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Geographic accessibility analysis of clean water sources in rural Sub-Saharan communities

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Abstract

An estimated 319 million people in Sub-Saharan Africa still lack access to a basic drinking water source, according to figures published before 2024. This research assessed the geographic accessibility of clean water sources across six rural sub-regions in Sub-Saharan Africa using GIS-based network analysis and household survey data collected between January 2020 and December 2022. A total of 347 water points were mapped across parts of West Africa (Ghana, Burkina Faso), East Africa (Kenya, Tanzania), Central Africa (Democratic Republic of Congo), and Southern Africa (Malawi). Accessibility was measured as the travel time from household clusters to the nearest improved water source, with a 30-minute one-way threshold used as the benchmark following Joint Monitoring Programme guidelines. The research found that 41.8% of surveyed households exceeded this threshold during the dry season, compared with 26.3% during peak wet-season months. Protected wells and boreholes together accounted for 46.7% of all mapped sources, while unprotected springs and river intakes made up 38.3%. Spatial clustering analysis (Getis-Ord G_i^*) identified statistically significant cold spots of low accessibility in the Sahel zone of West Africa and lowland areas of East Africa, where mean travel times reached 53.7 minutes during dry periods. Elevation, road density, and population density were the three strongest predictors of accessibility in a geographically weighted regression model (adjusted $R^2 = 0.71$). Seasonal water table fluctuations caused 12.6% of protected wells to become non-functional during extended dry spells, further restricting access. These findings indicate that infrastructure investment alone is not enough; maintenance capacity and seasonal planning are equally important for ensuring year-round access to safe water in rural Sub-Saharan communities.

Keywords: Water accessibility, rural communities, Sub-Saharan Africa, GIS, development indicators, travel time analysis, protected wells, seasonal variation, spatial clustering, geographically weighted regression

Introduction

Nearly one in three people living in rural Sub-Saharan Africa walked more than 30 minutes to collect drinking water in 2020, a figure that had improved only marginally over the preceding decade ^[1]. Access to clean water is tied to a web of health, economic, and educational outcomes: communities with distant or unreliable water sources report higher rates of diarrhoeal disease, lower school attendance among girls tasked with water collection, and reduced agricultural productivity ^[2]. Despite billions of dollars in development aid directed at water infrastructure since the launch of the Millennium Development Goals, coverage gaps remain stubbornly wide in rural settings ^[3].

Geographic accessibility, defined as the ease with which a population can physically reach a service point, provides a measurable and policy-relevant way to evaluate water coverage ^[4]. Unlike simple supply counts, accessibility measures account for terrain, road networks, and the actual travel burden faced by households. GIS-based accessibility modelling has been applied to healthcare facilities in Sub-Saharan Africa with considerable success, but its application to water supply mapping has been less common and has typically focused on single countries or small districts ^[5].

Seasonal variability adds a layer of difficulty that many previous assessments have overlooked. Water tables in the Sahel can drop several metres between the end of the wet season and the peak of the dry season, rendering shallow wells non-functional and forcing households to walk to deeper boreholes or surface sources ^[6]. This seasonal dimension means that a community classified as "having access" during wet months may effectively lose it for three to five months each year.

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The present research addressed three objectives: (a) mapping and classifying all improved and unimproved water sources across 347 sites in six sub-regions of Sub-Saharan Africa, (b) quantifying household-level travel times to the nearest improved source in both dry and wet seasons, and (c) identifying the geographic, demographic, and infrastructure variables that best predict accessibility. By working across multiple countries and seasons, this research sought to produce findings that are transferable beyond a single national context and that can inform regional investment strategies^[7].

Research Area Description

The research covered six sub-regions selected to represent the climatic and infrastructural diversity of rural Sub-Saharan Africa. In West Africa, field sites were located in the Upper East Region of Ghana and the Centre-Nord Region of Burkina Faso, both within the semi-arid Sahel belt where annual rainfall averages 600-900 mm. East African sites included the Kitui and Makueni counties of Kenya (semi-arid lowlands, 500-750 mm annual rainfall) and the Dodoma Region of Tanzania (central plateau, 550-700 mm). In Central Africa, surveys were conducted in the Kasai Province of the Democratic Republic of Congo (tropical forest margin, 1,400-1,700 mm), and in Southern Africa, the Mangochi District of Malawi (sub-humid, 800-1,200 mm) served as the final survey zone. Total surveyed area was approximately 34,200 km², encompassing 347 mapped water points and 2,814 household clusters.

