water

MDPI

Review

The Evolution of Potable Water Security: A Temporal Analysis of Key Indices and Trends

Jasna Bhargavan * and Kasthurba Ayikkara Kizhakkayil

National Institute of Technology Calicut, Kozhikode 673601, Kerala, India; kasthurba@nitc.ac.in
* Correspondence: jasnajeeva@gmail.com

Abstract: Water security is a critical global issue that has gained increasing attention from researchers, policymakers, and practitioners over the past few decades. This paper presents a comprehensive overview of the evolution of potable water security indices from the 1980s to the 2020s, focusing on the key research themes, trends, and influential factors in the field. We conducted a comprehensive search of the relevant literature and examined the development of water security indices to provide insights into the current state of research and identify future research directions. This paper will explore the historical context, key indicators, sector-specific challenges, climate change implications, governance and policy considerations, technological advancements, community engagement efforts, and future directions for research in this critical field. Researchers and policymakers will find this review valuable as it offers insights into the existing knowledge and the areas that require further exploration to address global water security challenges.

Keywords: water scarcity; water stress; potable water; SDG 6

check for updates

Citation: Bhargavan, J.; Ayikkara Kizhakkayil, K. The Evolution of Potable Water Security: A Temporal Analysis of Key Indices and Trends. *Water* **2024**, *16*, 3023. https://doi.org/10.3390/w16213023

Academic Editors: Yejun Xu and José Baltazar Salgueirinho Osório De Andrade Guerra

Received: 31 August 2024
Revised: 17 October 2024
Accepted: 19 October 2024
Published: 22 October 2024

1. Introduction

Access to safe and reliable water is a fundamental human right. However, many communities around the world continue to face challenges in securing adequate supplies of clean, potable water [1]. Despite advances in water infrastructure and treatment technologies, significant disparities persist, with some regions experiencing water scarcity while others grapple with the high costs of utilizing available freshwater resources [2], with a focus on community-level dynamics and potential solutions. One key aspect of water security is the role of ecosystems in maintaining and regulating water resources. This is particularly relevant at the community level, where local environmental factors play a significant role in determining water availability and quality. Equally important is the need to balance human and environmental water needs, as highlighted by the United Nations Sustainable Development Goal for water (SDG 6) [3]. The concept of water security has evolved to address this multifaceted challenge, acknowledging the inherent tensions among competing demands for scarce water resources. Water is important for sustaining life, serving a crucial function in both direct ingestion and maintaining the environment. The distribution, hygienic conditions, and accessibility of water have a direct impact on the well-being of people [4]. Defined as the sufficiency of freshwater supplies to satisfy human and environmental requirements, water security is a growing concern on a global scale [5]. The limited availability of safe drinking water is directly linked to human rights, as guaranteeing access to it is a crucial obstacle in development [6,7]. The scarcity of water has escalated in recent years due to climate change, population increases, and rising demands surpassing supply [8].

The two main types of water shortage are physical and economic water scarcity. Approximately 1.2 billion people, many of whom reside in arid or semi-arid regions, experience physical scarcity, where the demand for water exceeds the available supply in a certain area [9,10]. This scarcity can occur periodically, affecting over two-thirds of the world's population at least once annually, and is expected to worsen as a result of population increase and climate-induced shifts in water supply [9,11]. Approximately 1.6 billion people are currently experiencing economic water shortages due to inadequate infrastructure or the ineffective management of the available water resources, even in regions where water is accessible [9,12]. In such instances, inadequacies in water utilization, frequently caused by the insufficient economic value of water, worsen the issue, leading to unattainable or contaminated water sources [13].

Furthermore, water quality has emerged as a crucial dimension of water security. The environmental contamination caused by fertilizers, viruses, and pollutants has deteriorated water supplies worldwide [10]. The concentration of chemicals of concern, such as per- and polyfluoroalkyl compounds (forever chemicals), has surpassed the permissible threshold, therefore endangering the safety of water [14]. Furthermore, a staggering 80% of the world's wastewater is released without any treatment, therefore exacerbating the pollution of water ecosystems [15]. The deterioration of water quality poses a dual danger to both physical water security and economic water scarcity, particularly in areas with inadequate or ineffective water controls [16]. Climate change poses additional challenges to water security by modifying meteorological patterns and intensifying the occurrence of severe droughts and floods. These alterations have considerable effects on the availability and quality of water, disturb ecological systems, and diminish crucial water-related functions such as flood control and nutrient cycling [17–19]. In numerous areas, particularly those currently experiencing water scarcity, the availability of water is becoming less foreseeable and progressively unsustainable as a result of these multifaceted pressures [20,21].

In light of the escalating global water problems, the emphasis on ensuring access to safe drinking water is becoming increasingly important. Potable water security specifically pertains to the presence of safe and high-quality drinking water in adequate amounts to fulfill the requirements of a given community. It is imperative not only to tackle physical and economic water shortages but also to preserve water quality in order to guarantee this. The persistent degradation of water sources by untreated wastewater, industrial pollutants, and geogenic contaminants such as arsenic and fluoride is a significant threat in guaranteeing access to drinking water [16]. The insufficient availability of potable water constitutes substantial hazards to human well-being, intensifying disparities and reducing economic resilience in susceptible areas [6,7].

