Access to Water-Related Services Strongly Modulates Human Development

Amorocho-Daza, H.; van der Zaag, P.; Sušnik, J.

DOI
10.1029/2022EF003364

Publication date
2023

Document Version
Final published version

Published in
Earth's Future

Citation (APA)
Amorocho-Daza, H., van der Zaag, P., & Sušnik, J. (2023). Access to Water-Related Services Strongly Modulates Human Development. *Earth's Future*, *11*(4), Article e2022EF003364. https://doi.org/10.1029/2022EF003364

AGU ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2022EF003364

Key Points:

- Human development is correlated to access to water services and freshwater variability, yet not statistically linked to large water storage
- Water variables are long-term predictors of human development (2000–2017)
- Causality analyses indicate that water and human development are mutually interdependent

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

H. Amorocho-Daza,
ham001@un-ihe.org

Citation:

Amorocho-Daza, H., van der Zaag, P., & Sušnik, J. (2023). Access to water-related services strongly modulates human development. *Earth's Future*, *11*, e2022EF003364. https://doi.org/10.1029/2022EF003364

Received 17 NOV 2022
Accepted 18 MAR 2023

Author Contributions:

Conceptualization: P. van der Zaag, J. Sušnik
Data curation: H. Amorocho-Daza
Formal analysis: H. Amorocho-Daza, J. Sušnik
Investigation: H. Amorocho-Daza
Methodology: H. Amorocho-Daza, J. Sušnik
Project Administration: J. Sušnik
Resources: J. Sušnik
Software: H. Amorocho-Daza
Supervision: P. van der Zaag, J. Sušnik
Visualization: H. Amorocho-Daza
Writing – original draft: H. Amorocho-Daza, J. Sušnik

Access to Water-Related Services Strongly Modulates Human Development

H. Amorocho-Daza[1], P. van der Zaag[1,2], and J. Sušnik[1]

[1]Land and Water Management Department, IHE Delft Institute for Water Education, Delft, The Netherlands, [2]Water Management Department, Delft University of Technology, Delft, The Netherlands

Abstract Water enables health, education, and economic well-being opportunities for humanity. Access to basic water and sanitation services, freshwater variability, and water storage are some of the dimensions that may impact on human development worldwide. Yet few studies quantitatively explore the relationship between water and human development. This study uses a statistical approach to quantify the Water-Human Development relation in a global sample, both in terms of correlation and causality between variables. Correlation is established using a multiple linear regression approach, while causality is explored by implementing the multi-spatial convergent cross mapping technique. Our study finds strong interdependence between water-related variables and human development globally. Access to water services positively influences the Human Development Index (HDI), seasonal variability of freshwater resources restricts it, and large water storage is not significant. The analysis is robust between 2000 and 2017, and implies that a 1% increment in a country's HDI is associated with a 1.3%–3.2% increment in water and sanitation access. Causal analyses show strong coupling, suggesting positive feedback between access to water services and HDI that could be exploited. Reaching Sustainable Development Goal 6 requires closing the water and sanitation access gaps while addressing freshwater variability challenges. This will result in global human development benefits.

Plain Language Summary This research explores the relation between water dimensions and human development across the world. To do so we used publicly available global datasets of international organizations in the period between 2000 and 2017. Statistical tools were used to determine the strength and causality in the relation between water and development. We found that access to drinking water and sanitation services are deeply interrelated with human development. However, heavily marked dry and wet seasons represent a significant threat for human development. Interestingly, we also encounter that neither the density of large water reservoirs in a country nor the amount of stored water per person in a country affect human development in a significant way. Our results evidence that raising a country's water and sanitation coverage by around 2% is tied to a 1% increase of human development in the long run. More efforts are needed to prevent the negative effects of floods and droughts in countries with high water variability. Evidence shows that to have access to water rather than just store it represents the most benefit for people across the globe. Therefore, to prioritize access to basic water services will bring long term benefits for human development worldwide.

1. Introduction

The human development discussion explores the conditions of living that promote human life to flourish (Ranis et al., 2005). An influential definition of human development is "a process of enlarging people's choices" (UNDP, 1990, p. 10). It implies that the end of development is human well-being rather than economic growth. Water is essential for human development because it contributes to human well-being, expanding human capabilities and choice by contributing to human health and enabling the ability to undertake productive activities (Chenoweth, 2008; Mehta, 2014). Without access to safe drinking water and sanitation services there can be limits on health, food, dignity, and well-being. In short, the full enjoyment of life is restricted under water shortage (UN General Assembly, 2010; WHO, 2003).

Water supply and sanitation infrastructure have been widely recognized as a pre-condition for development due to their connection to quality of life, health, and wealth of human communities (Arimah, 2017). Personal access to water supply and sanitation is essential for guaranteeing basic human needs (e.g., direct consumption, food preparation, sanitation, and hygiene) (Chenoweth, 2008). Still, it is estimated that around 0.84 and 2.3 billion people lack basic drinking water and sanitation services, respectively (WHO & UNICEF, 2017). To address this,

Writing – review & editing: H. Amorocho-Daza, P. van der Zaag, J. Sušnik

the UN 2030 Agenda includes Sustainable Development Goal (SDG) 6: "Water and Sanitation for all" that aims to reach, among others, universal access to basic water services (UN General Assembly, 2015). However, the goal is currently off-track and several societal efforts and transformations are needed to reach it (Sadoff et al., 2020).

The lack of access to water, and sanitation services worldwide is a societal burden (Hutton & Chase, 2016). Poor water and sanitation services are estimated to account for 3.3% of the deaths and 4.6% of the health-related lost years (i.e., disability-adjusted life years -DALYs) worldwide (WHO, 2019). These figures are even more worrying for children under 5 years, accounting for 13% and 12% of the global deaths and DALYs of this group (WHO, 2019). It is estimated that nearly 1.6 million deaths and 105 million DALYs are preventable annually with better water, sanitation and hygiene (WASH) services (Prüss-Ustün et al., 2019).

The health related impacts of poor water and sanitation services extend to other human wellbeing dimensions such as education and income. Children are a priority group in this dimension. Child undernutrition is a condition strongly related to diarrheal disease and evidenced in features such as stunting (Checkley et al., 2008; Victora et al., 2008). There is strong evidence which indicates that child undernutrition has long lasting effects. Negative impacts are evident not only in shorter adult height, but also impact human capital negatively (i.e., in terms of lower school attendance, reduced adult income). Intergenerational effects are particularly worrying (i.e., decreased offspring birthweight) (Victora et al., 2008). Evidence suggests that child undernutrition follows a causal pathway that is driven not only by inadequate diets, but also by fecal contamination of domestic environments (Humphrey, 2009). Fecal contamination is the root cause of diarrhea and gut health disorders (i.e., environmental enteropathy) during childhood, and both issues are evidently linked to poor access to sanitation and handwashing (Humphrey, 2009; Ngure et al., 2014). Therefore, the health benefits derived from improved access to basic water and sanitation services may have long-lasting positive impacts in terms of educational and economic benefits, especially for children.

The economic costs of the lack of access to basic water and sanitation services are extensive. The economic burden associated to poor water and sanitation is estimated in 1.5% of the global GDP (WHO, 2012). Yet, some reports suggest that impacts can reach 7% of the GDP in countries that face serious water and sanitation related issues (The World Bank, 2008). Estimates of the capital costs required to reach universal access to basic services are 28.4 billion per year (ranging between US$13.8 to US$46.7 billion), this is equivalent to merely 0.1% (range 0.05%–0.16%) of the global GDP during the 2015–2030 period (Hutton & Varughese, 2016). As such, water investments are expected to be highly cost-effective. Time savings and health benefits are expected to be 11 times greater than the monetary resources to fund water infrastructural improvements (Banerjee & Morella, 2011). These benefits are likely to relate to overall human development indicators. Research suggests a strong relation between access to drinking water and the Human Development Index (HDI) (Sušnik & van der Zaag, 2017) and GDP per capita (Fukuda et al., 2019).

Severe hydroclimatological conditions (e.g., droughts and floods) have been highlighted as restricting factors for human wellbeing. High seasonal rainfall variability is related to poverty, and anomalously dry/wet conditions restrict economic growth (Brown & Lall, 2006; Brown et al., 2013). It has been argued that dams play an important role in dealing with hydroclimatological variability, and therefore are development mediators (Grey & Sadoff, 2007; Tortajada, 2014). Thus, it has been proposed that water storage per capita (e.g., m^3 $capita^{-1}$) can act as a proxy for resilience to droughts and floods, as well as a determinant factor for economic prosperity and development (Grey & Sadoff, 2007; Hall et al., 2014). However, this approach has received criticism for being reductionist and for misinforming policy recommendations (Zeitoun et al., 2016).

Little research has quantitatively explored the relation between water and development (Brown & Lall, 2006; Hall et al., 2014; Sušnik & van der Zaag, 2017). Previous efforts have limitations both in terms of number of water related predictors, and because they have mostly relied on narrow indicators that account for "development" via income (i.e., GDP per capita) without considering other human-wellbeing dimensions. UNDP's HDI represents a more comprehensive development indicator, as it considers the dimensions of health and education, in addition to sufficient income. Yet, the explicit relationships between the HDI and water-related variables needs further exploration. For instance, often water supply is the focus, while access to sanitation facilities is glaringly overlooked in analyses (e.g., Fukuda et al. (2019)). As a further limitation, the joint effect of water supply, sanitation, hydroclimatology, and water storage, remains unexplored, representing a significant opportunity of knowledge advance.

In light of these previous shortcomings, this study aims to fill these gaps, and therefore represents a novel analysis which hopes to lead to new insight on the role of water supply, sanitation, hydroclimatology, and water storage as likely contributing factors to human development. These limitations are addressed in this study by identifying the joint impact of various water-related factors on human development using a cross country analysis at global scale covering the period 2000–2017. A robust statistical approach, also often overlooked in previous work, including a multiple linear regression model as well as causality analysis evaluation are employed, demonstrating the combined effect of water infrastructure (supply, sanitation and storage) and hydroclimatological conditions (seasonal and interannual water availability) on human development globally. The paper aims to demonstrate the value and impact of investing in water and sanitation expansion to promote human development.

2. Materials and Methods

This section provides a description of the data sources and the proposed statistical analysis.

2.1. Data

The Human Development Index (HDI) is the output variable of the present study, it is used as a human development proxy (UNDP, 1990). Established by the United Nations Development Programme (UNDP) in 1990, the HDI is constituted by three equally weighted dimensions measured at country level: Longevity (i.e., life expectancy at birth), knowledge (i.e., mean years of schooling, expected years of schooling) and living standards (Gross National Income (GNI) per capita) (UNDP, 1990). A high HDI score aims to account for a long and healthy life, with access to education, and a decent standard of living, thus being subjectively "better" than lower HDI scores. UNDP reports the index on a yearly basis as a long-term estimate of global human development progress (UNDP, 2019). Harmonized HDI time series are available since 1990 and can be found in UNDP (2023). A detailed account of the index estimation can be found in the UNDP (2019) accompanying Technical Note 1.

