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Joint Modeling of Access to Improved Water and Sanitation in Nigeria: A Copula-Based Generalized Joint Regression and Spatial Semiparametric Approach

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ABSTRACT

This study investigates the joint determinants of access to improved water and sanitation facilities in Nigeria, accounting for dependence, nonlinear effects, and spatial heterogeneity. The analysis utilizes nationally representative data from the 2024 Nigeria Demographic and Health Survey (NDHS). A copula-based Generalized Joint Regression Model (GJRM) was employed to model water and sanitation access while capturing their interdependence. The results reveal a statistically significant positive dependence between access to improved water and sanitation facilities in the baseline model, indicating that households with access to one service are more likely to have access to the other. Socio-economic variables such as household wealth and urban residence were found to be strong predictors, with households in the richest quintile having over 3 times higher likelihood of accessing both services compared to the poorest quintile. Nonlinear effects were observed for household size and age. Spatial analysis further revealed pronounced regional disparities, with significantly higher access levels in southern regions compared to northern regions. Sanitation access exhibited stronger spatial clustering than water access, highlighting localized inequalities in infrastructure distribution. Overall, the study demonstrates that access to water and sanitation in Nigeria is shaped by a complex interplay of socio-economic, demographic, and spatial factors.

1 Introduction

Access to safe drinking water and improved sanitation remains a fundamental component of public health and sustainable development. These services are central to the achievement of the United Nations Sustainable Development Goal 6 (SDG 6), which aims to ensure availability and sustainable management of water and sanitation for all. Despite global progress, disparities in access persist, particularly in low- and middle-income countries. In Nigeria, access to improved water and sanitation remains uneven across regions and socio-economic groups. According to the World Health Organization and UNICEF Joint Monitoring Programme (JMP), a substantial proportion of households still lack access to safely managed drinking water and sanitation facilities (WHO & UNICEF, 2023). These deficiencies contribute to a high burden of waterborne diseases, including diarrhea and cholera, particularly among vulnerable populations such as children under five (Prüss-Ustün et al., 2019).

Previous studies have identified key socio-economic determinants of water and sanitation access, including household wealth, education, urban–rural residence, and household size (Fink et al., 2011; Bain et al., 2014). In the Nigerian context, regional disparities have been widely documented, with northern regions generally exhibiting lower access

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levels compared to southern regions (National Bureau of Statistics, 2022). However, most existing studies analyze water and sanitation outcomes separately, thereby ignoring the potential interdependence between the two services. The joint nature of water and sanitation access is important because both services are often simultaneously determined by underlying infrastructural, economic, and environmental conditions. Ignoring this dependence may lead to biased estimates and incomplete policy insights. To address this limitation, recent methodological developments have emphasized the use of copula-based models and multivariate regression frameworks that explicitly capture dependence between multiple outcomes (Nelsen, 2006; Marra & Radice, 2017). Also, previous studies have shown that inadequate sanitation is strongly associated with adverse child health outcomes including stunting and increased exposure to infectious diseases as highlighted by Fahrmeir *et.al.* (2013). Improved water quality has been shown to significantly reduce the incidence of diarrheal diseases, which remain a leading cause of child mortality in developing countries as demonstrated by Clasen *et.al.* (2007)

Furthermore, traditional regression models often assume linear relationships between covariates and outcomes, which may oversimplify complex real-world processes. Semiparametric approaches, such as Generalized Joint Regression Models (GJRM), provide a flexible framework for capturing nonlinear effects using smooth functions (Wood, 2017; Marra & Radice, 2020). These models are particularly useful in demographic and health studies where relationships between variables such as age, time, and household characteristics may not be strictly linear. In addition, spatial heterogeneity plays a crucial role in shaping access to water and sanitation. Geographic differences in infrastructure development, policy implementation, and environmental conditions can lead to significant regional disparities. Spatial modelling techniques, including random effects and structured spatial components, allow for the identification of unobserved regional influences and clustering patterns (Banerjee et al., 2014). In Nigeria, such spatial disparities are especially pronounced due to variations in socio-economic development and governance across states.