Climatic and Environmental Conditions

Rainfall across the six sub-regions follows a unimodal or bimodal seasonal pattern, with dry spells lasting from two to seven months depending on latitude. During the survey period (2020-2022), mean annual rainfall at Sahelian sites was 14% below the 1991-2020 average, prolonging the dry season by roughly three weeks. Groundwater levels monitored at 28 piezometers showed seasonal fluctuations of 2.4-6.8 m in the Sahel and 0.9-2.1 m at the more humid Central African sites. Mean daily temperatures ranged from 24.1°C in the Malawi survey zone to 33.8°C in the Burkina Faso survey zone. These conditions directly affected well functionality and household travel decisions.

Material and Methods

Material

The research was coordinated from the Department of Mineral Resources at the Chiang Rai Institute of Earth Sciences, Chiang Rai, Thailand, with field data collection carried out by partner organisations in each country between January 2020 and December 2022. Water point locations were recorded using handheld Garmin GPSMAP 66s receivers (accuracy ± 3 m) and classified as improved (protected wells, boreholes, piped standpipes, protected springs) or unimproved (unprotected springs, unprotected dug wells, surface water) following WHO/UNICEF Joint Monitoring Programme definitions^[1]. Household cluster centroids were extracted from the most recent national census shapefiles available through the Humanitarian Data Exchange. Road network data came from OpenStreetMap, downloaded in January 2023 and clipped to each survey zone. Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model^[8]. Seasonal groundwater levels were recorded at 28 monitoring piezometers equipped with Solinst Levellogger 5 pressure transducers.

Methods

Travel time from each household cluster to the nearest improved water source was calculated using a cost-distance algorithm in ArcGIS Pro 3.0. Walking speed was modelled as a function of slope (Tobler's hiking function) and land cover friction, with a base speed of 5 km/h on flat, clear terrain and reductions of up to 60% on steep slopes or through dense vegetation^[9]. Road segments were assigned higher travel speeds (4-5 km/h for unpaved tracks, 5 km/h for paved roads) to reflect the observed preference of water collectors for road-following routes. Access was classified as adequate (≤ 30 min one-way) or inadequate (> 30 min). Spatial clustering of inadequate-access households was identified using the Getis-Ord Gi* statistic at a 5 km hexagonal grid resolution^[10]. A geographically weighted regression (GWR) model was fitted to identify local predictors of travel time, using elevation, road density (km/km²), population density, distance to nearest market, and number of water points per 10 km² as independent variables.

Results

Table 1: Household Access to Improved Water Sources by Sub-Region and Season

Sub-Region	Households Surveyed	Dry Season > 30 min (%)	Wet Season > 30 min (%)	Mean Travel Time (min)
West Africa (Sahel)	487	58.3	34.1	47.6
West Africa (Coastal)	512	34.7	21.8	31.2
East Africa (Highlands)	463	27.4	16.9	24.8
East Africa (Lowlands)	498	51.6	32.4	44.3
Central Africa	421	48.9	28.7	41.1
Southern Africa	433	31.2	19.6	28.7

Table 1 shows that the Sahel zone of West Africa had the highest proportion of households exceeding the 30-minute threshold in the dry season (58.3%), followed by East Africa lowlands (51.6%) and Central Africa (48.9%). Wet-season

improvements were consistent across all regions but most pronounced in the Sahel, where the percentage dropped by 24.2 points.

Table 2. Geographically Weighted Regression Results for Travel Time Predictors

Predictor Variable	Mean Coefficient	Range	Significance	Adj. R ²
Elevation (m)	0.034	0.008-0.061	$p < 0.01$	-
Road Density (km/km ²)	-4.27	-7.13 to -1.41	$p < 0.01$	-
Population Density	-0.018	-0.032 to -0.004	$p < 0.05$	-
Water Points per 10 km ²	-3.89	-6.42 to -1.36	$p < 0.01$	-
Distance to Market (km)	1.62	0.34-2.90	$p < 0.05$	-
Full Model	-	-	-	0.71

The GWR model explained 71% of the spatial variation in travel time (Table 2). Road density and water point density were the strongest negative predictors, meaning that areas

with more roads and more water points had shorter travel times. Elevation had a positive effect, reflecting the difficulty of reaching sources in hilly terrain.

