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Public Debt and Water Supply and Sanitation Infrastructure in Sub-Saharan Africa: A Panel ARDL Study with Cross-Sector Infrastructure Insights

David Alaba Makanjuola*, Gilbert Deinde Ifarajimi and Oluwasola Oni
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Abstract: *Water supply and sanitation infrastructure remains a critical development challenge in Sub-Saharan Africa (SSA), amid rising public debt and persistent fiscal constraints. This study examines the short-run and long-run relationships between public debt and water supply and sanitation infrastructure in SSA over the period 2005–2023, accounting for institutional quality, economic output and population growth. The study employs a Panel Autoregressive Distributed Lag (PARDL) framework, estimated using the Mean Group (MG) and Pooled Mean Group (PMG) estimators, to capture heterogeneous short-run dynamics and assess long-run relationships across countries. Institutional quality is measured using an Institutional Quality Composite Index (IQI). The PMG estimates reveal a negative and statistically significant error-correction coefficient (−0.0461), indicating an annual adjustment of approximately 4.6% towards long-run equilibrium. Public debt exhibits a positive and statistically significant long-run association with water supply and sanitation infrastructure, while its short-run effect is statistically insignificant. Population growth is positive and significantly associated with infrastructure development in the long run, whereas institutional quality exhibits a positive but statistically insignificant coefficient. The Hausman specification test fails to reject the long-run homogeneity restrictions underlying the PMG estimator. These findings suggest that the relationship between public debt and water supply and sanitation infrastructure is more pronounced over the long run, highlighting the potential importance of sustained infrastructure financing. However, the results do not establish that public borrowing directly causes infrastructure improvements. The study underscores the need to align debt management with infrastructure investment priorities through sustainable borrowing, rigorous project appraisal, transparent procurement and adequate maintenance financing to support long-term improvements in water supply and sanitation services across SSA.*

Keywords*: Public debt; water supply and sanitation; infrastructure development; Panel ARDL; Pooled Mean Group; institutional quality; Sub-Saharan Africa.*

David Alaba Makanjuola
Department of Economics, Baze University, Abuja, Nigeria.
Email: david8171@bazeuniversity.edu.ng
https://orcid.org/0009-0005-0150-2277

Gilbert Deinde Ifarajimi.
Department of Economics, Caleb University, Lagos State, Nigeria.
Email: gilbert.ifarajimi@calebuniversity.edu.ng
https://orcid.org/0000-0002-6197-7007

Oluwasola Oni
Department of Economics, Caleb University, Lagos, Niger.
Email: onioluwasola@yahoo.com
https://orcid.org/0000-0003-4951-2480

1.0 Introduction

1.0 Introduction

Water supply and sanitation (WSS) infrastructure constitutes a fundamental component of sustainable economic development, public health and human welfare. Access to reliable and safe drinking water and adequate sanitation services contributes to the

reduction of waterborne diseases, improves environmental health, reduces household time costs, enhances school attendance and supports labour productivity. Furthermore, efficient water and sanitation systems facilitate industrial activities, agricultural production, urban development and the overall functioning of economic systems. Despite their importance, access to adequate water supply and sanitation infrastructure remains a major development challenge in Sub-Saharan Africa (SSA), where substantial spatial, socioeconomic and rural–urban inequalities persist. Previous studies have associated inadequate water and sanitation services with increased disease burdens, environmental degradation and socioeconomic vulnerability (Pullan *et al*., 2014; Armah *et al*., 2018; Fuente *et al*., 2020). The persistence of these infrastructure deficits highlights the need for sustained investment in water production, treatment facilities, distribution networks, wastewater management and sanitation systems to improve service accessibility and reliability across the region.

The magnitude of the WSS infrastructure challenge in SSA is reflected in the persistent gaps in access to safely managed drinking water and sanitation services. Progress towards universal access has remained uneven, particularly among rural communities, low-income households and rapidly expanding urban settlements. These challenges are further complicated by population growth, urbanisation, climate variability, water scarcity and the deterioration of existing infrastructure. According to the World Health Organization (WHO) and United Nations Children's Fund (UNICEF) Joint Monitoring Programme, disparities in access to safely managed drinking water and sanitation remain particularly pronounced in developing regions, including SSA. Consequently, expanding WSS infrastructure requires substantial investment in new facilities, rehabilitation of existing systems, improved distribution networks and effective wastewater treatment. Beyond capital expenditure, the sustainability of these investments depends on adequate operational funding, institutional coordination, technical capacity and continuous maintenance. These requirements make WSS development a long-term financing challenge that extends beyond the initial construction of infrastructure.

Financing this infrastructure remains particularly difficult because WSS projects are characterised by substantial upfront capital requirements, long construction periods, extended asset lifetimes and significant recurrent maintenance costs. In many SSA economies, limited domestic revenue mobilisation, competing public expenditure priorities and macroeconomic instability constrain the fiscal resources available for infrastructure development. Public borrowing has consequently become an important mechanism for financing government development programmes, including investments in essential infrastructure. In principle, public debt can expand available fiscal resources, facilitate capital formation and enable governments to undertake infrastructure projects whose economic and social benefits accrue over extended periods. However, the developmental contribution of public borrowing depends on the efficiency with which borrowed resources are allocated, utilised and managed. High borrowing costs, weak project appraisal, procurement inefficiencies, implementation delays and inadequate maintenance financing can undermine the productivity of debt-financed infrastructure. Furthermore, increasing debt-servicing obligations may reduce fiscal space for essential public services and the maintenance of existing infrastructure.

