Assessing the Blue Planet: Global Insights on Freshwater Challenges and Management Strategies

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Abstract

Globally, around 4 trillion cubic meters of water are consumed every year. However, 97.5% of the total water resources available on this planet consist of salt water. Thus, the access to a freshwater supply is of critical importance.

In this work, we use global data to analyze and illustrate the availability, usage, and treatment of freshwater on a worldwide scale. Two significant factors influencing water stress levels have been identified: population growth and changes in precipitation patterns. Additionally, it is noted that various strategies are employed to cope with water scarcity. Countries experiencing high water stress levels tend to allocate a greater proportion of available water resources to the agricultural sector. However, the treatment of wastewater appears to be primarily influenced by different factors.

1. Introduction

In today's world, the importance of freshwater cannot be overstated. It is not only essential for basic human needs like drinking and agriculture, but also for industrial activities. However, with the growing global population and environmental changes, freshwater is becoming increasingly scarce in many regions. This situation has led to increased *water stress*, defined as the ratio of freshwater withdrawal to its availability. Alarmingly, this ratio has exceeded 100% in some countries, indicating that more water is used than is naturally available.

This project aims to provide a comprehensive review of the predominant factors influencing global water withdrawal by investigating the impact of population growth and potential consequences of climate change. It explores the underlying causes of water stress and examines different water management strategies adopted by countries that are impacted by water scarcity. This report also illustrates the significant role that financial resources play in the access to clean water. Special attention is paid to agricultural water usage, which significantly contributes to the escalating demand for water. However, it's important to note that the scope of this paper is to provide a preliminary overview.

2. Methods

The *AQUASTAT* dataset (FAO, 2021), developed by the *Food and Agriculture Organization of the United Nations*, is the primary resource used in this analysis. It features an extensive compilation of over 193 different variables and indicators, gathered across 200 countries over a span of up to 57 years. The dataset encompasses information on water resources and their utilization, including water withdrawal, wastewater, pressure on water resources, as well as aspects related to irrigation, drainage, environment, and health.

Analyzing the *water stress* indicator lets us identify the countries which are facing water scarcity issues, and helps us focus our data analysis on the areas that are mostly impacted. Water stress is defined as the freshwater withdrawal as a proportion of available freshwater resources (United Nations, 2023). Countries that have an increased demand for fresh water or a decline in fresh water resource availability face higher water stress.
To identify the factors that have the highest impact on the water stress variable of a country, different statistical tests are conducted.

Initially, we examine the influence of the population on a countries total water withdrawal, given the presumption of a substantial interconnection between the two. To test this, we plot the variables over time and compute their correlation. Furthermore, we construct a hypothesis test where countries are divided into two groups based on their respective population size. The *total water withdrawal* variable is repeatedly rearranged, generating a total of

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$n = 100.000$ permutations. To compare the obtained results for both groups, the following metric is applied:

$$T = \left[\frac{1}{n} \cdot \sum_{i \in G_1} X_i\right] - \left[\frac{1}{n} \cdot \sum_{i \in G_2} Y_i\right] \tag{1}$$

where X_i and Y_i are permuted the total water withdrawal samples of their respective groups G_1 and G_2. After obtaining the distribution for n samples under the null hypothesis, we determine the p-value by comparing our result to the actual value of the dataset, which was calculated using the same metric.

The second factor we investigate is climate change. Previous work shows that different global climate models estimate a future increase in water stress impacting between 0.5 and 3.1 billion people by the year 2050 (Gosling & Arnell, 2016; Stringer et al., 2021). To identify countries currently affected by climate-induced water stress, geospatial data for temperature anomalies (Vose et al., 2022) and mean precipitation levels (Xie & Arkin, 2022) are visualized, as they are among the most significant contributing factors to freshwater availability (Berghuijs et al., 2017). The datasets are provided by the *National Oceanic and Atmospheric Administration* (NOAA).

