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# Exploring the socioeconomic determinants of water security in developing regions

Elias Nkiaka

Department of Geography, University of Sheffield, Sheffield S10 2TN, UK
E-mail: e.nkiaka@sheffield.ac.uk

EN, 0000-0001-7362-9430

## ABSTRACT

The objectives of this study are two fold: first, to develop a composite water security metric to assess water security at a national scale, and second, to explore the determinants of water security at the same scale in three developing regions – Africa, Asia-Pacific and Latin America and the Caribbean (LAC). The water security index (WSI) was developed using three bio-physical (water availability, climate risk and ecosystem vitality) and two socioeconomic (water accessibility and integrated water resources management) variables. Five independent variables (governance, gross domestic product (GDP) per capita, percentage of urban population, official development assistance for water and sanitation services (ODA-WSS) and female primary school completion rate) were used to explore the determinants of water security. Results show that >90% of countries in Africa and the Asia-Pacific regions are water-insecure, whereas most countries in LAC are water-secure except Haiti, Guatemala and Nicaragua. Statistical analyses show that GDP per capita, female primary school completion rate and governance are the key determinants of water security. This study provides empirical evidence on the link between female primary school completion rate and water security. Results further show a strong correlation between water security and ODA-WSS in the region with a higher ODA-WSS per capita than in regions with a low ODA-WSS per capita. This suggests that increasing ODA-WSS per capita may enhance water security in developing regions.

**Key words:** Africa, Asia-Pacific, Climate risk, Gender and education, Latin America and the Caribbean, Sustainable development goals

## HIGHLIGHTS

- A composite water security index was developed to assess the status of water security at a national scale in developing regions and to explore the determinants of water security.
- The composite indicator reveals high levels of water insecurity across Africa and the Asia-Pacific regions compared to Latin America and the Caribbean.
- GDP per capita, governance, and female primary school completion rate are important determinants of water security.
- Increasing per capita official development assistance for water and sanitation services may enhance water security.

## 1. INTRODUCTION

Achieving water security has become a critical global challenge due to unsustainable water resources management, and increasing pressure from climate change, population growth, changing lifestyle and economic development, leading to a rapid depletion of surface water and groundwater stocks and increased severity and frequency of droughts (Wang *et al.*, 2018; Pokhrel *et al.*, 2021). The situation is further exacerbated by the rapid degradation of freshwater ecosystems caused by poor environmental management, increased water pollution and the reduction of environmental flows resulting in the loss of aquatic biodiversity (Hogeboom, 2020). Anticipating an imminent global water crisis, the United Nations General Assembly adopted water security as one of the sustainable development goals (SDGs). UN-Water (2013) defines water security as:

'*The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*.'

Many studies have demonstrated that achieving water security (SDG6) can facilitate the achievement of other SDGs because water offers the highest potential synergies for attaining other goals (Di Baldassarre *et al.*, 2019; Taka *et al.*, 2021). Failure to achieve water security can have wider societal ramifications such as poor human health, ecosystems' collapse, exacerbate food and energy insecurity and could also result to armed conflict in water-scarce regions. Furthermore, it will disproportionately affect women and girls in developing regions because this group is mostly responsible for collecting water and engaging in reproductive roles such as caring for relatives with water-related illnesses, preventing them from pursuing an education or other employment thereby reinforcing gender inequality and poverty (Winter *et al.*, 2021). Limited education for girls and women could lead to a lack of gender-inclusiveness in water governance thereby undermining their ability to access water and sanitation services (WSS) (Bhattarai *et al.*, 2021). Considering these multiple challenges, the race to achieve water security particularly in developing regions has become one of the top priorities for governments and global policy institutions and has also become a prominent feature in contemporary science agenda in recent years.

Research on water security has increased significantly in the past decade and several metrics for measuring water security have been developed (Octavianti & Staddon, 2021). These metrics have evolved from the use of single attributes that measure water availability, vulnerability and sustainability (Srinivasan *et al.*, 2017) to encompass composite indicators covering the physical, socioeconomic, political and ecological aspects of water security (Vörösmarty *et al.*, 2010; Gain *et al.*, 2016). While incorporating these dimensions considers the human–water interactions, other critical dimensions with potential to influence water security such as climate change and environmental conditions have received scant attention in the literature. Furthermore, given that water security varies across spatial scales, many studies have also assessed water security using this approach from household to global scales (Gain *et al.*, 2016; Hailu *et al.*, 2020; Doeffinger & Hall, 2021). While studies focusing on subnational and national scales may be used to enhance water security at these scales, global level assessments have the advantage of informing high-level decision-making. However, such assessments can conceal the spatial disparity within regions and loss of valuable insights across different countries and regions. In addition, no study (to my knowledge) has attempted to explore the socioeconomic determinants of water security at a national scale as existing studies have focused on household and sub-national scales (Hinojosa *et al.*, 2017; Martínez-Santos, 2017; Adil *et al.*, 2021). There is therefore an urgent need to develop a water security metric that integrates climate change and environmental conditions, adopts a regional scale and explores the determinants of water security on a national scale.

This study posits that developing a water security index (WSI) that integrates climate risk and environmental conditions at a national scale and exploring the determinants of water security can guide governments and development partners to (1) adopt new approaches and policies aimed at enhancing water security as the world is nearing the 2030 target year for countries to achieve SDGs, (2) identify policies enhancing or impeding water security in each region and (3) adapt to the impacts of climate change and enhance environmental management. Furthermore, geospatial mapping can reveal disparity within regions which can be used to support decision-making in terms of policy prioritisation to target water insecure countries or adopt a sub-regional approach to tackle water insecurity. In addition, using school completion for females as an independent variable can show the influence of female education attainment on water security. This study focuses specifically on developing regions because the burden of water insecurity is more apparent here with wider societal ramifications compared to developed regions (Gain *et al.*, 2016; Nkiaka *et al.*, 2021b). Furthermore, many countries are now adopting a regional approach to water management given that many countries share the same hydrological basins. Hence, this approach represents an important scale for formulating and implementing regional and transboundary water policies.

