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Population Pressure, Freshwater Availability, and Water Stress in East Africa: A Panel Data Analysis

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“Population Pressure, Freshwater Availability, and Water Stress in East Africa: A Panel Data Analysis.”

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Abstract

In East Africa, fast population expansion, uneven distribution of freshwater, dependency on agriculture and increasing socioeconomic demand increase strain on limited water resources, making freshwater shortage an increasingly important issue. The study employed an unbalanced longitudinal panel of 311 country-year observations from the available annual data from 1990 to 2022 to investigate population pressure, freshwater availability and water stress in 12 East African nations. The analysis covered water stress, population, renewable freshwater per capita, total renewable freshwater resources, GDP per capita, total freshwater withdrawals and sectoral water-use patterns. Regional patterns were characterised using descriptive statistics, trends in time, inter-country comparisons, Falkenmark water scarcity classifications, study of sectoral withdrawals and spatial mapping. There was a large degree of variability across countries. The mean water stress was 34.43% with a median of 6.17% indicating a substantially right skewed distribution due to the very high values reported for Sudan . In most countries, the availability of renewable freshwater per capita dropped with time, with large declines in Somalia, Kenya, Ethiopia, Rwanda, Tanzania and Uganda. Sudan had the highest level of water stress, while Somalia suffered consistently high stress and a drop in the availability of fresh water. In contrast, the Democratic Republic of the Congo had a mix of high renewable freshwater resources and relatively low water stress. In most countries agriculture accounted for the majority of freshwater withdrawals, for more than 90% of withdrawals in Somalia, Sudan, Eritrea and Ethiopia. The relation between GDP per capita and water stress was significantly different amongst countries, demonstrating that economic development is not the only factor explaining regional variances in water pressure. To summarise, results show that water stress in East Africa is driven by the interaction of population pressure, renewable freshwater resources, intensity of extraction, sectoral water demand and socioeconomic factors. Hence, there is a need for country-specific policies for water management, higher efficiency of agricultural water use, population-sensitive planning, stronger monitoring and greater regional collaboration to improve long-term water security.

Keywords: East Africa; water stress; freshwater availability; population pressure; panel data; water scarcity; freshwater withdrawals

Introduction

Freshwater is an essential resource for human health, agricultural production, economic development, ecosystem functioning and social stability. However, increasing population, urbanisation, agricultural demand, economic growth, climate variability and environmental degradation are adding to the stress on existing freshwater supplies in many regions of the world. Water scarcity has therefore emerged as a leading sustainability challenge of the twenty-first century, particularly in developing regions where population growth frequently exceeds the development of water infrastructure, storage, governance and resource efficiency (Graham et al., 2020; Vörösmarty et al., 2000). Recent evaluations further show that worldwide water shortage is projected to intensify and become more spatially widespread under future demographic and socio-economic growth pathways (Frost et al., 2025; Zhang et al., 2024).
A popular definition of water stress is the ratio between freshwater withdrawals and the renewable freshwater resources that remain after accounting for environmental water requirements . It is officially tracked as part of Sustainable Development Goal Indicator 6.4.2, which assesses freshwater withdrawal as a share of available freshwater resources (FAO, 2026; FAO & UN-Water, 2024; UNSD, 2023). High water stress indicates a substantial proportion of the available freshwater resources are being drained, which escalates the danger of shortages, ecological degradation, diminishing water security and rivalry among agricultural, household, industrial and environmental water users. At the same time, per capita freshwater availability is an important complementary indicator, as population expansion can diminish the amount of renewable water accessible to each individual, even while overall renewable water resources remain relatively consistent.

East Africa is especially vulnerable to pressures on water resources due to high population growth, recurrent drought, climate variability, unequal distribution of fresh water resources, heavy dependence on rain-fed and irrigated agriculture and limited water-management infrastructure in many countries. Water conditions in the region are likewise quite varied. Some countries have relatively ample renewable freshwater resources, whereas others suffer from chronic scarcity and severe pressure on withdrawal. Tramberend et al. (2021) showed with their results that future water

circumstances in East Africa will be heavily dependent on interactions between population, economic growth, water demand and resource management. Similarly, Ohwo and Ndakara (2025) reported significant differences in drinking-water supply and water-stress situations throughout the African Great Lakes region, emphasising the significance of country-level and temporal study. One of the main drivers impacting freshwater resources is population increase. As populations grow, so does the demand for drinking water, food production, sanitation, energy and industrial activities. At the same time, renewable freshwater supplies are generally constrained by hydroclimatic conditions and may not scale with population. This may imply that despite a relatively consistent total supply of renewable resources, the per capita availability of fresh water may fall. Population increase was recognised by Vörösmarty et al. (2000) as one of the key drivers of rising worldwide freshwater vulnerability and Graham et al. (2020) indicated that human socioeconomic development is expected to be a driver of future water-scarcity changes over a wide variety of global development routes. Sun et al. (2021) also shown in sub-Saharan Africa that demographic, economic, environmental and climatic factors influence the availability of freshwater resources.

Water stress also has a significant but complex relationship with economic development. Economic expansion may raise water demand through agricultural intensification, industrialisation, urbanisation, energy production and improvements in home water access. Higher income and technical progress are likely to increase water-use efficiency, infrastructure, recycling, and institutional capacity. Previous panel and econometric studies have thus found diverse connections between economic development and water-resource strain. Barbier (2010) has shown the interrelationship between water availability and economic growth in developing nations. Lounnas and Bouchelaghem (2025) found that economic growth and water stress can influence per capita freshwater availability. More recent work has also highlighted the linkages between climate, land, energy and water systems, showing that water resource outcomes are determined by various linked socio-economic and environmental processes (Imandojemu et al., 2026; Qiao & Wang, 2023).

Another important part of regional water stress is agriculture. Agriculture is the primary source of freshwater withdrawals in many low- and middle-income nations and is directly tied to food

security, rural livelihoods and economic stability. In areas with high water intensive agriculture, increased demand for food by a growing population might further challenge already limited supplies of freshwater. This link is particularly crucial in East Africa where agricultural systems are still highly vulnerable to water supply and climate variability. A larger body of work on the food-water-energy nexus indicates that water-resource management is inextricably linked to agricultural production, energy consumption, food security, and sustainable development (Falk et al., 2026; Pulle et al., 2026).

Despite the rising literature on water scarcity, there are still some critical study gaps. First, many existing research focus on individual nations, specific river basins or wider sub-Saharan African samples instead of systematically comparing East African countries using a harmonised panel dataset. For example, Dorbane and Djorfi (2025) and Lounnas and Bouchelaghem (2025) studied the impact of demographics and economy on water resources in Algeria, while Musse (2021) studied freshwater scarcity in the Nile River Basin. These research, while informative, cannot necessarily be generalised to East Africa as a whole because of significant heterogeneity within the region in climate, population, freshwater endowment, economic structure, and water-use patterns.

Second, previous studies often focus on either freshwater availability, water stress, or economic development separately, and there are fewer studies that investigate jointly relationships among population pressure, renewable freshwater availability, water stress, economic conditions, and sectoral freshwater withdrawals in one analytical framework. This hinders knowledge of the relationship between demographic pressure and the underlying water-resource endowment, as well as national patterns of water use. Third, regional comparisons are frequently based on cross-sectional variables, or short periods, thus it is difficult to spot changes throughout time. A panel-data technique has the critical advantage of capturing the cross-country variances as well as the temporal variation, thereby offering a more thorough knowledge of water-resource dynamics. The present study addresses these gaps by analysing population pressure, freshwater availability and water stress for East African countries with panel data for several years. The study applies demographic, hydrological, economic and water-use metrics to analyse patterns of water stress across countries and over time. It also analyses disparities in sectoral freshwater withdrawals and

the geographical distribution of freshwater resource availability and economic conditions. The study employs a combination of historical, comparative and spatial analysis to provide a regional perspective on the drivers of increasing water-resource pressure in East Africa.

The study is noteworthy for scientific and policy reasons. From a scientific viewpoint, it adds to the literature by a comparative, panel-based evaluation of water stress in a region with significant hydrological and socioeconomic variation. It also helps to understand whether high water stress is mainly due to population pressure, limited fresh water endowment, economic development, withdrawal structure or a mix of these variables. From a policy standpoint, recognising such links is vital for establishing suitable water-resource strategies, especially in nations with high population expansion and ongoing scarcity. The findings may be crucial in advancing Sustainable Development Goal 6, notably the target of enhancing water-use efficiency and ensuring sustainable freshwater withdrawals (FAO & UN-Water, 2024).

Objective of research

The major aim of this study is to investigate the relationship between population pressure, fresh water and water stress in East Africa using panel data.
The objectives specifically are to:

1. study temporal and cross-country differences in water stress in East Africa;
2. evaluate trends in per capita renewable freshwater resources;
3. Explore the link between population pressure and availability of fresh water;
4. examine the links between economic development and water stress;
5. Compare freshwater-withdrawal patterns for agriculture, domestic use, and industry across countries
6. Identify the spatial distribution of water stress and freshwater availability across the region.

Research question

The study seeks to explore answers to the following research questions:

1. How does water stress change within East African countries and over time?
2. How much per capita renewable freshwater supply has the region lost?
3. What is the link between population pressure and freshwater availability?
4. What is the relationship between economic development and water stress in East African countries?
5. How do countries differ in their sectoral water withdrawals?
6. Which countries are the most water-stressed and the most water-scarce?