Despite extensive literature on water and sanitation access in sub-Saharan Africa, three key gaps remain. First, most existing studies analyze water and sanitation outcomes independently, ignoring their joint dependence structure (Fink et al., 2011; Pullan et al., 2014). Second, conventional regression approaches often fail to capture nonlinear relationships and spatial heterogeneity inherent in-service access (Banerjee et al., 2014). Third, there is limited use of recent nationally representative datasets such as the NDHS 2024 to provide updated evidence for Nigeria. This study addresses these gaps by jointly modelling access to improved water and sanitation using a sequence of increasingly flexible models. Specifically, a copula-based bivariate model is first employed to capture dependence between the two outcomes. This is followed by a Probit-based Generalized Joint Regression Model, which is extended to incorporate nonlinear effects through smooth functions and spatial heterogeneity via state-level random effects. By integrating dependence, nonlinearity, and spatial variation within a unified framework, this study provides a more comprehensive understanding of the determinants of water and sanitation access.

There are some limitations that were considered when interpreting the findings. Since the analysis was based on cross-sectional survey data; therefore, the observed associations between access to improved drinking water, improved sanitation, and the explanatory variables should not be interpreted as causal relationships. The findings instead describe statistical associations and patterns in access to these services. Also, the classification of water and sanitation facilities was based on the available survey variables and standard definitions of improved facilities. Such classifications may not fully capture important dimensions of service quality, including reliability, availability, safety, continuity, affordability, and actual functionality of water and sanitation facilities. Despite these limitations, the study provides a comprehensive joint assessment of improved water and sanitation access by combining copula-based dependence modeling, nonlinear covariate effects, and spatial heterogeneity. The findings therefore offer useful evidence on the socioeconomic, demographic, and geographic factors associated with disparities in access to these essential services in Nigeria.

2 Material and Methods

2.1 Data and Variables

This study utilizes data from the 2024 Nigeria Demographic and Health Survey (NDHS), conducted by the National Population Commission in collaboration with ICF International. The NDHS provides nationally representative data on household characteristics, water access, sanitation, and socio-economic indicators. The analysis is based on a weighted sample of 41,000 households after excluding observations with missing values. To ensure national representativeness, sampling weights provided by NDHS were applied in all descriptive and regression analyses. These weights adjust for unequal probabilities of selection and non-response bias.

Table 1: Descriptive Statistics of Variables Used

Variables	Description	Type
Water Access	Access to improved drinking water	Binary
Sanitation	Access to improved toilet	Binary
Wealth Index	Household wealth quantile	Categorical
Education	Household Education	Categorical
Residence	Urban/Rural	Binary
Gender	Male/Female	Binary
Age of House Head	Age of House Head	Continuous
Time	Time to get to Source of drinking water	Categorical
Size	Size of Household	Categorical
Television	Whether a Household has television	Binary

2.2 Model Specification

This study models the joint determination of access to improved water and sanitation facilities in Nigeria. A copula-based regression framework was employed, which allows flexible specification of joint distributions beyond traditional correlation structures (He & Zhu, 2021). Each outcome was specified using a logistic regression framework, while their dependence structure was captured using a copula function. Let Y_{1i} denote access to improved water and Y_{2i} denote access to improved sanitation (toilet) for household (i), where:

$$Y_{1i}, Y_{2i} \in \{0, 1\} \quad (1)$$

Given the potential dependence between these two outcomes, a joint modelling framework is adopted. A bivariate copula regression model was employed to jointly model access to improved drinking water and sanitation facilities. Each outcome was specified using a logistic regression framework, while their dependence structure was captured using a copula function. Let Y_1 and Y_2 denote access to improved drinking water and sanitation, respectively. The marginal distributions were modelled as:

$$logit\left(P\left(Y_j = 1 \mid X\right)\right) = X\beta_j, \ \ j = 1, 2 \quad (2)$$

The joint distribution of $(Y_1\ Y_2)$ was constructed using a copula function $C\ (\cdot)$ such that:

$$P(Y_1 = 1, Y_2 = 1) = C\left(p_{1,}p_2;\ \theta\right) \quad (3)$$

Where p_1 and p_2 are the marginal probabilities, and θ captures the dependence between the two outcomes. Different copula families, including Gaussian, Clayton, and Frank, were considered, and model selection was based on Akaike Information Criterion (AIC).