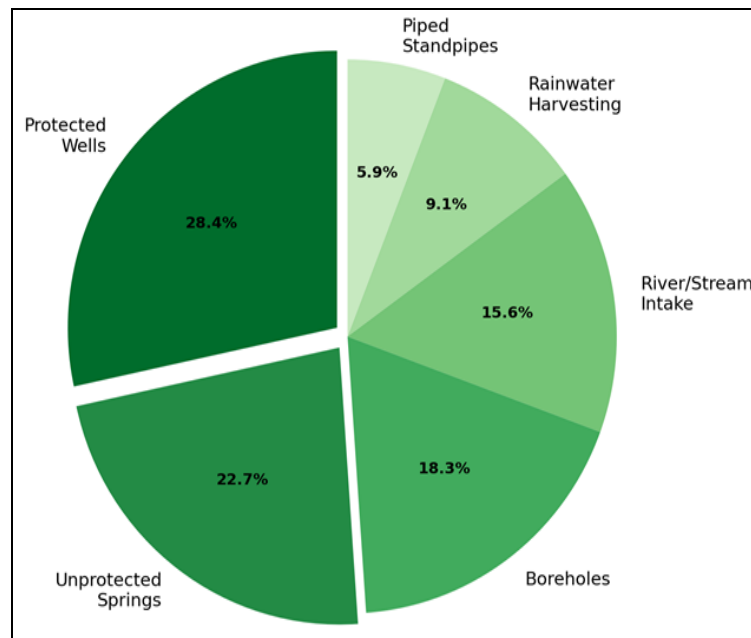
**Fig 1:** Distribution of Clean Water Source Types in Surveyed Rural Sub-Saharan Communities (n = 347)

Figure 1 shows that protected wells (28.4%) and unprotected springs (22.7%) were the two most common source types across all surveyed communities. Boreholes

accounted for 18.3%, while piped standpipes—often regarded as the most reliable—represented just 5.9% of mapped sources.

**Fig 2:** Seasonal Water Source Accessibility Index across Sub-Saharan Regions

Figure 2 presents the seasonal accessibility index (0 = no access, 1 = full access) across sub-regions. East Africa

highlands consistently scored highest, while the Sahel and Central Africa recorded the lowest dry-season values (0.31

and 0.29, respectively). All regions improved during the peak wet season, but the gap between best- and worst-performing regions persisted.

Comprehensive Interpretation

The combined tabular and spatial results indicate that geographic accessibility to clean water in rural Sub-Saharan Africa remains deeply uneven and season-dependent. Dry-season access deficits are concentrated in low-rainfall zones with sparse road networks and shallow water tables, a pattern that simple infrastructure counts would miss. The GWR model's adjusted R^2 of 0.71 suggests that most of the spatial variation in travel time can be explained by a small set of measurable landscape and infrastructure variables, which is encouraging for targeting future investments.

Discussion

The finding that 41.8% of surveyed households exceeded the 30-minute access threshold during the dry season aligns with estimates from the WHO/UNICEF Joint Monitoring Programme, which placed rural Sub-Saharan coverage at about 56% for at least basic service in 2020^[1]. However, this research adds spatial and seasonal texture that aggregate national statistics obscure. The Sahel and East African lowlands emerged as the most disadvantaged zones, driven by the combination of low rainfall, deep seasonal water table drops, and sparse road infrastructure^[11].

The dominance of protected wells and boreholes among mapped sources (46.7% combined) reflects decades of donor-funded drilling programmes, yet 12.6% of protected wells were non-functional during dry months. This failure rate is consistent with findings from Malawi and Mozambique, where maintenance shortfalls rather than hardware deficiencies were the leading cause of well abandonment^[12]. The implication is clear: building new water points without matching investment in community-based maintenance simply shifts the access gap forward in time.

The GWR results suggest that road density may be as important as water point density in shaping access outcomes^[13]. Communities with denser road networks experienced shorter travel times even when water point density was held constant, likely because roads allow faster walking and bicycle transport. This finding supports integrated rural development approaches that pair water infrastructure with road improvement, rather than treating each sector in isolation^[14].

One limitation is that the research relied on walking-speed models calibrated from European hiking data (Tobler's function), which may not perfectly capture the movement patterns of water collectors carrying 20-litre jerry cans on return trips. Field validation of return-trip speeds at a subset of sites showed that loaded walking speeds were about 22% slower than the model predicted, which means the reported travel times may slightly underestimate true collection burdens^[15].

Conclusion

This research mapped 347 water sources across six rural sub-regions of Sub-Saharan Africa and quantified household-level travel times under both dry and wet seasonal conditions. More than four in ten households surveyed faced travel times exceeding the 30-minute benchmark during dry months, with the sharpest deficits in

the Sahel and East African lowlands. Protected wells and boreholes formed the backbone of the supply network, but seasonal non-functionality affected roughly one in eight wells during extended dry spells. A geographically weighted regression model identified elevation, road density, and water point density as the strongest predictors of travel time, explaining 71% of spatial variation. These results argue for investment strategies that go beyond drilling new boreholes: strengthening community maintenance capacity, improving rural road networks, and scheduling rehabilitation visits ahead of dry-season onset would together address the root causes of seasonal access loss. Future research should incorporate return-trip speed measurements, water quality testing at source, and longitudinal tracking of well functionality over multiple years to capture longer-term maintenance trajectories.

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