Doctoral Thesis

WATER-ENERGY NEXUS: AN OPERATIONAL TOOL FOR ASSESSING ENERGY INPUT ASSOCIATED WITH DRINKING WATER SUPPLY IN AFRICA

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Dissertation

WASSERENERGIE-NEXUS: EIN BETRIEBSWERKZEUG ZUR BEWERTUNG DER ENERGIE IM ZUSAMMENHANG MIT DER TRINKWASSERVERSORGUNG IN AFRIKA

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Abstract

Energy is required by Water Services Providers (WSPs) for abstraction, treatment, and distribution of drinking water - about 90% of which is used by pumps and pumping systems. Energy costs could range between 30-50% of running costs of WSPs. However, energy use is the largest controllable input within the boundaries of WSPs with short payback periods on investment. The high costs associated with water supply, which is largely due to pump inefficiencies, peak-tariff water pumping, and energy associated with water losses compromise the ability of WSPs to meet the growing water demand. For WSPs in Africa, up to 70% non-revenue water losses in water supply systems have been reported. This translates into an equivalent energy input associated with such water losses. Consequently, water losses and associated energy input contributes to poor operational performance of WSPs and delays expansion of access to water services and achievement of universal access to safe drinking water by 2030 (SDG 6). At the same time, long-term water provision is highly influenced by water demand and supply drivers, e.g., population growth, urbanization, climate change and technological change. Accelerated population growth is projected for Africa, the region with the highest global urban growth rate, where about 60% of the total population is expected to be urban by 2050. This implies huge growth in water demand that calls for investment in technology, infrastructure, and improved understanding of energy use optimization for water supply. Therefore, an adequate understanding of the extent to which the water demand drivers influence energy demand is crucial for the long-term planning of water supply systems. Consequently, a data-driven understanding of the operational drivers for water supply and energy management to inform water-energy policies and to exploit the opportunities at the nexus of water and energy is required.

Therefore, this PhD thesis explores the potential application of the Water-Energy Nexus concept as an operational tool to provide an understanding of energy use for drinking water supply in Africa and examines the drivers of water supply and demand and how they influence energy input for water supply. In addition, the study evaluates the influence of projected increase in current water demand on energy input for water supply in the future under different scenarios. To set the stage, a literature review was conducted on the application of the Water-Energy Nexus concept for water supply in the African context. It emerged that there is limited literature available on the operationalization of the concept in the region, and energy use is not considered a key performance indicator by water regulators and WSPs in Africa. Most of the studies identified and evaluated have been undertaken in northern and southern Africa, where energy demand for desalination and deep groundwater exploitation is high compared to other regions of the continent.

To examine the relative impact of water supply and demand drivers on energy input for water supply in Africa, several key compound indicators were parameterized to generate cluster centres for 52 countries in Africa. The cluster analysis produced impact scores with five cluster centres that grouped countries with similar key compound indicators and impact scores. Three countries (Gambia, Libya, & Mauritius) were classified as outliers. Libya presented a unique case with the highest impact score on energy input for raw water abstraction, associated with largescale pumping from deep groundwater aquifers. Multivariate analysis of the key indicators for 20 countries in sub-Saharan Africa that are either water-secure or water-stressed illustrated the relative impact of drivers on energy input for municipal water supply. An analytical framework was developed to assess the impact of drivers on energy input for municipal water, with competing users and water losses in the distribution system exhibiting the highest impact.

Three plausible scenarios, namely, *Current State Extends* (CSE), *Current State Improves* (CSI) and *Current State Deteriorates* (CSD) were developed and nine quantifiable indicators for water demand projections were applied for five WSPs in Kenya to demonstrate the feasibility of the approach based on real data in sub-Saharan Africa. The projected water demand is expected to increase by at least twelve times the current demand to achieve universal coverage and an average daily per capita consumption of 120 l/p/d for the urban population by 2030. Consequently, the energy input could increase almost twelve-folds with the *CSI* scenario or up to fifty-folds with the *CSE* scenario for WSPs where desalination or additional groundwater abstraction is proposed. The approach used can be applied for other WSPs experiencing a similar evolution of their water supply and demand drivers in sub-Saharan Africa.

An accelerated increase in energy demand for water supply calls for wholistic energy management programs that are informed by energy checks and energy analysis. Consequently, selected energy metrics with potential to be incorporated in the routine performance assessment and benchmarking WSPs were applied for 42 out of 93 registered WSPs in Kenya. The average embedded energy for groundwater abstraction, treatment and distribution was 1.08 kWh/m³ (range 0.94 kWh/m³–1.4 kWh/m³) compared to 0.15 kWh/m³ (0.005 kWh/m³–0.61 kWh/m³) for surface water. The average specific energy use per volume billed was 1.59 kWh/m³ (0.35–2.29 kWh/m³) and 0.39 kWh/m³ (0.02–0.61 kWh/m³) for groundwater and surface water, respectively. However, 14-53% of energy input was associated with non-revenue water loss for WSPs supplying groundwater and up to 43% for those supplying surface water. The average electricity cost for water supply was US$ 0.09/m³, estimated at an average 13% of the operational costs but up to 36% for WSPs supplying groundwater. The approach demonstrates the potential of applying simple energy metrics to guide WSPs to undertake rapid energy inventories, identify inefficiencies and develop comprehensive energy management programs.

The findings could be used to support planning processes to build resilient drinking water infrastructure in developing countries with data challenges. There is a clear need for WSPs and the regulators to increase attention towards an understanding of energy input for water supply and the implications for benchmarking performance of WSPs against energy use efficiency. WSPs in the sub-region could explore aggressive strategies to jointly address persistent water losses and associated energy input. This would reduce the current water supply-demand gap and minimize energy input that will be associated with exploring additional water sources that are typically energy intensive. Such programs require systematic energy use assessments that identify areas of energy loss and energy efficiency optimization. The assessments could range from application of simple to use metrics that do not necessary require models and supporting tools to comprehensive energy assessments which require complex modelling of the water supply systems. Energy use could be included as a key performance indicator (KPI) with metrics incorporated into existing benchmarking exercises. The immediate benefits include improvements in operational efficiency of energy-consuming processes and reduction in cost associated with energy use. In the long-term, a comprehensive assessment of energy use could inform Water-Energy Nexus policies on reducing energy demand associated with water supply.

Kurzfassung

Energie wird von Wasserdienstleistern (Water Services Providers; WSPs) für die Entnahme, Aufbereitung und Verteilung von Trinkwasser benötigt, am meisten (ca. 90%) wird für Pumpen und Pumpsysteme verwendet. Die Energiekosten könnten zwischen 30-50% der laufenden Kosten von WSPs liegen. Der Energieverbrauch ist jedoch der größte kontrollierbare Eingangsparameter innerhalb der Versorgungsgrenzen mit kurzen Amortisationszeiten bei Investitionen. Enorme Energiekosten für die Wasserversorgung, die hauptsächlich auf Pumpenineffizienzen, Spitzentarife und mit Wasserverlusten verbundener Energie zurückzuführen sind, beeinträchtigen die Fähigkeit der WSPs, den aktuellen und wachsenden Wasserbedarf zu decken. Im Zusammenhang mit WSPs in Afrika wurden bis zu 70% nicht einnahmenbezogene Wasserverluste in Wasserversorgungssystemen gemeldet. Dies führt zu einem äquivalenten Energieeintrag, der mit solchen Wasserverlusten verbunden ist. Dies trägt folglich zu einer schlechten Betriebsleistung der WSPs bei und verzögert den Ausbau des Zugangs zu Wasserdienstleistungen und die Verwirklichung des universellen Zugangs zu sauberem Trinkwasser bis 2030 (SDG 6).

Die langfristige Wasserversorgung wird stark von zahlreichen Treibern der Wassernachfrage und -versorgung beeinflusst: z. B. Bevölkerungswachstum, Urbanisierung, Klimawandel und technologischem Wandel. Für Afrika wird wird ein beschleunigtes Bevölkerungswachstum mit der höchsten globalen städtischen Wachstumsrate prognostiziert, wobei bis 2050 etwa 60% der Gesamtbevölkerung in urbanen Siedlungen leben. Dies impliziert ein enormes Wachstum der Wassernachfrage und erfordert Investitionen in Technologien, Infrastruktur und ein besseres Verständnis der Energieoptimierung in der Wasserversorgung. Dafür ist ein datengestütztes Verständnis der betrieblichen Treiber für die Wasserversorgung und das Energiemanagement erforderlich, um eine anchhaltige Wasser-Energie-Politik zu formulieren und die Chancen des Wasser-Energie-Nexus zu nutzen.

Diese Doktorarbeit untersucht daher die mögliche Anwendung des Wasser-Energie-Nexus-Konzepts als operatives Werkzeug in der Praxis der Wasserversorgung, um ein Verständnis des Energieverbrauchs für die Trinkwasserversorgung in Afrika zu vermitteln und untersucht die Treiber von Wasserangebot und -nachfrage und wie sie den Energiebedarf für die Wasserversorgung beeinflussen. Darüber hinaus untersucht und bewertet die Studie den Einfluss des prognostizierten Anstiegs des aktuellen Wasserbedarfs auf den Energieeinsatz für die Wasserversorgung in der Zukunft unter verschiedenen Entwicklungsszenarien.

Eingangs wurde eine Literaturrecherche zur Anwendung des Water-Energy Nexus-Konzepts für die Wasserversorgung im afrikanischen Kontext durchgeführt. Es stellte sich heraus, dass es nur begrenzte Literatur über die Operationalisierung des Konzepts in der Region gibt und der Energieverbrauch von Wasserregulierungsbehörden und WSPs nicht als wichtiger Leistungsindikator angesehen wird. Regional wurden die meisten Studien im nördlichen und südlichen Afrika durchgeführt, wo der Energiebedarf für die Entsalzung und die Nutzung des Tiefengrundwassers hoch ist.

Darüber hinaus wurden Treiber der kommunalen Wasserversorgung und deren Wechselwirkung mit dem Energieeinsatz für die kommunale Wasserversorgung in Afrika untersucht. Mehrere wichtige zusammengesetzte Indikatoren wurden parametrisiert, um statistische Auswertungen für 52 Länder in Afrika durchzuführen, um die Auswirkungen von Wasserversorgungs- und Nachfragetreibern auf die kommunale Wasserversorgung und den damit verbundenen Energieeinsatz zu demonstrieren. Es wurde ein analytischer Rahmen entwickelt, um die Auswirkungen der Einflussfaktoren auf den Energieeinsatz für kommunales Wasser zu bewerten, wobei konkurrierende Nutzungsaspekte und Wasserverluste nachweislich die größten Auswirkungen zeigen. Folglich könnten die Erkenntnisse genutzt werden, um Planungsprozesse zum Aufbau einer resilienten Trinkwasserinfrastruktur in Entwicklungsländern mit schlechter Datenlage zu unterstützen.

Die Doktorarbeit entwickelte drei plausible Szenarien als Basis für die betrachtungen: *Current State Extends* (CSE), *Current State Improves* (CSI) und *Current State Deteriorates* (CSD). Neun quantifizierbare Indikatoren wurden für Wasserbedarfsprojektionen und die damit verbundenen Auswirkungen auf den Energieeinsatz für die Wasserversorgung für fünf WSPs in Kenia angewandt, um die Machbarkeit des Ansatzes auf der Grundlage realer Daten in Subsahara-Afrika zu demonstrieren. Es wird erwartet, dass der prognostizierte Wasserbedarf um mindestens das Zwölffache des aktuellen Bedarfs steigen wird, um bis 2030 eine flächendeckende Abdeckung und einen durchschnittlichen täglichen Pro-Kopf-Verbrauch von 120 l für die Stadtbevölkerung zu erreichen. Folglich könnte sich der Energieeinsatz mit dem CSI-Szenario fast verzwölffachten oder mit dem CSE-Szenario für WSPs, bei denen eine Entsalzung oder zusätzliche Grundwasserentnahme notwendig ist, bis zu fünfzigfach erhöhen. Der verwendete Ansatz kann auf andere WSPs angewendet werden, die eine ähnliche Entwicklung ihrer Wasserversorgungs- und Nachfragetreiber in Subsahara-Afrika erleben. WSPs in der Subregion sollten aggressive Strategien untersuchen, um gemeinsam gegen anhaltende Wasserverluste und den damit verbundenen Energieeinsatz vorzugehen. Dies würde die derzeitige Lücke zwischen Wasserangebot und -nachfrage verringern und den Energieeinsatz minimieren, der mit der Erkundung zusätzlicher Wasserquellen verbunden ist, die typischerweise energieintensiv sind.

Ein beschleunigter Anstieg des Energiebedarfs für die Wasserversorgung aufgrund des erhöhten Wasserbedarfs erfordert ein holistisches Energiemanagementprogramm unter den WSPs. Solche Programme erfordern systematische Energieverbrauchsbewertungen, die Bereiche der Optimierung und Bereiche mit Energieverlust identifizieren. Solche Bewertungen reichen von der Anwendung einfach zu verwendender Metrices, die keine Modelle erfordern, bis hin zu umfassenden Energiebewertungen, die eine Modellierung der Wasserversorgungssysteme erfordern. Diese Studie verwendete ausgewählte Energiemetrices, die in die routinemäßige Leistungsbewertung und das Benchmarking des Energieverbrauchs bei WSPs in Afrika einbezogen werden können. Der Ansatz wurde für 42 WSPs in Kenia (von 93 registrierten WSPs) angewendet. Die durchschnittliche Energie für die Grundwasserentnahme, -aufbereitung und -verteilung betrug 1,08 kWh/m³ (Bereich 0,94 kWh/m³-1,4 kWh/m³) gegenüber 0,15 kWh/m³ (0,005 kWh/m³–0,61 kWh/m³) für

Oberflächenwasser. Der durchschnittliche spezifische Energieverbrauch pro abgerechnetem Wasservolumen betrug 1,59 kWh/m³ (0,35-2,29) bzw. 0,39 kWh/m³ (0,02-0,61) für Grundwasser bzw. Oberflächenwasser. Bei Grundwasserentnahme waren jedoch 14-53% des Energieeinsatzes mit Wasserverlusten ohne Einnahmen für WSPs verbunden, und bis zu 43% für diejenigen, die Oberflächenwasser als Rohwasser nutzen. Die durchschnittlichen Stromkosten für die Wasserversorgung betrugen 0,09 US$/m^3, was auf durchschnittlich 13% der Betriebskosten geschätzt wird, aber bis zu 36% für WSPs, die Grundwasser nutzen. Der Ansatz zeigt das Potenzial der Anwendung einfacher Energiemetriken, um WSPs in Afrika dabei zu unterstützen, schnelle Energieinventare durchzuführen, Ineffizienzen zu identifizieren und den Energiebedarf zu senken.

Es besteht ein klarer Bedarf für WSPs und Regulierungsbehörden, die Aufmerksamkeit auf ein Verständnis des Energieeinsatzes für die Wasserversorgung und die Auswirkungen auf das Benchmarking der Leistung von WSPs im Vergleich zur Energieeffizienz zu richten. Die Energieeffizienz könnte als Key Performance Indicator (KPI) in die Bewertung von Wasserversorgern einbezogen werden, wobei Metrices in bestehende Benchmarking-Ansätze integriert werden könnten. Zu den unmittelbaren Vorteilen gehören Verbesserungen der betrieblichen Effizienz energieverbrauchender Prozesse und die Senkung der mit dem Energieverbrauch verbundenen Kosten. Langfristig hilft eine umfassende Bewertung des Energieverbrauchs im Rahmen des Water-Energy Nexus einer Entscheidungsfindung in Politik und betrieblicher Praxis und in weiterer Folge einer Reduzierung des Energiebedarfs und der treibhausgasbedingten Emissionen im Zusammenhang mit der Wasserversorgung. Darüber hinaus ist ein adäquates Verständnis darüber, inwieweit die Treiber für den Wasserbedarf den Energiebedarf beeinflussen, entscheidend für eine langfristige Planung der Wasserversorgung.

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- *Understanding the Water–Energy Food Nexus Conference*: Understanding the Water-Energy-Food Nexus and Its Implications for Governance Scientific Forum, in **Osnabruck, Germany**
- The 14th annual **African Utility Week** *held* in **Cape Town South Africa***:* Presentation and panel discussion on *Improving efficiencies by integrating water and energy planning.*
- 3rd International Expo and Conference on Unlocking Potentials for a Water Secure World, **Nairobi, Kenya.**
- WAT Seminar at the Water Security Research Group of the Biodiversity and Natural Resources Program, the International Institute for Applied Systems Analysis (IIASA), **Austria.**

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List of Abbreviations and Acronyms

ACCSAN	Access to improved sanitation facilities
AGRV	Annual growth rate of agricultural value- added
AfDB	African Development Bank
CSD	Current State Deteriorates
CSE	Current State Extends
CSI	Current State Improves
CWD	Per capita water demand
ERD	Energy Reducing Devices
IBNET	International Benchmarking Network for Water and Sanitation
IND	Net annual industrial production growth
GWD	Groundwater Dependency
KPIs	Key Performance Indicators
kWh	kiloWatt hour
NRW	Non-Revenue Water
PDEN	Population Density
PCWC	Per Capita water Consumption
PCWP	Per Capita water Consumption
PRV	Pressure Reducing Valves
SDGs	Sustainable Development Goals
STAN	subSTance flow Analysis
SWGWDEP	Relative dependency on surface and groundwater
UPG	Urban Population Growth
WASPA	Water Services Providers Association
WASREB	Water Services Regulatory Board
WEN	Water-Energy Nexus
WSPs	Water Services Providers
WEF	World Economic Forum
WQ	Water quality
WQA	Impact of agricultural production on freshwater quality
WQI	Impact of Industrial production on freshwater quality
WWM	Wastewater Management
WWTRT	Proportion of wastewater that is treated
YCELP	Yale Centre for Environmental Law and Policy

List of Publications from the PhD Thesis

The following papers have either been published or prepared for submission:

Paper I: Published in ***Water***

Macharia, P. Kitaka, N., Kreuzinger, N. Applying the Water-Energy Nexus for Water Supply—A Diagnostic Review on Energy Use for Water Provision in Africa. ***Water 2020, 12, 2560***

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Paper II: Published in ***Sustainability***

Macharia, P.; Wirth, M.; Yillia P.; Kreuzinger, N. Examining the Aggregate Impact of Drivers on Energy Input for Municipal Water Supply in Africa. ***Sustainability 2021, 13, 8480***

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Paper III: Published in ***Energies***

Macharia, P., Kitaka, N., Yillia, P., Kreuzinger, N. Assessing Future Water Demand and Associated Energy Input with Plausible Scenarios for Water Service Providers (WSPs) in Sub-Saharan Africa ***Energies 2021, 14, 2169***

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Paper IV: Prepared for submission to ***Frontiers in Water***

Macharia, P., Kitaka, N., Kreuzinger, N. Energy input indicators for Benchmarking Water Supply Systems: An Assessment of Water Service Providers (WSPs) in Africa.

Introduction

1.1 Background

Water and energy resources are closely linked in their supply and consumption and share several elements in their use and management. Some of the shared elements of water and energy resources as outlined in (Bazilian et al., 2011) include the fact that billions of people globally have limited access to both; there is increasingly growing demand for the two resources which create global supply scarcities and their production have strong interdependence. This close intrinsic interconnection gained increased attention within the Water-Energy Nexus Agenda since the Bonn 2011 Water-Energy-Food Nexus conference (Hoff, 2011), as a framework to address the complex global water and energy needs, interactions, conflicts and trade-offs, traditionally considered independently in their utilization, governance and policy formulation (Endo, Tsurita, Burnett, & Orencio, 2017). However, there is still no one clear definition of the 'nexus' due to the complexity and the trans disciplinary nature of the concept within the technological, social, political, environmental and economic dimensions (Dai et al., 2018; Hamiche, Stambouli, & Flazi, 2016). Consequently, as noted in Dai et al., 2018, there are challenges in the application of the framework for decision support as there is no singular framework for conducting nexus research and several information gaps still exist in the understanding of the linkages, synergies and trade-offs. In addition, research on the methods and tools for the assessment of the water-energy nexus framework at different scales is still at the 'understanding stage'. This necessitates a further analysis of the water-energy framework towards the 'implementing stage' where effect on water and energy policies trade-offs and synergies would be evidenced. The authors further note that there is potential in the adoption of the water-energy nexus framework to address sustainable and wise-use of energy and water resources through informing decision-makers on policy and governance structures. The broad definition of the Water-Energy Nexus addresses the close connectivity of the water and energy resources where one is required for the production and supply of the other, i.e., 'energy for water' and 'water for energy'. Therefore, efforts to conserve one may benefit or the other. This work focuses on the 'energy for water' side of the water-energy nexus.

The water and energy relationship is defined based on the exploration of the interlinkages between production, supply and consumption of water and energy resources (Hoff, 2011). Furthermore, the operationalization of this framework by various stakeholders in international development has been motivated by the fact that, despite progress in reducing the number of people without access to both resources, a large number of people are still without access especially in sub-Saharan Africa and production and consumption of each resource is dependent on the other (Hamiche, Stambouli, and

Flazi 2016). Therefore, a water-energy nexus thinking would accelerate the achievement of SGDs 6 and 7, on universal access to safe, reliable, and affordable water and energy supply by 2030.

As the demand for safe, reliable and secure water services grows, the demand for energy to abstract, treat and supply water also grows. Hence, application of the water-energy nexus in water supply is aimed at improving an understanding of maximizing energy efficiency and optimisation of water supply processes to propel WSPs to shift from traditional water supply sources and systems towards innovative and resilient water supply systems, some of which are energy-intensive. This is owed to the fact that changes in long-term socio-economic and climatic drivers are projected to influence the availability and use of water and energy resources which calls for a nexus thinking to address the interdependencies between water and energy (Yillia 2016). For instance, the proportion of total national energy consumption that is consumed in the water sector is estimated at 2% (Savary Pierre 2016) in Kenya, 1.8% in the United States and 1.3% in Germany (Voltz and Grischek 2018) while (He et al. 2019) reported about 3% in China and 3-4% in Portugal (Loureiro et al. 2020). However, the share of global energy consumption for water supply is expected to increase with projected upward global growth in population, urbanization, economic and technological development and associated changes in living standards (Wu et al., 2020). Hence, as water demand grows from increased population and urbanization growth especially in sub-Saharan Africa, coupled with reduced freshwater availability, there is a growing need to seek alternative water sources and improve energy efficiency of water supply systems which is linked to the economic viability and sustainability of water supply systems (Vincent et al. 2014).

The water supply is an energy-intensive sector with energy requirements as a major operational input to abstract, treat and distribute clean water as well as move and treat wastewater and associated resources as outlined in figure 1 (Liu et al, 2012). Energy consumption is major driver of operational performance of WSPs accounting up to 40% or more of the total operational costs, a major concern for water supply managers, coming second after labour costs, especially in developing countries. Nevertheless, energy costs are the largest controllable expenditure in the operations of water services within the internal boundaries of WSPs; with up to 40% potential savings on investment with short payback periods, through application of appropriate efficiency and optimization measures (Liu et al., 2012). In the context of high energy prices, intensified water demand and the need to explore additional and sometimes energy-intensive water sources and water transfers in the future grows, there is increased focus on water and energy efficiency enhancement, energy generation and recovery within water supply systems. Consequently, water sector players have increased their attention in the understanding of the water-energy linkage, its quantification to guide energy and water policies and its implications in sectoral investments as the demand for water services and the strive to improve service delivery grows (Kenway et al., 2011). For instance, operationalization of the Water-Energy Nexus by exploring the linkage between energy and water and the associated water and energy losses within the water supply processes presents benefits to water services providers (WSPs) and regulators such as reducing non-revenue water losses and associated energy input, optimization of energy consumption, increased revenue generation and expansion of water services coverage (Delcea et al., 2019). Additionally, with increasing energy prices, the push to mitigate greenhouse gases emissions and growing water demand, optimization of energy use and costs remains the largest controllable input within WSPs operations boundaries that should be prioritized (Moreira & Ramos, 2013).

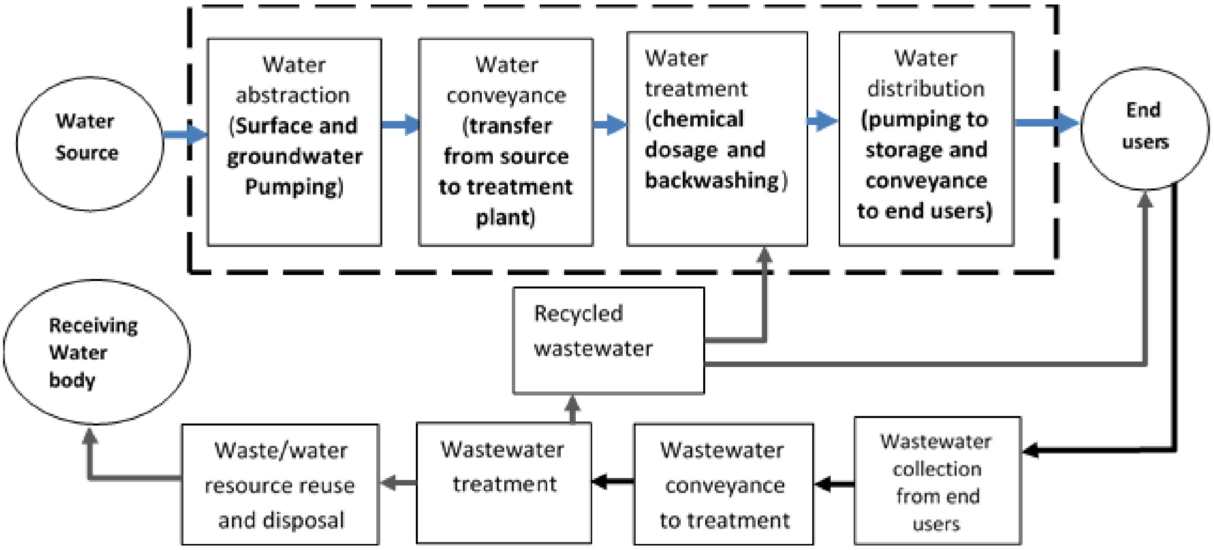


Figure 1: Water services supply cycle outlining processes where energy is consumed *(dotted lines mark the boundaries of the present study)*

The energy associated with water supply is classified as direct energy (energy needed for construction, operation and maintenance of water supply systems) and indirect energy (energy required for material use including water treatment chemicals and fuel (Mo et al., 2011). Energy entering the water supply systems is classified as either from natural input (energy through reservoirs or pressurised points outside the boundaries of the water supply) or shaft energy input supplied through pumping stations (Mamade et al., 2018). The energy input undergoes several transformations as illustrated in figure 2 where it may be dissipated in pumps, valves, treatment stations, through leaks, friction or excessive water pressure in distribution systems. The dissipation points are representative of energy input associated with unbilled consumption and with water losses. Hence, these are areas of focus for WSPs energy management as water losses inevitably translate to increased energy consumption especially for groundwater supply.

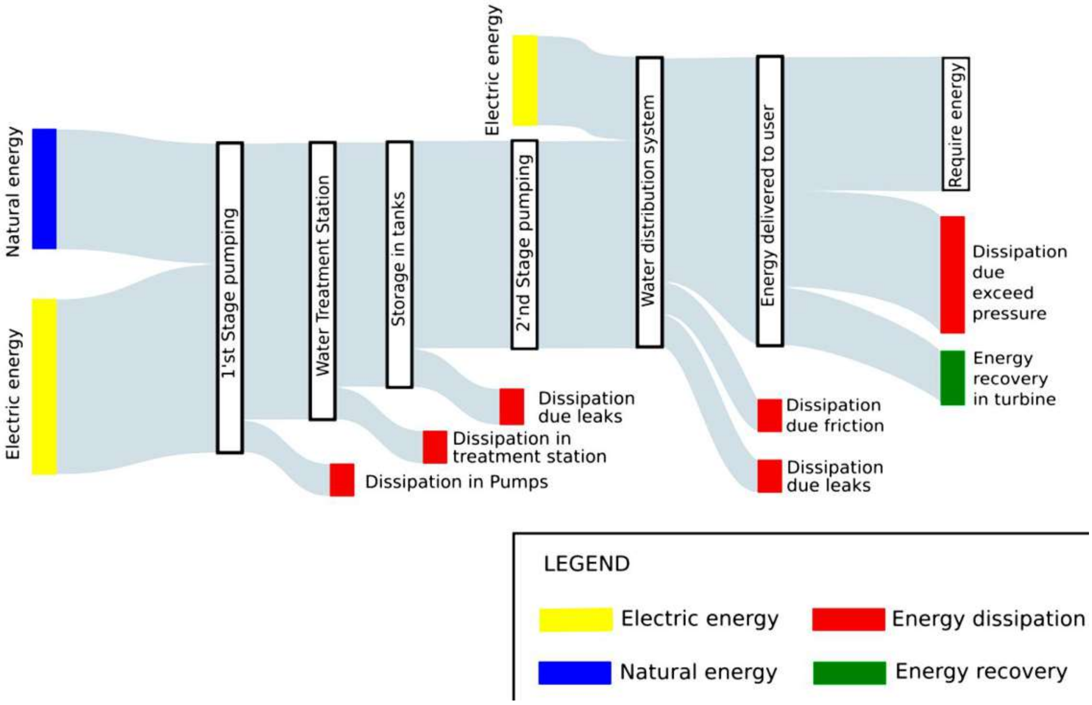


Figure 2: Energy transformation in a water supply system. Source: (Bylka and Mroz 2019)

Assessment of energy input in water supply systems is crucial in the operations and continuity of water supply services as an indicator of energy flows and energy transformations (Wakeel et al. 2018). Several studies have proposed metrics for the assessment of energy input in water supply systems including by Mamade et al., 2018, largely classified as bottom-up and top-bottom approaches which provides for simple assessments that do not require use of hydraulic models and comprehensive energy assessments which provides detailed energy consumption of hydraulically modelled systems embedded in the water balance components. Other metrics focus on individual components of the water supply systems including at pipe level (Cabrera et al., 2015) and on the pump systems (Livingstone et al., 2015).

Energy requirement for water supply is influenced by several factors as outlined in (Plappally and Lienhard 2012; Lam, Kenway, and Lant 2017). These factors are largely categorised into climatic (precipitation, temperature), topographic (elevation and distance between source and end-users, type of raw water), operational efficiency (energy efficiency measures, pump efficiency, water losses and system layout) and water use patterns (water demand, economic level, population served and number of service connections). While some of these factors including climatic and topographic conditions are beyond the control of WSPs, operational efficiency falls within the boundaries of WSPs. Consequently, addressing areas of operational inefficiencies where energy may be recovered is considered first line of energy management. As outlined in Mamade et al., 2017, efforts to address water losses in water supply networks provides equivalent benefits in energy savings especially among WSPs that rely on energy-intensive raw water sources like deep groundwater extraction and desalination. Additionally, (Arun Shankar et al., 2016) describes three interventions for energy efficiency including proper pump and motor selection, wholistic water supply system optimization and process optimization while (Voltz & Grischek, 2018) provides the benefits of focusing on energy efficiency including the fact that efficiency enhancement allows for a better operation of the water supply system which delivers additional benefits of saving water and improved reliability. However, persistent water losses contribute to associated energy losses which threatens operational sustainability of water supply systems. In addition, most water utilities concentrate on efforts to reduce daily volume of water losses alone which are not sufficient to support impactful operational efficiency and sustainability of service as water loss reduction interventions including pressure management, leak detection and repair affects energy demand (Loureiro et al., 2020; Mamade et al., 2018). Therefore, joint water and energy management efforts implemented through strategic, tactical and operational interventions increases the efficiency of both resources and provides opportunities for revenue generation and expansion of services.

A framework for the assessment of water energy efficiency and effectiveness of water supply systems was developed by (Loureiro et al., 2020) which assesses energy efficiency at different stages and process and effectiveness of water supply. Further, (Loureiro et al., 2017) applied an infrastructure asset management framework to assess and manage water-energy losses at tactical level of decision planning. These frameworks are applicable in the short- and medium-term horizons of one to five years. However, given the uncertainty in the evolution of water demand and supply drivers beyond the boundaries of WSPs, a framework to explore the influence of such drivers on the future water and energy demand is needed for long-term planning. Several challenges exist in the water supply sector and operationalization of a joint water-energy loss management in WSPs in Africa including (i) budgetary constraints for service expansion, (ii) rapidly evolving water demand and supply drivers, (iii) persistently huge water and associated energy losses, (iv) large proportions of the population still without access to water services, (v) a lack of metrics adopted to assess and benchmark energy use performance and (vi) aging infrastructure leading to high system inefficiencies.

1.2 Problem Statement and Justification

In the African context, although considerable progress has been achieved in the provision of safely managed water supply in the last decade, water losses within the distribution systems remain high, with up to 70% of total system input as non-revenue water losses (van den Berg and Danilenko 2017). Such water losses and associated energy input and revenue losses threaten sustainability of water services and efforts to achieve universal water supply by 2030 in line with SDG 6 targets. In addition, the projected growth in population and urbanization resulting in increased water demand will continue to expand the water demand-supply gap, leaving large populations especially the urban-poor and rural population without adequate supply (Eberhand, 2018). Further, due to poor performance, most water supply providers struggle to meet their full operational cost and expand service coverage. Additionally, there is increased pressure to treat increased levels of existing and emerging pollutant levels, high water losses on the network and ageing infrastructure. Although most WSPs in Africa are aware of their huge energy consumption, focus is largely on investment in water loss controls which only partly addresses the economic and sustainability of service dimensions. In addition, due to the limitation of storage facilities, most WSPs operate their pumps during peak tariff hours which leads to huge energy costs that water utilities struggle to meet. In addition, the huge no-revenue water losses lead to revenue losses thus unable payment of power bills. This leads to bill pilling and ultimately power disconnection which cripples sustainability of their operations.

There is a similar regulatory frameworks and governing legislations across the region with performance benchmarking as a regulatory requirement which attracts non-compliance penalties for poor performance. The performance assessment carried out at national level: for instance, Water Services regulatory Board (WASREB, 2019) in Kenya while at a regional level the East and Southern Africa Water Utility Regulators Association carry out benchmarking of the largest utilities in the region ((ESAWAS), 2018). The ownership of WSPs vary with countries but although it was observed not to influence the efficiency of WSPs, (Mbuvi, de Witte, & Perelman, 2012) cautions this could be attributed to the measurement errors in data collection and poor-quality data. Some WSPs are state-owned (Uganda) or operate as water departments within municipalities (South Africa), some are public companies owned by municipalities (Kenya) or contacted private providers (Niger, Mozambique). Registered WSPs within the jurisdiction of the regulators have a requirement to submit operational data based on a set of key performance indicators for performance assessment, often done on a yearly basis. However, the quality of data remains a significant challenge for WSPs operations research (Chini & Stillwell, 2017; Ghernaout, 2018) limiting such research efforts to WSPs willing to provide the data, most often those performing relatively well. In addition, most of the data provided through open calls to WSPs is largely siloed, unintegrated into files or computer systems that rarely communicate with each other. Across the region, water services regulators evaluate and benchmark the performance of WSPs through a series of key performance indicators which differ with region and country. An examination of such performance indicators for several countries in Africa showed that energy use for water supply is not considered as a key performance indicator and assessment of energy use for water supply is very limited. Two studies on performance of water utilities in Africa (Eberhard, 2018; van den Berg & Danilenko, 2017) concluded that the performance of WSPs is weak with a majority struggling to meet their operational costs, hence relying on government subsidies and with unsatisfactory customer service delivery. Despite these challenges, (Eberhard, 2018) noted that accelerated structural and organizational reforms in the water sector in SSA and increased investment in water infrastructure since the 1990s have demonstrated great potential for WSPs to meet their operational costs to deliver water services, expand coverage in a sustainable manner towards achievement of universal access in sub-Saharan Africa.

Water demand in sub-Saharan Africa is projected to increase with an increase due to growing population, increased urbanisation, rise in existing and emerging pollutants which are likely to require a shift in technology to achieve required water quality standards (Mc Donalds et al., 2011).. This, of course, depends on the type and quality of the raw water, the regulatory requirements and the state of the infrastructure (van den Berg & Danilenko, 2017). Consequently, with increasing energy prices and energy-intensive processes, the growing demand for water services and stricter regulations, WSPs are increasingly required to identify areas of intervention to reduce their energy costs and optimize operations. The water-energy nexus framework offers promising opportunities that WSPs can tap to optimize energy efficiency and reduce energy consumption.

Energy use for drinking water supply in the sub-Saharan Africa has not received as much attention from WSPs and regulators and is missing as a key performance indicator in the performance assessment efforts in the region. Although energy consumption in some WSPs which rely on gravity for water conveyance is not a primary concern at present, a clear understanding of the energy consumption and opportunities of the water-energy nexus on the WSPs' operations and investment decisions in the long-term cannot be ignored. As the role of energy in drinking water supply continues to be highlighted, WSPs need to embrace energy saving measures to optimize their energy use and enhance operational efficiency.

In the Kenyan context, universal access to safe, clean, reliable water services is enshrined in the Kenyan Constitution as a basic human right. Accordingly, as a major development enabler towards the achievement of the 2030 Sustainable Development Goals, the water supply sector in Kenya has three major mandates for improving access, enhancing operational cost recovery and reducing water losses (Water Services Regulatory Board Kenya (WASREB), 2019). Consequently, performance assessment of water utilities in Kenya has been undertaken and reported consistently for the last ten years based on a set of nine key performance indicators. WASREB reports that among other key performance indicators, non-revenue water has remained unacceptably high in the last decade, averaging at 41%- 47% among registered water utilities, and as high as 67% in some utilities, against a sector benchmark of less than 25% (Water Services Regulatory Board (WASREB), 2020). This is despite huge financial investments in programmes to support non-revenue water reduction through various water sector players. In addition, assessment of energy use for water supply and the potential benefits of promoting and enhancing energy efficiency and saving energy and water are still largely untapped. Most utilities have a poor understanding of their energy use patterns. Some utilities have incomplete records of the operations and maintenance of pumps and motors, which are the largest consumers of energy in their operations. Still, most WSPs largely relying on government subsidies given that they are struggling to recover their operational costs, which in turn affects service delivery and expansion to unserved areas.