The relationship between public debt and WSS infrastructure development is therefore complex and potentially dependent on the structure of public expenditure, institutional effectiveness and the economic conditions prevailing in individual countries. Unlike some transport, energy and telecommunications

investments, water supply and sanitation projects frequently generate substantial social and environmental returns that are not fully reflected in direct financial revenues. Consequently, private investment may be insufficient to meet the financing requirements of the sector, increasing the importance of government expenditure and public financing arrangements. While public borrowing can support the expansion of water treatment plants, distribution networks, sewage systems and sanitation facilities, excessive debt accumulation may constrain the financial capacity of governments to sustain these investments. The effectiveness of public debt as an infrastructure financing instrument may also vary according to institutional quality, economic output, population dynamics and the capacity of governments to translate financial resources into functional infrastructure. Understanding these relationships is important for determining whether public debt supports or constrains long-term improvements in WSS infrastructure across SSA.

Existing empirical studies provide useful but incomplete evidence concerning the relationship between public debt and infrastructure development. A first strand of literature examines the effects of public debt on public investment and aggregate infrastructure development. Frimpong, Fumey and Nketiah-Amponsah (2024), for instance, demonstrate that the relationship between public debt and infrastructure investment in Ghana varies across different time horizons. Similarly, Ezeaku *et al*. (2023) examine the influence of bilateral and multilateral concessional debt on public investment across SSA countries, providing evidence of the relevance of external borrowing arrangements to infrastructure financing. These studies establish important connections between public borrowing and investment expenditure but provide limited sector-specific evidence concerning water supply and sanitation infrastructure. Since infrastructure sectors differ in their financing requirements, revenue-generating capacity, investment gestation periods and maintenance obligations, findings based on aggregate public investment may not adequately explain the relationship between public debt and WSS development.

A second strand of literature focuses on the determinants of water supply and sanitation access, infrastructure deficiencies and their socioeconomic implications. Studies by Armah *et al*. (2018) and Fuente *et al*. (2020), among others, highlight the importance of socioeconomic, environmental and institutional conditions in explaining disparities in water and sanitation services. Dangui and Jia (2022) also contribute to the discussion of water and sanitation development and its associated determinants. Although this literature provides important insights into the challenges affecting WSS infrastructure, public debt has received comparatively limited attention as a central explanatory variable. Consequently, the financing implications of sovereign borrowing for the expansion and sustainability of water and sanitation infrastructure remain insufficiently understood.

A related body of empirical research investigates the contribution of foreign aid and official development assistance to infrastructure development and essential public services. Gopalan and Rajan (2016), for example, examine the relationship between external development assistance and water and sanitation outcomes, highlighting the relevance of financing arrangements and contextual differences in determining development effectiveness. Although foreign aid and sovereign public borrowing represent different financing channels, both influence the resources available for public infrastructure investment. However, their institutional arrangements, repayment obligations, allocation mechanisms and implications for fiscal sustainability differ considerably. Examining public debt separately from

development assistance is therefore important for understanding how domestic and external sovereign borrowing relates to the development of essential infrastructure in countries facing substantial financing constraints.

The relevance of infrastructure financing to economic and productive outcomes is also demonstrated by related cross-sector studies. Research on infrastructure accessibility and technical efficiency in small-scale aquaculture (Awolumate & Makanjuola, 2026), energy–water–profit trade-offs under electricity unreliability (Awolumate, Shani, & Okhogbe, 2026), ICT adaptability in fish farming (Awolumate, 2018), and communication infrastructure and information-use efficiency (Awolumate & Inyang, 2019b) illustrates how infrastructure availability, accessibility and reliability influence productive activities and resource utilisation. Similarly, studies on digital communication platforms (Mundi *et al*., 2024), infrastructure development and artisanal fishing efficiency (Awolumate & Fregene, 2025), and resource-use efficiency among fish farms (Awolumate & Inyang, 2019a) provide additional evidence of the relationship between infrastructure conditions and sectoral performance. Although these studies do not directly investigate public debt and national WSS infrastructure, they reinforce the importance of distinguishing between infrastructure investment, physical infrastructure availability and the effective utilisation of infrastructure services. This distinction is particularly relevant to WSS development, where the construction of facilities does not necessarily guarantee reliable access, adequate service delivery or long-term operational sustainability.

Despite the growing literature on public debt, infrastructure investment and water and sanitation development, an important empirical gap remains concerning the relationship between sovereign public borrowing and sector-specific WSS infrastructure across SSA. Existing public debt studies have predominantly focused on aggregate public investment, general infrastructure development or the macroeconomic implications of debt accumulation, while studies examining WSS development have concentrated largely on access determinants, socioeconomic outcomes and external development assistance. Consequently, limited empirical evidence exists on whether public debt is positively or negatively associated with WSS infrastructure development over different time horizons across SSA countries. Furthermore, insufficient attention has been given to the interaction between public debt, institutional quality, economic output and population growth in explaining variations in infrastructure development. The dynamic nature of infrastructure investment also creates a need to distinguish between short-run adjustments and long-run relationships, particularly because the benefits of WSS investments may take considerable time to materialise. Addressing these gaps is important for understanding the extent to which public borrowing is associated with the development of essential water and sanitation infrastructure under varying institutional and macroeconomic conditions.