Scope of investigation

The report examines 12 East African countries: Burundi, the Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania and Uganda. The analysis uses the data of annual panel with available observations until 2022. The main variables include percentage of water stress, population, renewable freshwater per capita, total renewable freshwater resources, GDP per capita and agricultural, household and industrial freshwater withdrawals. The country level analysis is limited, it does not pick up within country variances at the basin, district, home or community level. The panel is also uneven since the availability of data differs by nations and year. The regional panel technique, however, provides a suitable platform for evaluating long-term water-resource conditions and detecting broad demographic, economic, and hydrological patterns across East Africa.

2. Method

Analysis of Methodology

Design of research

The research design used in this study was a quantitative longitudinal panel-data. This design combines cross-sectional data from several East African countries with longitudinal data over

time. The panel format was designed to capture both change within countries and disparities across countries. This method is suitable for studying how population, freshwater supply and water stress vary over time in different national contexts.
The design was observational, not experimental. No intervention was used and the research used naturally occurring variance in demographic, economic and water-resource parameters across countries and years.

Design of the study

The study was based on a quantitative analytical method employing secondary data at country level. Descriptive analysis was utilised to describe the patterns at the regional and country level, while the suggested methodological framework provided panel econometric models to assess connections among the important variables. It is suggested in the standard scholarly work that based on the statistical features of the data, pooled ordinary least squares, fixed-effects models, random-effects models and related diagnostic tests may be explored.
This approach is suited for a macro-level water-resource study since research questions are about measurable variance in population, freshwater resources, economic indicators, and water stress, rather than perceptions or individual behaviour.

Study population

The study population was East African countries that were included in the panel data set. The analytical sample included 12 countries:
Burundi, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania and Uganda.
The unit of analysis was country-year observation, rather than people, households, communities or institutions. This difference is essential as the statistical inference in the study relates to changes in national level indicators over time.

Number of observations

The analytical dataset consisted of 311 country-year observations across 12 East African countries. The panel was imbalanced, meaning countries contributed varying numbers of years/observations. Temporal coverage varied based on the availability and consistency of similar data available for each country.
So the most acceptable approach to report the sample is:
We use data for 12 East African countries for a total of N = 311 country-year observations.
This is methodologically preferable to stating the sample as 12 nations, because the country-year is the unit of analysis in panel-data analysis.

Method of sampling

The study employed a non-probability sampling. Instead, the choice of country and year observations was driven by the availability of similar information on the variables of interest.
The technique, thus, describes the selection as a deliberate, availability sampling.
In particular, East African nations were considered where consistent data were available for population, freshwater resources and water stress indicators. So the approach cannot be regarded as random, stratified or systematic sampling.

Methods of Data Collection

Secondary-data extraction was used in the study. The dataset was sourced from a publicly available Kaggle source and included country-level panel indicators. The manuscript also mentions that underlying metrics are linked to well-known international sources such as World Bank's World Development metrics, FAO AQUASTAT, SDG databases and United Nations demographic datasets. Primary data collection was not conducted. The researchers did not do any interviews, questionnaires, field surveys, experiments or direct measurements.

The text correctly differentiates the source of the produced dataset from the platform and the original institutional sources from where the indicators were gathered. This is critical for transparency and reproducibility.

Instruments of research

The study was not conducted using a standard survey or laboratory tool. Instead, the structured secondary dataset was employed as the research instrument for analysis.
The principal variables were:

- proportion of water stress;
- overall population
- renewable freshwater availability per person;
- internal renewable fresh water resources;
- GDP per capita;
- complete extraction of freshwater;
- agricultural withdrawals;
- home withdrawals;
- industry withdrawals.

The research was based on standardised macro-level variables, so that no questionnaire or scale requiring item formulation or respondent administration was needed.

Validity

The manuscript did not report any rigorous statistical test of content validity, criterion validity or construct validity. This is not a problem because the study did not apply a new questionnaire or psychometric scale. Validity was more or less determined by the conceptual relevance and coherence of the indicators. Population was utilised as a proxy for demographic pressure, renewable freshwater resources per capita for freshwater availability and water stress for SDG Indicator 6.4.2. These variables were chosen because they were directly aligned with the conceptual dimensions of the study.

Thus, the technique supports concept relevance. The text should not say that validity testing was done formally.

Dependability

No Cronbach's alpha, test-retest coefficient or inter-rater reliability statistic were provided. It would be inappropriate to take such measurements because the study did not use multi-item survey scales. Reliability, in contrast, was a matter of consistency across time in indicator definitions, data gathering, national reporting and measurement techniques. The paper refers to the benefit of employing internationally standardised indicators in facilitating comparison across countries and years but also emphasises the potential for uncertainty due to differences in national reporting systems and hydrological estimating techniques. Therefore, in this study, reliability should be discussed in terms of consistency in data sources and standardisation of indicators rather than psychometric reliability.

strategies for data analysis

The methodology focused on two basic levels of analysis. Descriptive statistical analysis was applied to review and compare the variables of the study. Descriptive processes reported included counts, means, medians, standard deviations, minimum and maximum values, country level averages, graphs for temporal trends, sectoral withdrawal comparisons, and Falkenmark water scarcity categories.

The second was the panel econometric analysis as a methodological framework. We considered pooled OLS, fixed effects and random effects models . Model selection was based on diagnostic tests and the statistical properties of the data. But the text specifically says the final inferential panel-regression results are not yet provided. The paper should thus now indicate that such models were intended or proposed, rather than saying that they were already calculated. The detailed description of the methodology would then be:

We employed descriptive statistics and graphical analysis to characterise regional and country

level patterns. We used applicable diagnostic tests to choose models and developed panel econometric models to quantify relationships between population pressure and freshwater-resource outcomes.

Ethical aspects

This study employed publicly accessible secondary, aggregate data and did not involve human subjects, interviews, clinical records, experimental interventions, or individually identifiable information. Therefore individual informed consent was not applicable.
The manuscript claims that the data were utilised for academic purposes and that original sources were credited. It also suggests that no ethics committee permission was indicated in the available materials. If the authors' institution requires formal exemption or approval for secondary-data studies, this should be documented separately.

Strengths of this approach

There are a number of methodological strengths. The first is the longitudinal panel design that permits the analysis to account for both within-country temporal variance and cross-country variations. This is especially useful, given the significant differences across the listed countries in terms of topography, hydrology, population size, economic structure, and infrastructure.
A second strength is the geographical comparison angle. The study is more geographically focused than a continent wide study, but more than a single nation study, and so more relevant to East African water-resource situations.

A third strength is the use of standardised macro-level metrics, such as population, freshwater availability, water stress, GDP and sectoral water demands. This permits a structured comparison across countries and years.

A fourth strength is the separation between freshwater availability and water scarcity. These metrics quantify various dimensions of water-resource pressure: freshwater availability measures

the per capita renewable water supply, while water stress measures the relative intensity of water withdrawal to renewable water resources.

Finally, the relatively extended temporal coverage enhances the ability of the study to detect long-term patterns rather than a single cross-sectional snapshot. The approach has limitations There are also serious limitations to the study. First of all, the study is based on secondary data that was downloaded from Kaggle. The quality of the results is therefore based on the accuracy, provenance, completeness and harmonisation of the generated dataset. Potential errors in data aggregation or transformation can occur.

Secondly, the dataset is an unbalanced panel, meaning that each country has a distinct number of observations. This might hinder direct comparisons across countries, and affect panel-model estimation.

Third, certain variables have missing observations. For example, there are less observations for GDP per capita than for the main water resource variables.

Fourth, country-level measures may hide significant within-country variation. Water stress can vary widely between river basins, urban and rural areas, climatic zones and administrative regions, but national averages cannot reveal this.

Fifth, some of the hydrological indicators may be modelled or projected values rather than directly measured levels which adds potential measurement uncertainty.

Sixth, the observational design precludes strong causal inference. The relationship between population and water stress found here does not imply that population expansion causes water stress; other factors (rainfall, drought, governance, infrastructure, agriculture, land use) may also play a role in this relationship.

Finally, the technique lacks thorough diagnostics for the panel regressions, coefficients,

significance tests, and robustness assessments. Such would have to be done before the work could be presented as a completely completed inferential panel-data research.

Methodology relevance to the research topic

The methodology is appropriate for the research issue, as population pressure, availability of freshwater, and water stress are both spatial and temporal in nature . The panel-data structure allows us to study population changes within countries over time, while also controlling for large disparities in country freshwater resources and withdrawal trends. Thus, the country-year setup provides more information than a single-year cross-sectional study to test whether population changes are associated with changes in freshwater availability or water stress. It also provides a useful framework for analysing regional variability among countries with very diverse resource endowments.

Overall, the methodology offers a solid descriptive framework for the investigation. The key methodological problem at this level is the fact that the inferential panel-data component is not yet completed. To fit the phrase “Panel Data Analysis” in the title the final publication should include the estimated panel models, model-selection tests, diagnostics, effect estimates, confidence intervals or standard errors, significance tests and relevant robustness analyses.