Shifting the focus to a related concern, we investigate how countries that suffer from high water stress spend their available water resources. The water consumption is distinguished between three different sectors, the agricultural, industrial and municipal sector. To provide a stable and sufficient food supply for the population of a country, the agricultural water withdrawal is essential. We want to examine whether countries that have high water stress levels spend a larger share of their available water on the agricultural sector. To explore this hypothesis, a *Kruskal Wallis* test is performed. The countries are distributed in three groups, with the water stress level being the sorting criterion. The *Kruskal Wallis* test statistic H is approximately *chi-squared* distributed and can be computed as follows:

$$H = \left(\frac{12}{N(N+1)} \sum_{j=1}^{k} \frac{R_j^2}{n_j}\right) - 3(N+1) \tag{2}$$

where N is the total number of samples, n_j the sample size for group j and R_j the sum of ranks of the j-th group (Ostertagova et al., 2014). Before conducting the test, the data undergoes visual analysis using PP and QQ-plots to ascertain its adherence to the test prerequisites.

Building upon the analysis of water stress and resource allocation, the investigation of water management strategies also extends to an examination of wastewater management practices. The *WateReuse Association* defines wastewater as "the used water of a community or industry that contains dissolved and suspended matter". This study plots the ratio of *treated* wastewater to *total* wastewater per country in 2012, creating a baseline. We then visualize the progression in wastewater treatment up to 2020 by plotting the relative growth of this ratio. The relative growth measures the change in wastewater management as a proportion to the data in 2012. This metric is useful for evaluating the development of wastewater strategies in response to water stress and identifying regional variations.

After reviewing water management practices, it logically follows to explore the differences in making water resources usable, particularly in meeting the needs of the population. As currently over one billion people do not have access to safe drinking water (UNESCO, 2023), it is crucial to determine if this issue predominantly affects countries experiencing high water stress. Scatterplots allow for better visual identification of trends and general distribution patterns, providing a clear overview of these issues. In this approach, the relationships between water stress, GDP per capita, and access to clean drinking water are plotted to identify interesting influences through visual analysis. Due to an enormous water stress in a few countries, the variable was capped at 175%.

3. Results

The conducted analysis indicates a strong correlation ($r = 0.93$) between *total freshwater withdrawal* and *population*, highlighting a significant relationship between these two variables. With a steady increase in population, there is a parallel rise in freshwater demand, intensifying the strain on existing water resources. It is noteworthy that the majority of water consumption is attributed to agricultural activities, which play a crucial role in sustaining the population through food production. The conducted hypothesis test through permutation with the null hypothesis H_0 stating that the variable *population* has no effect on the *total water withdrawal* can be rejected, since we obtain a p-value smaller than $1 \cdot 10^{-5}$.

The analysis of the influence of climate change on water stress using geospatial data, shown in Figure 1, indicates that rising surface temperatures affect all countries, leading to heightened evaporation. Conversely, we also observe that decreases in precipitation seem to be concentrated in specific regions. This shift in precipitation patterns results in heightened rainfall in other areas. Since precipitation is an important factor influencing renewable freshwater availability, especially surface water and groundwater, this can drastically change the water stress level of affected countries. Areas that are mostly impacted by reduced precipitation of up to 50% as North Africa, the Arabian Peninsula, Australia, and North America.

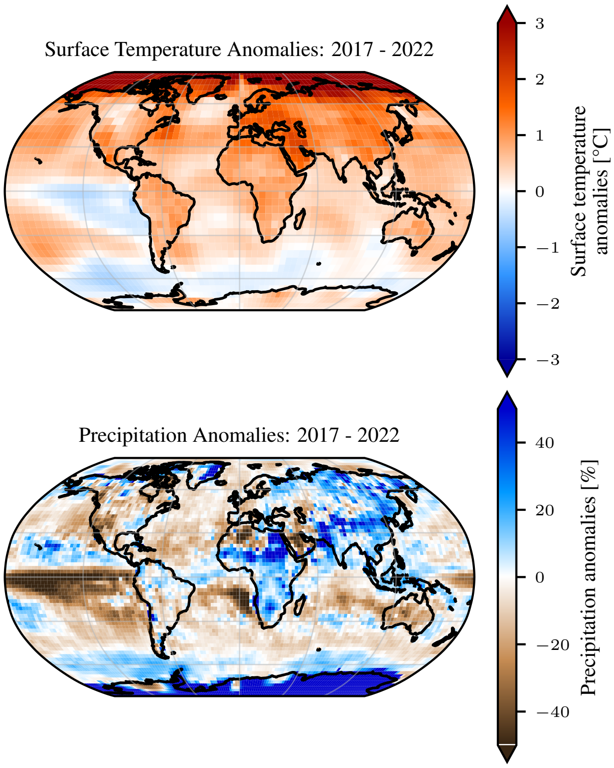


Figure 1. Surface temperature (1971 to 2000 baseline) and precipitation anomalies (1979 to 2000 baseline) for a time interval of six years from 2017-2022. While all countries are directly impacted by increasing surface temperatures, a decrease in precipitation only affects certain regions.

