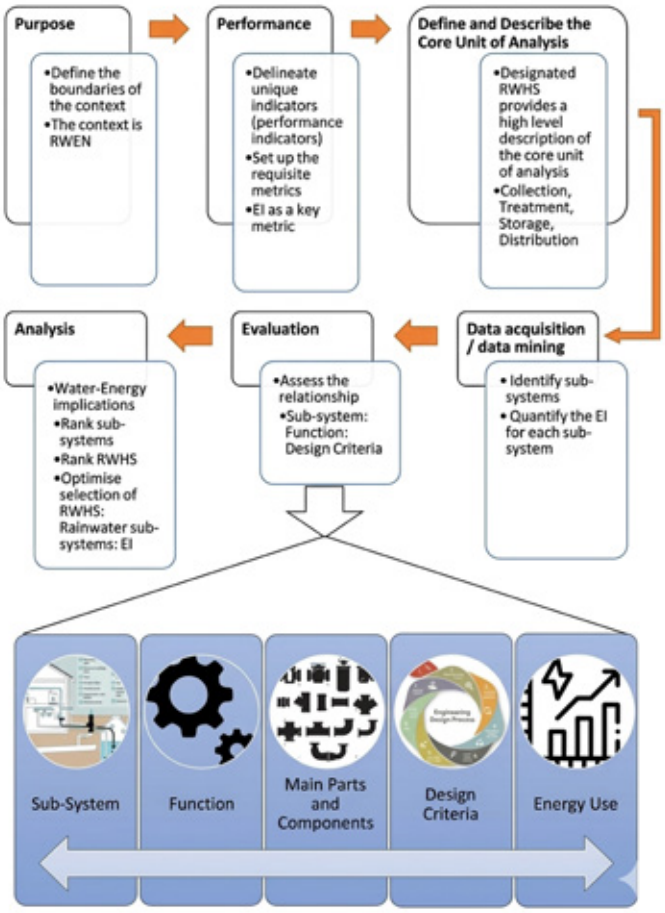


FIGURE 2: *The RWEN Framework. (Source: Ochieng et al., 2023)*

The S-el

A quantifiable **Socio-Economic Acceptance Index ()** was developed using a multi-criterion weighted index model. The is constructed as a weighted composite index aggregated from four core sub-indices/dimensions outlined in the methodology section. Where the overall Index is defined as follows:

$$S\text{-}eI = \sum_{i=1}^{n} w_i \cdot I_i = w_1 I_{per} + w_2 I_{dig} + w_3 I_{wil} + w_4 I_{gov} \quad (8)$$

Where:

- I_i represents the normalised score of each sub-index dimension.
- w_i represents the assigned empirical weight for each dimension, subject to the constraint:

$$\sum_{i=1}^{n} w_i = 1.0 \quad (w_i > 0) \quad (9)$$

The Application Protocol: Operationalising the S-eI Index



FIGURE 3: *S-eI Model Application Protocol*

Index Interpretation Matrix

At the final stage, the scores for are mapped to evaluate the feasibility of selecting the RWHS framework to form part of the HWSS. According to equations 8 and 9, the final computed value of the ranges strictly from (Absolute Rejection) to (Absolute Acceptance). Table 4 presents the index interpretation matrix.

TABLE 4: *The S-eI Interpretation Matrix*

S-eI Range	Acceptance Class	Strategic Implication for RWHS Selection
0.00 – 0.40	Low Acceptance	**High Risk:** High community resistance or poor institutional support. Implementation should be paused in favour of extensive public education and policy revision.
0.41 – 0.70	Moderate Acceptance	**Conditional Feasibility:** The system can be selected, provided that specific interventions target weak sub-indices (e.g., boosting water quality confidence or political awareness).
0.71 – 1.00	High Acceptance	**Optimal Feasibility:** Strong socio-economic alignment. The community and governance structures are fully primed for large-scale domestic RWHS roll-out.

Numerical Conjunctive Use Model

Table 5 presents the results of the optimisation using the linear programming model in Equation 7, along with the corresponding optimal distribution of hydraulic heads in both confined and phreatic aquifers in the study. From the model, optimal allocations of water resources, that is, optimal conjunctive use of surface water and groundwater resources between various users in the applied study area, are presented.