Attaining safe drinking water requires a holistic strategy that attends to water sustainability, which is defined as guaranteeing the availability, cleanliness, and accessibility of water for its designated use, be it for agriculture, industry, or human consumption. In order to minimize water wastage and contamination, it is necessary to enhance water infrastructure, refine management procedures, and promote a greater understanding of the economic worth of water [22,23]. Failure to implement these steps will result in a persistent increase in the disparity between water supply and demand, therefore jeopardizing both water security and global development [24]. The global demand for freshwater resources continues to grow, driven by factors such as population growth, urbanization, and climate change. Ensuring water security is an increasingly pressing challenge, and researchers worldwide have been investigating various aspects of water security to address this issue. A literature review is an essential component of academic research that involves systematically gathering and analyzing existing published studies, articles, and scholarly works related to a specific topic or research question. This review paper provides a comprehensive overview of water security indices from the 1980s up to the 2020s, highlighting the key findings and emerging trends. It also aims to identify the gaps in the current body of knowledge on domestic and potable water security indices.

2. Methodology

This study initially employed a bibliometric analysis to investigate the trends and developments in household potable water security over the past two decades (2001–2024). The research began with a comprehensive search of the relevant literature in the Scopus database, focusing on publications that contributed to the discourse on potable water security. This step was followed by the identification of relevant papers through back referencing. The indices related to potable water security were categorized based on their emergence in different time periods: 1980s–1990s, 2000s–2010s, and 2010s–2020s. This temporal division allowed for a detailed analysis of the evolution and focus of water security indices across different decades. For each of these periods, heatmaps were generated to visually represent the prevalence and focus areas of the identified indices, enabling a clear comparison of trends over time.

2.1. Heatmap Generation Process

The heatmaps were generated based on an evaluation of the different indices across various characteristics or criteria. The process followed the steps outlined below.

2.1.1. Identification of Indices

The water security indices were identified and listed (e.g., Water Stress Index, Water Insecurity Index).

2.1.2. Defining the Key Characteristics

The characteristics used in each heatmap depended on the aspects of water security that needed to be emphasized. The categories of characteristics selected for evaluating the indices are given in the Results Section.

2.1.3. Scoring Process

Each index was then rated or scored based on how well it performs against each of these criteria. In this case, subjective expert judgment (e.g., reviews or critical analysis of the indices) was used to assign scores. For each characteristic, the indices were rated on a scale of 1 to 5 to indicate their performance in that category:

1 (Low): the index performs poorly or does not account for the characteristic.

5 (High): the index excels in this aspect and offers strong coverage or applicability.

2.1.4. Data Input

The scores were input into a matrix, where the rows represent the indices and the columns represent the criteria.

2.1.5. Heatmap Visualization

Once the indices had been rated for each characteristic, the data were fed into a heatmap, where color gradients visually represent the performance across the categories. Darker shades indicate higher scores, while lighter shades show areas where the index may be lacking. The scores were visually represented in a heatmap, with the color intensities reflecting the performance levels.

3. Results

Ensuring adequate and reliable household water access is a critical global challenge, with significant implications for health, well-being, and economic development [25]. Existing methods used to assess household water insecurity have traditionally focused on measures of water quality, quantity, and affordability [26]. However, these narrow indicators often fail to capture the full extent of the water-related burdens experienced at the household level [25]. Emerging research has highlighted the need for a more comprehensive conceptualization of household water insecurity that incorporates considerations of water entitlements, human capabilities, and sociocultural dynamics [26,27]. The development and validation of the Household Water Insecurity Experiences Scale represents a significant advancement in this direction, providing a holistic assessment of a household's experiences with water-related stresses and scarcities and uncertain access to water [25]. Quantifying the prevalence and distribution of household water insecurity is crucial for identifying vulnerable populations, informing targeted interventions, and monitoring progress toward universal water access. By adopting a multidimensional approach to understanding household water issues, researchers and policymakers can better address the complex, context-dependent nature of water security challenges.

3.1. Comparing and Critically Analyzing Major Water Security Indices, 1980s–1990s

This section compares and critically analyzes six prominent indices from the 1980s to the 1990s: the Water Stress Index, the Vulnerability of Water Systems Index, the Basic Human Needs Index, the Water Resources Vulnerability Index, the Indicator of Water Scarcity, and the Water Availability Index [28–31]. The Water Stress Index, introduced in 1989, is a widely used metric that measures the ratio of the total annual water use to the total available annual water supply. It provides a general assessment of water scarcity, with values above 0.4 indicating high water stress. However, this index has been criticized for its limited scope, as it fails to consider factors such as water quality, environmental flow requirements, and adaptive capacity.

The Vulnerability of Water Systems Index, developed in 1990, focuses on the resilience and adaptability of water systems to external stresses [32]. It incorporates factors like water supply variability, infrastructure, and institutional capacity, providing a more comprehensive assessment of water system vulnerability. The Basic Human Needs Index, introduced in 1996, assesses water scarcity in terms of its impact on meeting basic human needs, such as access to safe drinking water and sanitation [33]. This index highlights the social dimensions of water scarcity and its implications for human development.

The Water Resources Vulnerability Index, developed in 1997, considers a broader range of factors, including water availability, water quality, and institutional capacity [34]. This index aims to capture the overall vulnerability of a region's water resources, making it a useful tool for water resource management and planning.