For this paper, six water related response variables were classified into three dimensions: Access, Storage and Hydroclimatology. The Access dimension includes access to basic drinking water and sanitation services. In essence, a basic drinking water service come from sources that have the potential to deliver safe water, while basic sanitation facilities hygienically separate excreta from human contact (WHO & UNICEF, 2017). Access is measured as "people using at least basic drinking water/sanitation services (% of population)," as defined by the WHO/UNICEF Joint Monitoring Programme (JMP) (2017). It is worth noting that this indicator refers to the coverage in terms of basic, rather than safely managed water and sanitation services, the later being a more comprehensive indicator taking into account dimensions of accessibility, availability and quality (WHO & UNICEF, 2017). In this paper, data on basic services (supply and sanitation) was used. This was done so as to be consistent through the period 2000–2017 which includes both the Millennium Development Goals (MDGs) and the updated SDGs.

The Storage dimension covers water storage per capita and reservoir density in a country. Water storage per capita is the amount of water that is stored in a country's reservoirs divided by its population (i.e., m^3/capita), as proposed by Grey and Sadoff (2007), and reservoir density is the number of reservoirs that exist per area unit within a country (i.e., #Reservoirs/km^2) as used by Tian et al. (2020). Data on dam capacity per capita, number of reservoirs and country area was obtained from the Food and Agricultural Organisation's (FAO) AQUASTAT database (FAO, 2021).

The Hydroclimatology dimension considers intra- and inter-annual blue water variability, that is water available in streams, lakes and aquifers (Lundqvist & Steen, 1999), and can be estimated using the coefficient of variation. Intra-annual variability accounts for the typical water variability *within* a year, for example, in terms of dry and wet seasons; while interannual variability accounts for water variability across years, for example, due to global phenomena such as El Niño Southern Oscillation (ENSO). Intra-annual (or seasonal) variability is defined as "the standard deviation of monthly total blue water divided by the mean of total blue water calculated using the monthly mean" (UNESCO IHP, 2013b); similarly, inter-annual variability is "the standard deviation of annual total blue water divided by the mean of total blue water from 1950 to 2010" (UNESCO IHP, 2013a). A summary of the data used is shown in Table 1.

2.2. Statistical Analysis

The statistical approach analyses both the correlation and the causality among water variables and human development. Table 2 summerizes the implemented methods as well as their corresponding time frames, variables and number of observations. Both aspects are described below.

2.2.1. Correlation Assessment

Correlation among variables was tested to identify significant HDI predictors. Statistical models are estimated based on a cross-country analysis for different years as detailed in Table 2. A correlogram for the studied variables

Table 1
Median (Range) of the Studied Variables for all Countries and Stratified by HDI Rank for the Year 2017 (UNDP, 2019)

			HDI rank countries' classification				Missing data
Dimension	Variables	All countries	Low	Medium	High	Very high	Country or region with missing data
Human Development	Human Development Index (HDI) (−)	72.7 (37.3.7–95.3)	48.7	61.2	74.4	87.1	None
	Number of countries	188	36	37	53	62	
Access	Drinking water coverage (% population)	95.6 (38.7–100.0)	64.3	82.5	95.6	99.9	Caribbean (2), Sub-Saharan Africa (2), Argentina
	Number of countries	183	34	37	51	61	
	Sanitation coverage (% population)	89.7 (7.3–100.0)	29.6	62.1	90.9	99.1	Caribbean (2), Sub-Saharan Africa (2), Argentina, Brunei Darussalam
	Number of countries	182	34	37	51	60	
Hydroclimatology	Interannual variability (−)	1.5 (0.6–4.9)	1.5	1.5	1.8	1.2	East Asia and Pacific (12), Caribbean (10), Sub-Saharan Africa (7), Cyprus, Moldova, Malta, Maldives
	Number of countries	155	33		29	39	54
	Seasonal variability (−)	2.3 (0.3–4.6)	3.3	3.1	2.3	1.2	East Asia and Pacific (12), Caribbean (10), Sub-Saharan Africa (7), Cyprus, Moldova, Malta, Maldives
	Number of countries	155	33		29	39	54
Storage	Dam capacity per capita (m^3/capita)	395.8 (1.7–33499.0)	128.8	555.3	361	552	East Asia and Pacific (20), Europe and Central Asia (15), Sub-Saharan Africa (15), Latin America and Caribbean (12), Middle East and North Africa (8), South Asia (4)
	Number of countries	114	22	20	30	42	
	Reservoir density (10^4 × Reservoirs/km^2)	1.1 (0.1–409.1)	0.8	0.6	1.7	1.7	Sub-Saharan Africa (12), East Asia and Pacific (10), Middle East and North Africa (6), Caribbean (5), Europe and Central Asia (4), Maldives
	Number of countries	150	28	27	46	49	

Note. The full list of countries (n = 188) is available in Supporting Information S1 (Table S1).

was estimated. Multiple linear regression models (ordinary least squares; OLS) were also examined, including all water-related variables and subsequently re-run to report only statistically significant water variables on human development. These models are a globally representative estimation valid at country scale for a particular year. Additionally, segmented multiple linear regression models were carried out according to the UNDP's human development categories (Table 3). This analysis was based on the approach proposed by Schell et al. (2007), who assessed the significance of health related determinants across different development categories (e.g., low, middle and high income countries). The correlation analysis was done initially on 2017 data.

The 2017 multiple linear regression model results were further analyzed in two ways. First, by estimating a regression model comparing the water-variable forecasted HDI with the actual HDI values. The model's prediction interval can be visualized along with a scatterplot of both variables to explore their proximity. And second, by estimating models to assess the water-human development for the period 2000–2016 and comparing these to the 2017 model to assess the long-term robustness of this approach. Rather than aiming to validate the 2017 model backwards, this analysis intends to explore the long-term water variables' significance in relation to human development, as well as the evolution of their coefficients over a long time span.

Visualization tools were used to improve analysis and understanding regarding the relationships between key water variables and human development. Dynamic and interactive 2D and 3D plots including color, size and time dimensions were developed to visualize variables such as seasonal variability as well as time-varying relationships between the variables (see the links in Figures 2–4 and Supporting Information S1). Several R packages such as ggplot2, gganimate, plot3D, and plotly were used for this purpose.

Table 2
Summary of the Statistical Analysis

Statistical analysis	Method	Year	Variables	Number of observations
Correlation	Correlation coefficient	2017	Human Development Index (HDI)	108 (countries that measure all the variables simultaneously)
			Drinking water coverage	
			Sanitation coverage	
			Interannual variability	
			Seasonal variability	
			Dam capacity per capita	
			Reservoir density	
	Multiple linear regression	2017	Human Development Index (HDI)	151 (countries that measure the significant variables simultaneously)
			Drinking water coverage	
			Sanitation coverage	
			Interannual variability	
			Seasonal variability	
			Dam capacity per capita	
			Reservoir density	
		2000–2016	Human Development Index (HDI)	138-155 (countries that measure all the variables simultaneously)
			Drinking water coverage	
			Sanitation coverage	
			Seasonal variability	
Causality	Multi-spatial convergent cross mapping (mCCM)	2000–2017	Human Development Index (HDI)	3,245 (a time series of the variables from 2000 to 2017)
			Drinking water coverage	
		2000–2017	Human Development Index (HDI)	3,237 (a time series of the variables from 2000 to 2017)
			Sanitation coverage	

2.2.2. Causality Analysis

To identify potential causality in the study of complex systems is both conceptually and technically challenging. To do this, Sugihara et al. (2012) developed convergent cross mapping (CCM) as a methodology to determine causality beyond correlation. CCM studies time series of paired variables which belong to a common dynamical

Table 3
Results of Statistical Models Linking Human Development to Water-Related Variables

			Country HDI rank classification			
Main categories	Predictor variables	All countries	Low	Medium	High	Very high
Access	Drinking water coverage	0.3500***	0.1573***	0.1151***	-	0.9952***
	Sanitation coverage	0.1963***	-	0.0925***	0.0952**	0.4957***
Hydroclimatology	Interannual variability	-	-	-	-	−1.8383**
	Seasonal variability	−4.4917***	−2.532***	-	-	-
Storage	Dam capacity per capita	-	-	-	-	-
	Reservoir density	-	-	-	-	-
Overall	Number of observations	151	31	37	51	52
	Significance	<0.0001	0.0013	<0.0001	0.0129	<0.0001
	R^2	0.831	0.3787	0.5631	0.1197	0.3501

Note. Shaded color intensities indicate the significance of regression coefficients. Red colors are negative correlations, blue is positive. Green indicates the number of observations and the strength of R^2. $^{**}p = 0.05$ $^{***}p = 0.001$.

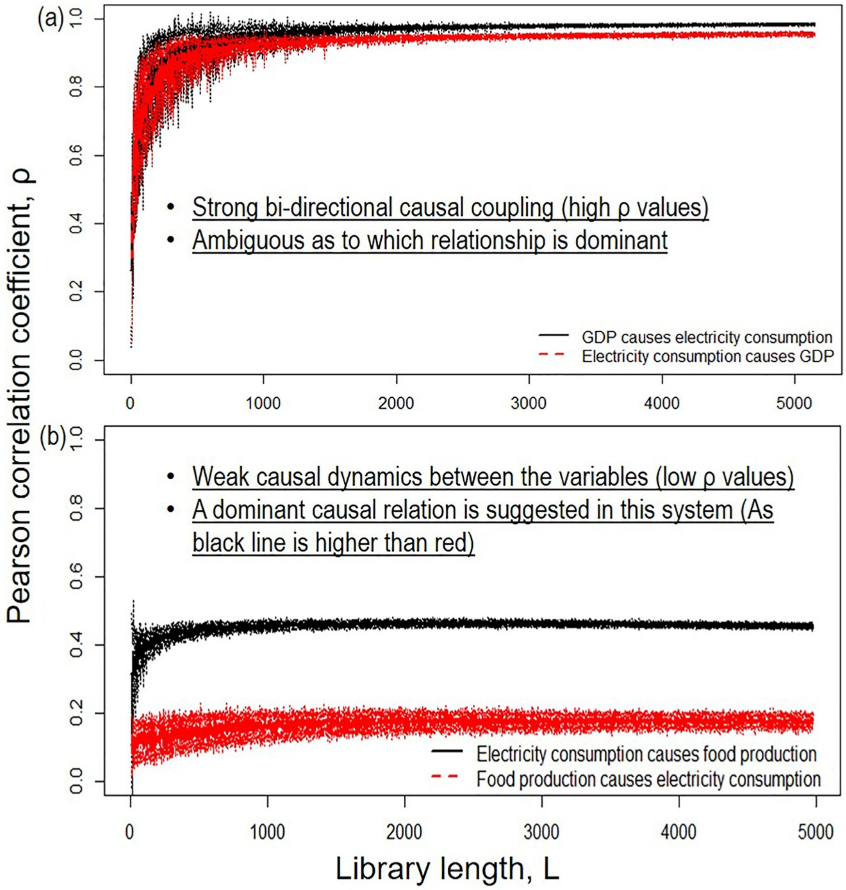

Figure 1. Examples of the application of the output from mCCM analysis. Panel (a) showing a system of GDP and electricity consumption; (b) a system of food production and electricity consumption. Panels (a and b) show contrasting causal dynamics within these two systems. See text for explanation and interpretation. Adapted from Sušnik (2018).

system and analyses causation by measuring the extent to which values of "Y" can reliably estimate states of "X", something that happens only if X is causally influencing Y (Sugihara et al., 2012). Predictability using CCM increases with the time series length (L). Clark et al. (2015) extended the CCM approach to multispatial CCM (mCCM) for contexts where the length of the time series is limited but spatial information is abundant. An important assumption of this approach is that separate observational plots being considered share similar dynamics and are not heavily influenced by stochastic noise. In this paper, the idea of the replicate observational plots in Clark et al. (2015) are represented by the reporting countries for which observed data are available (i.e., replicate plots here equals reporting countries).