The minimum water supply deficiency of 6.15 m³ was achieved under optimal water supply conditions, representing about 0.18% of the total existing water use in the study area. The initial water demand ratio of surface water to groundwater in the study area, benchmarked at 2:1, shows a greater improvement at the current optimal ratio of 44:1, thereby lowering the risks associated with aquifers under abstraction. However, the results indicate that dependence on surface water supplies to meet the study communities' water requirements will persist under the status quo scenario. This could be different, however, with the expected future scenarios of growth and development in designated special economic zones and development/growth nodes in the SDM. While optimal water supplies for users' current water demand are mostly satisfied, they cannot be met in some instances if over-abstraction control for the groundwater system is not maintained. This can be attributed to the uneven spatial distribution of the water infrastructure in command areas.

GENERAL FINDINGS AND ANALYSIS

The application of the numerical model to the EMLM in Sekhukhune District revealed that a mixed-strategy approach—using surface water primarily during wet seasons and cycling groundwater and harvested rainwater during dry periods—can satisfy 99% of daily demand. The literature analysis of GWP found that "sizing optimisation" is the most critical factor in reducing a system's carbon footprint; oversizing tanks leads to "embodied carbon" that never recovers its value through water savings. Social indicator monitoring is important for gauging community acceptance of RWHS implementation. The risk gauge can help policymakers avoid investing in projects that fail the community's uptake test.

TABLE 5: *Optimal water allocation of water resources for consumers (Unit: m3) (Source: Ochieng et al., 2023)*

Command Area/ water infrastructure	Command Area Water Demand	Groundwater supply			Surface water supply			Deficient water supply
		Phreatic consumers	Confined Aquifer consumers	Total	GWTW	RWTW	Total	
1	331.363	1.7	3.2	4.9	258.280	11.563	269.843	56.62
2	279.112	4.1	0.2	4.3	233.660	13.412	247.072	27.74
3	245.562	2.3	1.2	3.5	198.310	18.632	216.942	25.12
4	319.172	3.2	0.3	3.5	241.774	12.548	254.322	61.35
5	356.576	6.5	0.5	7.0	270.472	19.124	289.596	59.98
6	271.203	6.5	3.1	9.6	238.365	16.458	254.823	06.78
7	326.977	2.6	0.2	2.8	223.712	15.325	239.037	85.14
8	345.590	3.7	4.4	8.1	284.085	12.756	296.810	40.68
9	216.064	4.5	0.2	4.7	187.240	17.974	205.214	06.15
10	328.639	5.5	0.1	5.6	241.774	19.005	260.779	62.26
11	344.773	1.8	1.1	2.9	256.023	16.010	272.033	69.84
12	279.335	2.4	0.4	2.8	243.190	11.025	254.215	22.32
13	324.980	4.6	1.2	5.8	271.365	13.365	284.730	34.45
Note: GWTW = Groblersdal Water Treatment Works; RWTW = Rossenekal Water Treatment Works								

CONCLUSIONS

Reimagining South Africa's urban blueprints requires shifting away from the historical path dependency of centralised, linear water systems. South African water blueprints must be reimagined as hybrid, circular systems to achieve the goals of AU Agenda 2063 and ensure municipal resilience. In water- and energy-sensitive settlements, the hybrid water supply paradigm offers a viable approach to build climate resilience and safeguard basic human rights. This paper demonstrates that a nexus-driven approach—one that treats energy and carbon as equally important as water volume—provides the only judicious path forward for sustainable sanitation and water availability.

Future Research Trajectories

Future academic research trajectories should focus on:

1. Developing dynamic, real-world hydraulic models that simulate how hybrid water microgrids behave under erratic, multi-stage load-shedding schedules.
2. Quantifying the exact water-saving and energy-reduction trade-offs of micro-scale water treatment technologies powered by localised renewable energy grids.
3. Designing institutional and regulatory frameworks that allow municipal utilities to legally manage, support, and maintain decentralised, community-owned infrastructure assets.

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REFERENCES

African Ministers' Council on Water (AMCOW), & African Union Commission (AUC). (2026). *Africa Water Vision 2063 and Policy: A water secure and resilient Africa with safe sanitation for all*. AU Commission Publishing.

Behzadian, K., & Kapelan, Z. (2015). Modelling metabolism-based performance of an urban water system using WaterMet2. *Resources, Conservation and Recycling*, 99, 84–99.