The Indicator of Water Scarcity, introduced in 1998, is a refined version of the Water Stress Index, incorporating additional factors like environmental flow requirements and the virtual water trade [32]. This index provides a more nuanced assessment of water scarcity, but it still faces challenges in fully accounting for the complexities of water systems. The Water Availability Index, also introduced in 1998, focuses on the physical availability of water resources, considering factors like precipitation, surface water, and groundwater [32]. However, this index does not address the social, economic, and institutional factors that influence water accessibility and use.

The heatmap (Figure 1) visualizes these six water stress and vulnerability indices across different characteristics. The characteristics selected for this analysis are comprehensiveness (broadness of the index, covering various aspects of water security, such as availability, quality, governance, and socioeconomic conditions), data requirements (dependence on high-quality, accessible data), applicability (flexibility across global, regional, or local contexts), social factors, environmental factors, and institutional factors.

Each cell represents the score of a specific characteristic for a given index, with darker shades indicating higher scores. This heatmap provides a comparative overview of how each index performs across key dimensions like comprehensiveness, data requirements, and applicability.

In critically evaluating these indices, several key observations can be made. First, while each index provides valuable insights, they all tend to have a narrow focus, often overlooking the multidimensional nature of water scarcity [28]. Efforts have been made to address this limitation, such as the Sociotechnical Utility-Based Framework for Drinking Water Investment, which pairs the Falkenmark indicator with the UNDP's Human Development Index to create a more comprehensive social Water Stress Index [33]. Additionally, the indices have varying levels of data requirements and applicability, with some being more suitable for global or regional assessments, while others are better suited for local-level analysis [34]. Furthermore, the weighting and aggregation methods used in these indices can significantly impact the resulting assessments, highlighting the need for robust and context-specific approaches [28].

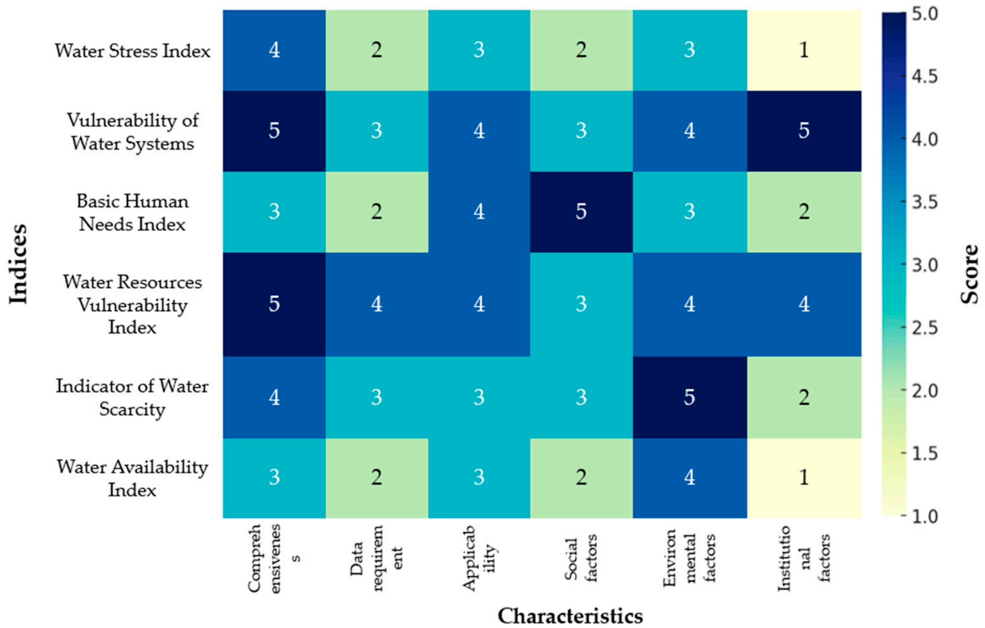

Figure 1. Heatmap of the selected water stress and vulnerability indices across the different characteristics.

In conclusion, the comparison and critical analysis of these water stress and vulnerability indices reveal the complexity and multifaceted nature of water scarcity. While these indices provide valuable insights, there is a need for a more holistic and adaptive framework that can account for the diverse social, economic, and environmental factors influencing water resources [28,32–34].

3.2. Comparing and Critically Analyzing Major Water Security Indices, 2000s–2010s

In this section, six prominent water sustainability indices developed in the time period from the 2000s to the 2010s—the Water Poverty Index, the Climate Variability Index, the Relative Water Stress Index, the Canadian Water Sustainability Index, the Watershed Sustainability Index, and the Arctic Water Resource Vulnerability Index—are analyzed [35–39].

The Water Poverty Index, introduced in 2003, is a comprehensive measure that considers the physical, economic, and social aspects of water [40]. It aims to capture the multidimensional nature of water poverty, including access to water, water quality, water use, water resources, and environmental factors [33]. The Climate Variability Index, developed in 2005, focuses on the impacts of climate variability on water resources, accounting for factors such as water availability, water quality, and adaptive capacity [28,41]. The Relative Water Stress Index, also introduced in 2005, evaluates the balance between water supply and demand, considering both natural and anthropogenic factors [33,40]. The Canadian Water Sustainability Index, proposed in 2007, takes a broader approach by assessing the sustainability of water resources at the community level, considering aspects like water quality, water quantity, infrastructure, environmental well-being, and human well-being [28,40]. The Watershed Sustainability Index, developed in 2007, focuses on the sustainability of watersheds, encompassing ecological, socioeconomic, and institutional dimensions [33,41].