Although several studies have been conducted on the water sector in Kenya, there is a dearth on literature exploring energy use and losses for water supply. To the best of the authors knowledge, only one study Sima et al., 2013 has been identified on energy use for water supply in Kisumu, Kenya. However, the extent of energy losses through water losses and the impact on the WSPs operational efficiency and service delivery in Kenya has not been previously examined.

Given the opportunities of the water energy nexus application for drinking water supply highlighted in (Kenway, Lant, Priestley, & Daniels, 2011; Savic, Kapelan, & Butler, 2011) especially in developed economies, the present study examines the current situation of energy use for drinking water supply in sub–Saharan Africa. In addition, the study identified the challenges, potential areas of operationalizing of the water-energy nexus and lessons learnt from other areas to support decision making in the management of energy use for water supply and applied for WSPs in Kenya to demonstrate the feasibility of the approach based on real data in sub-Saharan Africa.

1.3 Aims and Objectives.

The main aim of this work was to explore the Water-Energy-Nexus approach as an operational tool for assessing energy input for water supply in Africa.

1.3.1 Objectives of the study

This study sought to achieve the following main objectives.

1) To provide an understanding of the extent of the application of the water-energy nexus approach for water supply in Africa.
2) To explore the major water supply and demand drivers and their influence on energy input for water supply in Africa
3) To assess the influence of projected changes in water supply and water demand drivers on energy use for water supply in sub-Saharan Africa using plausible scenarios with feasibility of the approach applied in the Kenyan water sector
4) To evaluate the energy input for water supply processes and derive the energy input associated with water losses in Africa, using selected WSPs in Kenya to demonstrate the application of energy performance indicators to support energy efficiency and benchmarking in water supply.

1.3.2 Research questions

To address the objectives listed above, the following research questions were put into context.

(i) What is the state of the application of the water-energy nexus to support energy efficiency in water supply in Africa?

(ii) What indicators are available for the assessment of energy demand for water supply and what are the requirements for their application?

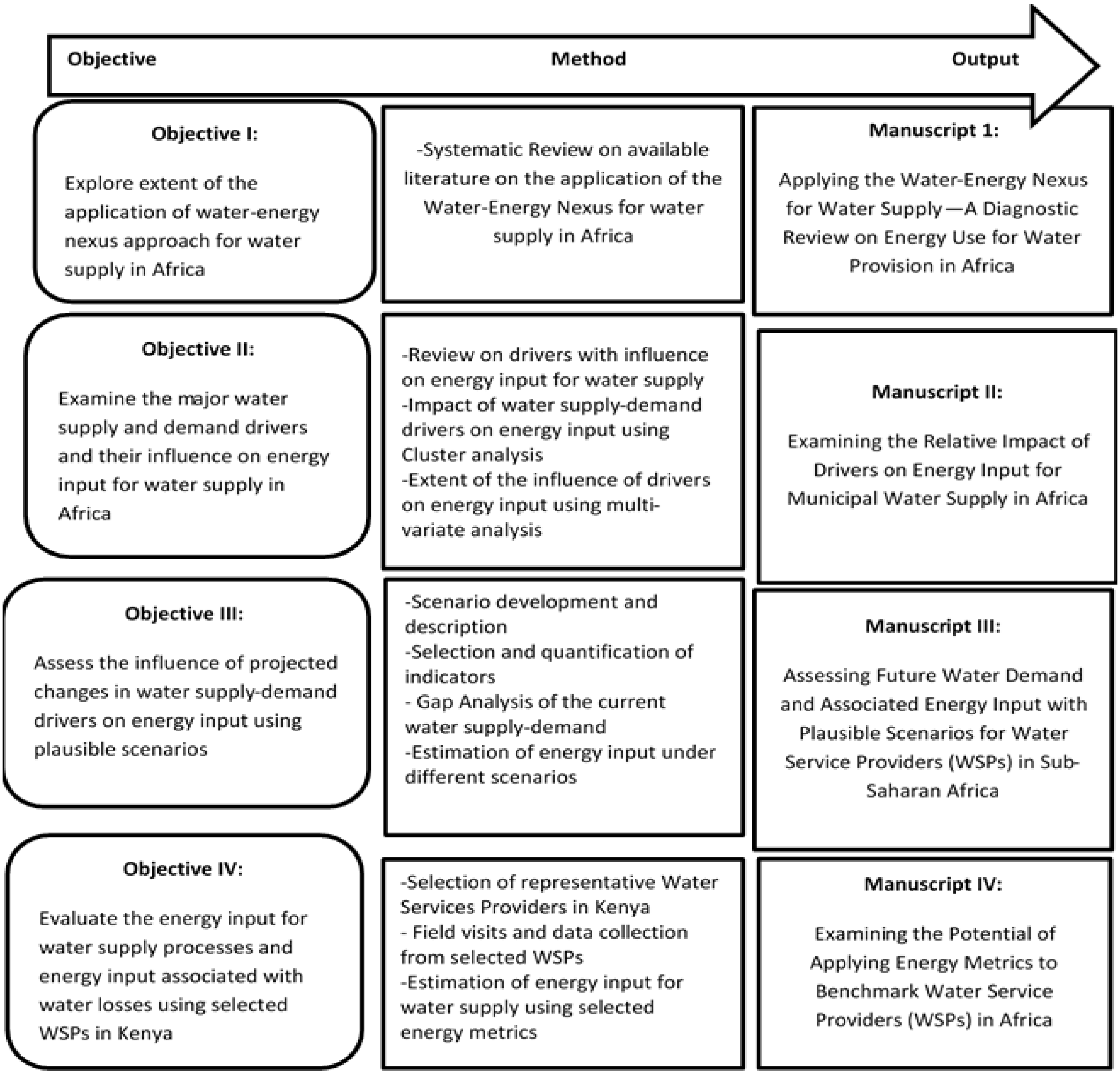
(iii) How will the changes in projected future water demand influence the energy demand for water supply?

(iv) How much energy is consumed in the supply of different raw water types and how much of such energy input is associated with water losses in WSPs?

(v) What strategies can WSPs implement to manage energy demand for water supply as WSPs strive to bridge the current water demand gap towards achievement of universal water supply by 2030

1.4 Methodological approach

The methodological approach to achieve above objectives are presented in a conceptual framework as illustrated in figure 3.



Objective	Method	Output
Objective I: Explore extent of the application of water-energy nexus approach for water supply in Africa	-Systematic Review on available literature on the application of the Water-Energy Nexus for water supply in Africa	**Manuscript 1:** Applying the Water-Energy Nexus for Water Supply—A Diagnostic Review on Energy Use for Water Provision in Africa
Objective II: Examine the major water supply and demand drivers and their influence on energy input for water supply in Africa	-Review on drivers with influence on energy input for water supply -Impact of water supply-demand drivers on energy input using Cluster analysis -Extent of the influence of drivers on energy input using multi-variate analysis	**Manuscript II:** Examining the Relative Impact of Drivers on Energy Input for Municipal Water Supply in Africa
Objective III: Assess the influence of projected changes in water supply-demand drivers on energy input using plausible scenarios	-Scenario development and description -Selection and quantification of indicators - Gap Analysis of the current water supply-demand -Estimation of energy input under different scenarios	**Manuscript III:** Assessing Future Water Demand and Associated Energy Input with Plausible Scenarios for Water Service Providers (WSPs) in Sub-Saharan Africa
Objective IV: Evaluate the energy input for water supply processes and energy input associated with water losses using selected WSPs in Kenya	-Selection of representative Water Services Providers in Kenya - Field visits and data collection from selected WSPs -Estimation of energy input for water supply using selected energy metrics	**Manuscript IV:** Examining the Potential of Applying Energy Metrics to Benchmark Water Service Providers (WSPs) in Africa

Figure 3: Conceptual framework illustrating the methodological approach of the study

One peer reviewed manuscript is dedicated to each of the research objectives and comprises the following content:

The **first manuscript** (published; doi:10.3390/w12092560) entailed a diagnostic and systematic literature review on available studies focusing on energy use for water supply in Africa. A literature search was conducted in journal articles, reports and books mostly retrieved from the

Science Citation indexes of the Web of Science Core Collection database, Google Scholar and ScienceDirect (Elsevier) to identify the existing literature on the water-energy-nexus as it relates or applies to water supply in different regions. The definition of the ‘water-energy-nexus’ was adapted from (Hoff, 2011), which defines the Water-Energy Nexus as the inter-linkage and dependence of production and use of water and energy resources on each other and the associated trade-offs and synergies of considering this connectedness. In this context, the focus was on the water sector’s dependence on energy. The literature search on the ‘Water-Energy Nexus’ was narrowed to the context of water supply, with literature focusing on the energy demand in the drinking water treatment and supply processes commonly referred to as ‘energy embeddedness’ (Yoon, 2018), for different raw water options and optimization processes. Particular emphasis on assessment and quantification of energy use for drinking water supply in Africa from peer-reviewed journals, country and regional level performance assessment reports by the utilities, the water service provision regulators and the International Benchmarking Network for Water and Sanitation Utilities (IBNET). The latter is an initiative of the World Bank which encourages water utilities to voluntarily submit data on their operations, based on a set of key performance indicators, to encourage peer benchmarking and sharing of best practices among water utilities. Further, available literature on drivers of water supply and water demand in selected countries in Africa was sought and synthesized.

The **second paper** (published; doi.org/10.3390/su13158480) explored the water supply and demand drivers that influence energy input for water supply in Africa, and the extent to which they influence energy input for water supply. This paper focused on examining and quantifying water supply and demand drivers and exploring the linked influence on energy use for water supply. Firstly, indicators for water supply and demand drivers were identified and parameterized, which were then applied to develop a conceptual flow model that illustrates the relative impact of drivers on each other. Furthermore, a cluster analysis was applied to establish which countries group together based on the identified indicators as the basis for possible similar intervention strategies. Lastly, a multi-variate analysis was performed to visualize the magnitude of impact of identified drivers on energy intensity for municipal water supply on selected countries for which credible data were available. Available data portals for the quantified indicators of water supply and demand drivers at the country level were also compiled.

Owing to the growing water demand from rapidly increasing population and urbanization in Africa and the need to explore new energy-intensive water sources, the **third paper** (published; doi.org/10.3390/en14082169) explored how such increase in water demand would influence future energy input under different plausible scenarios. Scenarios as defined in (Dong et al., 2013) are views or alternatives of what the future might look like which stimulates thoughts and decisions on possible occurrences, the opportunities, and the course of action. Visioning of scenarios entails building images about the desired future, or the future wished to be avoided relative to the past and present situation, and articulation of how the present-future gap may be bridged (van der Voorn et al., 2012). As outlined in Tourki et al., 2013, scenario building and scenario analysis are an excellent way of describing possible unrelated futures and corresponding paths to guide decisions and understanding of possible responses. Therefore, visioning of the energy demand for water supply in the present study was guided by responses from discussions with WSPs through questionnaires and face-to face interviews and WSPs' guiding vision and strategic plans which outline their perspective on the endeavour to provide quality water services. To achieve this vision, the basic questions of interest were; what is the current water demand and energy input and the water demand-supply gap in the areas of jurisdiction? how will the water demand and supply drivers evolve to influence water supply and energy requirements for water supply? how much water needs to be supplied to meet the projected future demand? What water sources? Will there be a significant change in the energy use for water supply based on the likely water sources in comparison to the present?

Lastly in a **fourth paper** (submitted for publication), as a basis to energy planning and managing for future water supply, an energy assessment was performed on selected WSPs in Kenya to establish an energy inventory for water supply processes. This forms a basis for system-wide energy management and planning. Although several metrics for the assessment of energy input for water supply have been proposed by different scholars, some are quite complex, requiring use of complex hydraulic modelling and large data requirements. Such metrics are not applicable in most WSPs in sub-Saharan Africa with limited data collection capabilities. This study selected energy metrics which do not require complex modelling but still provide crucial information on energy budget from WSPs. A representative sample of 42 WSPs were selected from 93 registered WSPs in Kenya to provide data on their water supply processes. The criteria for selecting the WSPs was based on the size categorization of WASREB (WASREB, 2020) and the type of raw water abstracted and supplied (groundwater, surface water or mixture of groundwater & surface water). An inventory of energy use for each WSP, the annual electricity input for water supply was estimated. In addition, the proportion (%) of energy input for each water supply process was estimated as a fraction of the total annual energy input. Furthermore, energy input associated with billed water consumption and that associated with non-revenue water was also estimated.

2. Summary of the scientific papers

Energy is a major operational input for water supply which accounts for up to 30% of WSPs running costs, ranking only second after labour costs in most water supply systems. Furthermore, over 90% of the energy input is consumed by pumps and motor operations. Several studies focusing on the Water-Energy Nexus have demonstrated the interdependence between water and energy resource production and utilization. Within water supply networks, energy is documented as the most controllable input within the boundaries of WSPs, with short payback periods upon investment in its optimization and efficiency improvement.

In this regard, the **first paper** sought to explore the potential for application of the Water-Energy Nexus for water supply in Africa. A review of publicly available literature revealed that there is paucity of studies regarding energy input for water supply, with very few publicly available studies found. Furthermore, publicly available reports on national and regional performance assessment of WSPs revealed that energy input is not considered as a key performance indicator for water services providers. Consequently, the national and regional regulators have not provided energy metrics for energy input assessment and energy benchmarking among WSPs. This makes it difficult to conduct consistent energy use monitoring and develop energy management plans for energy use optimization. Across the African region, major achievements have been realised in access to water services. However, a majority of population within urbanizing and metropolitan areas are still without access. In fact, five out of eight cities with the highest rates of urbanization globally are located in Africa. Additionally, it is projected that by 2050, about 67% of the population will live in urban areas. This implies increase in water demand, accelerated exploitation of existing supplies and exploration of additional sources, some of which are highly energy intensive. Furthermore, several drivers of water supply and water demand influence the energy input for municipal water supply. Therefore, the **second paper** published explored the water supply and water demand drivers in Africa and their influence on energy input for water supply at country level. A cluster analysis of country data allowed for the examination of how countries clustered based on these drivers. Additionally, a multi-variate analysis of the identified drivers revealed that competing water uses namely agricultural and industrial water use together with water losses with municipal water supply systems as the main factors that influence energy input for water supply.

Given the unpredictability of the water supply and water demand drivers as they are beyond the operational boundaries of WSPs, scenario building serves as an excellent tool through which possible futures of what could happen are envisioned based on some assumptions. The **third paper** sought to build up on the influence of identified driver of water supply and water demand by identifying quantifiable indicators of the drivers and envisioning their influence on energy input for water supply under three different plausible scenarios. This study therefore developed scenarios of three futures of water supply and water demand including a future where the current state of water supply continues, improves or deteriorates but the population increases as projected into the future. These scenarios explore the change in water demand and supply and the energy input required to meet the changes in demand. The study demonstrates that even in the ideal scenario of the current state improves, energy input for water supply is likely to increase several folds among WSPs where desalination and further groundwater exploration is expected. Such information is crucial in information WSPs as they make investment decisions for their energy sources.

Lastly, energy management for water supply requires a wholistic approach that starts with identification of energy consumptions through continuous energy assessments and energy checks to establishment of energy management plans. Energy assessments may entail simplified assessment of energy consuming devices to comprehensive energy analysis using complex models. However, application of such energy models is still in its infancy stages among most WSPs in Africa. The study presented in the **fourth paper** therefore identified available energy metrics which do not require use of complex hydraulic models to assess the energy input of selected WSPs in Kenya. The assessment showed that up to 50% of energy input for water supply was associated with water losses. Consequently, this calls for comprehensive joint efforts aimed at reducing water losses and energy input associated with such losses.

3. Scientific contributions from the research work

The following chapters are a summary of the main scientific contributions of this PhD work.

1) The review of existing literature on energy use for water supply in Africa indicates, that there are only very few studies on the application of the concept in the region and energy data and it is quite difficult to obtain data through open calls, given that many water services regulators do not consider energy use as a key performance indicator. As population growth and urbanization accelerates and the demand for water services grows in Africa, there is a compelling need by water regulators and WSPs to focus on assessment energy use for water supply. This would improve the understanding of the potential benefits of the Water-Energy Nexus for water supply.
2) Considerable progress has been achieved in provision of basic water services to populations in Africa. However, large proportions still remain unserved, and, in some cases, the per capita water demand is below the required minimum of 50 l/p/d. In addition, projections of future

water demand, population and rates of urbanization all show an increasing trend until 2050, with up to 60% of the 2020 population living in urban areas. This upward trend coupled with effects of climate change will influence availability of supply from the current water sources, and the need to explore new water sources to meet the water demand. Data constrains often make it difficult to assess the impact of water supply and demand drivers especially at country-scale, most notably population growth and other competing users including water demand for agriculture and industry. This study compiled data portals where such data may be found for the assessment of the impact of drivers of water supply and demand. in addition, this work examined to what extent these drivers impact energy input for water supply. Such information is useful in informing decision-making regarding investment in the water sector at country level.

3) Development of plausible future water scenarios comprising various assumptions for the development of water supply- and demand drivers is an important tool that informs decision makes and managers of possible developments. This study elaborates scenarios of future water demand based on projected population and possible additional water sources required to meet the projected increase in water demand until 2030 in the Kenyan situation. These scenarios are useful to inform WSPs on how their future energy demand is likely to change based on additional water sources, some of which are highly energy intensive including desalination and additional groundwater abstraction. The outcome of the scenarios on future energy demand based on existing and planned water sources to meet future water demand are important in informing investment decisions on energy sources. For instance, the management of WSPs can make informed decisions on investment required increase the present energy demand to meet the future demand and what would be the most cost-effective source of energy. Furthermore, investment in decentralised renewable energy sources is gaining traction and the outcome of the scenarios could inform WSPs on the investment plans to swich to renewables.

In-depth stakeholder involvement (e.g., stakeholder iteration workshops with WSPs) would have been very helpful in the scenario building and feedback. This would have improved the narratives and the assumptions. Nevertheless, building the plausible scenarios provided an important basis for informing WSPs with regard to investment in energy sources to meet the future water demand.

4) This work observes that although energy use for water supply represents a significant proportion of the running costs (up to 35 % in selected WSPs), assessment of energy input and benchmarking of energy use for water supply is not considered as a key performance indicator for water supply across the region. Additionally, there is a limited number of publicly available studies on energy use for water supply across the region. Among the available literature retrieved, most of the studies (50%) were carried out in South Africa and Northern Africa. These regions are also currently facing shortage of freshwater supplies and are largely reliant on desalination, an energy-intensive water source compared to conventional water supply systems. Non-revenue water losses remain high across WSPs in Africa, with up to 70% reported in some WSPs in Kenya. Consequently, huge energy input is associated with such unsustainable water losses which affects the operational sustainability of WSPs and compromises on service delivery. This work provided an analysis of energy use associated with supplying different raw water types and further energy input associated with billed consumption and that associated with water losses among selected WSPs in Kenya. The study applied a selection of available energy metrics which do not require use of complex hydraulic models but provide crucial basis for energy management programs which can be incorporated within the existing routine performance assessment and benchmarking of WSPs.

4. Key recommendations

This study presents the following practical and research recommendations.

- Although the operating environment for water supply is unique for WSPs, especially owing to the terrain, the size and the type of raw water supplied, all of which influence the energy input for water supply, there is need for adoption and harmonization of energy metrics by the water services regulators at national and regional level to assess the performance of WSPs as energy input influences their operational sustainability. Such metrics could be incorporated within the existing performance assessment frameworks.
- The International Benchmarking for Water and Sanitation Utilities (IBNET) provides an excellent data platform for performance of WSPs in Africa. However, most of the WSPs have not updated their data platforms which makes it difficult to benchmark their performance. In this regard, WSPs need to provide up-to-date accurate and reliable data at national and regional level to encourage benchmarking and peer learning of best practices.

- There is a growing need for WSPs ensure continued supply of uninterrupted, reliable, safe and affordable service provision. This requires WSPs to rethink innovative and resilient sources of energy for water supply to reduce over-reliance on the grid. Most of the WSPs in Kenya rely on grid electricity supply which not only affects water service delivery when there are power cuts but the electricity cost during peak hours when most WSPs operate their pumps. Furthermore, decentralised energy sources were not common among the WSPs participating in the study or such energy sources (mostly solar-powered energy for lighting) contributed only a small proportion of WSPs energy supply. Consequently, there is need to explore decentralised energy sources including solar, hydro and wave energy to improve service delivery reduce on their energy costs. In addition, potentials for energy generation in headwaters should be explored.
- Increased focus on energy input is required among researchers with interest in water supply in the African region as there is still very limited information on energy input and benchmarking of energy input for water supply in Africa. In particular, there is an information dearth on studies focusing on the application of energy models to optimize energy efficiency for water supply. Furthermore, continued research into innovative easy-to-use tools is needed to guide implementation of best-fit practices for energy management.
- This work focused on energy use for drinking water supply and not on the wastewater component. Research on the energy use dynamics and energy generation potential for wastewater is needed as most WSPs in Africa provide both drinking and wastewater services. Studies from other parts of the world especially in Europe and Australia have demonstrated the potential of energy savings and energy recovery from wastewater which has only been minimally explored in Africa.

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Review

Applying the Water-Energy Nexus for Water Supply—A Diagnostic Review on Energy Use for Water Provision in Africa

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Abstract: This work explores the application of the Water-Energy Nexus concept for water supply in the African context, where its operationalization is quite limited compared to developed regions. Furthermore, water supply and demand drivers and their influence on energy use are examined. This study found that there is limited literature available on the operationalization of the concept, and energy use is not considered a key performance indicator by water regulators and utilities. Regionally, most of the studies were carried out in the northern and southern Africa, where energy demand for water supply through desalination is high. An analysis of water supply and demand drivers show diminishing quantities of available freshwater, and increased anthropogenic pollutant loads in some areas are projected. Consequently, utilities will likely consider alternative energy-intensive water supply options. Increased population growth with the highest global urban growth rate is projected, with about 60% of the total population in Africa as urban dwellers by 2050. This implies huge growth in water demand that calls for investment in technology, infrastructure, and improved understanding of energy use and optimization, as the largest controllable input within utilities boundaries. However, it requires a data-driven understanding of the operational drivers for water supply and incorporation of energy assessment metrics to inform water-energy policies and to exploit the nexus opportunities.

Keywords: demand-side/supply-side drivers; energy use; key performance indicators; water-energy-nexus; water supply; water utilities

Introduction

Water and energy resources are intricately connected in their production and consumption [1–3]. On a global scale, water and energy are placed as Goals Six (6) and Seven (7) in the 2015 launched United Nations Sustainable Development Goals (SDGs), with targets 6.1 and 7.1 emphasizing increased universal access to water and energy, respectively, while 6.4 and 7.3 focus on improving water efficiency and energy efficiency [4]. Consequently, global efforts to address the role of water and energy resources in a coordinated manner through research and policy for sustainable development have increased steadily with the application of the Water-Energy Nexus framework [5,6]. This close intrinsic interconnection between production, consumption, and management of water and energy resources commonly referred to as the Water-Energy Nexus was discussed in the Bonn 2011 Water-Energy-Food Nexus conference [7], as a framework to address the complex global water and energy needs, interactions, synergies, conflicts, and trade-offs, which were traditionally considered independently in their utilization, governance, and policy formulation [8,9]. Since then, the application of the Water-Energy Nexus concept in the drinking water sector has received increased attention from researchers, water utilities, development partners, and regulators in the last decade. This is to enhance the understanding of the role of energy in water supply and energy saving potentials through technical assessments [10,11] and synergistic water and energy policy formulation [5,12].

Energy is required in the water supply cycle for abstraction, treatment, and distribution of drinking water, as well as collection and treatment of wastewater in the urban water cycle [3,8,13]. On the other hand, water is required for energy production, directly for hydroelectric power production or indirectly for cooling of thermal power plants [1,14,15]. Energy consumption for municipal water supply is a major driver of operational performance accounting up to 44% or more of the total operational costs, only coming second after labor costs [16,17]. However, energy costs are the largest controllable expenditure within the internal boundaries of water utilities; with up to 40% potential savings on investment with short payback periods, through optimization of pumps and motors, which are the main energy consumers, accounting for up to 90% of the energy use in water supply [11,18].

Several comprehensive reviews on energy use for water supply in different regions and cities have been conducted since the beginning of the last decade, for instance, For instance, on the energy consumption and associated greenhouse gases in water distribution systems [2], the energy consumption for water use cycles in selected countries [3], the assessment of the Water-Energy Nexus in the Middle-east and North Africa (MENA) region [13], the energy intensity for municipal and agricultural water supply processes [19], and the opportunities for improvement of energy efficiency for water supply [20–22]. In addition, several studies have undertaken assessments to quantify energy use for different water source options such as groundwater [22], surface water [23], and sea water desalination [24,25]. Others have presented future scenarios of energy use for various water supply options [12,26] and focus on performance assessment and benchmarking efforts for energy use in water supply in several countries have also been emphasized, for instance, Chile [17,27,28], the Nordic region [29], Australia [30,31], China [32,33], and Canada [34–36].

However, to the best of the knowledge and understanding of the authors, there is a paucity of research and available case studies on the application of the Water-Energy Nexus concept and its influencing factors for water supply in utilities in Africa. Such assessments have not received much attention in the performance assessment of water utilities by the utilities and water services regulators, or are publicly unavailable, coupled with the growing water demand and increased energy costs. Yet, there is growing evidence that improvement in energy efficiency has potential to yield substantial returns for water utilities within a short payback period [11,37–39]. This is especially crucial for water utilities with very weak operational efficiencies and limited ability to recover their full operational costs or generate revenue, which results in a delayed expansion of water supply and consistent provision of unsatisfactory services.

Literature on energy use and energy efficiency optimization for drinking water supply and the drivers of energy demand for water supply is also scant in Africa, with very few studies available to provide a comprehensive assessment in the region. In addition, an assessment carried out by the authors on energy use for drinking water supply in selected drinking water utilities in Kenya disclosed that, even though water utilities collect large amounts of data on their operations, there is a huge challenge in obtaining that data through open calls, especially where such data are not required as a performance indicator by water services regulators (Macharia et al., unpublished). Furthermore, where such energy data are present, the energy metering and billing in most cases is not disaggregated to reflect actual energy use for each treatment process in the water supply cycle. This makes it difficult to undertake a comprehensive qualitative analysis of energy use for water treatment and invariably identify any potential energy-saving opportunities in the water distribution system.

1.1 *Research Scope*

Efficient operational performance of water utilities is key in the delivery of water services, revenue generation, and expansion of coverage. However, insufficient real-time data on energy use and lack of fast, robust, and flexible feedback mechanisms as decision support tools on energy efficiency limits optimization of energy-intensive devices and processes within the water distribution network. Consequently, assessment of energy use is essential to understand the close linkage between energy and water use, cost and savings, and associated management implications of energy efficiency to support efforts towards universal access to water services. In addition, water utilities in Africa are faced with increased water demand from population growth and rapid urbanization, but also deteriorating water quality from increased pollution, which influences the energy input for water supply. Hence, it is crucial to explore the interaction of water supply and demand drivers and the extent to which they influence energy use now and in the future for improving operational efficiency of water utilities.

This paper therefore makes a diagnostic review on accessible literature to explore the level of application of the Water-Energy Nexus concept to address dynamics of energy use and efficiency for water supply in Africa. In addition, the operational performance of water utilities in Africa is explored, and available energy use performance indicators applicable in the context of limited availability of consistent data highlighted. Lastly, provision of water services is influenced by several internal and external supply and demand drivers, which in turn affect the energy demand for water supply. This work therefore synthesizes a selection of water supply-side and demand-side drivers and examines how they influence energy demand for water supply processes in the African context. This works makes an important contribution in highlighting the role of energy as a major input of operational efficiency of water utilities and the benefits of operationalizing the Water-Energy Nexus concept to improve performance of water utilities and enhance access to water services in Africa.

This paper is organized as follows: the first section presents a brief overview of available literature on the application of the Water-Energy Nexus concept and its operationalization in the African context; next, performance of water utilities in Africa highlighting the energy use for water supply processes and available energy use indicators is provided; furthermore, a synopsis of water supply and demand drivers and how they influence energy demand for water supply in Africa is presented; in conclusion, implications of the assessments of energy use for water utilities in Africa is explored.

Methodological Approach

A literature search to identify the existing literature on the water-energy-nexus as it applies to water supply in different regions was conducted in peer reviewed journal articles and publicly available reports and books, mostly retrieved from the Science Citation indexes of the Web of Science Core Collection database, Google Scholar and Elsevier. The definition of the 'Water-Energy Nexus' was adapted from [7], which defines the Water-Energy Nexus as the inter-linkage and dependence of production and use of water and energy resources on each other and the associated trade-offs and synergies of considering this connectedness. In this context, the focus was on the water sector's dependence on energy. The literature search on the 'Water-Energy Nexus' was narrowed to the context of water supply, with literature focusing on the energy demand in the drinking water treatment and supply processes commonly referred to as 'energy embeddedness' [21], for different raw water options and optimization processes.

Particular emphasis on assessment and quantification of energy use for drinking water supply in Africa from peer-reviewed journals, country and regional level performance assessment reports by the utilities, the water service provision regulators and the International Benchmarking Network for Water and Sanitation Utilities (IBNET). Furthermore, available literature on drivers of water supply and water demand in selected countries in Africa was sought and synthesized.

Results

1.2 *Literature on Energy Use for Water Supply in Africa*

Although compilations of best practices for energy use in municipal supply are available at least for Kenya, South Africa, and Zambia; energy use for the drinking water supply itself is not considered among the key performance indicators for water utilities. Instead, available energy data for most utilities solely reflect the operational costs associated to energy use. Literature on the application of the Water-Energy Nexus concept for water supply as well as assessment of energy use in the water sector in most of Africa is quite limited. A summary of available literature retrieved, and the area of study is presented in Table 1. There was increased attention in the last decade with available studies mostly carried out in South Africa and the Northern Africa regions (50% of the literature retrieved), focusing on life cycle assessments of water supply [25,40,41], while the authors in reference [13] provided an analysis of the application of the Water-Energy Nexus in water supply in the Middle East and North Africa (MENA) region. Few studies explored the use of renewable energy sources for water supply in rural areas in Ethiopia [42], Nigeria [43], and Tanzania [44], and the adoption of solar-powered borehole pumps to replace diesel-powered pumps for water supply in refugee settings [45–47] Furthermore, reference [48] compared the energy demand for different water supply options in the informal water supply chain in Kisumu, Kenya. At the level of water utilities, publicly available efforts to assess energy use for water supply were available for Zambia [49]. In addition, energy use per unit volume sold (kWh/m3) as a key performance indicator has recently been made available on IBNET, but only data for utilities in Nigeria were available during the study (available online at www.ib-net.org in January 2020)

Table 1. Summary of available literature on energy assessment for water supply in Africa.

Reference	Description	Country
[50]	Compared the environmental burdens of water supply through conventional water treatment and through membrane filtration.	South Africa
[51]	Outlined benefits of concentrating solar power for large-scale desalination over fossil fuels in the long term to enhance water security in the Middle-east and North Africa (MENA) region.	North Africa
[40]	Provided a life cycle assessment of urban water provision and a comparison of the environmental consequences of treating virgin portable versus recycled water.	South Africa
[52]	Assessed the sustainability of selected urban water treatment plants in Alexandria.	Egypt
[41]	Provided a review of life-cycle assessments of the South African water sector, outlining the potential application of life-cycle assessments to improve efficiency of the water sector in the future	South Africa
[43]	Explored the feasibility of using different alternative renewable energy options for clean water pumping.	Nigeria
[13]	Assessed application of the water energy nexus in the MENA region, bearing in mind desalination as the treatment process.	North Africa
[53]	Conducted a life cycle assessment of portable water production and associated impact to the environment.	Algeria
[42]	Explored the use of solar powered pumps for rural water supply.	Ethiopia
[48]	Compared the energy use for water supply in the informal settlements from different water sources.	Kenya
[54]	Conducted a systems analysis to examine the energy requirements of the water supply for different alternatives of urban water supply.	South Africa
[55]	Assessed the impact of variable energy prices on the financial stability of drinking water utilities in Accra and Ashanti regions.	Ghana
[47]	Assessed the potential of high-capacity solar-powered boreholes compared to diesel-powered pumps in an emergency context.	Kenya, Somalia
[56]	Provided the rationale for promoting energy efficiency for water utilities.	Tanzania
[46]	Outlined the benefits of switching from fuel-powered to solar-powered pumps in refugee camps.	East and Horn of Africa
[45]	Presented a cost-benefit analysis of switching from diesel-powered to a hybrid diesel-solar powered generator system for water pumping in refugee camps.	Kenya

[57]	Provided a design for solar-power operated water pumping system for water provision in Niger Delta.	Nigeria
[24]	Provided an energy and operational cost optimization model for seawater desalination.	South Africa
[44]	Demonstrated the potential of small-scale photo-voltaic powered water treatment system for brackish-water to enhance water supply in remote areas.	Tanzania
[25]	A life cycle assessment of desalination and mine-water reclamation as alternatives for portable water supply.	South Africa
[58]	Assessed the energy and carbon footprints of using centralized, decentralized or desalination options in treating brackish groundwater, Cape Town.	South Africa

1.3 Operational Performance of Water Utilities in Africa

Water supply coverage in Africa is still lagging, with only about 27% of the total population having access to safely managed water services, and a further 34% with access to basic water supply [59]. In a bid to expand water coverage, improved quality of service delivery and enhanced operational efficiency, performance benchmarking, and ranking of water utilities in Africa is routinely monitored by water services regulators through key performance indicators. In this context, several studies on the performance of water utilities in Africa exist. For instance, the performance assessment and benchmarking of the Uganda water supply [60], while reference [61] compared the urban water efficiency and effectiveness for different regions in Africa and reference [62] assessed the performance assessment of urban water supplies in Mozambique. Furthermore, reference [63] analyzed the performance of state water agencies in Nigeria, while references [64,65] provided an analysis of the performance of water utilities in Africa aimed to inform decision on water sector development and investment. The overall performance of water utilities in Africa based on financial, operational, and customer satisfaction indices was reported as weak [64,65]. Most water utilities report consistently unsatisfactory customer service delivery, often struggling to meet their operational costs, with over-reliance on government subsidies, as most utilities struggle to exploit their self-financing capacity. Consequently, the inability to meet full operational cost coverage hinders or delays the expansion of service coverage and delays the maintenance of aging infrastructure, especially pumps and motors, and hence, their operational efficiency. In addition, water losses remain the greatest challenge to water services delivery, highest among the largest utilities, serving over 1 million people across the region, as they often have the oldest infrastructure [64,66]. In Kenya, the Water Services Regulatory Board Kenya (WASREB) [67] estimates an average of 58% non-revenue losses among the largest utilities in Kenya, and an average of 42% at the national level, translating to an annual water loss of about 90 million M3, assuming an acceptable 20% water loss. This, as the regulator reports, is large enough to meet the daily water demand for Nairobi City for about four months. Furthermore, in response to the increase in population growth, i.e., urbanization, resulting in an increased demand for water services, water utilities are increasingly constrained by huge operational costs, rising energy costs and low self-financing of the sector to allow expansion of water services.

To benchmark and monitor the performance of water utilities aimed at improving the quality of water service delivery and expansion of water coverage, a set of key performance indicators is used, as presented in Table 2. The choice of performance assessment indicators depends on the local operating environment and the priority areas of performance for each country. A comprehensive list of various key performance indicators is provided in [68].

Table 2. Summary of clusters of Key Performance Indicators (KPIs) for assessing the water service performance in selected countries; number of KPIs within cluster in brackets.

Country	No of KPIs	Clusters of Key Performance Indicators (KPIs)	Literature Source
Kenya	9	Quality of service (3) Economic efficiency (3) Operational sustainability (3)	[67]

Lesotho	18	Water quality (2) Customer care (5) Network disruptions (4) Continuity of supply (1) Metering (4) Water supply (2)	[69]
Malawi	11	Access to water services (2) Sustainability of companies (4) Customer Care Service (3) Water quality (2)	[70]
Nigeria	16	Level of service (6) Technical indicators (3) Financial indicators (3)	[63]
Tanzania	11	Protection of users' interest (3) Sustainability of the operator (6) Environmental sustainability (2)	[71]
Uganda	10	Technical indicators (4) Financial indicators (3) Service indicators (4)	[72]
Zambia	15	Operational indicators (5) Staff efficiency (2) Service level (3) Financial indicators (3) Corporate governance and management (2)	[49]

1.4 Energy Demand as an Operational Performance Indicator in Africa

As observed from the cluster of key performance indicators presented, energy use for water supply is not considered among the key performance indicators during routine monitoring of water utilities. Among all the publicly available reports on utilities performance that were reviewed, energy use was only reported in Zambia [49], as specific energy in kWh/m3 for water production in the cluster of operational indicators. However, assessment of energy demand for water supply provides opportunities for water utilities to understand the drivers of their operational performance and make necessary interventions to reduce the cost of energy or increase its efficiency [73]. Furthermore, utilities need to develop an energy use management plan through a comprehensive assessment of energy-consuming devices, i.e., the embedded energy which provides insights into how much energy is consumed and dissipated within the system [27,74–76]. Bearing in mind the huge non-revenue water losses of up to 60% as observed in some utilities (www.ib-net.org), linking energy use and associated costs to water losses through the treatment and distribution process can inform water utilities on how much energy is lost with water losses and the associated revenue loss at each water supply process. However, the main challenge of such estimations is the disaggregated data on energy use and energy cost reflected in the electricity bills in most utilities, as observed in an assessment by the authors of selected water utilities in Kenya (Macharia et al., unpublished).