3. Results

3.1 Descriptive characteristics of the study dataset

The research covered 311 country-year observations for 12 East African countries: Burundi, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania and Uganda. The data set consisted of yearly observations from 1990 to 2022 when data were available, resulting in an unbalanced panel. The main outcome variable was water stress percentage, and demographic, hydrological and economic conditions were characterised by demographic, hydrological and economic variables such as population, freshwater availability per capita, renewable freshwater resources, GDP per capita, total water withdrawal, and sectoral withdrawal shares.

Mean water stress was 34.43% for all observations (median = 6.17%, SD = 123.43 percentage points). Water stress varied from 0.053% to 673.38% showing significant variability between countries. The average freshwater availability was 2,219.0 m 3 per person, but the median was much lower at 973.0 m 3 per person. The average GDP per capita was roughly US$846.48 and the mean population across country-year observations was approximately 29.1 million. Agricultural water consumption was the greatest average component of freshwater withdrawals and accounted for 64.08 percent of total withdrawals. Domestic withdrawals amounted for 29.93% while industrial withdrawals accounted for only 5.98% on average. These descriptive data reveal a strong variation in freshwater endowment, water-use structure and water stress across the research region.

3.2 Water stress temporal change in East Africa

Water stress revealed significant variance both between countries and over time. Sudan had the highest mean water stress in the sample at 673.38% followed by Somalia at 49.62%, Eritrea at 20.13% and Kenya at 13.20%. Conversely, the Democratic Republic of the Congo had the lowest mean water stress of about 0.07%.

In a number of countries there were significant rises in water stress at the beginning of their individual time periods. In Burundi, the share climbed from about 1.4% in 1990 to about 2.9% around 2000, with levels remaining generally consistent thereafter. Djibouti rose from 3.9% to more than 6%, and Rwanda rose from 1.6% to more than 6%. Ethiopia similarly saw a steady growth from about 4.6% in the early 2000s to about 8.6% in the later timeframe. Somalia saw one of the largest increases, with water stress growing from about 23% in the early part of the period to about 55%, then remaining pretty steady. Kenya’s path was more complicated, dropping initially from around 10% to 7.5% and then rising to around 19.5%

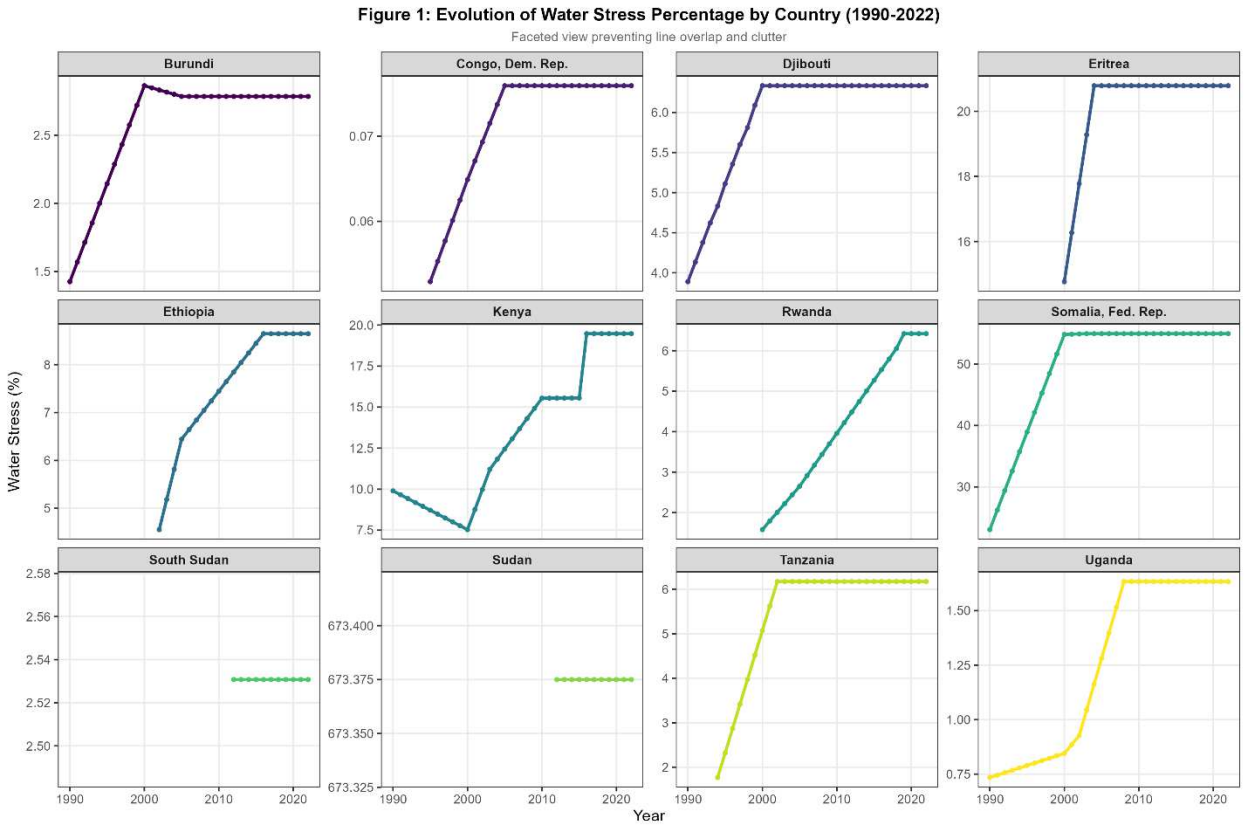


Figure 1. Evolution of water stress percentage by country, 1990–2022.

Thus, Figure 1 shows that the temporal evolution of water stress was quite country-specific. While a number of countries saw growing pressure on their water, the timing, amount and final stabilisation of these changes ranged greatly from country to country in the region.

3.3 Availability of water and population pressure

Freshwater availability per capita dropped considerably in most nations over the observation period. This trend was most pronounced in Burundi, Ethiopia, Kenya, Rwanda, Somalia, Tanzania, Uganda, Djibouti and the Democratic Republic of the Congo. For instance, the availability of freshwater in Burundi dropped from about 1,800 m3 per person at the start of the research period to less than 800 m3 per person by its end. Kenya's has fallen from around 800 m^3 per capita to around 380 m^3 per capita and Somalia's from around 800 m^3 per capita to below 300 m^3 per capita . In Tanzania the decline was likewise large, from roughly 2,700 to about 1,200 m^3 per capita.

The Democratic Republic of the Congo was the water-abundant country with a mean freshwater availability of around 14058 m3 per capita while the lowest mean availability was in Sudan with about 94.16 m3 per capita. Djibouti averaged about 365.46 m3 per capita while Kenya and Somalia averaged about 590 m3 per capita.

Increasing demographic pressure on freshwater resources is a result of the simultaneous increase in population and the decrease in per capita availability of renewable freshwater resources. Yet the descriptive results do not show evidence for population expansion causing water stress.

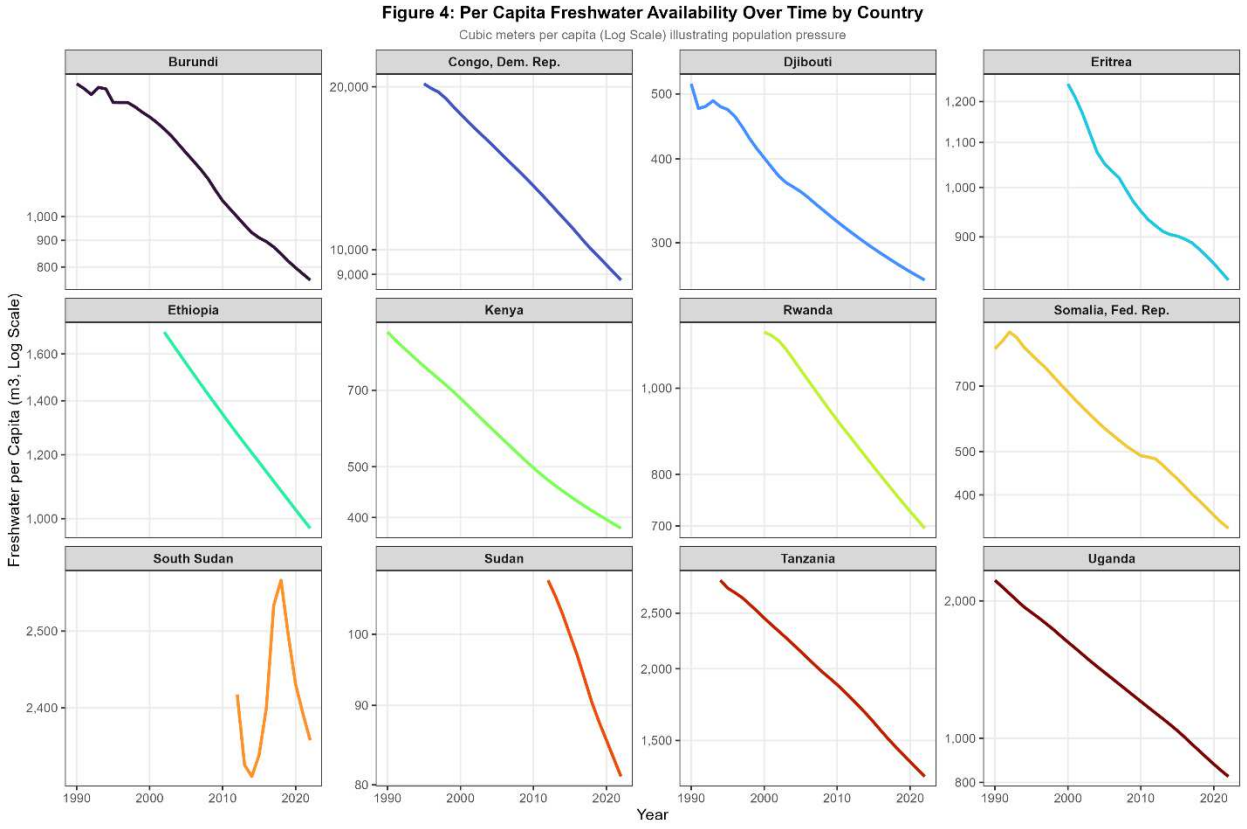


Figure 4. Per capita freshwater availability over time by country.

