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Review

Sustainable Water Infrastructure: Visions and Options for Sub-Saharan Africa

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Abstract: Developing a sustainable water infrastructure entails the planning and management of water systems to ensure the availability, access, quality, and affordability of water resources in the face of social, environmental, and economic challenges. Sub-Saharan Africa (SSA) is currently in an era where it must make significant changes to improve the sustainability of its water infrastructure. This paper reviews the factors affecting water infrastructure sustainability and the interventions taken globally to address these challenges. In parallel, it reflects on the relevance of these interventions to the context of Sub-Saharan Africa through the lens of the STEEP (societal, technological, economic, environmental, political) framework. The paper goes on to recommend an extended analysis that captures additional critical dimensions when applying the concept of sustainability. Furthermore, this paper sheds light on the practice of sustainable development and fosters a deeper understanding of the issues, thereby forming the basis for further research and the development of sustainable and resilient solutions for water infrastructure and water asset management more generally.

Keywords: sustainability; water infrastructure; drivers of change; Sub-Saharan Africa

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1. Introduction

Water has always been a fundamental resource since the dawn of civilization, and it was not just essential for existence; it was an integral part of the way humans expressed their thoughts and emotions [1]. For centuries, communities settled and thrived where they were close to water bodies, and the unavailability of water resources, sanitation systems, and infrastructure led to diseases and premature death [2]. Since then, water supply has remained a significant part of social organisation and the structural dynamics of human societies [1]. Subsequently, the relationship between water, fertile land agriculture and food production, and social organisation has led to major changes in the way societies have evolved and developed over time.

However, the global availability of water is not limitless. More than 71% of the Earth's surface is covered with water, with the oceans holding 96.5% of it, but only about 3% being fresh water. Out of the 3% freshwater sources, it is estimated that 69% of this is in glaciers, 30% is underground, and less than 1% is in lakes, rivers, swamps, soil, and the atmosphere. Additionally, water is continuously moving in the hydrological cycle, and climate change is projected to have significant effects on the hydrological cycle. These include sporadic changes in precipitation patterns, causing droughts, floods, and increased temperatures, leading to more evaporation and less availability of water in lakes and rivers, as well as the changes in the general quality of water, such as increased contamination and salinity [3].

Furthermore, this very important resource has an uneven spatio-temporal distribution on the surface of the Earth, making some geographic areas more vulnerable to physical and/or social access. In addition to climate change, the global population is expected to increase from around 8.0 billion in 2022 to 11.2 billion by 2100, with about 70% of this growth being in developing countries [4]. The global urban population living in water scarcity is projected to increase from 933 million in 2016 to approximately 2.4 billion in 2050 [5]. This increase in the demand for and the decrease in the supply and quality of freshwater will put significant stress on the global water resources, as well as on the inadequate and ageing asset infrastructure in most cities. Therefore, there is a growing necessity to incorporate sustainability and resilience in water infrastructure planning and management.

1.1. Sustainable Water

The introduction of the concept of sustainability can be traced back to German forestry scientist Hans von Carlowitz in a published work in 1713 [6], where it was proposed that for sustainable forest management, the number of trees cut down at any point in time should not exceed the number of trees grown. This was later adapted by the Brundtland Commission to define sustainable development as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [7]. As per this definition, sustainability in the water industry is achieved when the abstraction rate from water sources per unit time is as much as the natural or artificial recharge rate [6]. According to Loucks [8], the sustainability of water resources is a concept that encourages the active consideration of future and long-term objectives, alongside current targets in the way water resources are managed. Briefly, sustainable water infrastructure entails the planning and management of water systems to ensure the availability, access, quality, and affordability of water resources in the face of social, environmental, and economic challenges. This, however, poses significant difficulty to accomplish, not least when competing/conflicting agendas ensue.

The challenge of efficiently managing water infrastructure systems is not uncommon to both advanced and developing countries alike [9]. For advanced economies, the challenge mostly is in managing an already existing but ageing infrastructure, and ensuring robust policies and regulations for resource and infrastructure management are in place, while dealing with the challenges of climate change and population increase in a sustainable and resilient way [10]. However, the challenges associated with water resource management in Sub-Saharan Africa are far more complex and multi-faceted than in other regions. First, the supply is limited in quality and quantity, due to inadequate infrastructure and weak policies to ensure their maintenance and improvement. Second, there is an increase in demand due to the rapid population growth, socio-economic development, and rapid urbanisation, which is worsened by climate change. These challenges can be categorised into two major competing agendas, which Briscoe [11] dubbed the old and new agendas. The old agenda constitutes the general lack of water and sanitation services, while the new agenda comprises challenges associated with delivering these services in an environmentally sustainable manner.

Based on the literature, several challenges are impacting access to clean water in Sub-Saharan Africa. These include but are not limited to unequal access; water scarcity; water quality; financial challenges; poor governance; inadequate policy and institutional frameworks; human resource constraints; cultural beliefs; pollution; corruption; and resource (and project) management challenges [11–18]. These challenges are exacerbated by the fact that wastewater management is in its infancy, and untreated wastewater is mostly disposed of in water bodies or wetlands, endangering human and aquatic ecosystems [16].

This is particularly concerning since the financing of water infrastructure management in most SSA countries is dependent on government funding, which is largely insufficient to cover all costs, including operation and maintenance [19]. Governments in SSA are also often politicised and bureaucratic, and are plagued with inefficiencies, meaning that there is either no service, services are of poor quality, or services are heavily rationed with little or no incentive for sustainable management [20]. Furthermore, the industry is heavily subsidized and supply driven; when rationed, it is the rich who are connected to the municipal supply and its benefits, and the poor people are left to pay excessive amounts for basic water services via alternative sources [16].

Over the past few decades, countries in SSA have invested significantly in water infrastructure development to stimulate socioeconomic development [13,14]. However, according to the African Water Vision 2025, access to clean water services remains, at best, difficult, and at worst, non-existent, particularly in rural communities [21]. Furthermore, and in addition to the physical infrastructure (assets), there is a need for policies and institutions to be established for the successful management of the system as a whole entity (i.e., Integrated Sustainable Water Resource Management—ISWRM). Irrespective of the progress in meeting Sustainable Development Goal (SDG) 6 (i.e., Clean water and sanitation for all), several challenges remain: the performance of water infrastructure systems in SSA has been broadly perceived as unsatisfactory, both in terms of the impact on the environment and in terms of the output [20]. The management, operation, and maintenance of publicly provided infrastructure services have been inefficient, which puts a lot of strain on public finances and provides few or no benefits to the end-users [11,14]. A recent World Bank report on the performance of water utilities in SSA classed water infrastructures as weak, and, even though there is a huge variance in the performance of utilities for different SSA countries, they propose that there is a need for improvement in governance and for balancing revenue sufficiency and affordability [20].

Even though several studies have been carried out, and considerable resources have been invested in the research for sustainable water infrastructure planning management in SSA, most of the solutions proposed are political and follow a top-down approach [20,22,23]. Moreover, the interaction among the pillars of sustainability (i.e., Environmental, Economic, and Social) and resilience is complicated further by their intrinsic uncertainties, meaning that SSA cannot continue to deliver services in the usual way and somehow expect different results. There is a need to move away from siloed thinking and piecemeal approaches, as is the status quo, and to better prepare/plan for the future [24]. A more transdisciplinary approach involving all stakeholders for the collaborative identification of the challenges and propositions of solutions is recommended [25]. This starts firstly with understanding the system, the relationships between and among the different components, and identifying the drivers of change (Section 3). Rational decisions would have to be made to ensure that the future trajectory and the resulting solutions account for all the elements of sustainability and in their right proportion. There is, therefore, a need for research that inspires a paradigm change in the design, implementation, management, operation, and maintenance of water infrastructure systems.

1.2. Scope and Structure

The purpose of this paper is to provide a general overview of the factors affecting sustainable water infrastructure in SSA, the interventions that have been employed globally to tackling similar challenges, and their relevance to SSA through the lens of the STEEP framework. This article seeks to contribute to the larger global conversation by presenting an in-depth analysis of the status of the relevant literature on the integration and incorporation of sustainability and resilience in the planning and management of water infrastructure systems. Water infrastructure in this article refers to both hard and soft infrastructure. Hard infrastructure entails the physical systems needed for efficient water storage, distribution, and management, while soft infrastructure refers to the people, skills, policies, regulations, and institutions necessary for the provision of water services. The focus is on assessing the research status globally and the applicability to SSA, and exploring the potential insights and lessons that can be derived from this analysis. We conclude with a summary of the findings, identifying the knowledge gap and outlining areas for further research.