Carden, K. (2018). *Challenges and opportunities for implementing Water Sensitive Design in South Africa*. Gezina: Water Research Commission. Report No. 2412/1/18.

du Toit, J., & Chilwane, L. (2021). Urban household uptake of water sensitive urban design source control measures: an exploratory comparative survey across Cape Town and Pretoria, South Africa. *Urban Water Journal*, 19(2), 141–150.

Ghimire, S. R., Johnston, J. M., Ingwersen, W. W., & Sojka, S. (2017). Life cycle assessment of a commercial-scale rainwater harvesting system: Environmental impacts and trade-offs. *Journal of Cleaner Production*, 149, 539–551.

Gupta, J. P. (2026). Challenges of Water-Energy Nexus in BRICS Nations: A Qualitative Approach. *Waterlines*, 44(1s), 260–278.

Hasnat, A. (2025). Water Microgrids as a Hybrid Water Supply System: Review of Definitions, Research, and Challenges. *Sustainability*, 17(18), 8418.

Huang, Y., Zhang, J., Ren, Z., Xiang, W., Sifat, I., Zhang, W., Zhu, J., & Li, B. (2023). Next generation decentralised water systems: a water-energy-infrastructure-human nexus (WEIHN) approach. *Environmental Science: Water Research & Technology*, 9(9), 2446–2471.

Institute for Security Studies (ISS Africa). (2026). *Johannesburg's water crisis clouds Africa's bold new water vision*. ISS Today Analysis.

Maxwell, C. O., Oonge, Z. I., Odira, P. M., Ouma, G. O., Lompi, M., Pacetti, T., Bacco, M. D., & Caporali, E. (2023). Water–Energy Nexus-Based Optimisation of the Water Supply Infrastructure in a Dryland Urban Setting. *Water*, 16(21), 3073.

Mjadu, L. (2025). Agenda 2063 and the Right to Water as a Human Right: An Assessment of the Legal Perspectives and Trajectory Toward Sustainable Water Access in Africa. *E-Journal of Humanities, Arts and Social Sciences*, 6(12), 3052–3061.

Msimanga, L. (2026). Intersecting inequalities: A household-level WEF nexus assessment in Thabo Mofutsanyane district, South Africa. *Interdisciplinary Journal of Rural and Community Studies*, 8(1), 112–131.

Ochieng, G.M., Marrengane, Z.G., & Mkolo, N.D. (2023). Hybrid Water Supply Systems and Conjunctive Use in the Context of Water Sensitive Settlements: A Case Study of Sekhukhune District Municipality, Limpopo Province (WRC Report No. 2534/1/23). Water Research Commission (WRC), South Africa. ISBN 978-0-6392-0533-5. Web link: https://bit.ly/46xAMzc

Sapkota, M., Arora, M., Malano, H., Moglia, M., Sharma, A., George, B., & Pamminger, F. (2014). An Overview of Hybrid Water Supply Systems in the Context of Urban Water Management: Challenges and Opportunities. *Water*, 7(1), 153–174.

Sapkota, M., Arora, M., Malano, H., Moglia, M., Sharma, A., George, B., & Pamminger, F. (2015). An Integrated Framework for Assessment of Hybrid Water Supply Systems. *Water*, 8(1), 4.

Sharif, M. N., Haider, H., Farahat, A., Hewage, K., & Sadiq, R. (2019). Water–energy nexus for water distribution systems: a literature review. *Environmental Reviews*, 27(4), 519–544.

Sikhwivhilu, K. (2020). *Understanding the water-energy-health nexus in urban contexts in Africa: towards a biogas-supported decentralised water treatment system for communities in Diepsloot (South Africa) and Chambisi (Zambia)*. Pretoria: Human Sciences Research Council (HSRC).

Taguta, C. (2026). The state of the water-energy-food nexus at sub-national scales in southern Africa: the case of South Africa and Zimbabwe. *Frontiers in Sustainability*, 7, e1768279.

United Nations Office of the Special Adviser on Africa (UN OSAA). (2026). *Africa's Water Future Demands a New Mindset: Strategic Asset Management to Achieve the Goals of Agenda 2063*. United Nations Africa Renewal Policy Briefs.