Against this background, this study examines the short-run and long-run relationships between public debt and water supply and sanitation infrastructure development across selected Sub-Saharan African countries over the period 2005–2023. Specifically, it investigates the relationship between public debt and WSS infrastructure, evaluates the influence of institutional quality, economic output and population growth on infrastructure development, and examines the speed of adjustment towards long-run equilibrium. The study employs the Panel Autoregressive Distributed Lag (PARDL) framework, using the Mean Group (MG) and Pooled Mean Group (PMG) estimators to account for heterogeneous short-run country dynamics while examining

the plausibility of common long-run relationships across the panel. The inclusion of institutional quality is particularly important because differences in governance effectiveness, regulatory capacity, public financial management and institutional accountability may influence the allocation, implementation and maintenance of debt-financed infrastructure projects.

The significance of this study is both academic and policy-oriented. Academically, it extends the empirical literature on public debt and infrastructure development by focusing specifically on water supply and sanitation infrastructure, thereby providing sector-specific evidence that complements existing studies based on aggregate public investment and external development assistance. It also contributes to the literature by distinguishing between short-run dynamics and long-run relationships within a heterogeneous panel framework. From a policy perspective, the findings provide relevant evidence for finance ministries, debt-management authorities, water-sector institutions and development partners seeking to strengthen infrastructure financing strategies across SSA. Understanding the relationship between public debt and WSS development can inform decisions concerning sustainable borrowing, infrastructure investment prioritisation, project appraisal, transparent procurement and the allocation of resources for operations and maintenance. The findings may also support the development of financing arrangements that balance infrastructure expansion with debt sustainability and institutional accountability. Ultimately, the study provides evidence that can contribute to more effective public financing strategies and the long-term improvement of water supply and sanitation services across SSA.

The remainder of the paper is organised as follows: the next section reviews the theoretical and empirical literature; the subsequent section presents the data, variable measurements and econometric methodology; this is followed by the presentation and discussion of empirical findings; and the final section provides the conclusion and policy recommendations.

2.0 Theoretical Underpinning

The relationship between public debt and water supply and sanitation (WSS) infrastructure development can be explained through complementary theoretical perspectives concerning public borrowing, infrastructure investment, economic productivity and institutional effectiveness. This study draws on the Debt Overhang Theory, the Infrastructure-Led Development and Endogenous Growth perspectives, and Institutional Theory to explain the mechanisms through which public debt may influence infrastructure development across Sub-Saharan Africa (SSA). These perspectives provide a theoretical basis for understanding why public borrowing may support infrastructure expansion under favourable fiscal and institutional conditions but constrain development when debt-servicing obligations, inefficient resource allocation and weak governance undermine investment effectiveness. Furthermore, economic output and population growth are recognised as important macroeconomic and demographic factors influencing the demand for, and financing capacity of, WSS infrastructure.

2.1 Debt Overhang Theory and Fiscal Crowding-Out Mechanism

The Debt Overhang Theory provides an important explanation of how excessive public indebtedness can constrain investment and economic development. The theoretical foundation is associated with Krugman (1988), who explains how high external debt obligations can discourage investment when the expected benefits of additional economic activity are perceived to be appropriated through future debt-service obligations. Although originally developed in the context of external debt and investment, the underlying argument is relevant to public infrastructure

financing, particularly in developing economies with limited fiscal capacity.

Applied to WSS infrastructure, public borrowing can initially provide governments with the financial resources required to construct water treatment plants, expand distribution networks, develop wastewater treatment facilities and improve sanitation systems. Such investments can address infrastructure deficits that would otherwise persist because of inadequate domestic revenue mobilisation. However, as public debt accumulates, increasing interest and principal repayment obligations may reduce the fiscal resources available for new infrastructure projects, rehabilitation and routine maintenance. This situation creates a potential crowding-out effect in which debt servicing competes with productive public expenditure, thereby weakening the capacity of governments to sustain infrastructure development.

The relationship between public debt and WSS infrastructure is therefore theoretically ambiguous. Public borrowing may have a positive association with infrastructure development when borrowed resources are allocated to economically and socially productive projects with sustainable long-term returns. Conversely, the relationship may become negative when excessive borrowing, high debt-servicing costs, inefficient project selection and weak fiscal management constrain public investment. The theory consequently provides a basis for examining both the short-run and long-run relationships between public debt and WSS infrastructure development.

2.2 Infrastructure-Led Development and Endogenous Growth Theory

The Infrastructure-Led Development perspective, supported by the public capital and Endogenous Growth frameworks, explains how investment in essential infrastructure contributes to economic productivity and long-term development. Aschauer (1989) establishes the importance of public infrastructure capital in influencing aggregate productivity, while Barro (1990) demonstrates theoretically how productive government expenditure can contribute to economic growth through its effect on the productivity of private capital.

Within the context of WSS infrastructure, public investment in water supply, sanitation facilities, wastewater management and distribution networks generates both direct and indirect economic benefits. Reliable water services support industrial production, commercial activities, agricultural processing and household welfare, while adequate sanitation reduces disease transmission, environmental contamination and productivity losses associated with poor public health. These benefits can improve labour efficiency, reduce household expenditure on alternative water sources and create favourable conditions for private-sector activities. Consequently, WSS infrastructure represents a form of productive public capital capable of generating economic and social returns over extended periods.

The relevance of this perspective to public debt lies in the potential for borrowing to finance infrastructure investments whose benefits extend beyond the immediate fiscal period. Where borrowed resources are directed towards productive WSS projects, the resulting improvements in public health, economic productivity and service delivery may strengthen the capacity of governments and communities to support long-term development. However, the extent to which these benefits materialise depends on project quality, implementation efficiency, institutional capacity and the availability of adequate maintenance financing.