3.4 Distribution of freshwater scarcity categories

The Falkenmark classification also showed significant variations in freshwater scarcity among the studied countries. Countries with lower per capita freshwater supply spent a much larger

proportion of the research period in the water stress, scarcity, or absolute scarcity categories. Djibouti was primarily in the absolute shortage group, while Sudan likewise stayed in the extreme scarcity category over the length of time for which it was observed. Many observations in the scarcity and absolute-scarcity categories characterised Somalia and Kenya. Rwanda and Eritrea were dominated by scarcity and water-stress circumstances. Conversely, the Democratic Republic of the Congo stayed mostly in the low-stress category, indicating its far greater availability of renewable freshwater. South Sudan, as well, was mainly in the no-stress group over a shorter period of observation.

The results show that freshwater shortage in East Africa is highly heterogeneous, with some nations enduring chronic severe resource limits, while others are endowed with relatively plentiful freshwater resources.

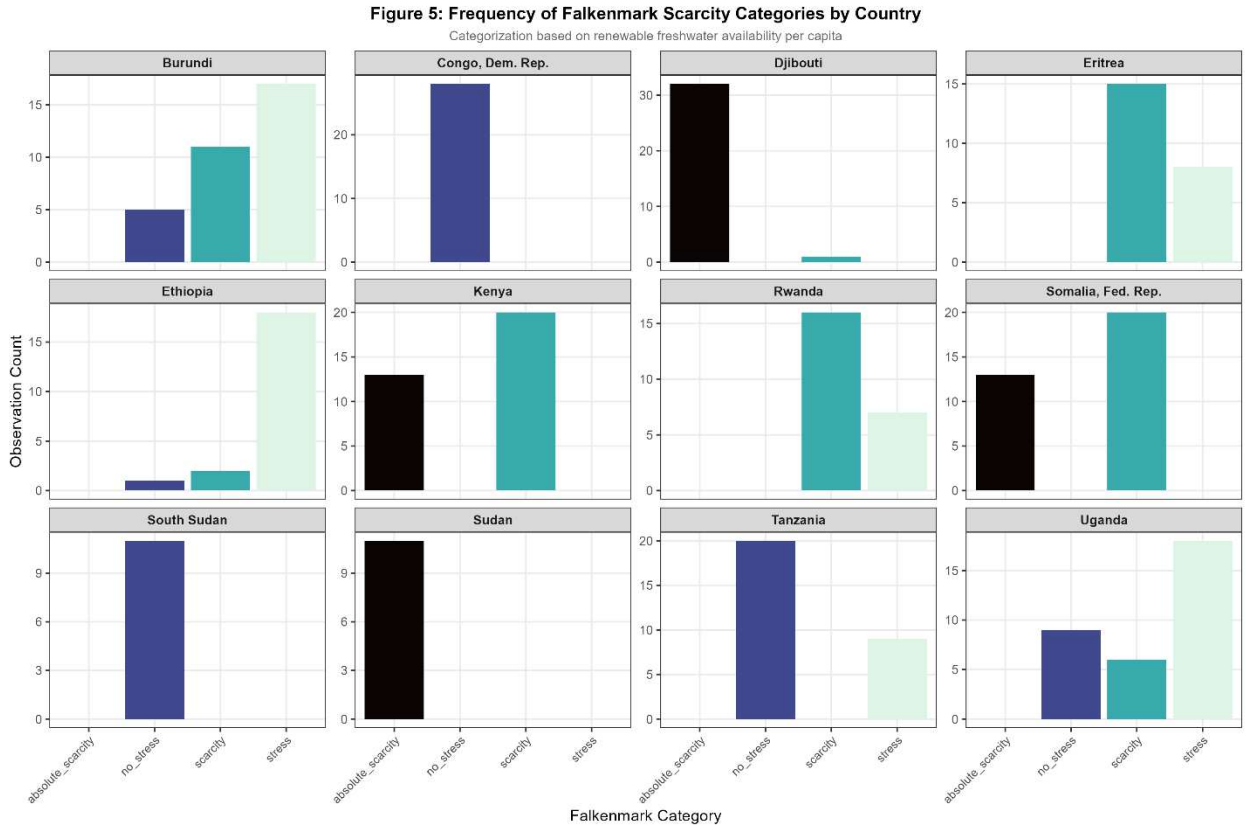


Figure 5. Frequency of Falkenmark freshwater scarcity categories by country.

3.5 Five-year changes in water stress

Further information came from the five-year rolling water-stress indicator which gave some indication of the pace of change in water pressure within countries. Positive numbers showed increases in water stress over successive five-year periods, while values close to zero represented relatively constant conditions.

Somalia saw notably substantial positive five-year gains in the early half of the research period, with increases of more than 3 percentage points throughout the strongest part of the increase. However, the five-year change thereafter dropped to almost nil, with water stress remaining steady at around 55%.

Eritrea, Ethiopia, Rwanda, Tanzania, Uganda, Djibouti and Burundi also had periods of positive five-year change. In some of these countries the size of the increase slowed significantly in later years.

Kenya had a more varied pattern, with decreasing water stress followed by large positive gains. This variation is an expression of the non-linear pattern noticed in the annual water-stress series .

Figure 6: 5-Year Rolling Water Stress Trend (Percentage Points)

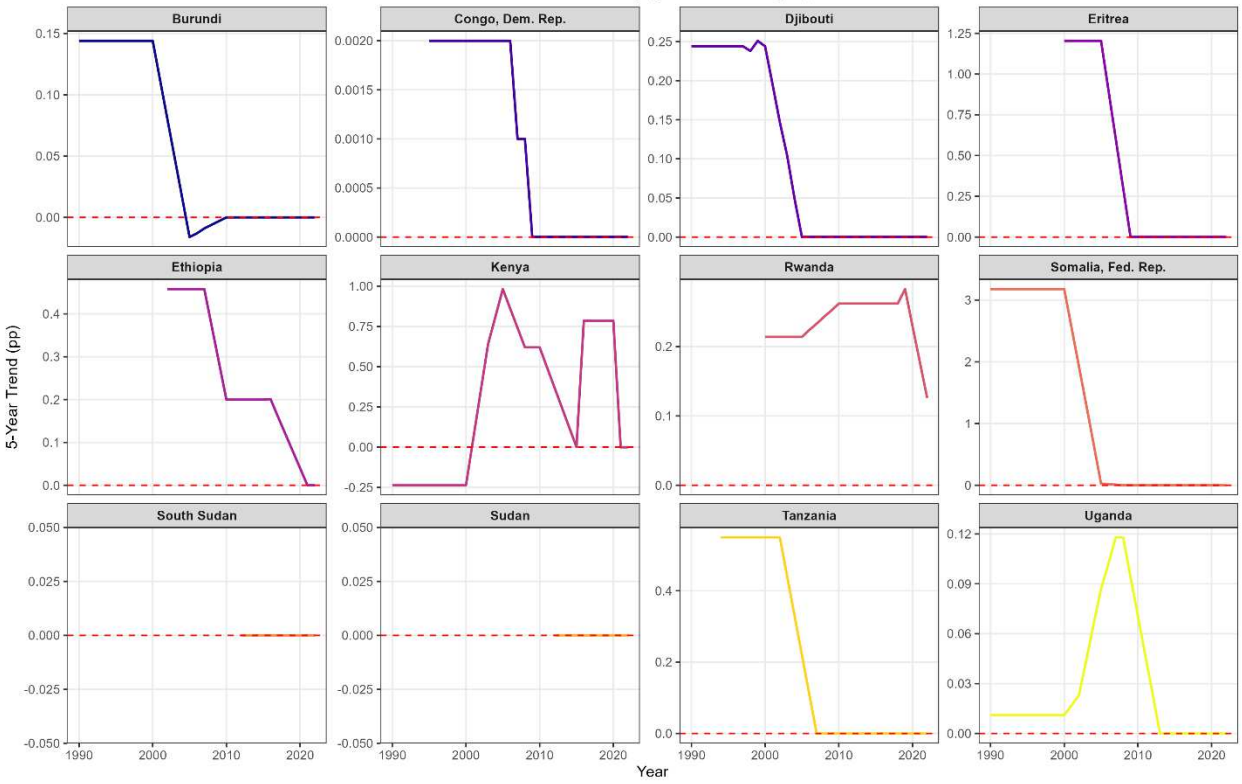


Figure 6. Five-year rolling trend in water stress by country.