2.2.1 Marginal models

The marginal probabilities of access to improved water and sanitation are modeled as:

$$P(Y_{1i} = 1) = F_1(\eta_{1i}),\ P(Y_{2i} = 1) = F_2(\eta_{2i}), \quad (4)$$

where $F_1(\cdot)\ and\ F_2(\cdot)$ are cumulative distribution functions corresponding to the chosen link functions (logit or probit), and η_{1i} , η_{2i} are linear predictors defined as functions of observed covariates.

2.2.2 Copula-Based Joint model

The joint probability is defined using a copula function as

$$P(Y_{1i} = y_1, Y_{2i} = y_2) = C_\theta\left(F_1(\eta_{1i}), F_2(\eta_{2i})\right) \quad (5)$$

Where $C_\theta(\cdot,\cdot)$ is the copula function parameterized by θ capturing the dependence between the two outcomes, η_{1i} , η_{2i} are linear predictors defined as functions of observed covariates. $F_1 F_2$ = marginal cumulative distribution functions, $C(\cdot)$= copula function and θ= dependence parameter

In this study, a Gaussian is employed written as

$$C_\theta(u, v) = \Phi_2(\Phi^{-1}(u), \Phi^{-1}(v);\ \theta) \quad (6)$$

Where Φ_2 is bivariate normal CDF, Φ^{-1} is the inverse normal CDF and θ is the correlation between the two latent variables which mean that the probability that a household has (or does not have) both water and sanitation is determined not only by their individual probabilities, but also by a dependence structure captured through the copula. The copula model is extended within the Generalized Joint Regression Model (GJRM) framework, allowing for flexible specification of marginal distributions and dependence structure.

The linear predictors for water and toilet access are defined as:

$$\eta_{1i} = \beta_{10} + \sum_{k=1}^{p} \beta_{1k} x_{ik}\ ,\ \eta_{2i} = \beta_{20} + \sum_{k=1}^{p} \beta_{2k} x_{ik} \quad (7)$$

Where x_{ik} represents the kth covariate for the ith household and β_{1k}, β_{2k} are the corresponding regression coefficient.

2.2.3 Semiparametric extension

To capture potential nonlinear relationships, the linear predictors are extended to incorporate nonlinear covariate effects using smooth functions:

$$\eta_{1i} = \beta_{10} + \sum_{k=1}^{p} \beta_{1k} x_{ik} + f_1(age_i) + f_2(hhsize_i) + f_3(time_i) \quad (8a)$$

$$\eta_{2i} = \beta_{20} + \sum_{k=1}^{p} \beta_{2k} x_{ik} + g_1(age_i) + g_2(hhsize_i) + g_3(time_i) \quad (8b)$$

where $f_j(\cdot)$ and $g_j(\cdot)$ are smooth functions estimated using penalized regression splines, allowing for flexible nonlinear relationships between the covariates and the response variables

2.2.4. Spatial effects model

To account for spatial heterogeneity, state-level random effects are incorporated into the linear predictors:

$$\eta_{1i} = \beta_{10} + \sum_{k=1}^{p} \beta_{1k} x_{ik} + f_1(age_i) + f_2(hhsize_i) + f_3(time_i) + u_{s(i)} \quad (9a)$$

$$\eta_{2i} = \beta_{20} + \sum_{k=1}^{p} \beta_{2k} x_{ik} + g_1(age_i) + g_2(hhsize_i) + g_3(time_i) + v_{s(i)} \quad (9b)$$

where $u_{s(i)}$ and $v_{s(i)}$ are spatially structured random effects

2.3 Model Estimation

The parameters of the model, including regression coefficients, smooth functions, and dependence parameter, are estimated using a penalized maximum likelihood approach. The estimation is implemented within the Generalized Joint Regression Modeling (GJRM) framework, which allows simultaneous modeling of marginal distributions and dependence structures. All analyses were conducted using the GJRM package in R statistical software, which provides a flexible framework for estimating joint regression models with copula-based dependence structures, smooth terms, and spatial effects. The study utilizes secondary data from nationally representative surveys. All data are anonymized, and no identifiable personal information is used.