The theory also provides a basis for including economic output in the empirical model. Higher economic output may increase government revenue and fiscal capacity, thereby improving the resources available for

infrastructure investment. At the same time, expanding economic activities increase demand for reliable water and sanitation services. Accordingly, economic output is expected to have a positive relationship with WSS infrastructure development, although the magnitude of this relationship may vary across countries depending on their economic structures and public investment priorities.

2.3 Institutional Theory and Public Sector Efficiency

Institutional Theory emphasises the importance of governance structures, regulatory arrangements and administrative capacity in determining the effectiveness of economic policies and public resource allocation. North (1990) explains that institutions shape economic performance by establishing the formal and informal rules governing interactions, incentives and resource allocation. In the context of public infrastructure development, institutional effectiveness influences how financial resources are mobilised, allocated, implemented and monitored.

For WSS infrastructure, strong institutions can improve project identification, feasibility assessment, procurement transparency, contract management, regulatory oversight and maintenance planning. Effective institutional arrangements also support accountability in public expenditure, reduce opportunities for corruption and improve coordination among government agencies responsible for water supply and sanitation services. Conversely, weak institutions may result in inefficient resource allocation, cost overruns, abandoned projects, inadequate infrastructure maintenance and poor service delivery. These challenges can reduce the developmental benefits of public borrowing even when substantial financial resources are available.

Institutional quality is particularly relevant to SSA, where differences in governance effectiveness, regulatory capacity and public financial management may influence the outcomes of infrastructure investment. Manasseh et al. (2022) and Sandow et al. (2022) provide related empirical evidence on the relevance of governance and public-sector management to the developmental implications of public debt. Consequently, this study incorporates an Institutional Quality Composite Index (IQI) as an explanatory control variable to account for differences in institutional conditions across the sampled countries.

The institutional perspective also suggests that the relationship between public debt and WSS infrastructure may depend on the effectiveness of institutions responsible for managing borrowed resources. However, where institutional quality is included only as a separate explanatory variable, its independent association with infrastructure development is estimated rather than its moderating effect on public debt. Testing the moderating role of institutional quality would require an additional interaction term between public debt and the institutional quality index.

2.4 Demographic Pressure and Infrastructure Demand

Population growth provides an additional theoretical explanation for variations in WSS infrastructure development. The relationship between demographic expansion and infrastructure requirements can be understood through the induced-investment and infrastructure-demand perspectives. As population increases, demand for drinking water, sanitation facilities, wastewater treatment and distribution networks also expands. Rapid population growth, particularly in urban settlements, places additional pressure on existing infrastructure and may accelerate the need for new public investment.

In SSA, population expansion and urbanisation can intensify infrastructure deficits where the expansion of public facilities does not keep pace with demographic requirements. Governments may consequently increase capital expenditure and mobilise additional

financing, including public borrowing, to expand WSS infrastructure and improve service coverage. However, the relationship is not necessarily positive in all circumstances. Where population growth exceeds the capacity of public institutions and available financial resources, existing infrastructure may become overstretched, resulting in service deterioration and widening access inequalities.

Population growth is therefore incorporated into the empirical model to account for demographic pressure on infrastructure demand. Its expected relationship with WSS infrastructure development is generally positive where governments respond to increasing population needs through expanded infrastructure investment. Nevertheless, the actual outcome depends on fiscal capacity, investment efficiency and the ability of public institutions to translate demographic demand into effective infrastructure provision.

2.5 Theoretical Synthesis and Implications for the Empirical Model

The theoretical perspectives discussed above collectively explain the potential channels through which public debt and other macroeconomic and institutional factors influence WSS infrastructure development in SSA. Debt Overhang Theory explains the possibility that increasing public indebtedness and debt-servicing obligations may constrain infrastructure investment, while the Infrastructure-Led Development and Endogenous Growth perspectives establish the potential productivity and long-term developmental benefits of productive public infrastructure expenditure. Institutional Theory highlights the importance of governance and administrative efficiency in determining whether borrowed resources translate into functional infrastructure. The demographic-demand perspective further explains how population growth generates additional requirements for water supply and sanitation facilities.

Taken together, these perspectives suggest that public debt may exhibit either a positive or negative relationship with WSS infrastructure development, depending on the productivity of borrowing, debt sustainability and the effectiveness of public institutions. Economic output is expected to support infrastructure development through increased economic activity and fiscal capacity, while population growth may stimulate additional infrastructure demand. Institutional quality is expected to contribute positively to infrastructure development by improving the efficiency of public resource allocation and project implementation.

These theoretical arguments provide the foundation for the empirical investigation using the Panel Autoregressive Distributed Lag (PARDL) framework. The framework enables the study to distinguish between short-run adjustments and long-run relationships among public debt, WSS infrastructure and the selected institutional and macroeconomic variables. The Mean Group (MG) and Pooled Mean Group (PMG) estimators further allow the investigation of heterogeneous short-run country dynamics while examining the possibility of common long-run relationships across the sampled SSA economies.