Finally, the Arctic Water Resource Vulnerability Index, introduced in 2008, is specifically designed to assess the vulnerability of water resources in the Arctic region, addressing factors such as water quantity, water quality, and socioeconomic conditions [28,41].

Each of these indices has its own strengths and limitations, and the choice of which to use depends on the specific context and objectives of the assessment. The Water Poverty

Index and the Climate Variability Index provide a more comprehensive and holistic view of water sustainability, while the Relative Water Stress Index and the Canadian Water Sustainability Index offer a more targeted approach to specific aspects of water resources. The Watershed Sustainability Index and the Arctic Water Resource Vulnerability Index, on the other hand, are more tailored to specific geographical regions and their unique challenges [28,33,40,41].

The heatmap (Figure 2) visualizes these six water sustainability indices across different characteristics. Each cell represents the score of a specific characteristic for a given index, with darker shades indicating higher scores. This heatmap provides a comparative overview of how each index performs across key dimensions, like comprehensiveness, geographical focus, adaptability, data requirements, and focus on emerging threads. The characteristics selected for this analysis are comprehensiveness, geographical focus, adaptability (this measures how well an index can be adapted across different scales), data requirements (how dependent the index is on high-quality, accessible data), and the focus of these indices on emerging threads.

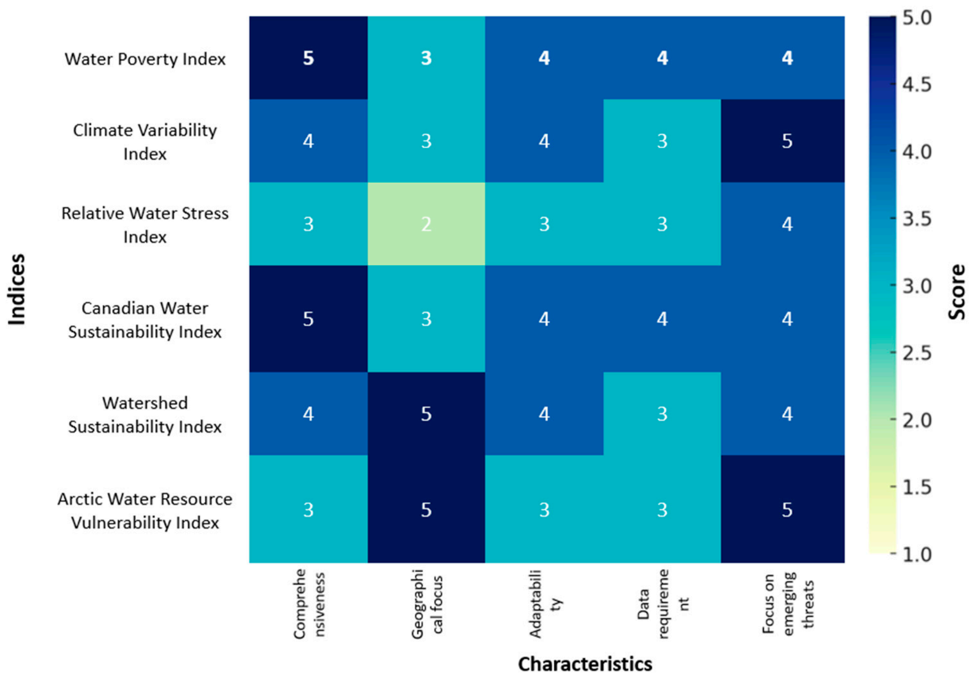

Figure 2. Heatmap of the water security indices (2000s–2010s) for the appropriate characteristics.

One common limitation of these indices is the reliance on data availability and reliability, which can be particularly challenging in developing countries or regions with limited data collection and monitoring capabilities [28,33]. Additionally, some indices may not adequately capture the dynamic and complex nature of water systems, especially in the face of emerging threats like climate change [42]. To address these limitations, researchers have proposed the development of more robust and adaptable indices that can better account for local and regional variations, as well as the integration of advanced technologies and expert systems to enhance the accuracy and relevance of water sustainability assessments [28].

In conclusion, the comparative analysis of these six water sustainability indices highlights the importance of a multifaceted approach to water resource management and the need for continuous refinement and adaptation of these tools to address the evolving challenges in the water sector.

3.3. Comparing and Critically Analyzing Major Water Security Indices, 2010s–2020s

This section provides a comparative analysis of five important indices during the time period 2010–2020: the Water Security Status Indicators, the Water Insecurity Index, the

National Water Security Index, the Objective Index, and the Synthesized Water Quality Index [39,43,44].

The Water Security Status Indicators, developed in 2013, is a framework that evaluates water security across five dimensions: water resources, water access, water capacity, water use, and water environment [45]. This comprehensive approach provides a holistic assessment of water security, but the authors note that the uneven distribution of water resources across time and space can lead to challenges such as floods and droughts, which are not fully captured by this index [45]. The Water Insecurity Index, introduced in 2014, focuses on the household-level experience of water insecurity, considering factors such as access, reliability, and affordability. This index is particularly useful for identifying vulnerable populations and targeting interventions [46]. However, it may not adequately capture the broader systemic issues of water security at the national or regional level. The National Water Security Index, developed in 2016, assesses water security across five pillars: water resources, water access, water environment, water disasters, and water governance. This index provides a more nuanced and comprehensive evaluation of water security, incorporating both biophysical and socioeconomic factors. The Objective Index, introduced in 2018, takes a different approach by focusing on quantifiable, objective indicators of water quality, availability, and access. This index aims to provide a more standardized and replicable measure of water security, but it may lack the contextual nuance of some of the other indices.

