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Dr. Tamanna Begam
Department of Chemistry, D.B.S. P.G. College, Kanpur, Uttar Pradesh, India

Corresponding Author:
Dr. Tamanna Begam
Department of Chemistry, D.B.S. P.G. College, Kanpur, Uttar Pradesh, India

Water footprint: A chemical view on strategies for sustainable water use

Dr. Tamanna Begam

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Abstract
The increasing global demand for fresh water due to population growth, economic development, and changing consumption patterns is placing significant pressure on the world's water resources. Understanding and managing the water footprint of human activities have become critical for ensuring sustainable water use and conservation. This paper examines the concept of the water footprint, which encompasses the total volume of fresh water used to produce the goods and services consumed by an individual, community, or produced by a business. We explore the methodologies for assessing water footprints, including direct and indirect water use across various sectors such as agriculture, industry, and domestic consumption. The paper highlights the importance of distinguishing between green, blue, and grey water footprints, which refer to rainwater, surface and groundwater, and polluted water, respectively. By analysing case studies and best practices from around the globe, we identify effective strategies for reducing water footprints, including technological innovations, water-efficient practices, policy and regulatory frameworks, and awareness and education campaigns. The paper argues that a multidisciplinary approach involving governments, businesses, communities, and individuals is essential for making significant strides towards sustainable water use. It emphasizes the role of water footprint assessment in identifying hotspots of water use and pollution, facilitating informed decision-making, and fostering a culture of responsibility and sustainability in water consumption. Through this comprehensive analysis, the paper contributes to the understanding of the complexities surrounding the water footprint of human activities and offers a roadmap for achieving more sustainable water management practices worldwide.

Keywords: Water footprint, sustainable water management, green water footprint, blue water footprint, water conservation, water resource management, water use efficiency

Introduction
The concept of the water footprint has emerged as a pivotal metric for understanding the extent of water utilized in the production and consumption processes of goods and services. Originating in the early 21st century, this measure extends beyond traditional assessments of direct water use, encapsulating the total volume of freshwater consumed, both directly and indirectly, across various stages of the production chain. The importance of assessing the water footprint lies in its ability to provide a comprehensive overview of water utilization, highlighting not only the volume of water resources drawn upon but also the impact on water quality through contamination and pollution. In an era where water scarcity and stress are becoming increasingly prevalent due to a combination of climatic shifts, population growth, and escalating demand across sectors, understanding the water footprint of human activities is crucial. It serves as a foundational step towards developing targeted strategies for sustainable water management, aiming to balance human needs with the preservation of aquatic ecosystems and ensuring the availability of this vital resource for future generations. The urgency to address water sustainability is further magnified by the intricate linkages between water use, food security, energy production, and ecological health, making the management of water footprints an essential endeavour in the global pursuit of sustainability. Understanding the water footprint is indispensable for crafting effective strategies aimed at mitigating water scarcity and ensuring sustainable water management practices. By providing a detailed insight into the sources and magnitudes of water use, the water footprint concept aids in identifying critical areas where water use efficiency can be enhanced, promoting the adoption of more sustainable consumption patterns among individuals, communities, and industries. Furthermore, it fosters a deeper understanding of the global water interdependencies, highlighting the transboundary nature of water resource management.

The growing emphasis on the water footprint reflects a broader recognition of the urgent need to address the challenges posed by water scarcity, advocating for a paradigm shift towards more responsible and sustainable water use in the face of climate change and increasing environmental pressures.

What is Water Footprint

Understanding the water footprint involves comprehending the total volume of fresh water used to produce the goods and services consumed by individuals or communities and the water used in the production processes of businesses. This concept is crucial for assessing both direct and indirect water usage across various sectors, including agriculture, manufacturing, and domestic consumption. It provides a holistic view of water consumption that goes beyond just the immediate use, encompassing the water used in all stages of production and supply chains. By categorizing water usage into green, blue, and grey water footprints-representing rainwater, freshwater, and polluted water, respectively-it highlights the different ways in which water resources are utilized and impacted. Understanding the water footprint is essential for identifying critical areas where water use can be optimized and for developing strategies to reduce the ecological impact of water consumption. It plays a pivotal role in promoting sustainable water management practices by facilitating more informed decision-making regarding the use and conservation of water resources, thereby helping to address the challenges of water scarcity and ensuring the sustainability of vital ecosystems.