3.0 Literature Review and Research Gap

3.1 Public debt, public investment and infrastructure

Evidence on the debt–investment relationship is mixed and highly dependent on the financing structure, macroeconomic context and time horizon. Ncanywa & Masoga (2018) document dynamic relationships among public debt, public investment and economic growth in South Africa, while Frimpong *et al*. (2024) find asymmetric effects of public debt on infrastructure investment in Ghana. In a broader SSA setting, Ezeaku *et al*. (2023) employ dynamic Panel ARDL estimators and report that bilateral and multilateral concessional debt have significant long-run

effects on public investment. These studies support the proposition that borrowing can affect public capital formation but do not establish whether this effect is specific to WSS. Nigerian sectoral evidence provides complementary hypotheses about the conversion of infrastructure into productive outcomes. Awolumate and Makanjuola (2026) examine infrastructure accessibility alongside extension intensity and technical efficiency; Awolumate, Shani & Okhogbe (2026) analyze energy–water–profit trade-offs under unreliable electricity; and Awolumate and Inyang (2019b) examine technical-efficiency differentials in aquaculture resource use. Research on ICT adaptability (Awolumate, 2018), communication infrastructure and information-use efficiency (Awolumate & Inyang, 2019b), and digital platforms in aquaculture communication (Mundi *et al*., 2024) further illustrates the role of access and information systems. Studies of artisanal fishing and infrastructure development (Awolumate & Fregene, 2025), digital market information and fish supply-chain performance (Awolumate, 2026a), and post-harvest storage behaviour (Amos & Awolumate, 2026) extend this contextual evidence to resource management, market coordination and infrastructure use. These publications concern sectoral settings in Nigeria rather than sovereign debt or national WSS systems; they are used here to frame hypotheses, not as direct empirical evidence for the macro-panel coefficients.

At the regional level, financing conditions also shape infrastructure gaps. Kodongo *et al*., (2023) show that deeper bond markets can help reduce infrastructure deficits in SSA. This suggests that the source, maturity and cost of finance matter for infrastructure delivery. Yet aggregate infrastructure indicators can conceal sectoral differences because water and sanitation projects differ from transport, electricity and ICT in commercial structure, maintenance requirements, institutional responsibilities and social returns.

3.2 Water supply and sanitation infrastructure

Research on WSS consistently documents large cross-country and within-country inequalities across SSA. Pullan *et al*. (2014) show pronounced geographical differences in the use of improved drinking water and sanitation, while Armah *et al*. (2018) find that progress in water access has outpaced sanitation and remains uneven across socioeconomic and spatial groups. Fuente *et al*. (2020) demonstrate that inadequate WSS continues to impose substantial mortality and economic losses in parts of SSA and that economic growth alone will not automatically eliminate these deficits.

Dangui & Jia (2022) examine the drivers and economic implications of water infrastructure performance in SSA and reinforce the importance of sector-specific analysis. However, the direct role of public debt as a determinant of financing remains underdeveloped in this literature.

3.3 Financing of water and sanitation

A substantial financing literature focuses on foreign aid rather than sovereign borrowing. Gopalan & Rajan (2016) find that aid to water supply and sanitation can improve access, particularly in lower-middle-income and rural settings, but also document nonlinear and diminishing returns. Such evidence demonstrates that financing matters, but aid and public debt differ fundamentally in repayment obligations, fiscal risk and implications for future expenditure. This distinction motivates a direct analysis of debt-financed WSS.

3.4 Research gap and contribution

The literature reveals a clear empirical gap. Public-debt studies generally focus on growth, aggregate public investment or broad infrastructure; WSS studies emphasize access,

health consequences and socioeconomic determinants; and WSS financing studies concentrate heavily on aid and official development assistance. Relatively little evidence integrates public debt, WSS infrastructure, institutional quality and dynamic short-run/long-run analysis within one multi-country SSA framework. This study addresses that gap using Panel ARDL with MG and PMG estimators.

4. 0 Methodology and Data

4.1 Research design and empirical framework

The study employs a quantitative dynamic-panel design to examine the short-run and long-run relationship between public debt and water supply and sanitation infrastructure in Sub-Saharan Africa over 2005–2023. The Panel Autoregressive Distributed Lag (PARDL) framework is appropriate because the variables may be integrated of different orders, provided none is integrated of order two, and because the estimator separates short-run country-specific adjustment from the long-run equilibrium relationship. The Mean Group (MG) and Pooled Mean Group (PMG) estimators are used as complementary heterogeneous-panel estimators, following Pesaran *et al*., (1999).

4.2 Functional specification

Water supply and sanitation infrastructure is the dependent variable. Public debt is the principal explanatory variable, while economic output, population growth and institutional quality enter as controls. The preferred empirical relationship is specified as:

$$WSS_{it} = f(PD_{it}, LGDP_{it}, POPG_{it}, IQI_{it}) \quad (1)$$

where WSS_it denotes water supply and sanitation infrastructure in country i at time t; PD_it denotes public debt, measured by the debt-to-GDP ratio; LGDP_it denotes the logarithm of gross domestic product; POPG_it denotes population growth; IQI_it denotes the Institutional Quality Composite Index; and i and t index countries and years, respectively.

The corresponding static representation is:

$$WSS_{it} = \alpha_i + \beta_1 PD_{it} + \beta_2 LGDP_{it} + \beta_3 POPG_{it} + \beta_4 IQI_{it} + \varepsilon_{it}. \quad (2)$$

Institutional quality enters the model strictly as a standalone explanatory variable through IQI. No interaction term is included in the preferred manuscript specification.

4.3 Panel ARDL specification

The unrestricted PARDL(p, q1, q2, q3, q4) model is written as:

$$WSS_{it} = \alpha_i + \sum_{j=1}^{p} \varphi_{ij} WSS_{i,t-j} + \sum_{j=0}^{q^1} \beta_{1ij} PD_{i,t-j} + \sum_{j=0}^{q^2} \beta_{2ij} LGDP_{i,t-j} + \sum_{j=0}^{q^3} \beta_{3ij} POPG_{i,t-j} + \sum_{j=0}^{q^4} \beta_{4ij} IQI_{i,t-j} + \varepsilon_{it} \quad (3)$$

In equation 3, p is the lag order of the dependent variable and q1–q4 are the lag orders of the explanatory variables. This dynamic specification allows current water and sanitation infrastructure to depend on its own past values and on contemporaneous and lagged movements in public debt, output, population growth and institutional quality.