Since monitoring, benchmarking, and ranking of water utilities in Africa at a country and regional level exists, regulators and utilities should seek to incorporate appropriate energy use metrics in their routine performance assessments to assess, monitor, optimize, and benchmark their energy use. A summary of the available energy use indicators, which can be incorporated in the routine performance assessment and benchmarking, are outlined in Table 3. The choice of key performance indicators is guided by the ambition to boost revenue generation, optimize and reduce energy costs, reduce water and energy losses, expand water services delivery, and reduce greenhouse gases emissions [73]. However, the unique operational factors that influence energy demand for water supply including terrain, size, age, and configuration of the water distribution network should not be overlooked while formulating the objectives for performance assessments. Hence, as outlined in [68], before settling on the appropriate indicators, regulators and utilities are required to set achievable objectives, provide a strategy to achieve the objectives, outline the drivers to achieve the set objectives, and lastly establish an energy performance indicators system. Several indicators exist for the assessment of energy use for water supply including those provided by the International Water Association (IWA) in [68], which, as reference [73] noted, although they provide a good starting point for energy assessment and management, they do not provide for cost-benefit analysis of implementing energy efficiency measures. In addition, some of the proposed indicators, for instance a pump energy indicator that considers the energy use and the working hours of the pump expressed as kWh/m3/m, has been used for nation-wide water utilities benchmarking in Australia [77]. Others including the indicator for energy in excess per unit of authorized consumption, energy loss due to dissipation in the pumps, energy loss embedded in leaks, and energy loss due to network operations and system layout applied in pressurized systems [75], require knowledge of hydraulic models and only run online [78,79]. This limits their application in water utilities, with limited access to the internet and with frequent power interruptions.

Table 3. Energy use metrics for energy use assessment for water services provision.

Metric	Description	Remarks	Source
Ph5 (kWh/m^3/100 m)	Standardized energy consumption. Assesses the average pumping energy use per unit volume at 100 m of head.	Provides information on minimum energy used.	[68]
E1 (kWh/m^3)	Energy in excess per unit of input volume Represents the potential for energy reduction per unit of total input volume.	Provides information on the impacts of energy management measures. No provision for the assessment of impact of leakage control measures.	[76]
E2 (kWh/m^3)	Energy in excess/unit of revenue water Represents the theoretical potential for energy reduction per unit of billed water.	Allows for assessment of impact of leakage control measures on the energy demand. Requires a hydrological model.	[76]
WSEE	Water Supply energy efficiency Defined by the ratio between the minimum energy required by a pump and the actual energy used.		[74]
PEI kWh/ML/m	Pump energy indicator Normalizes the pump energy consumption against work done (pump operating hours).	Possibility to benchmark pump energy use for several utilities. Does not provide for the measurement of efficiency of individual pump stations.	[77]
I1 and I2 (Structure, and quality) indicators (kWh/m^3)	I1 shows the influence of the difference in elevation between source and consumers on energy demand. I2 shows the difference between actual energy used and the minimum energy required for water supply processes.	Do not require the use of complex hydraulic models. Do not consider frictional energy losses.	[80]
Fi 10 (% cost of electrical energy)	Provides the percentage share of electricity cost as a proportion of total operational cost.	Provides information on cost trends useful for management decisions.	[68]
D1 (€/m^3 sold) D3 (€/m^3 distributed)	Specific energy costs per volume of water sold. Specific energy cost per volume of distributed water.	D1 Provides cost estimates of energy for each billed unit of water. D3 estimates of energy cost /volume distributed).	[81]
D2, (€/m^3 sold)	Specific energy cost in peak hours.	D2 provides cost estimates of energy during the peak hours/during high tariffs hours.	[81]
D4,(kWh/m^3 sold)	Specific energy consumption per volume of water sold.	Can be used to make an inventory of energy use for each pumping station/treatment plant.	[82]
WNEE, Water Network Energy Efficiency	Ratio of the minimum required energy and the actual consumed energy.		[83]
UME, Unavoidable Minimum Energy	Minimum energy required at the tap.	Applicable to one or more pumps/pump stations.	[83]

EEI, Energy Efficiency Indicator	Ratio between UME and the actual energy consumed by each device.	Accounts for the possible daily volume left in the reservoir (considered as excess energy).	[83]

Data Required Energy Use for Drinking Water Supply

As the call to examine the benefits of operationalizing the Water-Energy Nexus in the water supply intensifies, water utilities and regulators should harmonize the definition of metrics of energy used to standardize their data collection. Several terms are used interchangeably in most papers including 'energy intensity,' 'embedded energy,' embodied energy,' and 'associated energy.' In most papers, the energy used for the abstraction, treatment, and distribution of water in pressurized water distribution systems is reported as the sum of the direct and indirect embodied energy required to produce a certain unit volume of water [16,23,84]. Direct energy is defined as the onsite energy for the operation, water treatment, and distribution of water in terms of electricity and fuel, while indirect energy comprises the off-site administrative energy and chemical usage [3,22]. The embodied energy demand estimated through life-cycle assessments, input-output analysis or process-based hybrid approaches, vary with the water supply options either groundwater supply systems, surface water systems, or reclaimed water systems as outlined in [3,19]. Direct energy use for supplying ground water is estimated at 20–30% higher than that of surface water per unit of water supplied depending on the well yield, the height over which the water is lifted and the efficiency of the pumping devices [22]. In surface water supply options, the main determinants of direct energy include the pipe characteristics, the treatment technology, the quality of raw water and the distance from the source [3,30].

Estimates of the total direct and indirect energy use for different water treatment processes is provided as the unit of energy required (kWh) to produce one-unit volume (1 m^3) of water, expressed in most papers as kWh/m^3, as summarized in other reviews [3,13,30]. Consequently, to demonstrate the broad span of energy used for the supply of different water types, a summary for selected countries is provided in Table 4. Note that the expression of energy use for water supply varies, with several authors using different metrics. For instance, the energy consumption is expressed as kWh acre/foot [85], in kWh/annum [86], in kWh/KL [41], or Petajoules/year [86].

Table 4. A summary of studies on energy use for drinking water supply processes.

Water Type	Process	Energy Intensity kWh/m^3	City/Country	Reference
Mine water	Reclamation	2.16 **	South Africa	[25]
Sea water	Reverse osmosis	2.5–7.0	Libya	[13]
Sea water	Reverse osmosis	3.69	South Africa	[25]
Sea water	Multistage flash distillation	3–5	Libya	[13]
Surface water	Water supply	0.29	China	[87]
Surface water	Water distribution	0.41	Toronto, Canada	[23]
Surface water	Water distribution	0.31	Turin Italy	[23]
Surface water	Water treatment	0.07–0.21	Chile	[27]
Surface water	Water supply	0.02	Alexandria, Egypt	[52]
Surface water	Water supply	0.02–0.14	Kenya	Macharia et al. (Unpublished)
Groundwater	Water extraction	0.14–0.69	California, USA	[19]
Groundwater	Water extraction	2.87	Florida, USA	[22]
Groundwater	Water extraction	0.32–0.47 *	South Africa	[58]
Groundwater	Water abstraction	1.1–2.4	Kenya	Macharia et al. (Unpublished)

* Converted from MJ/m^3 and ** converted from kWh/kL.

1.5 Drivers of Water Demand and Water Supply on Energy Use and their Relevance for Africa

Analyses of water scarcity, defined as the gap between the freshwater resource available and the demand under prevailing conditions, have revealed that about 54% of countries in Africa, especially in the Northern and Southern regions, are either water scarce or severely water stressed, with 20% of the 2016 population living under water scarcity conditions. It is projected that approximately 37% and 57% of the total population in the continent will live under severe water crisis by 2025 and 2050, respectively, as presented in Figure 1 [88]. This is largely driven by water insecurity largely driven by physical shortage, lack of infrastructural capacity, and economic vulnerabilities, which influences water supply and availability. As the population increases and demand for water services soars among African utilities, an understanding of the interdependence of water and energy and their interaction is crucial in the water supply sector. This will ensure the sustainability of water supply services, reduction of water and energy losses, as well as mitigation of greenhouse gas emissions and guiding water-energy policy formulations and future implications of investment in energy efficient systems [6,89]. Population growth, high rates of urbanization, and effects of climate change have been observed as the major drivers of water demand in Africa, where water utilities should incorporate water supply planning in their future [90,91]. The increase in urban population, especially in urban informal and peri-urban settlements, pose a major challenge in the operations of water utilities due to huge non-revenue water losses arising from illegal connections and increased pressure to the already ageing infrastructure. Several drivers of water supply and demand influence the energy demand for the water treatment processes and their influence on energy use for water supply have been explored.

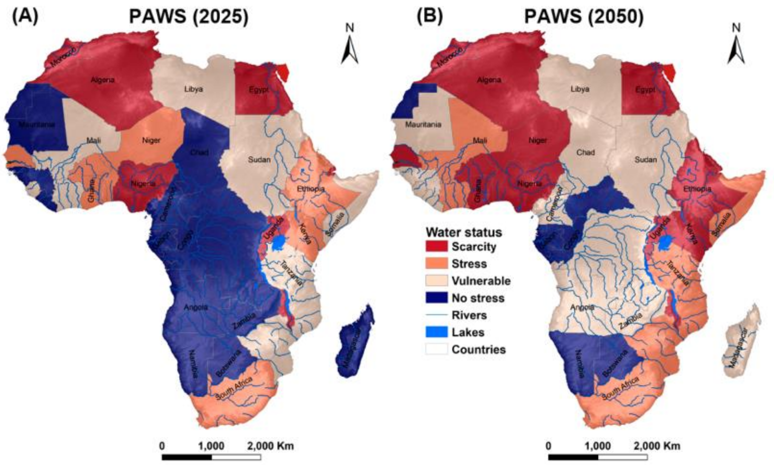

Figure 1. (**A**,**B**) Projected available water status showing total available renewable freshwater per capita in African countries in the year 2025 (**A**) and 2050 (**B**) [88].

Demand-Side Drivers

This chapter explores the influence of selected water demand drivers on water utilities energy demand, crucial for future planning of expansion and sustainability of service coverage, especially in the metropolitan areas of large cities where utilities need new infrastructure for service expansion as the cities expand.

Population Growth and Accelerated Urbanization

The United Nations Department of Economic and Social Affairs (UNDESA) projects that the total population in Africa will be approximately 2 billion by 2050. Furthermore, about 50% of the population in low-income countries and 59% in lower middle-income countries will be city-dwellers in 2050 compared to only 30% and 41%, respectively, in 2018 [92]. This is a 20% increase in about three decades from the current population estimates. In addition, the rate of urbanization in low-income and lower middle-income countries is expected to be two times that of the global rate (0.6%) between 2030 and 2050, the highest among the world's income categories.

As reported in reference [90], eight out of 10 countries with the highest rates of urbanization in the world are in Africa. Furthermore, reference [91] noted that countries in sub-Saharan Africa that have achieved continued growth in gross domestic product (GDP) have the fastest rate of urbanization, among them Ethiopia, Nigeria, Mali, and Burkina Faso. The urban growth is expanding into the metropolitan areas, most of which do not have an existing water supply infrastructure. This results to low rates of piped water supply coverage, as water utilities are already struggling to meet current demand which outpaces the speed of service expansion. The challenge is further exacerbated by the rise in unplanned urban settlements of low-income households where most of the non-revenue water losses and hence energy losses occur through vandalism and poor management [93]. This has pushed water utilities to increase water production and exploit new raw water sources, such as groundwater and sea water desalination, which often increase the energy demand [24,25].

The 2018 performance assessment report, WASREB, Kenya, indicated that most water utilities in Kenya recorded an average 27% increase in energy costs, attributed to an increase in water production, a rise in national energy prices, and prolonged drought, which resulted in reduced surface water levels; hence, most utilities sought more energy-intensive groundwater options. Increased demand for water implies more energy to abstract and supply water but also require utilities in areas with limited water supplies to explore additional alternative sources, including groundwater and desalination, which are often highly energy intensive. On the other hand, the expanding metropolitan areas present water utilities opportunities to make informed planning of the infrastructure especially with respect to water harvesting and storage structures, renewable energy sources, and energy saving technologies to reduce over-reliance on the grid [91,94].

Per Capita Consumption

The daily per capita water consumption is influenced by socioeconomic status, meteorological conditions, household behavior, and characteristics and restriction of supply through conservation measure, tariffs, price, and metering technology [95,96]. On the supply side, water utilities influence the water demand through the enforcement of smart metering and pre-paid options for access to water services, which reduces non-billed water and enhances increased revenue collection. In the African utilities' context, there is a huge variation in the daily per capita consumption between and within countries and even among utilities within the same country [64,97]. The average daily water production and consumption for the largest utilities in the country and for those with multiple large utilities, serving a population above 5,000,000, were selected as presented in Figure 2 for the years between 2013 and 2017, for which most data were available at IBNET except for Sudan (latest data available was for 2009), 2005 for Namibia and Madagascar, and 2010 for Mauritius [98]. Huge intra-country variations in production and consumption were observed among utilities in Nigeria and South Africa, attributed mainly to variations in income level. The expansion of the middle-class in most urban areas in Africa with the ability to pay for quality water services have led to increased demand for domestic water supply, and hence, a need for increased production [67]. Consequently, water utilities need to plan for such increase in demand, which is highly dependent on quality data on trends of residential per capita water use within the supply area essential for demand forecasting, pump scheduling, and optimization.

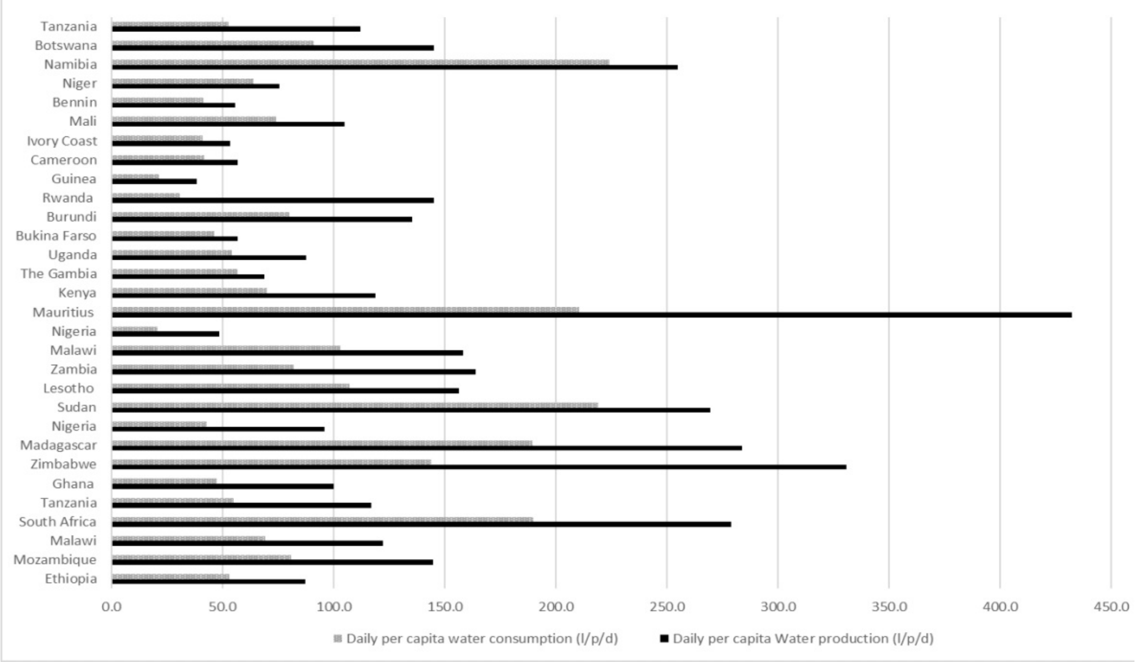

Figure 2. Daily per capita water production and consumption for selected countries in Africa. Data obtained from [98].

Supply-Side Drivers

The supply-side drivers are mostly external factors that influence the quantity and quality of raw water entering the boundaries of water treatment and distribution systems. Projections of water supply drivers are crucial in the long-term planning of water utilities regarding water sources and possible exploration of alternative sources, which would be energy intensive. In addition, a clear understanding of the water supply drivers outlined below is crucial in the management of water losses along the water distribution network where the bulk of non-revenue water occurs. Operationalization of the Water-Energy Nexus thus presents opportunities to save water and energy, with energy management measures such as correct sizing of the pumps and motors reported to have as much as 30% energy savings within a 3–6 months payback periods [11].

Variation in Precipitation Patterns

Climate change and its influence on precipitation patterns in Africa is widely reported [99–102]. Of interest to water supply is the future projections of the spatio-temporal distribution of rainfall, which would influence the balance between water supply and demand, and consequently, the energy requirement to abstract, transfer, or lift the water. Several studies project prolonged drought and reduced groundwater recharge rates of about 30–70% in the northern and southern regions, compared to the increased precipitation and groundwater recharge in the eastern, western, and central part of Africa under the high-emission and low-emission climate change scenarios [100,101]. In addition, increased flooding events are projected along the Niger delta and the Blue Nile by an over 10% increase in high flows under the global climate low-emission scenarios of 2 °C [101]. It is further noted that the effects of climate change are likely to be more severe, especially in Sub-Saharan Africa due to low adaptive capacities [101,102]. Water utilities in areas facing more frequent severe droughts have to adjust their production to cope with the growing demand by seeking alternative water sources such as sea water desalination and mine-water reclamation, often with huge energy intensities [25]. Furthermore, longer pumping hours, and hence higher energy demand, may be required to meet the increased water demand during drought periods. Therefore, more investment is required to increase water harvesting and storage capacity to meet the growing demand.

Water Losses within the Systems

Water loss within the water supply network is categorized as either physical losses through leakages in the storage and pipe network or real losses that occur through incorrect customer meter billing, vandalism, or any unauthorized consumption [103]. These losses pose one of the greatest challenges of water supply sustainability, both in hindering expansion of supply to the unserved areas, thus weakening the utilities operational efficiency. As reported in [64,66], large utilities, serving more than 1 million persons, tend to report higher non-revenue losses, since in most cases their infrastructure is quite old, with frequent bursts and leakages where energy is lost too. Based on the data submitted to IBNET, non-revenue water losses in participating utilities in Africa were reported as a percentage of billed water and as volume lost per kilometer of connection. The percentage non-revenue water ranged on average from 54% in Gabon and to about 20% in Burkina Faso, with the continent's lowest non-revenue water losses as in Figure 3. However, values as high as 72% have been reported in Nigeria. Additionally, non-revenue water loss reported as volume lost per km of connection per day in 2018/2019, ranged from 73 m3/km/day in Nigeria, 61 m3/km/day in Zambia, 4.7 in Burkina Faso, and 10 m3/km/day in Lesotho.

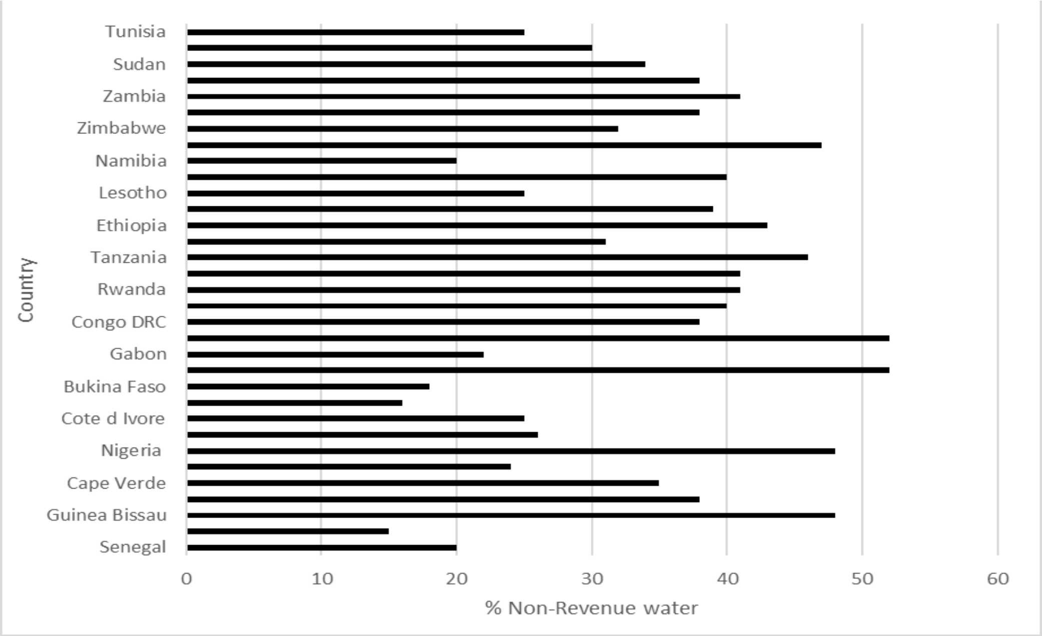

Figure 3. Levels of % non-revenue water (NRW) for selected countries in Sub-Saharan Africa. Data obtained from [98].

As noted in [104], reducing and managing non-revenue losses and hence energy losses require comprehensive supply and demand side programs that are both sustainable and realistic. Although it is not technically possible to reduce the water losses to zero especially in systems with aged infrastructure, means to reduce the losses in the system starts with thorough assessment of the system to prioritize management options. Hence, keeping in mind the close linkage between water and energy, utilities can exploit a joint wholistic water-energy balance where a link between energy consumption in water supply processes and associated water and energy losses can be quantified [82,105,106].

Nature and Type of Pumps and Motors

The nature of pumps and the associated pipe network largely determines the energy demand and energy and water losses within the system. In addition, these are the highest consumers of energy within the water supply networks, accounting for over 90% of the total water utilities energy consumption, but also present the utilities' greatest energy-saving potential [11,83]. Pumping accounts for about 30% of the total energy consumption for groundwater extraction, and about 80% of the clean water transmission and distribution; hence, their operational efficiency is crucial in energy savings and reducing water losses through leakages [11]. The amount of energy consumed is highly dependent on the nature, age, and pump running hours and the maintenance schedules, but poor sizing and installation, as well as high variability in pressure and head losses, can greatly increase the energy consumption due to increased inefficiencies. In an unpublished study carried out by the authors in water utilities in Kenya, most utilities have not invested much in improving or optimizing their energy efficiency. Similarly, most utilities had no separate metering and billing of individual pumping station and none of the utilities under study had an energy management plan, although strategic plans to explore renewable energy sources were mentioned. Separation of energy consumption by energy-intensive consumers provide valuable disaggregated trends of energy use and efficiency crucial for the detection of inefficiencies responsible for energy losses and establishment of maintenance schedules.

Water Source and Water Quality

Different raw water sources require varying amount of energy to abstract, treat, transmit, and distribute clean water. As already outlined in [22], groundwater extraction accounts for about 31% of total direct energy compared to surface water. Furthermore, surface water supply systems have a higher indirect energy requirement due to higher amounts of chemicals required to treat the water. The type and quality of raw water entering a water treatment system influences inputs such as energy and treatment chemicals where in a typical conventional water treatment that employs coagulation/flocculation and uses filters, the energy intensity is largely influenced by the concentration of the total suspended solids and the nature of the filters [107]. Furthermore, land-use activities, population density in the catchment areas, and possible effects of climate change influences the quality of water from the catchment areas. The concentration of suspended matter, total organic carbon, and water conductivity, which are highly influenced by seasonality, have been identified as water quality parameters that contribute to a high energy intensity in the water treatment system [17]

Discussion

Since the beginning of the last decade, Water-Energy Nexus research has gained a lot of attention both in the application of the nexus concept and models to address the nexus challenges. However, as noted in [108], in one of the latest reviews on the Water-Energy Nexus, there are challenges in the application of the framework for decision support since there is no singular framework for conducting a nexus research. In addition, research on the methods and tools for the assessment of the Water-Energy Nexus framework at different scales even in developed economies is still at the ‘understanding stage.’ This necessitates a further analysis of the water-energy framework towards the ‘implementing stage,’ where effects on water energy policies trade-offs and synergies would be evidenced. The authors further note that there is potential in the adoption of the Water-Energy Nexus framework to address sustainable and wise-use of energy and water resources through informing decision-makers on policy and governance structures in the water sector in Africa.

Upward shifts in the supply side and demand side drivers of energy use for drinking water supply is expected in the future. On the supply side, the quality of raw water is likely to deteriorate or reduce due to increased pollutant loads from various users; moreover however, the water treatment technologies will need to change to cater for higher efficiency and maintenance of required water quality standards. Additionally, water utilities will be required to consider alternative water supply options including desalination and re-use, which will likely increase their energy demand. On the demand side, Africa is expected to have the highest growth rate in the cities, with about 60% of the total population living in urban areas in 2050 [109]. This implies a huge growth in the water demand, which calls for investment in technology, infrastructure, and labor as well as improved understanding of the water supply system inputs and how they can be optimized.

Estimation of the energy use for drinking water among water utilities in Africa is a key enabler of universal water access through sustainable and resilient operations of water utilities; it should be a requirement that water utilities and regulators are implemented in the existing performance assessment data collection, considering differences in their operating environments. Several indicators do exist for the assessment of energy use for water supply [76]. Such indicators are based on the concept of the minimum energy required to deliver a unit volume of water between a point of source and delivery point, considering the terrain, the nature of the water supply system, and areas of losses within the system, all of which influences the system operational energy requirements. For instance, for the assessment of energy use in small and medium sized water utilities, reference [80] proposed two indicators that do not require hydrological modeling: the structure indicator I1 and the quality indicator I2. Structure indicator (I1) represents the energy consumption to lift water from a water source to consumers, while quality indicator (I2) shows how well a utility is utilizing the energy for water supply processes compared to minimal energy required to lift a unit volume of water, maintaining the operational pressure required at the end user tap.

Water utilities needs to prepare to be 'fit for the future' by adapting ways to achieve maximum operational cost recovery, expand service connectivity and transform into customer-oriented service providers through innovative solutions that address water supply and energy reduction [110]. Water utilities in cities such as Kampala (Uganda), Lagos (Nigeria), Bamako (Mali), and Niamey (Niger) have been projected to experience exponential growth in water demand due to high rates of urbanization, since they are located in areas of high-risk water stress [90,111]. Planning for increased water harvesting and storage is thus paramount. However, as already reported in reference [112], the water storage facilities within the distribution network influence the energy intensity for water pumping, which should be considered to optimize energy use for pumping, especially when water utilities need to invest in new pumping and storage systems.

Transformation into smart utilities will help utilities to leverage the vast amount of data they generate to optimize their service delivery [113–115]. Availability of comprehensive data on the performance of water utilities and energy use for water supply is not a unique situation to water utilities in Africa, as already discussed in reference [116]. However, the quality of data remains a significant challenge for water utility operations research in areas without a comprehensive database, thus, limiting such research efforts to utilities willing to provide the data, and more often those performing relatively well. In addition, most of the data provided through open calls to utilities is largely siloed, disintegrated into files or computer systems that rarely communicate with each other [115].

Conclusions

There is a compelling need to assess energy use in water utilities in Africa to properly inform their decisions for water service provision and improve the understanding of the application of the Water-Energy Nexus concept by water utilities and water services regulators. There are still very few studies on the application of the concept in the region and energy data is quite difficult to obtain through open calls, given that many water services regulators do not consider energy use as a key performance indicator. There are indications of an upward shift in the demand-side drivers of water supply, especially population growth and urbanization, while on the supply-side, available water sources are continuously being depleted and/or increasingly being polluted. These trends have triggered an increase in energy requirements for water utilities as they switch to remote water sources and/or abstracting and treating increasingly polluted sources that are often more energy intensive. Despite these challenges, it is clear that accelerated structural and organizational reforms in the water sector in Africa and increased investment in water infrastructure since the 1990s have demonstrated great potential for water utilities to meet their operational costs. Furthermore, it shows the possibility to deliver water services and at the same time expand coverage in a sustainable manner towards the achievement of the SDG goal on universal access to water in Africa. Moreover, several opportunities exist for water utilities to adequately understand their energy consumption and the extent to which the supply-side and demand-side drivers for water supply affect energy demand for efficiency and sustainability considering the increasing demand for water and the associated obligations to provide quality services in the region. This review supports the ambition of regulators of water services to incorporate energy use assessment indicators through which utilities can be evaluated and benchmarked in their routine monitoring and reporting. However, accurate understanding of the operational drivers for water supply lies in data collection, which will help to inform water-energy policies.

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largely contributed to the conceptualization, analysis, interpretation of the work and step-by step revision of the work in progress. N.K. (Nzula Kitaka) facilitated collection of data and contributed to the critical revision and input to the manuscript.

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Examining the Relative Impact of Drivers on Energy Input for Municipal Water Supply in Africa

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Abstract: This study examines supply-side and demand-side drivers of municipal water supply and describes how they interact to impact energy input for municipal water supply in Africa. Several key compound indicators were parameterized to generate cluster centers using k-means cluster analysis for 52 countries in Africa to show the impact of water supply–demand drivers on municipal water supply and associated energy input. The cluster analysis produced impact scores with five cluster centers that grouped countries with similar key compound indicators and impact scores. Three countries (Gambia, Libya, & Mauritius) were classified as outliers. Libya presented a unique case with the highest impact score on energy input for raw water abstraction, associated with largescale pumping from deep groundwater aquifers. Multivariate analysis of the key indicators for 20 countries in sub-Saharan Africa that are either water-secure or water-stressed illustrate the relative impact of drivers on energy input for municipal water supply. The analytical framework developed presents an approach to assessing the impact of drivers on energy input for municipal water supply, and the findings could be used to support planning processes to build resilient drinking water infrastructure in developing countries with data challenges.

Keywords: drivers and indicators; energy input; municipal water supply; water demand; water–energy nexus

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1. Introduction

Energy is needed in the municipal water sector for drinking water production and supply processes (i.e., raw water abstraction, treatment, and distribution), as well as for wastewater collection, conveyance, treatment, and disposal or reuse. Globally, 7% of total energy generation is used in the municipal water sector [1]. The intensity of energy used for drinking water supply varies widely across the world with the type of water supplied and the supply system characteristics. Energy intensity for drinking water supply could range from, for example, 0.2 kWh/m^3 in Australia to 4.07 kWh/m^3 in Spain [1]. In addition, about 0.0027 kWh/m^3 are required to lift groundwater a distance of 1 m in a frictionless system operating at 100% efficiency [1]. Furthermore, the costs associated with energy input for municipal water supply are significant, reaching up to 40% or more, especially in water-stressed regions where utilities pump groundwater from greater depths or exploit alternative water sources such as brackish and saline water sources, which are typically energy-intensive [2]. Depending on the source and quality of raw water and the size and topography of the service area, energy input can account for up to 70% of the total operational costs of municipal water utilities [3]. Furthermore, energy input constitutes the largest single controllable operational cost factor for many municipal water utilities worldwide [2]. Therefore, managers of municipal water infrastructure must examine the implications of raw water abstraction, treatment, and supply choices to minimize or optimize energy use. As a result, there is a growing awareness of the potential for energy use planning in the municipal water sector. Planning and implementing a resilient energy management and control strategy is important, especially for small-scale operations, which are most vulnerable to fluctuations in energy prices. Adequate planning ensures that water supply infrastructure is built to cope with environmental and socio-economic transitions, especially in countries with rapidly growing water demand due to accelerated population growth and limited capacity for adaptation to climate change [4].

The growing awareness of the potential for efficient resource use has earned the interaction between water and energy, defined within the Water–Energy Nexus framework as the relationship between production and consumption of water and energy resources, a prominent position in the United Nations (UN) post-2015 Development Agenda to ensure that water and energy policies are consistent with other development sector objectives through the Sustainable Development Goals (SDGs) [5,6]. For instance, the operationalization of the water–energy nexus in water supply (Figure 1) through interventions into structural energy inefficiency in the operations of municipal water utilities could translate directly into climate action on both mitigation and adaptation when interventions are carefully thought through. Many countries in sub-Saharan Africa still produce a large fraction of their electricity from coal-fired power plants. In fact, coal accounted for 99.6% (in 2018) and 87.6% (in 2019) of total electricity generation in Botswana and South Africa, respectively [7]. A switch to renewable energy sources to power decentralized water-supply infrastructure, especially in rural areas of sub-Saharan Africa, could accelerate access to drinking water supply [8] whilst reducing emissions and building the resilience of countries to deal with the impacts of climate change. Much of Africa in general is considerably affected by serious physical and or economic water security challenges. A major development constraint the UN post-2015 Development Agenda is seeking to address is SDG 6 regarding universal access to water, sanitation, and hygiene. Physical water scarcity is widespread in some parts of the arid northern, eastern, and southern regions of the continent, while almost all African countries face economic water scarcity, with Eritrea, Somalia, Burkina Faso, Niger, and Senegal identified as the most vulnerable [9]. With respect to economic water scarcity, renewable freshwater recharge is sufficient to cover human and ecosystem needs, but shortages in water supply have persisted due to inadequate infrastructure and underinvestment, in addition to problems with operational inefficiencies and lack of access to energy for municipal water supply. As a result, several countries, especially in sub-Saharan Africa, are experiencing a decrease in access to safe drinking water, as progress on universal access has been outpaced by additional demand due to population growth and rapid urbanization [10]. According to the Joint Monitoring Programme (JMP) for Water Supply and Sanitation of WHO and UNICEF (the official United Nations mechanism tasked with monitoring progress on SDG 6), 400 million people in Africa still relied on limited services, unimproved water sources, or surface water for domestic use in 2017. Furthermore, the proportions of the population using at least safely managed water sources varied significantly among urban (84% and 87%) and rural populations (44% and 49%) between 2015 and 2020, respectively [11].

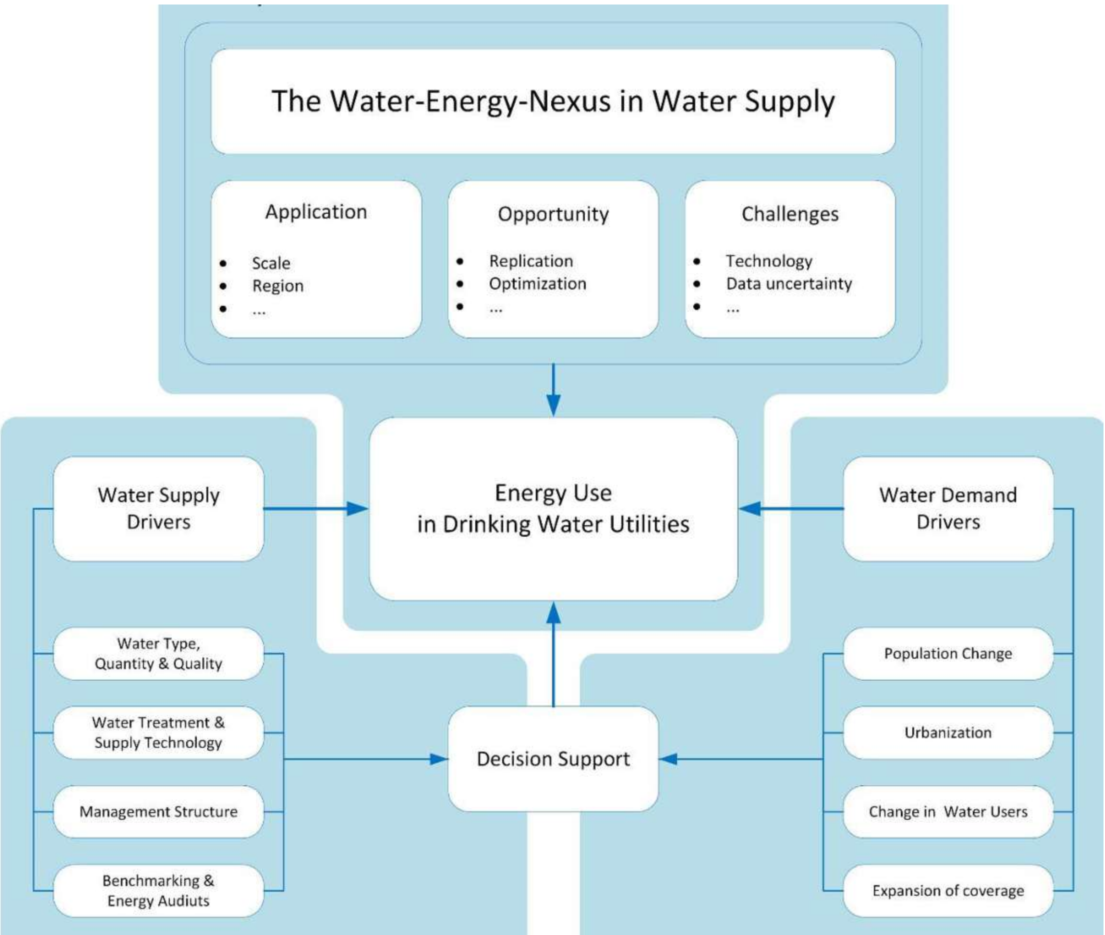

Figure 1. An illustration of the operationalization of the water–energy nexus framework with drivers of municipal water supply (authors' conceptualization).