From what follows, the objectives of this paper are to (1) develop a new water security metric at a national scale considering climate risk and environmental conditions, (2) use the composite indicator to explore the socioeconomic determinants of water security and (3) use geospatial mapping techniques to reveal the disparity in water security among countries in the same region. Our approach follows recent calls to consider climate risk and environmental conditions in water security metrics (Lemos *et al.*, 2016; Babel *et al.*, 2020), to also look at the role of gender and education in water security assessments (Shah, 2021) and to use geospatial mapping techniques to identify water insecurity hotspots (Doeffinger & Hall, 2021; Nkiaka, 2022).

## 2. METHODS

This study targets three developing regions including Africa, Asia-Pacific and Latin America and the Caribbean (LAC) comprising 117 countries. By carrying out this study across three different regions, our overarching goal was to measure water security in each region and to identify the factors underpinning success or failure in each region. This may facilitate the adoption of a regional approach to tackle water insecurity in regions lagging behind. Table 1 provides a summary of the socioeconomic characteristics of each region. Data used in this study were retrieved from trusted third-party sources including international governing bodies, non-governmental organisations and academic research institutions. Several other studies have used data from similar sources to

**Table 1** | Socioeconomic and demographic characteristics of the regions.

| | Region | | | |
|---|---|---|---|---|
| **Factor** | **Africa** | **Asia-Pacific** | **Latin America and the Caribbean** | **Data source** |
| Number of countries | 54 | 30 | 33 | – |
| Population (millions) | 1,300 | 3,900 | 650 | UNDESA (2019) |
| Human development Index (min–max) (mean) | 0.39–0.80 (0.56) | 0.51–0.84 (0.67) | 0.51–0.85 (0.75) | UNDP (2020) |
| GDP per capita PPP $US (min–max) (mean) | 784–30,516 ($5,970) | 2,156–64,848 ($10,568) | (3,034–38,742) ($16,672) | www.data.worldbank.org |
| Total population with access to basic drinking water services | 58% | 76% | 96% | WHO (2018) |
| Total population with access to basic sanitation services | 28% | 72% | 85% | WHO (2018) |

measure water security at different scales (Gain *et al.*, 2016; Doeffinger *et al.*, 2020). We used the most recent data available from each of the data sources, hence there could be differences in the years where data are available at each dimension of water security in this study.

### 2.1. Composite indicators

Composite indicators are widely used in environmental research to measure and rank countries in terms of environmental performance, resource sustainability and governance (Becker *et al.*, 2017). Indicators are particularly useful for condensing complex scientific information and concepts that are not directly measurable into easily understandable and communicable quantitative scores to inform policy decisions (Jensen & Wu, 2018). It has been argued that applying indicators in environmental science can offer several advantages such as (1) using indicators to rank countries may inspire governments to question their standards and approaches, thereby, pushing them to adopt innovative strategies that lead to positive outcomes (Becker *et al.*, 2017) and (2) using indicators may also facilitate regional policy integration; promote evidence-based policy making; align priorities between development partners and incentivize greater financial commitments to target countries (Jensen & Wu, 2018).

This study uses five different indicators to develop a composite WSI. These indicators are grouped into the biophysical sub-index comprising water availability, environmental conditions and climate risk, and the socioeconomic sub-index comprising access to WSS and integrated water resources management (IWRM). The choice of indicators was guided by the fact that (1) the selected indicators are among the prominent ones used in water security assessments by global policy institutions as well as the research community and have been applied in several studies, (2) representative of the physical water availability and accessibility, climate risk, socioeconomic and environmental conditions prevailing in each country at the time of writing this paper and (3) the availability of data for the selected indicators.

### 2.2. Selection of indicators and justifications

Table 2 provides a summary of the different indicators, their description and sources of data used to represent each indicator.

**Table 2** | Data, description and weight attached to each dimension/indicator.

| Water security component | Dimension (weight) | Indicator (weight) | Description | Source of data |
|---|---|---|---|---|
| Biophysical component | Water availability (50%) | Total renewable water resources per capita | Total annual renewable water resources per inhabitant | FAO (2020) |
| | Environmental conditions (25%) | Ecosystem vitality index | Provide information on the state of ecosystems including water resources | Wendling *et al.* (2020) |
| | Climate risk (25%) | Climate risk index | Information on the extent countries have been affected by high impact weather events | Eckstein *et al.*, (2021) |
| Socioeconomic component | Accessibility (70%) | Access to drinking water (60%) | The percentage of population with access to basic drinking water | FAO (2020) |
| | | Access to sanitation (40%) | Percentage of the population with access to basic sanitation services | FAO (2020) |
| | IWRM (30%) | Degree of implementation | Measures how governments are working towards implementing IWRM in each country | UNEP (2018) |

### 2.2.1. Biophysical sub-index

**a. Water availability**

Availability of water resources including surface water and groundwater of acceptable quality is a crucial dimension of water security. For example, in areas with limited access to water services, the availability of free-flowing untreated surface water and shallow groundwater can alleviate water scarcity for millions of people (Martínez-Santos, 2017; Cassivi *et al.*, 2021). To assess water availability, estimates of total annual renewable water resources per capita comprising both renewable surface water and groundwater resources available in each country in each calendar year are used. The advantage of using per capita renewable water resources is that it accounts for the impact of interannual rainfall variability, the impact of slow onset events such as drought and groundwater recharge and the impact of population dynamics on water availability.