The rest of this paper is structured as follows. Section 2 looks at the key drivers of change that influence sustainable infrastructure and future resilience, and outlines some of the common frameworks used to describe these factors. This section goes on to investigate the global interventions in the water sector and their applicability to SSA through the STEEP framework. Section 3 concludes the paper with directions and recommendations for further research.

2. Drivers of Change

The world is shifting away from the conventional attributes we recognise, to one plagued with complexity and uncertainty [26]. To enhance decision making and move towards proactive rather than reactive choices, it is essential to gain a deeper understanding of the forces driving this change.

Within the futures research community, there is a consensus that these drivers of change can be collectively represented by acronyms, such as STEEP (i.e., social, technological, environmental, economic, political). However, several other modifications do exist, and debate also exists as to which is most preferred. For instance, Ratcliffe and Sirr [26] identify nine forces that are driving change in human and built environments. Another example is Outsight's 21 Drivers for the 21st Century™, developed to help challenge the current norms, allowing people to rethink the future [27]. Additionally, the 'Drivers of Change' cards were developed by ARUP for the engineering community in order to help decision makers to effectively plan for the future. These cards follow the STEEP framework and consist of sets of colour-coded cards, produced for eight topics—water, energy, climate change, urbanisation, demographics, poverty, waste, and food—with twenty-five questions on each topic [28]. In considering the drivers of change, the context and research area, to a great extent, determines the level of detail to be employed, and the types of drivers to be examined [29]. As SSA makes critical decisions and balances design options for tackling challenges of both old and new agendas, it is essential to imagine/visualise/create the future they want. This requires a better understanding of the driving forces that affect change, and the planning of pathways toward a more desirable future.

It is worth noting that intersections do exist between and among the drivers, and there is a notable overlap in domains. For instance, 'integrated water resource management' can be considered a governance, economic, and environmental driver of change. Also, governance, for instance, has been frequently identified as a major driver in water infrastructure sustainability research, but it cannot be dissociated from water financing [30]. The interconnections between and amongst themes are inevitable, and an understanding of these connections is essential for an adaptive, sustainable, and resilient system. This paper therefore uses themes that are based on a synthesis of elements of the driving forces of change, based on the STEEP framework. The key themes considered for this review include societal; technological or technical; environmental; economic or financial; and political or governance factors. A summary of the various influencing factors is shown in Table 1. An in-depth discussion of each factor follows.

Table 1. STEEP framework and future factors influencing sustainable water infrastructure in SSA.

Societal (See Section 2.1)	**Technological (See Section 2.2)**	**Environmental (See Section 2.3)**	**Economic (See Section 2.4)**	**Political (See Section 2.5)**
• Demographics • Water Access and Utilisation Patterns • Water Conservation • Stakeholder Engagement	• Strategic Planning and Asset Management • Water Re-use and Recycling • Rainwater Harvesting	• Ecosystem Pollution • Natural Disasters • Groundwater Depletion	• Water Financing • Water–Food–Energy Nexus • Virtual Water	• Water Rights • Transboundary Cooperation • Institutional Cooperation • Regulation • Integrated Water Resource Management

2.1. Societal Factors

Societal factors generally play a critical role in driving change for water infrastructure sustainability. The end users of water services are, after all, the people, and they must understand the implications of their actions and feel engaged in the decision-making process. These factors encompass demography; access and utilisation patterns; and the general engagement of stakeholders on how water is used and managed.

2.1.1. Demography

In 2022, the world population reached 8 billion people, and this is expected to increase over the century, reaching approximately 9 billion by 2050 [31]. Much of this growth is projected to be seen in developing regions [32]. Sub-Saharan Africa's population is projected to increase from approximately 680 million in 2000 to 2.1 billion by 2050, accounting for 10% and 17%, respectively, of the world population [31]. In addition to population increase, the percentage of the population living in urban areas is expected to increase significantly, especially in developing countries. According to a recent UN report, more than 50% of the world's population now live in urban areas, and this is projected to increase to 75% by 2050 [33]. Approximately 41% of the population of SSA lived in urban areas in 2020, and this is expected to double in the next 25 years [34]. SSA is classed as the most rapidly urbanising region, and its global share of urban dwellers is projected to increase from 11.3% in 2010 to 20.2% by 2050 [35]. This situation will result in land-use changes, a surge in informal settlements, and heightened climate change vulnerability. An increase in population will also cause an increase in water demand, putting additional pressure on the inadequate urban water infrastructure systems in SSA.

2.1.2. Water Access and Utilisation Patterns

In 2020, a quarter of the world's population still did not have access to safe drinking water [31]. However, huge disparities do exist, with high-income countries having 98% access to safely managed drinking water facilities, compared to SSA at 30% [36]. Water demand largely depends on several factors including access, potential cost, socio-economic status, population, weather conditions, and water policies [15]. According to the World Health Organisation (WHO), the average water for householder/domestic use per person per day to meet basic human needs should be in the range of 50–100 litres [37]. However, the average domestic water use in England, for example, is approximately 142 litres per person per day [38], and in Mali, it is around 14 litres per person per day [39]. For most countries in Sub-Saharan Africa, this lack of access is mostly due to economic rather than physical scarcity [40], which is exacerbated by the lack of finance for the construction of infrastructure for a piped water supply and the general lack of data to understand the effects of demand and supply [41]. With the projected increase in population, particularly in urban areas, and increased vulnerability to climate change, closing this gap is becoming more challenging.

With regard to availability, it is necessary to have a clearer understanding of water withdrawal patterns, including return flow and water use, and the impacts on the hydrological cycle [42]. To achieve this, several researchers and research institutions have been working on filling this data gap via the development of tools and the use of modelling and simulations for water quantification (see [43]). For instance, the Water Global Assessment and Prognosis (WaterGAP) model, developed at the University of Kassel, quantifies the global water availability and the human use of surface and groundwater storage on all surfaces of the Earth [44,45]. However, whilst these models are essential for risk assessment and planning, their applicability is limited by the complexity of, and uncertainty in, characterising water systems [40,46,47]. Their limitation is further exacerbated by the unavailability of reliable data on real-world phenomena, such as irrigation abstractions; climate change; population and economic growth; and total water availability and use, especially for developing countries, leading to unrealistic outcomes [40]. A study attempting to model the availability of freshwater in the sub-continent of West Africa highlighted the lack of information and data as the main limitations to the accuracy of the models [48]. Notwithstanding, whilst it is important to better understand water demand patterns, it is essential that conservation approaches are introduced, and context-specific financial policies are developed, in addition to education and sensitization solutions, all designed to fit the needs of the people [49].

2.1.3. Water Conservation

Due to the finite nature of water and the growing pressures on the Earth, water conservation and demand management is one of the main measures of incorporating sustainability in the water industry. There is growing evidence supporting the fact that it is cheaper and more sustainable to increase the efficiency of water use than to entirely rely on new sources of supply to meet the population's growing, and sometimes profligate, demands [3,15,50]. Therefore, there has been an increase in the shift from a supply driven paradigm to a demand-driven approach which includes socio-political, economic, or technical measures. These can be in the form of encouraging or enforcing approaches—'the carrot and the stick'.

A host of developed countries have incorporated conservation and demand management into their water resource management policy and governance with legal, institutional, and regulatory frameworks put in place [51,52]. For instance, Singapore's Public Utility Board instituted a water conservation programme that consisted of pricing, regulation, and incentive strategies as they transitioned from supply-driven to demand management solutions for efficiency and sustainability in the supply of water. These and other measures have contributed to making Singapore one of the most successful countries in terms of the implementation of water demand management strategies [49,52,53]. However, others have argued that using pricing alone to manage scarcity and demand could have severe implications, such as a reduction in revenue for water utilities, affecting their ability to recover costs for the general operation and maintenance of assets [54,55]. Therefore, strategies for demand management should be context-specific and should incorporate the integration of different approaches.

In SSA, notable progress has been made in incorporating conservation strategies in water resource management. However, despite progress shown by countries such as South Africa (see [56]), Malawi (see [57]), and Namibia (see [58]), significant challenges still exist. These challenges range from poor infrastructure and its operation and maintenance to cost recoupment challenges and high subsidy requirements [15]. Unfortunately, in many cases, progress appears to yield only short-term benefits [15]. As such, conservation measures can only be effective with complementary regulation, education, and technical and human capacity improvements.

2.1.4. Stakeholder Engagement

In broad terms, stakeholder engagement can be defined as the process of informing, collaborating, and partnering with stakeholders to understand their interests and influence in implementing a common course [59]. In water management, the need for a participatory decision-making process is essential for building a sense of ownership and trust in both the process and outcome, whilst considering the needs and interests of the local communities [60]. Stakeholder engagement is believed to improve both the efficiency and effectiveness of project and/or policy outcomes, as well as building trust, something often lacking in this realm [61]. As such, it is based on the principles of open and clear communication, trust, and ethical decision-making, thereby fostering a bottom-up approach to decision-making, rather than a top-down approach [62]. However, since all stakeholders might have different views about a specific problem, engagement does come with its challenge; however, these are, on-the-whole, surmountable.