Municipal water supply is subject to environmental and technical constraints, which are further exacerbated by global trends and drivers such as climate change, population growth, urbanization, and changing lifestyles, as illustrated in Figure 1. These trends are driving up the operational costs of municipal water utilities [12,13]. For example, it is projected that the total population of Africa will reach 2 billion in 2050, about 67% of which will live in urban and urbanizing areas [14]. A large set of supply-side and demand-side drivers have been reported in [15–17]. Furthermore, a growing number of studies, e.g., [18,19], have discussed the environmental and human impacts on water systems. Drivers such as hydrological, demographic, or socio-economic changes influence water supply and demand, which consequently impact the energy input for municipal water supply [12,13]. However, most operators of municipal water utilities in sub-Saharan Africa lack the analytical tools to understand how current and future developments impact the energy requirements of water utilities. While some engineering models exist to predict and estimate the energy requirements of water utilities, it is still challenging to aggregate the impact of drivers in decision-making processes. Decision makers and operators of municipal water infrastructure in sub-Saharan Africa could learn from the results of several empirical and modeling studies on energy audits [20] and operational assessments [21] of water infrastructure management elsewhere. However, these findings cannot be generalized, as they vary in scale within and between countries, depending on a multitude of factors and processes that are usually context-specific (e.g., data availability, location, source of raw water abstracted, size of the municipal water utility, etc.). This makes planning extremely difficult in developing countries, especially in sub-Saharan Africa, where data challenge is a major constraint for decision making. One way to overcome data limitations is to derive proxy and quantifiable indicators of drivers for which data are available. By connecting environmental and socio-economic variables into technical and operational processes of municipal water infrastructure, water utilities can undertake long-term resource optimization to their advantage. Another incentive to focus on drivers is the fact that additional improvement in the technical efficiency of energy-consuming devices and processes along the water supply chain flattens at peak levels of performance [22,23]. The objective of this study was to describe supply-side and demand-side drivers of municipal water supply in Africa and demonstrate how several drivers interact to impact energy input for municipal water supply. The study applied the water–energy nexus concept to municipal water supply with a focus on Africa for the following reasons: (i) there is a widespread lag in water infrastructure expansion behind demographic change in many countries in the region due to rapid population growth, urbanization, and underinvestment in water infrastructure; (ii) a large proportion of the population still lacks access to improved drinking water, sanitation, and hygiene services; (iii) improvements in energy efficiency and the potential to minimize operational costs could free financial resources for upgrading and expanding existing water services; (iv) every kWh of electricity and the associated costs that are saved by water utilities through energy efficiency operations could translate into more kWh of electricity for other productive uses and increased potential for expansion of water supply services. The key research questions this paper sought to answer included: (a) What are the key drivers of municipal water supply and demand in Africa? (b) What data sources can be explored at the country-level to quantify the identified drivers? (c) How do the identified drivers interact with each other among different countries in Africa and how do they impact energy input for water supply?

Approach of the Study

This study examines water supply and water demand drivers of municipal water supply, defined as natural as well as socio-economic, political, and technological factors that may contribute to changes in water supply and demand and ultimately the energy input for municipal water supply in the short and long term. A combined influence of these drivers on municipal water supply has created the need to explore additional, and in some cases, energy-intensive water sources to meet increasing water demand. In this regard, most water utilities in sub-Saharan Africa are faced with an increased need to understand how these drivers will influence their energy needs, energy sources, and energy costs in the future. While there is growing interest in understanding the interaction between water and energy in water utilities, the influence of water supply and demand drivers on their operations remains largely unexplored in Sub-Saharan Africa. This study advances on work performed by [19] specifically for African countries by examining and quantifying these drivers and exploring the linked influence on energy use for water supply. Figure 2 summarizes the methodological approach of the present work. Firstly, indicators for water supply and demand drivers were identified and parameterized, which were then applied to develop a conceptual flow model that illustrates the relative impact of drivers on each other. Furthermore, a cluster analysis was applied to establish which countries group together based on the identified indicators as the basis for possible similar intervention strategies. Lastly, a multi-variate analysis was performed to visualize the magnitude of impact of identified drivers on energy intensity for municipal water supply in general.

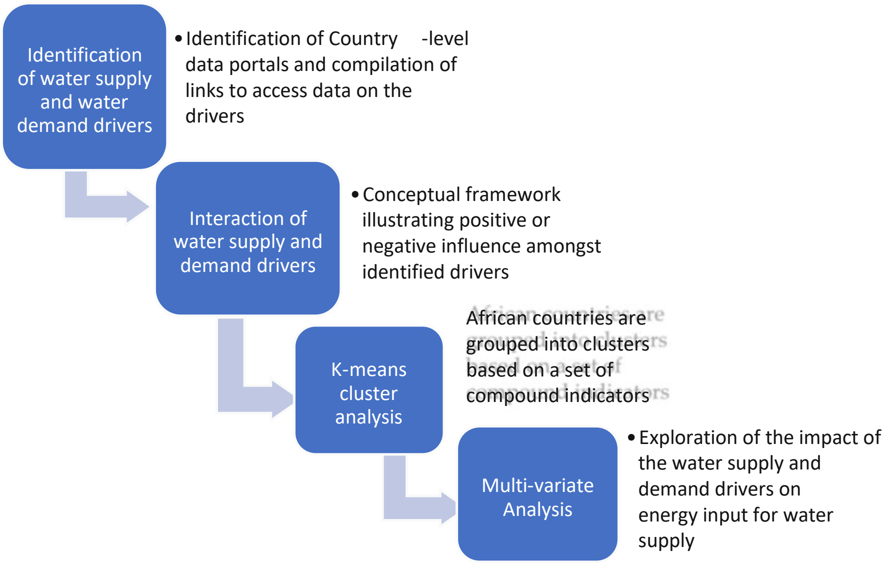

Figure 2. Summary of the methodological approach.

2. *Materials and Methods*

This section provides the review of data portals to identify the country-level water supply and demand drivers and how these drivers were categorized. The relationship between the drivers and how the countries cluster based on selected indicators for the water supply and demand drivers is provided. Furthermore, the relative impact of selected drivers on energy intensity for water supply in selected countries is visualized through principal component analysis.

2.1. *Parameterization of Indicators*

A systematic review of publicly available data portals, particularly those with country-wide data on national water availability, water supply and demand, and socio-economic parameters for countries in Africa, was conducted to identify and parameterize indicators of supply-side and demand-side drivers of municipal water supply. Additionally, several studies including [12,13,15–19] examining the following issues were included: (i) energy input for single water systems (e.g., utilities or cities/municipalities that manage them), (ii) global and regional models and assessments of climate and hydrological processes applicable to Africa, (iii) freshwater water withdrawal by water use sectors (municipal, agriculture, manufacturing, mining, power generation, etc.), and (iv) water use patterns and related impacts on water quantity and quality. It is worth noting that the following factors were not reflected in the analysis: (i) conditions at a sub-national scale, (ii) influences originating from foreign countries, (iii) topography, (iv) type of technology used and related operational efficiency, (v) economies of scale, and (vi) inter-annual variability of the indicators identified.

Indicators were identified, parameterized, and grouped into either supply-side or demand-side drivers based on the forcing factors they represent, which either directly or indirectly affect the energy input for municipal water supply due to changes in the volume of municipal water that must be produced and distributed to address a forcing factor. The following categories were used to group the indicators into supply-side and demand side drivers for municipal water supply.

1. Drivers affecting freshwater availability (water quantity):

Data on the total annual renewable freshwater resources per capita (m^3/capita) were obtained for each country. Freshwater withdrawal by the main water-using sectors was divided into municipal, agricultural, and industrial water demand, as provided by the main reference data portals AQUASTAT [24] and World Bank Open Data [25]. The annual freshwater withdrawal for agricultural use as a fraction of total annual freshwater withdrawal was used to indicate the influence of agricultural water demand and its impact on water resources relative to the other two main water use sectors (i.e., manufacturing and municipal water use). The same procedure was applied to water use by the manufacturing sector. In the absence of data on actual annual abstraction by the type of raw water sourced, the ratio of total renewable surface water to total renewable groundwater was applied to indicate the relative dependency on the type of freshwater source. The present paper uses value-added (VA) growth rates of the two major competing sectors to capture the effect of rising demand for agricultural and industrial goods as a driver of freshwater withdrawal. By definition, imports are excluded from value-added growth rates, which include only domestic production. Agricultural and industrial VA growth rates were accessed from the AfDB Socio Economic Database [26], which provides more recent values than the World Bank Open Data database [25], although no data were found for South Sudan.

2. Drivers affecting freshwater availability (water quality):

Drivers of water quality were quantified based on the WorldQual model, validated for the European region [27–31] and applied to Africa [29]. Due to the general lack of data on contamination levels in groundwater and surface water, several parameters were compared to the results of the pollution model, which was conducted by [29] for the African continent. The distribution of national-level values for number of people living in agglomerations larger than 1 Million as a percentage of the total population and average population density per km^2 [25] was compared to the modeled contamination levels, of which the latter coincided most with the outputs of [29].The portion of wastewater (%) that is treated was quantified based on updated data provided by the Yale Center for Environmental Law and Policy (YCELP), Center for International Earth Science Information Network (CIESIN), and World Economic Forum (WEF) for all countries, except Comoros, Somalia, and South Sudan [32].

Several demographic and socio-economic factors influence municipal water demand, including population growth, the share of the total population that is urban, and the rate of urbanization [33–35]. These factors including the annual population growth rate (%) were quantified using data by [25]. The same data portal was used to generate data on annual per capita income (GDP) (USD/cap), which were used to quantify the influence of the changing lifestyle and economic capacity of the population on improved water supply and sanitation services. The International Benchmarking Network for Water and Sanitation Utilities (IBNET) portal [36] was used to retrieve data on population with access to improved municipal water services. The total annual municipal withdrawal was estimated as the fraction of withdrawals (%) for domestic needs from total annual freshwater withdrawals (m^3). In addition, the annual municipal withdrawal per capita was estimated to capture how much this metric could increase as economic development advances.

3. Utility operations directly impacting energy input for municipal water supply:

For groundwater abstraction, the median values of the depth of boreholes from which groundwater was abstracted were calculated. Data for the depth of boreholes were provided in [37,38]. Data on cost of electricity (USD/kWh) for raw water abstraction, treatment, and distribution for different countries in Africa were obtained from the World Bank database on "Doing Business: cost of electricity" [25]. Data on non-revenue water (l/capita/day), or distribution losses, were quantified from the most recent available data on [36], and the median estimates of non-revenue water loss were computed for those countries where several utilities operate within their jurisdiction. Non-revenue water loss was identified and computed as an operational driver within the operational boundaries of utilities that directly affect energy input per unit volume of municipal water produced and supplied as energy input associated with water losses.

2.2. Developing the Conceptual Flow Model and Generating Impact Scores

A conceptual flow model was developed from the output of the literature review on the demand-side and supply-side drivers to show the impact of the selected drivers on each other. The indicators identified from the review process were related to each other in a conceptual flow model using subSTance flow ANalysis (STAN), a material flow analysis software developed by the Technical University of Vienna [39]. The key indicators quantified were combined into compound indicators, and a Microsoft Excel spreadsheet was used to harmonize the data and calculate/quantify the compound indicators.

2.2.1. Generating Impact Scores to Compare Countries within a Reference Group

Compound indicators express a range of impact scores (0–1, i.e., low to high, respectively) at the country level to generate impact clusters that group of countries with the same impact scores from similar indicators and drivers. The fifty-three (53) countries in Africa were grouped by the ten compound variables. A hierarchical cluster analysis was performed in Statistical Package for the Social Sciences (SPSS Version 22.0) using median linkage and Ward's method, with Squared Eucledian Distance [40]. The common denominator of both approaches was an optimal partition at eight (8) clusters based on the error coefficients at the subsequent clustering stage. A k-means cluster analysis (k = 8) was performed to define narrower groups. The map was generated with CartoDB.

To combine and compare data with different units and ranges, the values were standardized using z-score normalization.

$$z_i = \frac{x_i - min(x)}{max\,(x) - min(x)} \qquad (1)$$

where *xi* is the country-level values of the two original vectors (*x*), respectively.

In this way, the variables maintain different means and standard deviations, but the ranges are the same, which maintains reflecting single high or low values in proportion within the 0–1 scale of the impact score. The weighted indicator, or compound variable (*Cvar*), is the sum of normalized sub-indicators:

$$Cvar(V) = \sum_{i=1}^{n} z_i(v_i) \qquad (2)$$

where $V = (V1, V2 \ldots Vn)$ is the vector of observed values for the defined variables measuring the impact of the drivers, and zi stands for the normalized components with values $(V1, V2 \ldots Vn)$ for all countries in Africa.
Finally, the weighted indicator was normalized for comparison with other weighted indicators, yielding a 0–1 value.

2.2.2. Compound Indicators Affecting Freshwater Availability by Impact on Water Quantity

The impact of an increase in net agricultural production, i.e., domestic production, using annual growth rate of agricultural value-added (%), is expressed by *AGR*. Using value-added growth to capture the effect of rising demand for agricultural and industrial goods as a driver of freshwater withdrawal captures only domestic production, not imports. This is weighted by the industry's proportion of total water abstraction, i.e., annual freshwater withdrawal by agriculture as a fraction of total withdrawal (%). The indicator is corrected for overall resource use and availability, using the scalar fraction of total annual freshwater abstraction (m^3/year) over total renewable freshwater (m^3/year). If the fraction of annual renewable water withdrawn from overall available freshwater in a country is very low, there is room to expand total abstraction without municipal water utilities having to move to more energy-intensive freshwater sources.
The three vectors are standardized and added, yielding:

$$AGR\ (V) = \sum(i = 1)\ \hat{}\mathrm{n\ zi\ ([v]i)} \tag{3}$$

Additionally, the impact of net industrial production growth corrected for its contribution to total freshwater abstraction and water availability is expressed using *IND*. Annual freshwater withdrawal by agriculture as a fraction of total withdrawal (%), annual growth rate of industrial value addition (%) and total abstraction over total recharge are combined as in *AGR*. Furthermore, the impact from relative dependency on groundwater adjusted for different groundwater tables is expressed by *GWD*. The scalar fraction of total renewable surface water (m^3/year) over total renewable groundwater (m^3/year) is combined with the normalized values of annual renewable groundwater over land area (m^3/km^2). Country-level data on average groundwater tables are available only for few African countries so renewable groundwater over land area is used as a proxy. The regional distribution of the results is largely consistent with the estimates for the African mainland modeled by the Natural Environment Research Council (NERC), [41].

2.2.3. Compound Indicators Affecting Freshwater Availability by Impact on Water Quality

The impact of population density adjusted by population growth rates is abbreviated as PDEN, while the impact of wastewater collection and treatment rates against relative source dependency is expressed by WWM. Wastewater management practices influence water quality through the coverage of wastewater collection (population with access to improved sanitation facilities (%)—ACCSAN) and treatment levels (fraction of wastewater that is treated (%)—WWTREAT). Both access to sanitation and treatment levels are reversed using 1-*zi* (*xi*). Their mentioned relationship is captured by the coefficient a(WQ), defined as the parabolic relationship between the difference of the normalized values of the two variables (range 0–1). Therefore, if there is a large disparity between wastewater collection and treatment rates, water quality is threatened most strongly. This is true for both high positive and negative values. A high positive amplitude indicates that access to sanitation is widely in place, while treatment levels are low. A high negative difference indicates that treatment levels are high, but wastewater collection covers only a small fraction of human waste, which means that water quality is again threatened more strongly than if the difference is low.

$$aWQ_i = (-1)\ [\,z_i(ACCSAN_i) - \ z_i(WWTREAT_i)]^2 + 1 \tag{4}$$

As *a(WQ)* does not reflect whether the absolute values of collection and treatment levels are high or low, it is multiplied with the sum of the two components as follows:

$$\gamma_i = a_{(WQ)i} \sum_{i=1}^{n} z_i(WWTREAT_i), z_i(ACCSAN_i) \tag{5}$$

If coefficient *a(WQ)*, *ACCSAN*, and *WWTREAT* are high, but surface water to groundwater dependency is low, this yields the least impact on water quality and is therefore represented by the lowest value of WWM. Therefore, the product γi is reversed to capture the low values, which imply high impact. High relative dependency on surface water (as surface water over groundwater, *SWGWDEP*) leads to a higher impact on treatment requirements for potable water if surface water is more severely polluted by municipal wastewater.

The compound variable for risk from requirements for purification is defined as follows:

$$WWM(V) = \sum_{i=1}^{n}(1 - zi\ (\gamma\mathrm{i})), zi\ ([SWGWDEP]\_i) \tag{6}$$

where $zi(\gamma i)$ is the normalized value of each component, respectively, and $V = (V1, V2 \ldots Vn)$ is the vector of observed values for each of the variables.

The impact of agricultural sector growth on water quality is represented by *WQA*. The compound variable is the sum of the fraction of freshwater withdrawal by agriculture, agricultural value-added (VA) growth, renewable groundwater per land area, and reversed relative source dependency. Using annual renewable groundwater over land area (m^3/km^2) excludes fossil aquifers. The normalized score of relative source dependency is reversed to reflect that high relative dependency on surface water means a lower impact from agriculture, as agriculture primarily pollutes groundwater.

The impact of industrial sector growth on water quality is represented by *WQI*. If the relative surface water dependency ratio is high, the industrial sector has a stronger influence on potable water treatment requirements.

2.2.4. Compound Indicators Affecting Municipal Water Demand

The increase in urban inhabitants is captured by UPG, which comprises the normalized scores of annual urban population growth rates (%) and annual population growth rates (%). Both create the need to expand water services. On the other hand, increasing per capita water demand is expressed by *CWD*. This combines (1) rising living standards, with annual average per capita income growth, α, (%) as a proxy; (2) expected expansion of access to improved water sources, or scope for further expansion, parameterized with the reversed score of population with access to improved water sources, β, (%) as a proxy; and (3) the difference (γi) between the average municipal water withdrawal per urban inhabitant in developed countries, as the OECD mean, and the average annual municipal water withdrawal per urban inhabitant (m^3/urban inhabitant) for each country *i*. A large distance between average OECD-level consumption and the respective volume in country i suggests that per capita water demand will steeply rise from this low level if enabled by economic development and increased access to public water services.

The compound variable is calculated as follows:

$$CWD\ (V) = \sum(i = 1)\ \text{^n zi } (\alpha\_i), (1 - z\_i\ (\beta\_i)), z\_i\ (\gamma\_i) \qquad (7)$$

Finally, *CRW* reflects the contribution of water losses, using non-revenue water (NRW) as a fraction of total municipal water produced that does not reach the consumer (%) and daily volume of municipal water supply that is lost per water supply connection (m^3/connection/day). Non-revenue water loss directly affects energy input for municipal water supply. It can be used to quantify potential savings in costs of electricity for municipal water supply, including other related operational costs. However, this compound indicator was not included in the cluster analyses of compound indicators due to the lack of sufficient data.

2.3. Impact Analysis of Parameterized Indicators for Water Security Clusters

Principal component analysis (PCA) was applied to fourteen (14) of the indicators that were parameterized to examine and visualize the relative impact of identified drivers on energy intensity for municipal water supply using Sigma Plot version 14.0. The indicators selected included the daily per capita water production and daily per capita water consumption, water coverage, water losses within water utilities distribution networks, the proportions of water withdrawal for agriculture and industrial use, proportions of water withdrawal for municipal water supply, annual gross domestic product per capita, median depth of boreholes, and the electricity tariff levied on water utilities by the electricity providers. PCA was chosen as a multi-variate statistical tool to identify the indicators with the highest component loadings and hence the highest influence on energy input. PCA reduces the dimensionality of the data by building up on correlation analysis to identify the indicators, which account for the largest proportion of variance in the dataset that are not captured by the correlation analysis [42,43]. As outlined in [42], only those principal components with the highest loadings were assigned attributes to show the impact on energy input. The analysis was performed for twenty (20) countries in sub-Saharan Africa, which were selected based on the best possible complete data available. Among the twenty countries selected, there was a wide range in the total renewable per capita annual freshwater available. Therefore, the countries were grouped into two categories of water-secure and water-stressed countries according to the Falkenmark Water Stress Indicator [44].

3. Results

This section provides water supply and demand drivers that were identified from the literature search and the references where these drivers can be accessed. A conceptual framework of the influence of the identified drivers showing either a positive or negative influence is also provided. In addition, a cluster analysis showing how the countries grouped together based on the indicators of water supply and demand drivers is presented. Lastly, the relative impact of selected indicators on energy use for municipal water supply in selected water-secure and water-stressed countries in Africa is illustrated through principal component analysis.

3.1. Supply-Side and Demand-Side Drivers of Municipal Water Supply

Table 1 presents the main demand-side and supply-side drivers of municipal water supply identified from the literature review, with notes on the indicators and the units used to parameterize the drivers. In addition, Table 1 shows the key data portals and additional sources from which the data for each of the quantified indicators was obtained. The drivers identified were categorized into four overarching categories: (i) drivers affecting freshwater availability (water quantity), (ii) drivers affecting freshwater availability (water quality), (iii) socio-economic factors affecting freshwater water availability (water quantity), and (iv) operational factors directly impacting energy input for municipal water supply as described in the methods section. Data portals for quantified indicators are provided as Supplementary Materials [S1].

Table 1. Supply-side and demand-side drivers of municipal water supply with indicators (ticked are those that were quantified in the present study).

Drivers	Indicators Identified	Units	Quantified	Data Sources
Drivers affecting freshwater availability (water quantity and quality)				
Freshwater availability	Total annual renewable freshwater per capita	m^3/capita/yr	√	[24]
Climate forces	Precipitation and potential evapotranspiration	mm/yr		[34,35]
Biophysical exchange	Surface runoff and infiltration	mm/Km^2		[25]
Exploitation of available water resources	Fraction of total annual renewable freshwater abstracted	%		[24]
Relative water source dependency	Ratio of total renewable surface water to total renewable groundwater	10^9 m^3/yr	√	[24]
Storage capacity	Capacity of dams/reservoirs	km^3		[24]
Borehole depth	Median depth of boreholes for groundwater abstraction	mbg	√	[37,38]
Urban sprawl	Built-up area expressed as settled area over a given land area	km^2		[45]
Agricultural water demand	Fraction of total annual withdrawal due to withdrawal by agriculture	%	√	[24]
Livestock densities	Number of livestock per unit area	livestock/km^2		
Industry (manufacturing) water demand	Fraction of total annual freshwater withdrawal by industry (manufacturing)	%	√	[24]
Increase in agricultural activity	Annual growth rate of agricultural value-added	%		[26]
Increase in industrial activity	Annual growth rate of industrial (manufacturing) value-added	%		[26]
Water use efficiency of productive sectors	Water use per unit produced; volume of water reuse/recycled	m^3		
Vulnerability to upstream water abstraction	Total surface water and groundwater entering the country	10^9 m^3/yr		[26]
Institutional factors/water governance	Government effectiveness, control of corruption, political stability	Governance ratings (%), corruption perception index		[10,46]
Environmental drivers of water quality	Natural increase/decrease in temperature, oxygen, salinity, pH, concentrations of heavy metals, arsenic, fluoride, etc.			
Wastewater treatment	Fraction of wastewater safely treated through treatment processes	%		[32]
Pollution by agriculture	Fraction of freshwater abstraction by agriculture and VA growth	%		[25]

Pollution by industry (manufacturing)	Fraction of freshwater abstraction by industry and VA growth	%		[25]
Increased pollutant discharge	Population density, which reflects regional distribution of pollution across Africa (based on [30])	population/km^2	√	[25]
Cross-border upstream water pollution	Water quality indicators for freshwater sources beyond the jurisdiction especially Phosphorus and Nitrogen	mg/l		[27–30]
Demographic factors affecting freshwater water availability (water quantity)				
Municipal water withdrawal	Total annual demand for municipal water	10^9 m^3/yr	√	[25]
Population growth	Annual population growth rate	%	√	[25]
Per capita municipal water production and per capita water consumption	Municipal water supplied per capita	l/p/d	√	[36]
Lifestyle change	Annual per capita GDP growth rate	%		[25]
Access to improved water sources	Population with access to improved water sources	%	√	[36]
Water demand management	Household demographic and economic variables	Number of persons, age, daily per capita consumption, and income		[3,15–17]
Per capita income	GDP per capita	USD per capita	√	[25]
Operational factors directly impacting energy input for municipal water supply				
Electricity price (tariffs)	Electricity tariffs (price per kWh) levied on municipal water utilities	USD/kWh	√	[25]
Energy intensity for water supply	Energy needed to deliver a unit of groundwater to the surface and to treat and deliver water from source to end user	kWh/m^3		[1]

Layout of the water supply system	Pumping distance	m		[1,3]
State of water infrastructure	Pipe breaks, pump efficiency	breaks/km/yr %		[25,36]
Water loss in the water distribution system	Proportion of water produced that does not reach consumers	m^3/km/day and % Non-Revenue Water (NRW)	√	[36]
Water supply technology	Efficiency of devices and processes, especially pumps and motors used for water production, treatment, and distribution	% Efficiency		[2,20,21,36]

3.2. Interactions between Supply-Side and Demand-Side Drivers

Figure 3 presents the conceptual flow developed with STAN software (see methods section), which illustrates the interactions between the supply-side and demand-side drivers. The arrows indicate whether the drivers amplify (+) and/or dampen (−) the influence of other drivers and indicate how the drivers contribute to the four overarching categories of drivers (Section 3.1 and Table 1), which interact to influence energy input for municipal water supply. For interactions between drivers where both amplification and dampening occur, the designation (+, −) is applied to the conceptual flow model. The colors represent different set of drivers (forcing factors) including environmental, social/demographic, and water utility operational drivers. The conceptual flow model comprises forcing factors belonging to the natural environment (green); impacts from the water productive use sectors, e.g., agriculture and the manufacturing industry (purple); demographic changes (yellow); and operational conditions/processes related to municipal water infrastructure within the operational boundaries of water utilities (red). As a natural forcing factor, climate (green) produces precipitation (which in turn increases freshwater availability) and drives potential evapotranspiration (which reduces available water from exposed surfaces and reservoirs, and through vegetation losses (evapotranspiration)). Precipitation has an amplifying effect on total runoff, which is captured as surface runoff (1a). On the other hand, evapotranspiration reduces total runoff (flow 1b) and water held in reservoirs (1c). Land-use change (blue) could amplify or dampen biophysical exchange drivers (6), which may be altered by climate forces, either by increasing or decreasing total runoff (1d) and/or by increasing or decreasing freshwater demand for agriculture (1e). Biophysical drivers such as land cover, soil type, and the nature of the topography could increase or reduce total runoff (2a), whereas topography on its own may directly influence the energy needs of water utilities for pumping and pressure maintenance (2b). Total surface runoff may increase available freshwater resources (3) for abstraction with increased storage capacity (4), which can be natural (green) or manmade (purple), although evaporation/evapotranspiration in reservoirs could decrease water availability (1c).

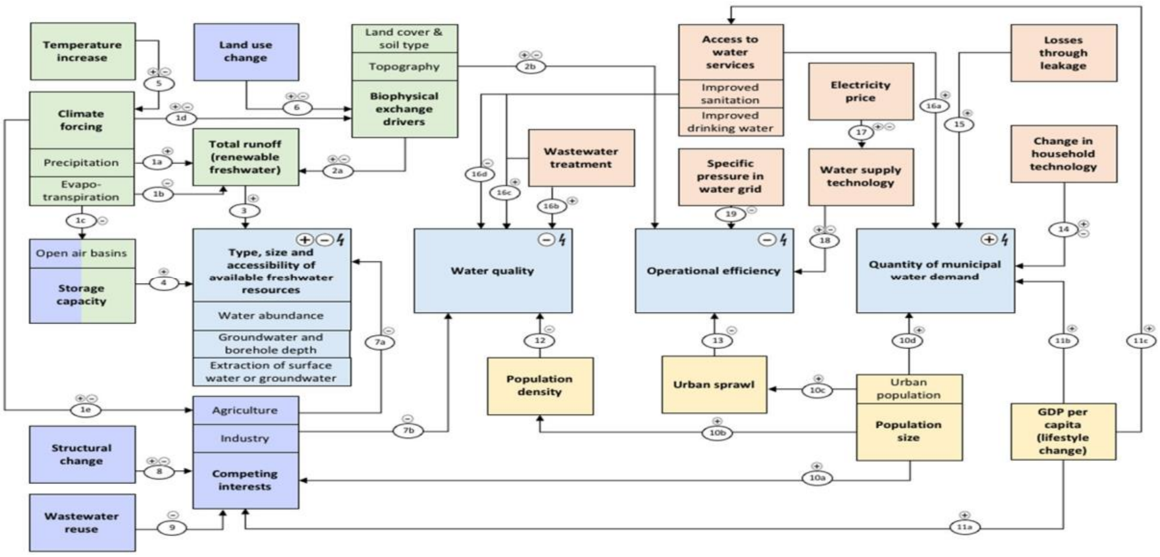

Figure 3. Interactions between supply- and demand-side drivers of municipal water supply (designed with STAN).

The productive sectors, e.g., agriculture and the manufacturing industry (purple), compete directly for available freshwater resources with demand for municipal water supply. These competing uses reduce the quantity of freshwater available for municipal water supply (7a). In addition, they impact the water quality of receiving water bodies (7b), which in turn could reduce the available freshwater for municipal water supply and/or increase the cost of drinking water treatment, with direct consequences for energy input. Structural changes can amplify or dampen the water use of the productive sectors (8), and wastewater reuse/recycling may reduce the water demand (9) of the productive use sectors, as well as their impact on water quality. The impact of productive use sectors is typically amplified by population growth (10a) and growth in per capita income (11a). High population densities, amplified by population growth (10b), especially in urban settings with inadequate solid waste and wastewater collection and treatment, could reduce water quality (12). Growth of the urban population increases municipal water demand (10d), whereas urbanization may cause urban sprawl (10c), which in turn directly increases energy input for water production and distribution (13). Additional amplifying drivers of municipal water demand include per capita income growth (11b), water losses within the distribution network of water utilities (15), and access to water services (16a). Demand for water services increases with improvements in living standards, as per capita income grows (11c). Change in household technology could either increase or decrease water demand (14). Wastewater treatment improves water quality (16b). Without adequate wastewater treatment facilities, increased access to improved sanitation could reduce ambient water quality (16d), but improved sanitation access (when combined with adequate wastewater collection, treatment, and disposal or reuse) may reduce the impact of wastewater effluents on receiving water systems (16c). Through reduced electricity tariffs, water utilities can be incentivized to adopt energy-efficient water supply technologies (17), which in turn influences the overall operational efficiency (18) and reduce energy use and the associated electricity costs for water production. Higher specific pressure that must be met within the water distribution network may reduce the operational energy efficiency and increase energy input (19) for municipal water supply.

3.3. Relative Impact of Demand-Side and Supply-Side Drivers on Energy Input

Table 2 presents a summary of the parameterized indicators of drivers for water-secure and water-stressed countries in sub-Saharan Africa, used as a basis for principal component analysis.

Agriculture was the main competing user of available freshwater resources in several countries, except for Equatorial Guinea and Central African Republic (CAR), with 15% and 17% freshwater withdrawal for agriculture, respectively. In Mali, freshwater withdrawal for agriculture accounted for up to 98% of total annual withdrawals (the highest in for the countries listed). Municipal water withdrawal as a proportion of total annual freshwater withdrawal ranged from 2% in Mali to 83% in CAR. Municipal water withdrawal was relatively low in Ethiopia, Senegal, and Tanzania with less than 10% of the total annual freshwater withdrawal for each country compared to Kenya (35%), Nigeria (40%), and Uganda (51%). In contrast, municipal water withdrawal was relatively high in Equatorial Guinea (80%), where the population with access to drinking water services (water coverage) was also relatively high (72%), although the daily per capita water production (42 l/p/d) and consumption (29 l/p/d) were low.

The GDP per capita (USD/cap) for Equatorial Guinea was relatively high (18,558) compared to South Africa (12,482), Nigeria (5135), Kenya (4329), or CAR (945). In addition, Equatorial Guinea had the second highest total annual renewable freshwater per capita among the 20 countries in sub-Saharan Africa for which data were available (Table 2). In fact, Equatorial Guinea is classified as water-secure, although the daily per capita water production (42 l/p/d) and consumption (29 l/p/d) were relatively low. Similarly, CAR has the highest total annual renewable freshwater per capita and is classified as water secure. Nevertheless, the country had the lowest water coverage (46%) among the countries listed and relatively low per capita daily water production (79 l/p/d) and consumption (39 l/p/d). In contrast, South Africa, with close to 100% coverage, had the highest per capita water production (235 l/p/d) and consumption (190 l/p/d) in the region, although the total annual renewable freshwater per capita is among the lowest in the region (786 m^3/cap/yr). In addition, agriculture and industry together accounted for more than 70% of the total annual freshwater withdrawals in South Africa compared to municipal water withdrawal, which was 27%.

The price of electricity impacts the fraction of the total operating costs of water utilities that can be attributed to energy input for operational processes such as abstraction and distribution. The price of electricity was relatively high for Equatorial Guinea (0.217 USD/kWh) compared to South Africa (0.072 USD/kWh) or Zambia (0.047 USD/kWh) and Ethiopia (0.020 USD/kWh), with the lowest electricity tariffs in the region. Additionally, the cost of electricity as a proportion of total operating costs varies with water utilities due to the unique operating conditions and the varying energy requirements for water supply depending on the type of raw water supply. Based on the data available, electricity costs as a proportion of operating costs ranged between 9% in both Malawi and Mozambique and 40% in Senegal.

Both Equatorial Guinea and CAR recorded higher average water losses, i.e., 33 and 44 m^3/km/day, respectively, compared to South Africa with 30 m^3/km/day. Water loss has been identified as a major driver for energy use and cost multiplier in the operations of water utilities. The highest average water loss was reported for Tanzania (59 m^3/km/day) and Kenya (50 m^3/km/day), both with relatively lower water coverage levels, i.e., 63% and 56%, respectively. Water loss was relatively low for Benin (5.3 m^3/km/day), Niger (6.6 m^3/km/day), and Rwanda (7.21 m^3/km/day), and the three countries had higher water service coverage (78%, 86%, and 78%, respectively) compared to Tanzania and Kenya.

Figure 4 presents the mono-plot of the selected water-secure countries in sub-Saharan Africa presented in Table 2. It was observed that Principal Component 1 (PC1) accounted for the highest variation (41.7%) in the data set compared to PC2 (27.95%) and PC3 (12.4%). Collectively, the three principal components accounted for 82% of the total variations in the data. PC1 was attributed to water demand from competing uses from the productive sectors (agriculture and industry), whereas PC3 and PC2 were ascribed to municipal water supply and water loss within the distribution system, respectively. Water loss correlated negatively with population density, a major influence on the complexity of the water supply network and energy input for municipal water supply. Daily per capita water production and per capita water consumption and GDP per capita were clustered closely with similar trajectories, implying that an increase in one indicator directly resulted in an increase in the other. GDP per capita correlated positively with industrial water demand, suggesting that the higher the GDP per capita, the higher the industrial water demand as the demand for manufactured goods increase. Agricultural water demand and municipal water demand had higher vector magnitudes in opposite directions, implying that agricultural water demand is a major competing user with municipal water demand, which correlated positively with the proportion of the population with access to water services (water coverage), which correlated negatively with water loss.

Table 2. Cross-section of parameterized indicators for water-secure and water-stressed countries based on the Falkenmark Water Stress Indicator for 20 countries in sub-Saharan Africa.

Water Security Category	Total Annual Renewable Freshwater (Tarf) Per Capita *	Municipal Withdrawal (Proportion of Tarf) *	Agricultural Withdrawal (Proportion of Tarf) *	Industrial Withdrawal (Proportion of Tarf) *	GDP Per Capita **	Water Coverage ***	Per Capita Water Production ***	Per Capita Water Consumption ***	Average Water Loss in Distribution Systems ***	Electricity Price (Tariff) **	Electricty Cost as a Proportion of Total Operating Cost	Median Depth of Boreholes ****
	m^3/cap/yr	%	%	%	USD/cap	%	l/p/d	l/p/d	m^3/km/day	USD/kWh	%	Mbg
Water-secure												
CAR	30,679	83	17	1	945	46	79	39	44	0.108	17	15
Eq. Guinea	20,602	80	15	5	18,558	72	42	29	33	0.217	$^{\lambda}$	120
Ivory Coast	3144	28	52	21	5212	69	49	37	12	0.124	11	58
Mali	3241	2	98	0	2321	68	116	75	18	0.148	17	85
Mozambique	3501	25	73	2	1218	64	131	82	25	0.087	9	100
Madagascar	13,179	3	96	1	1647	90	282	187	30	0.146	$^{\lambda}$	27
Zambia	4759	18	73	8	3470	85	152	61	35	0.047	14	70
Water-stressed												
Benin	922	31	45	24	3287	78	51	39	5.3	0.150	21	15
Ethiopia	1147	6	93	1	2221	54	127	65	38.6	0.020	10	165
Ghana	1040	20	73	6	5412	80	95	46	42.0	0.138	26	35
Kenya	412	35	60	5	4329	56	70	35	50.0	0.102	13	276
Malawi	913	11	85	4	1060	77	90	65	18.0	0.167	9	53
Niger	162	30	67	3	1225	86	75	63	6.6	0.120	$^{\alpha}$	100
Nigeria	1158	40	44	16	5135	70	98	46	36.0	0.105	18	220
Rwanda	793	22	68	10	2626	78	53	31	7.2	0.098	$^{\lambda}$	35
Senegal	1673	6	92	2	3395	98	73	59	9.4	0.250	40	353
South Africa	786	27	63	11	12,482	99	235	190	30	0.072	$^{\alpha}$	130
Tanzania	1537	9	90	1	2660	63	119	71	59.0	0.102	16	110
Uganda	947	51	41	8	2187	75	72	48	12.0	0.157	22	45
Zimbabwe	861	12	82	6	2836	67	101	62	9.0	0.155	25	90

Data sources/portals: * [47]; ** [26]; *** [37] (except for Madagascar (2005 data); **** [38,39]. CAR: Central African Republic; Eq. Guinea: Equatorial Guinea. $^{\lambda}$ Data were not credible and α Data were not available.