In brief, mCCM tests to determine the dominant causal direction (if any) in a system of two variables "X" and "Y." It tests to see whether X can be said to cause changes in Y or vice-versa, or if such a distinction can even be made due to very close coupling between the two causal directions (i.e., X causing Y, or Y causing X). Results are given over a "library length", L, and are reported using the Pearson correlation coefficient, ρ. Such causal forcing is determined on two conditions: (a) "when ρ is significantly greater than zero for large library length L"; and (b) ρ increases significantly with increasing L. These criteria are determined graphically resulting from the output of mCCM analysis (carried out in this paper using the "multispatial CCM" package in R (Clark, 2022)). An example is used here to guide interpretation of the graphs shown later in this paper. In Figure 1, two contrasting examples from Sušnik (2018) are shown. The graphs in the current paper can be interpreted in the same way as those in Figure 1. Each graph in Figure 1 shows two lines (black and red), with one line being the results for the "X causes Y" direction, and the other line showing results for the "Y causes X" direction. The x-axis is the series length (called the library length, L), and the y-axis is the ρ value. Figure 1a shows a system comprising of gross domestic product (GDP) and electricity consumption. This figure suggests that there is a strong bi-directional causal relation between GDP and electricity consumption. Both criteria are fulfilled: ρ is >>0 and; the rise of ρ away from 0 is rapid with increasing L. Both directions (GDP causing electricity consumption—black line; electricity consumption causing GDP—red line; Figure 1a) rise rapidly to very similar "rho" values (~0.95). This indicates strong causal dynamics in this system, and makes statements regarding a dominant causal direction challenging. In contrast, Figure 1b shows a system comprising of food production and electricity consumption. Neither line (electricity consumption causing food production—black line; food production causing electricity consumption—red line; Figure 1b) rises very high above 0 (~0.45 maximum) indicating a weak causal relationship in this system. In addition, the black line rises (relatively) much higher then the red, suggesting that this relationship is the stronger in this system, driving the dynamics in this system. A more detailed technical description of the mCCM method can be sound Text S3 in Supporting Information S1, and a complete descriptive, mathematical, and algorithmic description of the CCM and mCCM methods are found in Sugihara et al. (2012) and Clark et al. (2015).

In this paper, variables are the water- and human-development variables. The causality analysis is performed at a global scale and aims to characterize the long-term causal relation, if any, between water and human development variables. Observational plots are reporting countries, and it is assumed that the dynamics within the water-development systems are broadly similar globally. Due to the large number of countries (observational plots), and the length of data available for each (2000–2017), the size of L in the causal analysis is >3,200 (Table 2), which will lead to good causal descriptive power, as descriptive power using mCCM increases with L (Clark et al., 2015). Sušnik and van der Zaag (2017) implemented the mCCM method to assess causality between human development and personal wealth and use of resources, where plots represent countries, as is the case in this paper. The present research uses this approach and implements the algorithm proposed by Clark et al. (2015) to assess causal relationships, if any, between access to basic water services and the Human Development Index (HDI). Hydroclimatological variables cannot be used for the causality analysis as are indices capturing the long-term water variability (i.e., they do not change on a yearly basis). The code used to implement the mCCM approach described in Clark et al. (2015) is linked to the article and freely available as open-source R code. In addition, the datasets used in this paper are all in the public domain, and can be found in Supporting Information S1 to this paper.

3. Results

This section presents the main insights from the correlation and causality analyses.

3.1. Correlation Between Water Variables and Human Development

Access to drinking water and sanitation, and hydroclimatology, are the most influential factors on human development (Figure 2). Results show strong positive correlation between drinking water access and HDI ($\rho = 0.84$), consistent with previous research (Fukuda et al., 2019; Sušnik & van der Zaag, 2017). There is an even stronger positive correlation between HDI and access to sanitation services ($\rho = 0.87$). Freshwater seasonal variability is negatively and strongly correlated with HDI ($\rho = -0.7$). This is compatible with and extends previous research, which focused solely on economic development variables (Brown & Lall, 2006; Brown et al., 2013).

Other water-related variables do not to show statistically significant relationships with human development. Freshwater interannual variability is not correlated with HDI globally, supporting and extending previous analyses (Brown & Lall, 2006). Water storage variables (i.e., dam capacity per capita and reservoir density) do not show a significant relationship with HDI nor seasonal variability.

3.2. Water Variables Are a Strong Predictor of HDI

A statistical model assessing the combined effect of water variables on development is proposed (see Table 3 and Equation 1). There is a significant and positive effect of drinking water and sanitation access on human development which is counterbalanced through the negative effects of freshwater seasonal variability at a global scale. Water storage variables do not have a significant effect on HDI. The three predictors have a strong effect on HDI at a global scale (Figures 3 and 4). There is a clear trend showing that countries with high access to water services and low freshwater seasonal variability have higher HDI scores than countries with lower access and higher seasonal variability.

10.1029/2022EF003364

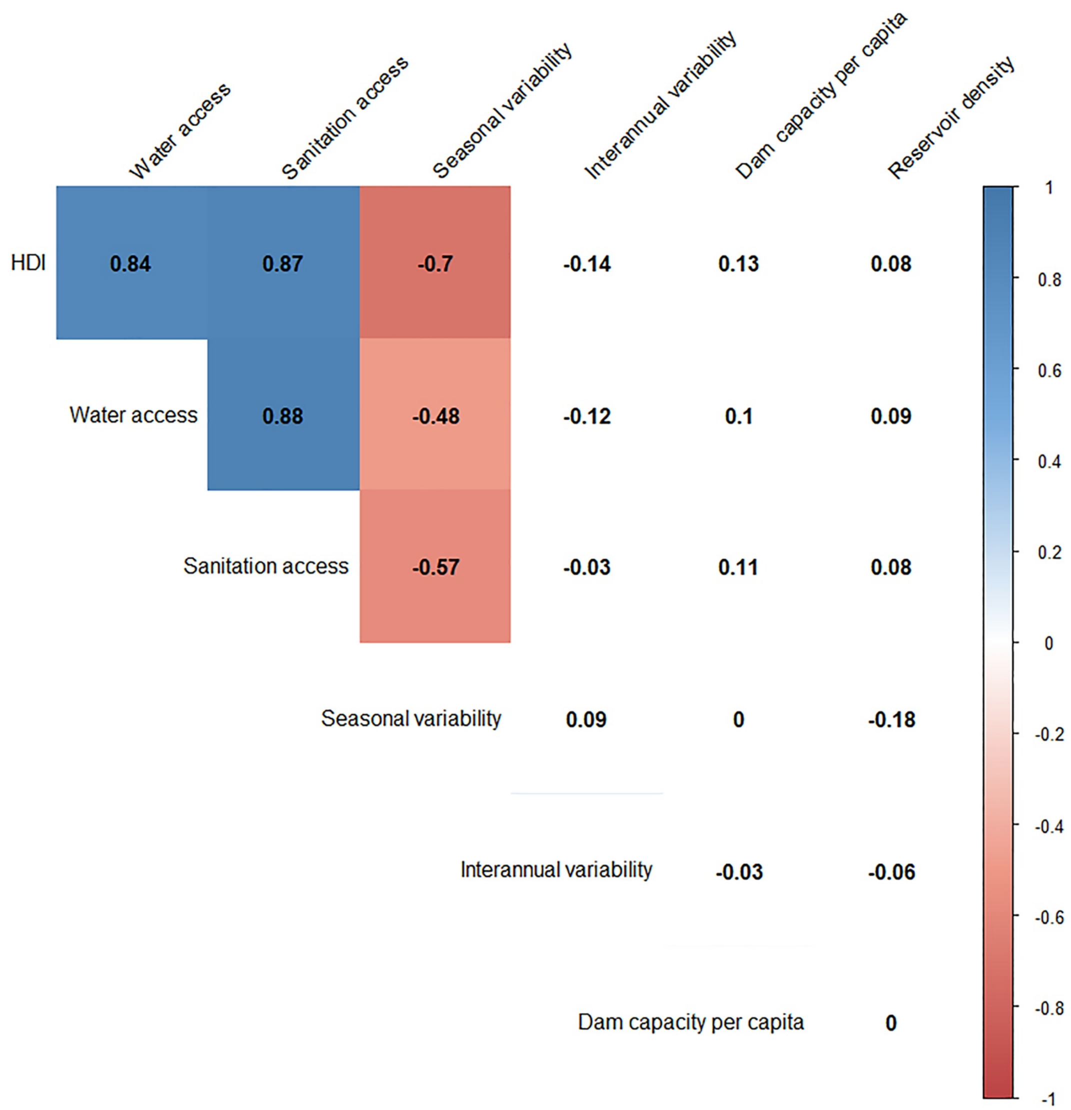

Figure 2. Correlogram of human development and water related variables. Significant relationships are colored ($p = 0.05$). Positive correlations are shown in blue, negative in red. The estimations were done using the Pearson coefficient for complete pairs of countries' observations ($n = 108$). A correlogram including scatterplots is also available in Supporting Information S1 (Figure S1).

Results show that the importance of water variables is not consistent across UNDP development categories (Nielsen, 2013) (Table 3). This means that the influence on HDI of water-related variables can differ across HDI categories. The dominant variables come from the "access" and "hydroclimatology" dimensions. Access to water and sanitation are significant at every development category and have a very strong combined effect in the global model. Regarding hydroclimatology, the most important variable related to HDI is seasonal variability when all countries are considered, and particularly for low development countries. Interannual variability is significant only for countries of very high human development. None of the water storage variables are significant (Figure 2, Table 3), neither when considering all countries, nor segmented by development category. These results strongly suggest that access to basic water and sanitation services, as well the modulating influence of intra-annual variability on freshwater resources, are influential determinants of HDI globally.