Next, the current water stress levels are visualized to identify countries that currently suffer from water scarcity. As illustrated in Figure 2 one can observe that some countries with high water stress levels are also heavily impacted by reduced precipitation. Since this metric implies that a large amount of the renewable freshwater resources are already consumed by the respective countries, various measures and strategies must be adopted (Tortajada et al., 2019; Belhassan, 2021) to counteract this.

The initial strategy investigated is whether countries facing high water stress allocate a larger proportion of their freshwater withdrawals to agriculture, a sector critical for food supply and a major consumer of water resources. The conducted analysis shows that countries that face high water stress levels use a far larger share of the available water for agricultural purposes. For nations with water stress levels over 40% the median share of water allocated for the agricultural sector is 75% while for countries with water stress levels under 20% the median share reduces to 51%. The p-value for the performed *Kruskal Wallis* test with the null hypothesis H_0 stating all mean group ranks are equal independent of their respective stress levels is 0.01.

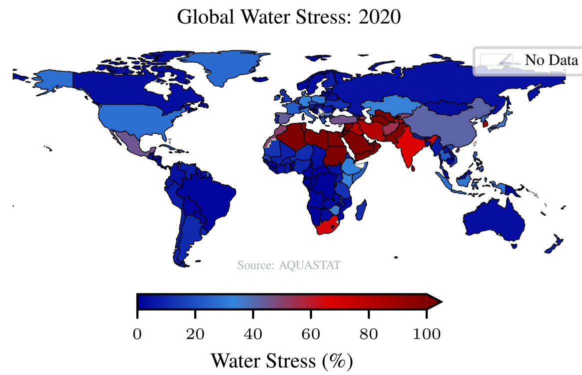


Figure 2. 2020 Global Water Stress Levels show a vast difference when comparing North- and South Africa and South-eastern countries to the rest of the world.

Another aspect we explore is wastewater management, encompassing water treatment and reuse. Figure 3 highlights

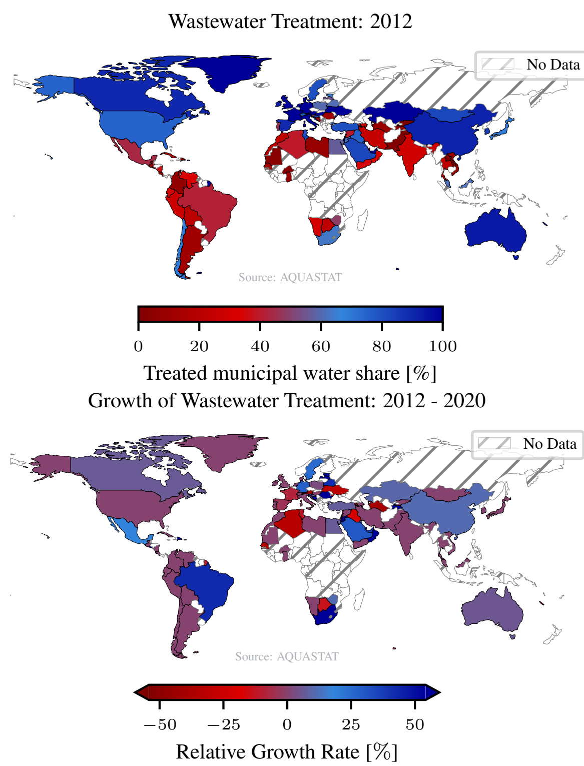
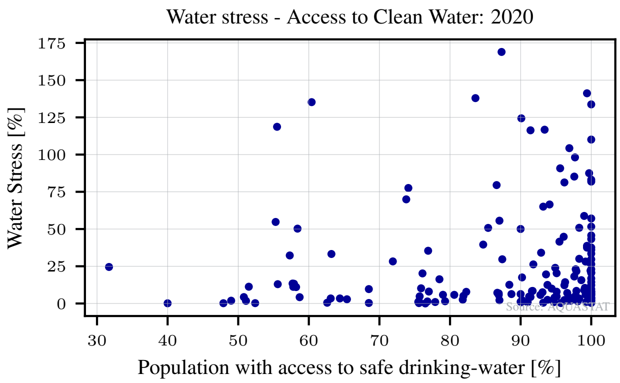