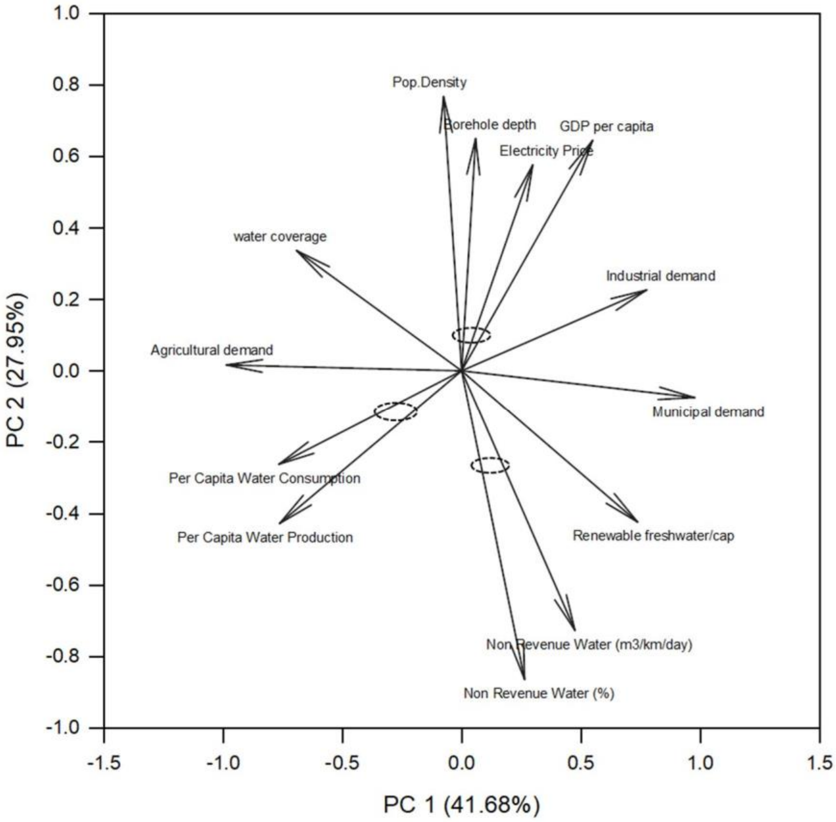

Figure 4. Mono-plot of the pooled data for the selected indicators for water-secure countries.

Additionally, Figure 5 shows the mono-plot of the pooled data for the selected water stressed countries in sub-Saharan Africa (as shown in Table 2). Most of the variation in the data was explained by the first three principal components, which contributed 72% of the total variance, with PC1 accounting for 27.5%, while PC2 and PC3 were responsible for 22.9% and 21.1%, respectively. PC1 was attributed to demand-side drivers, i.e., water demand from competing uses. PC2 was assigned to the operational processes, including water loss in the distribution system and electricity costs for water production. It was difficult to assign PC3 to any compound indicator. The indicators were grouped into four clusters with non-revenue water losses, agricultural water demand, municipal water demand, and water coverage displaying the longest vector lengths. Agricultural water demand clustered with total renewable freshwater per capita, which correlated negatively with municipal water demand. Water loss, which is represented by the non-revenue water, correlated positively with population density and negatively with water coverage and per capita water consumption. Water coverage in terms of per capita production and consumption correlated positively with GDP per capita, suggesting that the ability to pay for water services reflects the proportion of the population with access to water services (water coverage), which correlated negatively with water loss, as illustrated for water-secure countries.

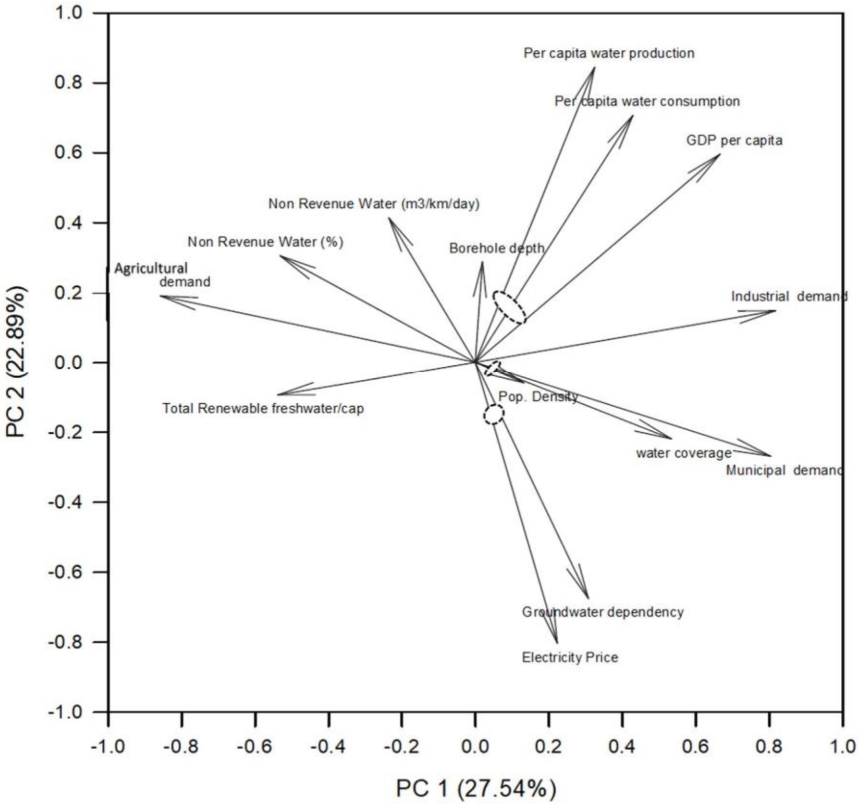

Figure 5. Mono-plot of the pooled data for selected indicators among water-stressed countries.

3.4. Cluster Centers with Identical Compound Indicators and Impacts Scores for African

The compound indicators provided in Section 2.2.1 were used for the cluster analysis to group the countries with similar impact scores where the k-means cluster analysis produced five (5) cluster centers based on the dendrogram using Ward Linkage with 0.401 being the minimum Squared Eucledian Distance between clusters (Figure 6). The dendrogram was used as a first visualization of distances and possible clusters, not to allocate cases (countries) to clusters. The dendrogram shows which cases are more similar to each other. The differences are shown as the length of the clades (horizontal lines before connection to other clusters/cases). Cluster centers 1, 2, and 3 had eight (8) countries each and Cluster 4 had four (4) countries, whereas Cluster 5, which was the largest cluster center, had twenty-one (21) countries. Three countries—Gambia, Mauritius, and Libya—did not cluster, and they were classified as outliers. Figure 6 shows the map of Africa, delineating countries according to the cluster centers from the data of the key compound indicators. Mauritius deviated from the other cluster centers with a significantly lower impact arising from the manufacturing industry, extremely high impact of population density, and even greater impact of agriculture to water quality. Low impact on infrastructure management is derived from extremely low values of change in municipal water demand. The Gambia had significantly lower impact from agriculture and groundwater pumping requirements on energy intensity of water withdrawal and much lower impact of agriculture on groundwater quality than elsewhere, while experiencing much higher potential increases in surface water pollution by urban wastewater and industrial effluents. The

Gambia had a remarkably high relative impact by growing numbers of the population demanding municipal water and a relatively lower increase in per capita demand compared to the average levels of impact in Clusters 1–5. Libya presented an extreme case with the highest impact score on energy input for raw water abstraction. A table of cluster membership is also provided in the Supplementary Section [S2].

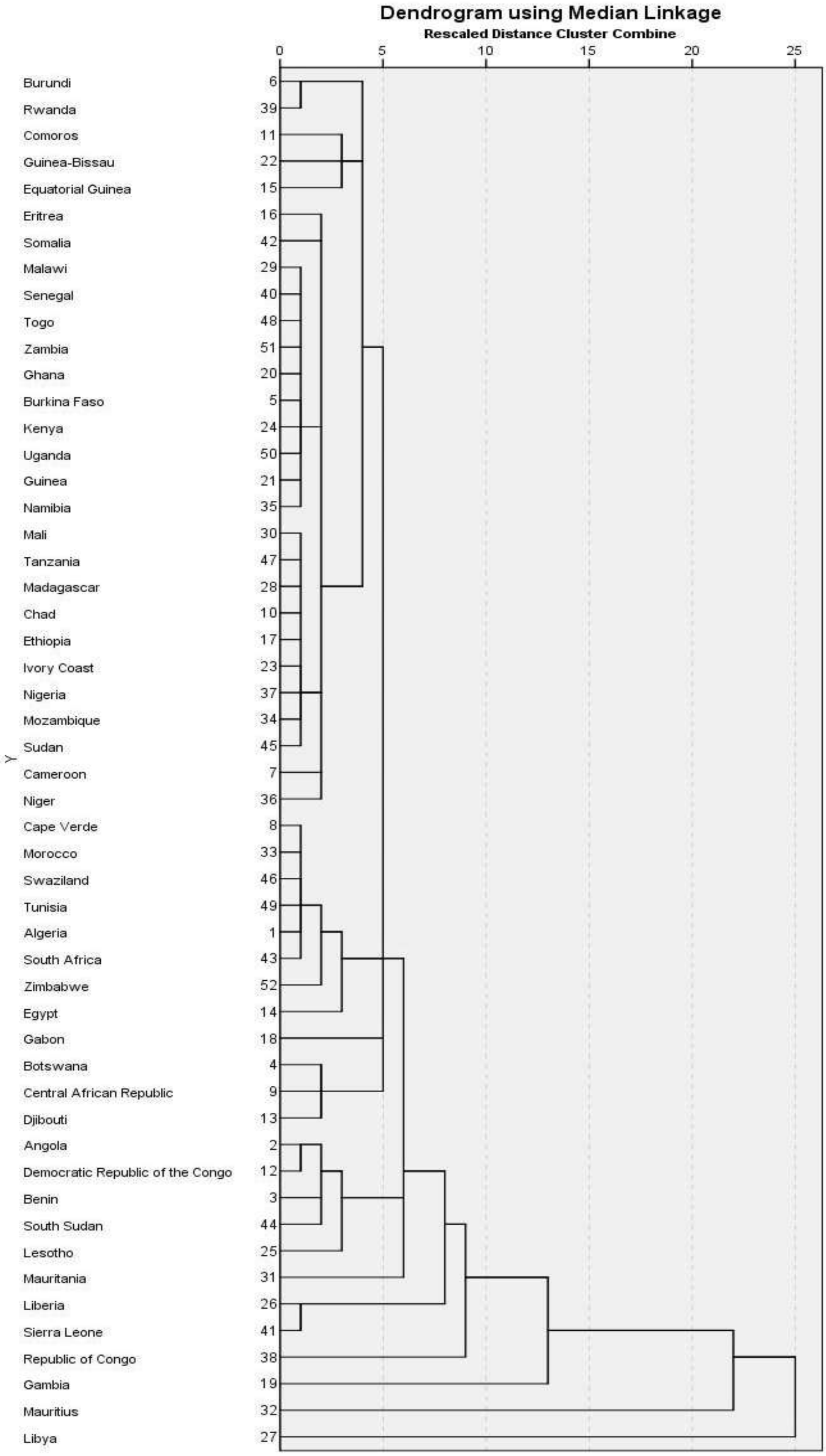

Figure 6. Dendrogram of key compound indicators showing Squared Euclidian Distance between clusters.

Figure 7 provides a further visualization of the country cluster centers. Countries in Cluster 1, which included Angola, Benin, Botswana, Ivory Coast, Lesotho, Democratic Republic of Congo, Central African Republic, and South Sudan, had a relatively low impact from agriculture compared to industry in those countries with respect to both water availability (quantity) and water quality challenges. Interestingly, South Sudan and Sudan are not in the same cluster, even though the value added (VA) growth rates of Sudan were used for South Sudan. This means hydro-climatic variations are large enough to separate the two countries, which suggests that analyzing the two countries as a homogeneous entity, as has been performed in a wide range of research, may significantly distort results. Cluster 2 countries (Djibouti, Eritrea, Mozambique, Namibia, Somalia, and Sudan) were defined by a high impact of municipal wastewater management compared to other drivers of water quality. Countries in Cluster 2 have the highest expected increase in per capita demand for municipal water supply following a combination of low demand and limited water services combined with relatively high increase in per capita income. Countries in Cluster 3 are in the arid and semi-arid zones of northern and southern Africa. Cluster 3 countries experience the highest impact of freshwater withdrawal from agriculture and lowest impact from industrial withdrawal. The impact on energy costs associated with pumping groundwater for countries in this cluster was higher compared to countries in other clusters, except for Libya, with the highest impact score on energy input for groundwater abstraction. Cluster 3 countries had the least pressure from population density and population growth. This cluster had South Africa, Swaziland (Eswatini), and Zimbabwe in the south, and Egypt, Tunisia, Algeria, and Morocco in the north, as well as Cape Verde, an island state in the Atlantic Ocean off the west coast of Africa. These countries had the least impact from wastewater due to improved wastewater management practices compared to countries in other clusters. Countries in Cluster 4—Congo, Gabon, Liberia, and Sierra Leone—are characterized by abundant freshwater resources with relatively low withdrawals for agriculture and industry and low-to-moderate withdrawal for municipal water supply. On the other hand, water withdrawal by agriculture was dominant for the countries grouped in Cluster 5, with a significant impact on water quality. Cluster 5 countries, among them Burkina Faso, Burundi, Cameroon, Chad, Ethiopia, Ghana, Guinea, Malawi, Madagascar, Nigeria, Rwanda, Senegal, Togo, and Uganda, were characterized by water withdrawals from relatively shallow groundwater reservoirs where seepage of excess irrigation water with high nutrient content could contaminate shallow groundwater reservoirs more easily compared to countries with deep groundwater aquifers. A combination of high impact from urban population growth and increasing per capita water demand for Cluster 5 countries suggests increasing energy input for municipal water supply.

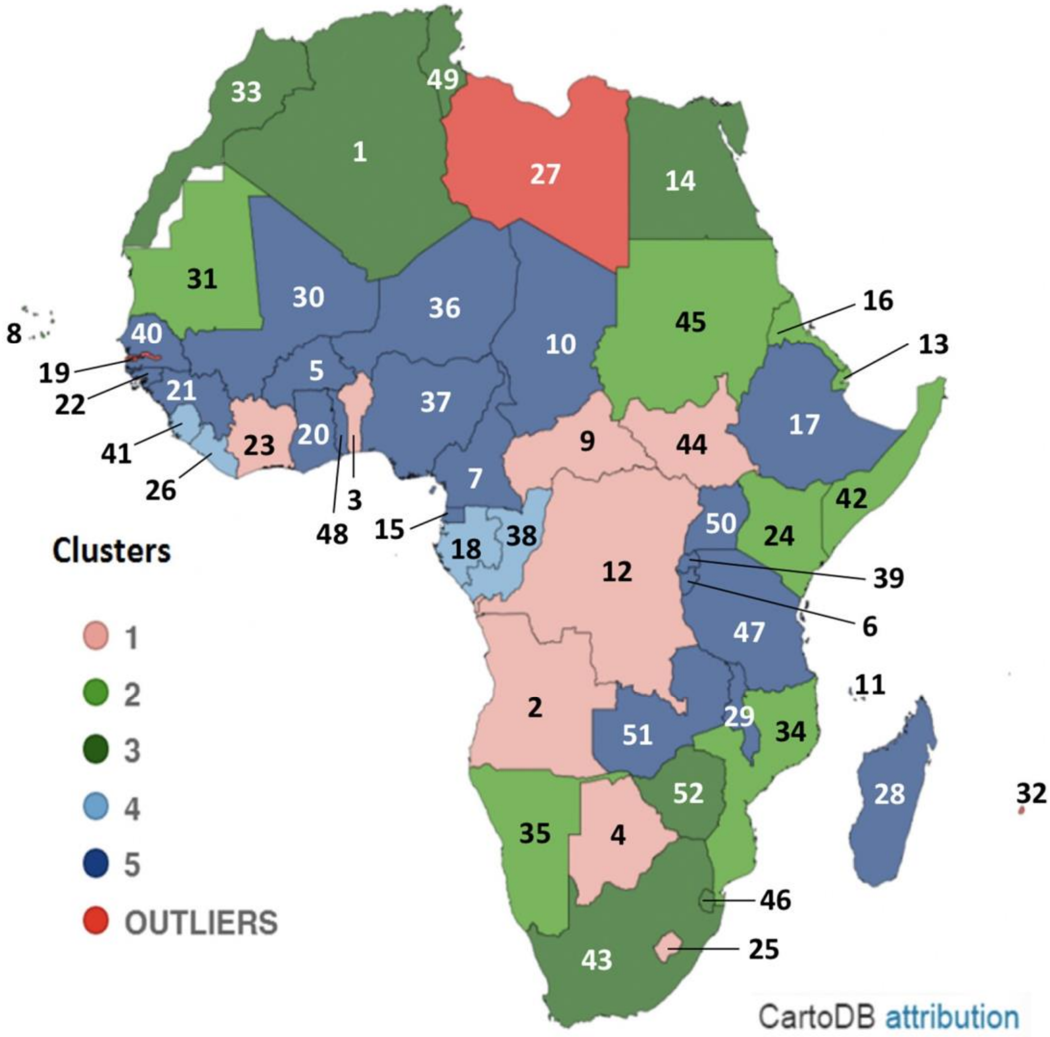

Figure 7. Map of Africa delineating African countries according to the cluster centers in Figure 6.

4. Discussion

Examining the relative impact of key compound indicators of water supply and demand drivers is important for policy and operational considerations to identify which policy and operational interventions are required for effective water–energy consistent policies and planning to reduce energy input and associated operational costs. The cluster analysis sheds light on regions that could benefit from cross-learning and exchange both within and beyond the water sector. For example, the cluster with Egypt, Tunisia, Algeria, and Morocco in the north of Africa and South Africa and Zimbabwe in southern of Africa shows that physical water scarcity plays an important role in this cluster, although many of these countries have relatively more advanced economies with previous investments in relatively more resilient water infrastructure for different water-use categories compared to other countries. For example, Equatorial Guinea, DRC, and CAR have abundant freshwater resources but relatively low investments in water infrastructure. However, the complexity of the interactions among drivers requires thorough analysis of the key indicators even for a single country.

On the supply-side, hydroclimatic conditions are driven largely by differences in climatic factors, which determine variables such as precipitation and evapotranspiration, depending on the specific geographic position [47]. Ambient temperature, wind speed, specific humidity, atmospheric pressure, and net radiation may influence freshwater recharge rates via precipitation and potential evapotranspiration [48]. Biophysical factors such as canopy, soil type, and topography are more important to determine the actual evapotranspiration rate and effective precipitation, i.e., throughfall, thus determining how much water gained from precipitation is transpired by vegetation, evaporates from the surface, infiltrates to underground aquifers, or runs into surface water bodies. Therefore, they determine the total runoff from land along with the fraction of fast surface water runoff and infiltration or slow subsurface runoff [49]. Prolonged drought conditions on the other hand deplete freshwater reserves beyond their average annual minimum flow (base-flow), which is necessary to sustain ecosystems, and similar alterations occur from direct land use change for human activities [49]. Drought destroys land cover and soil texture, which are critical to local water storage. Water storage reduces inter-annual variability of precipitation and increases the available volume during dry periods [47]. The construction of dams and water towers helps to capture precipitation during heavy rainfall periods, but open-air basins are subject to evaporation losses, as mentioned above. However, such infrastructural investments are expensive and difficult to undertake for many countries in Africa [10,50]. Inter-basin transfers are often extremely energy-intensive so that, in some cases, seawater desalination, which is also energy-intensive, can be a cheaper alternative in water-scarce areas [50,51].

Other clusters tend to group countries largely according to the socio-economic characteristics even if other factors are important. Human-induced drivers provide useful insights into how water supply conditions may impact the operations of water utilities. This is because several demographic factors influence municipal water demand, including population growth, the fraction of the total population that is urban, and the rate of urbanization [34,36]. Urban and metropolitan areas in Africa are rapidly expanding, with many urban areas projected to host over 60% of the population by 2050 [14,52]. Rwanda, Burkina Faso, Burundi, Uganda, Tanzania, Niger, Eritrea, and Mali have the highest rates of urbanization in Africa and in the world [52]. Most of the population in urban and urbanizing areas is currently under-served because expanding metropolitan areas lack adequate water supply infrastructure. Demographic changes impact water availability through direct use of water for domestic needs. The average water intensity of urban households increases as coverage of safe drinking water connections expands. According to [33], in regions where access to water is least developed, the water resources are least exploited, also observed for Central African Republic, which had the highest available freshwater per capita but the lowest water services coverage. Water use tends to increase with proximity to the water source, and in addition, per capita water use rises further as more households gain access to sanitation facilities [53]. Where coverage with water and sanitation connections is very low, there is a high growth potential for water utilities in those areas. However, this depends on national socio-economic conditions, whether infrastructure can be developed or the fraction of the population with access to public water services remains low. Furthermore, the annual municipal water withdrawal per capita can be expected to rise with economic development in the future, especially in cities where per capita municipal water use is currently low. However, as the water withdrawal per capita rises, households eventually become saturated with water-using appliances and habits, which then assimilate/plateaus at peak levels observed in developed countries, leading to a stabilization of per capita municipal water demand [54]. Meanwhile, current trends in Africa are expected to continue as the population grows and more people live in cities and continue to demand more water [4,52]. The increase in water demand will create the need for exploration of alternative water sources in addition to increased water storage, recycling, and reuse [19]. This is already happening in many parts of the continent. Accelerated growth in water demand has led to exploration of alternative water sources including further groundwater exploration, water reuse, and desalination, especially in south Africa and the Maghreb countries in north Africa [55]. Alternative water sources including desalination and increased groundwater exploration are often highly energy intensive. As reported in [56], desalination capacity in South Africa has increased since the last decade, with energy intensities up to 3.70 kWh/m^3. Energy requirements for water supply are highly dependent on the water type, the operational efficiency of energy-using devices and processes, and the elevation between water supply points and the end user [57]. Energy input for surface water supply may range from 0.002 to up to 4.07 kWh/m^3 for a conveyance distance of 745 km [1]. On the other hand, energy input for groundwater is estimated at 0.0027 kWh/m^3 to lift groundwater up 1 m in a frictionless system at peak efficiency, while for desalination, the requirements vary depending on treatment technology, ranging from 0.36 kWh/m^3 for reverse osmosis of brackish water to 106 kwh/m^3 for multiple-effect distillation of seawater [1]. Groundwater must be lifted from below to make it accessible. Depending on the water level, this can range between 0.14–0.69 kWh/m^3 in California [53] or 3.3 kWh/m^3 in a water utility in Arizona [58].

Per capita water consumption patterns vary with average per capita income. At the country level, GDP per capita and annual per capita GDP growth rate can give an indication of lifestyle change and the ability to pay for water services. However, water use often levels out with the rate of improvement in the water-use efficiency of domestic appliances and activities [55,59]. Household technology can either increase or decrease the volume of domestic water usage, depending on the type and efficiency of the water-using appliances. However, the greatest impact of technology on municipal water supply is connected to addressing the challenges of aging water infrastructure and poor maintenance culture in Africa. Infrastructure maintenance influences the volume of water loss across the water supply system and hence increases the volume of drinking water that must be produced and delivered to end-users. Water loss from leaking pipes and taps, also termed non-revenue water, correlated negatively with water coverage. Although the share of municipal water withdrawal in CAR and Equatorial Guinea was above 80%, average water losses were also high, at 33 and 44 m^3/km/day, respectively. Such high water losses compromise the ability to accelerate water coverage and improve per capita water availability. In addition, water loss in the distribution system impacts energy input associated with water supply to compensate for water loss, which varies depending on the source and quality of raw water, the treatment technology applied, the nature of the distribution system, and the operational efficiency of energy consuming devices and processes. Consequently, the price of electricity is a major driver of energy input for water supply, especially for water utilities abstracting groundwater, which have a higher energy intensity for pumping compared to surface water. This was typically the case for water utilities in Senegal where the median depth of boreholes was reported at more than 300 m compared to the average price of electricity at a global level, which averaged at 0.173 USD/kWh in 2019 [25]. Non-revenue water loss due to leakages in the distribution system remains a serious concern for utilities in Africa. Based on data from the latest country data available in [36], water losses averaged at 45% for most countries in sub-Saharan Africa. However, at the utility level, up to 70% water losses were reported in Zimbabwe and 84% in utilities in Nigeria. Such water losses and associated energy input are unsustainable and compromise the ability to accelerate water coverage. However, most water utilities in sub-Saharan Africa concentrate on increased water production rather than addressing persistent water losses [60]. In addition, many African countries have low adaptive capacities and low uptake and adoption of highly efficient water supply technologies, including designs of new water supply systems, which are crucial for pump optimizations and overall energy efficiency improvements. Instead, water utilities in Africa undertake operational measures to overshoot demand by an average of 30% to compensate for leakages within the distribution system [36]. This means an increase in the volume of drinking water that must be produced and delivered to end-users, which in turn necessitates an increase in the energy required to produce and distribute drinking water.

Electricity price and tariffs from electricity suppliers influence the cost of energy for water supply as a proportion of the total operational costs for municipal water supply. Several tariffs exist for different countries, and the rates are also classified as peak or off peak. Energy prices and energy tariffs for peak and off-peak power supply are drivers of energy input for water supply that influence the operational sustainability and quality of service delivery. Due to poor operational performance, lack of energy efficiency measures and limited revenue collection efficiency, most water utilities in sub-Saharan Africa face challenges in paying electricity bills, as reported in [61] for Tanzania. Furthermore, a significant challenge exists in the operation of pumps during off-peak hours due to limited storage facilities in most countries in sub-Saharan Africa. The electricity prices influence the proportion of electricity cost for water supply as part of total operational costs. Based on data available in [36], the proportion of electricity price as part of running costs for water supply has been reported to range between 5–40%. Therefore, inability to meet such costs influences service delivery and ability to expand service to under-served areas.

Long-term planning of water supply in sub-Saharan Africa will require an investment in the adoption of renewable energy to reduce over-reliance on the grid and adoption of integrated strategies including hybrid grid and off-grid decentralized renewable energy systems utilizing solar, wind, wave, geothermal, and waste-to energy [8,62]. Furthermore, there is high potential in energy generation from micro-hydropower systems [63,64]. Such investment calls for policy and planning that can leverage energy-saving technologies at the national and utility levels. Differences in policy, institutional, and management frameworks across the African region will continue to influence operations and decision-making processes.

Anthropogenic activities also impact water quality [29]. Pollutant concentrations and composition entering water supply systems from municipal, industrial, and agricultural origins influence freshwater quality, especially water turbidity, which in turn has implications for the energy requirement for drinking water treatment. As described in [65], the type and concentration of contaminants present in raw water as well as the treatment technology may influence energy intensity at the treatment. The authors note that water utilities with rapid-gravity treatment technologies are more energy-efficient compared to those using pressure filtration. Furthermore, in contrast to surface water, deep well water (up to 300 m depth) is generally considered microbial-free and usually requires only basic purification through chlorination. However, if underground aquifers interact with surface water flow, they are exposed to microbial contamination from agricultural sources and human waste, as well as chemicals from industrial discharges [53]. Scattered settlements also work as diffuse sources when they lack improved human waste disposal systems [30]. Pollution through human waste is reduced with increased access to improved sanitation facilities [34], but notably only if wastewater treatment is in place [27]. Further, a high relative dependency on surface water suggests a higher impact on treatment requirements caused by wastewater discharge [28]. According to the pollution model by [29], pollution hotspots across the African continent are in regions with high population density and increased human activities. Like allocation of freshwater sources, water quality is also influenced by the institutional setting, specifically, the stringency of regulations [51], the ability to pay for effluent treatment, and the awareness or willingness to pay for water treatment impact receiving water quality [66].

Agriculture and industry water demand may increasingly compete with municipal water demand for easily accessible freshwater sources, leading to the necessity of drawing municipal water from deeper borehole depths or water sources that require more energy-efficient treatment to reach municipal water quality requirements, such as saline or brackish water. Agricultural water withdrawal was the main competing water user with over 90% of total water withdrawal in countries such as Mali, Ethiopia, Senegal, and Tanzania and only less than 10% for municipal water supply. Therefore, action to enhance water use efficiency in competing sectors can help to preserve freshwater sources for municipal water and avoid the need to adopt more energy-intensive technologies for water extraction, treatment, and conveyance. Furthermore, the water abstracted for productive use sectors (e.g., manufacturing, agriculture, power generation, mining, etc.) may weigh strongly on water quality by discharging excessive nutrient loads, pesticides, metals, and other organic and inorganic substances into freshwater reservoirs. This creates the need for more energy-intensive treatment processes such as aeration, ozonation, and membrane treatment [53]. As heavy-polluting industries are transferred from high-income to low-income countries with lenient effluent treatment frameworks, the latter countries face a double burden with limited economic capacity and equipment to treat industrial waste. According to [67], national thermal electricity production was identified as the main driver of industrial water use. They set water consumption intensity by the energy sector as an indicator for the overall improvement of industrial water-use efficiency. Water-intensive industrial processes, such as mining or fuel production, textiles, metallurgy, and paper industries, contribute to structural water intensity of economies [66].

Finally, it was not possible to quantify all the indicators for the drivers due to data constraints. Although it was possible to include all countries in Africa for the k-means cluster analysis, it was not possible to do the same for the multivariate analysis of key indicators. Instead, data on several key indicators are presented and analyzed for twenty (20) countries in sub-Saharan Africa. The number of countries included was constrained by data availability for the parameterized indicators, given that complete data for the indicators listed were not available for some countries. In addition, there were some inconsistencies and uncertainties for some of the data used. For example, Madagascar had the highest daily per capita water production. However, these data were interpreted with caution given that the data presented were for 2005 and not suitable for comparison with more recent data presented for other countries. It was not possible to obtained more recent data for Madagascar from the same data portal where more recent data were obtained for the other countries. Similarly, the data presented for average water loss in the water distribution system per km per day for Senegal, Zimbabwe, Niger, and Benin are the 2013 data. Regular update of established data portals will address data inconsistencies and strengthen analytical work to improve understanding of the relative impact of drivers on energy input for municipal water supply.

5. Conclusions

This study shows how several supply-side and demand-side drivers interact to impact energy input for municipal water supply. A conceptual flow model illustrates how competing drivers interact and affect municipal water supply for several African countries with varying degrees of water security challenges. Key compound indicators generated impact scores that were used to delineate countries into cluster centers. Multivariate analysis of key indicators for demand-side and supply-side drivers showed that agricultural water use is a major competing user, especially in water-stressed countries. Within the operational boundaries of municipal water utilities, the volume of water loss in the distribution system was a key indicator that strongly impacted energy input for municipal water supply. The analytical framework provides an approach to assess the relative impact of drivers on energy input for municipal water supply in developing countries. Additional research could explore the use of predictive models to elucidate future systemic impacts of changing drivers on energy requirements for municipal water supply.

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Abbreviations

ACCSAN	Access to improved sanitation facilities

AQUASTAT	The Food and Agriculture Organization global information system on water resources and agricultural water management.
AGRV	Annual growth rate of agricultural value-added
AfDB	African Development Bank
CWD	Per capita water demand
CWR	Municipal water losses
IBNET	International benchmarking Network for Water and Sanitation Utilities
IND	Net annual industrial production growth
GWD	Groundwater dependency
PDEN	Population density
STAN	subSTance flow Analysis
SWGWDEP	Relative dependency on surface and groundwater
UPG	Urban population growth
WEF	World Economic Forum
WQ	Water quality
WQA	Impact of agricultural production on freshwater quality
WQI	Impact of industrial production on freshwater quality
WWM	Wastewater management
WWTRT	Proportion of wastewater that is treated
YCELP	Yale Center for Environmental Law and Policy

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Assessing Future Water Demand and Associated Energy Input with Plausible Scenarios for Water Service Providers (WSPs) in Sub-Saharan Africa

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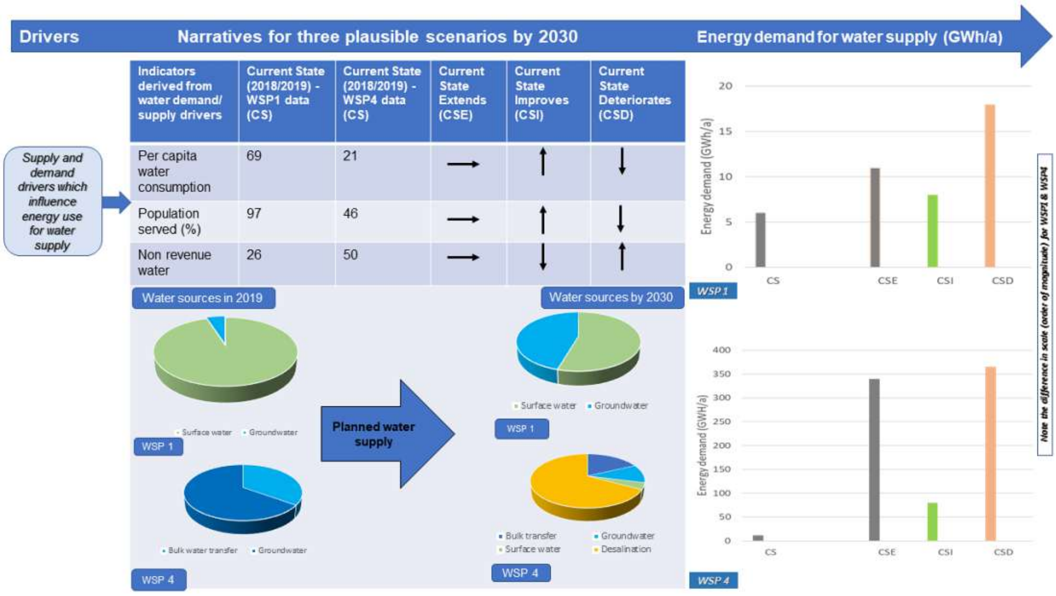
Abstract: This study examined the current state of water demand and associated energy input for water supply against a projected increase in water demand in sub-Saharan Africa. Three plausible scenarios, namely, *Current State Extends* (*CSE*), *Current State Improves* (*CSI*) and *Current State Deteriorates* (*CSD*) were developed and applied using nine quantifiable indicators for water demand projections and the associated impact on energy input for water supply for five Water Service Providers (WSPs) in Kenya to demonstrate the feasibility of the approach based on real data in sub-Saharan Africa. Currently, the daily per capita water-use in the service area of four of the five WSPs was below minimum daily requirement of 50 L/p/d. Further, non-revenue water losses were up to three times higher than the regulated benchmark (range 26–63%). Calculations showed a leakage reduction potential of up to 70% and energy savings of up to 12 MWh/a. The projected water demand is expected to increase by at least twelve times the current demand to achieve universal coverage and an average daily per capita consumption of 120 L/p/d for the urban population by 2030. Consequently, the energy input could increase almost twelve-folds with the *CSI* scenario or up to fifty-folds with the *CSE* scenario for WSPs where desalination or additional groundwater abstraction is proposed. The approach used can be applied for other WSPs which are experiencing a similar evolution of their water supply and demand drivers in sub-Saharan Africa. WSPs in the sub-region should explore aggressive strategies to jointly address persistent water losses and associated energy input. This would reduce the current water supply-demand gap and minimize the energy input that will be associated with exploring additional water sources that are typically energy intensive.

Keywords: drinking water supply; energy input; future water demand; water demand-supply gap; water service providers (WSPs)



Indicators derived from water demand/ supply drivers	Current State (2018/2019) - WSP1 data (CS)	Current State (2018/2019) - WSP4 data (CS)	Current State Extends (CSE)	Current State Improves (CSI)	Current State Deteriorates (CSD)
Per capita water consumption	69	21	→	↑	↓
Population served (%)	97	46	→	↑	↓
Non revenue water	26	50	→	↓	↑

1. Introduction

Energy is a major input and cost factor for water supply. It effects the operational costs recovery of water supply and the ability of Water Services Providers (WSPs) to extend and deliver quality water services [1]. The largest energy consuming devices are the pumping systems which take up to 90% of the total energy input for water abstraction, conveyance, treatment, and distribution [2]. Energy requirement for water supply is influenced mainly by the operational efficiency of water supply infrastructure, type of raw water input, climate, topographical features, and water consumption patterns [3].

In recent years, there is an increased focus on water and energy efficiency measures for WSPs due to high and unstable energy prices, an ever-increasing water demand and the need to explore alternative water sources that are relatively less energy intensive. Consequently, undertaking energy efficiency measures provides opportunities for WSPs to manage operational costs and enhance operational sustainability through a systematic reduction in energy costs without compromising on the quality of service delivered [4]. However, as noted in [5], the motivation to implement energy efficiency measures by most WSPs is largely due to requirements by the sector regulators or legislation to avoid penalties as opposed to an intrinsic motivation for improving revenue generation for the expansion of service. In addition, most WSPs concentrate on efforts to reduce daily volume of water losses alone. However, such efforts are not sufficient to support impactful operational efficiency and sustainability of services since water loss reduction interventions including pressure management, leaks detection and repair also affect energy demand [6–8].

The provision of water services is largely influenced by demographic and socio-economic drivers on the demand side, and climatic variables, technological development, and pollution of water sources on the supply side. Whereas demand side drivers are usually within the operational and management boundaries of WSPs, supply side drivers especially availability of water supply typically go beyond those boundaries [9]. Long-term projections of water service provision by WSPs show increase in water demand in areas projected to experience sustained population growth and the influence of climate change on water sources [10,11]. Consequently, a shift in the state of these drivers continues to widen the water supply-demand gap and the need to explore alternative water sources that are often energy intensive [10]. High rates of urbanization which is largely arising from expansion of metropolitan areas and population growth within the service areas of WSPs requires increased production of water and associated increase in energy demand to convey water from different sources to consumers. In addition, growth in Gross Domestic Product resulting in increased per capita income increases the per capita water demand as consumers can afford to pay for water services. On the other hand, the role of climate change on water supply especially in Africa has been addressed in [11,12]. Most projections point to increased precipitation and wetter days in the Eastern, Central and Western Africa regions compared to the Northern and Southern Africa where reduced precipitation and extended drier period months are expected by 2050 [12]. Hence, there will be increased need to explore energy-intensive water sources including deep-aquifer groundwater supplies or extensive desalination schemes in the latter regions [13]. Additionally, increased infrastructural capacity challenges to cope with water shortages especially in urbanizing areas in sub-Saharan Africa are expected [14].