There are different approaches to stakeholder engagement. For infrastructure projects in general, the 'design and defend' approach is well-established in the way non-experts are being engaged [63]. Engineers and designers have so much faith in their technical expertise that they use engagement as a way to inform or announce to the public their well-articulated technical plans, disregarding the complexity of the socio-technical water infrastructure system [63]. In a World Bank report on the Bumbuna Hydro-Electric Project in Sierra Leone for example, efficient and effective communication and involvement strategies were employed to keep the public informed about the delivery of the project [64]. However, stakeholders were informed, or plans were communicated to them after the design was confirmed, and there was very little engagement at the feasibility stages, a typical 'design and defend' approach. Another example is seen in a study on stakeholder engagement for sustainable water resource management in South Africa. In this research, it was found that only the most vocal were involved in decision making, leaving out marginalised groups like women and the poor [65]. The study claimed that communities were not adequately informed or equipped to participate in water management decision making, and there was a general lack of capacity, education, and trust. This is crucial for achieving buy-in from any stakeholder group.

Interestingly, this trend is not uncommon, even in advanced economies. In the project assessment review, conducted on public participation and stakeholder engagement in the European water policy, a comparable pattern was noted [62]. The study examined water-related project evaluation in five European countries (UK, Netherlands, Portugal, Spain, and Greece), and the results suggest that a significant number of projects primarily adopted a tokenism approach merely to fulfil the Environmental Impact Assessment guidelines [66].

Arnstein [67] referred to the 'design and defend' approach as a form of manipulation dressed up as participation. The 'ladder of participation' was then developed as a conceptual framework that outlines the levels of stakeholder engagement in decision-making processes, as shown in Figure 1.

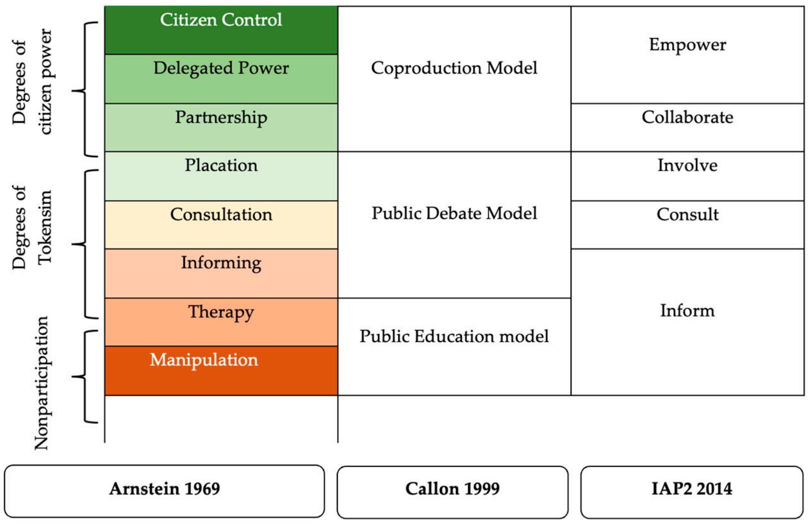

Figure 1. Levels of participation—Adapted after Conallin, Dickens [60].

Arnstein [67] pointed out that most projects engaged the public at the tokenism level, stressing the significance of engagement at higher levels of the 'ladder' for improved governance, trust, and accountability. More recently, there have been several adoptions of the 'ladder of public participation', including the work of Callon [68], and the spectrum for public participation as developed by the International Association of Public Participation—IAP [69].

Since water is mostly considered a public good and is a fundamental requirement for human survival, decisions on its sustainable management must be grounded in trust, ethical considerations, and open communication [70]. Stakeholder engagement can be used as a tool to leverage collective and collaborative dialogue, education and awareness, whilst exploring different expertise and viewpoints for sustainable water solutions [59]. Also, technology provides a significant opportunity for keeping stakeholders informed and making it possible for more people to participate, since there are several platforms, forums, or methods of communication.

In as much as stakeholder engagement is vital, it comes with its challenges. One of the biggest problems highlighted in the literature is the limitation of resources [59,60,65]. For this reason, policymakers, engineers, or project designers tend to limit public engagement to mostly a tokenism approach in order to cut down costs [60], which leads to conflict and a general lack of trust. Other challenges include the complexity caused by varying and conflicting stakeholder interests and expectations, and understanding the level of engagement required; the lack of capacity or education of some stakeholders to fully understand the challenges meaning they cannot fully participate in better decision making; and balancing the multiple channels of communication that might suit different stakeholders, ensuring all stakeholders are clear about what is being communicated [62]. Moreover, while technology serves as an enhancer, it poses threats and tends to exclude certain groups (e.g., those who lack access, the elderly, or the poor) and can be a conduit for the spread of misinformation [62]. Even when full stakeholder engagement is solicited, there is the possibility of responses not representing justice and good practice [63]. Furthermore, concerns do exist over culture, religion, ethnic and gender issues, local power structures, under-represented groups, and the effects they may have on fair decision making [71]. While it is inviting to always consider engagement at the higher levels of the 'ladder of public participation', the level of engagement should be appropriate to the needs of the project and participants [62]. There is a need, therefore, to widen the engagement horizon and include views that are important, irrespective of how well the stakeholders are represented.

In response to some of the above challenges and opportunities, a growing body of stakeholder decision support tools and frameworks have been developed to encourage stakeholder engagement for sustainable water resource and infrastructure planning and management. One example is the 'shared vision planning' by the US Army Engineers Institute for Water Resources [60]. This planning approach is structured in a way that public participation is central to creating a collaborative system where stakeholders are an integral part of decision making. Similarly, Eaton, Brasier [72] developed a conceptual framework which acts as a guide to understanding the effects of stakeholder engagement on environmental, social, and behavioural change. However, regardless of the approach used, stakeholder engagement must be integrated into an adaptive management system for managing risks and uncertainties [60,73].

2.2. Technological or Technical Factors

The provision of water services requires a complex network of infrastructure, which is highly technical, long-lived, and expensive [74]. The infrastructure must be strategically operated and maintained for efficiency and long-term performance, as well as providing reliable and cost-effective services. In addition, with resources being limited, there is also the need to consider non-conventional alternative sources of water to augment the supply. In all of this, a whole lifecycle analysis is pivotal to assessing the role and impact of technology.

2.2.1. Strategic Planning and Asset Management

Infrastructure asset planning and management involves the decision making and resource allocation that is required to ensure that assets are performing as needed, with reasonable cost and impact on the environment [75]. In the water sector, strategic planning is essential for the continuous provision of water and sanitation services that are essential for the health and wellbeing of the society.

To promote sustainability, several studies have been undertaken and tools have been created to underscore the importance of strategic planning in the management of infrastructure assets. Examples include the 'TRUST' approach and professional tools developed to foster decision making that embraces sustainability in infrastructure asset management, using long-term vision and foresight while incorporating risk, cost, performance, and key ISO 55000 [76] requirements [77]; or, the strategic planning framework developed at the Water, Engineering and Development Centre, University of Loughborough, to help water utilities in developing countries plan strategically and improve performance [78]. However, in as much as the development of frameworks and tools to foster strategic planning is essential for infrastructure asset management, others have argued that the development and implementation process is complex, resource-intensive, and requires highly skilled expertise [79,80]. For the most part, developing countries are faced with two sets of asset management challenges—balancing the financial and environmental management of assets, and the consolidation of these two in the presence of risks and uncertainties [19]. As a case in point, a study conducted on three urban utilities in South Africa showed that strategic planning was well established in all the utilities. However, due to lack of funding and capacity/skills challenges, the plans remained unrealised [81].

In addition to strategic planning, life cycle assessment and management are critical and beneficial to a strategic asset management approach. Recognising the environmental impacts of water infrastructure and processes throughout its lifecycle, is vital for incorporating efficiency, sustainability, and resilience. Moreover, for an improved comprehension of the impact of energy consumption and greenhouse gas (GHG) emissions, two primary factors influencing the environmental pillar of sustainability, is required [82]. Therefore, for the incorporation of sustainability and resilience in infrastructure asset management, Buchanan, Roth [83] suggest firstly understanding the level of service of the assets, which involves considering customer expectations, organisational goals, technical capabilities, and lifespan plans. To accomplish this, the Water Environmental Research Foundation (WERF), for example, has completed extensive research on the combination of performance, sustainability, and resilience management with recommendations for enhancing comprehensive management of water infrastructure assets [84]. Nonetheless, the general state of the performance of water utility infrastructure in SSA is unsatisfactory, and this is mostly due to the lack of strategic planning, whole life-cycle assessment, and the institutional systems and structures to facilitate adoption [85]. Developing countries still employ the 'fix on failure' approach to asset management, which stifles performance and long-term sustainability [79].