**b. Environmental conditions**

This is a crucial dimension of water security that is often ignored even though it can capture the ability of a country to maintain its ecosystems in an acceptable state. Anthropogenic activities such as land use change, agriculture, urbanisation and mining can lead to environmental degradation including water pollution (Rakotondrabe *et al.*, 2018; Chishugi *et al.*, 2021). Water pollution can in turn limit the use of available water resources by humans and in the provision of ecosystem services such as providing habitat for biodiversity (Vörösmarty *et al.*, 2018; Chishugi *et al.*, 2021). This can have adverse impact on water security especially in areas where access to water services is limited and the population depends on free-flowing surface water and shallow groundwater. To represent environmental conditions, the ecosystem vitality index (EVI) which is a sub-index of the environmental performance index (EPI) is used (Wendling *et al.*, 2020). The EVI provides information on the status of terrestrial and aquatic ecosystems, biodiversity, as well as the abiotic processes affecting them at a national scale. Several studies have used ecosystem vitality as a proxy for measuring water security (Vörösmarty *et al.*, 2010, 2018; Acuña-Alonso *et al.*, 2021).

**c. Climate risk**

Climate change is a critical dimension of water security which has rarely been considered in water security metrics despite its considerable impact on water security. Climate change can affect water security at all scales through drought, sea level rise and increase in the frequency and intensity of extreme weather events. Extreme events such as tropical storms and cyclones can exacerbate water insecurity through flooding and destruction of water infrastructure. Climate change is therefore a risk multiplier that can alter water security dynamics at all scales (Lemos *et al.*, 2016). The increasing risk posed by climate change and the vulnerability of developing countries to climate risk coupled with their lack of adaptive capacity suggest that climate risk can no longer be ignored in water security assessment metrics in developing regions.

The climate risk index (CRI) (Eckstein *et al.*, 2021) was used to represent climate risk in this study. The CRI provides information on the level of exposure and vulnerability of countries to extreme climatic events and the impact of such events on the society including economic losses and fatalities (Eckstein *et al.*, 2021). The CRI for 2021 was used in this study and was calculated using data covering a 20-year period from 2000 to 2019 (Eckstein *et al.*, 2021). Countries with a low CRI indicate high exposure and vulnerability to extreme events and vice-versa.

### 2.2.2. Socioeconomic sub-index

The socioeconomic index is made up of the factors that influence the development and sustainable management of water resources. These factors include accessibility to WSS and IWRM.

**a. Access to WSS**

Access to water resources is a critical dimension of water security and is a direct measure of the level of financial investment in water infrastructure and management to enhance access to WSS. In fact, many studies have reported that water insecurity in many developing countries can largely be attributed to limited access due to the absence of water infrastructure rather than availability of water resources (Hamlet *et al.*, 2020). Estimates of access to WSS were used to represent the accessibility factor in this study. These estimates are given as the percentage of the population with access to basic drinking WSS.

**b. Integrated water resources management**

IWRM encapsulates the different social and political aspects of water security including water governance, legislation, institutional and human capacity, and financing and it is one of SDG6 targets. The degree of implementation of IWRM reflects the level of policy implementation, enactment of water legislation, institutional coordination and the financial commitment of governments to enhance water access and management. It also reflects the skills, knowledge and the extent of stakeholder engagement, and their mastery of IWRM processes. Although IWRM is one of the SDG6 targets, this is one of the first study to consider quantitative scores of IWRM in WSI assessment. Data for IWRM were obtained from UNEP (2018).

### 2.3. Data normalisation and assignment of weights

Data obtained from different sources with different units of measurements were normalised into the range [0 1] using Equation (1) to ensure comparability across countries.

$$N = \frac{X_i - X_m}{X_M - X_m} \tag{1}$$

where $N$ is the normalised value, $X_i$ is the observed variable, $X_m$ is the minimum observed variable and $X_M$ is the maximum observed variable. The 5–95% method was used to eliminate the influence of outliers on the normalised scores (Varis *et al.*, 2017). After normalising the data, outliers removed from the top were given a score of '1' and those removed from the bottom received a score of '0'.

Prior to data aggregation, weights were assigned to each dimension and its indicator based on its relevance and importance to contribute towards water security as shown in Table 1 and applied in other studies (e.g., Gain *et al.*, 2016; Greco *et al.*, 2019). For the biophysical sub-index, water availability was given the highest weight (50%), whereas CRI and EVI received 25% each. For the socioeconomic sub-index, access to WSS was given the highest weight (70%), whereas IWRM received 30%) To calculate access to WSS, access to drinking water services received a weight of 60%, whereas access to sanitation services received a weight of 40% as used in other studies (Gain *et al.*, 2016).

### 2.4. Data aggregation and development of the WSI

After normalising and weighting the indicators, the data were aggregated to form the composite indicator. Two sub-indicators were created and used to develop the WSI. The biophysical sub-index was created by aggregating water availability, and CRI, EVI and the socioeconomic sub-index were created by aggregating access to WSS and IWRM using Equations (2) and (3). The two sub-indicators were then averaged to produce the WSI.

$$\text{Biophysical index} = (0.50 \times WA) + (0.25 \times CRI) + (0.25 \times EVI) \tag{2}$$

where $WA$ is the water availability, $CRI$ is the climate risk index and $EVI$ is the ecosystem vitality index.

$$\text{Socioeconomic index} = (0.70 \times WSS) + (0.30 \times IWRM) \tag{3}$$

where $WSS$ is water and sanitation services and $IWRM$ is integrated water resources management. Weights were applied based on the proven contribution of the selected dimensions such as $WA$, $WSS$ and $IWRM$ to likely water security. The WSI was calculated as the mean of the biophysical and socioeconomic indicators using Equation (4).

$$WSI = \frac{\text{Biophysical index} + \text{Socioeconomic index}}{2} \tag{4}$$

Several data aggregation methods are available for computing composite indicators such as arithmetic mean, geometric mean and multi-criteria analysis (Talukder *et al.*, 2017). This study adopted the arithmetic mean to highlight the importance of both biophysical and socioeconomic factors for achieving water security. After creating the indicators, geospatial mapping techniques were used to create thematic maps for the WSI and sub-indicators using ESRI ArcGIS 10.7 software. To achieve this, the index scores were exported from Microsoft Excel and joined with the attribute table in ArcGIS 10.7 containing the shapefiles of all the countries considered in this study. The symbology tab under the layer properties was then used to create thematic maps for the different indicators.