The Synthesized Water Quality Index, also developed in 2018, combines multiple water quality parameters into a single metric, providing a holistic assessment of water quality. This index is particularly useful for evaluating the suitability of water for various uses, such as drinking, agriculture, and industry [45]. While these indices share the common goal of evaluating water security, they differ in their scope, their methodology, and the specific aspects of water security they prioritize [45–48].

The heatmap (Figure 3) visualizes these five water security indices across different characteristics. Each cell represents the score of a specific characteristic for a given index, with darker shades indicating higher scores. This heatmap provides a comparative overview of how each index performs across key dimensions, like comprehensiveness, geographical focus, governance, standardization, and focus on water quality. This heatmap provides a clear and concise way to compare the strengths and weaknesses of each index across the different characteristics, aiding in the selection of the most appropriate index for specific research or policy needs.

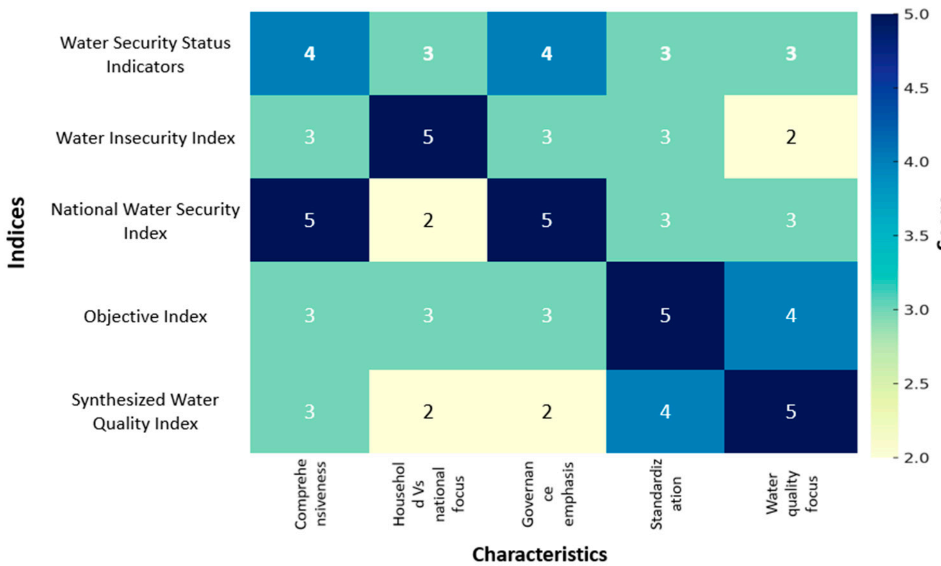

Figure 3. Heatmap visualization of the indices from the 2010s to the 2020s across the different characteristics.

The Water Security Status Indicators provide a broad assessment of water security, covering both physical and governance-related aspects. The Water Insecurity Index, on the other hand, focuses specifically on household-level water insecurity, highlighting the sociocultural dimensions of water security. The National Water Security Index offers a comprehensive national-level assessment, while the Objective Index strives for a more standardized and quantifiable approach. The Synthesized Water Quality Index, in contrast, specializes in assessing water quality, a crucial component of water security. The comparison of these indices highlights the importance of considering multiple perspectives and scales when evaluating water security [45–47,49].

Integrating qualitative and quantitative methods, as proposed in the literature, offers valuable insights into the social, political, and cultural factors that mediate household water experiences. Examining the interplay between household water insecurity and various domestic water indices further elucidates the drivers and consequences of water-related stresses, ultimately supporting more equitable and sustainable water resource management.

4. Conclusions

After analyzing and comparing the water stress and vulnerability indices, as well as the sustainability and security indices provided, several key insights and conclusions emerge regarding their effectiveness, strengths, and limitations. The indices, such as the Water Stress Index, the Vulnerability of Water Systems Index, and the Basic Human Needs Index, primarily focus on assessing the balance between water demand and availability. They also consider the impact of external stressors on water systems, which is crucial for understanding regional water scarcity and vulnerability. Indices like the Water Poverty Index, the Climate Variability Index, and the Watershed Sustainability Index offer a more comprehensive approach, integrating physical, social, economic, and environmental factors. This broader scope allows them to capture the multidimensional nature of water sustainability, which is essential for long-term planning and management. The Water Security Status Indicators, the Water Insecurity Index, and the National Water Security Index emphasize the overall security of water resources. They address a range of issues, from governance and infrastructure to household-level water access, offering a holistic view of water security challenges. One of the notable limitations of the current water security indices is the lack of consideration of recycled water as a vital resource for enhancing water security. Despite significant advancements in water recycling technologies and their growing application, particularly in water-scarce regions like the Middle East and North Africa [50], most indices fail to account for this emerging trend. There are studies that underscore the critical role that recycled water can play in reducing water stress [51]. Future iterations of water security frameworks could benefit from integrating water reuse parameters to provide a more comprehensive assessment of water management strategies.