Figure 3. Change in Proportion of Treated Municipal Wastewater to Total Wastewater (2012 to 2020 baseline). Countries that face high water stress (Figure 2) show minimal to no alterations in treatment practices.

a significant divide in wastewater treatment across the globe. Developed countries generally tend to treat a large portion of their wastewater, in stark contrast to many countries in the global south. Regions experiencing high water stress seem to have lower rates of municipal wastewater treatment, though some countries on the Arabian Peninsula (Saudi Arabia, UAE) are an exception with higher treatment levels than other countries in their region. Furthermore, when this data is compared to areas most impacted by negative rainfall anomalies and even by water stress, similar disparities in the increase in water treatment are observed.



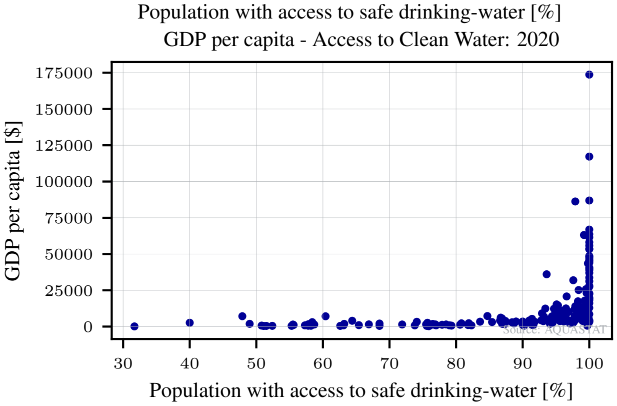


Figure 4. Correlations in 2020 between *total population with access to safe drinking water* and two key factors: *GDP per capita* and *water stress levels*.

Examining the relationship between access to safe drinking water and water stress in 2020 (Figure 4) reveals no straightforward link. Countries exhibit varying levels of water stress yet can have both high and low access to safe drinking water, indicating that factors apart from water stress alone may play significant roles in determining water accessibility.
When considering GDP per capita in relation to access to safe drinking water (Figure 4), a much stronger association is evident. All countries with limited access to safe drinking water also exhibit a lower GDP per capita, suggesting that economic strength is a crucial factor in ensuring the availability of safe drinking water.

4. Discussion

In section 3, we identified population growth and climate change as the predominant factors of high water stress. As the population growths, more food has to be produced, which is increases the demand of water in the agricultural sector. This is also underlined by our finding that countries with high water stress often prioritize water allocation for the agricultural sector. The impact of climate change, on the other hand, is much more difficult to quantify. Our analysis shows that shifting precipitation patterns affect specific regions, potentially leading to water scarcity and impacting food supply. The precipitation dataset helped identify affected countries, laying the groundwork for future predictive models on precipitation trends.

The examination of wastewater treatment reveals that economic factors and developmental progress seem to exert a significantly greater impact on advancements in water treatment technologies than the immediate need for water reclamation, which arises from high water stress and limited precipitation. But although it appears intuitive that development and therefore economic factors coincide with enhanced water treatment capabilities, further analysis is necessary to fully understand the underlying reasons for the observed discrepancies.
Similar dynamics seem to be at play regarding access to clean drinking water. Water stress does not appear to be a major determinant of this access, hinting that scarce water resources may not be the main determinant of this issue. Instead, a clear link can be observed with GDP per capita, as no country with restricted access to clean drinking water has a GDP akin to those countries in the "developed world". This devalues water stress as an indicator, giving poor countries their whole own set of problems and opening up more topics for subsequent research.
Furthermore, this overview of water access and treatment strategies, though preliminary and in need of further investigation, highlights how discussions on technical solutions for the impacts of climate change need to include the significant role of financial resources. Many countries appear to already face challenges in making water accessible to their populations, hindering their ability to consider more advanced, technologically intensive, and costly water management strategies.

Contribution Statement

Simon Fehrenbach performed a comprehensive analysis of global wastewater treatment strategies, assessing their effectiveness and sustainability. Christian Jestädt explored the factors influencing water stress and availability, including environmental and human-driven elements. Marten Kreis executed the statistical analysis, correlating precipitation, temperature, and population data. Josef Müller assisted in researching wastewater strategies and maintained the codebase for data analysis and visualization. All authors contributed equally to the development of visualizations and the writing of the report.

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