In addition, the sustainable and resilient management of infrastructure assets require robust data, advanced technology, and innovation. This includes the need for optimizing the performance of assets, monitoring assets remotely and the ability to predict maintenance needs [86]. A host of technological innovations and tools have been developed over the years to support infrastructure asset management. For instance, building information modelling (BIM) has been used extensively to foster data management and provide a data-rich point for collaboration throughout the lifecycle of infrastructure projects [86]. After its establishment, there were possibilities that the models developed might be slightly different from what is constructed. Therefore, Scan-to-BIM technologies are being considered more feasible in modelling the as-is condition of assets [87]. Complementary to this is the use of Geographical Information Systems (GIS) for spatial data to buttress BIM, especially for pipeline utilities. An example of the applicability is in the framework developed by Lee, Wang [88], which integrates BIM with advanced 3D GIS for the improvement in the management and maintenance of utility infrastructure systems. More recent innovations include the employment of IoT (Internet of Things) and smart solutions for real-time asset monitoring, which enhances predictive maintenance and improves decision making [89,90], as well as the use of autonomous robots for pipeline inspection, condition monitoring, and maintenance prediction in utilities [91]. While these advanced technologies are in the early stages of implementation in SSA [92], and in the case of the autonomous pipeline inspection robots are still in the research and development phase, it is vital that they are built into new infrastructure planning and design immediately. This is because of the huge growth in demand for water infrastructure (as described in Section 2.1.1), the cost of its provision, the very considerable consumption of natural resources required for its construction, and the need to avoid ongoing repair and maintenance costs wherever possible. Getting the systems 'right first time' and embracing the latest technologies is absolutely essential if developing countries are to thrive. However, in as much as the deployment of these advanced technologies will lead to efficiency and cost savings, there have been existing debates around environmental consequences, safety, resilience to cyber security risks, return on investment, and public perception [86]. Even though developing countries can learn and adopt technologies from their developed counterparts, for sustainability, this must be tailored to their country-specific capabilities and needs. Therefore, foresight and an integrated and adaptive planning and budgeting strategy are both crucial [24].

2.2.2. Water Reuse and Recycling

The pressures exerted by climate change, population increase, and the decline in water availability have encouraged a growing interest in the circular economy model as opposed to the traditional linear model of water resource use and management [93]. The concept of circular economy, introduced by Pearce and Turner [94], aimed at encouraging reuse and regeneration, as well as maximising efficiency and minimising waste, has gained attention in several industries, including the water industry. Several frameworks and strategies have been developed to inform and guide professionals and researchers in the principles of circular economy, and how it could be integrated into the water industry. For instance, ARUP [95], in a published whitepaper, explores the connections between the principles of circular economy and water resource management and identifies opportunities for incorporation. Similarly, the World Bank has developed a framework that aims to guide practitioners in incorporating circular economy principles in the policies, planning, design, and operations of water systems [96]. However, Voulvoulis [97] warns about the significant risks of water reuse and recycling, especially with wastewater recycling, citing water quality, and human health as the major concern [water reuse suggests that little/no treatment is required, whereas water recycling suggests some sort of treatment, from basic to extensive, is included]. Their paper outlines allowable levels of contamination in reclaimed water and emphasizes the need for robust water quality standards in addition to other considerations.

To address the challenges associated with wastewater reuse or recycling, a host of studies have been conducted in advanced wastewater treatments and toxic pollution control to ensure that effluents meet high water quality standards [98–100]. Notwithstanding this research and development, all wastewater treatment technologies have their drawbacks including substantial energy requirements, the potential for deterioration, and the production of toxic by-products [98]. All of that said, the public acceptance of wastewater reuse or recycling has also been a major challenge [101], and researchers believe perception can be improved with better communication, engagement, and critical framing. However, low-income countries, especially those in SSA, are in the infancy stage of wastewater treatment and management, due to underdeveloped infrastructure and financial constraints [20,102,103]. The few countries, such as South Africa, that do have wastewater treatment and management facilities, often fail to meet the minimum effluent standards [104]. On the other hand, some countries in SSA do informally use reclaimed water for agricultural and other purposes without a thorough grasp of the environmental and health impacts [102]. Notwithstanding the concerns, there is still the opportunity for the incorporation of these technologies (especially for industrial cooling processes, non-potable household purposes, or landscape irrigation) in the future as developing countries grow and gear towards meeting their SDGs [96].

2.2.3. Desalination

Desalination is a technically viable alternative to freshwater sources, especially for regions facing water scarcity. However, its sustainability has been questioned over the years due to high costs, high energy consumption, and negative ecological and environmental impacts related to saline deposition [105]. Nevertheless, arid and semi-arid countries, especially in the Middle East, have invested significantly in research and in the incorporation of desalination in their water supply systems [106]. Significant water scarcity, coupled with elevated levels of surface water pollution, has prompted SSA to consider desalination as an alternative source of potable water [107]. Kenya, Eritrea, and Ethiopia have been identified as having good access to the sea, combined with high potential sources of geothermal energy for desalination purposes [108]. On the other hand, South Africa, Namibia, and Ghana do have existing desalination plants to augment the water supply [107]. However, the Ghanaian desalination plant, inaugurated in 2015, has already encountered difficulties related to financial feasibility [109]. With proposed plans for the construction of a desalination plant in Nigeria [106], lessons could be learnt from Ghana, and such hurdles should be considered to avoid obsolescence.

Despite the challenges of desalination, recent studies have been devoted to investigating advanced technologies and strategies to reduce its energy intensity [110,111] and environmental impacts [112], and to improve its cost-effectiveness [113], all in support of desalination as a sustainable source for water-scarce regions.

2.2.4. Rainwater Harvesting

Rainwater harvesting has been around for centuries, and it is an effective, affordable, and sustainable practice of collecting and storing water, rather than letting it run onto open ground or into stormwater systems (should they exist). Over the past few decades, there has been an increasing amount of literature on rainwater harvesting as a sustainable alternative to surface and groundwater, and an essential part of an integrated approach to water resource management [114]. System design and optimisation; performance monitoring and evaluation; water quality and treatment; social and economic effects of rainwater harvesting especially in rural communities; and policy, governance, and regulatory frameworks are some of the factors to be examined for the design, operation, and management of a sustainable rainwater harvesting system [115–117]. The success of the system is related to the dynamics of storage tanks both filling and emptying [118]. The primary influence on the performance of such systems is the amount and frequency of rainfall, which, in SSA, can be low and accompanied by shifting rainfall patterns.

Domestic rainwater harvesting in SSA has been shown to be a reliable and affordable source of supply of water particularly in rural areas, with systems ranging in scale from household systems to community initiatives [118]. Also, because barely 5% of agricultural land in SSA is irrigated, compared to approximately 35% in, say, Asia [119], there is a lot of room for improvement in the adoption of rainwater harvesting and improved infrastructure for irrigation and increasing crop productivity. However, even though NGOs, development organisations, and, in South Africa for instance, the government have invested significantly in improved techniques and technologies, and in financial assistance for rainwater harvesting, challenges remain, especially in maintenance and the risk of diseases [115,120]. For instance, a study on rainwater harvesting in Mekelle City, Ethiopia found the existing systems unreliable due to inefficient design [121]. Therefore, there is a need for a policy shift to integrated systems and decision-support tools that are guided by traditional indigenous knowledge systems [118].

2.3. Environmental Factors

Environmental drivers shape the water infrastructure landscape, especially in the face of climate change. These include a range of natural and human-induced factors that influence decision making for sustainable water infrastructure.

2.3.1. Ecosystem Pollution

Water covers over 70% of the Earth's surface, therefore the pollution of aquatic ecosystems is one of the major challenges of sustainable development. Pollution can come from several sources, such as sewage and improper wastewater disposal; fertilizers and pesticides from agricultural practices; industrial processes; solid waste and plastic pollution; and oil spillages. These pollution sources are not unique to SSA and have a detrimental impact on human health and the health of other living organisms.