Furthermore, the total population in Africa is expected to reach 2 billion people, with about 55% of this population expected to live in urban and urbanizing areas by 2050 [14]. Additionally, the expansion of unplanned urban sprawls complicates establishment and expansion of safely managed water supply infrastructure. Hence, most of the population rely on water vendors where the quality is sometimes compromised [15]. Although progress has been reported in access to basic water services, with an average of 56% of urban population with access to improved water supply in 2018, large populations in rural and urban poor areas are still without access to improved water services in many countries sub-Saharan Africa [16]. Additionally, the lack of water supply infrastructure and the poor state of existing water supply infrastructure in some places makes the ambition to achieve target 6.1 of the 2015 Sustainable Development Goal 6 on universal water coverage by 2030 unattainable. Although there are some WSPs which are performing relatively well with non-revenue water losses below the stipulated national benchmark, many WSPs in the sub-region are performing poorly with very high non-revenue water losses [17]. Therefore, joint long-term strategies to address the growing water demand, persistent water losses and associated energy needs for water supply are needed.

However, implementing joint water and energy management measures to increase efficiency is a major challenge for many WSPs, especially in low-income countries in sub-Saharan Africa. Such challenges include (i) budgetary constraints for service expansion, (ii) rapidly evolving water demand and supply drivers, (iii) persistently huge water losses and associated energy input, (iv) large proportions of the population still without access to water services, (v) increased energy demand and a lack of appropriate metrics to assess and benchmark energy use performance and (vi) aging infrastructure leading to high system inefficiencies. These challenges have persisted despite numerous interventions to address poor performance of WSPs and inability to deliver water services effectively [17]. Consequently, there is a clear need to make a turn-around from the business-as-usual approach to address the persistent water losses and inefficiencies in the associated energy input for water supply [18]. This shift can be explored through envisioning plausible future scenarios of water availability and supply-demand ratio and exploring long-term feasible options available. This approach is particularly useful when dominant trends are part of the problem (e.g., increased water scarcity, persistent water losses and inefficiencies in associated energy input). In addition, the approach can be applied when the problem is complex and requires a major overhaul and the time horizon is long enough for consideration of alternative possibilities and developing strategic action plans [19].

The aim of this study is to assess the energy requirements for water supply against a rapid change in water demand. Three plausible scenarios are developed and applied to estimate future water demand and the associated energy input required. The approach was applied for five WSPs in Kenya to demonstrate the potential application of the approach for WSPs in sub-Saharan Africa with similar evolution of their water supply and demand drivers. In addition, some potential solution options WSPs could implement are explored to address the anticipated water demand-supply gap and the associated energy input that would be required. The following research questions are put into context: What is the current state of water demand and supply and associated energy input for water supply? How will the expected increase in water demand influence energy input for water supply to meet water demand in future? What are the feasible solution options for WSPs to address current and expected increase in water demand and the associated energy input for water supply?

2. Rationale for the Study

Long-term planning for water demand and supply requires an understanding of the major water demand and supply drivers through projections and predictions of evolution of these drivers. The future state of these drivers is highly uncertain and complex water supply challenges will likely continue in the future. Accordingly, several studies have provided projections of future water demand and supply at short and medium-term [20] and long-term horizons [11] and at global, regional, national, and local scales [21]. Nevertheless, uncertainty in the evolution of water demand and supply drivers remains a major threat to water supply. Consequently, WSPs need to explore possible alternatives and consider the implications of exploring and pursuing plausible scenarios and water management options associated with those scenarios. Deriving plausible narratives from likely scenarios in the future is a powerful tool to understand uncertainties and inform policy and planning in water sector management [22]. Long-term planning and management strategies of future water supply and demand are guided by the following fundamental questions: How much water would be supplied to meet projected water demand in the future? How will water demand and supply drivers evolve to influence water supply and energy requirements for water supply? Which additional water sources would be abstracted to meet projected water demand? How will energy input for water supply change based on the likely water sources that would be abstracted?

To address these questions, different approaches including forecasting, backcasting and scenario building are applied [19]. Forecasting entails predicting the future based on assumptions and extrapolation of current and historical trends over a specific period (hours, days, weeks or years) while backcasting is a normative approach which entails exploration of desired and attainable futures and pathways to achieve set goals by looking at the current situation from a future perspective in a retrospective way and directing strategies towards achieving the desired futures. On the other hand, scenario building entails formulation of hypothetical narratives of possible futures which are employed in strategic decision planning to explore alternatives to deal with future uncertainties. A scenario is a consistent view of what the future might look like without forecasting it. It entails building images about the desired future or the future wished to be avoided relative to the past and present situation, and articulation of how the present-future gap may be bridged [19]. Scenario building seeks to understand the pathways and approaches of the potential futures that can be avoided or could be missed to promote preparedness for the future. According to [22], scenario building approach in addressing water sector challenges entails the following steps:

1) Definition of the problem and driving forces from which uncertainties arise,
2) Drafting the narratives (storylines) and assumptions,
3) Quantification of the future development and intensification of the driving forces
4) Quantification of water-related variables

Broad narratives of socio-economic changes under different future pathways have been quantified and described at a global scale as shared socio-economic pathways presented in [21]. However, alignment of the proposed scenarios with globally developed and modelled pathways enhances consistency of the scenarios. It also allows for assessment of different studies across different disciplines and are an important tool for research with limitations to generate own comprehensive scenarios of future changes in socio-economic parameters, for which projections do not vary significantly with different models [22,23]. In this context, comprehensive narratives of three future development scenarios namely the sustainability road, the middle of the road and the regional rivalry until 2050 and some projections extended until 2100 have been provided in [21].

This study builds upon the background work and approach of scenarios development used by the Water Security Research Group at the Internal Institute for Applied Systems Analysis (IIASA) [21]. The approach was adapted to generate specific narratives for three plausible futures relevant for water supply and demand management with implications on energy demand for water supply in sub-Saharan Africa until 2030.

3. Materials and Methods

3.1. Scenarios Development

Table 1summarizes narratives of water demand and supply drivers, associated parameters, and their likely evolution across three plausible scenarios, namely, *Current State Extends* (*CSE*), *Current State Improves*

(*CSI*), and *Current State Deteriorates* (*CSD*). These narratives are the basis for data acquisition and scenario calculations used for the current study. Population growth and urbanization are major water demand driver which influence service coverage and the daily per capita water demand. Furthermore, economic growth influences the per capita water demand and hence per capita energy demand for water supply. In addition, leverage on technology influences system operations through optimization and scheduling of pumps and motors and enhances the efficiency of the water supply system.

Table 1. Summary of the key narratives for three plausible scenarios (*Current State Extends*, *Current State Improves* and *Current State Deteriorates*) that were developed and applied for the current study.

Parameter	***Current State Extends (CSE)***	***Current State Improves (CSI)***	***Current State Deteriorates (CSD)***	**Parameter Quantified**
		Water demand drivers:		
Economic growth:	Moderate	Accelerated	Slow	
Population growth:	High	High	High	√
Urbanization:	High	High but planned	High	√
Population served:	Large population without access	Universal/near universal coverage	Large population without access	√
Per capita water consumption:	Moderate to high	High	Low	√
Per capita energy demand for water supply:	Moderate to high	Low	High	
Water supply/demand management programs:	Moderate	High	Low	
Service connection density (connections per km):	High	Low	High	
Water supply drivers:				
Impact of climate change (droughts and floods):	Moderately high	Moderate	High	
Water production:	High	High	High	√
Water loss:	High	Low	High	√
Leakage reduction potential:	High	Low	High	√
Water-Energy efficiency:	Moderate	High	Low	√
Adoption of decentralized or hybrid renewable energy sources:	Gradual	Fast	Slow	
Energy demand for water supply:	High	Low	High	√
Leverage on technology for treatment, optimization of pumps, asset management and online monitoring of leaks & water use:	Gradual	Advanced	Slow	
Energy use benchmarking:	Absent	Fully adopted	Absent	

√(denotes the parameter was quantified in the present study.)

3.1.1. Scenarios Description

The *Current State Extends* (*CSE*) scenario would mean continued high population growth and expansion of urban and metropolitan areas and large population especially in urban poor and rural areas without access to safely managed water supply; WSPs would still struggle to meet the projected water demand with huge uncertainty in fulfilling future increase in water demand; In addition, the adoption of highly efficient water treatment and supply technology develops gradually, and the huge water losses currently would continue unchecked or moderately addressed, requiring WSPs to explore other water sources, which would be energy intensive; The water losses and associated energy input would remain above the regulated benchmark for most WSPs; Huge energy bills and frequent power outages would affect service delivery and operational sustainability.

The *Current State Improves* (*CSI*) scenario would lead towards sustainability in water supply systems. It assumes that even though increased water demand is expected from a huge population growth and high rates of urbanization, WSPs can meet the water demand and achieve universal coverage of water supply services. Further, planned urban development would translate to increased water demand but a large part of the population would afford to pay for water services due to increase in income levels. Increased cooperation between WSPs would enhance peer learning on best practices and benchmarking would be fully adopted to enhance water and energy efficiency. Water losses would be below the regulated benchmark and energy inefficiencies associated with water losses would be at or below stipulated benchmark levels. In addition, WSPs would seek to transition to decentralized renewable energy sources which would reduce over-reliance on the national energy grid and reduce service interruption. High energy efficiency and low energy costs due accelerated leverage on technology including for pump scheduling and system-wide optimization would mean WSPs operate efficiently.

The *Current State Deteriorates* (*CSD*) scenario would mean a huge segment of population are still without water services in most regions; There would be little or no motivation to address water losses and system inefficiencies, hence, little progress in efficiency enhancement and in implementation of water and energy-saving technologies; some WSPs would continue to perform well while others lag behind due to high competition and non-cooperation; water losses remain high and transition to clean energy for water supply would progress at a slow pace; benchmarking and peer learning of best practices in energy efficiency would be lacking. Lack of water demand management strategies would result in accelerated non-revenue water losses and reduced ability for WSPs to meet operational costs and generate revenue. In addition, continued reliance on the grid would mean huge electricity bills and frequent power cuts leading to service interruption. The possibility of this scenario playing out is credible as an increase in non-revenue water by up to 23% points and a reduction in the per capita water production by half in the last decade in some WSPs in Kenya was observed. An illustration of deterioration regarding non-revenue water, reduction in per capita water consumption and water coverage for selected WSPs in Kenya over the last decade is provided as Supplementary Material. The data was compiled from the annual performance reports of the Water Services Regulatory Board of Kenya (WASREB) and additionally from the WSPs.

3.1.2. Quantification of Scenario Parameters

Table 2 provides a selection of water supply and demand parameters and the reference values that applied in this study for calculations. The criteria for the selection and definition of quantified parameters list as outlined in [24] and the quantified values were adopted from the key performance indicator benchmark values set by WASREB [25].

Additionally, since energy assessment is not considered a key performance indicator for the assessment of WSPs in Kenya, reference values were adopted from literature. The quantified parameters were then applied in selected WSPs in Kenya to assess the current state of water supply drivers and energy input as presented in Section 4.1 in the results section and for the estimation of future water demand and the energy requirement for water supply under the three plausible scenarios.

Several assumptions were developed to generate the coefficients used for the quantifiable parameters applied for the three plausible scenarios (Table 2). Although the assumptions were developed from analysis of the Kenyan water supply and demand situation, the assumptions and approach used can be applied for other WSPs in sub-Saharan Africa. The assumptions are as follows:

- Population growth and urbanization continues to grow at similar rates for all three scenarios until 2050.
- Universal water supply by 2030 with a per capita water demand of 120 L/p/d is assumed for the *CSI* scenario. For the *CSE* scenario, the average value of the current per capita water demand for each WSP is considered, whereas the basic daily per capita water demand of 20 L/p/d as prescribed by the World Health Organizations hierarchy of water requirements was used for the *CSD* scenario.
- The WASREB benchmark for non-revenue water loss (20%) is assumed as the most feasible option in the foreseeable feature and applied for the *CSI* scenario while the current values reported for each WSP were assumed for the *CSE* scenario. A non-revenue water loss of 20% for the CSI scenario is still very high compared to reported values in developed countries, which averages at 10% in Australia and Japan or less than 10% in the Netherlands (5%), Denmark (7%), [26]. However, achieving 20% level can be considered a significant improvement of the current state given that the current non- revenue water loss levels in Kenya average at 43%, having reduced by only four-percentage point in the last decade.
- The average non-revenue water loss reported in 2018/2019 is assumed for the *CSE* scenario. On the other hand, the highest non-revenue water loss reported among the five WSPs was assumed for the *CSD* scenario. An increase in non-revenue water loss to 63% from 25% (WSP1) for the *CSD* scenario may seem unlikely but the likelihood of this scenario playing out is plausible. An illustration showing such a deterioration over a ten-year period is provided as supplementary material for two WSPs in Kenya which are not considered in the current study. (see supplementary material)
- Universal coverage of piped water supply by registered WSPs is assumed for the projections and applied for the *CSI* scenario. Whereas the reported coverage for each WSP is assumed to continue in the *CSE* scenario. 50% coverage in piped water supply in the respective service area of the WSPs is assumed for *CSD* scenario.

Table 2. Selected quantifiable parameters applied for the three plausible scenarios.

Parameter	Unit	Scenarios			Reference
		Current State Extends (*CSE*)	*Current State Improves* (*CSI*)	*Current State Deteriorates* (*CSD*)	

Population growth	No. of people	2c [λ]	2c [λ]	2c [λ]	[27]
Urban population	% of total population	60–90	60–90	60–90	[28]
Access to water services	% pop. coverage	60	100	50	[25]
Unit water supply for domestic use	L/p/d	16–69 *	120	20–50 **	[25]
Water loss as a fraction of system input volume	%	26–63 [a]	20	63 [b]	[25]
Leakage reduction potential	%	20–50	<20	>70	[29]
Water–Energy efficiency	%	50	100	<50	[30]
Standardized pump efficiency	kWh/m^3 100 m	0.40–0.54	0.27–0.40	0.54–5.0	[6]
[α] Pump efficiency	%	50	70–100	<50	[6]

[λ] Medium variant population projection which projects the 2030 population in the service areas will be double the current population * Range for current per capita water demand among selected WSPs ** Basic and minimum per capita water demand as required in the World Health Organization hierarchy of water requirements [31] [a] Range for current water losses for each WSP under consideration [b] Highest non-revenue water loss reported among the selected WSPs [α] Varies with the water supply system layout and the water-energy efficiency and only current state estimates are provided.

3.2. Water Demand and Water Demand-Supply Gap Analysis

Municipal water demand is categorized into residential and non-residential water demand. This study focuses on residential water demand. The water demand was estimated as the total annual volume of water needed to meet the daily per capita water demand as provided in [3]. This was estimated by multiplying the total population served by the average daily per capita water use and converting the estimates to m^3/year. These estimates assume no significant seasonal variation in the daily per capita water use.

On the other hand, a water supply-demand gap is defined as the difference between the quantities of water available and supplied and the unmet demand which exists if the available supply is lower than the demand. Gap analysis helps to assess the current situation and what is required to achieve the target milestones [32]. Gap analysis entails identification of a desirable target level, analysis of the current situation and assessment of the difference between the current and the desired level.

To provide an overview of the current situation regarding water demand, water supply and the unmet demand, a baseline situation analysis was undertaken on the water demand, the major water sources composition, total energy budget, pump and total energy efficiency assessment and the projected population growth, urbanization was analyzed. Three-year data was obtained from selected WSPs reports and examination of the last ten-year performance reports by the water services regulator. This provided a starting point of the diagnostic picture of the current energy demand, the energy consuming processes and extent of water and energy losses and the water demand gap.

3.3. Water Loss Reduction

Water losses within the water supply networks are largely attributed to background leaks and pipe bursts. The volume of water lost through detectable leaks is highly dependent on the response time to detect and repair the leaks. Thus, the volume of water saved through leaks could be estimated as shown in Equation (1) following a similar approach in [33]. It is crucial in the water balance to show the state of the network and the annual volumes lost based on the leaks detected and repaired per year. This approach assumes that about 95% of leaks within the supply network are detected and corrected:

$$\text{Volume lost per detectable leak} = \frac{\text{Total volume lost through leaks } (\text{m}^3)}{\text{Total number of leaks detected}} \tag{1}$$

Furthermore, once the volume lost through detectable leaks is established, it is possible to estimate the leakage reduction potential based on the current leakage levels. This was estimated following a similar approach in [29]:

$$\text{Leakage Reduction Potential} = \text{Volume lost through Current Leakage} - \text{Minimum Leakage level} \tag{2}$$

3.4. Estimation of Energy Input and Assumptions for the Three Scenarios

Several metrics exist for the estimation of energy input for water supply [24,30]. Specific energy input is a widely used metric for energy checks and energy performance assessment. However, this metric is not applicable for comparison of energy use for water supply systems in varying topographic locations. To estimate the energy intensity for water supply, the lower limit of energy intensity values obtained from peer-reviewed literature for different water sources was applied for the *CSI* scenario, whereas the upper limit of the same was applied for the *CSD* scenario. For the *CSE* scenario, data on energy input for water supply and the type of raw water supplied was obtained from selected WSPs. The unit energy intensities for the supply of the different water types were used for the estimation of energy requirements for each WSP based on estimates provided in [3,34,35]. For the supply of surface water, the energy intensity was 0.02 kWh/m^3 for the *CSI* and 0.64 kWh/m^3 for the *CSD* while for groundwater supply, 0.40 kWh/m^3 and 0.94 kWh/m^3 were applied under *CSI* and *CSD* scenarios, respectively. For desalination using reverse osmosis, 0.79 kWh/m^3 was adopted for *CSI* and 3.5 kWh/m^3 for *CSD* scenarios, respectively.

The theoretical minimum energy consumption for lifting one cubic meter of groundwater to a height of one meter in a frictionless, water-loss free system at high-efficiency (up to 100% efficiency) is estimated at 0.0027 kWh [34]. Furthermore, the energy requirement for surface water supply is highly dependent on the distance from source to consumers, water losses and pump efficiency. This has been reported to range from 0.02–0.41 kWh/m^3 in Kenya [35] and up to 4.07 kWh/m^3 for inter-basin water transfer over about 745 km in Spain [34]. On the other hand, the minimum specific energy requirement for conventional desalination processes varies greatly with salt concentration, water recovery potential and the treatment process used [36]. Reverse osmosis is the most common desalination process with specific energy requirement for sea water estimated at 3–7 kWh/m^3 for a production capacity of 24,000 m^3/day, while for electrodialysis it is estimate at 2.6–5.1 kWh/m^3, for multi-stage flash thermal distillation is estimated at 23–68 kWh/m^3 and 6.5–11 kWh/m^3 for multiple-effect distillation for a production capacity of 5000–15,000 m^3/day [37,38]. Reverse osmosis was chosen for this study as it is the most common desalination process with relatively lower energy intensity compared to thermal processes [34,38].

In addition, the per capita energy input for water supply was estimated as stated in [3] by multiplying the energy intensity for water supply by the expected per capita water consumption (PCWC) for the three scenarios.

3.5. Data Collection

Five representative Water Service Providers (WSPs) in Kenya were selected for the current study. For anonymity, the WSPs have been labelled WSP1, 2, 3, 4, & 5. Field visits were made to each WSP and structured questionnaires were used to obtain the reported data from representatives of the technical team at the WSPs.

Table 3 summarizes the systems characteristics based on the latest available data from the WSPs. The transmission length averaged at 592 km in WSP5 and slightly over one thousand in WSP3. The number of hours of water supply per day was lowest in WSP3 and WSP4, averaging at 6 and 5 h per day respectively against an acceptable benchmark of 16–20 h per day. Additionally, the average pump efficiency ranged from 60–70% and the age of the pumps in operation ranged from 8–14 years. The maintenance schedules were mostly scheduled on monthly basis.

The first question posed in the selection of the WSPs as suggested in [6], was: is energy efficiency an issue for the WSPs and if so, is it likely to be an issue of major concern as water demand grows? This was an important reflection since some WSPs are largely gravity-fed, with relatively low energy costs compared to their total operational costs. Hence, energy input for water supply is currently not of major operational concern. A minimum three-year data was obtained through field visits, questionnaires, and interviews with selected WSPs in Kenya. Data was obtained on water supply, water demand, energy use for water supply and proposed water supply plans for the WSPs as outlined in [25]. Further, the 2030 Kenya National Water Management Plan (NWMP2030), drafted to provide estimates of available water resources and propose water resources available to close the water demand-supply gap in Kenya, was analyzed for projections on water demand and supply and proposed raw water sources for the year 2030 [39]. Additionally, the strategic plans of the selected WSPs were examined to derive scenario narratives and quantify the selected parameters

Due to the projected accelerated urbanization and expansion of metropolitan areas, four of the five WSPs selected were in the Very Large (with over 35,000 connections within the service area) and one Large (with 10,000–34,999 connections) category of WSPs, based on the size categorization used by WASREB. The five WSPs abstracted both surface and groundwater in varying proportions. The population in the service areas is largely urban, with all of them experiencing expanding metropolitan areas some of which lack water supply infrastructure. The WSPs operate several boreholes with groundwater wells about 150–200m below ground. WSP2, WSP3 and WSP4 largely rely on bulk water transfer pumped at estimated distances of 30–50 km from the source to the treatment plants and or to the consumers.

Table 3. Water supply network characteristics of selected WSPs as at 2018/2019.

Water Service Providers (WSPs)	*Length of the Transmission and Distribution Network (km)*	*No. of Connections*	*Total Number of Leaks Detected and Repaired/yr*	*Hours of Water Supply*	*Average Source-Distribution Elevation Difference (m)*	*Average Age of Pumps (years)*	*Average Efficiency of Pumps (%)*
WSP 1	*650*	*58,316*	*2419*	*21*	*60*	*10–13*	*70*
WSP 2	*615*	*61,034*	*400*	*19*	*35*	*8*	*65*
WSP 3	*1066*	*593,424*	*2730*	*6*	*50*	*12*	*65*
WSP 4	*673*	*86,326*	*1045*	*5*	*30*	*14*	*60*
WSP 5	*592*	*24,820*	*1368*	*12*	*40*	*10*	*60*

Data source: (Selected WSPs in Kenya).

4. Results

4.1. Estimates of Water Demand and Supply Driver Parameters

To provide an overview of the current state of the water supply and demand drivers for selected WSPs and a basis to show evolution of the drivers for the three plausible scenarios, this section presents an analysis of quantified parameter as outlined in Table 2. The parameters quantified include population in the service areas of WSPs, current water demand and the water demand-supply gap, water losses and the estimated leakage reduction potential as well as the energy input for current water supply.

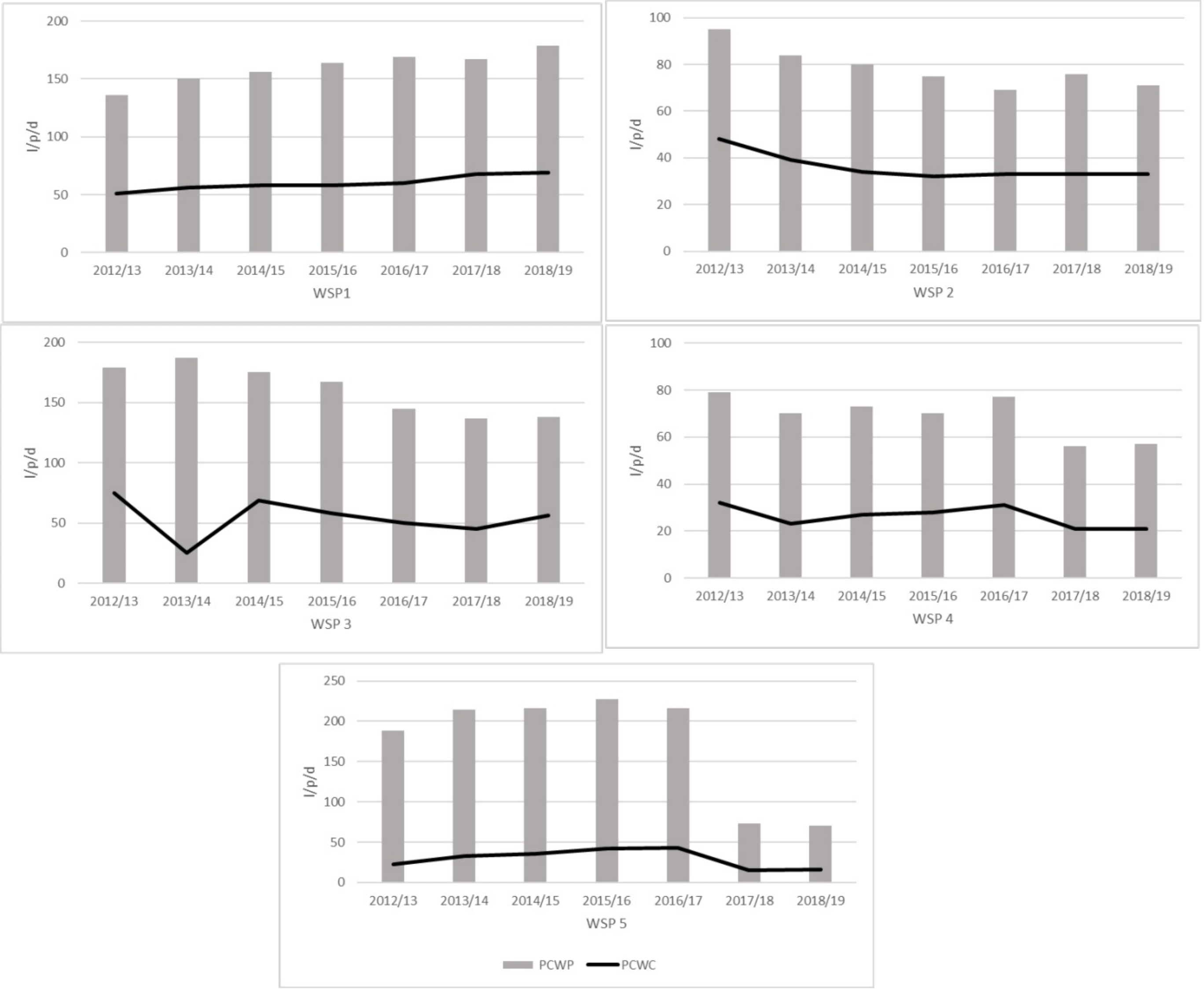


Figure 1. Seven-year trends of daily Per Capita Water Production (PCWP) and per Capita Water Consumption (PCWC) for WSP1, 2, 3, 4 & 5. (Source: Water Sector performance Reports available on [24]).

4.1.1. Total and Urban Population in the Service Areas of WSPs

Table 4 shows the total population and the urban population within the service area of the five WSPs for 2020 and the projected years (2030 and 2050) using the medium-variant population growth as the base for all scenarios. The population in the service areas of the five WSPs is expected to double between 2020 and 2030, reaching almost three times the 2020 estimates by 2050. However, most of the expanding urban areas do not have water supply infrastructure in place and most of the population rely on decentralized water supply sources through tankers and small-scale vendors. The urban population is expected to accelerate in all WSPs, except for WSP5 where about 66% of the population within its service area are projected to live in urban areas compared to WSP3, for example, where over 90% of the population in the service area will be urban.

Table 3. Total and urban population (×1000) within the service area of the five WSPs for 2020 and the projected years (2030 and 2050) as provided in [27].

Water Services Provider (WSPs)	2020		2030		2050	
	Urban	**Total**	**Urban**	**Total**	**Urban**	**Total**
WSP 1	200	237	430	513	630	749
WSP 2	383	528	550	1156	1130	1687
WSP 3	4640	4735	6502	7031	8054	8881
WSP 4	800	1090	1889	2644	3086	3858
WSP 5	174	528	282	852	771	1150

4.1.2. Water Production and Consumption

The daily per capita water production (PCWP) and per capita water consumption (PCWC) provides estimates of the average daily volume of water supplied and utilized per person in liters per person per day (L/p/d) within the jurisdiction of the WSPs. ***Error! Reference source not found.*** presents a seven-year trend of daily per capita water production and per capita water consumption for five WSPs in 2012–2019. During this period (2012–2019), WSP1 reported the highest per capita water consumption among all the WSPs. The per capita water consumption increased 5% per annum (51 in 2012/2013 to 69 L per person per day in 2018/2019). On the other hand, per capita water consumption decreased for the other four WSPs at an annual average of 7%, 6%, 10% and 21% in WSP 2, WSP3, WSP4 and WSP5, respectively. For instance, there was a decrease in the per capita water consumption in WSP2 from 48 L/p/d in 2012/2013 to 33 L/p/d in 2018/2019 and 75 L/p/d to 56 L/p/d in WSP 3 within the same period.

Additionally, WSP1 had an increase in per capita water production from 136 L/p/d to 179 L/p/d between this period. In comparison, WSP4 had a decline in per capita water production from 79 L/p/d to 57 L/p/d and a reduction in per capita water consumption from 79 L/p/d to 21 L/p/d. At WSP5, per capita water production decreased from 188 L/p/d to 70 L/p/d while per capita water consumption declined from 25 L/p/d to 16 L/p/d within the same period. However, an increase in per capita water production and consumption was observed between 2014 and 2017, and a steep decline in the years 2017 through 2019.

In the 2018/2019 financial year, water coverage in the service areas of WSP1 and WSP2 was 97% and 93% respectively. The coverage for WSP3, WSP4 and WSP5 was comparatively lower, i.e., 79%, 46% and 62%, respectively. However, although WSP2 reported drinking water coverage above the acceptable benchmark set by the national water regulator (>80%), the daily per capita water consumption was below the minimum requirement of 50 L/p/d. WSP4 and WSP5 also reported water coverage below the stipulated benchmark and the daily per capita water consumption was almost half the recommended daily consumption.

4.1.3. Water Demand-Supply Gap Analysis

Table 5 compares the per capita water demand to the volume supplied (i.e., volume produced less the non-revenue water) and the deficit (gap) thereof to achieve the domestic water demand at the current water loss levels for all WSPs. WSP1 had the smallest water-demand-supply gap of 3% and as noted above, the highest per capita water consumption among all the WSPs considered. WSP2 and WSP3 have a 12% and 30% gap respectively between the water supplied and the water demand. The largest gap was observed for WSP4 and WSP5 with 50% and 35% of the current water supply needed. Intriguingly, WSP4 and WSP5 had the highest rates of non-revenue water losses (Table 6 This implies that although the per capita water production was relatively higher at WSP4 and WSP5, 57 L/p/d and 68 L/p/d, respectively in 2019, a large proportion of the water produced was lost as non-revenue water.

Table 5. Comparison of annual water demand and volume of water supplied and percentage water demand-supply deficit.

Water Services Provider (WSPs)	Water Demand (Mm^3/a)	Water Supply (Mm^3/a)	Deficit (%)
WSP1	6.0	5.8	3
WSP2	6.4	5.6	12
WSP3	76.0	57.5	24
WSP4	8.4	4.2	50
WSP5	3.1	2.0	35

4.1.4. Water Losses and Leakage Reduction Potential for the Year 2019

Non-revenue water (NRW) loss at the five WSPs was above the regulated benchmark for WSPs in Kenya. Non-revenue water at WSP 3 was 40%. However, further analysis in this section was not possible as the data on leakage that was provided was inconsistent.

WSP5 had the highest non-revenue water loss (63% of the water supplied) compared to the other WSPs. This was more than 3 times the regulated benchmark of 20%. WSP4 reported an NRW loss of 50% while NRW loss at WSP1 and WSP2 were 26% and 32%, respectively. WSP5 had the highest water loss per connection per day which was 1213 L/connection/day compared to 264 L/connection/day for WSP1.

On the other hand, the water losses associated with leaks was estimated for each detectable leak. The estimated volume of water loss was highest for WSP2 at over 8000 m^3/a compared to 788 m^3/a for WSP1. Furthermore, WSP1 had the highest leakage reduction potential of up to 85% while the leakage reduction potential for WSP2 was 70%. WSP4 and

WSP5 had a leakage reduction potential of 69% and 90%, respectively. This leak reduction translates to a water savings of 4333 m^3/a and 5130 m^3/a for WSP4 and WSP5, respectively i.e., water that could be saved from each of the leaks detected.

Both WSP4 and WSP5 had the lowest water coverage of 62% and 46%, respectively, and a per capita water consumption of 16 L/p/d and 21 L/p/d, respectively. If these high number of leaks were minimized, water savings from leaks could provide a year's supply of the minimum per capita water requirement of 50 l per person for over 86,000 persons and over 100,000 persons in the service areas of WSP4 and WSP5, respectively. The volume of water that could be reclaimed from leakage reduction could reduce the water coverage deficits within service areas of the WSPs. For instance, the annual per capita water demand to meet the minimum daily per capita water requirement for the population within the service area of WSP2 was 9.6 M m^3/a. However, only 58% of the water demand was met, yet 32% of the water supplied was lost as non-revenue water.

Table 6. Non-revenue water, leakage and leakage reduction potential for the WSPs in 2019. Data for WSP3 is not shown.

Water Services Provider (WSPs)	NRW (%)	NRW (L/conn/day)	Vol. Lost/ Detectable Leak (m^3/a)	Current Leakage Level (m^3/a)	Minimum Leakage Level (m^3/a)	Leakage Reduction Potential (m^3/a)
WSP1	26	264	788	6450	966	5484
WSP2	32	309	8607	5598	1698	3900
WSP4	50	565	4013	6321	1988	4333
WSP5	63	1213	2454	5680	550	5130

4.1.5. Energy Input for Water Supply–2019

Table 7 presents the energy input for water supply at the selected WSPs in 2019. The specific energy input for water supply was highest at WSP2 (1.60 kWh/m^3) which largely rely on groundwater as its main raw water source. On the hand, the specific energy use for water supply was lowest at WSP5 (0.20 kWh/m^3) which mostly supplied surface water. The WSPs abstracting surface water used conventional drinking water treatment methods (mixing, flocculation, sedimentation, filtration, and chlorine disinfection), with energy required mostly for chemical dosage and backwashing. The energy intensity for water treatment was very low for all five WSPs (Mean: 0.02 ± 0.03 kWh/m^3; Range: 0–0.04 kWh/m^3).

The standard average efficiency of the pumps was above the regulated benchmark of 0.27–0.40 kWh/m^3 100 m. The specific energy input associated with water supply was also high at WSP3 and WSP4 (the largest among the selected WSPs). As a result of their size, WSP3 and WSP4 transfer water over long distances from source to consumers, thereby requiring higher energy input for pumping. Although WSP5 had the highest water losses recorded, the energy input associated with water loss was lowest as the water supply source was largely surface water with minimal energy requirements.

Per capita energy input for water supply was highest at WSP2 (37.6 kWh/p/a) largely due to the high energy consumption for groundwater supply and WSP 4 with bulk transfer of water over long distances from source to consumption. Per capita energy consumption was lowest at WSP 5 owed to the large proportion of surface water supply with minimal energy requirement and reliance on gravity for water conveyance.

WSP2 had the highest energy input associated with water loss estimated at 54 kWh/m^3. However, implementation of leakage reduction could provide energy savings of up to 6 MWh/a forWSP2 and up to 2 MWh/a for WSP1 from the energy associated with water losses through leaks.

Table 7. Specific energy input for water production, the standard efficiency of pumps and the energy input associated with water loss for the five WSPs in 2019.

Water Services Provider (WSPs)	**Specific Energy Input Per Vol Supplied (kWh/m^3)**	**Specific Energy Input Per Vol. Billed (kWh/m^3)**	**Standard Average Efficiency of the Pump (kWh/m^{3}100m)**	**Per Capita Energy Consumption/ Vol. Supplied (kWh/p/a)**	**Specific Energy Input Associated with Water Loss (kWh/m^3)**	**Energy Savings Associated with Leak Reduction (kWh/a)**
WSP1	0.39	0.45	0.42	21.5	9.6	2139
WSP2	1.60	1.76	0.52	52.8	54	6240
WSP3	0.34	0.45	0.64	24	18.7	No credible data
WSP4	0.32	0.61	0.69	37.6	16.2	1387
WSP5	0.40	0.57	0.56	19.9	5.9	1026

4.2. Future Water Supply and Demand and Energy Input for the Scenarios

4.2.1. Water Demand Estimates under the Scenarios

Table 8 shows the water demand in 2019 for the five WSPs and estimates for 2030 under the three scenarios. The values presented for each WSP under the scenarios are estimated following the approach described earlier. The water demand estimates for all scenarios considers the projected population for 2030. A continuation of the current state (*Current State Extends*) would mean water demand at WSPs 1,2,4 and 5, for example, will be double the current water demand largely attributed to increase in projected population. At WSP3, the projected water demand is expected to be almost twice as much as the current water demand under the same scenario. Estimates of the water demand under the CSI shows that the water demand could increase over four times the current state in WSP4 to meet the water demand for the total population in service area at 120 L/p/d. The highest increase in water demand is observed for WSP4 and WSP 5 which as earlier stated currently covers 46% and 62% at 21 L/p/d and 16 L/p/d respectively.

Table 4. Water demand for 2019 (current state) and 2030 under the three scenarios.