4.4 Error-correction representation

For estimation and interpretation, Equation (3) is reparameterised into the error-correction form:

$$\Delta WSS_{it} = \lambda_i [WSS_{i,t-1} - \theta_0 - \theta_1 PD_{i,t-1} - \theta_2 LGDP_{i,t-1} - \theta_3 POPG_{i,t-1} - \theta_4 IQI_{i,t-1}] + \sum \psi_{ij} \Delta WSS_{i,t-j} + \sum \gamma_{1ij} \Delta PD_{i,t-j} + \sum \gamma_{2ij} \Delta LGDP_{i,t-j} + \sum \gamma_{3ij} \Delta POPG_{i,t-j} + \sum \gamma_{4ij} \Delta IQI_{i,t-j} + \mu_i + \varepsilon_{it}. \quad (4)$$

The coefficient λ_i is the error-correction or speed-of-adjustment parameter. A negative and statistically significant value indicates convergence toward the long-run equilibrium after a short-run disturbance. Its absolute magnitude measures the proportion of the previous period's disequilibrium corrected in one year. The θ parameters are the long-run coefficients, whereas the γ parameters capture short-run responses.

4.5 Long-run and short-run equations

The long-run equilibrium relationship implied by the PARDL model is:

$$WSS_{it} = \theta_0 + \theta_1 PD_{it} + \theta_2 LGDP_{it} + \theta_3 POPG_{it} + \theta_4 IQI_{it} + u_{it}. \quad (5)$$

The coefficient θ_1 is the principal parameter of interest and measures the long-run effect of

public debt on water supply and sanitation infrastructure. A positive coefficient indicates that higher public borrowing is associated with improved WSS infrastructure, whereas a negative coefficient is consistent with debt-service pressure, fiscal crowding out or inefficient allocation of borrowed resources.

The short-run dynamics can be written compactly as:

$$\Delta WSS_{it} = \lambda_i ECT_{i,t-1} + \Sigma\gamma_{1ij}\Delta PD_{i,t-j} + \gamma_{2ij}\Delta LGDP_{i,t-j} + \Sigma\gamma_{3ij}\Delta POPG_{i,t-j} + \Sigma\gamma_{4ij}\Delta IQI_{i,t-j} + \varepsilon_{it}. \quad (6)$$

where ECT_i,t-1 is the lagged deviation from the long-run relationship in equation 5.

4.6 PMG and MG estimation

The PMG estimator imposes equality on the long-run coefficients across countries while allowing short-run coefficients, intercepts, adjustment speeds and disturbance variances to differ. Formally, $\theta_{ki} = \theta_k$ for all i in the long run, while λ_i, γ_{kij}, μ_i and σ_i^2 remain country-specific. This restriction is plausible when countries share a common long-run development relationship but differ in short-run fiscal, demographic and institutional responses.

The MG estimator, by contrast, estimates a separate dynamic regression for each country and computes the unweighted mean of the country-specific coefficients:

$$\hat{\theta}^{MG} = (1/N)\ \Sigma_{i=1}^{N}\ \hat{\theta}_i. \quad (7)$$

MG therefore allows both short-run and long-run coefficients to vary across countries and serves as the principal comparator to PMG.

4.7 Hausman model-selection test

The Hausman specification test is used to assess whether the long-run homogeneity restrictions imposed by PMG are supported by the data. The null hypothesis is that PMG is efficient and consistent, while the alternative favours MG. A statistically insignificant Hausman probability supports PMG. In the current WSS estimation, the reported Hausman statistic is 10.59 with p = 0.1575; hence the null is not rejected and PMG is retained as the preferred estimator.

4.8 Data Sources, Variable Description and Measurement

The study uses annual panel data for Sub-Saharan African countries over the period 2005–2023. Water supply and sanitation infrastructure is the dependent variable, while public debt is the principal explanatory variable. Gross domestic product, population growth and institutional quality are included to account for differences in economic capacity, demographic pressure and institutional performance. Table 1 summarizes the variables, their measurement, data sources and expected coefficient signs.

5.0 Empirical Results

5.1 Preliminary tests

The unit-root evidence in the supplied output indicates a mixture of level-stationary and first-difference-stationary variables, with no evidence that the variables are integrated beyond order one. This mixed I(0)/I(1) structure is compatible with Panel ARDL estimation.

The empirical analysis employs variables representing water supply and sanitation infrastructure, public debt, economic output, population growth and institutional quality. To ensure clarity and consistency in the econometric estimation, the operational definitions, measurement procedures and corresponding data sources for these variables are presented in Table 1.

Cointegration evidence is mixed under the Pedroni statistics for the WSS model, while the Westerlund variance-ratio statistic for the corresponding objective is significant. The negative and significant PMG error-correction term provides additional evidence of an equilibrating long-run relationship in the estimated dynamic specification.