In 2017, the HDI score for a country, i, can be estimated using a multiple linear regression model that includes three water related variables as shown in Equation 1:

$$\begin{aligned} \text{HDI}_i = {} & 0.3500 \times \%\ \text{Access to drinking water}_i + 0.1963 \times \%\ \text{Access to sanitation}_i \\ & - 4.4917 \times \text{Seasonal variability}_i + 36.1806 \end{aligned} \quad (1)$$

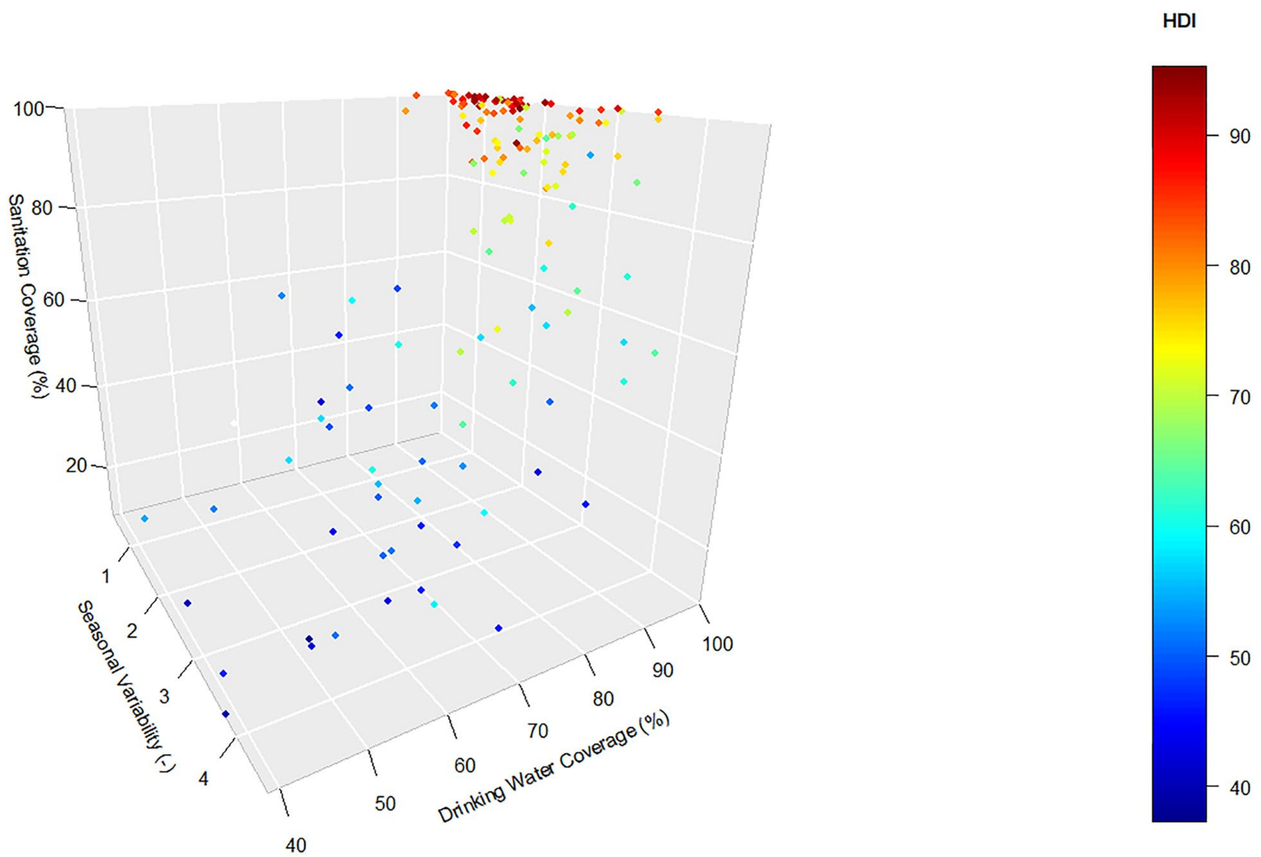

Figure 3. Water variables in space and HDI as a color variable. Countries with the lowest HDI scores generally have very low access to sanitation, relatively high seasonal variability and a wide spread of values for drinking water coverage. The cluster of the most developed countries (red dots) have virtually universal access to water and sanitation and generally low seasonal variability. An interactive version of this model is available online.

This model accounts for approximately 83% of the observed HDI variance worldwide. When the predicted HDI is compared with the reported HDI in 2017, a linear, unbiased, and strong relation is found (Figure 5 and Table 4). Results indicate that for the vast majority of countries the relation between the predicted and observed HDI is

Table 4
Linear Regression Model's Main Results With HDI Forecast as HDI Predictor

Main results of the model	
Number of observations	151
P-Value	<0.0001
R-squared	0.831
Root MSE	6.449
Coefficient	
HDI forecast (−)	0.9999
P-Value	<0.0001
Standard error	0.0369
95% Confidence Interval (Lowest, Upper)	(0.9269, 1.0729)

Note. The model is strongly significant, unbiased (as the coefficient is virtually 1 and the confidence interval includes 1), and can predict 83% of the observed HDI variance. The expected error of the model is ±6.4 percent points of the reported HDI score.

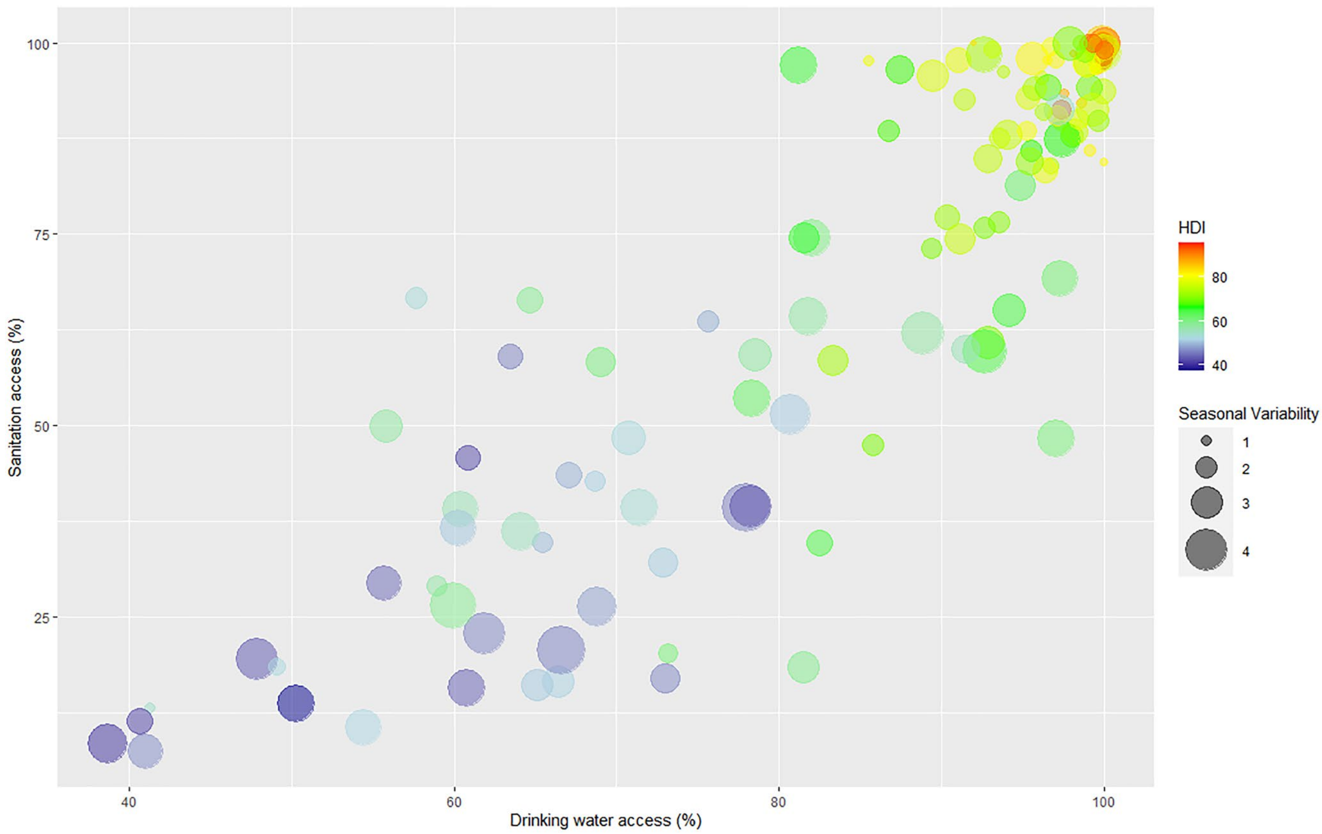

Figure 4. 2D scatter plot of drinking water and sanitation access with HDI as a color dimension and seasonal variability representing bubble size. A time-dynamic version of this model is available online. There is a clear pattern between access to drinking water and sanitation and HDI. Note that the least developed countries also have very high values for seasonal variability.

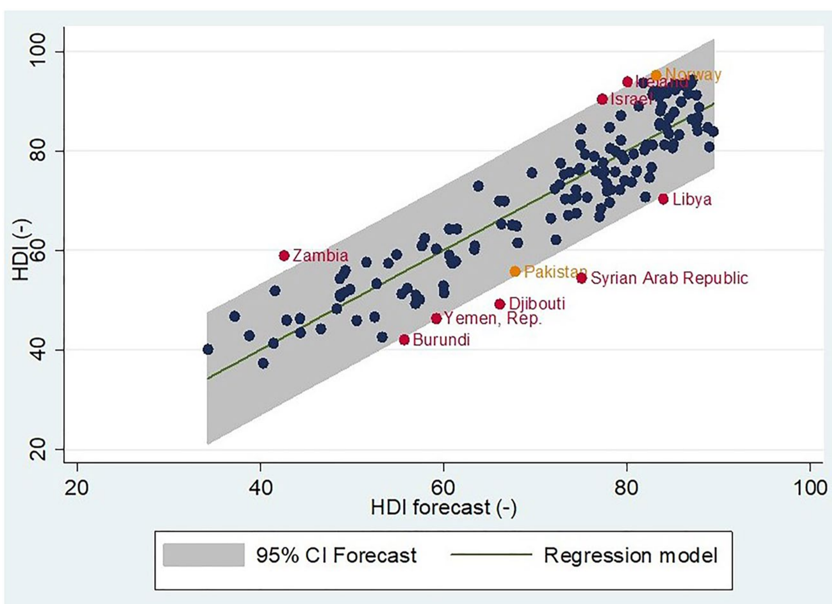

Figure 5. Observed against modeled HDI. Countries labeled in red are outside the 95% model prediction interval, countries labeled in orange are in the limit of the prediction interval. A mathematical description for the interval estimation is available in Supporting Information S1 (Text S2). A time-dynamic version of this model is available online.

statistically very strong ($R^2 = 0.831$, $p < 0.0001$), offering further support in favor of the link between HDI and water related variables.