In SSA, the pollution of aquatic ecosystems can predominantly be linked to poverty, the underdevelopment of sewage and wastewater management, poor regulation and enforcement mechanisms, and the general lack of knowledge of the impacts on human health [122]. For instance, septic tanks and pit latrines are common, particularly in rural areas, as sanitary solutions [16]. Linkages have been shown between these sanitary services and the presence of faecal matter in groundwater aquifers, which accounts for approximately 1.5 million deaths annually in developing countries [123]. Other instances include for example the identification of heavy metals in groundwater systems from dolomitic gold mining in South Africa [124], accidental oil spillages in Nigeria [125], and the leaching of agricultural chemicals in Tanzania [126]. These examples are not isolated and are consistent with trends in other countries in SSA. On an international scale, several campaigns and initiatives have been established to help protect aquatic ecosystems and provide a legal framework for better governance, with examples including the 'Clean Seas Campaign' aimed at raising awareness on plastic pollution [127] and the 'Biodiversity Beyond National Jurisdiction 2023′ initiative, which is a UN legal framework geared towards conserving and maintaining sustainable marine ecosystems [128]. On a local scale, the sustainable management of aquatic ecosystems requires understanding water pollution with a focus mostly on the identification of pollution sources, impact assessment, and proposing strategies for prevention and mitigation. In addition, robust regulation, education, and consistent water quality monitoring are vital for maintaining ecological balance [129].

2.3.2. Natural Disasters

Natural disasters can have devastating impacts on the economy, infrastructure, food security, agriculture, and the general health and well-being of people, and they are exacerbated by the uncertainty of climate change. Research has also shown the existence of linkages between disasters and conflict, and the pressures exerted on the economy as in the case of the Darfur War in Sudan in 2003, which had been linked to drought [130].

Despite SSA not being a major emitter of GHGs contributing to climate change, it disproportionately bears the brunt of the associated consequences [130]. SSA's vulnerability to natural disasters, encompassing weather-related events, geophysical occurrences, or biological incidents, is believed to be mostly a consequence of poverty [131]. Meanwhile, floods and droughts are the most common weather-related disasters, with SSA having the highest hotspots [131]. Examples of disasters in SSA include the 2010–2012 drought in Somalia, claiming over half a million lives [132], the flooding and landslide in Sierra Leone in 2017, accounting for over 1100 deaths [133], and the 2014–2015 Ebola epidemic in West Africa, killing over 11,000 people [134].

Furthermore, research has shown compelling correlations between the unavailability of potable water or the pollution of water bodies due to floods, and the increase in the prevalence of famine and diseases threatening the health and livelihood of humans [135]. Even though governments in SSA have established disaster-reduction strategies and are dedicated to global agreements and treaties, the implementation of these strategies remains a challenge [136]. The literature advocates for stakeholder engagement and effective communication, as well as early preparedness and tailored mitigation strategies [137]. For example, the 'Sendai Framework for Disaster Risk Reduction 2015–2030′ gears towards the prevention of new risks, reducing existing risks, and increasing resilience, which is a global step in the right direction for strengthening disaster risk management and governance [138]. Furthermore, the literature emphasises the need for the exploration of the long-term social, economic, and technical impacts of natural disasters, while integrating preparedness into daily routines and refraining from treating disasters as isolated events [130,131,136].

2.3.3. Groundwater Depletion

Groundwater is the most reliable alternative to surface water, and has been abstracted for domestic, irrigation, and industrial use for a very long time. However, over the years, this resource has been over-exploited, which in some areas has led to subsidence, depletion of groundwater basins, and (in some cases) pollution and saline intrusion [139]. A large and growing body of literature has investigated sustainable groundwater management, with much of the literature exploring topics including innovative technologies and data integration [140–142]; managed aquifer recharge techniques [143]; groundwater resource assessment, monitoring and water use efficiency [144,145]; socio-economic impacts, policy, and regulation [146]; contamination and remediation techniques [147,148]; and general participatory approaches to groundwater management [149]. There is a growing consensus among researchers that local and context-specific robust policies and regulations, as well as the integration of surface and groundwater management, are essential for optimal groundwater allocation and reducing conflict among competing sectors.

Due to economic water scarcity and the lack of water infrastructure, most rural communities in SSA rely on groundwater sources for their sustenance [150]. Boreholes and water wells provide an excellent source of potable water for domestic purposes and for irrigation [151]. To support this agenda, local governments and NGOs have invested substantial amounts of money in the construction of water wells in rural areas in SSA, yet most are not sustainably managed [152]. On one hand, groundwater provides an alternative source of potable water in rural communities. However, on the other hand, groundwater rights are directly related to land ownership, with few or no policies and regulations on abstraction levels, pollution, and water quality [150]. This threatens the global water supply and availability, and the environmental and social well-being of the people [153]. There is, therefore, a need for effective regulation, aquifer management and recharge approaches, education, and the promotion of simple water-efficiency practices for the sustainable management of groundwater resources in SSA [154].

2.4. Economic Factors

Water plays an essential role in promoting economic development and enhancing the welfare of society. Therefore, the financing of water security is fundamental to achieving Sustainable Development Goal (SDG) 6. Water financing is typically classed under four main cost streams: grey infrastructure, green infrastructure, behaviour change and institutional and management improvements [155]. This review will focus on grey infrastructure, which refers to the physical assets that are required to collect water from the source, treat and distribute it to users, and transport it from users to wastewater treatment plants. These systems are long-lived; require significant investment costs for capital, operation, and maintenance; have high sunk costs and a long return-on-investment period; and are the reason the water sector is said to be one of the most capital intensive [74]. However, due to the existing debate that water is a common good and must not be commercialised, the sector remains underfinanced and unattractive for investment. Compared to other infrastructure sectors, water only attracts approximately 6% of the total global infrastructure investment [155].

As a result of underfinancing, the evidence shows that all countries struggle to meet the financial requirements of their water infrastructure systems [156], and. despite efforts being made globally, the water sector is not on course to attain the SDG 6 objectives [157]. This is evident in an Organisation for Economic Cooperation and Development (OECD) report, which highlights that the global water infrastructure financial need is projected to increase from $6.7 trillion by 2030 to $22.6 trillion by 2050 [158]. In addition to the direct financial commitments for sustainable water infrastructure, other concepts including virtual water (see Section 2.4.3) and the water–food–energy nexus (see Section 2.4.2) have significant economic impact on water financing and water security.

2.4.1. Water Financing

In water asset planning and management, the three main cost categories are investment or capital costs (which covers rehabilitation or new construction of assets), maintenance costs, and operating costs; whilst the three main sources of revenue, usually referred to as the 3Ts, are taxes, tariffs, and transfers, as shown in Figure 2. However, for most utilities, both in developed and developing countries, the revenue generated from the 3Ts is insufficient to cover all costs. Drawing from an extensive range of sources, this challenge can be due to inadequate long-term planning, challenges with capacity and human resources (especially in developing countries), and problems with the complex optimization of setting a sustainable tariff system [157–160]. Furthermore, the challenges of developing countries are amplified by inefficiency, the poor performance of existing infrastructure systems, and the sector being heavily subsidized and mostly dependent on donor funds, especially for capital costs [12,161,162]. Furthermore, donor funding has not seen much of an increase compared to the increase in funding requirements, and the 3Ts (even in developed economies) are insufficient to meet the financial requirements of utilities. Therefore, there is a need for other funding options.

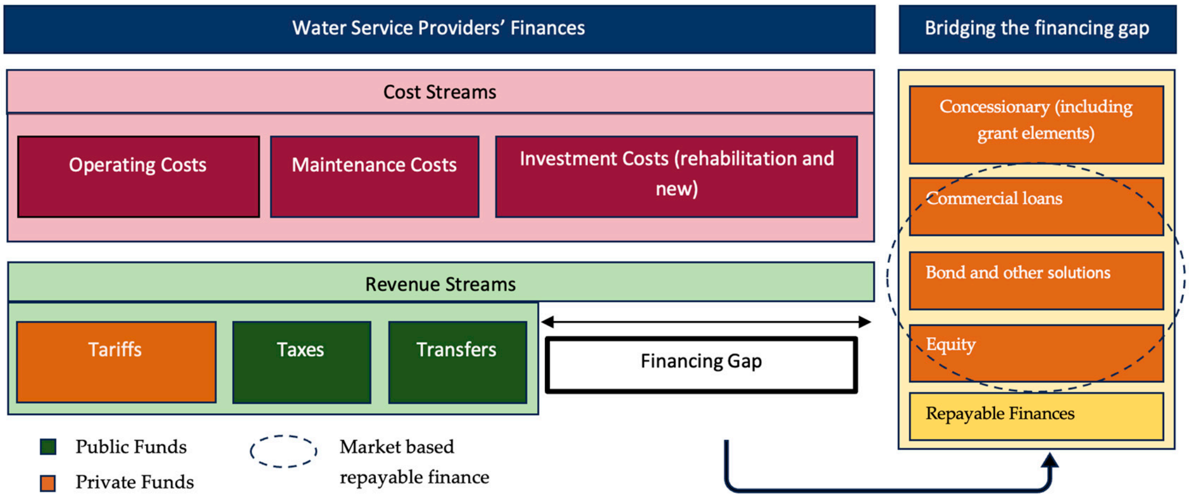

Figure 2. Mechanisms to bridge the water financing gap—Adapted after OECD [163].