Table 1: Variable definitions, measurement and data sources

Variable	Symbol	Measurement / operational definition	Data source
Water supply and sanitation infrastructure	WSS	Water supply and sanitation component of the Africa Infrastructure Development Index, reflecting access to water and sanitation services.	AfDB, AIDI (2005–2023)
Public debt	PD	Public debt stock expressed as a percentage of GDP.	World Bank / IMF 2023
Gross domestic product	LGDP	Natural logarithm of gross domestic product, capturing the scale of economic activity.	World Bank, WDI 2023
Population growth	POPG	Annual population growth rate (%).	World Bank, WDI 2023
Institutional quality	IQI	Composite index constructed from selected governance indicators; higher values denote stronger institutional quality.	Authors' computation from governance indicators 2023

Source: Authors' compilation based on the African Development Bank (AfDB), World Development Indicators (WDI), relevant public debt databases and governance indicators.

Following the preliminary unit-root analysis, panel cointegration tests were conducted to examine the existence of long-run equilibrium relationships among water supply and sanitation infrastructure, public debt, economic output, population growth and institutional quality. The Pedroni and Westerlund cointegration test statistics and their corresponding probability values are presented in Table 2.

Table 2: Panel cointegration tests for the WSS model

Test	Statistic	p-value
Pedroni modified Phillips–Perron t	10.2484	0.0000***
Pedroni Phillips–Perron t	1.1332	0.1286
Pedroni augmented ADF t	0.9723	0.1655
Westerlund variance ratio	14.7978	0.0000***

Note: The attached estimation output labels the WSS equation as Model Three. *, ** and * indicate significance at the 1%, 5% and 10% levels**

5.2 MG and PMG estimates for water supply and sanitation

To establish the short-run and long-run relationships between public debt and water supply and sanitation infrastructure, the study estimates the Panel ARDL model using the Mean Group (MG) and Pooled Mean Group (PMG) approaches. The estimated coefficients, error-correction terms, standard errors and Hausman specification test results are presented in Table 3.

Table 3 : MG and PMG estimates for water supply and sanitation infrastructure

Variable	MG	PMG
Error-correction term	−0.0290	−0.0461***
	(0.122)	(0.0108)
Δ Public debt	−0.00391**	0.000224
	(0.00177)	(0.000770)
Δ Log GDP	−0.00500	0.0150*
	(0.0786)	(0.00803)
Δ Population growth	−0.00707	−0.00160
	(0.0273)	(0.00885)
Δ IQI	0.147	−0.0425
	(0.443)	(0.0336)
Long-run public debt	0.0946*	0.00486***
	(0.0486)	(0.000729)
Long-run log GDP	−0.323	−0.000139
	(0.421)	(0.00277)
Long-run population growth	−0.0858	0.0761***
	(0.582)	(0.0116)
Long-run IQI	−2.159	0.0238
	(3.311)	(0.0145)
Constant	−0.487	0.102**
	(0.432)	(0.0411)
Hausman test	—	10.59
		[p = 0.1575]
Observations	714	714

Note: Standard errors are reported in parentheses. *, ** and * denote significance at the 1%, 5% and 10% levels, respectively. The Hausman p-value of 0.1575 supports PMG relative to MG., IQI is presented as a standalone explanatory variable and interaction-term estimates are excluded from the table.**

Table 3 reports only the standalone coefficients for public debt, log GDP, population growth and IQI. The interaction terms are not part of the model and are not reported or interpreted.

5.3 Interpretation of the PMG results

The Hausman statistic of 10.59 with p = 0.1575 does not reject the null that the long-run homogeneity restrictions are valid. PMG is therefore the preferred estimator for interpretation relative to MG in the supplied output.

The error-correction coefficient is −0.0461 and significant at the 1% level. The negative sign confirms convergence following short-run disturbances. Its magnitude implies that approximately 4.6% of the gap from long-run equilibrium is corrected annually. The adjustment is therefore statistically reliable but

slow, a pattern consistent with the long gestation period, maintenance constraints and institutional complexity associated with WSS infrastructure.

The short-run public debt coefficient under PMG is positive but not statistically significant. This suggests that changes in borrowing do not translate immediately into measurable improvements in water and sanitation infrastructure. Such a result is plausible because debt-financed WSS projects require planning, procurement, construction, and network expansion before service outcomes become visible.

In contrast, the reported long-run public-debt coefficient is positive and significant at the 1% level. This result is consistent with the proposition that public borrowing can support WSS infrastructure when financing is sustained over time and converted into productive assets. It also accords with the broader public-investment literature, which finds that concessional and other forms of debt can affect long-run public investment (Ezeaku *et al*., 2023). The finding should nevertheless be interpreted jointly with debt sustainability: a positive infrastructure response does not imply that all additional borrowing is welfare-improving, particularly where servicing costs later displace maintenance and social expenditure.

Population growth has a positive and highly significant long-run coefficient. One interpretation is that demographic pressure increases demand for water and sanitation networks and induces governments to expand service provision over time. The absence of a significant short-run effect indicates that infrastructure supply responds slowly to demographic change.

The long-run IQI coefficient is positive but statistically insignificant in the reported results. This does not imply that institutions are unimportant. The wider literature shows that governance and public-sector management affect the developmental consequences of debt, while project implementation in WSS is institutionally intensive. Rather, the result indicates that the standalone IQI coefficient is not estimated precisely in the reported specification.

Log GDP is statistically insignificant in the long run. This suggests that economic scale by itself is insufficient to guarantee water and sanitation infrastructure expansion. Fiscal allocation, financing structure, institutional capacity and sector prioritization may matter more than aggregate income growth alone.

5.4 Discussion of the results

The positive long-run public-debt coefficient extends the debt–public-investment literature into a sector-specific WSS setting. Frimpong *et al*. (2024) show that public debt affects infrastructure investment in Ghana, while Ezeaku *et al*. (2023) identify long-run public-investment effects of concessional borrowing in SSA. The present evidence narrows that relationship to water supply and sanitation.