### 2.5. Selection of independent variables

The selection of independent variables to establish the socioeconomic determinants of water security was informed by previous research (Hinojosa *et al.*, 2017; Gomez *et al.*, 2019). As such, six independent variables were selected including the human development index (HDI), governance, gross domestic product (GDP) per capita, official development assistance for water and sanitation (ODA-WSS), female primary school completion rate and percentage of urban population.

The Worldwide Governance Indicator (WGI) was used to represent governance. Due to the existence of many governance indicators, the Government Effectiveness Index (GEI) was used in this study. The GEI is a measure of the quality of public services, civil service, policy formulation, policy implementation and credibility of the government's commitment to raise these qualities or keep them high (WGI, 2019). The data were normalised into the range [0 1] using Equation (1). Table 3 provides a full description of the independent variables selected.

#### 2.5.1. Exploring the determinants of water security

All statistical analyses were carried out using Statistical Package for Social Scientists (SPSS) version 26. Multicollinearity among the variables was tested using correlation analysis and any variable showing statistically strong correlation coefficient (CC $>$0.75) with other variables was tagged for elimination. Once palpable overlap was removed, different regression techniques were used to explore the determinants of water security. In the first step, a bivariate linear regression analysis was conducted between each independent variable and the WSI and sub-indicators (biophysical and socioeconomic indicators) to establish if there was any correlation between them. In the second step, linear regression was conducted between each dependent variable and all the independent variables to reveal the effect of the independent variables on the dependent variable. Finally, a stepwise multivariate linear regression using forward selection was used to identify the independent variable with the most influence on the dependent variable. In this step, all the independent variables were loaded at the same time while maintaining the dependent variable and the model selected the variable with the highest influence on the dependent variable. This process was repeated separately for each region. Finally, average per capita

**Table 3** | Description of independent variables.

| Variable name | Variable description | Source of data used |
|---|---|---|
| GDP per capita | GDP measures economic growth of a country and thus an indication of resources available for investing in water security | www.data.worldbank.org |
| Water and sanitation official development assistance | Refers to the amount of foreign aid directed towards water sector development | www.data.worldbank.org |
| Primary school completion rate | Refers to the percentage of kids particularly girls who complete primary school at relevant ages given the key role they play in fetching water and providing care for sick family members | www.data.worldbank.org |
| Governance (Government effectiveness index) | Quality of governance in each country | World Governance Indicators (WGI) (2019) |
| Urban population | The percentage of the country population living in urban areas | www.data.worldbank.org |
| Human development index | Measure key dimensions of human development | UNDP (2020) |

ODA-WSS for the three regions was calculated to reveal the relationship between ODA-WSS per capita and water security.

## 3. RESULTS

### 3.1. Water security index

The results in Figure 1 indicate that several countries in Africa and the Asia-Pacific regions obtained low WSI scores, whereas most countries in the LAC region had moderate to high WSI scores. It can also be observed that there is a spatial pattern in the distribution of WSI scores across Africa. For example, all countries in East Africa and several countries in Central and West Africa obtained low WSI scores with only few exceptions such as Gabon. Meanwhile majority of countries in southern and north Africa obtained moderate to high WSI scores. Across the three regions, eight countries in Africa and one country each in LAC (Haiti) and Asia-Pacific (Afghanistan) obtained a WSI score ($<0.20$) (Figure 1). Gabon (Africa), Bhutan (Asia-Pacific) and Belize, Brazil, Chile, Guyana, and Suriname (LAC) obtained the highest scores ($\geq 0.70$) indicating high water security (Figure 1). Overall, results show that there are more water-insecure countries in Africa compared to the other two regions.

### 3.2. Biophysical sub-index

Figure 2 shows the results of the spatial distribution of the biophysical index. It can be observed that several countries in Africa and the Asia-Pacific regions obtained low scores for this index, whereas most countries in the LAC region obtained moderate to high scores. At the sub-regional scale, all countries in the Central Africa sub-region obtained medium to high biophysical index scores except Chad (Figure 2). Gabon (Africa), Bhutan (LAC) and Guyana, Suriname, and Venezuela (LAC) obtained the highest biophysical index scores ($>0.65$) (Figure 2).

### 3.3. Socioeconomic sub-index

Figure 3 shows the spatial distribution of the socioeconomic sub-index. Results show that several countries in Africa obtained very low socioeconomic sub-index scores compared to countries in the Asia-Pacific and LAC regions. However, there are substantial disparities in socioeconomic index scores across Africa. For example,