3 Results and Discussion

Three candidate copula families; Gaussian, Clayton, and Frank were considered to characterize the dependence between access to improved water and sanitation. Model selection was based on the Akaike Information Criterion (AIC), with smaller values indicating better relative model fit after accounting for model complexity. To ensure a fair comparison, the three copula specifications were estimated using the same marginal distributions, covariates, nonlinear smooth terms, state-level random effects, and sample. The Gaussian copula produced the lowest AIC (66,329.68), compared with 72,754.01 for the Clayton copula and 72,769.49 for the Frank copula. Gaussian copula provided substantially stronger support than the Clayton and Frank alternatives and was retained for the final spatial semiparametric analysis. This section presents and discusses the results of Bivariate Copula Model, Generalized Joint Regression Model (GJRM) with Gaussian Copula and Probit Margins.

3.1 Bivariate Copula Model

Table 2: Results on Bivariate Copula Regression Model

Parameter Estimates	**Water**			**Toilet**		
	Estimated	STD Error	P value	Estimated	STD Error	P values
Intercept	0.5416	0.0553	< 2e-16	-2.0301	0.0654	< 2e-16
Urban	0.0970	0.02832	0.0006	0.7735	0.0309	< 2e-16
Poorer	-0.0384	0.0435	0.3765	0.8050	0.0435	< 2e-16
Middle	0.1823	0.0463	8.30e-1	1.8054	0.0464	< 2e-16
Richer	-0.0717	0.0533	0.1791	3.1948	0.0604	< 2e-16
Richest	-1.3394	0.0625	2e-16	5.4585	0.1093	< 2e-16
Primary	-0.3598	0.0405	< 2e-16	-0.2342	0.0411	< 2e-16
Secondary	-0.49223	0.0384	< 2e-16	-0.2994	0.0398	1.26e-08
High	-0.5821	0.0435	< 2e-16	0.1780	0.0529	6.01e-14
Female	0.1273	0.0284	7.36e-06	0.1199	0.0356	0.0008
Age of Household	0.0057	0.0008	1.64e-12	-0.0007	0.0009	0.4644
Size household	0.0918	0.0045	<2e-16	0.0582	0.0046	< 2e-16
Time	0.0003	0.00002	<2e-16	0.00062	0.0000	< 2e-16
Television	0.3119	0.0365	<2e-16	-0.3305	0.0418	2.59e-15

θ= 0.292(0.269,0.312)

The Gaussian copula model with logit link functions was first estimated to examine the joint determination of access to improved drinking water and sanitation facilities. The dependence parameter (θ = 0.292, 95% CI: 0.269–0.312) is positive and statistically significant, indicating a moderate degree of dependence between the two outcomes. This suggests that households with access to improved water sources are more likely to also have access to improved sanitation facilities, even after controlling for observed socio-economic and demographic characteristics. The result highlights the interconnected nature of water and sanitation infrastructure in Nigeria, reinforcing the need for integrated policy interventions. The strong association between sanitation access and improved outcomes supports earlier findings that sanitation plays a critical role in reducing child stunting and disease burden (Cumming & Cairncross, 2016; Spears, 2013)

The results for the water equation reveal that urban residence significantly increases the likelihood of access to improved water sources ($\beta = 0.097$, $p < 0.01$), reflecting better infrastructure coverage in urban areas. Likewise, toilet access in urban residence has a substantial positive effect ($\beta = 0.774$, $p < 0.001$), indicating significant urban–rural disparities in sanitation infrastructure.

Household size exhibits a strong positive effect in access to water ($\beta = 0.092$, $p < 0.001$) respectively, increasing demand for water may necessitate the diversification and improvement of water supply strategies (UNESCO, 2024; FAO, 2024).

All wealth categories (poorer, middle, richer, richest) have large and highly significant positive coefficients, increasing monotonically with wealth in relation to toilet access compare to result in water. This indicates that access to improved sanitation is strongly concentrated among wealthier households, highlighting pronounced inequality in sanitation provision.