For example, after a decade-long civil war that ended in 2002, Sierra Leone has made strides towards post-conflict reforms in the water sector. However, there exists a huge financial gap between revenue and costs [164]. Approximately 80% of water infrastructure expenditure is from external donor financing, and this has been declining in recent years; there is a lack of capacity and human resources especially in local government authorities; cost recuperation is inadequate; and there is almost no formal private sector financing [164]. These challenges are not uncommon in other countries in the sub-region. In Burkina Faso, the rural water services sector is financially starved as most of the little available funding (which is largely from donor funding) goes to prioritised urban municipalities [165].

The privatisation movement has been extensively advocated and researched with the hope of bringing in more needed finances and introducing efficiency and improved performance [157,166]. However, the drawbacks include the need for private funds to be repaid mostly with compensation, and the focus on profit generation leads to expensive services and places a financial burden on the customers [167]. From a developing country's perspective, the lack of policies, human capacity, weak performance, and the general lack of a robust maintenance culture makes the water infrastructure industry unattractive and risky for private sector investment [159,168].

As the 3Ts are insufficient to cater for the cost requirements of the water sector, a host of reports have been published, and a range of financial mechanisms and instruments have been investigated to help bridge the financial gap in the delivery of water and sanitation services. For example, The World Panel on Financing Water Infrastructure in 2003 published a report on a 25-year perspective of the financial state and needs of the global water sector, the challenges, mitigation mechanisms, and priority areas that need to be addressed. The report concluded that water security is essential for development and in achieving most of the Millennium Development Goals (now Sustainable Development Goals), and not just the water-specific goals [169]. The Roundtable on Water Financing was also established in 2017 as a central platform for engaging a diverse range of stakeholders for researching/exploring investment options that will facilitate the sustainability and security of water and sanitation services [158]. The OECD has also developed a framework for bridging the financial gap in water and sanitation service delivery [163]. The report articulates the availability and use of market-based repayable finance, such as loans, bonds, and equity as viable options, especially for capital expenditure. Due to their compensatory nature, however, they should only be used to bridge the gap in capital expenditure, whilst improvements in revenue from a mix of the 3Ts cater for ongoing operations and maintenance. There are also concessionary options where funding support is provided under more financially favourable conditions.

Other recommended financing tools or instruments include Output-Based Aid (OBA); an array of insurance products and guarantees from donors and financial institutions; forming grouped financial vehicles; and direct lending to sub-sovereigns [74]. For low-income countries deemed too risky for investment, mechanisms explored include, for example, Hybrid/Blended finance, which considers the investment impact and sustainable (social, economic, and environmental) return on investment [155]. Blended finance involves strategically combining development finances with commercial finances to improve risk-return profile and creditworthiness, and enhance financial sustainability [155]. There are also catalytic capital options and the investment of pension funds in infrastructure development through public–private partnerships [170].

However, the water sector is viewed by most repayable finance providers as high risk and low return in terms of investment [157]. In addition, these instruments require institutional and human capacity, local capital and financial markets, and specific conditional requirements for access and successful incorporation, which are lacking in low-income countries where they are needed the most [74]. In Kenya, for instance, the commercialization of water to bridge the financing gap is causing a shift towards market feasibility and profit generation rather than meeting the basic needs of the people [171], which in turn increases the gap in access to water and sanitation services between urban and rural areas and between the rich and the poor.

Concisely, the consensus is that additional funding for water infrastructure is essential for better functioning. Notwithstanding the challenges, a thorough consideration of the context, with the right regulation and oversight, private sector participation in water service financing will bring in the needed reliable and efficient delivery in water service delivery in SSA [159]. In addition, funding alone is not enough to make a change; there is a need for sustainable improvements in policies and governance, robust institutions, tariff setting and revenue collection, data and information, and an all-round efficiency built into water service delivery systems.

2.4.2. Water–Food–Energy Nexus

There is a growing conflict for resources between and among the water, energy, and agricultural industries, and this is a huge challenge in addressing water security [172]. The water–food–energy nexus is described as a concept to better understand the complexity and interconnectivity of these global resource systems, pivotal to the question of global sustainability [173]. The nexus or interlinkages have been described as being dependent on the number of nodes and can be two-, three-, and four-node nexuses [174]. These include for instance the water–energy interlinkage, which describes the link in the role water plays in energy production; the water–food linkage, in which water plays a pivotal role in irrigation and food production; or the water–food–energy interlinkage, which highlights the connections between and among energy used for irrigation and water treatment, and in the water requirements for energy generation. Rising global population, increases in urbanisation, changes in diet, and economic growth are causing increased demand for these resources. This has been exacerbated by global pandemics (e.g., COVID-19) [175] and wars (e.g., Russia–Ukraine) [176,177], which have put a huge strain on the supply chain. Food production and energy generation are both water intensive industries. To illustrate, the energy industry uses water in hydrogeneration, for cooling purposes in power plants, for irrigation of crops used in biomass plants, and in the extraction and manufacturing processes of other energy sources [178]. On the other hand, agriculture alone accounts for approximately 72% of global freshwater withdrawals [179], and the FAO (Food and Agriculture Organisation) recommends that food production will need to double by 2050 if the needs of the growing population are to be met [180]. Understanding these interlinkages is significant for the design of sustainable solutions.

In SSA, the lack of access to electricity, potable drinking water and nourishing food is predominant. In a bid to better understand these interlinkages and trade-offs among these resources, the Pardee RAND Food–Energy–Water (PR-FEW) index was developed in 2016. Nkiaka, Okpara [181] used this tool to conduct a spatial 'FEW' nexus assessment of countries in SSA. The results indicate that 41 out of 49 SSA countries reviewed were FEW insecure, with countries in the West African sub-region performing worst. On a scale of 0–1, 87% of the countries reviewed scored below 0.5, with only Gabon, Botswana, Mauritius, Namibia, South Africa, and Eswatini scoring 0.5 or above. A similar tool has been recently developed: the Water–Energy–Food (WEF) Nexus Index [182], which was created using open databases and based on 21 indicators. An assessment of SSA countries using this tool [177] saw similar results to Nkiaka, Okpara [181], with African countries performing sub-optimally.

Generally, the water–food–energy nexus is specific to the country and varies by context. In as much as the performance of SSA countries is suboptimal, a few countries like South Africa and Namibia are improving in performance. There is, therefore, an opportunity for an in-depth investigation and understanding of the critical challenges, and an opportunity for learning from other well-performing countries. Solutions must be focused on integrated rather than sectoral approaches, whilst moving from nexus thinking to nexus action [177,181].

2.4.3. Virtual Water

The Virtual Water concept was introduced by Professor Allan [183] in 1993, and it refers to the water embedded in the production of food and other goods. Virtual water is essential in understanding the constraints of the movement of goods and services, especially agricultural products, and in essence water from one region to another. This means that water consumption is much more than what is used directly. It is generally defined as the usual water consumed in addition to the embedded water, which makes up the 'water footprint', a concept introduced by Hoekstra [184]. These two concepts are interrelated and have come to be an integral part of the definition of water consumption.

Over the past few decades, water resource management problems were thought to be unique for several regions, and water problems do not exist at the global scale [3]. However, subsequent findings invalidate these assertions. Hoff [185] points out that the teleconnections in global water systems can introduce water pressures originating from other regions. It is stated that these teleconnections can be biophysical, socio-economic, or institutional, and could largely lead to the significant disruptions of social and ecological systems that are dependent on water. For example, research has found that there is a high correlation between the exploitation of Brazilian water resources and the increase in water-intensive food imports to China [186]. Another instance is the claim that 20% of the drying of the Aral Sea is believed to be related to water abstractions, relating to cotton import to the EU [186]. Virtual water enables the trade of water-intensive crops or products from regions with abundant water to water scarce regions, with water abundant regions being compensated for the embedded water, thereby fostering economic development. Understanding such linkages is a step forward in designing sustainable water systems for society and ecosystems [187].

In the context of SSA, the virtual water concept holds significant relevance as the region heavily relies on agriculture. Virtual water will help provide insights into water-intensive agricultural practices, food security, and sustainable water resource management [188]. The results of a study that sought to understand food trade systems in two West African cities indicate that virtual water flows were largest in grains and cereals [189]. This creates significant opportunities for SSA in managing their water footprint whilst enhancing revenue generation. However, due to Sub-Saharan Africa's reliance on agriculture, it is recommended that the virtual water policies are efficient and fair, and does not lead to further scarcity or increased pollution [188].