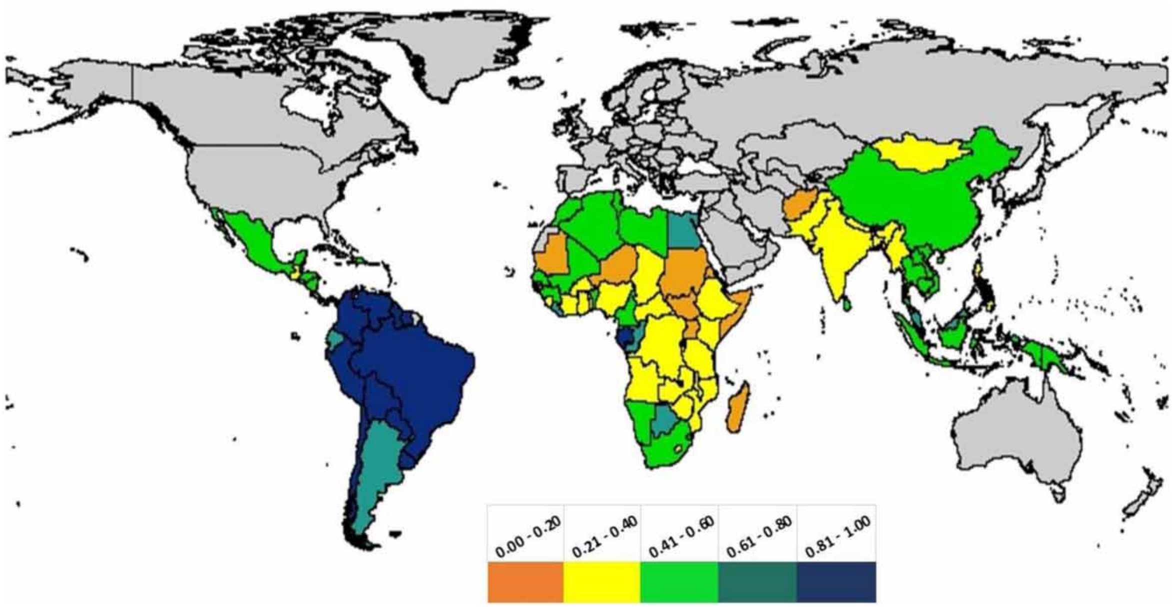


**Fig. 1** | Spatial distribution of the WSI scores at the national level.

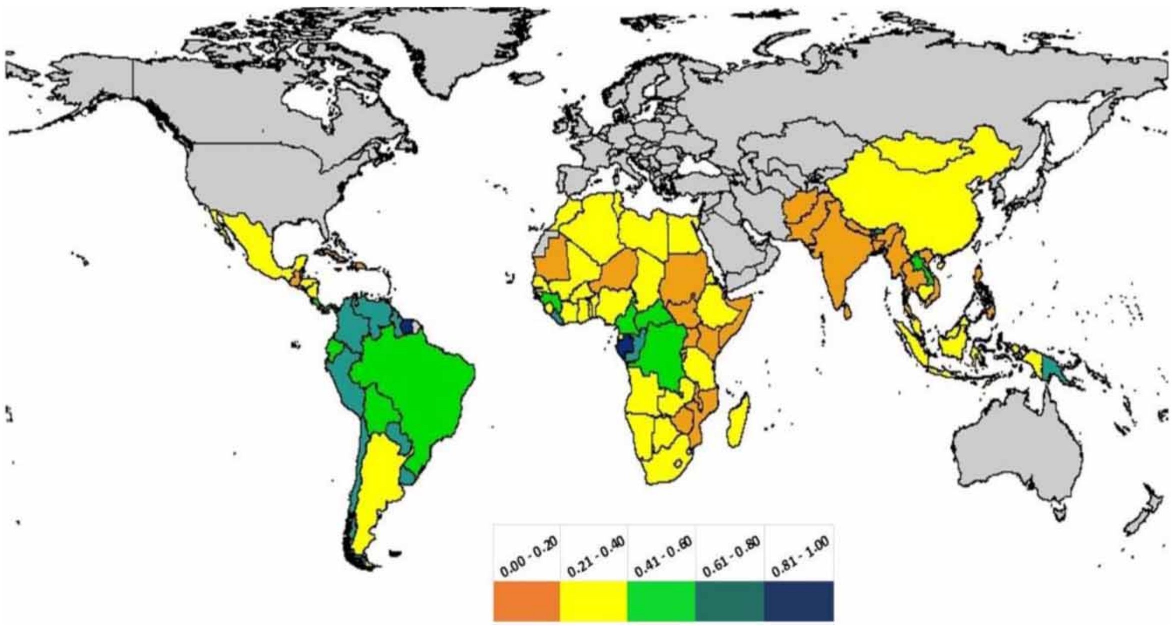


**Fig. 2** | Spatial distribution of the biophysical index scores at the national level.

countries in southern Africa obtained better scores than the rest of the countries in the continent (Figure 3). Across the three regions, Central African Republic and Somalia (Africa) obtained the lowest socioeconomic index scores ($\leq$0.20), whereas Botswana, Mauritius and Seychelles (Africa), China, Tuvalu and Maldives (Asia-

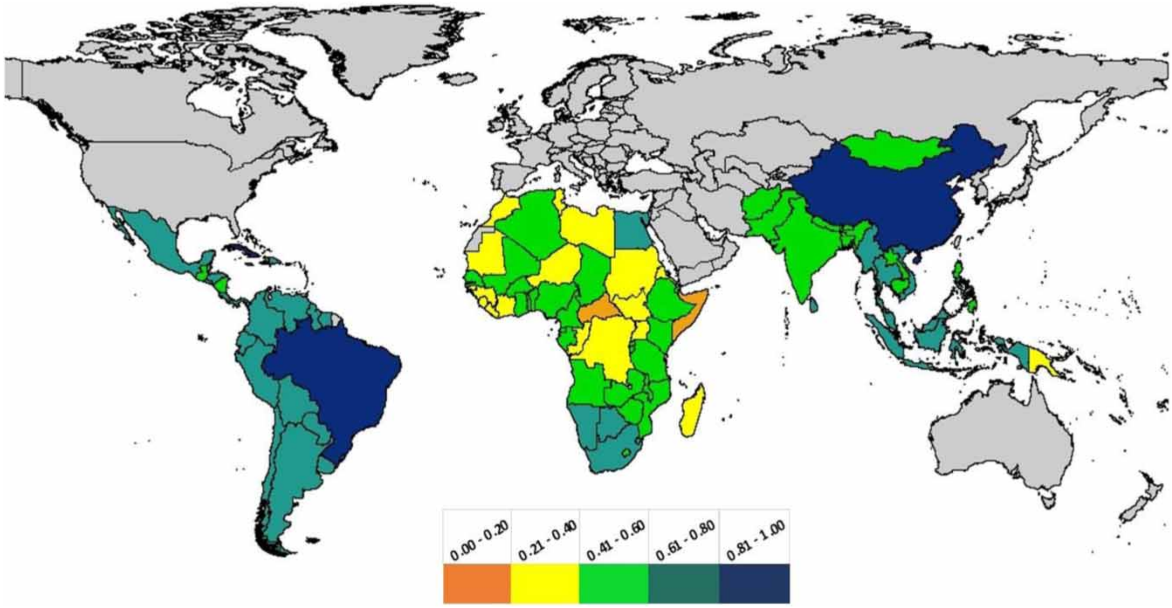


**Fig. 3** | Spatial distribution of the socioeconomic index scores at the national level.

Pacific) and Brazil, Barbados and Saint Lucia (LAC) obtained the highest scores (>0.80). Resuts also indicate that several countries obtained better socioeconomic index scores compared to biophysical index scores.