Comparing the two equations reveals that access to sanitation facilities is more strongly driven by wealth and urbanization than access to water. While water access shows mixed socio-economic patterns, sanitation access is clearly stratified along economic lines.

The positive dependence parameter further confirms that interventions targeting one dimension (e.g., water supply) may yield spillover benefits for sanitation access. However, the stronger inequality observed in sanitation suggests that targeted policies are required to address structural barriers, particularly among poorer and rural households. Previous intervention studies have demonstrated that improvements in water quality can substantially reduce diarrheal diseases, reinforcing the importance of integrated WASH strategies (Clasen *et al*., 2007)

3.2 Generalized Joint Regression Model (GJRM) with Gaussian Copula and ProbitMargins

In this Sub -Section, the findings and results of Generalized Joint Regression model with Gaussian Copula and Probit Margins. Table 3 presented results of the model.

Table 3: Results on GJRM Model

Parameter Estimates	**Water**			**Toilet**		
	Estimated	STD Error	P value	Estimated	STD Error	Z values

Intercept	0.3482	0.0329	< 2e-16	-1.2150	0.0375	< 2e-16
Urban	0.0644	0.0169	0.0001	0.4567	0.0181	< 2e-16
Poorer	-0.0296	0.0253	0.2420	0.4749	0.0254	< 2e-16
Middle	0.0938	0.0268	0.0004	1.0890	0.0271	< 2e-16
Richer	-0.0563	0.0315	0.0735	1.9040	0.0345	< 2e-16
Richest	-0.8361	0.0371	<2e-16	2.9500	0.0510	< 2e-16
Primary	-0.2069	0.0234	< 2e-16	-0.1414	0.0240	< 2e-16
Secondary	-0.2851	0.0223	< 2e-16	-0.1767	0.0233	4.00e-09
High	-0.3388	0.0256	< 2e-16	0.1028	0.0303	6.01e-14
Female	0-0805	0.0171	0.0000	0.0703	0.0206	0.0007
Age of Household	0.0033	0.0005	0.0000	-0.0003	0.0005	0.0006
Size household	0.0517	0.0026	<2e-16	0.0337	0.0067	< 2e-16
Time	0.0002	0.0000	<2e-16	0.0003	0.0000	< 2e-16
Television	0.1838	0.0215	<2e-16	-0.1939	0.0204	< 2e-16

θ = 0.294(0.275,0.317)

Table 3 shows the joint regression model for Gaussian copula and Probit margins. The Gaussian copula models with logit and probit link functions consistently reveal a positive and statistically significant dependence between access to improved water sources and sanitation facilities. The estimated dependence parameters are remarkably stable across specifications ($\theta \approx 0.29$), indicating a moderate positive association between the two outcomes. This suggests that households with access to improved water are more likely to also have access to improved sanitation, even after controlling for socio-economic and demographic characteristics. The consistency of θ across link functions confirms the robustness of this relationship in Nigeria and underscores the interconnected nature of water and sanitation infrastructure.

Across both the logit and probit specifications, the determinants of water access exhibit broadly consistent patterns, reinforcing the robustness of the findings. Urban residence significantly increases the likelihood of access to improved water sources, reflecting better infrastructure availability in urban settings which was same with the access to toilet.

Households that have access to improved drinking water are significantly more likely to also have access to improved sanitation.

The comparative analysis of water and sanitation models reveals important differences in their underlying determinants. While water access is influenced by a combination of demographic and socio-economic factors with some unexpected patterns, sanitation access is strongly and consistently driven by wealth and urbanization.

The stronger inequality observed in sanitation access suggests that it remains a more exclusive service, disproportionately available to wealthier households. In contrast, water access, although still uneven, appears to be relatively more widespread.

The positive dependence between the two outcomes implies that policies targeting one dimension may generate spillover effects in the other. However, the magnitude of socio-economic disparities—particularly in sanitation—indicates that integrated but targeted interventions are necessary.

Overall, the findings highlight the need for location-specific and equity-focused policies aimed at reducing disparities in access to basic services across regions of Nigeria. Investments in rural infrastructure, poverty reduction strategies, and inclusive service delivery mechanisms will be critical in addressing the observed inequalities.