There are countries that do not follow the trend. The top 10 countries with highest absolute errors are identified in Figure 5. Countries below the regression 95% prediction interval face other conditions negatively influencing their HDI scores. Indeed, five of these nations are classified as countries in state of "alert" according to the Fragile State Index (2022), implying that their economic, social, political and military circumstances (e.g., civil wars and authoritative regimes) put them in conditions of vulnerability to conflict or collapse (Graves et al., 2015). Conversely, countries such as Norway, Ireland, Israel and Zambia have higher HDI scores than predicted. Norway and Ireland had the first and third highest HDI scores in 2017, supporting the idea that countries at the most developed stages reach universal services coverage but keep improving HDI scores, reflecting the composition of the HDI (i.e., health, education and income). The case of Israel demonstrates an example of effective water management practices under challenging hydrological conditions (Siegel, 2017). The case of Zambia is striking. Despite high seasonal variability and poor water and sanitation access, these conditions have not seriously restricted the HDI score. Further research is needed to understand the underlying policies and programs that have allowed this to happen in the identified countries as outliers.

3.3. Temporal Dynamics Between Water Variables and HDI

To demonstrate a long-term relationship between water-related variables and development, multiple linear regression models were developed for each year in the period 2000–2016, complementing the 2017 model (Tables 3 and 5). A dynamic scatter plot complements the statistical results. Results confirm the significance and predictive power of water related variables as HDI predictors between 2000 and 2017. The model is highly significant for every year ($P < 0.0001$), and R^2 ranges from 0.843 to 0.879 (Table 5). An exploration of the coefficients shows that the estimated values for the 2017 global model are in the confidence interval for all years. This suggests that the model can help to understand long-term dynamics between water variables and human development. This also indicates that the dynamics in the system were stable over the period of analysis.

Some interesting insights are evident by analyzing the temporal dynamics of the statistical models. First, results show that the model is losing predictive power since 2007. R^2 decreased almost 0.05 points after 2007, possibly due to more countries reaching very high basic water services coverage and HDI scores (see Figure 4 accompanying animation). We hypothesize that at this stage, human development benefits from water and sanitation become marginal, rather being derived from other factors (e.g., schooling, healthcare). This is more evident when exploring Figure 5 accompanying animation, which shows that the countries of very high HDI move mostly in the upper direction, meaning that at that stage, water related variables loose predictive power for estimating HDI progress. Second, the effect of seasonal variability increases over the analysis period. The increasing negative effect of seasonal variability could be related to climate change factors (e.g., longer and more frequent droughts, more intense rainy seasons) that are becoming more difficult to manage. It could also be a symptom of a widening gap between countries of high development/low variability and low development/high variability. Third, the model constant increases year-on-year (Table 5). This may correspond to an average overall increase in the HDI score worldwide during the analysis period.

Drinking water and sanitation access coefficients are relatively constant over time. Taking into account the 2000 model, a 1% increase in HDI is associated with 1.84% joint increase in water and sanitation coverage. Similarly, to increase 1% of HDI using the 2017 model would require a 1.83% joint increase in water and sanitation services. This shows that the global effect of water and sanitation access on HDI is quantifiable and remarkably steady over the 21st century. There is strong statistical evidence to affirm that, accounting for the minimum and maximum values of the coefficients' confidence intervals, an average 1% increment in a country's HDI is associated with a 1.3%–3.2% joint country-level increment in water and sanitation access. These estimations are valid for the period 2000–2017 and serve as a quantitative reference for the likely development benefits that are associated with investments in water supply and sanitation coverage.

3.4. Causality Between Water Variables and Human Development

The analysis here focuses only on the water access variables, as the FAO values for seasonal variability are long-term estimates with only one observation, so cannot be used. Figure 6 shows the mCCM causality assessment results between HDI and access to water and sanitation. Results indicated by the very high and similar values of

Table 5
Multiple Linear Regression Models With Access to Drinking Water, Sanitation and Seasonal Variability as Predictors of HDI

Year			2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Number of observations			138	140	141	142	143	150	152	153	153	153	154	155	155	155	155	155	154	151
P-Value			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
R-squared			0.8639	0.8675	0.8669	0.8700	0.8719	0.8744	0.8778	0.8789	0.8773	0.8751	0.8714	0.8675	0.8693	0.8588	0.8512	0.8465	0.8431	0.8310
Root MSE			6.5673	6.4803	6.4495	6.3949	6.2810	6.1993	6.0609	5.9829	5.9610	5.9017	5.9203	5.9768	5.8883	6.1071	6.2312	6.3168	6.3831	6.4925
Predictor variables	Access to drinking water (%)***	Upper (CI)	0.4127	0.4055	0.3951	0.3907	0.3925	0.3888	0.3896	0.3919	0.3979	0.3998	0.4181	0.4260	0.4364	0.4557	0.4649	0.4807	0.4885	0.4950
		Coefficient	0.3172	0.3105	0.2984	0.2921	0.2929	0.2882	0.2880	0.2881	0.2910	0.2905	0.3051	0.3089	0.3182	0.3298	0.3335	0.3453	0.3498	0.3500
		Lower (CI)	0.2217	0.2155	0.2016	0.1936	0.1933	0.1876	0.1863	0.1844	0.1841	0.1812	0.1920	0.1919	0.2000	0.2039	0.2021	0.2098	0.2110	0.2049
	Access to sanitation (%)***	Upper (CI)	0.2915	0.3012	0.3112	0.3217	0.3238	0.3281	0.3287	0.3292	0.3269	0.3217	0.3108	0.3053	0.3000	0.2920	0.2887	0.2815	0.2803	0.2825
		Coefficient	0.2250	0.2351	0.2441	0.2537	0.2557	0.2600	0.2606	0.2604	0.2569	0.2509	0.2385	0.2312	0.2258	0.2138	0.2078	0.1988	0.1963	0.1963
		Lower (CI)	0.1585	0.1689	0.1769	0.1857	0.1875	0.1919	0.1925	0.1917	0.1868	0.1801	0.1662	0.1570	0.1516	0.1356	0.1269	0.1161	0.1123	0.1101
	Seasonal variability (−)***	Upper (CI)	−2.2232	−2.1682	−2.1460	−2.1818	−2.1958	−2.2402	−2.3476	−2.4082	−2.4555	−2.4980	−2.6031	−2.6498	−2.7104	−2.8859	−2.9777	−3.1309	−3.2317	−3.2433
		Coefficient	−3.6397	−3.5330	−3.4982	−3.5176	−3.5030	−3.4851	−3.5617	−3.6008	−3.6409	−3.6683	−3.7736	−3.8201	−3.8595	−4.0738	−4.1854	−4.3504	−4.4624	−4.4917
		Lower (CI)	−5.0562	−4.8978	−4.8504	−4.8535	−4.8097	−4.7302	−4.7758	−4.7935	−4.8262	−4.8386	−4.9441	−4.9904	−5.0087	−5.2616	−5.3932	−5.5698	−5.6931	−5.7402
	Constant (−)***	Upper (CI)	37.2003	36.9745	37.6973	37.9554	38.0925	38.4851	39.0941	39.6658	40.2110	40.9573	41.1901	41.9382	41.8835	42.8924	43.7399	44.1308	44.4735	44.9975
		Coefficient	30.0376	29.9659	30.6433	30.8706	31.0486	31.5523	32.1991	32.7388	33.1812	33.8642	33.9388	34.6206	34.5531	35.1604	35.7278	35.8937	36.0505	36.1806
		Lower (CI)	22.8749	22.9574	23.5894	23.7858	24.0047	24.6194	25.3040	25.8118	26.1515	26.7712	26.6876	27.3029	27.2228	27.4285	27.7157	27.6566	27.6275	27.3637

Note. The tables shows the results of the model for the period 2000–2017. The number of observations, global significance, goodness-of-fit, mean error as well as the coefficients with their respective confidence intervals are reported for every year. ***Individual significance: *P*-value<0.01.

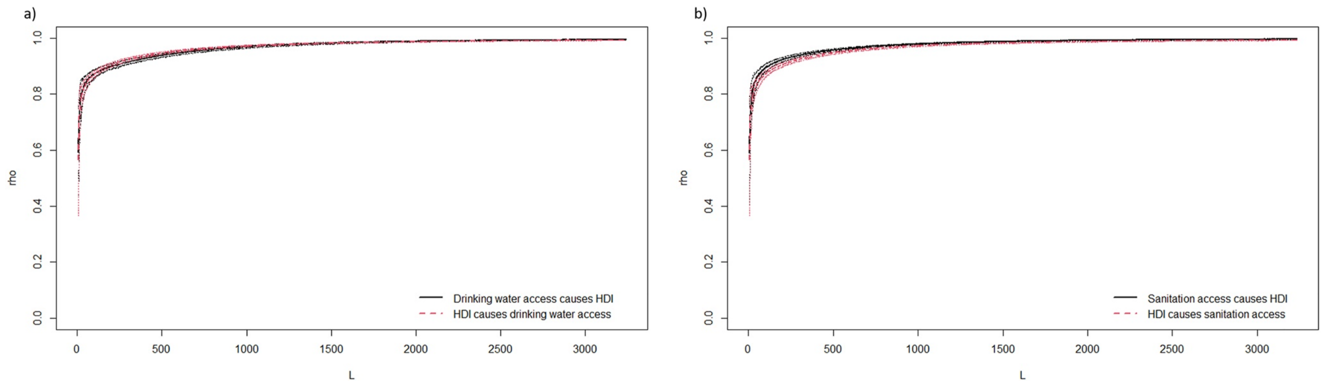

Figure 6. Causality between (a) drinking water access and HDI and (b) sanitation service access and HDI for all countries analyzed. X-axis represents the length of the data series, *y*-axis shows the value for rho, the Pearson coefficient, indicating how well the mCCM method replicates values compared to their observations. See text in Section 2.2.2 for full explanation of rho (ρ). Black lines indicate the degree to which water-related variables causally influence HDI. Red lines indicate the opposite. Solid lines are result medians, dashed lines indicate 10th and 90th percentile confidence intervals. See text in Section 2.2.2 for information how interpretation of the figures.

the "rho" value on the *y*-axes suggest that there is no dominant driving causal direction between the variables, instead showing strong bi-directional coupling (i.e., a system in synchrony, Sugihara et al. (2012)), suggesting a positive feedback, where changes in one variable strongly influence the other, and vice versa (Sušnik & van der Zaag, 2017). Similar results are apparent when analyzing world regions (Figures 7 and 8). It therefore cannot be stated from these statistical analyses with confidence if, e.g., advances in drinking water access promote HDI improvements, or the other way round.

4. Discussion

This paper has quantitatively explored the contribution of water related factors on human development, grouped into three dimensions: access, hydroclimatology and storage. Previous research reported that economic and human development is associated with access to drinking water (Sušnik & van der Zaag, 2017), rainfall seasonal variability (Brown & Lall, 2006), and is closely related to water storage (Grey & Sadoff, 2007). No previous research addresses these water factors together to assess dominant determinants in terms of human development as measured by the HDI. In addition, and further extending previous work, this paper has used robust statistical analyses to demonstrate the strength and consistency of the impacts of water-related variables and HDI gains over time. The comparison between the "water predicted" HDI and the actual HDI values shows a remarkable precision over the long-term, demonstrating the efficacy of the proposed model. Further, through the analyses, statements are able to be made about potential reasons for the observed effects, or lack therefore. These are discussed below.