Indices like the Water Poverty Index and the National Water Security Index excel in offering a detailed and holistic assessment of water resources by incorporating multiple dimensions such as social, economic, and environmental factors. However, their broad scope can sometimes lead to challenges in data collection and interpretation. Indices such as the Water Insecurity Index are particularly effective at the household level, identifying vulnerable populations and addressing specific local issues. On the other hand, indices like the National Water Security Index provide a macro-level assessment, which is crucial for national policymaking but may overlook local nuances. The National Water Security Index and the Vulnerability of Water Systems Index highlight governance and institutional capacity, which are critical for sustainable water management. However, they may underemphasize other dimensions, like water quality or ecosystem health. The Objective Index and the Synthesized Water Quality Index focus on quantifiable and standardized measures, which enhance comparability and replicability. However, they may lack the contextual nuance needed to fully understand water security in diverse settings. Indices like the Arctic Water Resource Vulnerability Index and the Watershed Sustainability Index are tailored to specific regions or ecosystems. This specificity makes them highly relevant for their intended contexts but limits their applicability in other regions.

The heatmaps created for comparing water security indices offer a multifaceted view of the strengths and weaknesses of each framework. Using different sets of characteristics across the heatmaps enables us to focus on the specific dimensions most relevant to the indices being analyzed, whether that be household-level security, national governance, or broader water availability metrics. This approach ensures that each index is evaluated fairly and accurately, allowing for a more comprehensive understanding of their respective advantages and limitations.

No single index can fully capture the complexity of water security, sustainability, or vulnerability. Each index has its own strengths and is best suited for specific contexts or scales of analysis. The comparison of these indices highlights the importance of integrating multiple perspectives and methodologies. A combined or hybrid approach that incorporates the best elements of each index could provide a more comprehensive and nuanced understanding of water-related challenges. As water-related challenges evolve, especially with the impacts of climate change and increasing demand, these indices will need continuous refinement and adaptation. There is also a growing need for indices that can incorporate real-time data and advanced technologies like remote sensing and AI for more dynamic assessments. The analysis of these water indices underscores the complexity and multifaceted nature of water resource management. While each index offers valuable insights, they each also have inherent limitations, particularly in their ability to address the diverse challenges posed by water scarcity, governance, quality, and security. For effective water management, it is crucial to select indices that align with specific assessment goals, geographical contexts, and policy needs. In many cases, a combination of indices may be necessary to achieve balanced and comprehensive evaluation. Moving forward, the development of more integrated and adaptable indices, capable of addressing both local and global water challenges, will be essential in guiding sustainable water management practices.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, and visualization was performed by J.B.; supervision was performed by K.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nounkeu, C.D.; Dharod, J.M. Status on the Scale Development to Measure Water Insecurity Experiences at the Household Level: A Narrative Review. *Adv. Nutr. Int. Rev. J.* **2019**, *10*, 864–875. [CrossRef] [PubMed]
2. Dinka, M.O. Safe Drinking Water: Concepts, Benefits, Principles and Standards. In *Water Challenges of an Urbanizing World*; Glavan, M., Ed.; IntechOpen: London, UK, 2018.
3. Srinivasan, V.; Konar, M.; Sivapalan, M. A dynamic framework for water security. *Water Secur.* **2017**, *1*, 12–20. [CrossRef]
4. Visser-Quinn, A.; Beevers, L.; Lau, T.; Gosling, R. Mapping future water scarcity in a water abundant nation: Near-term projections for Scotland. *Clim. Risk Manag.* **2021**, *32*, 100302. [CrossRef]
5. van Vliet, M.T.H.; Jones, E.R.; Flörke, M.; Franssen, W.H.P.; Hanasaki, N.; Wada, Y.; Yearsley, J.R. Global water scarcity including surface water quality and expansions of clean water technologies. *Environ. Res. Lett.* **2021**, *16*, 024020. [CrossRef]
6. Grillos, T.; Zarychta, A.; Nuñez, J.N. Water scarcity & procedural justice in Honduras: Community-based management meets market-based policy. *World Dev.* **2021**, *142*, 105451. [CrossRef]
7. Orimoloye, I.R.; Belle, J.A.; Olusola, A.O.; Busayo, E.T.; Ololade, O.O. Spatial assessment of drought disasters, vulnerability, severity and water shortages: A potential drought disaster mitigation strategy. *Nat. Hazards* **2021**, *105*, 2735–2754. [CrossRef]
8. Orimoloye, I.; Ololade, O.; Mazinyo, S.; Kalumba, A.; Ekundayo, O.; Busayo, E.; Akinsanola, A.; Nel, W. Spatial assessment of drought severity in Cape Town area, South Africa. *Heliyon* **2019**, *5*, e02148. [CrossRef]