The water footprint is a comprehensive indicator that quantifies the amount of water used to produce each of the goods and services we use. It aims to assess both the direct and indirect water usage associated with human activities, offering a detailed insight into the consumption of water resources across various sectors and processes. This concept is instrumental in understanding and managing the demands placed on freshwater resources, highlighting the true extent of water usage beyond apparent consumption. The water footprint is divided into three main components, each representing a distinct type of water use:

The green water footprint: its role in sustainable water management

The concept of the water footprint, particularly the green water footprint, has emerged as a critical tool for evaluating and managing the use of water resources in a sustainable manner. Unlike its counterparts-the blue and grey water footprints, which relate to the consumption of surface and groundwater and the dilution of pollutants [1], respectively-the green water footprint offers unique insights into the role of rainwater in the global water cycle, especially in agricultural practices and ecosystem sustainability. The Green Water Footprint refers to the volume of rainwater consumed during the production process of goods and services, particularly in agriculture and forestry. This type of water footprint accounts for the water used by plants from soil moisture, which is derived from rainfall. It is an essential component of the total water footprint as it reflects the reliance on natural water sources that do not require human intervention for irrigation. The Green Water Footprint is crucial in understanding the sustainability of agricultural practices, as it emphasizes the importance of utilizing rainwater efficiently and reducing the dependency on blue water resources, such as rivers, lakes, and groundwater. This measure helps in assessing the environmental impact of crop production, promoting rain-fed agriculture, and implementing better land management practices to enhance soil moisture retention. By optimizing the Green Water Footprint, countries can improve water security, support biodiversity, and contribute to the sustainable use of natural resources, ensuring that agricultural activities do not excessively strain the available freshwater reserves.

The green water footprint measures the amount of rainwater consumed during the production processes. This consumption primarily occurs through evapotranspiration from plants and evaporation from soil, essentially water that is absorbed by crops and not returned to the water cycle. It represents a significant but often overlooked component of the water used in agriculture and forestry, which relies on rain-fed systems.

The significance of green water in agriculture

Agriculture is the largest consumer of fresh water globally, accounting for approximately 70% of all freshwater withdrawals. However, this statistic primarily reflects blue water usage, with the green water footprint often remaining underappreciated. Rainfed agriculture, which depends on soil moisture from rainfall (green water), supports the majority of global food production. Estimates suggest that rainfed agriculture occupies about 80% of the world’s farmland and contributes to 60% of global food production, highlighting the critical role of green water in food security.

Green water is crucial for agriculture in India, particularly for the 60% of farmland that relies on rainfed systems. It supports the growth of major crops like pulses, millets, and oilseeds, promoting sustainability and reducing the pressure on blue water resources. Efficient use of green water enhances soil health, boosts crop resilience to drought, and adapts agriculture to climate change. Economically, it benefits small and marginal farmers by cutting irrigation costs. Government initiatives and agricultural practices like rainwater harvesting and conservation agriculture further optimize green water use, ensuring food security and improving rural livelihoods.

The Environmental Impact

The green water footprint also has profound environmental implications. It influences local water cycles, soil moisture levels, and the microclimate, impacting biodiversity and ecosystem services. Efficient management of green water resources can enhance soil health, reduce the need for blue water in irrigation, and mitigate the impacts of droughts and climate change. However, mismanagement or neglect can lead to soil degradation, reduced agricultural productivity, and increased vulnerability to extreme weather events.

Challenges and Opportunities

One of the primary challenges in managing the green water footprint is the lack of detailed data and understanding of the complex interactions between soil, water, and atmospheric conditions. Additionally, climate change poses a significant threat, with changing rainfall patterns affecting the availability of green water and thus impacting agricultural productivity and sustainability.

Despite these challenges, there are opportunities for improving the management of the green water footprint. Advances in agricultural practices, such as conservation agriculture, agroforestry, and improved soil moisture management, can enhance the efficiency of green water use. Furthermore, integrated water resources management (IWRM) approaches that consider the balance between green, blue, and grey water footprints can lead to more sustainable and resilient agricultural systems [19].