The findings also complement the WSS financing literature. Gopalan & Rajan (2016) show that foreign aid can improve WSS access but with nonlinear and context-dependent effects. Public debt differs from aid because it creates future repayment obligations, but both literatures point to the importance of financing design and absorptive capacity.

The slow speed of adjustment is consistent with persistent WSS deficits documented across SSA. Pullan *et al*. (2014), Armah *et al*. (2018) and Fuente *et al*. (2020) show that service deficits and inequalities remain substantial despite long-term development efforts. This persistence suggests that capital financing must be accompanied by maintenance systems, institutional coordination and sustained service delivery. Cross-sector studies from Nigeria reinforce the importance of service reliability and effective use: electricity unreliability is linked to energy–water–profit trade-offs in aquaponics (Awolumate *et al*., 2026), while infrastructure accessibility has been examined

in relation to technical efficiency in aquaculture (Awolumate & Makanjuola, 2026). Research on digital market information (Awolumate, 2026a) and post-harvest storage behaviour (Amos & Awolumate, 2026) similarly points to the relevance of access and infrastructure use for sectoral performance. These are contextual parallels, not direct evidence about public WSS infrastructure or debt financing.

6. 0 Conclusion and Policy Implications

This study examines the dynamic relationship between public debt and water supply and sanitation infrastructure in Sub-Saharan Africa using a Panel ARDL framework for the 2005–2023 period. The analysis is motivated by the coexistence of persistent WSS deficits and increasing reliance on public borrowing across the region. MG and PMG estimators are used to distinguish heterogeneous short-run adjustment from the long-run relationship.

The reported PMG evidence indicates a slow but statistically significant return to long-run equilibrium. Public debt has no significant immediate effect on WSS infrastructure, but its reported long-run coefficient is positive and significant. Population growth is also positively associated with WSS infrastructure in the long run, while the coefficients on log GDP and the standalone IQI variable are not statistically significant. These results point to a long-horizon financing mechanism: borrowing may support infrastructure expansion, but the effect materializes gradually and depends on implementation capacity.

The policy implication is not simply to borrow more. Debt-financed WSS investment should be embedded in credible debt-sustainability frameworks and supported by rigorous project appraisal. Governments should favour concessional and long-maturity financing for projects with large social returns but limited commercial cash flows. Procurement transparency, life-cycle costing, ring-fenced maintenance budgets and independent performance monitoring are essential to prevent the erosion of infrastructure value after construction.

Second, water and sanitation should receive greater protection within capital budgets. Because the sector produces large health and productivity spillovers, project selection frameworks should explicitly recognize social returns rather than relying exclusively on direct financial revenue. Blended finance, development-bank lending and well-designed public–private arrangements can complement sovereign borrowing where risks are appropriately allocated.

Third, institutional capacity requires continued strengthening even where the standalone IQI coefficient is statistically weak. Water agencies often operate across multiple ministries and levels of government; clearer mandates, reliable billing and tariff systems, transparent procurement and professional asset management can raise the productivity of borrowed resources.

Finally, debt policy and infrastructure policy should be jointly evaluated. Borrowing decisions should be linked to measurable service indicators such as access, continuity, water quality, sanitation coverage and maintenance performance. This would shift policy attention from the volume of borrowing to the development outcomes generated by borrowed funds.

7. 0 Contribution to Knowledge

The paper contributes by providing a sector-specific analysis of the public debt–water and sanitation nexus in SSA rather than relying on aggregate infrastructure or public-investment measures. It integrates debt financing, WSS infrastructure and institutional quality within a dynamic Panel ARDL framework and separates short-run adjustment from long-run effects. It also bridges two literatures that have largely evolved separately: sovereign debt and public investment, and WSS financing dominated by aid and service-access studies.

8.0 Limitations and Further Research

The study is constrained by the availability and comparability of annual infrastructure indicators across SSA countries. Aggregate WSS indices may not fully capture service quality, continuity, affordability or subnational inequality. The current debt measure also does not distinguish domestic from external debt, concessional from commercial borrowing, or creditor composition. Future research should examine these financing dimensions and consider nonlinear debt thresholds, climate vulnerability, urbanization and project-level efficiency. A further extension would combine national infrastructure indicators with household or geospatial access data to evaluate distributional outcomes. Sector-level research from Nigeria offers possible constructs for future work, including infrastructure accessibility and technical efficiency (Awolumate & Makanjuola, 2026; Awolumate & Inyang, 2019a), ICT access and information-use efficiency (Awolumate, 2018; Awolumate & Inyang, 2019b; Mundi *et al*., 2024), electricity reliability (Awolumate, Shani, & Okhogbe, 2026), infrastructure development and artisanal fishing performance (Awolumate & Fregene, 2025), digital market information (Awolumate, 2026a), post-harvest storage behaviour (Amos & Awolumate, 2026), and financial constraints in small-scale fish processing (Awolumate & Muyiwa, 2025). These sectoral studies should inform future hypotheses and measurement design rather than be treated as direct evidence for macro-level debt–WSS relationships.

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Declarations

Consent for publication

Not Applicable

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The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethical Considerations

Not applicable

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David Alaba Makanjuola conceptualised the study, developed the methodology, conducted the econometric analysis and prepared the original manuscript. Gilbert Deinde Ifarajimi contributed to the theoretical framework, literature review, interpretation of findings and critical revision. Oluwasola Oni contributed to data validation, policy analysis, manuscript review and editing. All authors read and approved the final manuscript.