9. Petruzzello, M. Water Scarcity. Encyclopedia Britannica. Available online: https://www.britannica.com/topic/water-scarcity (accessed on 13 September 2024).
10. UN, W. The United Nations World Water Development Report 2018. *Technol. Water Treat.* **2018**, *4*, 34.
11. Ismail, Z.; Go, Y.I. Fog-to-Water for Water Scarcity in Climate-Change Hazards Hotspots: Pilot Study in Southeast Asia. *Glob. Chall.* **2021**, *5*, 2000036. [CrossRef]
12. Alobireed, A. Global Water Desalination: A Comparison between Saudi Arabia and The United States of America. Ph.D. Dissertation, University of Pittsburgh, Pittsburgh, PA, USA, 2021. Available online: http://d-scholarship.pitt.edu/id/eprint/40982 (accessed on 13 September 2024).
13. Egbueri, J.C.; Agbasi, J.C. Data-driven soft computing modeling of groundwater quality parameters in southeast Nigeria: Comparing the performances of different algorithms. *Environ. Sci. Pollut. Res.* **2022**, *29*, 38346–38373. [CrossRef]
14. Persson, L.; Almroth, B.M.C.; Collins, C.D.; Cornell, S.; de Wit, C.A.; Diamond, M.L.; Fantke, P.; Hassellöv, M.; MacLeod, M.; Ryberg, M.W.; et al. Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environ. Sci. Technol.* **2022**, *56*, 1510–1521. [CrossRef] [PubMed]
15. Wwap, U. *WWAP (United Nations World Water Assessment Programme)*; Unesco: Paris, France, 2017.
16. Baba, A.; Gündüz, O. Effect of Geogenic Factors on Water Quality and Its Relation to Human Health around Mount Ida, Turkey. *Water* **2017**, *9*, 66. [CrossRef]
17. Nosetto, M.D.; Jobbágy, E.G.; Brizuela, A.B.; Jackson, R.B. The hydrologic consequences of land cover change in central Argentina. *Agric. Ecosyst. Environ.* **2012**, *154*, 2–11. [CrossRef]
18. Schwärzel, K.; Zhang, L.; Montanarella, L.; Wang, Y.; Sun, G. How afforestation affects the water cycle in drylands: A process-based comparative analysis. *Glob. Chang. Biol.* **2020**, *26*, 944–959. [CrossRef]
19. Stringer, L.C.; Mirzabaev, A.; Benjaminsen, T.A.; Harris, R.M.; Jafari, M.; Lissner, T.K.; Stevens, N.; der Pahlen, C.T.-V. Climate change impacts on water security in global drylands. *One Earth* **2021**, *4*, 851–864. [CrossRef]
20. Dasgupta, A.; Sen, D.S. Terrestrial water system and hydrological cycle alteration antecedent to adverse climate change in indian sub-continent a literature review. *Asian J. Sci. Technol.* **2021**, *12*, 11939–11945.
21. Nolte, A.; Eley, M.; Schöniger, M.; Gwapedza, D.; Tanner, J.; Mantel, S.K.; Scheihing, K. Hydrological modelling for assessing spatio-temporal groundwater recharge variations in the water-stressed Amathole Water Supply System, Eastern Cape, South Africa. *Hydrol. Process.* **2021**, *35*, e14264. [CrossRef]
22. Enderlein, R.; Bernardini, F. Nature for water: Ecosystem services and water management. *Nat. Resour. Forum* **2005**, *29*, 253–255. [CrossRef]
23. Tsegaye, S.; Gallagher, K.C.; Missimer, T.M. Coping with future change: Optimal design of flexible water distribution systems. *Sustain. Cities Soc.* **2020**, *61*, 102306. [CrossRef]
24. Burak, S.; Mat, H. Municipal water demand and efficiency analysis: Case studies in Turkey. *Water Policy* **2009**, *12*, 695–706. [CrossRef]
25. Young, S.L.; Boateng, G.O.; Jamaluddine, Z.; Miller, J.D.; Frongillo, E.A.; Neilands, T.B.; Collins, S.M.; Wutich, A.; Jepson, W.E.; Stoler, J. The Household Water InSecurity Experiences (HWISE) Scale: Development and validation of a household water insecurity measure for low-income and middle-income countries. *BMJ Glob. Health* **2019**, *4*, e001750. [CrossRef]
26. Wutich, A.; Budds, J.; Eichelberger, L.; Geere, J.; Harris, L.M.; Horney, J.A.; Jepson, W.; Norman, E.; O'Reilly, K.; Pearson, A.L.; et al. Advancing methods for research on household water insecurity: Studying entitlements and capabilities, socio-cultural dynamics, and political processes, institutions and governance. *Water Secur.* **2017**, *2*, 1–10. [CrossRef] [PubMed]
27. Rosinger, A.Y.; Young, S.L. The toll of household water insecurity on health and human biology: Current understandings and future directions. *WIREs Water* **2020**, *7*, e1468. [CrossRef]
28. Kansal, M.L.; Gaur, A. Expert System Based Water Sustainability Index. In Proceedings of the World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability, Palm Springs, CA, USA, 22–26 May 2011.
29. Falkenmark, M.; Lundqvist, J.; Widstrand, C. Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development. *Nat. Resour. Forum* **1989**, *13*, 258–267. [CrossRef]
30. Veettil, A.V.; Mishra, A.K. Potential influence of climate and variables on water security using blue and green water scarcity, Falkenmark index, and freshwater provision indicator. *J. Environ. Manag.* **2018**, *228*, 346–362. [CrossRef]
31. Norman, E.S.; Dunn, G.; Bakker, K.; Allen, D.M.; de Albuquerque, R.C. Water Security Assessment: Integrating Governance and Freshwater Indicators. *Water Resour. Manag.* **2013**, *27*, 535–551. [CrossRef]
32. Liu, J.; Yang, H.; Gosling, S.N.; Kummu, M.; Flörke, M.; Pfister, S.; Hanasaki, N.; Wada, Y.; Zhang, X.; Zheng, C.; et al. Water scarcity assessments in the past, present, and future. *Earth's Future* **2017**, *5*, 545–559. [CrossRef]
33. Schwetschenau, S.E.; Schubert, A.; Smith, R.J.; Guikema, S.; Love, N.G.; McElmurry, S.P. Improved Decision-Making: A Sociotechnical Utility-Based Framework for Drinking Water Investment. *ACS EST Eng.* **2022**, *2*, 1475–1490. [CrossRef]
34. Prabha, A.S.; Ram, A.; Irfan, Z.B. Exploring the relative water scarcity across the Indian million-plus urban agglomerations: An application of the Water Poverty Index. *HydroResearch* **2020**, *3*, 134–145. [CrossRef]
35. Sullivan, C.A.; Meigh, J.R.; Giacomello, A.M. The Water Poverty Index: Development and application at the community scale. *Nat. Resour. Forum* **2003**, *27*, 189–199. [CrossRef]