To capture potential nonlinear relationships between key continuous variables and access to improved water and sanitation, a semiparametric GJRM specification with smooth functions was estimated. The results reveal strong evidence of nonlinear effects, particularly for age of household head, household size, and time.

For access to improved water sources, all smooth terms are highly significant ($p < 0.001$), indicating that the effects of these variables cannot be adequately captured using simple linear specifications. The estimated degrees of freedom (edf > 1) confirm substantial nonlinearity. Specifically, the effect of age of household head suggests that water access does not increase uniformly with age, but rather follows a nonlinear trajectory, possibly reflecting life-cycle dynamics and changes in economic stability over time.

Household size exhibits a pronounced nonlinear effect, with a large Chi-square statistic, indicating that the relationship between household size and water access is complex. This may reflect competing mechanisms: while larger households may have greater resource pooling capacity, they may also face increased demand pressure on limited water resources.

The time variable also shows a strong nonlinear pattern, suggesting that improvements in water access over time are not constant but may reflect periods of rapid infrastructure development followed by stagnation or uneven progress.

For sanitation access, nonlinear effects are also evident, although with some differences in magnitude and significance. The smooth term for age of household head is significant at the 5% level, indicating a weaker but still meaningful nonlinear relationship compared to the water model. In contrast, household size and time remain highly significant, with strong nonlinear effects similar to those observed for water access.

These findings highlight the importance of accounting for nonlinearities when modeling access to basic services. Linear models may obscure important thresholds, saturation effects, or diminishing returns, leading to incomplete or misleading conclusions.

3.3 Nonlinear Effect

The semiparametric results revealed in Figure 1 bellow shows that there are significant nonlinear relationships for age, household size, and time which are continuous variables. These findings demonstrate that the effects of these variables are not constant across their ranges, highlighting the limitations of purely linear models. The nonlinear patterns observed are consistent with the flexible modelling framework proposed by Wood (2017), which emphasizes that demographic processes rarely follow linear trends. For instance, household size exhibits a nonlinear effect, suggesting that the marginal impact of additional household members varies depending on the size of the household. Similarly, temporal trends indicate non-uniform improvements in access over time, reflecting fluctuations in policy implementation and infrastructure development.