Overall, Figure 6 suggests that higher water stress occurred at certain historical intervals, rather than at a constant rate over the entire study period.

3.6 Economic development and water stress.

There was a lot of variation between countries in the link between GDP per capita and water stress. Positive fitting correlations were found in some countries, including Ethiopia, Kenya, Rwanda, Tanzania, Uganda, Djibouti and the Democratic Republic of the Congo. These patterns imply that periods of economic growth were usually accompanied by rising water stress.

This association, however, was not general. Burundi and Eritrea have largely unfavourable associations between GDP per capita and water stress. While Somalia had a favourable overall fitted relationship, the scatter distribution indicated some clustering and nonlinearity, particularly when water stress approached 55%.

Water-stress recorded values revealed little temporal fluctuation during the available study years in South Sudan and Sudan, thus, almost horizontal connections were observed.

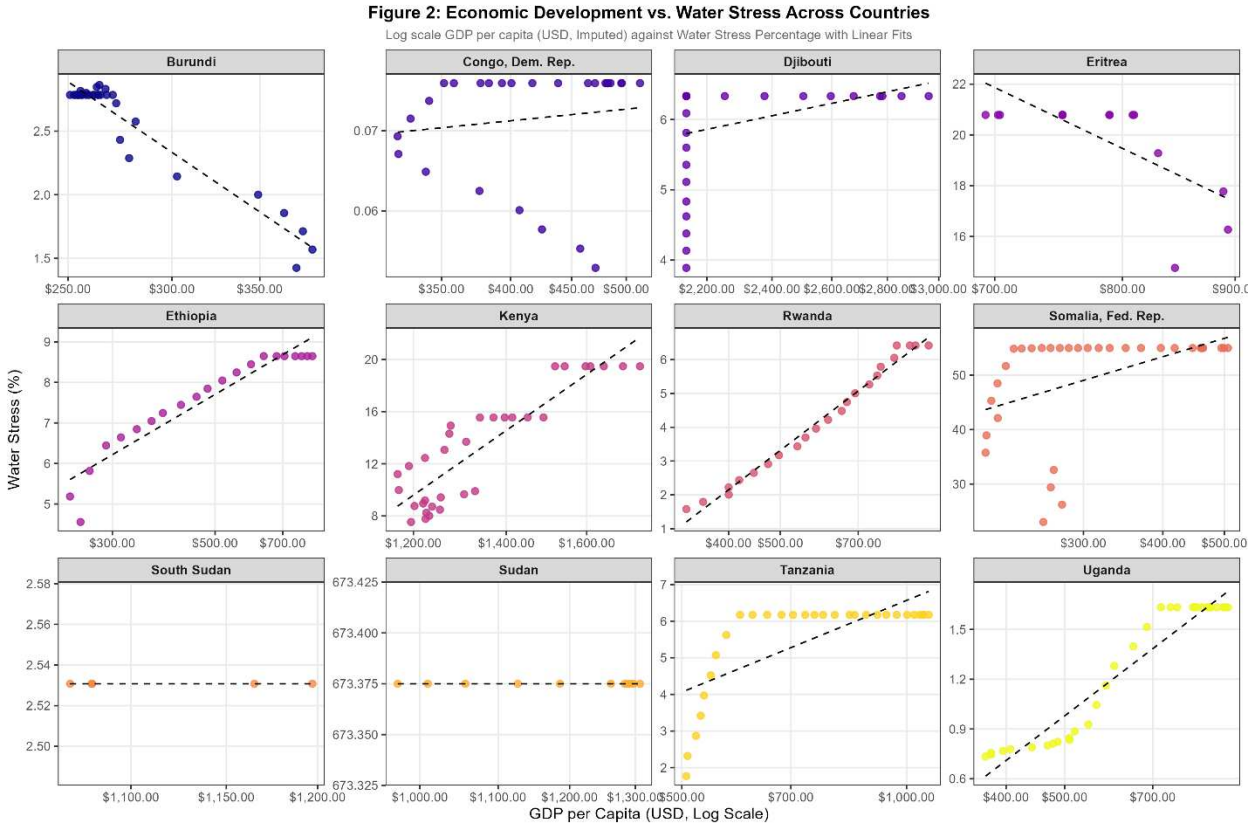


Figure 2. Relationship between GDP per capita and water stress across countries.

The country-specific patterns show that regional disparities in terms of water stress cannot be explained just by economic development. Rather, the link seems to depend on a complicated combination between economic conditions, water supply, population, and national patterns of freshwater usage.

3.7 Distribution of freshwater extractions by sector

The proportion of freshwater withdrawals in the 12 countries was very different. Agriculture was the primary water-consuming sector in most countries. The agricultural proportion was notably high in Somalia (99.41%), Sudan (96.19%), Eritrea (92.08%), Ethiopia (91.11%), Tanzania (87.39%), Burundi (77.47%) and Kenya (70.13%).

Somalia therefore had the highest reliance on agricultural water withdrawal of any country in the

dataset, with household and industrial uses accounting for only extremely modest amounts of total withdrawals.

But in all countries, agriculture was not always the primary water-use sector. In Djibouti, domestic water withdrawals were about 79.54% of total withdrawals . In the Democratic Republic of the Congo, home use was about 67.31% . Uganda also had a sizable domestic share of about 49.31%. South Sudan demonstrated the most balanced sectoral structure where the agricultural sector accounted for around 36.47 %, residential usage about 29.33 % and industrial use about 34.19**%**.

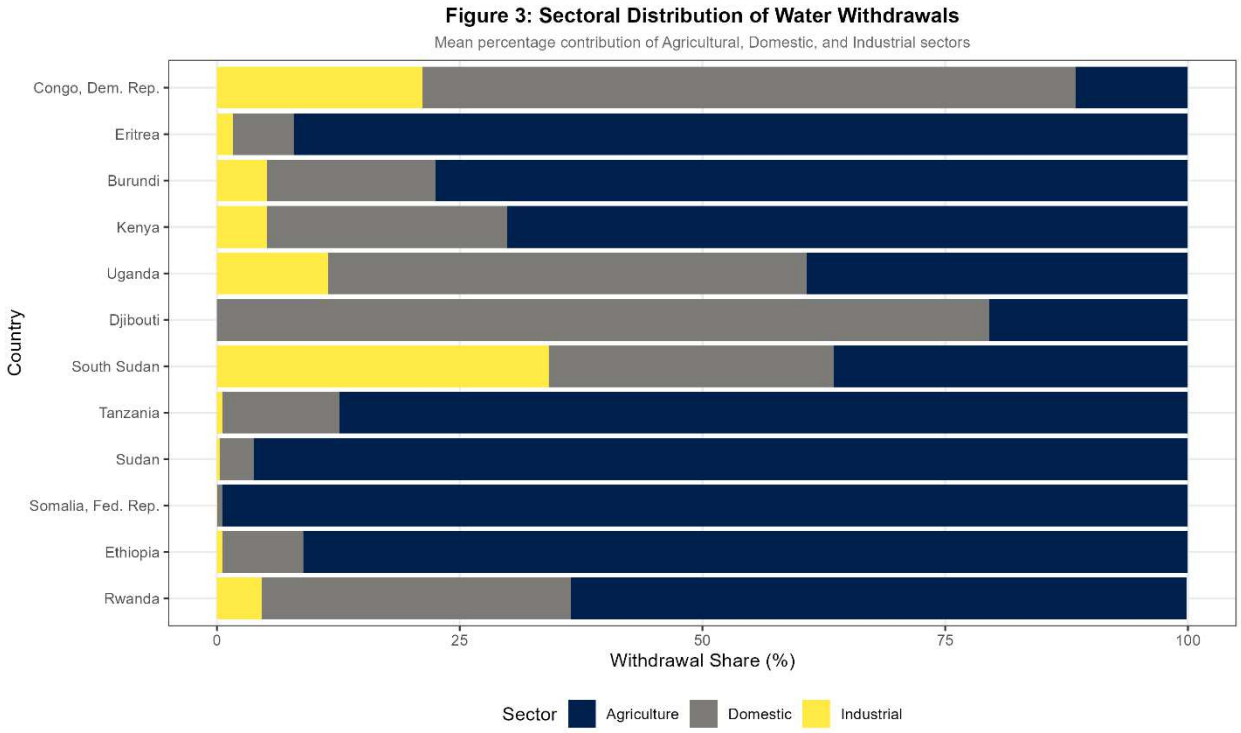


Figure 3. Mean sectoral distribution of agricultural, domestic, and industrial freshwater withdrawals across East African countries.

The data suggest that the mechanisms affecting water demand are very different from country to country. In several water strained nations, like Somalia and Sudan, agricultural withdrawal is the dominant use of national freshwater.

3.8 Water stress spatially

Spatial research indicated large spatial heterogeneity in water stress across East Africa. Sudan was the most noticeable regional hotspot, with significantly greater water stress than all the other countries. Somalia likewise presented high levels compared to the great majority of neighbouring countries.

In contrast, the Democratic Republic of the Congo showed very little water stress, which was consistent with its considerable renewable freshwater supplies.