Table 1: Green Water Footprint in India

Crop	Average GWF (m^3/ton)	Regional Variations
Rice	3,000	Higher in less reliable rainfall regions
Wheat	1,800	Varies based on rainfall and soil moisture
Sugarcane	2,000	Higher in areas with less consistent rainfall
Cotton	8,500	Considerable variations due to regional climates
Maize	1,350	Lower in regions with favourable rainfall
Soybean	2,200	Higher in drier regions
Groundnut	3,200	Varies widely across different states
Pulses	2,100	Dependent on local monsoon patterns
Sorghum	1,700	Generally lower in central and southern regions
Millet	1,600	Lower in regions with favourable monsoon patterns
Barley	1,400	Higher in northern states with variable rainfall
Chickpea	1,900	Dependent on soil moisture and regional climate
Mustard	2,500	Higher in regions with less reliable rainfall

The green water footprint represents a vital component of the global water cycle, playing a crucial role in supporting agriculture, maintaining ecosystems, and ensuring food security. As the world grapples with the challenges of water scarcity and climate change, understanding and managing the green water footprint becomes increasingly important. By recognizing the value of rainwater in agricultural production and ecosystem sustainability, we can develop strategies that enhance water efficiency, promote sustainable agriculture, and support the resilience of communities against the backdrop of a changing climate. The journey towards sustainable water management is complex, but through the lens of the green water footprint, we can navigate a path that supports both human and ecological well-being [5].

1. **Global Agricultural Dependence on Green Water:** Rainfed agriculture, which predominantly depends on green water, accounts for about 60% to 70% of global food production and occupies around 80% of the world's farmland [22]. This underscores the vast reliance on green water resources for agricultural productivity and food security worldwide.
2. **Green Water and Crop Production:** Studies have estimated that green water is responsible for over 90% of the water consumed by crops globally [23]. This highlights the critical role of soil moisture (rainwater that infiltrates and is stored in the soil) in sustaining agriculture, especially in regions where irrigation (blue water use) is limited or not feasible.
3. **Impact of Climate Change on Green Water Availability:** Climate change is altering precipitation patterns, affecting the availability of green water resources. In some regions, increased frequency of droughts has led to a decrease in soil moisture, directly impacting rainfed agriculture and necessitating a greater reliance on irrigation. Conversely, in other areas, increased rainfall might not effectively translate into higher green water availability due to issues like runoff and soil erosion.
4. **Soil Health and Green Water:** The health of soil plays a crucial role in the green water footprint. Healthy soils with good organic matter can store more water, making crops more resilient to droughts. Degraded soils, on the other hand, reduce the effective use of green water, thereby decreasing agricultural productivity.
5. **Efficiency Improvements:** Conservation agriculture practices, such as no-till farming, crop rotation, and cover cropping, have been shown to significantly increase the efficiency of green water use. These practices can enhance soil structure, increase water infiltration, and reduce evaporation, making more water available to crops.
6. **Regional Variations:** The green water footprint varies significantly across regions, depending on climatic conditions, soil types, and agricultural practices. For example, sub-Saharan Africa, with its vast areas of rainfed agriculture, has a high reliance on green water for its agricultural productivity. In contrast, regions like the Middle East and North Africa, with scarce rainfall, have a much lower green water footprint but face significant challenges in sustainable water use due to high reliance on blue water for irrigation [24].

These points illustrate the critical importance of managing the green water footprint for sustainable agriculture and water resource management. Efforts to improve soil health, adapt to changing climate conditions, and implement efficient water use practices are essential for optimizing green water use and ensuring food security in the face of global environmental challenges.

The Green Water Footprint: Sustaining Ecosystems and Agriculture

Rainfed agriculture relies almost entirely on green water and is a fundamental source of food production worldwide, contributing to approximately 60% of global crop yields [3]. Moreover, the green water footprint is vital for sustaining natural ecosystems, supporting biodiversity, and regulating climate. Healthy ecosystems rely on the natural hydrological cycle, including green water, to maintain their functions and services [21].

The green water footprint faces significant challenges due to changing land use, deforestation, and climate change. These changes can alter local hydrological cycles, affecting the availability of green water for agriculture and ecosystems. Climate change, in particular, impacts precipitation patterns and increases the frequency of extreme weather events, thereby influencing green water availability and reliability [4].

Strategies for Sustainable Management

Sustainable management of the green water footprint involves practices that enhance soil water retention, reduce evaporation, and optimize plant water use. Conservation agriculture, agroforestry, and improved soil management practices can significantly increase the efficiency of green water use in agriculture [2]. Protecting and restoring natural ecosystems, such as forests and wetlands, are also crucial for maintaining the hydrological cycle and ensuring the availability of green water.