4.1. Untangling the Water and Human Development Relation

A global scale, national-level sample spanning 18 years (2000–2017) suggests that access to water supply and sanitation are the most important water related factors contributing to human development, followed by hydroclimatology. Large water storage infrastructure has no statistical influence on HDI.

While the correlation between water variables and human development is strong, demonstrating causality is an elusive task (Fukuda et al., 2019). Results support the findings of Sušnik & van der Zaag (2017), extending that analysis to include access to sanitation as a critical development driver. Sanitation coverage is, individually, the variable with the strongest correlation with HDI globally. Causality analyses indicate that the relation between water services and human development is highly interdependent. This is congruent with previous research (Sušnik & van der Zaag, 2017) and literature statements claiming the existence of a virtuous cycle between water and sanitation services, socio-economic development and human well-being (Libanio, 2021). To our knowledge, this is the first empirical quantification supporting such a hypothesis.

Therefore, joint progress to close basic drinking water and sanitation gaps is tied to overall improvement in HDI. It is posited that investment in water and sanitation services expansion, rather than in large water storage

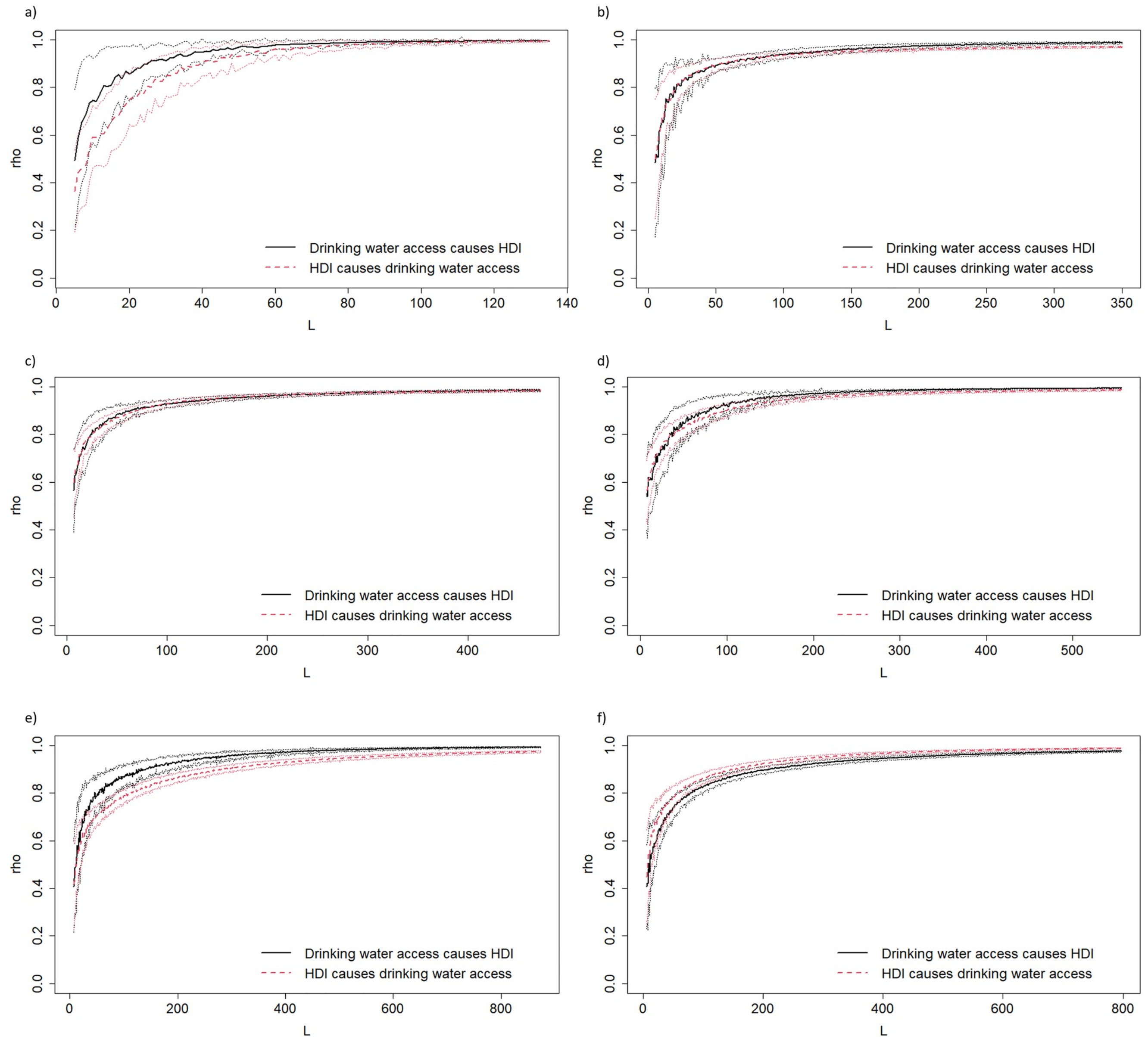

Figure 7. Causality between drinking water access and HDI for several world regions (following the World Bank classification) (a) South Asia (b) Middle-East and North Africa (c) East Asia and Pacific (d) Latin America and the Caribbean (e) Europe and Central Asia (f) Sub-Saharan Africa. X-axis represents the length of the data series, *y*-axis shows the value for rho, the Pearson coefficient, indicating how well the mCCM method replicates values compared to their observations. See text in Section 2.2.2 for full explanation of rho (ρ). Black lines indicate the degree to which water-related variables causally influence HDI. Red lines indicate the opposite. Solid lines are result medians, dashed lines indicate 10th and 90th percentile confidence intervals. See text in Section 2.2.2 for information how interpretation of the figures.

infrastructure development, will be accompanied by long-term socio-economic development gains, especially in world regions that are lacking basic water and sanitation infrastructure. This is in line with evidence linking access to water and sanitation services with reduced mortality, recovery of lost education opportunities, and wider economic benefits (Banerjee & Morella, 2011; Cheng et al., 2012; Günther & Fink, 2011; Hutton & Chase, 2016; UNDP, 2006). Nonetheless, as countries increasingly close basic water and sanitation gaps, an opportunity for further research will be to use a stricter indicator that accounts not only for basic but safe access to water and sanitation services (WHO & UNICEF, 2017). This will become an opportunity as these data are collected and reported as part of the SDGs assessment and monitoring.

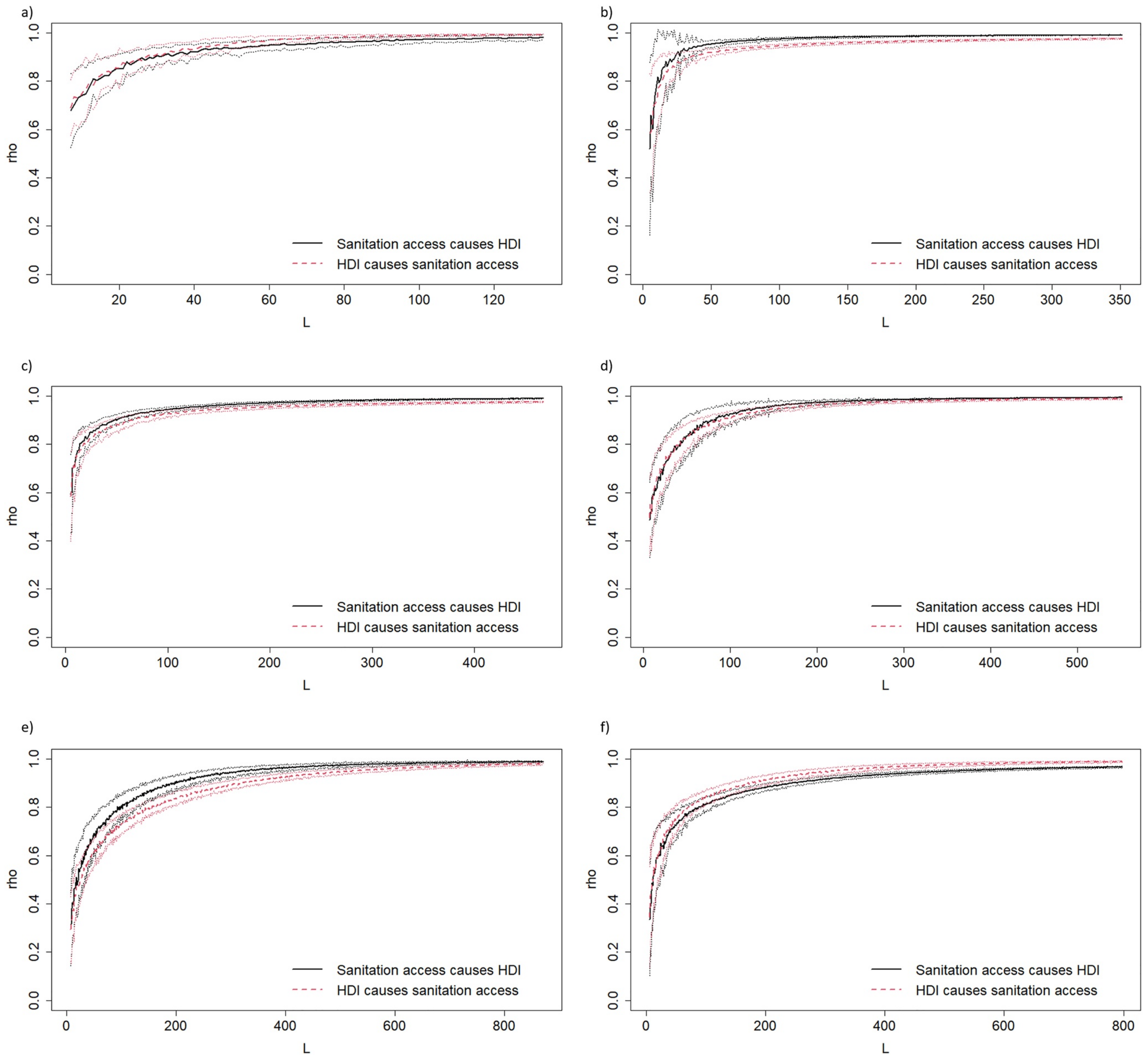

Figure 8. Causality between sanitation access and HDI for several world regions (following the World Bank classification) (a) South Asia (b) Middle-East and North Africa (c) East Asia and Pacific (d) Latin America and the Caribbean (e) Europe and Central Asia (f) Sub-Saharan Africa. X-axis represents the length of the data series, *y*-axis shows the value for rho, the Pearson coefficient, indicating how well the mCCM method replicates values compared to their observations. See text in Section 2.2.2 for full explanation of rho (ρ). Black lines indicate the degree to which water-related variables causally influence HDI. Red lines indicate the opposite. Solid lines are result medians, dashed lines indicate 10th and 90th percentile confidence intervals. See text in Section 2.2.2 for information how interpretation of the figures.