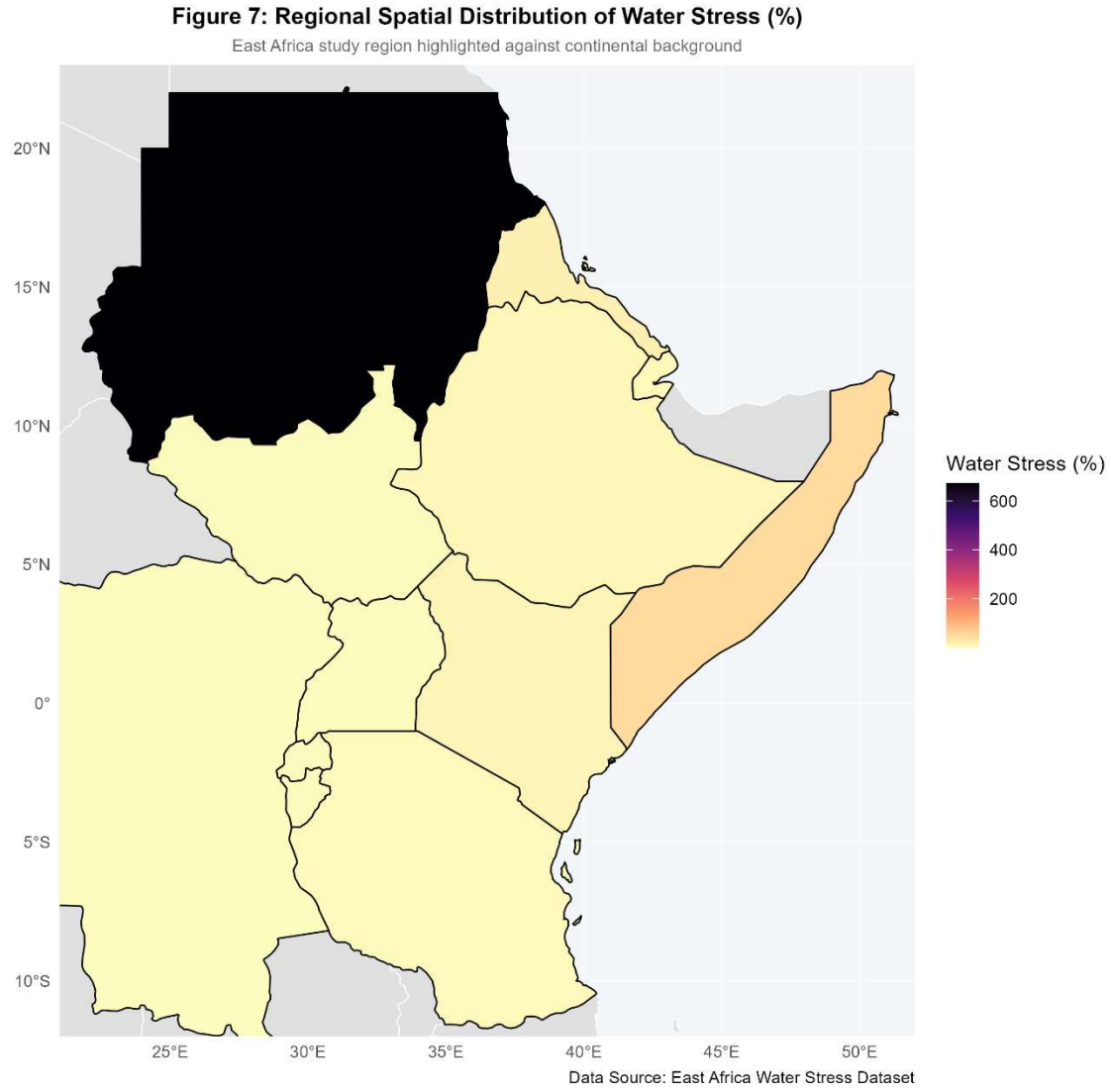


Figure 7. Regional spatial distribution of water stress across East Africa.

The spatial distribution thus demonstrates that severe water stress is regionally confined, not uniformly spread over the territory.

3.9 Distribution of fresh water availability geographically

The spatial trend for freshwater availability was the inverse of that reported for water stress. The Democratic Republic of the Congo had the highest availability of freshwater per capita by far, and Sudan, Djibouti, Somalia and Kenya had comparatively low availability of freshwater.

Generally, this spatial discrepancy implies that locations with low renewable freshwater supplies are more likely to face higher freshwater pressure. But water stress is not only a function of the natural availability of freshwater, but overall withdrawal volumes and sectoral water demand also play a role in national disparities.

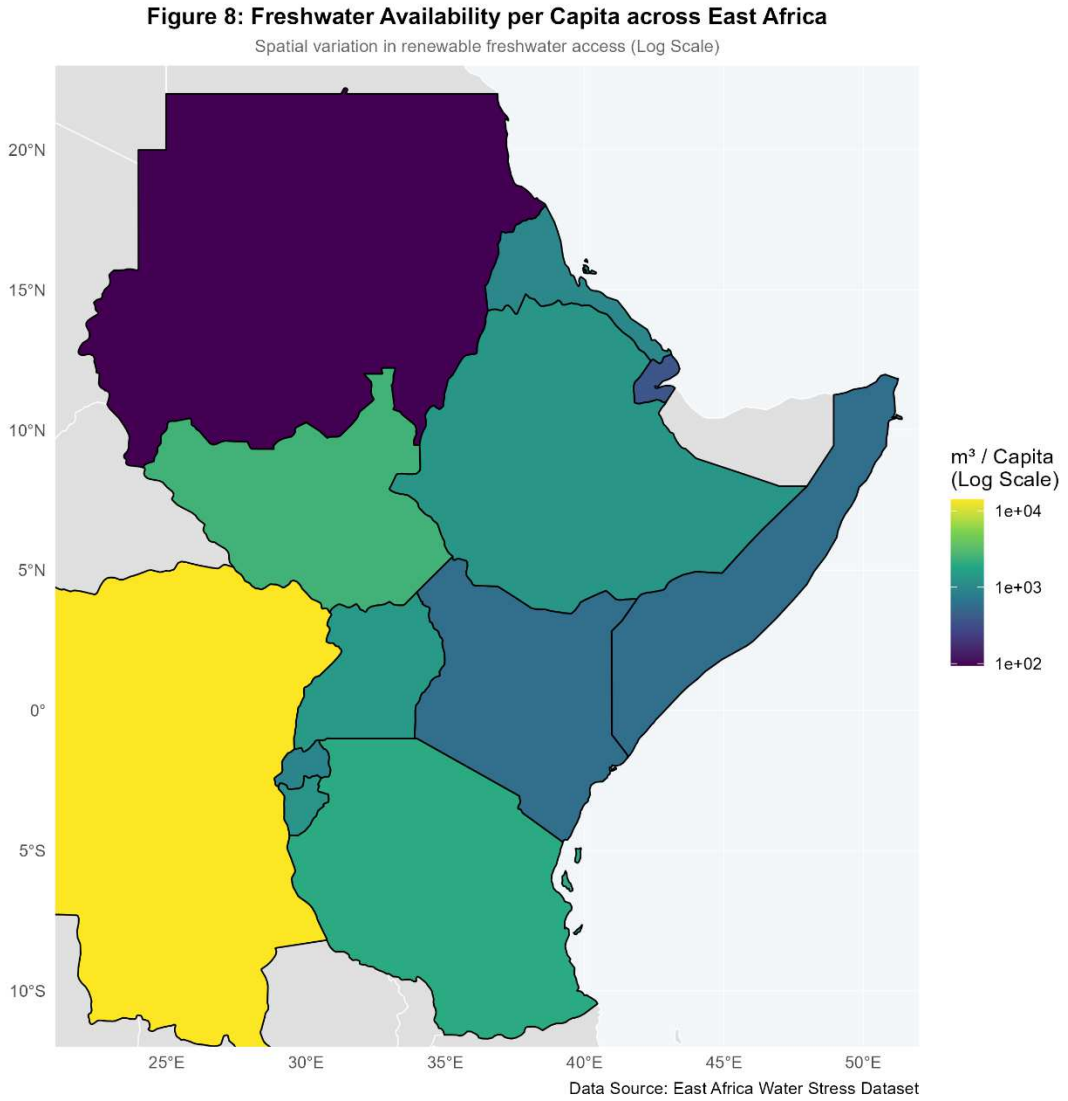


Figure 8. Spatial distribution of renewable freshwater availability per capita across East Africa.

3.10 Spatial distribution of economic development

GDP per capita also showed significant regional variability. Djibouti had a relatively high GDP

per capita while Somalia and several others had much lower ones. Importantly, the geographical distribution of GDP did not necessarily match the spatial distribution of water stress. For instance, high and low water stress circumstances occurred at different income levels. This result confirms the notion that water stress is not only driven by economic development but by a mix of demographic pressure, availability of freshwater-resources, water demand, sectoral water consumption and economic conditions.