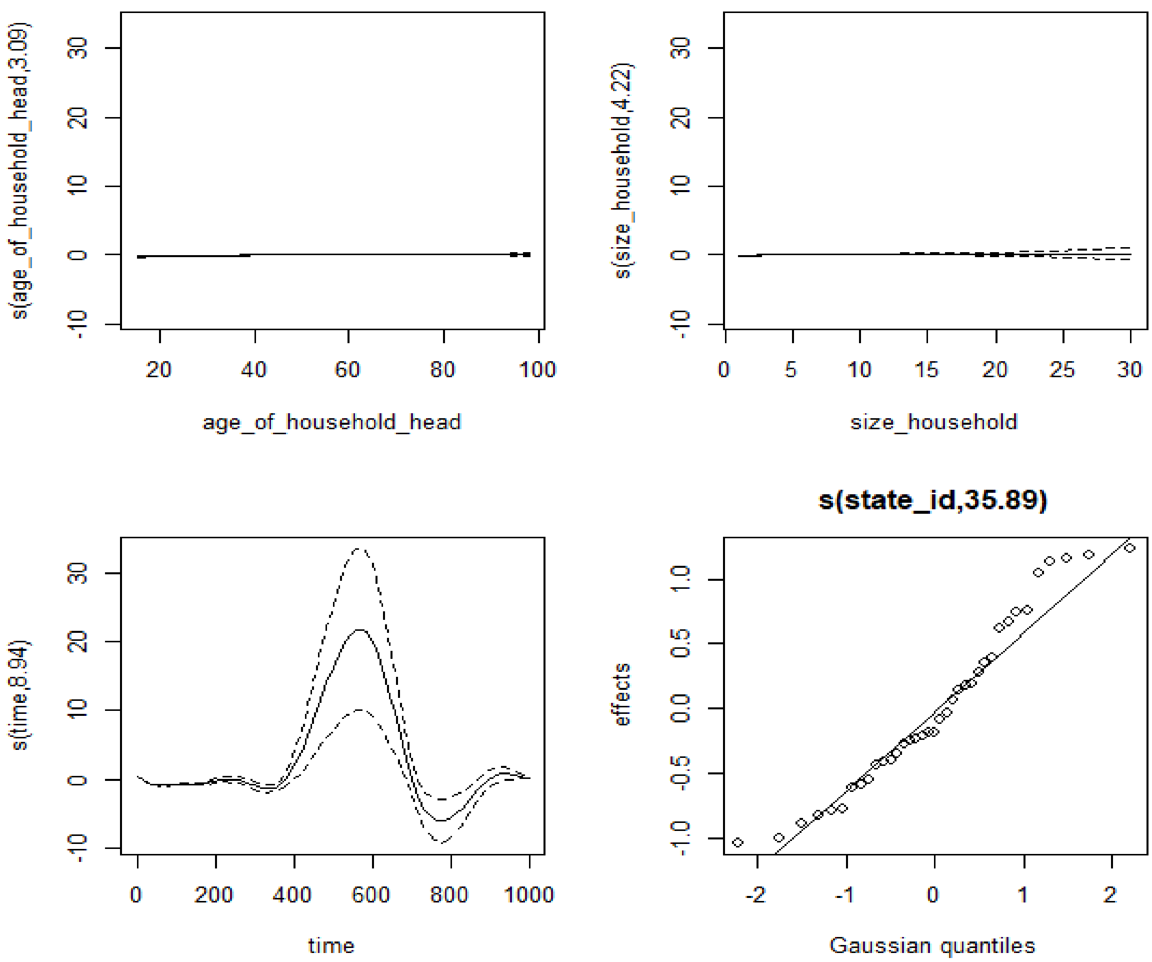

Figure 1: Nonlinear effect of the continuous variables

3.4 Spatial Heterogeneity

The spatial distribution of water access reveals pronounced regional disparities across Nigeria. The southern regions, particularly the South-West and South-South zones, exhibit strong positive spatial effects, indicating higher likelihood of access to improved water sources after controlling for socio-economic and demographic factors. In contrast, many northern states display negative spatial effects, suggesting structural disadvantages that are not fully explained by observed covariates. The Middle Belt region shows a mixed pattern, reflecting transitional and heterogeneous development conditions. These findings highlight the critical role of geographic location and suggest that spatial inequalities are a key driver of disparities in water access as shown in Figure 2. Yellow / light colors indicate positive spatial effect meaning that there is higher likelihood of water access while purple / dark colors show negative spatial effect that is lower likelihood of water access

Figure 2: Spatial effect of access to water in Nigeria

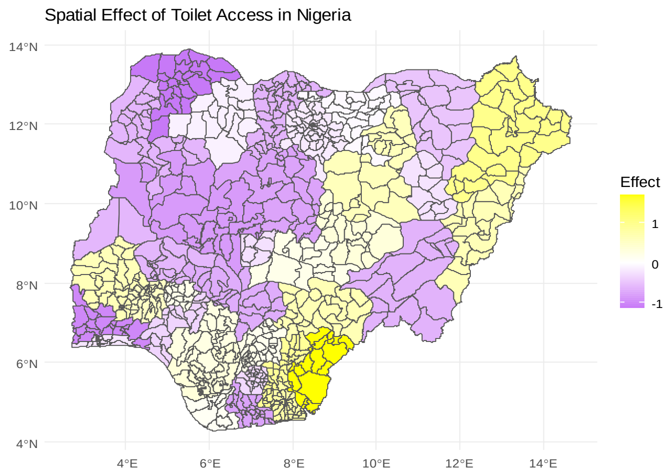

Figure 3: Spatial effect of access to toilet in Nigeria

The spatial distribution of sanitation access across Nigeria as presented in Figure 3 reveals pronounced and highly heterogeneous regional disparities. Northern regions, particularly the North-West and parts of the North-Central zones, exhibit predominantly negative spatial effects, indicating significantly lower access to improved sanitation facilities even after controlling for socio-economic and demographic factors. In contrast, the southern and eastern regions demonstrate positive spatial effects, with particularly strong clustering observed in parts of the South-South zone. Compared to water access, sanitation exhibits greater spatial fragmentation and more localized clustering, suggesting that access to toilet facilities is less uniformly distributed across regions. These findings highlight that sanitation inequalities are more severe and geographically concentrated, underscoring the need for targeted regional interventions. Colors indicated in the map above represents same as in Figure 2 that is yellow areas has higher likelihood of toilet access while purple has lower likelihood.