### 3.4. Determinants of water security

Results of the multicollinearity test revealed the presence of statistically strong correlations (CC >0.75) among some of the independent variables. Strong correlations were observed between the HDI and GDP per capita, HDI and governance, and HDI and female primary completion rate. Therefore, HDI was excluded from the independent variables. The table with the results of the multicollinearity test is not shown in the manuscript.

Results of the Pearson correlation analysis between the WSI, socioeconomic and biophysical sub-indices and the independent variables indicate the presence of statistically significant correlations between some of the independent variables and the dependent variables (Table 4). GDP per capita and percentage of urban population had statistically significant correlations in all regions, governance had statistically significant correlations in the Asia-Pacific region and female school completion rate had statistically significant correlations in the LAC region (Table 4). ODA-WSS had very low and non-statistically significant correlations with the WSI and sub-indicators (Table 4). Results also revealed that the socioeconomic sub-index had statistically significant correlations with several independent variables across all the regions (Table 4).

Results of the correlation between all the independent variables and each dependent variable revealed that the correlation coefficient (CC) between them ranged from 0.25 to 0.50, 0.25 to 0.45 and 0.25 to 0.39 for Africa, Asia-Pacific and LAC regions (Table 4). Figure 4 shows a scatter plot between GDP per capita and WSI for Africa and Asia-Pacific regions and female primary school completion rate and WSI for the LAC region. We observe a non-linear relationship between GDP per capita and the WSI (Figure 4(a) and (b)) and a linear relationship between female primary school completion rate and WSI (Figure 4(c)).

Results of the stepwise multivariate regression indicate that GDP per capita was the main determinant of water security in Africa and the Asia-Pacific regions, whereas female primary school completion rate was the key

**Table 4** | Pearson correlation coefficient between the WSI and the independent variables

| | | Independent variables | | | | | |
|---|---|---|---|---|---|---|---|
| **Region** | **Indicator** | **Governance** | **GDP per capita** | **ODA-WSS** | **School completion** | **Urban population** | **All variables combined** |
| Africa | Biophysical | 0.00 | 0.099 | 0.03 | 0.00 | **0.18** | **0.25** |
| | Socioeconomic | **0.38** | **0.29** | 0.01 | **0.22** | **0.04** | **0.50** |
| | **WSI** | 0.12 | **0.35** | 0.03 | 0.07 | **0.20** | **0.39** |
| Asia-Pacific | Biophysical | 0.01 | 0.09 | 0.20 | 0.00 | 0.09 | 0.25 |
| | Socioeconomic | **0.43** | **0.35** | 0.02 | 0.08 | **0.26** | **0.45** |
| | **WSI** | **0.19** | **0.34** | **0.18** | 0.00 | **0.36** | **0.44** |
| LAC | Biophysical | 0.03 | 0.02 | 0.05 | **0.15** | 0.06 | 0.25 |
| | Socioeconomic | 0.08 | **0.17** | 0.00 | **0.17** | **0.13** | 0.33 |
| | **WSI** | 0.03 | **0.20** | 0.01 | **0.25** | **0.11** | **0.39** |

Values in bold indicate statistically significant relationship at 5% significance level ($\alpha = 0.05$).

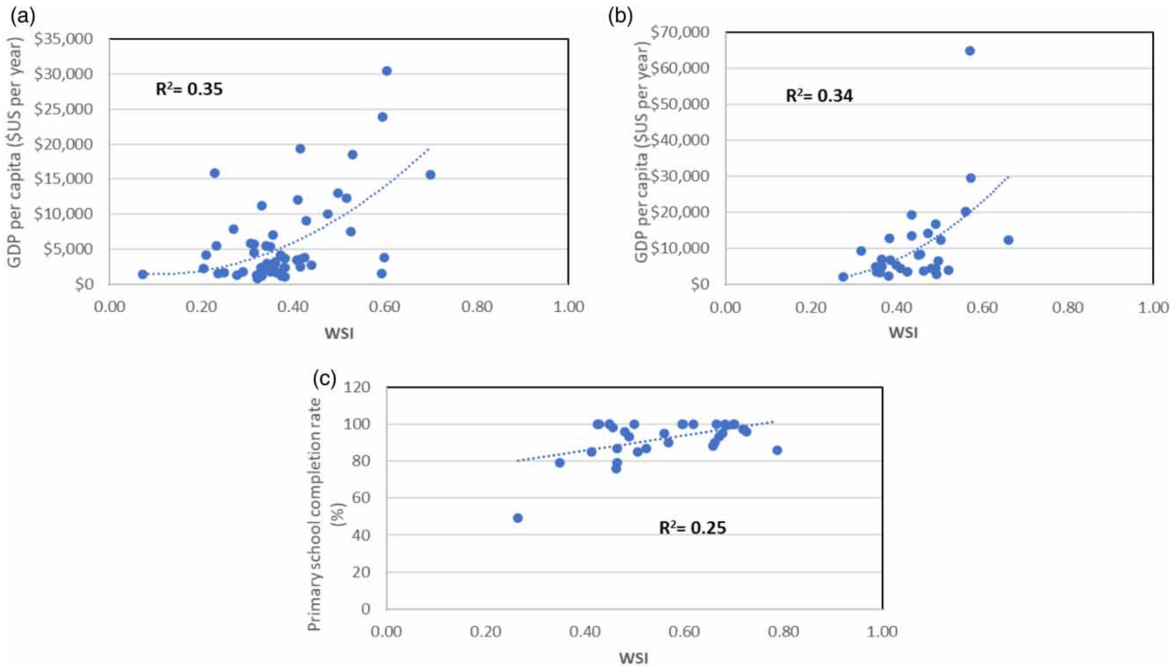


**Fig. 4** | Scatterplot between GDP per capita and the WSI for (a) Africa and (b) Asia-Pacific, and (c) scatterplot between school completion and the WSI for LAC.