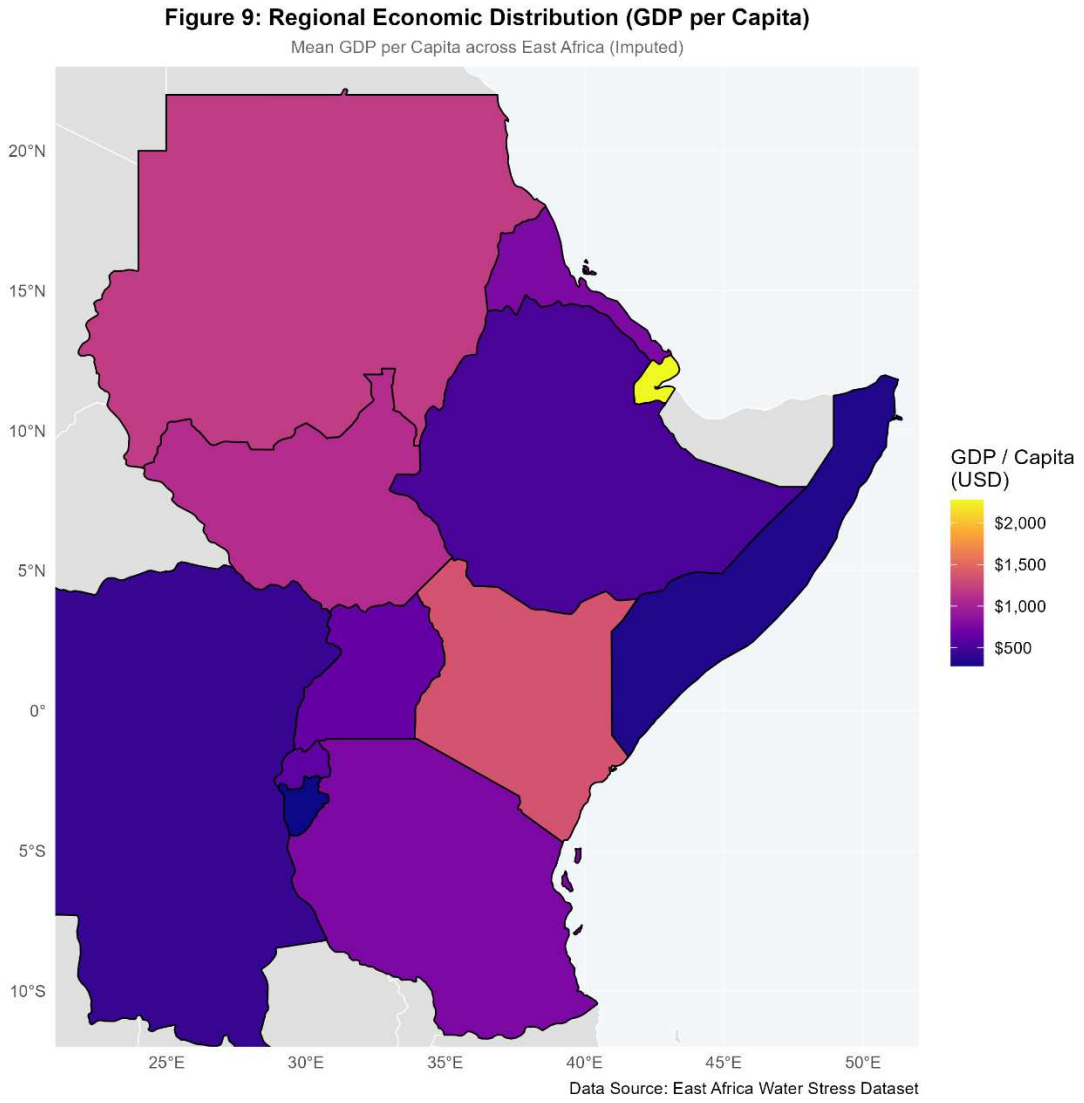


Figure 9. Regional spatial distribution of mean GDP per capita across East Africa.

3.11 General pattern of water stress in the region

The data together reveal great temporal and spatial variation in freshwater conditions across East Africa. Most countries saw a decrease in the amount of renewable freshwater available per person, although the degree of water stress that ensued was strongly dependent on the country's freshwater resources and the amount of water being extracted. Sudan was an extreme case of water stress, Somalia had relatively limited availability of freshwater paired with persistent high water stress and an overwhelming agricultural extraction structure. Meanwhile, the Democratic Republic of the Congo has the largest availability of fresh water with very minimal water stress. Taken together, the descriptive evidence suggests that population pressure alone is not a determinant of national water stress. Instead, water-resource strain across East Africa appears to be driven by an interplay of variations in freshwater endowment, withdrawal intensity, sectoral demand and socioeconomic factors.

4. Discussion

In this study, longitudinal panel data were used to explore the relationship between population pressure, freshwater availability and water stress in 12 East African countries. Results suggest significant regional and temporal differences in water-resource circumstances. Overall, the data suggest that water stress in East Africa is driven by decreasing freshwater availability, increasing demographic pressure, sectoral water demand and disparities in national resource endowment.

4.1 Population pressure and falling availability of fresh water

A very important finding was the broad drop in per capita availability of renewable freshwater in the study region. As seen in Figure 4, nations including Burundi, Ethiopia, Kenya, Rwanda, Somalia, Tanzania, Uganda and Djibouti have seen significant declines in freshwater availability over time. This pattern indicates that population increase is placing pressure on renewable freshwater supplies, particularly if total freshwater supply is relatively static. Figure 8 shows a regional pattern which confirms this finding and indicates that nations such as Sudan, Somalia and Djibouti have relatively little freshwater availability while the Democratic Republic of the Congo has a substantially bigger renewable freshwater resource base. This contrast shows that population pressure is not independent of hydrological circumstances.

This conclusion corroborates earlier studies that have demonstrated that population expansion and socioeconomic development might raise freshwater vulnerability when the demand exceeds available water resources (Graham et al., 2020; Sun et al., 2021; Vörösmarty et al., 2000). Continued demographic increase across Africa may therefore significantly limit per-capita freshwater supply unless improvements are made in water storage, conservation, infrastructure and management.

4.2 International Variations in Water Stress

The study showed significant disparities in water stress across nations in East Africa. Fig. 1 demonstrates that Sudan had the highest level of reported water stress, although Somalia also had consistently high levels. Conversely, the Democratic Republic of the Congo was characterised by very low water stress during the study period. The geographical distribution in Figure 7 demonstrates that water stress is localised in some areas of the region and is not spread evenly across East Africa. Sudan and Somalia are critical areas of concern . Countries rich in freshwater are under much lower pressure. These differences align with previous studies which highlight the differential distribution of water stress across African countries because of differences in renewable water resources, climate, intensity of withdrawal, economic structure and infrastructure (Mensah & Appiah-Twum, 2023; Ohwo & Ndakara, 2025; Tramberend et al., 2021). However, the result for Sudan is extremely high and should be taken with caution since extreme observations can greatly alter regional statistics. Verification against the original water-stress indicator and source data set is therefore required.

4.3 Types of Freshwater Scarcity

Figure 5 also shows the large heterogeneity in freshwater scarcity as reflected in the Falkenmark classification. Sudan and Djibouti exhibited chronic absolute-scarcity circumstances, whereas Somalia and Kenya frequently fell into the scarcity or absolute-scarcity categories. By comparison, the Democratic Republic of the Congo stayed mostly in the no-stress category. This conclusion points out the necessity of distinguishing between freshwater availability and water stress. One country may have low per capita freshwater availability but modest demand to

withdraw it, but another may be in severe water stress because withdrawals are excessive relative to the renewable resource base.

The results encourage the use of numerous indicators of water security instead of a single signal. This technique allows for a more holistic evaluation of both the physical availability of freshwater and human impact on water resources.

4.4 Temporal Variation of Water Stress

Figure 6 illustrates the 5-year rolling trends, which reflect the temporal variability of the changes in water stress. Many countries underwent periods of high growth and then stabilisation. For example, Somalia had substantial rises in water stress in previous eras, but the five-year trend moved closer to zero as the overall water stress stabilised at a high level. Similar tendencies were also noted in Ethiopia, Rwanda, Tanzania, Uganda, Djibouti and Burundi.
This is crucial since stabilisation does not necessarily mean improvement. A country can not see any change in water stress in recent times but be under tremendous pressure of freshwater. Therefore, both the absolute amount of water stress and the direction of change are relevant for assessing national water-security situations.

4.5 Economic Development and Water Scarcity

The relationship between economic development and water stress was varied between countries. Positive connections were detected in some countries such as Ethiopia, Kenya, Rwanda, Tanzania, and Uganda (Figure 2). However, other countries showed weaker, negative, or generally steady relationships.
Figure 9 further exhibits the spatial distribution of GDP per capita, implying that economic progress is not directly correlated with the geography of water stress. Some countries with relatively high GDP per capita had moderate water stress and some countries with lower income levels encountered much larger pressures on freshwater resources. These data imply that water stress does not necessarily correlate with economic development. Economic growth can boost water demand through agricultural expansion, industrial activity, urbanisation and household

consumption, but it can also boost the capacity to invest in water-efficient technology, infrastructure, recycling and enhanced management. This heterogeneous relationship is consistent with previous econometric studies, which highlight the interaction between economic development and water availability depends on resource endowment, the production structure, and water use efficiency (Barbier, 2010; Lounnas & Bouchelaghem, 2025; Qiao & Wang, 2023).