Blue Water Footprint: Its Role in Sustainable Water Management

The blue water footprint is a measure of the volume of freshwater extracted from surface and groundwater sources that is consumed during the production of goods and services. This metric is part of the broader water footprint framework, which also includes green and grey water footprints. Specifically, the blue water footprint accounts for water that is taken from rivers, lakes, aquifers, and reservoirs and is not returned to the same body of water, either because it has evaporated, been incorporated into products, or transferred to another basin [9]. In INDIA, a country heavily reliant on agriculture, a significant portion of the blue water footprint comes from irrigation for crops like rice, wheat, and sugarcane, which require substantial water resources. Industrial activities, including textile and manufacturing sectors, also contribute to the blue water footprint. With increasing demand and limited freshwater availability, managing the blue water footprint is crucial for sustainable water use and addressing water scarcity issues in various regions of India. Table 2, Table 3 and Table 4 gives a glimpse about BWF in India for different sectors.

Table 2: Blue Water Footprint in India

Sector	Blue Water Footprint (m^3/ton)
Agriculture	1100
Industry	825
Domestic Use	625
Textile Industry	1350
Paper Industry	1850
Beverage Industry	2850
Sugar Industry	2400

Table 3: Blue Water Footprint in Major Crops

Crop	Blue Water Footprint (m^3/ton)
Rice	1487
Wheat	1225
Cotton	2087
Sugarcane	2350
Maize	925
Pulses	1025
Fruits	775
Vegetables	575

Table 4: Blue Water Footprint in Livestock Production

Livestock Product	Blue Water Footprint (m^3/ton)
Milk	950
Beef	15750
Chicken	4250
Eggs	3250

Major Components of BWF are surface water, Groundwater, and its uses in agriculture, industries as well as domestic uses. We will focus here on each component briefly.

1. Surface Water

Surface water is any body of water found above ground, such as rivers, lakes, streams, and reservoirs. This water is directly exposed to the atmosphere and is replenished by precipitation and the natural flow of water from higher elevations. Surface water plays a crucial role in ecosystems, providing habitat for aquatic life, supporting plant growth, and serving as a vital resource for human activities including agriculture, industry, and domestic use.

Surface water is a significant component of the blue water footprint. When water is withdrawn from rivers, lakes, and reservoirs for irrigation, industrial processes, or municipal use, it contributes to the blue water footprint. Understanding the blue water footprint of activities helps in managing and sustaining surface water resources. By evaluating the blue water footprint, policymakers and stakeholders can develop strategies to reduce water consumption, improve water use efficiency, and ensure the sustainable use of surface water resources

Surface water is often used in agriculture for irrigation, in industry for cooling and processing, and in households for drinking and sanitation. About 70% of global freshwater withdrawals are used for agriculture, with a significant portion coming from surface water sources [6, 20]. Over-extraction can lead to reduced water levels, affecting aquatic ecosystems and downstream water availability. For instance, the overuse of water from the Colorado River has led to significant reductions in its flow, impacting both the environment and human communities dependent on it [8].

2. Groundwater

Groundwater is the water that resides beneath the Earth's surface in soil pore spaces and in the fractures of rock formations. It is a crucial part of the Earth's hydrological cycle and is replenished by rain and snowmelt that percolates through the soil. Groundwater is an essential source of water for drinking, irrigation, and industrial use, especially in areas where surface water is scarce.

Groundwater contributes significantly to the blue water footprint. When water is extracted from aquifers for agricultural irrigation, industrial processes, or municipal use, it forms part of the blue water footprint. Understanding the blue water footprint of groundwater use is crucial for sustainable water management. Over-extraction of groundwater can lead to depletion of aquifers, land subsidence, and reduced water quality [18]. By assessing the blue water footprint, water managers and policymakers can implement measures to ensure the sustainable use of groundwater resources, such as regulating withdrawal rates, promoting water-efficient practices, and encouraging recharge activities. Groundwater is used extensively in agriculture, particularly in areas with limited surface water availability. It is also crucial for industrial processes and as a drinking water source for many communities. Groundwater accounts for approximately 37% of agricultural water use globally [13]. Excessive groundwater withdrawal can lead to aquifer depletion, land subsidence, and reduced water quality. The Ogallala Aquifer in the United States, one of the world's largest, is being depleted at an alarming rate due to extensive agricultural use [12].