Hydroclimatological variables are significantly related to human development, supporting the findings of Brown and Lall (2006), and extending them to not only account for rainfall but seasonal variability of "blue water" (Lundqvist & Steen, 1999), as significantly related with socio-economic development. It is acknowledged here that using an "average" value for hydroclimatological variability over a country can mask large intra-nation variability, especially in large countries (such as the USA), or countries high hydroclimatological gradients (e.g., the north-west to south-east precipitation gradient in Spain). However, multi-country statistical studies require national-level simplification to be able to identify *global* trends and be able to compare biophysical data with socio-economic data at the national scale (e.g., Brown and Lall (2006)). Extending the analyses presented in this work to the sub-national level to account for such variability is an avenue for future research.

Current hydroclimatology related findings also have important implications in the context of climate change. A global temperature increase is intensifying the earth's hydrologic cycle, evidenced in the form of increased water variability and more recurrent extreme events (i.e., floods and droughts) (Donat et al., 2016). Despite limited spatiotemporal scale, the present study's variability indicator (i.e., coefficient of variation) is able to capture the effect of water variability on human development. The present article shows evidence of a long-term increasingly negative effect of seasonal variability on human development (Table 5), a process likely linked to climate change effects. This observation is in line with recent literature studying the socio-economic impacts of hydroclimatology (Damania, 2020), for instance: rainfall variability negatively impacts national economic growth (Brown et al., 2013); more severe droughts and floods are expected to have broad worldwide implications for human health (Watts et al., 2021); and droughts seriously detriment human capital with intergenerational effects (Hyland & Russ, 2019). Yet, the present article is, to the best of our knowledge, the first assessing a long-term systematic effect of seasonal variability on an overall human development indicator. In short, our results suggest that seasonal variability is posing a ever increasing challenge for human development worldwide, presumably as a consequence of climate change.

4.2. The Role of Water Storage

It has been claimed that large water storage infrastructure in "difficult" hydrologies is a precondition to deal with water seasonal variability (Grey & Sadoff, 2007; Hall et al., 2014) and promote development. The empirical analysis in this study does not support these claims. This study directly contradicts the thesis of Grey and Sadoff (2007) asserting that water storage helps to manage water variability and thus can help promote development. It neither supports research suggesting relationships between economic development (i.e., GDP per capita) and a combination of water storage and institutional aspects (Hall et al., 2014).

In contrast, these results suggest that while seasonal variability of water resources is a burden for socio-economic development, conventional large water storage is not likely the solution to promote human development. This research offers global empirical evidence that water storage is not a dominant factor in promoting socio-economic development, contradicting Grey and Sadoff's (2007) thesis. More recently Hall et al. (2014) report on a combined indicator for storage capacity per capita and institutional capacity that was related to rainfall seasonal variability and economic development. However, that work did not determine the individual significance of water storage on development. The results presented here contradict Hall et al. (2014) by suggesting that water storage per capita is neither related to seasonal variability nor to human development.

The impact of small water storage solutions on human development needs further quantification. Studies highlight the need for small, nature-based, water storage for crop irrigation and local access to water supply, particularly in rural Sub-Saharan Africa (Bossio, Jewitt, & van der Zaag, 2011; IWMI, 2009; R. Lasage et al., 2008; Mccully & Pottinger, 2009). A wide spectrum of storage alternatives (i.e., natural wetlands, soil moisture, aquifers, ponds, tanks and small reservoirs) are potentially scalable and may have broad benefits for farmers in arid and semi-arid regions (Duker et al., 2020; R Lasage et al., 2013; Tuinhof, et al., 2012). However, the results of this, and other research (Grey & Sadoff, 2007; Hall et al., 2014), do not consider such alternative water storage strategies and are therefore generally "blind" to identify their likely development benefits. This represents a major future direction of research in the water storage—human development discussion.

Evidence hints at the negative effect of high seasonal variability on the lowest development countries, but our results contest discourse promoting large water storage infrastructure (i.e., large dams) as an unequivocal development driver. Water infrastructure does have an important role for socio-economic development, yet it comes in form of access to basic water and sanitation and not in form of large-scale water storage infrastructure. This is an important policy and investment message.

4.3. Policy Implications for the Water and Sanitation Sector

The article's findings have important implications for policy in the water and development sectors. They suggest that closing the water and sanitation access gap to citizens will have long-term tangible returns in terms of human development (i.e., HDI - health, education and income) and vice-versa, offering promising directions toward reaching SDG 6 targets, among others. More effort, including political backing and targeted investments are needed to expand access to basic water and sanitation services (Alaerts, 2019; Banerjee & Morella, 2011), especially in less-developed countries, and in places experiencing rapid population and urban development. Several

10.1029/2022EF003364

constraints and challenges need to be addressed to close the water and sanitation coverage gaps faster than the population growth (Hunter et al., 2010; Sadoff et al., 2020).

Our results support evidence pointing out to global health indicators improvement in the previous decades. Diarrheal disease is still the most burdensome water and sanitation related disease worldwide (Prüss-Ustün et al., 2019). Yet, an analysis of the recent global evidence has shown that the DALYs associated to diarrheal disease has decreased from 1990 to 2017 (Karambizi et al., 2021). This is congruent with these results showing a significant trend of increasing water and sanitation access as closely related with higher human development metrics across the 21st century. Despite recent improvement, the situation remains critical, especially for children under 5 years old (Cheng et al., 2012). More targeted investments and interventions are urgent to provide better water and sanitation services to reduce the child mortality and the disease burden worldwide, specially in world regions characterized by low and medium HDI scores. Despite the urgency of this global issue, it is important to recognize that water issues related to health are complex and go beyond simply diarrheal prevention (Humphrey, 2009; Hunter et al., 2010; Mara et al., 2010; WHO, 2019).

Recent research has explored the causal pathways that explain how water services are expected to affect human wellbeing, extending from health to education and economic dimensions (Humphrey, 2009; Victora et al., 2008). The indicator that was proposed to assess human development in this study (i.e., HDI) aims to capture these benefits. Therefore, these results are congruent with this hypothesis as it was found that the effect of water related variables on human development is significant and long-lasting at a global scale. By examining the effect of water related variables on human development, the statistical models presented here were able to explain between 83% and 88% of the HDI global variance from 2000 to 2017. These findings add up to the extensive evidence that calls for urgent action to close water and sanitation access gaps worldwide (Hutton & Chase, 2016; UNDP, 2006). Results provide robust evidence for policy makers to prioritize extensive investment in the water and sanitation services provision sector to reap long term global societal benefits in terms health, education and income.

5. Conclusions

This paper explored the relationship between water-related variables and human development indicators globally during most of the 21st Century (2000–2017). It was shown that access to water supply, and especially to sanitation infrastructure, are significant drivers for improvements in human development progress, particularly for the least developed countries. Seasonal variability in freshwater resources is inversely related to human development progress. A statistical model was developed for the year 2017, showing that a 1% increment in a country's HDI is associated with a 1.3%–3.2% joint country-level increment in water and sanitation access. The 2017 analysis was repeated for the years 2000–2016, and results demonstrate that the relationships are nearly identical globally over this period. Complementary causal analyses show the tight two-way relationships between water variables and human development, strongly suggesting that investment in the improvement in one aspect will lead to concomitant improvements in the other, and vice-versa, potentially kick-starting a beneficial positive feedback loop where mutual benefits "feed" off each other to improve living standards more generally.

The main implication of our findings is that investment in water and sanitation infrastructure will very likely have long-run societal benefits, and will pay back in terms of healthier citizens living better lives, thus able to contribute more fully to personal and national growth and development. Another crucial finding is that contrary to other studies, these results show no robust statistical link between large water storage infrastructure (i.e., dams and reservoirs) and improvements in human development figures. Thus, it is suggested that investing in large water storage is not the best way to further nation-level human development. However, the role of small, local, nature-based water storage is generally overlooked, and represents an avenue for future research in the context of its benefits for human development. This article provides strong evidence to strengthen investment for improving national access to water and sanitation worldwide. This will be significantly beneficial in terms of human development and evidenced in the improvement of national health, education and income indicators. This is an important long-term, large-scale financing finding for advancing human development.

Data Availability Statement

The supporting data used for the correlation and causality analyses in the study are available at 4TU.ResearchData via DOI: https://doi.org/10.4121/20110397 with CC BY 4.0 license.

Acknowledgments

HA-D acknowledges Colfuturo for funding his MSc degree at IHE Delft Institute for Water Education in the period 2019–2021. We acknowledge funding from DUPC2, the programmatic cooperation between the Directorate-General for International Cooperation of the Dutch Ministry of Foreign Affairs and IHE Delft in the period 2016–2020 for contribution towards research and the writing of this manuscript. Part of the writing of this manuscript was funded by the EC H2020 project "NEXOGENESIS" (Grant 101003881). We would like to thank the three reviewers who aided in considerably improving the quality of this manuscript. In particular, we wish to acknowledge the time, effort, and depth of the reviews, and the quality of the comments received by the authors.

References

Alaerts, G. (2019). Financing for water—Water for financing: A global review of policy and practice. *Sustainability*, *11*(3), 821. https://doi.org/10.3390/su11030821

Arimah, B. (2017). Infrastructure as a catalyst for the prosperity of African cities. *Procedia Engineering*, *198*, 245–266. https://doi.org/10.1016/j.proeng.2017.07.159

Banerjee, S. G., & Morella, E. (2011). *Africa's water and sanitation infrastructure: Access, Affordability and Alternatives*. The International Bank for Reconstruction and Development / The World Bank.

Bossio, D., Jewitt, G., & van der Zaag, P. (2011). Smallholder system innovation for integrated watershed management in Sub-Saharan Africa. *Agricultural Water Management*, *98*(11), 1683–1686. https://doi.org/10.1016/j.agwat.2011.07.006

Brown, C., & Lall, U. (2006). Water and economic development: The role of variability and a framework for resilience. *Natural Resources Forum*, *30*(4), 306–317. https://doi.org/10.1111/j.1477-8947.2006.00118.x

Brown, C., Meeks, R., Ghile, Y., & Hunu, K. (2013). Is water security necessary? An empirical analysis of the effects of climate hazards on national-level economic growth. *Philosophical Transactions of the Royal Society A*, *371*(2002), 20120416. https://doi.org/10.1098/rsta.2012.0416

Checkley, W., Buckley, G., Gilman, R. H., Assis, A. M., Guerrant, R. L., Morris, S. S., et al. (2008). Multi-country analysis of the effects of diarrhoea on childhood stunting. *International Journal of Epidemiology*, *37*(4), 816–830. https://doi.org/10.1093/ije/dyn099

Cheng, J. J., Schuster-Wallace, C. J., Watt, S., Newbold, B. K., & Mente, A. (2012). An ecological quantification of the relationships between water, sanitation and infant, child, and maternal mortality. *Environmental Health*, *11*(4), 4. https://doi.org/10.1186/1476-069x-11-4

Chenoweth, J. (2008). Minimum water requirement for social and economic development. *Desalination*, *229*(1–3), 245–256. https://doi.org/10.1016/j.desal.2007.09.011

Clark, A. T. (2022). MultispatialCCM: Multispatial convergent cross mapping. Retrieved from https://cran.r-project.org/web/packages/multispatialCCM/index.html