4.6 Sectoral Breakdown of Water Withdrawals

In the sectoral allocation, agriculture represented the biggest share of freshwater withdrawals in most countries (Figure 3). Agricultural water consumption dominated mainly in Somalia, Sudan, Eritrea, Ethiopia and Tanzania.

Agriculture was most concentrated in Somalia, where it accounted for more than 99% of freshwater withdrawals. It demonstrates that agricultural productivity is highly correlated with national water pressure and that improving agricultural water-use efficiency could greatly contribute to alleviating freshwater stress. But the pattern of withdrawal was not universal among countries. household water usage constituted a bigger percentage in Djibouti and Democratic Republic of the Congo while South Sudan had a more equitable allocation of water for agricultural, household and industrial applications.

These distinctions mean that water management policies have to be country specific. In nations where agriculture dominates, effort should be paid to improving agricultural efficiency, whereas urban and home water management may be more significant in other countries.

4.7 Spatial Patterns of Water Scarcity, Freshwater Resources and Economic Development

The combined reading of Figures 7, 8 and 9 gives an essential geographical viewpoint. The spatial distribution of water stress is shown in Figure 7, freshwater availability per capita in Figure 8 and economic inequalities in the study region in Figure 9. Taken together, these maps suggest that countries with less freshwater tend to experience more water stress, but the correlation isn't perfect. The Democratic Republic of the Congo has high water availability and relatively low water stress,

whereas Sudan and Somalia have substantially higher freshwater constraints. The comparison with GDP also suggests that economic progress alone does not explain these differences. Rather, the water stress appears to be driven by the interconnections between freshwater endowment, population pressure, sectoral demands and socio-economic factors. This is consistent with the regional view presented by Tramberend et al. (2021) who stated that water conditions in East Africa vary greatly depending on the demographic, economic, and hydrological characteristics of each country.

4.8 Water Resource Management Implications

The results have substantial implications for water resource strategy in eastern Africa. First, countries facing dwindling freshwater supplies should incorporate population expansion into their long-term water planning. It may be increasingly required to invest in water storage, efficient distribution systems, rainwater harvesting, groundwater monitoring and wastewater reuse. Second, in many of the nations under high stress, agriculture is responsible for a large share of freshwater withdrawals, and so there is a need to increase irrigation efficiency, drought-resistant crops, soil moisture conservation and water-saving agricultural technologies. Third, countries facing serious water stress need to improve monitoring of freshwater withdrawals as a proportion of renewable resources. Internationally standardised metrics such as SDG 6.4.2 can allow governments to identify unsustainable levels of withdrawal and monitor progress toward more efficient use of resources (FAO, 2026; FAO & UN-Water, 2024). Finally, regional collaboration is needed as many East African countries share rivers, aquifers, lakes and climatic systems. Increased resistance to growing scarcity could arise from improved data sharing and coordinated transboundary water management.

4.9 Limitations of the Study

Limitations should be taken into account when interpreting the findings. The study used an unbalanced panel which means the number of observations was not equal across the countries. Some variables have missing observations, especially GDP per capita. Country level data can hide important sub-national heterogeneity between river basins, urban and

rural areas and administrative regions. Secondary hydrological indicators could be modelled or calculated values, too. The observational nature of the study also restricts causal inferences. Declining freshwater availability coincides with population increase in many countries, but other variables such as rainfall unpredictability, drought, infrastructure, governance, agricultural demand and land use can all contribute to water stress.

Finally, the presented results are mostly descriptive; To evaluate if population, GDP, freshwater supply and withdrawals are independent predictors of water stress, after accounting for country-specific and temporal impacts, more advanced panel econometric research would be necessary.

4.10 General Interpretations

To summarise, results indicate that water stress in East Africa is the result of the interplay of population pressure, freshwater supply, withdrawal intensity, economic conditions and sectoral water demand. The data do not support the hypothesis that population expansion alone explains regional water stress. Instead, the national freshwater endowment is a key determinant of how demographic pressure translates into water scarcity. The difference between the Democratic Republic of the Congo, Somalia and Sudan is a striking illustration of this. The Democratic Republic of the Congo has good availability of freshwater and minimal stress, despite its enormous population, whereas Somalia has diminishing availability of freshwater and significant water stress, with a major dependence on agricultural water withdrawals. Hence, sustainable water resource management in East Africa needs to be based on integrated, country-specific plans combining population planning, agricultural water efficiency, sustainable withdrawals, infrastructure investment and regional cooperation.

5. Conclusion and Recommendations

5.1 conclusion

This study studied the relationship between population pressure, freshwater availability and water stress in 12 East African countries with 311 country-year observations. The results reveal a wide

variety in the water-resource situation across the region and suggest that water stress can not be accounted for by a single issue. One noteworthy conclusion was the general trend of declining renewable freshwater supply per capita over time in many nations. This pattern reflects the rising burden on accessible freshwater supplies as populations rise. But the data also suggest that population size alone does not determine water stress. huge endowments of renewable freshwater, as those of the Democratic Republic of the Congo, can mean moderate water stress even with huge populations, but countries with less freshwater resources may incur far more pressure. The study also showed considerable disparities in water stress between countries. Sudan had the greatest stress level in the dataset. Somalia showed consistently high water stress and a significant drop in freshwater per capita. Conversely, several countries have comparably low stress levels. These discrepancies underline the importance of national hydrological conditions, intensity of extraction and patterns of water use by sector.

Agriculture was the main consumer of freshwater in most of the countries, especially in Somalia, Sudan, Eritrea, Ethiopia and Tanzania. This implies that agricultural demand is a key driver of regional water pressure. Meanwhile, the relationship between GDP per capita and water stress ranged from one country to another, implying that economic growth might either increase or decrease water stress, depending on the national economic structure, the efficiency of water usage, technology and managerial ability.

To summarise, the study highlights that the water stress in East Africa is a complex challenge driven by the interaction of population increase, freshwater resource availability, economic conditions, withdrawal intensity and sectoral demand. Hence, effective water-resources management requires integrated, country-specific policies, rather than single regional strategies.

5.2 Suggestions

The outcomes of the study lead to some recommendations. East African states should first develop long-term water-resource planning, including population predictions. Future water demand should be predicted along with projected demographic increase for better planning of residential supplies, agricultural, sanitation and industrial expansion.

Second, countries facing dwindling freshwater resources need to enhance water-use efficiency and conservation measures. Investments in rainfall collection, water storage, wastewater reuse, leakage reduction, groundwater monitoring and efficient distribution systems can help to relieve pressure on limited resources.

Third, more attention should be paid to water management in agriculture, especially in nations where agriculture accounts for the majority of freshwater withdrawals. Efficient irrigation systems, drought resistant crops, increased soil moisture conservation and better scheduling of irrigation can decrease wasteful water losses.

Fourth, countries with high or persistent water stress should strengthen monitoring of freshwater withdrawals and of renewable water resources. Reliable national water information systems are required for the early warning of unsustainable extraction levels and evidence-based decision-making.

Fifth, sustainable water planning should be integrated into national economic development strategies. Economic growth should be supported by water-efficient technology, better infrastructure, recycling and stricter regulation so that development does not further aggravate freshwater strain.

Sixth, East African countries should enhance regional and transboundary collaboration. Coordination of monitoring, data interchange, drought preparedness and integrated water-management plans across shared rivers, lakes, aquifers and climatic systems are needed. Finally, future research should use advanced panel econometric models such as fixed-effects or random-effects techniques, robust standard errors, diagnostic tests and sensitivity analysis. Additional research should combine meteorological variables such as rainfall, temperature, drought and evapotranspiration with governance, land use and infrastructure to give a more comprehensive explanation of water stress across East Africa.

Data Availability Statement

The data supporting the findings of this study were obtained from the publicly available Kaggle-distributed dataset, water_stress_panel.csv. The dataset contains country-level indicators of water stress, renewable freshwater resources, population, economic development, and sectoral freshwater withdrawals. The present study analyzed data from 12 East African countries covering the period 1990–2022. The dataset is publicly accessible at https://www.kaggle.com/datasets/belbino/global-water-stress-and-scarcity-index-1990present, subject to the original dataset's licensing and access conditions. The processed data and analytical scripts may be made available by the corresponding author upon reasonable request.

Ethics Statement

This study was based exclusively on publicly available, secondary, country-level aggregate data. No human participants, personally identifiable information, clinical records, or animal subjects were involved. Therefore, ethical approval and informed consent were not required for the analysis, subject to applicable institutional and journal requirements.

Conflict of Interest

The authors declare that they have no known financial or non-financial competing interests that could have influenced the research, analysis, interpretation, or publication of this study.

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Author Contributions

- **Yasir Mohamed Abdinur:** Conceptualization, methodology, investigation, data curation, and writing – original draft.
- **Nur Dahir Warsame:** Methodology, data interpretation, validation, and writing – review and editing.
- **Omar Aweis Ali:** Conceptualization, methodological development, formal analysis, visualization, and writing – review and editing.

- **Fatima Abdijabbar Ibrahim:** Literature review, investigation, data interpretation, and writing – review and editing.
- **Nasra Salad Ahmed:** Literature review, data organization, validation, and writing – review and editing.

All authors reviewed and approved the final version of the manuscript and agree to be accountable for their respective contributions to the work.

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