determinant in the LAC region (Table 5). Among the independent variables, GDP per capita contributed 38 and 39% of the total variance in the WSI scores in Africa and the Asia-Pacific regions, respectively, whereas female primary school completion rate contributed 29% of variance in the WSI scores in the LAC region (Table 5). Results further show that governance was the main determinant of socioeconomic sub-index in Africa and the Asia-Pacific regions contributing 33 and 34%, respectively, of the total variance for this index in these regions

**Table 5** | Determinants of water security (stepwise multivariate regression).

| Indicator | Region | Variable | Regression coefficient ($R^2$) | Adjusted $R^2$ | *t*-statistic | *F*-value | *p*-value |
|---|---|---|---|---|---|---|---|
| WSI | Africa | GDP per capita | 0.38 | 0.35 | 3.29 | 24.58 | 0.00 |
| | Asia-Pacific | GDP per capita | 0.39 | 0.33 | 3.22 | 10.38 | 0.01 |
| | LAC | School completion | 0.34 | 0.29 | 2.82 | 7.23 | 0.00 |
| Socioeconomic index | Africa | Governance | 0.33 | 0.32 | 5.06 | 25.57 | 0.00 |
| | Asia-Pacific | Governance | 0.34 | 0.31 | 3.69 | 13.59 | 0.00 |
| | LAC | School completion | 0.24 | 0.20 | 2.97 | 8.83 | 0.01 |

(Table 5). Female primary completion rate was the main determinant of the socioeconomic sub-index in the LAC region contributing 24% of the total variance for this index (Table 5). Finally, average ODA-WSS disbursement were calculated as \$5.5, \$20 and \$5 per capita for Africa, Asia-Pacific and LAC, respectively.

## 4. DISCUSSION

In-line with a need to compute a water security metric considering climate risk and environmental conditions, this study developed a new composite WSI to assess water security at a national scale in three developing regions. Our results reveal a strong coupling between the biophysical and socioeconomic sub-indicators which have an overall impact on the WSI scores. For example, countries with high biophysical sub-index scores and low socio-economic sub-index scores obtain an overall low WSI score and vice-versa suggesting that both the biophysical and socioeconomic factors are critical for achieving water security. Notwithstanding, countries with low bio-physical sub-index score, but higher socioeconomic sub-index have the capacity to invest in water infrastructure to increase access to water services and alleviate the burden of water scarcity (Gunda *et al.*, 2019).

### 4.1. Water security index

Results from this study reveal widespread water insecurity in Africa and the Asia-Pacific regions which is consistent with results from other studies (Gain *et al.*, 2016). Results further show that most countries in the LAC region appear to be water-secure except Haiti, Guatemala and Nicaragua. However, the level of water security varies among countries with high-income countries being more water-secure than low-income countries which is also consistent with the results of a previous study of the region (Willaarts *et al.*, 2014). The WSI scores obtained in the LAC region are comparable to scores obtained in a similar study of the region (Mohammadpour *et al.*, 2019). However, it is worth highlighting the challenge of comparing composite index scores obtained from different studies due to differences in weights and aggregation methods used in calculating the metrics in each study. The results also show that countries with the lowest WSI scores (Afghanistan, Haiti, South Sudan and Somalia) have experienced prolonged political crisis, suggesting that peace and security could be an important dimension to consider in future water security assessment as earlier highlighted (Doeffinger *et al.*, 2020). Taking together, countries that exhibit better governance, higher HDI and GDP per capita performed better with higher WSI scores than countries with poor governance and lower HDI and GDP per capita.

### 4.2. Biophysical sub-index

Results revealed that countries in the Central African sub-region and Latin America had moderate to high biophysical index scores. This may be attributed to abundant water resources availability from the Congo and Amazon basins, high EVI scores and low vulnerability and exposure to climate risk. High water availability and EVI scores may be attributed to high annual rainfall over both basins and the provision of ecosystem services such as water quality regulation to countries in these sub-regions. Notwithstanding, studies from both sub-regions have revealed an increasing trend in water pollution and environmental degradation attributed to urbanisation and mining activities (Rakotondrabe *et al.*, 2018; Nathaniel *et al.*, 2021). On the other hand, several countries in Africa, Asia-Pacific and the Caribbean obtained low biophysical index scores. These low scores may be attributed to low water availability resulting from low annual rainfall caused by climate change, variability, and high vulnerability and exposure to climate-induced disasters. In fact, several studies have shown climate change and variability as key constraints to water security in East Africa (Thomas *et al.*, 2020), Asia-Pacific (Tang, 2019) and the Caribbean (Reyer *et al.*, 2017). Groundwater depletion has also been identified as a major threat to water security in India (Jain *et al.*, 2021). In fact, countries in these regions have been affected by devasting droughts and cyclones in recent years which reflects the high vulnerability and exposure to climate risk.

### 4.3. Socioeconomic sub-index

Results of the socioeconomic index indicate medium to high scores for most countries in the Asia-Pacific and the LAC regions, whereas several countries in Africa obtained low scores. Results further show strong spatial disparity in WSI scores among African countries which is consistent with results from other studies (Gain *et al.*, 2016). This highlights the need to level-up development initiatives in Africa to ensure that no country is left behind in terms of achieving water security and other SDGs as stipulated in the United Nations Agenda 2030. The low socioeconomic sub-index scores also reflect the low implementation of IWRM across the three regions. For example, in the Asia-Pacific region, only China and Samoa have an implementation rate >70%; in the LAC region, only Brazil has an implementation rate >50% and in Africa, only Benin, Cape Verde, Mauritius, Morocco and South Africa have implementation rates >60%. The low implementation of IWRM in developing regions can be attributed to numerous compounding factors such as limited skills and capacity, lack of financial resources, weak governance, limited stakeholder participation, fragmented institutions and lack of coordination between them (Malaza & Mabuda, 2019).