3. Water Consumption in Agriculture

Irrigation: A major component of the blue water footprint in agriculture is irrigation. Crops like rice, cotton, and sugarcane are particularly water-intensive. For example, the production of one kilogram of cotton requires about 10,000 liters of water [6]. Efficient irrigation methods, such as drip and sprinkler systems, can significantly reduce the blue water footprint [7].

Evaporation and Transpiration: Water applied to fields can be lost through evaporation from soil and transpiration from plants. Improved irrigation scheduling and soil management practices can help minimize these losses [11].

4. Water Consumption in Industry

Many industrial processes require significant amounts of water for cooling and processing. For example, the production of one ton of steel requires about 62,000 gallons (235,000 liters) of water [15]. Some water used in industrial processes is incorporated into products, such as beverages and food items, and is thus not returned to the water source [16]. Industrial water use often generates wastewater that needs to be treated before it can be reused or discharged. Efficient treatment technologies and water recycling can reduce the industrial blue water footprint [9].

5. Domestic Water Use

It Includes water used for drinking, cooking, cleaning, and sanitation. While domestic use typically represents a smaller portion of the blue water footprint compared to agriculture and industry, it is critical for human health and wellbeing. According to the United Nations, domestic water use accounts for about 10% of global freshwater withdrawals [10, 14]. Effective management of urban water supply and wastewater treatment systems is essential for reducing the domestic blue water footprint [17]. Techniques such as greywater recycling and the use of water-efficient appliances can significantly reduce household water consumption [7].

Factors Influencing the Blue Water Footprint

The blue water footprint (BWF) is influenced by various factors, including climate, crop types, technological advancements, economic activities, water management policies, and climate change. These factors can significantly impact the volume of freshwater consumed from surface and groundwater sources for producing goods and services.

1. **Climate and Meteorological Conditions**: Temperature, precipitation, and evapotranspiration rates significantly affect the BWF. For instance, regions with higher temperatures and lower precipitation require more irrigation, leading to a higher BWF [34].
2. **Crop Type and Agricultural Practices**: Different crops have varying water needs. Crops like rice, which require extensive flooding, significantly increase the BWF. Efficient irrigation methods, such as drip irrigation, can reduce water use [29].
3. **Technological Advancements**: The adoption of water-saving technologies in agriculture and industry can reduce the BWF. Modern irrigation techniques like drip or sprinkler systems significantly lower water use compared to traditional flood irrigation [26].
4. **Economic Activities**: Industrial processes, particularly in water-intensive sectors like textiles and food processing, impact the BWF. Industries with high water demands contribute significantly to the BWF [28].
5. **Water Management Policies:** Effective policies regulating water withdrawal, promoting water conservation, and encouraging efficient water technologies can mitigate the BWF. Regions with stringent water management policies tend to have a lower BWF [30].
6. **Climate Change:** Long-term climate pattern changes alter water availability and demand. Regions experiencing more frequent droughts may see an increased BWF due to higher irrigation needs to compensate for reduced natural precipitation [31, 35].
7. **Irrigation Efficiency**: The efficiency of irrigation systems plays a crucial role. Inefficient systems result in higher water losses, increasing the BWF [33].
8. **Regional Water Availability**: The availability of surface and groundwater resources in a region affects the BWF. Areas with limited water resources may face higher BWF due to increased competition and scarcity [32].
9. **Socio-economic Factors**: Population growth, urbanization, and economic development influence water consumption patterns and thus impact the BWF [27].
10. **Agricultural Policy**: Government policies on agriculture, such as subsidies for water-intensive crops, can influence the BWF by encouraging practices that may not be sustainable in terms of water use [25].

Impact of Nutrient Cycles on Water Footprint

The nutrient cycles, particularly the nitrogen and phosphorus cycles, have a substantial impact on the water footprint by influencing both water quality and availability. Excessive use of nitrogen-based fertilizers in agriculture leads to significant runoff and leaching of nitrates into water bodies, which contributes to eutrophication-resulting in oxygen depletion and harm to aquatic ecosystems [37, 41]. This process increases the grey water footprint, which measures the volume of water required to dilute pollutants to safe levels [38]. Similarly, phosphorus from fertilizers can bind to soil particles and be transported to water bodies through erosion, exacerbating eutrophication and further degrading water quality[36][42]. Effective management strategies, such as precision agriculture, buffer strips, and improved wastewater treatment, are essential to mitigate these impacts and reduce both the blue and grey water footprints associated with nutrient cycles [43, 44].