Clark, A. T., Ye, H., Isbell, F., Deyle, E. R., Cowles, J., Tilman, G. D., & Sugihara, G. (2015). Spatial convergent cross mapping to detect causal relationships from short time series. *Ecology*, *96*(4), 1174–1181. https://doi.org/10.1890/14-1479.1

Damania, R. (2020). The economics of water scarcity and variability. *Oxford Review of Economic Policy*, *36*(1), 24–44. https://doi.org/10.1093/oxrep/grz027

Donat, M. G., Lowry, A. L., Alexander, L. V., O'Gorman, P. A., & Maher, N. (2016). More extreme precipitation in the world's dry and wet regions. *Nature Climate Change*, *6*(5), 508–513. https://doi.org/10.1038/nclimate2941

Duker, A., Cambaza, C., Saveca, P., Ponguane, S., Mawoyo, T. A., Hulshof, M., et al. (2020). Using nature-based water storage for smallholder irrigated agriculture in African drylands: Lessons from frugal innovation pilots in Mozambique and Zimbabwe. *Environmental Science & Policy*, *107*, 1–6. https://doi.org/10.1016/j.envsci.2020.02.010

FAO. (2021). AQUASTAT core database. Retrieved from https://www.fao.org/aquastat/en/databases/

Fragile States Index (2022). Measuring fragility: Risk and vulnerability in 179 countries. Retrieved from https://fragilestatesindex.org/

Fukuda, S., Noda, K., & Oki, T. (2019). How global targets on drinking water were developed and achieved. *Nature Sustainability*, *2*(5), 429–434. https://doi.org/10.1038/s41893-019-0269-3

Graves, C. M., Haakenstad, A., & Dieleman, J. L. (2015). Tracking development assistance for health to fragile states: 2005-2011. *Globalization and Health*, *11*(1), 12. https://doi.org/10.1186/s12992-015-0097-9

Grey, D., & Sadoff, C. W. (2007). Sink or swim? Water security for growth and development. *Water Policy*, *9*(6), 545–571. https://doi.org/10.2166/wp.2007.021

Günther, I., & Fink, G. (2011). Water and sanitation to reduce child mortality: The impact and cost of water and sanitation infrastructure. In *Policy research working paper 5618*. The World Bank.

Hall, B. J. W., Grey, D., Garrick, D., Fung, F., Brown, C., Dadson, S. J., & Sadoff, C. W. (2014). Coping with the curse of freshwater variability. *Science*, *346*(6208), 429–430. https://doi.org/10.1126/science.1257890

Humphrey, J. H. (2009). Child undernutrition, tropical enteropathy, toilets, and handwashing. *The Lancet*, *374*(9694), 1032–1035. https://doi.org/10.1016/s0140-6736(09)60950-8

Hunter, P. R., MacDonald, A. M., & Carter, R. C. (2010). Water supply and health. *PLoS Medicine*, *7*(11), e1000361. https://doi.org/10.1371/journal.pmed.1000361

Hutton, G., & Chase, C. (2016). The knowledge base for achieving the sustainable development goal targets on water supply, sanitation and hygiene. *International Journal of Environmental Research and Public Health*, *13*(6), 536. https://doi.org/10.3390/ijerph13060536

Hutton, G., & Varughese, M. (2016). The costs of meeting the 2030 sustainable development goal targets on drinking water, sanitation, and hygiene. In *Water and sanitation program: Technical paper 103171*. The World Bank.

Hyland, M., & Russ, J. (2019). Water as destiny – The long-term impacts of drought in sub-Saharan Africa. *World Development*, *115*, 30–45. https://doi.org/10.1016/j.worlddev.2018.11.002

IWMI. (2009). Flexible water storage options and adaptation to climate change. In *IWMI water policy brief 31*. International Water Management Institute (IWMI).

Karambizi, N. U., McMahan, C. S., Blue, C. N., & Temesvari, L. A. (2021). Global estimated disability-adjusted life-years (DALYs) of diarrheal diseases: A systematic analysis of data from 28 years of the global burden of disease study. *PLoS One*, *16*(10), e0259077. https://doi.org/10.1371/journal.pone.0259077

Lasage, R., Aerts, J., Mutiso, G. C. M., & de Vries, A. (2008). Potential for community based adaptation to droughts: Sand dams in Kitui, Kenya. *Physics and Chemistry of the Earth*, *33*(1–2), 67–73. https://doi.org/10.1016/j.pce.2007.04.009

Lasage, R., Aerts, J. C. J. H., Verburg, P. H., & Sileshi, A. S. (2013). The role of small scale sand dams in securing water supply under climate change in Ethiopia. *Mitigation and Adaptation Strategies for Global Change*, *20*(2), 317–339. https://doi.org/10.1007/s11027-013-9493-8

Libanio, P. A. C. (2021). WASH services and human development: A tangible nexus for achieving water-related SDGs. *International Journal of River Basin Management*, *20*(1), 57–66. https://doi.org/10.1080/15715124.2021.1909603

Lundqvist, J., & Steen, E. (1999). The contribution of blue water and green water to the multifunctional character of agriculture and land. In *Background paper 6: Water*. FAO.

Mara, D., Lane, J., Scott, B., & Trouba, D. (2010). Sanitation and health. *PLoS Medicine*, *7*(11), e1000363. https://doi.org/10.1371/journal.pmed.1000363

Mccully, P., & Pottinger, L. (2009). Spreading the water wealth: Making water infrastructure work for the poor. *Ecology Law Currents*, *36*, 177–184.

Mehta, L. (2014). Water and human development. *World Development*, *59*, 59–69. https://doi.org/10.1016/j.worlddev.2013.12.018

Ngure, F. M., Reid, B. M., Humphrey, J. H., Mbuya, M. N., Pelto, G., & Stoltzfus, R. J. (2014). Water, sanitation, and hygiene (WASH), environmental enteropathy, nutrition, and early child development: Making the links. *Annals of the New York Academy of Sciences*, *1308*(1), 118–128. https://doi.org/10.1111/nyas.12330

Nielsen, L. (2013). How to classify countries based on their level of development. *Social Indicators Research*, *114*(3), 1087–1107. https://doi.org/10.1007/s11205-012-0191-9

Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M. C., et al. (2019). Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: An updated analysis with a focus on low- and middle-income countries. *International Journal of Hygiene and Environmental Health*, *222*(5), 765–777. https://doi.org/10.1016/j.ijheh.2019.05.004

Ranis, G., Stewart, F., & Samman, E. (2005). Human development: Beyond the HDI. In *Center discussion paper 916*. Economic Growth Center Discussion Paper - Yale University.

Sadoff, C. W., Borgomeo, E., & Uhlenbrook, S. (2020). Rethinking water for SDG 6. *Nature Sustainability*, *3*(5), 346–347. https://doi.org/10.1038/s41893-020-0530-9

Schell, C. O., Reilly, M., Rosling, H., Peterson, S., & Ekstrom, A. M. (2007). Socioeconomic determinants of infant mortality: A worldwide study of 152 low-middle-and high-income countries. *Scandinavian Journal of Public Health*, *35*(3), 288–297. https://doi.org/10.1080/14034940600979171

Siegel, S. M. (2017). *Let there be water: Israel's solution for a water-starved world*. Thomas Dunne Books.

Sugihara, G., May, R., Ye, H., Hsieh, C. H., Deyle, E., Fogarty, M., & Munch, S. (2012). Detecting causality in complex ecosystems. *Science*, *338*(6106), 496–500. https://doi.org/10.1126/science.1227079

Sušnik, J. (2018). Data-driven quantification of the global water-energy-food system. *Resources, Conservation and Recycling*, *133*, 179–190. https://doi.org/10.1016/j.resconrec.2018.02.023

Sušnik, J., & van der Zaag, P. (2017). Correlation and causation between the UN Human Development Index and national and personal wealth and resource exploitation. *Economic Research-Ekonomska Istraživanja*, *30*(1), 1705–1723. https://doi.org/10.1080/1331677x.2017.1383175

The World Bank. (2008). *Economic impacts of sanitation in Cambodia. A five-country study conducted in Cambodia, Indonesia, Lao PDR, the Philippines and Vietnam under the economics of sanitation initiative (ESI) research*. The World Bank.

Tian, F., Wu, B., Zeng, H., Ahmed, S., Yan, N., White, I., et al. (2020). Identifying the links among poverty, hydroenergy and water use using data mining methods. *Water Resources Management*, *34*(5), 1725–1741. https://doi.org/10.1007/s11269-020-02524-5

Tortajada, C. (2014). Dams: An essential component of development. *Journal of Hydrologic Engineering*, *20*(1). https://doi.org/10.1061/(asce)he.1943-5584.0000919

Tuinhof, A., van Steenbergen, F., Vos, P., & Tolk, L. (2012). *Profit from storage. The costs and benefits of water buffering*. 3R Water Secretariat.

UNDP. (1990). *Human development report 1990*. United Nations Development Programme.

UNDP. (2006). *Human Development Report 2006 - Beyond scarcity: Power, poverty and the global water crisis*. United Nations Development Programme.

UNDP. (2019). *Human Development Report 2019 - Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century*. United Nations Development Programme.

UNDP. (2023). Human development index (HDI). Retrieved from https://hdr.undp.org/data-center/human-development-index#/indicies/HDI

UNESCOI HP. (2013a). Water supply interannual variability in 2013. Retrieved from http://ihp-wins.unesco.org/layers/interanvar:geonode:interanvar

UNESCOI HP. (2013b). Water supply seasonal variability in 2013. Retrieved from http://ihp-wins.unesco.org/layers/geonode:seasonalvar

UN General Assembly. (2010). A/RES/64/292 the human right to water and sanitation. Retrieved from https://digitallibrary.un.org/record/3992110?ln=en

UN General Assembly. (2015). A/RES/70/1 Transforming our world: the 2030 Agenda for Sustainable Development. Retrieved from https://digitallibrary.un.org/record/3923923?ln=en

Victora, C. G., Adair, L., Fall, C., Hallal, P. C., Martorell, R., Richter, L., & Sachdev, H. S. (2008). Maternal and child undernutrition: Consequences for adult health and human capital. *The Lancet*, *371*(9609), 340–357. https://doi.org/10.1016/s0140-6736(07)61692-4

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., et al. (2021). The 2020 report of the Lancet Countdown on health and climate change: Responding to converging crises. *Lancet*, *397*(10269), 129–170. https://doi.org/10.1016/S0140-6736(20)32290-X

WHO (2003). *The right to water*. World Health Organization.

WHO (2012). Global costs and benefits of drinking-water supply and sanitation interventions to reach the MDG target and universal coverage. Retrieved from https://apps.who.int/iris/handle/10665/75140

WHO, & UNICEF. (2017). *Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines*. World Health Organization (WHO) and the United Nations Children's Fund (UNICEF).

WHO (2019). *Safer water, better health. 2019 update*. World Health Organization.

Zeitoun, M., Lankford, B., Krueger, T., Forsyth, T., Carter, R., Hoekstra, A. Y., et al. (2016). Reductionist and integrative research approaches to complex water security policy challenges. *Global Environmental Change*, *39*, 143–154. https://doi.org/10.1016/j.gloenvcha.2016.04.010