### 4.4. Determinants of water security

By exploring the determinants of water security, results from this study show that all the independent variables produced positive and statistically significant, albeit weak to moderate correlations with the WSI. The results are consistent with those from previous studies highlighting governance, female primary school completion rate and GDP per capita as key factors for achieving water security (Hinojosa *et al.*, 2017; Ding *et al.*, 2019). In fact, it has been reported that good governance can enhance the capacity of countries to develop and implement policies and regulations that can enhance water security (Nathaniel *et al.*, 2021). Among the independent variables analysed, GDP per capita had the strongest correlation with water security which is also consistent with results from a previous study (Yuan & Lo, 2020). From the results obtained, it is logical to suggest that the low WSI obtained by most countries in sub-Saharan Africa may partly be attributed to low GDP per capita which limits countries' capacity to invest in water infrastructure to increase access to water services. In fact, several studies have identified low economic capacity and weak governance as key constraints to water security in developing regions (Ding *et al.*, 2019; Mutschinski & Coles, 2021). While several studies assessing water security at local scale have identified income as an important determinant of household water security (Hailu *et al.*, 2020; Bacon *et al.*, 2021).

Results also show female primary school completion rate as the main determinant of water security in the LAC region which is also consistent with results from other studies (Gomez *et al.*, 2019; Adil *et al.*, 2021). This suggest that ensuring more girls of relevant age groups complete primary school is critical to enhancing water security in developing regions. This is very important given the role of girls and women as key agents in obtaining water for their families and communities. Better education for girls and women can lead to more awareness on the sources of household drinking water contamination and how to prevent it (Cassivi *et al.*, 2021), as well as enhance the knowledge and willingness of women and girls to participate in water governance processes (Bhattarai *et al.*, 2021), thereby supporting policies aimed at ensuring sustainable water resource management (Okumah *et al.*, 2020). This study provides empirical evidence on the link between gender and education and water security which has so far been lacking in contemporary research on water security as recently highlighted (Shah, 2021).

Results from this study also revealed that ODA-WSS had a low and statistically non-significant relationship with the WSI in our target regions. This is consistent with results from other studies particularly in Africa (Nkiaka *et al.*, 2021a). The low correlation between the WSI and ODA-WSS may be attributed to low ODA-WSS per capita which appear to have a negligible impact on water security. However, correlation was slightly stronger in the Asia-Pacific region (0.18) where average ODA-WSS was highest ($20 per capita) compared to Africa and LAC regions where average ODA-WSS were as low as $5.5 and $5 per capita, respectively. This suggest that increasing average ODA-WSS per capita may have a positive knock-on effect on water security in developing regions. However, we wish to caution that increasing average ODA-WSS per capita without addressing structural challenges such as poor governance may not substantially enhance water security in these regions.

## 5. STUDY LIMITATIONS

Methods used in this study are limited by the choice of variables due to data availability, weights assigned to the different variables and aggregation methods used. It is important to note that there is no consensus among scholars on the best method for assigning weights or aggregating variables when developing composite indicators because each method has its merits and demerits with no one-size-fits-all approach. Furthermore, the water availability variable does not consider other water sources such as desalinated water which may be used to increase water availability in water-scarce regions such as North Africa. In addition, the composite indicator developed here provides information on the state of water security at a given time and cannot be used for future projections. Nevertheless, the index scores can be used to guide future water policy and funding decisions. The low to moderate ($R^2$) values obtained between the independent variables and the WSI suggest that beyond the factors identified, there could be other factors impeding water security in the studied regions, therefore, results from this study should be regarded with caution.

## 6. CONCLUSIONS

The objectives of this study were to develop a new metric to assess water security at the national scale considering climate risk and environmental conditions and to use this metric to explore the determinants of water security. Geospatial techniques were used to reveal the spatial heterogeneity and patterns in water security among different countries in the regions studied which can be useful to support targeted policies for highly water-insecure countries and sub-regions. Results from the study show that Africa and Asia-Pacific are the most water-insecure regions, whereas LAC appears to be the most water-secure region. Results also revealed that GDP per capita, female primary completion rate and governance are important determinants of water security in the regions studied. As such, regions with high scores in governance, GDP per capita and female primary school completion rate had higher WSI scores than regions with poor governance, low GDP and low female primary school completion rate.

Results further revealed that countries endowed with abundant water resources with low socioeconomic factors had low WSI scores because of the lack of the economic capacity to enhance access to this vital resource. Results therefore suggest that enhancing economic growth, improving governance and increasing access to primary education particularly for the girl child can substantially reduce water insecurity. There is equally a need for development partners to review and increase ODA-WSS per capita as this may have a positive impact on water security.

By establishing the status of water security and its determinants at a national scale, incremental and progressive actions may be implemented to reduce water insecurity by the 2030 target for SDGs achievement. This is one of the first studies to use empirical data to demonstrate the link between female school completion rate and water security. This paper contributes to contemporary debates on the role of gender and education inequalities on water security, aid effectiveness, water security and the factors undermining the achievement of SDG6 in developing regions. Results from this study have practical implications with regards to the allocation of ODA-WSS to developing regions and the urgent need to enhance access to primary education for girls of relevant age groups as one of the approaches to enhance water security in developing regions.

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## CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest in this study.

## DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (GDP per capita, www.data.worldbank.org; water and sanitation official development assistance, www.data.worldbank.org; primary school completion rate, www.data.worldbank.org; Governance (Government effectiveness index), WGI 2021 Interactive > Home (worldbank.org); urban population, www.data.worldbank.org; Human Development Index, Latest Human Development Index Ranking | Human Development Reports (undp.org).

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