4 Conclussion

The findings from this study provide important insights into the joint dynamics of access to improved water and sanitation in Nigeria by integrating dependence structures, nonlinear covariate effects, and spatial heterogeneity within a unified modelling framework. The significant positive dependence observed between water and sanitation access in the baseline copula model confirms that these services are jointly determined, reflecting shared infrastructural and socio-economic drivers. This result is consistent with earlier studies that emphasize the interconnected nature of water and sanitation systems Bain *et al*. (2014), Fink *et al*. (2011). However, the observed reduction in dependence after incorporating spatial effects suggests that a substantial portion of this association is attributable to unobserved geographic factors. This aligns with findings by Pullan et al. (2014), who demonstrated that spatial clustering plays a critical role in sanitation access across sub-Saharan Africa.

The strong influence of socio-economic status, particularly household wealth and urban residence, corroborates a large body of empirical literature identifying economic capacity as a primary determinant of access to basic services WHO & UNICEF, (2023); Prüss-Ustün *et al*. (2019). Similar patterns have been reported in studies by Rheinländer et al. (2015), where wealthier households were significantly more likely to have access to improved sanitation facilities. The persistence of urban–rural disparities further reflect structural inequalities in infrastructure development, consistent with observations in developing countries Montgomery *et al.* (2009); Günther & Fink (2010).

The inclusion of semiparametric smooth functions revealed important nonlinear relationships between key covariates and service access. For instance, the nonlinear effect of household size suggests diminishing or threshold effects, which would not have been captured under a purely linear specification. This finding supports the argument by Wood (2017) and Marra and Radice (2020) that flexible modelling approaches are essential for capturing complex demographic and socio-economic processes. Similarly, the nonlinear effect of age indicates that access varies across life stages, reflecting changing household needs and economic conditions.

Spatial analysis revealed pronounced regional disparities, with southern regions exhibiting significantly higher levels of access compared to northern regions. This spatial inequality is consistent with national reports and previous empirical studies National Bureau of Statistics, (2022); Pullan *et al*. (2014). Notably, sanitation access exhibited stronger spatial clustering than water access, suggesting that sanitation infrastructure is more sensitive to localized policy implementation and cultural practices. This finding is in line with Jenkins and Scott (2007), who emphasized the role of behavioral and contextual factors in sanitation adoption.

Furthermore, the results demonstrate that ignoring spatial heterogeneity can lead to overestimation of dependence between outcomes. This highlights the importance of incorporating spatial effects in multivariate modelling frameworks, as emphasized by Banerjee et al. (2014) and Diggle et al. (1998). The use of a copula-based Generalized Joint Regression Model (GJRM) in this study extends existing approaches by simultaneously accounting for dependence, nonlinearity, and spatial variation, thereby providing a more comprehensive analytical framework compared to traditional single-equation models.

From a policy perspective, the findings underscore the need for geographically targeted interventions that address regional disparities in service provision. While national-level policies remain important, the strong spatial heterogeneity observed suggests that localized strategies are essential for achieving equitable access. This supports the growing consensus in the literature that context-specific interventions are more effective in improving water and sanitation outcomes Wolf *et al*. (2019).

In conclusion, this study contributes to the existing literature by demonstrating that access to water and sanitation is jointly determined by a complex interplay of socio-economic, nonlinear, and spatial factors. By employing an advanced modelling framework, the study provides deeper insights into the mechanisms underlying service access and highlights the importance of integrated and spatially informed policy approaches. Future research could extend this framework by incorporating temporal dynamics and causal inference techniques to further enhance understanding of access patterns over time.

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