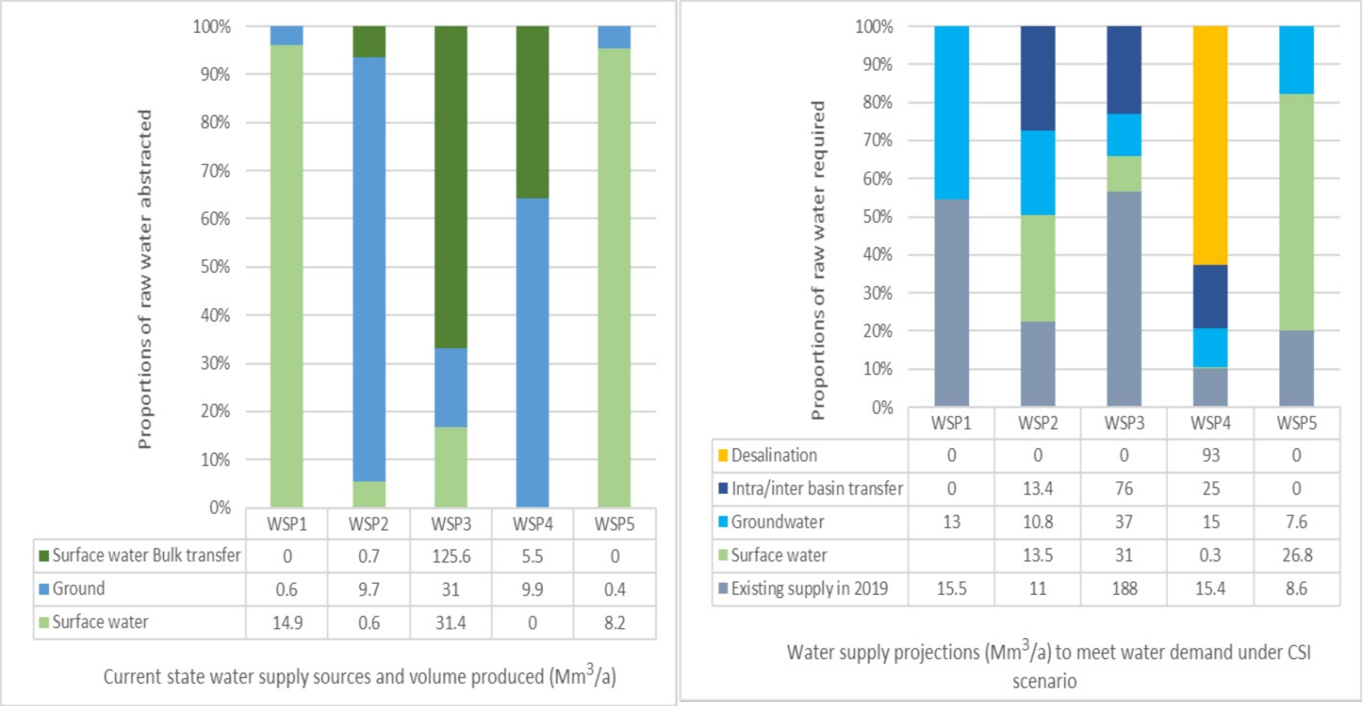
	Current State (2019)	***Current State Extends* (*CSE*–2030)**	***Current State Improves* (*CSI*–2030)**	***Current State Deteriorates* (*CSD*–2030)**
Water Services Provider (WSPs)	**Water demand (Mm^3/a) ***	**Demand ** (Mm^3/a)**	**Demand *** (Mm^3/a)**	**Demand *** (Mm^3/a)**
WSP1	5.8	12.5	28.1	1.9
WSP2	5.8	12.7	63.3	4.2
WSP3	57.6	85.8	384.9	25.7
WSP4	4.2	10.1	144.8	9.7
WSP5	1.9	3.1	46.6	3.1

* Assumes the proportion of current population served continues for each WSP as presented in 4.1.2 and at the current daily per capita water demand as shown in Table 2, ** Assumes total population in the service areas is served, and the per capita water demand is 120 L/p/d *** Assumes only 50% of the population is served with basic daily per capita water demand of 20 L/p/d as outlined in WHO hierarchy of water requirement [30].

4.2.2. Water Sources to Meet Projected Water Demand

Figure 2 compares the proportions of different raw water types and volumes currently produced by each WSP and projections to meet the projected water demand under the *Current State Improves* (*CSI*) scenario. The current water production and projected estimates were used in this case as data on water sources and proportions abstracted was available.

A 100% increase in groundwater abstraction is expected at WSP1 to achieve 13 Mm^3/a production needed to meet the projected demand. This increase will provide 47% of the total supply required while the existing water supply is expected to contribute 53%. On the other hand, desalination is expected to supply 93 Mm^3/a at WSP4, contributing almost 60% of the total volumes required and an additional 10% increase in groundwater abstraction is expected by 2030. In addition, these projections show that existing supply only accounts for 10% of the water supply required at WSP4 to achieve the target supply and almost 90% will be contributed from new sources. An increase in bulk water transfer is expected to continue at WSP3 while for WSP2, an increase in precipitation in the catchment area (projection in NWMP2030) coupled with an increase in surface water abstraction and bulk transfer. The existing capacity for water supply will contribute to slightly over 20% at WSP2 and 50% at WSP3. WSP3 is expected to increase the proportions of bulk-transfer which will contribute over 80% of the supply.



	WSP1	WSP2	WSP3	WSP4	WSP5
🟩 Surface water Bulk transfer	0	0.7	125.6	5.5	0
🟦 Ground	0.6	9.7	31	9.9	0.4
🟩 Surface water	14.9	0.6	31.4	0	8.2

Current state water supply sources and volume produced (Mm^3/a)

	WSP1	WSP2	WSP3	WSP4	WSP5
🟨 Desalination	0	0	0	93	0
🟦 Intra/inter basin transfer	0	13.4	76	25	0
🟦 Groundwater	13	10.8	37	15	7.6
🟩 Surface water		13.5	31	0.3	26.8
■ Existing supply in 2019	15.5	11	188	15.4	8.6

Water supply projections (Mm^3/a) to meet water demand under CSI scenario

Figure 2. Comparison of current state water production and the projected supply needed to meet projected demand in 2030 under the *Current State Improves* (*CSI*) scenario (Projections assume service coverage to total population within service area to meet a per capita water demand of 120 L/p/d at 20% non-revenue water loss).

4.3. Estimates of Energy Requirement to Meet Projected Water Demand

4.3.1. Energy Intensity for Water Supply

Figure 3 provides estimates of total energy input for water supply in 2019 and the projected energy input for projected water demand in 2030 under the three scenarios (*Current State Extends*, *Current State Improves* and *Current State Deteriorates*).

An increase in energy input is expected at WSP1 due to increase in groundwater abstraction compared to the current groundwater production. Across the three scenarios, energy input under *Current State Improves* is expected to be slightly higher than the present energy demand. However, energy input could double with the *Current State Extension* scenario. On the other hand, energy intensity for water production could increase four-fold at WSP1 under the *Current State Deteriorates*.

In the case of WSP5 the energy intensity for water production will increase almost ten times due to the expected increase in groundwater abstraction under *Current State Extends*. With *Current State Improves* scenario, the energy intensity is estimated to increase by about five times compared to the current energy input. However, reduction of the current huge water losses (over half of the total production is currently lost due to NRW losses), could reduce the need for the planned investments in huge groundwater abstraction which is projected to increase from less than 1 Mm^3/a to 7 Mm^3/a by 2030. Addressing current NRW losses at WSP5 could reduce the need for additional groundwater abstraction and subsequently reduce the need for increased energy input for water supply in future.

WSP4 is expected to have the largest energy budget due to the plans by the service provider to abstract and desalinate saline raw water sources in addition to the extension of groundwater production and intra/inter-basin water transfer. As observed earlier, the existing water supply in the service area of WSP4 represents less than 5% of the total supply required for universal water supply by 2030. Hence, alternative water supply options will be needed to bridge the water supply-demand gap, which could partly be addressed through measures to reduce of water losses. NRW loss reduction of over 4000 m^3/ a could be achieved potentially. The energy intensity to meet the projected water demand would increase almost fifty times the current energy intensity with the *Current State Extends* scenario. Under *Current State Improves*, the energy intensity would increase twelve times the current energy input with the use of desalination techniques that are less energy intensive like reverse osmosis.

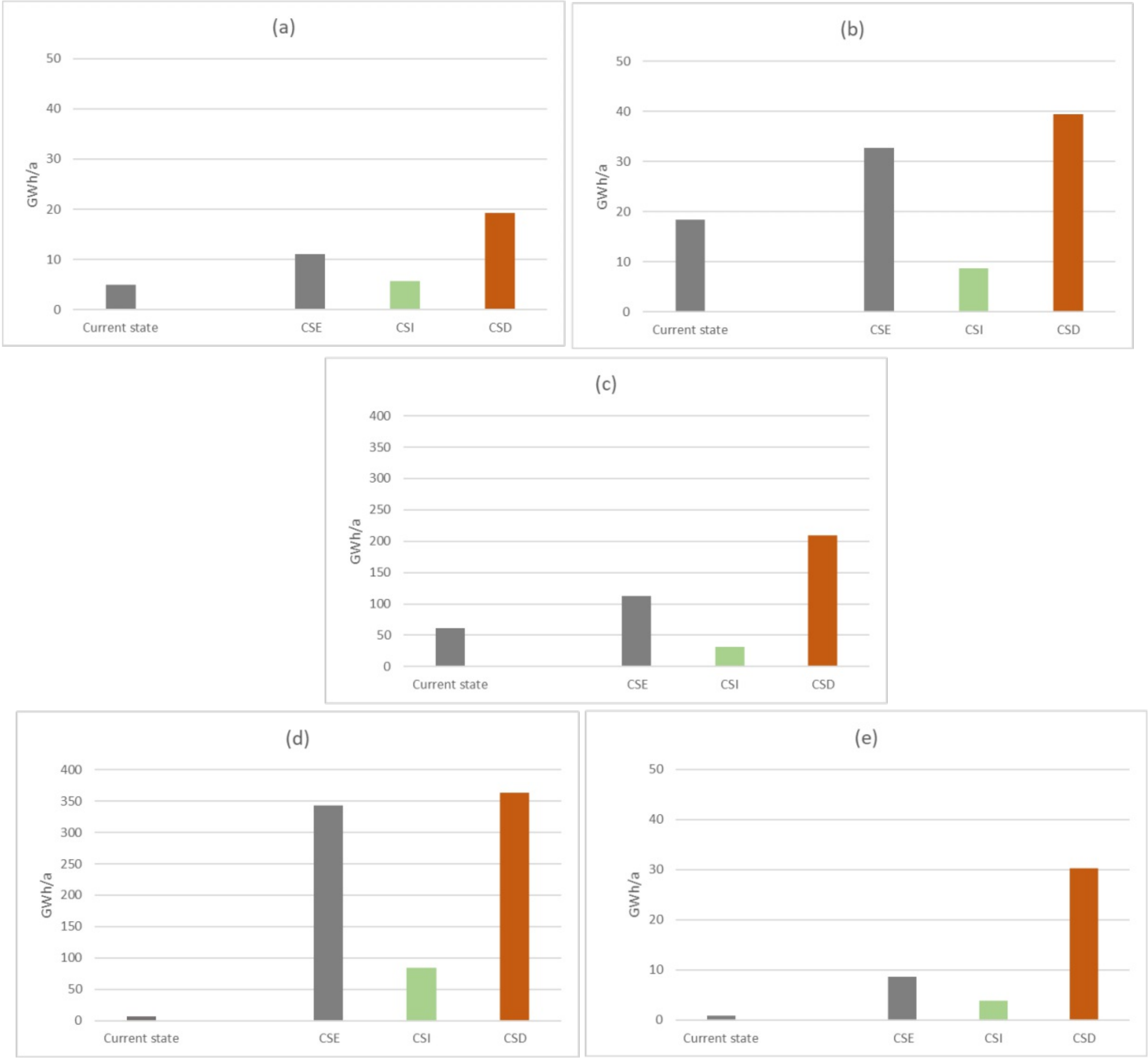


Figure 1. Estimates of energy intensity for water production with the three scenarios (*Current State Extends (CSE)*, *Current State Improves (CSI)* and *Current State Deteriorates (CSD)* for 2030 compared to current energy intensity (2019). Note the difference in magnitude for energy intensity between WSP1 (**a**), WSP2 (**b**) & WSP5 (**e**) and WSP 3 (**c**) & WSP4 (**d**).

4.3.2. Per Capita Energy Use for Water Supply.

Table 9 presents estimates of per capita energy use for water supply in five WSPs. The per capita energy use for water supply is expected to increase as water demand and energy intensity for water supply increases. No change is expected in the per capita energy use for water supply between the current state and the *CSE* scenario. However, per capita energy input is expected to increase by three folds at WSP 4 with the *CSI* scenario due to an increase in energy intensity for water supply attributed to groundwater abstraction and sea water desalination. Furthermore, per capita energy use for water supply is expected to increase twice as much the current use at WSP 5 under the *CSI* scenario due to an expected increase in groundwater abstraction. Although non-revenue water losses are expected to deteriorate and remain high with the *CSD* scenario, per capita energy use for water supply is expected to decrease in comparison to the current state. This is largely due to the very low per capita water consumption that is expected for this scenario among the WSPs.

Table 9. Current state Per capita energy use for water supply and across the CSE, CSI and CSD scenarios.

Water Services Provider (WSPs)	Current State (kW/p/a)	*CSE* (kWh/p/a)	*CSI* (kWh/p/a)	*CSD* (kWh/p/a)
WSP 1	21.5	21.5	30.66	9
WSP 2	52.8	52.8	39.42	12
WSP 3	24	24	39.42	6
WSP 4	37.6	37.6	105.12	7
WSP 5	19.9	19.9	52.56	4

5. Discussion

The water demand-supply gap is likely to widen as population and urbanization accelerates. Although considerable progress was achieved in the proportion of the population with access to improved water services in sub-Saharan Africa, coverage and expansion of service remains low in poorer neighborhoods in expanding urban and rural areas [14]. Many countries in the sub-Saharan have undertaken developed plans and/or measures to improve water service provision to achieve universal access by 2030. For example, Kenya has plans to expand water service provision to achieve universal access to drinking water by 2030. This is an ambitious plan that requires investment in the production capacity, the water supply infrastructure, and accelerated leverage in technology in the water sector [10]. Yet, whereas the current water supply infrastructure remains inadequate, key drivers of water demand such as population, irrigation water needs, expanding middle-class and urbanization of metropolitan areas are expected to increase water demand significantly in the coming years [10]. As observed in the service areas of some of the WSPs in the current study, some WSPs meet less than 50% of the water demand and most supply about half of the minimum daily drinking water requirement of 50 L/p/d. This situation cuts across many WSPs in sub-Saharan Africa [40]. Therefore, in light of the global and regional efforts to accelerate universal water service coverage in sufficient amounts to meet the daily per capita water needs within this decade, there is a need for WSPs to plan well for the projected increase in water demand to address the anticipated increase in the water supply-demand gap and the energy input associated with water supply amidst unpredictable energy prices. In their study on the future of African cities, [41], argue that to reduce the water demand-supply gap in Africa, water-sector players need a wholistic approach to water supply management through integrated water resources management. This would also include among other approaches, matching the water quality to its needs, stormwater harvesting, scaling of wastewater re-use and stage development of alternative water sources. Such approaches present different energy needs for water supply and hence, dynamic water demand and energy management programs should be implemented to address the energy requirements.

As water demand and the drivers of demand change, so does the need to explore new water sources to meet that demand [42]. Some of those additional water sources are typically energy intensive. For instance, proposals for desalination by WSP4 under the *CSI* scenario in the current study could increase energy input by about twelve to fifty times the current energy input for water supply depending on which scenario plays out. Currently, WSP4 relies on the national electricity grid for its energy requirement for groundwater abstraction and distribution. Hence, the proposed shift to desalination will significantly increase the energy requirement of WSP4. Investment in large-scale desalination would require careful consideration of the influence of the increased energy demand on WSP's operational costs. For instance, the energy demand for desalination varies with the water treatment process, with membrane filtration processes including reverse osmosis and nano-filtration gaining increased application as they are less energy intensive compared to thermal processes [36]. Energy intensity for reverse osmosis is estimated to range between 3.5–5.0 kWh/m^3 whereas multi-stage flash thermal distillation which uses heat to vaporize freshwater from sea water consumes up to 80 kWh/m^3 [43]. However, with improved technologies and efficiencies and hybridization of desalination energy sources, lower energy intensities can be achieved for desalination, e.g., about 0.79 kWh/m^3 for reverse osmosis of sea water at 55–70 pressure bars and 26–69 kWh/m^3 for multi-stage flash thermal distillation [34]. Furthermore, the energy costs associated with using conventional grid electricity for raw water abstraction, treatment and distribution compared to decentralized renewable energy options owned and operated by WSPs is important as some WSPs pivot from conventional water treatment processes to energy intensive options such as desalination and additional groundwater abstraction. The most common sources of renewable energy are solar-powered plants, geo-thermal, wind and wave energy [43,44]. However, establishing cost-effective and high-efficiency energy systems are quite difficult to achieve, largely due to cost constrains and environmental concerns [45]. Therefore, hybrid energy solutions have been highlighted in several studies. For instance, [45,46] summarize the energy demand for sea water desalination and water production cost of hybrid desalination process including a combination of reverse osmosis with solar stills, solar ponds, geothermal and wind energy. The choice and design of such alternatives is site-specific and highly dependent on the economic and technical capabilities as well as the local climatic conditions such as solar insolation, wind intensity and ambient temperature. Furthermore, [45,46] provides an evaluation of energy recovery in existing water supply networks through optimal scheduling of pumps, resulting in up to 36% energy use reduction.

The total energy input in a water supply system is either associated with water consumption that is authorized and accounted for or associated with water losses and/or dissipated at consumption nodes within the water supply system [7]. High and unsustainable water losses for some WSPs and the cost of associated energy required to abstract and distribute that water is a huge impediment for achieving planned universal access objectives. The high non-revenue water losses among WSPs could be attributed largely to lack of incentives and/or disincentives to tackle the water loss challenge. As long as the cost of water production remains relatively lower than the cost of repairs of the infrastructure to reduce water losses, most WSPs will opt for increased production to meet rising demand [40]. This, in addition to aging infrastructure, illegal connections and high densities of leakages could partly explain the little progress achieved so far with reducing non-revenue water losses in many developing countries in Africa. The *CSI* scenario assumes reduction of current water losses to 20% by 2030. Such a target especially among WSPs with up to 60% no-revenue water losses require strategic and wholistic water loss management plans and investment. As observed in the current study, there is huge potential for addressing such water losses. For instance, a leakage reduction potential of up to 85% was possible for WSP 1 and about 70% for WSP 2 and 3. This would save the WSPs an equivalent amount of energy needed for water supply. Consequently, achieving such leakage reduction would delay the need to explore additional water sources that are energy intensive at least for a short-term horizon [5].

Leakage control in water supply systems can be addressed following two broad strategies: pressure management and improvement of pipe resistance [47]. A positive correlation exists between water pressure reduction and leakage reduction, with one-unit reduction in distribution water pressure in meters at the inlets of hydraulically separated zones resulting in about 1% reduction in leakage. This invariably have consequences on energy input for water supply. Furthermore, leakages contribute to joint water and energy inefficiencies through increase in water losses in addition to the energy required to deliver the required water pressure at the point of consumption. Pressure management entail location of areas of high pressure and implementation of pressure reduction valves to control pressure at different times of the day depending on water demand [2,33]. On the other hand, pipe wall friction imposes frictional energy dissipation due to age or deteriorating quality which leads to energy inefficiencies which can vary across pipe types and across the water distribution system [47]. Consequently, frequent variations in peak and off-peak daily water demand and intermittent water supply often creates pressure variations which then results in high frequencies of leaks and bursts in the pipe networks [33]. Leakage reduction in water supply requires comprehensive water loss reduction plans, considering the environmental and financial consequences of water loss targets and an understanding of the limit of such water loss reduction programs, beyond which, it is not economically feasible for further reduction [29]. Implementation and follow-up measures to enhance energy efficiency in water supply is a big challenge. For WSPs in low- and middle- income countries with budgetary constraints, it is sometimes considered 'cheaper' to abstract raw water from new water sources than to focus on reducing losses within the system [17]. In addition, the motivation to commit to energy efficiency programs is largely driven by the requirements of water regulators which often attracts penalties and disincentives for non-compliance as opposed to making any financial gains or energy saving associated with such programs [5]. The success of energy efficiency intervention measures is site-specific and depends on the operating environment of the WSPs. Since pumps are the largest energy consuming devices for WSPs, they also present the largest opportunities for energy efficiency improvements [2]. Interventions may include: i) operation of pumps closest to the best operation points ii) correct sizing of the pumps and motors iii) Increasing pipe diameter to match the flow iv) pressure management and leakage reduction v) use of variable speed drives (VSDs) and vi) off-peak pumping and storage facilities optimization [30].

The benefits of pursuing joint water and energy efficiency for water services providers are outlined in [6,8] for Portugal, Romania [48] and Italy [49]. Such efforts lead to saving not only water and the associated energy input but also reductions in the energy costs and energy demand associated with water losses. Strategies to explore a joint energy and water management approach to conserve both water and energy have been summarized in six levels of cost and complexity in implementation [30]. According to the authors, reduction of leakage through speedy detection and repair and increasing the efficiency of energy consuming devices top the list while decentralization of supply and water demand management are ranked fifth and sixth, respectively. Exploration of renewable energy sources and water re-use and recycling rank third and fourth, respectively. In addition, several studies have outlined the benefits of water and energy savings through pump optimization and scheduling [2], benchmarking [1] and leaks and pressure management [30,47]. These benefits are optimized through consideration of the whole system energy consumption, controlling peak demand energy use through investment in water storage and improvement in reliance to the grid energy supply through generation of own energy or investment in renewable energy source. As presented [30], the correct pump sizing to match the water supplied and delivered could save up to 15–25% of the annual energy consumption while investment in storage facilities to maximize pumping at off-peak rates could save between 10–20% of the energy consumption. In addition, as WSPs plan for expansion of the water supply infrastructure to meet the projected demand, knowledge of cost and high-efficiency technology in the market is crucial in the selection of the best technologies that suit the water supply needs of WSPs.

Fulfilling long-term water demand projections and associated energy needed to meet the projected demand requires planning and investment in energy supply systems that are both cost-effective and highly efficient, especially where desalination is proposed as an additional source of water supply. Given the uncertainty in the evolution of water demand and supply drivers, WSPs need to explore strategies for joint water-energy efficiency and innovative integrated water-energy solutions to fulfil long-term water demand through strategic planning. Joint water and energy management efforts implemented through strategic and careful water demand-supply management measures and operational interventions increase the efficient use of both resources and provides opportunities for revenue generation and expansion of water services. This would also benefit realization of the CSI assumptions. In this regard, WSPs can integrate robust water and energy efficiency goals including energy recovery, venturing into renewable energy options and enhanced energy efficiency within their overall decisions on utility management [8]. As noted in [5,49], focusing on efficiency enhancement though regular monitoring of the energy balance ranks better as constant interaction with the major energy consuming processes and stages allows for a better understanding of their operation which delivers additional benefits of saving water and improved reliability. As a long-term strategy WSPs should develop and evaluate comprehensive energy management plans. According to [50,51], an energy management strategy entails a four-tiered process that involves routine and basic energy checks, energy consumption analysis, energy audits and implementation of energy management system as a prerequisite for successful operational sustainability of WSPs, Figure 4). Such a system allows for the auditing and benchmarking of energy use through the management principle of the Plan-Do-Check-Act cycle outlined in the International Standards of Operation (ISO). It should be guided by clearly outlined goals and targets towards system-wide energy use improvement. Furthermore, such a program should effectively respond to changes in the water supply and demand drivers which influence energy demand for water supply, guided by a robust data collection system and monitoring [4].

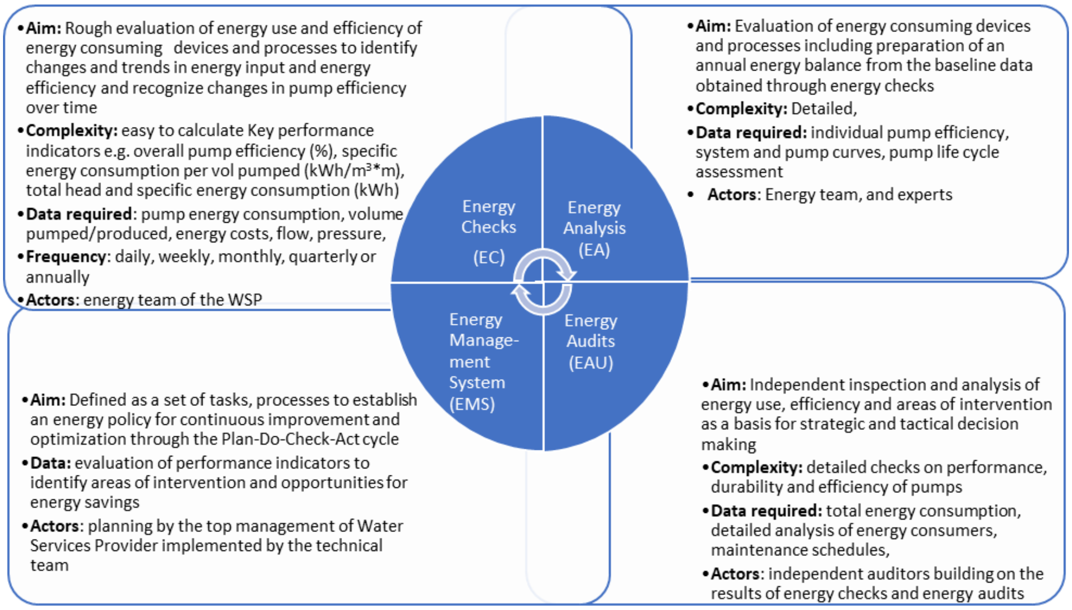


Figure 4. Energy management strategy processes for water supply adapted from [51].

6. Conclusions

An approach to assess the influence of changes in water supply and demand drivers on future energy requirement for water supply against future water demand under three plausible scenarios is presented. Due to expected rapid population growth and urbanization in sub-Saharan Africa, future water demand is expected to increase to achieve universal access to drinking water by 2030. In the Kenyan situation, water coverage in three of the five WSPs selected is below the regulated benchmark of above 80% of the population in the service area and water use is below the minimum recommended daily per capita water use of 50 L/p/d in the service areas of the three WSPs included in the study. Yet, non-revenue water losses are 2–3 times above the benchmark stipulated by the national regulator although a leakage reduction potential of up to 70% and associated annual energy savings of up to 6000 kWh/a was possible.

The projected water demand will necessitate additional raw water abstraction based on analysis of Kenya's 2030 National Water Management Plan (NWMP2030) and the individual strategic plans of each WSP that were examined. For some WSPs, additional groundwater abstraction or desalination of saline water have been proposed, expected to contribute up to 50% of the expected growth in water demand. However, these raw water sources would significantly increase the energy input for water supply even with *Current State Improves* scenario. Consequently, efforts to integrate hybrid decentralized sources of energy should be considered in WSPs tactical and strategic planning.

Reducing current water losses to achieve the regulated benchmark presents opportunities to minimize energy input for water supply. Therefore, it is necessary to jointly address current non-revenue water losses and the associated energy input given that most WSPs showed a high leakage reduction potential. Furthermore, water supply network conditions including the nature, age and type of piping systems which influence water losses and ultimately associated energy input can be considered in future studies. In addition, such interventions could reduce the current water demand-supply gap and increase the daily per capita water use above the minimum requirement that is recommended. This would ensure that WSPs are better prepared to respond to the expected increase in water demand and potentially reduce the need for additional water sources that are energy intensive.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: Trends of NRW, Water Coverage and per capita water production and consumption for all registered WSPs in Kenya. Figure S2: Nine-year trend of selected parameters among selected WSPs. Compiled from WSP performance Reports available at www.wasreb.go.ke. Figure S3: Trends of selected parameters in two additional WSPs illustrating deteriorating water losses, water coverage and per capita water production and consumption. Compiled from WSP performance Reports available at www.wasreb.go.ke.

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Full text submitted paper IV:

Examining the Potential of Applying Energy Metrics to Benchmark Water Service Providers (WSPs) in Africa

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Energy costs account for a significant fraction of the total recurrent operational costs of Water Service Providers (WSPs). However, currently no energy metrics are applied as Key Performance Indicator (KPI) to assess to benchmark WSPs in Africa. This study examines the potential of applying simple energy metrics to assess the performance of WSPs in Africa. The approach was applied for 42 WSPs in Kenya (out of 93 registered WSPs). The average embedded energy for groundwater abstraction, treatment and distribution was 1.08 kWh/m³ (range 0.94 kWh/m³-1.4 kWh/m³) compared to 0.15 kWh/m³ (0.005 kWh/m³–0.61 kWh/m³) for surface water. The average specific energy use per volume billed was 1.59 kWh/m³ (range) and 0.19 kWh/m³ (range) for groundwater and surface water, respectively. However, 14-53% of energy input was associated with non-revenue water loss in the distribution system for WSPs supplying groundwater only and up to 43% for those supplying surface water only. The average electricity cost for water supply was US$ 0.09/m³, estimated at an average 13% of the total operational costs but up to 36% was reported for WSPs supplying groundwater only. The average per capita energy input for water supply was 6 kWh/p/a but WSPs in the “very large” size category averaged at 5 kWh/p/a with a wide range (0.1-20.6 kWh/p/a) given that they supplied mostly groundwater or a mix of groundwater and surface water. The approach demonstrates the potential of applying simple energy metrics to guide WSPs in Africa to undertake rapid energy inventories, identify inefficiencies and manage their energy needs.

Keywords: *benchmarking; drinking water supply; energy metrics; key performance indicator (KPI); water service providers (WSPs)*

1. Introduction

Benchmarking is a strategic tool that measures both performance assessment and performance improvement of firms (Blokland, 2010 in Kurian and McCarney). Benchmarking of energy use for water supply has been carried out at utility level (Molinos- Senante and Guzman, 2018), at process level (Loureiro et al.,2020) and equipment level e.g., pump systems (Livingstone et al., 2015). Benchmarking is a fundamental requirement for Water Service Providers (WSPs), as it helps WSPs to evaluate their performance with time and compare their operations with the processes of best preforming utilities, while being able to identify gaps and define best practices for improvement. However, benchmarking at the level of utility is complicated by the fact that WSPs operate in environments of differing terrains and distances between source and users, abstract and supply varying raw water types with different energy requirements and individual WSPs operational performance and layouts (Krampe, 2013). Furthermore, energy performance changes with time and efficiency of energy consuming devices which is subject to the specific maintenance regimes of WSPs.

The performance of registered WSPs in Africa is benchmarked and regulated based on a set of key performance indicators set by the water services regulatory boards at national and regional level. However, available WSP performance assessment reports of national regulators for instance in Kenya (www.wasreb.go.ke), Zambia (www.nwasco.org.zm) or the regional Eastern and Southern Africa Water and Sanitation Regulators Association (www.esawas.org) show that no energy metrics is considered as a Key Performance Indicator (KPI). Additionally, to the best of the authors' knowledge, performance assessment of energy input for water supply using the energy metrics selected for the current study has not been previously undertaken for WSPs in Africa. Yet, such energy accounting procedures are necessary to identify areas of high energy consumption and those with energy saving potentials. In addition, energy accounting provides crucial information on energy use associated with water loss and the measures necessary on operational efficiency to reduce the energy costs associated with water loss. Furthermore, inclusion of energy metrics in international benchmarking platforms like IBNET (International Benchmarking Network for Water and Sanitation Utilities) could be useful for peer performance analysis. Currently, the only energy use metric available for water supply at the IBNET platform is electricity consumption per unit volume sold and the only data available during the current study was for WSPs in Nigeria and Ethiopia. This makes peer performance analysis and benchmarking difficult. Other immediate benefits include an understanding of energy consumption for various water supply processes, which could translate into improvements in operational efficiency, boosting revenue collection and enhanced operational cost recovery for WSPs.

Currently, there is paucity of information in the literature on energy assessment and benchmarking using energy metrics for municipal water supply in Africa as observed in an earlier review by the authors and reported in Macharia et al., 2020. Energy use for drinking water supply is not a regulatory requirement for performance assessment. Hence, WSPs are not bound by regulation to assess and scrutinize their energy use. In fact, much of the data on energy use are either aggregated or stored in separate files in different departments and/or lack crucial information to perform any meaningful energy audits. In addition, collection of primary data from different WSPs with different types of water supply systems and sources of raw water is typically difficult and time-consuming given that data access must be granted by the WSPs. Consequently, the potential benefits of promoting and enhancing energy efficiency to reduce operational costs are still largely untapped as most WSPs in Africa have poor accounting and understanding and of their energy use patterns (Macharia et al., 2020). Moreover, many WSPs in Africa have incomplete records on the operations and maintenance of their pumps and motors, although these devices consume about 90% of the total energy input (Liu et al., 2012). In addition, there is limited use of modern information and communication technology (ICTs) systems and the ability to leverage big-data techniques to improve operating systems is still very much rudimentary. Such interventions could support system optimization to improve operational efficiency, reduce operational costs and maximize efforts towards the expansion of water services.

The purpose of this study was to examine the potential of applying simple energy metrics to assess the performance of WSPs in Africa by using WSPs in Kenya to apply the approach. Several energy metrics were selected to assess the energy use for water supply processes. In addition, the energy input associated with non-revenue water losses was estimated to show how water loss is directly related to energy use associated costs. The novelty of this work is the applicability of simple energy metrics for which data is readily available to evaluate performance and benchmark the operational efficiency of WSPs in Africa.

2. Conceptual approach of the study

Performance assessment of energy use for water supply systems

Assessment of energy input for water supply has emerged as an important requirement for wholistic evaluation WSPs operational, social, economic, policy and environmental and to guide investment in energy efficiency programs (Bylka et al., 2020). Such assessments are carried out through use of hydraulic models or application of metrics in specific case studies (Mamade et al. 2017). The former is a comprehensive data-intensive assessment which requires calibrated hydraulic models like EPANET and simulations to provide detailed energy consumption at every node including identification of minor head losses on bends and fittings and accounting of the total energy input into water supply system (Mamade et al., 2017). This assessment separates the total energy input associated with billed water consumption and energy input associated with water losses (Delcea et al., 2019). Consequently, it is useful for identifying areas of inefficiencies in the system when water balance calculations are undertaken (Figure 3).

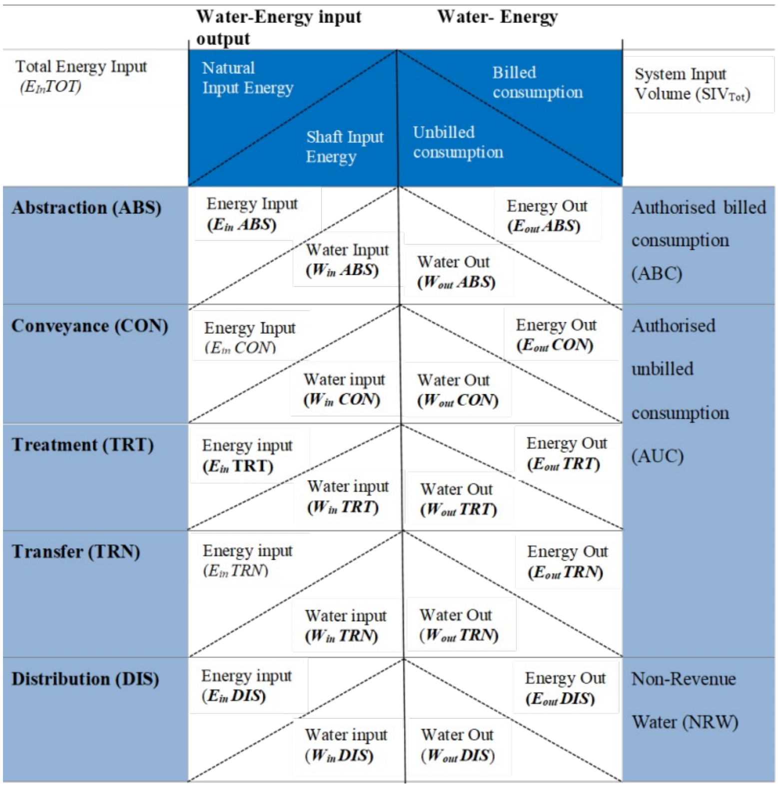

Figure 2: Water-Energy input and output into water supply system processes

On the other hand, simple energy metrics which are less data-intensive, can be applied for energy checks and energy analysis to assess performance and the results can be used to inform detailed energy audits and energy management planning (Mamade et al., 2017). Texeira et al., 2016 has described the process of the development of metrics to assess energy use. It may include: i) a literature search on available metrics and their applicability in individual systems; ii) establishment of a performance matrix based on a set of criteria; and iii) application in a real case study and evaluation for improvement. Although energy use for drinking water supply is largely site specific, application of such metrics is important in informing energy planning and policy, as well as for promoting energy use efficiency in water supply systems through benchmarking.

Indicators and metrics for evaluating energy use for water supply processes

Several energy metrics have been applied for assessing energy use for water supply processes and their applicability vary depending on the objectives of the water sector player (Texeira et al., 2016). For instance, the structural and quality indicators proposed by Pelli & Hitz, 2000 are simple to calculate and provides estimates of the difference between the theoretically minimum energy required to lift water from the source to the user with the required operational pressure and the actual energy used. On the other hand, indicators for dissipated energy due to head losses in the valves and pipe friction, as well as energy embedded in leaks in pressurised systems are complex and require the use of hydraulic models (Cabrera et al., 2014; Mamade et al., 2017). Other indicators include those proposed by Scanlan and Filion (2015) which focus on energy associated with pipe friction and leakage in modelled water distribution systems. Further, the International Water Association (IWA) provides KPIs for assessing pump and utility-wide energy input, which include standard energy consumption for water pumping (*Ph5*), reactive pump energy consumption (*Ph6*) and energy recovery (*Ph7*) in the physical indicators category (*Ph*). The electricity energy cost indicator (*Fi10*) is the proportion of electricity cost from the total recurrent costs in the economic and financial indicators category (Alegre et al., 2016). Other indicators like specific energy input per unit volume of water distributed or specific energy input per unit volume of water billed are aimed at identifying energy inputs associated with non-revenue water (Teixeira et al., 2016).