2.5. Political or Governance Factors

Political interventions for sustainable water infrastructure planning and management are mostly hinged on policy and governance. Governance is defined as the norms, rules, and institutions created by societies to facilitate decision making and conflict resolution concerning collective problems [190]. In the water industry, this takes into consideration the multi-level participation of public institutions, civil society, and the private sector for effective decision making and the management of water resources. Due to the complexities of collaboration, transparency, accountability, and planning, coupled with the common pool nature of water resources, it is usually the consensus that the global water challenges are mostly due to problems with governance [191]. To provide a structured set of guidelines, multiple tools and frameworks have been developed such as the popular OECD's governance framework, which is a comprehensive toolkit that aims to help countries in the development of water policies and good governance [192]. However, the solution for better governance is not one-size-fits-all. Resolutions must be context-specific and should address the key elements of water rights, institutional arrangements, transboundary cooperation, and regulation.

2.5.1. Water Rights

Water right refers to the legal aspects of water allocation, and is defined as who has the right to use water, when and where this is possible [193] with the intention of conflict reduction, fair allocation, and sustainability. Schlager and Ostrom [194] refer to a bundle of rights for common pool resources, including the right to access and withdrawal, the right to management, the right to exclusion, and the right to alienation. Water, being a common-pool resource and due to its mobile nature, can be plagued with allocation and management complexities. Global water scarcity due to climate change, increases in population, and the over-extraction of water from several sources intensifies the competition for water resources and exacerbates the allocation challenge.

Water rights are either state-governed or governed via customary laws, and can come from ownership of the land on which a water body is or flows (riparian rights), or from the actual right to access and use the water body (prior appropriation). A considerable amount of the literature has been published on the types and layers of water rights for defining the legal principles of entitlement, permission, and control of water resources [193,195], and on justice in water decision making [196].

In addition, parties with water rights can opt to trade their rights or resources, with water markets being the tool used to facilitate this process. Water market is an approach that involves the transfer of water rights from one user to another in order to deal with the challenges of water scarcity. It can be argued that water markets enhance efficiency in water allocation, due to the applicability of market principles, and promote sustainable water use [197]. However, challenges do exist that might impede the success of water markets. These include infrastructure costs and logistical hurdles, transparency, political and social challenges, legal reform, water rights systems and access to information, allocation inequities, and pricing [197–199]. Notwithstanding these difficulties, success stories do exist with the application of the right principles. For example, in the Murray–Darling Basin in Australia, water markets are used to encourage efficient and sustainable water allocation, and this is one of the most successful cases of the advantages and benefits of water markets globally [197,198].

Countries in Sub-Saharan Africa have made significant progress, especially regarding the formation of water rights administration structures [119]. However, these efforts are stifled by the lack of economic resources and capacity to manage these complex systems and frameworks. In rural communities in Sub-Saharan Africa, customary water tenure is the prevalent socio-legal system to meet domestic, farming, and pastoral needs [200]. These rights usually also cover arrangements for sharing with other communities or with third parties. Yet, because farmers lack the resources or expertise to advocate for written rights, it is common for powerful third parties or large-scale users with better bargaining power to oppress local communities [201]. A hybrid approach which legitimatizes customary/traditional laws to facilitate water sharing is usually recommended [201]. However, although Uganda and Kenya, for example, have made significant strides towards incorporating a hybrid approach for the protection of small-scale users, the systems are still inadequate and unsustainable in the long term [200]. Moreover, due to the diversities in culture, economic activities, and environment, there is no 'single bullet' for improvement in water rights. Therefore, an iterative process of learning via several pathways is recommended [202].

2.5.2. Transboundary Cooperation

Political borders hardly align with watershed or aquifer borders. According to UN-Water [203], approximately 60% of the global freshwater flow is transboundary, and more than 286 river basins and 592 aquifers are shared by two or more nations. Population increases, urbanisation, and the effects of climate change have increased the scarcity of water resources, which in turn increases the tension in the governance of shared water resources and worsens the competition between and among the sectors and uses of water resources. In addition, the increased reliance on groundwater sources and the confined nature of aquifers pose opportunities for conflict relating to abstraction rate, environmental pollution impact, and inadequate data and monitoring [204]. This leads to a conflict of ownership and control, with upstream or richer or more powerful nations seeking dominance [205]. There is, therefore, a need for policy and governance strategies to manage these shared resources.

Over time, the establishment of institutions and the application of diplomatic approaches for conflict resolution and cooperation have been used to manage transboundary water resources [204]. However, many have argued that, even though diplomacy is seen as a solution to resolve conflict, due to hydro-politics and hydro-hegemony, in some cases, it may lead to unintended conflict when cooperation is narrow, token-based, or coercive [206]. In addition, others claim that historical and cultural background, technical capabilities, and legal institutions and frameworks hinder the effects of cooperation [207]. This risk of conflict and limited institutional capacity, especially with implementation, is particularly evident in Sub-Saharan Africa [206]. This is exacerbated by the fact that low-income nations are at the initial stages of water infrastructure development, and the possibility exists for contemplating the construction of large-scale infrastructure, such as dams to address some of their water-related problems [204]. Others have drawn on the masculine nature of transboundary water management with the focus being on economic, technical, and political operations with little or no attention paid to the needs of the users, and the effects on women and the poor [208,209].

One of the most controversial cases is the transboundary management of the Nile basin with its complex socio-economic, political, and environmental challenges. The Nile basin covers around 10% of Africa's land mass, flows through eleven countries, and is credited as the longest river in Africa [210]. Disputes had always existed, including the one between Egypt and Ethiopia over the construction of the Grand Ethiopian Renaissance Dam [210]. The establishment of the Nile Basin Initiative (NBI), among ten of the riparian states, had seen the significant progress in promoting peaceful cooperation and the sharing of socio-economic benefits. However, owing to the complex physical and socio-political nature of the basin, challenges still do exist regarding efficient and equitable allocation and the general variation in regional developmental priorities [210].

Generally, the establishment of institutions and management organisations has never been the problem; it is due to the varying priorities and the lack of capacity for implementation [211]. This has mostly stemmed from the lack of technology, data, and information sharing for the strengthening of the interface between policy and science [205,207]. In the face of challenges, a gendered, state, and institution-focused approach; technology and innovation; and an adaptive governance of transboundary resources have been shown to produce better outcomes, whilst involving and engaging all stakeholders via analytical deliberations, nesting, and dynamic institutional arrangements [205,212].

2.5.3. Institutional Arrangements

Water institutional arrangements are generally the organisational structures or frameworks that are established to legitimize, influence decision making, and shape and control the planning and management of water resources [146]. Over the years, institutional structures were initially based on the old institutionalism paradigm, which focuses mainly on formal organisational structures. This mostly consists of traditional state-owned market-driven models. More recently, the focus has been shifting more towards neo-institutionalism, which integrates both formal and informal structures in addition to cultural aspects, and was developed in response to the limitations of the old institutionalism [213,214]. Neo-institutionalism can be classed as historical—where institutions rely on history and are path-dependent; rational choice—where institutions are aimed at maximising self-interest; and sociological—where culture helps to shape institutions [213]. The applicability of this construct is new in water governance and most cases involve a combination of two or more types.

In SSA, for example, community-based models in institutional arrangements and water governance are common in rural settings, and are also emerging in urban areas to support failing traditional market-driven systems, including the privatisation movement [166]. Several models of such partnerships have been advocated and implemented, showing great opportunities in some regions, but also a few challenges in others. These include, for instance, the delegated management model, in which utilities delegate the operation of water services to private operators or to individuals. An example is seen in Kisumu Kenya, where water is supplied, via pipe connections to the household, and revenue is collected by private master operators [215]. This has led to an increase in revenue for the utility, generated employment for the operators, and has led to an expansion of the network. However, corruption, theft, and misappropriation are some of the obstacles that have compromised the sustainability of this model [166].

Despite the advantages of effectiveness, efficiency, and fiscal sustainability, some researchers have criticised the process of bricolage in neo-institutional governance reforms. They claim these combined institutional arrangements are not meeting performance requirements, especially in low-income countries [214,216]. Challenges cited include equity, politics, unavailability of data, problems with power dynamics, and, most importantly, how the integrated water resource management paradigm and the complexities in water financing compromise operationalization and the management of risks and uncertainties [216–219]. As a case in point, the development of the National Action Committee in Zimbabwe as an institutional reform for better water governance remained unsuccessful in fulfilling its mandate [220]. Another instance is shown in the effort to combine local laws with privatisation and the commodification of water resources, which led to challenges in mediating between the pastoralists and agricultural groups in Narok, Kenya [221]. Irrespective of the flaws, there is huge potential for combining the strengths of both formal public utilities and community-based solutions to fill the water access gap in SSA [166]. At the global scale, the need for the development of global institutional arrangements for dealing with the trade-offs of virtual water trade, water reuse and circularity, water pricing protocol and water footprint permits, and the sustainable reporting of water-intensive goods have been recommended [222,223].