36. Alessa, L.; Kliskey, A.; Lammers, R.; Arp, C.; White, D.; Hinzman, L.; Busey, R. The arctic water resource vulnerability index: An integrated assessment tool for community resilience and vulnerability with respect to freshwater. *Environ. Manag.* **2008**, *42*, 523–541. [CrossRef] [PubMed]
37. Chaves, H.M.L.; Alipaz, S. An integrated indicator based on basin hydrology, environment, life, and policy: The watershed sustainability index. *Water Resour. Manag.* **2007**, *21*, 883–895. [CrossRef]
38. Wagener, T.; Sivapalan, M.; Troch, P.A.; McGlynn, B.L.; Harman, C.J.; Gupta, H.V.; Kumar, P.; Rao, P.S.C.; Basu, N.B.; Wilson, J.S. The future of hydrology: An evolving science for a changing world. *Water Resour. Res.* **2010**, *46*. [CrossRef]
39. Sullivan, C.; Meigh, J. Targeting attention on local vulnerabilities using an integrated index approach: The example of the climate vulnerability index. *Water Sci. Technol.* **2005**, *51*, 69–78. [CrossRef] [PubMed]
40. Attari, J.; Mojahedi, S. Water Sustainability Index: Application of CWSI for Ahwaz County. In Proceedings of the World Environmental and Water Resources Congress 2009: Great Rivers, Kansas City, MI, USA, 17–21 May 2009; pp. 1–7. [CrossRef]
41. Zhang, X.Y.; Zhu, J.W.; Xie, J.C.; Liu, J.L.; Jiang, R.G. Selection of an evaluation index for water ecological civilizations of water-shortage cities based on the grey rough set. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *82*, 012079. [CrossRef]
42. Garcia, C.A.B.; Silva, I.S.; Mendonça, M.C.S.; Garcia, H.L. Evaluation of Water Quality Indices: Use, Evolution and Future Perspectives. In *Advances in Environmental Monitoring and Assessment*; Sarvajayakesavalu, S., Ed.; IntechOpen: Rijeka, Croatia, 2018. [CrossRef]
43. Asian Development Bank, Asian Water Development Outlook 2020. Available online: https://www.adb.org/publications/asian-water-development-outlook-2020 (accessed on 31 January 2023).
44. Shrestha, S.; Aihara, Y.; Bhattarai, A.P.; Bista, N.; Kondo, N.; Futaba, K.; Nishida, K.; Shindo, J. Development of an objective water security index and assessment of its association with quality of life in urban areas of developing countries. *SSM-Popul. Health* **2018**, *6*, 276–285. [CrossRef]
45. Ahmed, A.; Srikanth, R. Application of Geospatial Techniques and the MCDM Method to Optimize Interlinking of Rivers in India. *J. Indian Soc. Remote Sens.* **2023**, *51*, 849–863. [CrossRef]
46. Assefa, Y.T.; Babel, M.S.; Sušnik, J.; Shinde, V.R. Development of a Generic Domestic Water Security Index, and Its Application in Addis Ababa, Ethiopia. *Water* **2018**, *11*, 37. [CrossRef]
47. Moglia, M.; Burn, S.; Tjandraatmadja, G. Vulnerability of water services in Pacific Island countries: Combining methodologies and judgment. *Water Sci. Technol.* **2009**, *60*, 1621–1631. [CrossRef]
48. Howlett, M.P.; Cuenca, J.S. The use of indicators in environmental policy appraisal: Lessons from the design and evolution of water security policy measures. *J. Environ. Policy Plan.* **2017**, *19*, 229–243. [CrossRef]
49. Robinne, F.-N.; Bladon, K.D.; Miller, C.; Parisien, M.-A.; Mathieu, J.; Flannigan, M.D. A spatial evaluation of global wildfire-water risks to human and natural systems. *Sci. Total. Environ.* **2018**, *610–611*, 1193–1206. [CrossRef] [PubMed]
50. Mateo-Sagasta, J. Water Reuse: A Potential Game-Changer for Water Security in the Middle East and North Africa. IWMI. Available online: https://www.iwmi.cgiar.org/blogs/water-reuse-a-potential-game-changer-for-water-security-in-the-middle-east-and-north-africa/ (accessed on 17 October 2024).
51. Garrick, D.; Hall, J.W. Water Security and Society: Risks, Metrics, and Pathways. *Annu. Rev. Environ. Resour.* **2014**, *39*, 611–639. [CrossRef]