The terms 'embedded energy' and 'energy intensity' have been used interchangeably to evaluate energy input for water supply processes (Berger et al., 2016). For the current study, the term 'energy intensity' is used to express the energy input for individual water supply processes and 'embedded energy' is used to express the total energy input for all the water supply processes combined (i.e., abstraction, conveyance, treatment, distribution, and auxiliary services). To provide an overview of energy input and associated cost for water supply, the total energy input and energy intensity for water supply processes was estimated. The term 'water loss' is used according to IWA Best Practice Water Balance and Water Loss Performance Indicators guideline, i.e., 'water loss' is the difference between system input volume and authorised consumption (Alegre et al., 2016). The IWA guidelines attributes a significant fraction of Non-Revenue Water to 'water loss', which consists of apparent losses (unauthorised consumption, and customer metering inaccuracies) and real losses (leakage on transmission and/or distribution mains, leakage and overflows at storage tanks, and leakage on service connections up to the point of customer metering).

Table 5 shows the energy metrics applied in the present study. The metrics selected include energy metrics that provide estimates of the total energy consumption, including consumption by water supply processes, metrics associated with energy costs, metrics for energy associated with billed water consumption and metrics for energy associated with water losses. The energy metrics listed have minimal data requirements and they do not require any use of sophisticated hydraulic models. Hence, the metric can be applied for energy checks and energy analysis for WSPs in Africa where limitations exist for complex assessments, irrespective of size, location and type of raw water abstracted and supplied.

Table 5: Energy metrics applied for energy use assessment in the present study.

#	**Energy Metrics**	**Unit**	**Abbreviation**
EI1	Total embedded energy input (electricity use)	kWh	TEEi*
EI2	Energy intensity for water supply processes,	kWh/m³	SEC***
E13	Energy intensity of water supply process as a proportion of total energy consumed	%	IS2
EI4	Specific Energy Cost per unit volume of water supplied	USD/m³	D3*
EI5	Specific Energy Cost per unit volume of water sold	USD/m³	D1*
EI6	Electricity cost as a fraction of total recurrent cost	%	% EC*
EI7	Specific energy for water distributed	kWh/m³	D4*
EI8	Specific energy for water sold	kWh/m³	D5*
EI9	Energy input associated with water losses	kWh/m³	SECWL***
EI10	Per capita energy for water supply	kWh/p/a	EUpC**
EI11	Per capita energy for non-revenue water	kWh/p/a	EUNRWpC**

Sources: Teixeira et al., 2016*; Lam et al., 2017**; Nogueira Vilanova & Perrella Balestieri, 2015***

3. Method

Data Collection

A representative sample of 42 WSPs were selected from 93 registered WSPs in Kenya to provide data on their water supply processes. The criteria for selecting the WSPs was based on the size categorization of WASREB (WASREB, 2020) and the type of raw water abstracted and supplied (groundwater, surface water or mixture of groundwater & surface water). The size categorization comprises: Very Large (VL) WSPs (>35,000 connections), Large (L) (10,000-34,999 connections), Medium (M) (5,000-9,999 connections) and small (S) (<4,999 connections). Most of the selected WSPs were drawn from "Very Large" and "Large" categories. The two size categories represent about 90% of the water market share and the largest proportion of water production among the registered WSPs in Kenya.

Initial contacts were made via email by the lead author to the secretariat of the Kenya Water Services Providers Association (WASPA) (www.waspakenya.or.ke), the umbrella association of WSPs to act as a bridge between the authors and its members. On behalf of the authors, WASPA contacted the selected WSPs to provide information on their operations. Follow-up mails were sent to the WSPs with a detailed structured questionnaire to guide the data collection process. This was followed by at least one visit to each WSP for data collection and interviews with at least one representative of the technical team on the premises of the WSPs.

Thirty-four (34) WSPs responded favourably with sufficient data for the evaluation; 8 WSPs were in the WASREB category "Very Large", 20 were classified "Large", 4 "Medium" and 1 in the "Small" category. Eight (8) WSPs from the 42 selected for the study either provided data that was incomplete and insufficient for the evaluation, or they did not provide the data that was requested. Consequently, they were excluded from the analysis. A minimum of three years of data on operations for the financial years 2015/16, 2016/17 and 2017/2018 was obtained. The data included annual water balance, electricity use and electricity cost. In addition, the WASPA secretariat provided additional data they had collected from the WSPs during a peer-benchmarking exercise they undertook in the financial year 2017/18. Furthermore, a trend analysis of performance of WSPs was performed with secondary data obtained from WASREB annual performance reports.

To ensure data reliability, WASREB performs regular inconsistency checks on the performance data uploaded by each WSP on a designated online portal managed by WASREB. Inconsistent data is usually excluded from all WASREB reports. In addition, the data obtained by the authors were checked for any outliers and clarification requested from the WSPs. Outliers which could not be verified were omitted in the analysis.

Estimation of energy use associated with water supply processes

EI1 - Total embedded energy input (TEEi)

An inventory of energy use for each WSP, the annual electricity input for water supply was estimated by summing the annual electricity input associated with the water supply processes, (i.e., raw water abstraction, treatment, and distribution) and the electricity input for auxiliary services (e.g., lighting, administrative buildings, and operating office appliances). In addition, the proportion (%) of energy input for each water supply process was estimated as a fraction of the total annual energy input. Furthermore, the total embedded energy (electricity) for water supply, (kWh/m³) was estimated by dividing the annual electricity input by the annual volume of water produced as shown in $[TEE]\_i = (\sum E\_A + E\_T + E\_D + E\_Ax)/V$ (Equation 1 (Sanders & Webber, 2012):

$$[TEE]\_i = (\sum E\_A + E\_T + E\_D + E\_Ax)/V \qquad \text{(Equation 1)}$$

Where,

[TEE]_i; Total Embedded Energy (electricity) input in kWh/m³
EA; energy input for water abstraction
ET; energy input for water treatment
ED; energy input for water distribution
EAx; energy input for auxiliary services
V; total annual volume of water produced in m³

EI9 - Energy use associated with water loss (SECWL)

The energy input in water supply systems is categorised into two: the natural input energy which represents the potential energy supplied by storage tanks, reservoirs, or pressurised points outside the water supply system, and the shaft input energy which is energy supplied by pumping stations within the water supply system (Mamade et al., 2017). For the present study, energy input assessed was primarily shaft input as there was no assessment of the energy generated from turbines or pressurised points outside the supply system. Therefore, energy input associated with water loss for the water supply processes was estimated following a similar approach used in (Delcea et al., 2019). Assuming each water process where energy input occurs is represented by *i*, then, the energy input associated with water loss for each water supply process *i* was estimated using equation 2.

$$\mathrm{E}i\mathrm{WL} = W_{WL}^{i} \cdot \sum_{k=1}^{i} \cdot \frac{E^{k}in}{W^{k}in} \qquad \textit{Equation 2}$$

Where;

$\mathrm{E}_{i\mathrm{WL}}$; energy input associated with water loss the process *i*
$\mathrm{W}^{i}_{\mathrm{WL}}$; annual volume of water loss in the process *i*
$E^{k}in$; energy input in water process *k* upstream of process *i*
$W^{k}in$; annual volume of water supplied in process *k*.

Energy use associated with leaks in the distribution system

The energy input associated with leaks is estimated by dividing the total energy input by the volume of water lost through leakage. The volume lost due to leakage and hence the energy associated with the leaks is highly dependent on the number of leaks in the water supply system and the speed of detection and repair.

The volume lost per detectable leak was estimated as outlined in Pillot et al., 2016 (Equation 3).

$$\text{Volume lost per detected leak} = \frac{\text{Total volume lost } (\mathrm{m}^3)}{\text{No.of leaks detected and repaired}} \qquad \textit{Equation 3}$$

Assumption: These estimates assume that 95% of the leaks were detected and repaired. This volume could be higher in some cases depending on the response time between leak detection and repair.

4. Results

Energy input for water supply for WSPs in Kenya

Table 6 shows the total water production and total embedded energy (electricity) for the WSPs during the 2017/2018 financial year. The total electricity input for water supply was estimated at 47 GWh/year with “Very Large” WSPs consuming estimated 27.8 GWh/year and 13 GWh/year by “Large” WSPs. Based on raw water type abstracted, 45% of the WSPs included in the study abstracted and supplied a mixture of groundwater and surface water, 40% abstracted surface water only and 15% abstracted groundwater only (Table 6). More than 70% of the WSPs that supplied mixed raw water types were classified in the “Large” and “Very

Large" categories, accounting for more than 90% of water production and 88% of the total embedded energy (electricity) when the data was pulled for all WSPs combined. "Large" and "Very Large" WSPs account respectively for 31% and 43% of residential water use. "Small" and "Medium" WSPs accounted for a small fraction of embedded energy irrespective of the type of raw water abstracted and processed and accounting for 36% of the residential water use.

Table 6: Total water production and total embedded energy (electricity use) for WSPs in 2017/2018

Size categories of WSPs	Number of WSPs by type of raw water abstracted and supplied			Water production (Mm³/a)	Electricity use (GWh/a)
	Groundwater only	Surface water only	Groundwater & surface water		
Very Large	2	2	4	80	28.5
Large	3	11	7	78	13
Medium	2	0	2	10	3.7
Small	0	0	1	0.8	1.8
Total	7	13	14	170	47

GWh/a: Gigawatts hour per annum

***EI1** - Total Embedded Energy (electricity) for water supply*

Figure 3 presents the average embedded energy for the three financial years. The embedded energy varied with the type of raw water abstracted by the WSPs. The total embedded energy input for the WSPs that abstracted, processed and supplied groundwater only averaged at 1.08 kWh/m³± 0.6 (range 0.94 kWh/m³-1.4 kWh/m³). This was significantly higher than the embedded energy input for WSPs supplying surface water only, which averaged at 0.15 kWh/m³± 0.50 (range 0.005 kWh/m³–0.61 kWh/m³). Some WSPs supply both surface water and groundwater in different proportions. The embedded energy input for those WSPs averaged at 0.63 kWh/m³±0.52 with a wide range of values (0.07 kWh/m³-1.5 kWh/m³). The wide variation in the embedded energy for WSPs supplying a mixture of raw water types compared to those supplying groundwater only or surface water only was expected. Besides differences associated with depth at which raw water was abstracted and variations in the methods of conveyance (e.g., gravity flow or pumping), there were also significant differences associated with the size of WSPs.

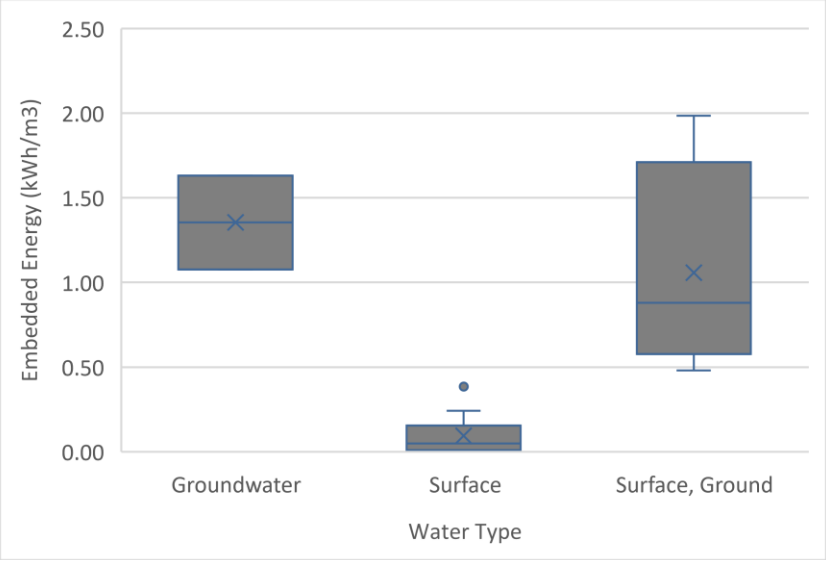

Figure 3: Total Embedded energy (electricity) input for different raw water types

***EI2** - Energy intensity for water supply processes*

The energy intensity estimates for water supply processes are presented in

Table 7. The data was pooled for all the WSPs combined regardless of size categories. The energy intensity for water treatment (Mean: 0.02±0.03; Range: 0-0.04 kWh/m³) was relatively small for groundwater compared to the energy intensity for abstraction (Mean: 0.79kWh/m³±0.35; Range: 0.64-0.94 kWh/m³) and distribution (Mean: 0.84±0.43; Range: 0.54-1.15 kWh/m³), which were on average 40 times more than the energy intensity for treatment. On the other hand, the energy intensity for treating surface water (Mean: 0.06±0.02 kWh/m³; Range: 0-0.16 kWh/m³) was six times more compared to the energy intensity for abstraction (Mean: 0.01±0.02 kWh/m³; Range: 0 - 0.21 kWh/m³) and twice as much compared to the energy intensity for distributing surface water (Mean: 0.03±0.10 kWh/m³; Range: 0-0.65 kWh/m³).The energy intensity for water treatment process irrespective of the water type was 0.02±0.06 ranging between 0-0.2 kWh/m³, most of which was consumed by backwashing pumps and chemical dosers.

The energy intensity for abstraction and treatment was 0.88±0.21 kWh/m³ (Range: 0.49-1.01 kWh/m³) and 0.04±0.45 kWh/m³ (Range: 0-0.20 kWh/m³) respectively, for WSPs that supplied both surface and groundwater combined. There was no significant difference in the energy used for water treatment based on the raw water type. This could be due to the similar water treatment process across the sampled utilities.

When considering distribution, WSPs that supplied a mixture of surface water and groundwater had lower energy intensities (Mean: 0.75±0.11 kWh/m³ (Range: 0.48-0.91 kWh/m³) compared to those that supplied groundwater only (Mean: 0.84±0.47 kWh/m³; Range 0.54-1.15 kWh/m³). The fraction of energy input for water supply processes was lowest for water treatment and auxiliary services, accounting for only 1% of the total energy input for all raw water types combined. For the WSPs that supplied groundwater, the energy intensity for groundwater abstraction represented 64% of the total electricity use for water supply while 33% was associated with water distribution. For those WSPs that supplied surface water, most of the energy input (89%) was associated with water distribution although significant variations were observed among WSPs. Variations were even higher for energy use for abstraction and distribution among WSPs that supplied both groundwater and surface water, ranging between 30-90% of total electricity use. Gravitational flow played a role in water abstraction (surface water) and distribution in some WSPs which could explain the relatively low energy intensities for some WSPs.

Table 7: Energy intensity for water supply processes for WSPs grouped by raw water type

	Abstraction		**Treatment**		**Distribution**	
WSPs	Mean (kWh/m³)	Range (kWh/m³)	Mean (kWh/m³)	Range (kWh/m³)	Mean (kWh/m³)	Range (kWh/m³)
Groundwater	0.79	0.64 - 0.94	0.02	0 - 0.04	0.84	0.54 - 1.15
Surface water	0.01	0 - 0.21	0.06	0 - 0.16	0.03	0 - 0.65
Surface water & groundwater	0.88	0.49-1.0.1	0.04	0 - 0.20	0.75	0.48 - 0.91

***EI4** - Specific energy for water distributed and **EI5 -** specific energy for water sold.*

The specific energy water distributed and specific energy for water billed are presented in

Table 8 for the raw water types. There was a significant variation in the specific energy input per unit volume of water distributed and billed for the raw water types. The specific energy per unit volume of water billed was higher than the specific energy per unit volume of water distributed for all raw water types. The differences between the specific energy per unit volume of water distributed and the specific energy per unit volume of water billed represents the energy input associated with physical water loss in the water supply network. This is the energy input associated with Non-Revenue Water (

Table 8). For groundwater, the specific energy per unit volume of water billed (1.59 kWh/m³) was higher than the specific energy per unit volume of water distributed (1.08 kWh/m³). This was also observed for the estimates derived for surface water, i.e., 0.19 kWh/m³ and 0.10 kWh/m³, respectively, for the specific energy of water billed and specific energy for water distributed.

Table 8: Specific energy and energy input associated with water loss (averages with range in brackets)

Type of raw water	Specific energy input/volume distributed kWh/m³	Specific energy input/volume billed kWh/m³	Energy use associated with non-revenue water kWh/m³
Groundwater	1.08 (0.18-1.29)	1.59 (0.35-2.29)	0.51
Surface water	0.20 (0.01-0.38)	0.39 (0.02-0.61)	0.19
Groundwater & surface water	0.40 (0.05-1.71)	0.80 (0.08-2.47)	0.40

Specific energy per unit of water distributed and specific energy per unit of water billed

Figure 4 presents the specific energy per unit volume of water distributed and the specific energy per unit volume of water billed for the WSP categories by size. The specific energy per unit volume of water billed for all the WSP categories was higher than the specific energy per unit volume of water distributed. As stated earlier the difference between the two could be attributed to energy input associated with non-revenue water. For example, for "Very Large" WSPs the average energy input associated with non-revenue water was for the three years was 0.28 kWh/m³ while that of "Large" WSPs was 0.25kWh/m³. The results show that specific energy per unit distributed and billed was higher in 2016 for all WSPs. However, the specific energy per unit billed for "Very Large" WSPs was significantly higher in 2016 compared to the other years. It is to be noted that size categorization of WSPs is reviewed yearly based on the increase in number of connections within the service area and thus the comparison of selected energy metrics by size may be influenced by the movement of WSPs from "Large" to "Very Large" or from Medium to Large size category.

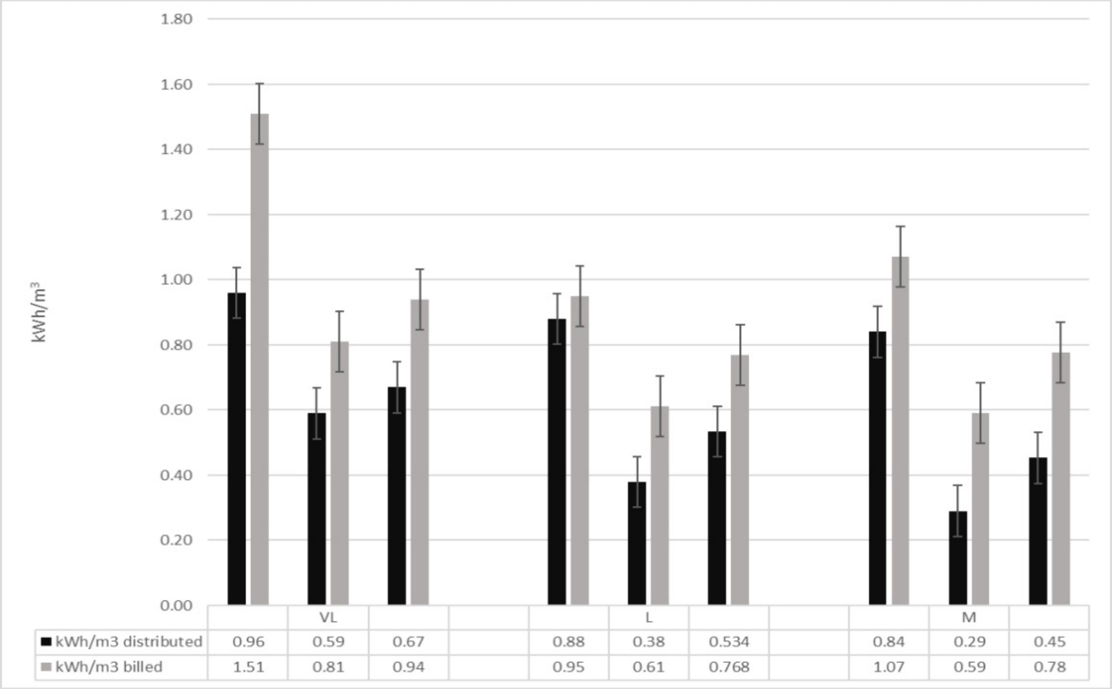

Figure 4: Specific energy intensities of WSP (VL: Very Large; L: Large; M: Medium) for 2016 (left), 2017 (middle) and 2018 (right).

***EI6** - Cost of electricity per unit volume of water sold (EC)*

The average cost of electricity per unit volume of water produced averaged at 0.03±0.1 US\$/m^3 and 0.05±0.2 US\$ per unit volume of water billed among the “Very Large” WSPs while the cost of electricity per unit volume of water produced and billed among the “Large” WSPs was 0.01 US\$/m^3 and 0.02 US\$/m^3 respectively (Table 9). The highest observed values (0.7 US\$/m^3) were for the Small WSP category, but it is to be noted only one Small WSP provided data. The cost of electricity as a percentage of total recurrent operational cost averaged at 13% (range 0.5-36%) for all WSPs combined. The median values presented show the huge variation in the cost of electricity due to differences in water supplied, mode of conveyance and energy data aggregation.

Table 9: Median electricity cost per unit produced and unit billed and the proportion of electricity cost for different categories of WSPs. (Range values in brackets)

Site category of WSPs	Electricity cost (% total recurrent costs)	Unit electricity cost (US\$/kWh)	Electricity cost per volume produced (US\$/m^3)	Electricity cost per volume billed (US\$/m^3)
Very Large	6 (1-23)	0.18	0.03 (0*-0.2)	0.05 (0*-0.7)
Large	1.7 (0*-36)	0.18	0.01 (0*-0.3)	0.02 (0*-0.4)
Medium	22 (0.5-25)	0.20	0.20 (0.2-0.3)	0.30 (0.2-0.7)

Small	35	0.20	0.7	0.7
All WSPs	13 (0.5-36)		0.06±10.7 (0-0.5)	0.10±18.5 (0-0.8)

* The bills provided by the WSPs do not show disaggregate costs for electricity input for water supply processes

__EI10__ - Per capita energy use and __EI11 -__ energy use associated with water loss

Estimates of the total energy input among selected WSPs were 47 GWh/a. However, the energy use associated with water loss was estimated at 33.6 GWh/a. It was higher among “Very Large” WSPs (23.4 GWh/a) which supplied groundwater, or a mixture of groundwater and surface water (Table 10). The per capita energy input associated with water loss was higher among “Very Large” WSPs which also reported the highest non-revenue water (57%).

Per capita energy use for water supply is highly influenced by the type of water supplied and the distance between source and users. The estimated per capita energy input for water supply was 6 kWh/p/a (range 0-20.6 kWh/p/a). Further, in comparison to the Very “Large” and the “Medium” WSPs, the “Large” WSPs category had the lowest per capita energy use (median was 2.5 kWh/p/a) for water supply as they mostly supplied surface water, which had the lowest embedded energy intensity.

The median per capita energy use for non-revenue water among all WSPs water was 3.5 kWh/m^3, representing 48% of the total energy input. This indicated that almost half of the per capita energy use for water supply was associated with non-revenue water losses. The proportion of energy input associated with non- revenue water for the WSPs under study averaged at 48%, which was almost half of the total energy input for water supply.

Table 10: Per capita energy and energy input associated with Non-Revenue Water (NRW)

Size category of WSPs	Per capita energy input for water supply (kWh/p/a)	Per capita energy input associated with NRW (kWh/p/a)	Energy input associated with NRW (GWh/a)	Energy input associated with NRW (expressed as % of total energy input)
Very Large	5.1±7(0.1-20.6)	10±14 (0.1-39)	23.4	61
Large	2.5±3.4 (0.02-12)	4.1±5.8 (0.02-21)	7.8	47
Medium	4.9±3.3 (0-9)	7.7±4.6 (0-12)	2.4	57
All WSPs	6	3.5	33.6	47.9

EI9 *- Energy input associated with water loss*

According to the IWA's water balance, leaks are classified as a proportion of real water losses in the water supply systems. Figure 5 presents leak loss for WSP categories in 2016/17 and 2017/18. There was a huge variation in leak loss especially for "Large" WSPs in 2016 with up to 13000m^3/year leak loss. "Very Large" WSPs reported higher leak loss in 2017 compared to 2016 with a maximum leak loss of 8,400m^3/year. A closer examination of the data showed there was only a slight difference in leak loss for the WSPs between the two years. Movement of WSPs from "Large" to "Very Large" could have contributed to the observed increase in 2017 for the "Very Large" category.

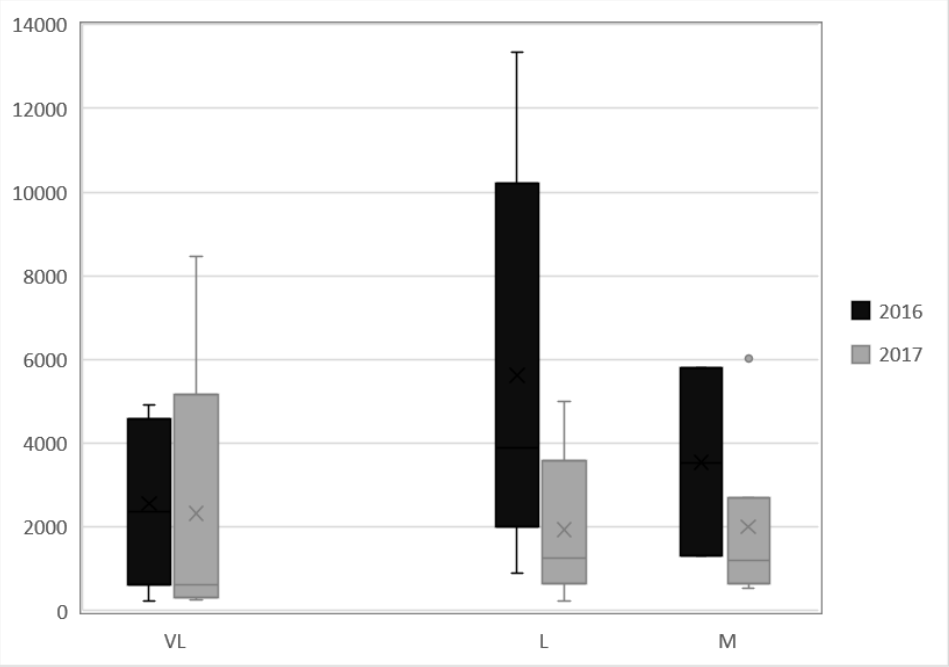

Figure 5: Estimates of leak loss for WSPs (VL: Very Large; L: Large; M: Medium) in 2016 and 2017

The energy associated with leaks for WSPs is presented in Table 11. Although there were huge variations among and within WSPs categories, the energy associated with leaks was three times higher in 2016 compared to 2017 for "Large" WSPs. "Very Large" WSPs recorded up to five times higher energy use associated with leaks in 2016 compared to 2017. This category of WSPs also recorded higher energy input associated with leaks compared to the other WSP categories.

Table 11: Comparison of energy input associated with leaks (Kwh/a) for WSP in 2016 and 2017

Size of WSPs	**2016** **Median**	**Min**	**Max**	**2017** **Median**	**Min**	**Max**
Very Large	2364	579	6258	497	313	2029
Large	1181	147	8722	325	88	1325
Medium	1013	418	1178	209	127	2672
All	1414	147	8722	326	313	2672

The energy input associated with total water loss along the water supply processes is presented in Table 12. The specific energy input associated with water loss for groundwater supply was 1.34 ±3.7 kWh/m³ while that of surface water was 0.192 ±1.6 kWh/m³. The lower reported values for energy losses for surface water supply could be attributed to the fact that most of the WSPs that supplied surface water had smaller energy budgets as they relied on gravitational flow for water distribution. The fraction of energy input associated with the water treatment process ranged between 0.18-5.1%, which may be associated with leaks and overflows within the water treatment plants. The energy input associated with groundwater distribution process were up to 53% and 43% for surface water distribution. It is to be noted that the electricity consumption at some WSPs was not disaggregated into processes and such data was thus difficult to assign the energy use and energy dissipated along the water supply processes.

Table 12: Energy input associated with water loss computed for raw water types and water supply processes

Type of raw water	**SECWL (kWh/m^3)**	**% Energy input in treatment**	**% Energy input in distribution**
Groundwater	1.34±3.7 (0-8.2)	0.18-5.1	14-53
Surface water	0.192±1.6 (0-3)	0-0.01	0-43
Ground & Surface	0.529±1.1 (0-5)	0-0.3	4.4-19

SECWL: Specific Energy input associated with Water Loss for different raw water types

5. Discussion

There is growing attention to the energy use for water supply due to the undisputed role of energy in the operational sustainability and economic viability of water supply services. As water demand grows, so does the need to focus on operational areas where water, energy and revenue savings are possible as energy demand is also likely to increase due to rapid population growth and exploitation of new energy- intensive water sources as well as stricter regulatory requirements (Molinos-Senante and Sala-Garrido, 2018). This is especially important for WSPs in Africa where such savings are largely unexplored, although it is needed to support measures on accelerating coverage of water supply services to the rapidly growing population.

Energy requirements for water supply varies with water treatment technology, level of pollutant removal, terrain, type of raw water, the state of water supply infrastructure, the population served (number of connections) and operational efficiency of energy consuming devices (Plappally & Lienhard, 2012; Lam et al., 2017). Performance assessment of energy use for water supply could forms the basis for benchmarking energy use for water supply across countries and regions. For systems abstracting groundwater, energy input is highly dependent on the pump efficiency, pump and piping characteristics and the depth of the wells (Lam et al., 2017; Wakeel et al., 2016). Total embedded energy for groundwater supply has been reported to be 27% higher than surface water supply (Wakeel et al., 2016). However, there is a huge variation in the reported energy use for different regions. For instance, the observed embedded energy for groundwater supply for the WSPs in Kenya was 1.08 kWh/m³± 0.6 (Range: 1.03-1.4 kWh/m³). This is higher compared to the range values reported by for WSPs in South Africa (0.3-0.44 kWh/m³) California, U.S.A (0.14-0.69 kWh/m³) and Sydney, Australia (0.48-0.53 kWh/m³) (Wakeel et al., 2016: Gobin et al., 2019). The Embedded energy for surface water supply computed in the present study (0.005 kWh/m³–0.61 kWh/m³) was comparable to that reported estimated in China (0.13-0.20 kWh/m³) and in Australia (0.20 kWh/m³) (Plappally & Lienhard, 2012; Wakeel et al., 2016).

On the other hand, the energy input for treatment systems abstracting and processing surface water are largely driven by the nature of infrastructure, treatment technology, the topography, the local climatic conditions and the distance between source, treatment and end users (Wakeel et al., 2016). The specific energy input for water supply processes is driven by several factors, including topography, depth of groundwater wells, the distance between raw water source and consumers, the quality of the raw water and treatment technology. Energy use for water treatment in conventional water supply systems is mostly for chemical dosage and backwashing. For the WSPs in Kenya, the energy input for water treatment was 0-0.2 kWh/m³ for all raw water types combined. In comparison, energy input for water treatment was 0.16-0.25 kWh/m³ for treatment systems in Taiwan (Wakeel et al., 2016). In South Africa, Gobin et al., 2019 reported 0.3-0.4 kWh/m^3 for groundwater treatment and 2.16 kWh/m³ for treating mine water reclaimed. Among the water supply processes, water distribution is reported to have the highest energy input (about 60% of the total energy use in water WSPs that largely rely on direct pumping). For instance, in Germany, the energy use for water distribution was reported to be 1.71 kWh/m³ and 1-2 kWh/m³ in Australia (Sharif et al., 2019). In contrast, most of the WSPs in the present study relied on gravitational flow for water distribution. Hence, their energy input for distribution were comparatively low.

The cost of electricity for water supply influences WSPs revenue generation, the financial sustainability and potential recovery of operation and maintenance costs. These costs vary with the operational environment of the WSPs, the type of raw water and the means of conveyance of raw and treated water, with the highest electricity costs being for water groundwater abstraction. The electricity tariff provided by the national electricity provider (Kenya Power and Lighting Company) for WSPs ranged between US$ 0.18/kWh and US$ 0.20/kWh. The cost of electricity for water supply averaged at 13% of the total recurrent expenditure while the unit cost per unit volume of water supplied was 0.12±0.2 US$ was in the same range (0.14 US$ per unit volume) reported by (Nogueira Vilanova & Perrella Balestieri, 2015) for Brazilian water supply. Energy costs for water supply could range between 5-30% of the total operational running cost (Liu et al., 2012). Limaye & Welsien, 2019 reported electricity costs for water and wastewater services as a fraction of total running cost for Bulgaria (19%), Nigeria (32%), Vietnam (34%), Bangladesh (40%) and Iraq (55%). The cost for energy input is one of the most controllable operational costs for WSPs, with short payback periods between 1-5 years on investment. Some of the energy efficiency measures with potential to reduce energy use for water supply include comprehensive water demand and supply interventions like correct pump sizing and scheduling optimization leaks control and water loss reduction and comprehensive pump energy efficiency assessments and benchmarking (Luna et al., 2019). Such measures geared to improve electricity consumption and reduce energy costs provide WSPs with quick-to implement opportunities to make full recovery of operational and maintenance costs and allow for expansion of service coverage.

Analysis of the energy input for water supply in Kenya show high energy requirements especially for abstracting groundwater. This is contrary to what have been reported elsewhere, with over 90% of energy input for water supply directed for water distribution (Dziedzic et al., 2015; Limaye & Welsien, 2019). For WSPs in Kenya supplying a mixture of groundwater and surface water, highest energy consumption was for water abstraction since distribution was largely gravity-fed. This implies that energy management options for such WSPs should largely focus on identification of areas of energy inputs associated with water loss within the system to develop appropriate energy management interventions. Such plans guided by a systematised data collection and processing of energy metrics could focus on operational efficiency of the energy-consuming devices within the water supply system.

The Energy input associated with water loss vary with the operating environment of WSPs (Plappally & Lienhard, 2012). WSPs that largely depended on gravitational flow for abstraction and distribution are favoured by terrain. Although such WSPs may record huge water loss, their energy demand can be quite low. The proportion of energy use associated with water loss for the WSPs was 48% which was equivalent to an associated energy input of almost 34 GWh/a. Water loss was highest among "Very Large" WSPs which was attributed to the relatively large and extensive water supply network of this size categories of WSPs and deficiencies in the infrastructure of their water supply systems. If WSPs operated at the regulated benchmark in Kenya of 25% for non-revenue water loss, water loss could reduce energy use to 35 GWh/a, and save approximately 11Gwh/a. At a unit cost of electricity of about US$ 0.18/kWh, the energy use associated with water loss is approximately US $60,000 per annum among the Very Large WSPs.

Although WSPs are aware of their energy costs and the impact on their operational sustainability, their attention currently now is largely concentrated on investments in water loss controls, which only partly addresses what is a bigger problem, including aged and inefficient pumps and motors. It is estimated that about 40% of the energy input of WSPs (and in some cases up to 90%) are mainly for running pumps and motors (Luna et al., 2019). Therefore, a joint water and energy management programme is useful for both long-term and short-term decision making to reach optimal benefit on service reliability, expansion of coverage and environmental benefits of greenhouse gas reduction. Such an energy management programme entails assessment of inefficiencies through a comprehensive diagnosis of the system processes as outlined in a framework developed for assessing energy efficiency in urban water systems by Dália Loureiro et al., 2020. The analysis can be followed by prioritization of the processes and areas for intervention with high potential return on investment and short payback periods. They are aimed at promoting efficiency (Luna et al., 2019), enhancing sustainability of water supply systems (Vakilifard et al., 2018), reducing greenhouse gases emissions and improving the cooperate footprint of WSPs (Meng et al., 2019).

The joint management of water loss and associated energy use in municipal water supply systems have been addressed elsewhere, for example, the energy and water conservation measures presented in the energy use assessments for the water systems in Brazil (Nogueira Vilanova & Perrella Balestieri, 2015) and in England and Wales (Majid et al., 2020). Others like the "Watergy" approach, which was coined by the Alliance to Save Energy for WSPs and municipalities, identify areas of intervention to reduce water loss and energy use, and increase revenue generation (Liu et al., 2012). The "Watergy" framework identifies four areas of intervention with opportunities to reduce water loss and associated energy use, including improvements in the pumping systems, leaks management, leveraging on technology and regular monitoring and maintenance of the distribution network. On the water supply-side, reduction in leaks and water loss by improving pumping systems through pump operation scheduling and pumping water at off-peak hours of electricity supply to take advantage of off-peak electricity tariffs may yield 5-10% energy cost savings and a further 3-7% through optimization of pumps and motors (Liu et al., 2012). Additionally, about 30% gains are possible through installation of correct sized pumps and motors or by using variable speed drives. On the demand-side, metering water use is crucial for improving revenue collection and ensuring that consumers use water more efficiently. WSPs in Kenya generally report excellent performance of about 98% for metering (WASREB, 2020). In addition, several WSPs have introduced prepaid metering of water services which reduces wastage and illegal connections and consumption of water.

Energy efficiency measures typically have immediate impacts on energy and water savings and regular assessment of the electricity consuming devices provides a better understanding of the system and make troubleshooting easier (Voltz and Grischek 2018). However, several barriers which hinder implementation of energy efficiency measures in water supply systems exist. The barriers include poor operational data management to guide prioritization of interventions, limited budgets, and limited knowledge on choice of technological interventions that are appropriate to address specific needs. Some of these challenges were observed, making the application of energy metrics for assessing performance and benchmarking WSPs difficult. Generally, the motivation by the WSPs to improve energy use for water supply is low. In fact, none of the WSPs included in the current study had ever implemented an energy management plan. In addition, data aggregation on energy use was widespread. Most of the energy metrics applied require disaggregate data to assess water system processes and energy consuming devices separately. This is crucial for routine energy checks to identify deficiencies at energy use points in the water supply system. In addition, there were data gaps and inconsistencies on crucial data like pump operating hours and pump efficiency curves were largely unavailable as most WSPs carry out reactive maintenance. A comprehensive database on energy use would be crucial in tactical and strategic planning on energy use for water supply systems.

6. Conclusion

The energy metrics applied vary significantly with size of WSPs and the type of raw water they abstracted and supplied. The results demonstrate the need for WSPs to regularly monitor their energy use and evaluate their performance to identify gaps and best practices for improvement. The approach can be applied by WSPs to facilitate analysis of energy consuming processes and devices of their water supply systems. The metrics applied could be useful to operators of water systems to perform energy checks and energy analysis useful for planning towards long-term energy management plans. Regulatory authorities in Africa should increase their attention to energy use in national and regional benchmarking efforts and consider the inclusion of energy metrics among the Key Performance Indicators (KPI) for performance assessment of WSPs.

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