2.5.4. Regulation

Regulatory mechanisms are essentially a substitute for the conventional competitive market incentives, thereby reducing monopoly practices to protect customers' interests, promote efficiency, and ensure the delivery of a service that is sustainable and resilient [224]. It is achieved via implementing procedures for controlling quality and price, in addition to benchmarking schemes that facilitate improvement in performance regardless of public or private ownership [225]. Water utilities that have been characterised by market failures, and yet are of public interest, require some form of regulation for the provision of control, cohesion, and efficiency. Irrespective of the benefits of regulation in the water industry, there exist some drawbacks, including cost implications, a compliance-focused mindset, regulatory burden, and unexpected ramifications (i.e., unforeseen consequences) [226].

Economic regulation and the regulation of the quality of service are the two primary areas of concern for any service provider. Water regulation can be executed via contract or agency. The three main institutional configurations, based on the countries pioneering this approach, are the English model, the French model, and the Dutch model [225]. In the English model, water and wastewater services are fully privatised and the utility company owns and manages the assets. The regulator is independent of the government, protects the interest of the customers, and establishes a market with measures to foster benchmark competition. The French model follows the regulation-by-contract approach in which the water and wastewater services are only managed by private companies, but ownership is with the municipality. Private companies bid to manage the utility, and regulation is ensured via a contract with the municipality. On the other hand, the Dutch model has the public sector owning and managing the assets, and is self-regulating. There is also a hybrid model, which combines elements of the other models [227]. Regulation for the quality of services uses approaches such as sunshine regulation and benchmarking [228], whilst economic regulation employs rate of return regulation and performance incentives as the most common approaches [229]. However, in most cases, these entities (cost and quality) are regulated by different regulating bodies, and it has been argued that, due to the intrinsic relationship between quality of service and cost to the utility, an integrated approach should be employed that consolidates both economic and quality of service regulations [230]. It is worth noting that all regulatory models/arrangements come with benefits and drawbacks, and context plays a huge role in deciding what works.

Previously, most low-income countries operated on the Dutch model, which has been criticised on the basis that utilities owned, managed, and regulated by the government are not commercially motivated, and tariff-setting is mostly myopic without considering long-term consequences [229,231]. The adoption of the Millennium Development Goals (MDGs) saw an increase in the introduction of the privatisation movement in SSA, with the hope that it will boost efficiency and productivity, and help attract private investment [166]. Even though a few countries in SSA operate on a full privatisation model like Cote d'Ivoire and Senegal, this model has been marred by widespread failure in the sub-region [232]. Some of the reasons for failure highlighted in the literature include prioritising investment only in richer urban areas over poorer or informal settlements; political interference, especially in contract negotiations; and the general precarious status of water infrastructure and the level of improvements needed [166,232]. Even though different forms and approaches to privatisation have been central in more recent reforms in Sub-Saharan Africa, this has not led to an all-round improvement in performance or the provision of services [119,233]. Equity and affordability have been cited, even in advanced economies, as a downside to privatisation. For instance, the English regulatory model has been criticized on the basis that, with privatisation, the focus is on profit generation with equity and affordability being tertiary concerns [225]. Therefore, the choice of the regulatory approach involves the optimization of several objectives, and the best approach is always contextual with the customers central in every decision made.

2.5.5. Integrated Water Resource Management

The sustainable management of global water resources is transdisciplinary and involves optimising several complex and competing concepts and resources. This has led to the emergence of the Integrated Water Resource Management (IWRM) concept. IWRM is defined as *"a process that promotes the coordinated development and management of water, land and related resources to maximise economic and social welfare equitably without compromising the sustainability of vital ecosystems"* [234]. IWRM has been broadly promoted, especially by researchers, donors, and international organisations, as an integral part of the solution to global water management problems [235]. However, several researchers have challenged its holistic useability, success rate, and applicability to real-life situations [236–238]. This is exemplified in the work undertaken by Biswas [235], challenging the definition and concept of IWRM, and pointing out that, due to the complex and the associated nature of water, complete integration at the macro and mesoscale will lead to more problems than solutions. He argues that the concept is ambiguous and that it remains a popular concept with no validity or usefulness.

Nonetheless, others have suggested that IWRM should be considered as a paradigm with tools and guidance that can be tailored to the specific needs of a region or country, rather than seeing it as the answer to all water resource management problems [1,239]. Significant research has been conducted on the incorporation of IWRM practices in Sub-Saharan Africa for sustainable water security. However, as per Biwas' arguments [235], even though a significant amount of research has been conducted and administrative commitments made, the challenge is that SSA lacks the economic and human capacity to fully operationalise the recommendations [119,240]. Briefly, nations should understand their unique problems and apply context-specific strategies and commitments for sustainable water security.

3. Conclusions

The world as we know it is changing. These changes are projected to have significant consequences on our water systems, including reduced access, increased pollution, and an increase in uncertainty. To mitigate or adapt to these challenges and to foster sustainability and resilience, various measures have been taken by both developed and low-income countries. However, progress in SSA is significantly lagging. The challenge of providing water and sanitation services is still existing, and this is intensified by climate change and the need to provide these services sustainably. This review has examined the factors, influencing the sustainability of water infrastructure, along with the approaches implemented to tackle these challenges using the STEEP framework, and further assessing their applicability within the Sub-Saharan Africa context. From the review, the following is evident:

- SSA is the most rapidly urbanizing region globally, and it lacks the adequate infrastructure systems to deal with these population increases. In addition, water infrastructure is expensive, and the water sector is unattractive for investment.
- The lack of human and technological capacity in SSA has several impacts on the management of old, and the development and construction of new, infrastructure.
- Institutional structures do exist to some extent, but generally lack efficiency and therefore face challenges in the implementation of strategies.
- The provision of water and sanitation services is expensive and cannot be managed sustainably if these services are provided free of charge. However, due to poverty, there is a challenge of balancing equity and affordability.
- There is a lack of financial resources to efficiently manage water systems, and fewer resources to devote to aquatic and environmental considerations and protection.
- The people are central in the management of water systems and need to be involved in decision making to get their buy in.
- Water should be managed as a scarce resource with context specific approaches for the conservation, prevention of over abstraction, and active consideration of alternative supply sources.

This review has shown that for all five STEEP (societal, technical, environmental, economic, and political) drivers, significant progress has been made globally to tackle the challenging effects of climate change, population increase, urbanisation, and other factors for sustainable water resource management. However, the world is still off course in meeting Sustainable Development Goal (SDG) 6. This is more the case for low-income countries in Sub-Saharan Africa (SSA). Although significant progress has been made, the focus in SSA has been mostly on the development of policies and structures with insufficient funds and or human capacity/skills for the implementation or enforcement of said policies. Therefore, the state of the water infrastructure in SSA is generally classed as inadequate, unreliable, and in need of significant improvement. On the one hand, there is the challenge of the efficient provision of water and sanitation services, and on the other, there is the challenge of incorporating sustainability and resilience in these processes, especially in the face of climate change.

Though significant progress has been made, the measures proposed in the SSA context often function as mitigation strategies implemented post hoc, proving to deliver only short to medium-term benefits, or serving to minimise impact rather than pre-emptively addressing the issues to prevent occurrence altogether. Since water infrastructure systems are resource-intensive and long-lived, the need for more proactive strategies that take a systems approach, consider the uncertain and unforeseen future, and yield long-term benefits is crucial. There is a closing window of opportunity for SSA to act in incorporating sustainability and resilience into the built environment, as countries therein are at an evolving stage in the development of sustainable water infrastructure systems. Consequently, the decisions made today are crucial, and they should not compromise the ability of future generations to cater to their own needs.

Therefore, this review recommends an extended analysis of the applicability of the discussed interventions and their applicability in SSA, not just to deal with present challenges, but including an exploration of potential future scenarios and trends. Foresight is essential for better preparedness and for ensuring the availability of sufficient and clean water for future generations, while reducing negative environmental, economic, and social impacts. Due to unpredictable changes seen in various sectors including the water sector, foresight will provide valuable insights for anticipating and engineering solutions to future challenges and shaping the future research initiatives as long as it is embedded in a 'whole systems' approach, and one that is founded on systems thinking and systems practices that articulate a comprehensive theory of change. Further transdisciplinary research is recommended in integrating foresight and future thinking in water infrastructure systems planning and management in SSA, and in making informed decisions to protect and manage the limited water resources.

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