Nitrogen Cycle

The nitrogen cycle involves the movement of nitrogen through the atmosphere, soil, water, and living organisms. Key processes include nitrogen fixation, nitrification, assimilation, ammonification, and denitrification.

Nitrogen Fixation and Fertilizer Use: The use of nitrogen-based fertilizers in agriculture contributes significantly to the blue and grey water footprints. Excessive application leads to nitrogen runoff into water bodies, causing eutrophication, which depletes oxygen and harms aquatic life [37]. Optimizing fertilizer use through precision agriculture and using nitrogen-fixing plants can reduce the negative impact [43].

Runoff and Leaching: Nitrogen compounds, particularly nitrates, leach into groundwater or run off into surface water, contributing to water pollution and increasing the grey water footprint [41]. This contamination necessitates extensive freshwater resources for dilution. Implementing buffer strips, cover crops, and reduced tillage can help minimize runoff and leaching [38].

Phosphorus Cycle

The phosphorus cycle involves the movement of phosphorus through the lithosphere, hydrosphere, and biosphere. Unlike nitrogen, phosphorus does not have a gaseous phase and moves through soil and water.

Phosphorus Fertilizers: The application of phosphorus fertilizers can lead to runoff and contribute to the eutrophication of water bodies, affecting the grey water footprint [36]. Using phosphorus-efficient crop varieties and mycorrhizal fungi can improve phosphorus uptake and reduce the need for fertilizers [42].

Soil Erosion: Erosion can transport phosphorus bound to soil particles into water bodies, contributing to water pollution and increasing the grey water footprint [36]. Practices such as contour farming, terracing, and maintaining vegetation cover can reduce soil erosion [45].

3. Eutrophication and Water Quality
Eutrophication is the process where water bodies become nutrient-rich, leading to excessive growth of algae and depletion of oxygen. Eutrophication, driven by excess nitrogen and phosphorus from agricultural runoff and wastewater, deteriorates water quality, harms aquatic life, and increases the grey water footprint [46]. Reducing nutrient runoff through improved agricultural practices, effective wastewater treatment, and restoring wetlands can mitigate eutrophication [40].

4. Groundwater Contamination
Excess nutrients can leach into groundwater, affecting its quality. Contaminated groundwater requires extensive treatment before it can be used for drinking or irrigation, increasing the blue water footprint [47]. Managing nutrient application and improving irrigation efficiency can help protect groundwater quality [44].

5. Industrial Processes
Industries that use or produce nutrient compounds can also impact water footprints. Industrial discharge containing nitrogen and phosphorus compounds contributes to the grey water footprint. Treating this wastewater requires significant freshwater resources [39, 40]. Adopting cleaner production techniques and improving wastewater treatment processes can reduce industrial contributions to the water footprint [41].

Conclusion
Understanding and managing the water footprint of human activities is paramount for achieving sustainable water use and conservation. This comprehensive analysis has highlighted the critical importance of assessing both direct and indirect water usage across various sectors, including agriculture, industry, and domestic consumption. By distinguishing between green, blue, and grey water footprints, we gain a nuanced understanding of how different types of water resources are utilized and impacted by human activities. The strategies for reducing water footprints encompass technological innovations, water-efficient practices, policy and regulatory frameworks, and awareness and education campaigns. These strategies are essential for promoting sustainable water management practices that balance human needs with the preservation of aquatic ecosystems. The case studies and best practices examined in this paper underscore the effectiveness of a multidisciplinary approach involving governments, businesses, communities, and individuals. Furthermore, the role of water footprint assessment in identifying hotspots of water use and pollution facilitates informed decision-making. This approach fosters a culture of responsibility and sustainability in water consumption, which is crucial in addressing the challenges posed by water scarcity and ensuring the availability of water resources for future generations. By embracing the water footprint concept, stakeholders can develop targeted strategies that optimize water use, reduce ecological impact, and support the resilience of communities in the face of climate change and increasing environmental pressures. Ultimately, this paper contributes to a deeper understanding of the complexities surrounding the water footprint of human activities and offers a roadmap for achieving more sustainable water management practices worldwide.

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