A Comprehensive Review of Green Water Accounting

by - -

Interconnection: An Economic Perspective Horizon

A Comprehensive Review of Green Water Accounting

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ABSTRACT

Water resources are vital for sustaining life, ecosystems, and economic development, with traditional management focusing primarily on blue water (surface and groundwater). However, the equally crucial role of green water, soil moisture used by vegetation, has been underrepresented in water management policies. This study explores the concept of green water accounting, emphasizing its significance in rain-fed agriculture, ecosystem health, and sustainable water management. Through a mixed-method approach involving remote sensing, field surveys, and modeling, the research quantifies green water flows and highlights their importance for agricultural productivity and ecosystem services. The findings underscore the need for integrating green water into broader water management frameworks, developing holistic strategies that consider the interplay between water, land, and ecosystems. The study concludes with recommendations for policy integration, capacity building, and further research to enhance the understanding and application of green water accounting.

Keywords: Green Water Accounting, Rain-Fed Agriculture, Ecosystem Services, Sustainable Water Management, Soil Moisture

Fields: Hydrology, Economy, Business

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INTRODUCTION

Water resources are fundamental to sustaining life, supporting ecosystems, and driving economic development. They are essential not only for drinking and sanitation but also for agriculture, industry, and energy production. As the global population continues to grow and climate change exacerbates water scarcity in many regions, the sustainable management of water resources has become increasingly critical. Traditionally, water management efforts have focused on "blue water," which includes surface water in rivers, lakes, and reservoirs, as well as groundwater. However, this approach often overlooks the equally important "green water", the water stored in soil and used by vegetation through processes like transpiration and evaporation (Wang et al., 2021).

Green water plays a pivotal role in rain-fed agriculture, which accounts for a significant portion of global food production. It is also crucial for maintaining the health of natural ecosystems, such as forests, grasslands, and wetlands, which provide vital services like carbon sequestration, habitat for biodiversity, and regulation of the water cycle. Despite its importance, green water has traditionally been underrepresented in water management policies and accounting systems (Renaldo et al., 2021). This is partly because it is more challenging to quantify than blue water, as it involves complex interactions between soil, vegetation, and climate (Correia, 2019).

Green water is a critical component of the hydrological cycle, particularly in rain-fed agriculture, forestry, and natural ecosystems. It represents the water that is absorbed and stored in the soil after precipitation and is subsequently used by plants for growth and transpiration. This form of water is essential for the sustenance of vegetation, which in turn supports biodiversity, regulates local climates, and contributes to carbon sequestration. Despite its integral role in supporting terrestrial ecosystems and agricultural productivity, green water has often been overshadowed by the focus on blue water in traditional water accounting practices (Islam & Murakami, 2020).

Blue water (T. Chandra et al., 2024), which includes surface and groundwater resources, has been the primary focus of water management due to its direct use for irrigation, industrial processes, and domestic consumption. As a result, water policies, infrastructure investments, and management strategies have been largely centered around the extraction, distribution, and conservation of blue water resources. However, this blue watercentric approach fails to capture the full dynamics of the hydrological cycle, leading to an incomplete understanding of water availability and use, especially in regions dependent on rain-fed systems.

The oversight of green water in traditional accounting systems has significant implications for sustainable water management. In many parts of the world, especially in developing countries, rain-fed agriculture is the backbone of food security and rural livelihoods. By not accounting for green water, we risk underestimating the water needs of these agricultural systems, potentially leading to unsustainable land use practices, soil degradation, and reduced crop yields. Furthermore, the lack of integration of green water into broader water management frameworks hinders the development of holistic strategies that consider the interconnections between water, land, and ecosystems.

Recognizing the importance of green water and incorporating it into water accounting practices is crucial for creating more resilient agricultural systems and sustainable ecosystem management. This paper aims to delve deeper into the concept of green water accounting by exploring its methodologies, the challenges associated with its quantification, and the implications for water policy (Renaldo, Sally, et al., 2023) and sustainable development. By doing so, it seeks to highlight the need for a more inclusive approach to water management that acknowledges the vital role of green water in sustaining both human (Tanjung et al., 2023) and ecological communities.

LITERATURE REVIEW

Green water accounting has emerged as a vital tool for understanding the role of soil moisture in agricultural productivity and ecosystem health. Early studies by Falkenmark and Rockström (2006) highlighted the significance of green water in ensuring food security, particularly in regions dependent on rain-fed agriculture. These studies paved the way for subsequent research, which emphasized the need to integrate green water into broader water accounting frameworks (Gazal et al., 2022; Maniam et al., 2021; McCarroll & Hamann, 2020).

Research has shown that green water plays a pivotal role in biomass production, carbon sequestration, and climate regulation. Liu et al. (2010) demonstrated that green water contributes significantly to crop yields in semi-arid regions, where blue water resources are scarce. Moreover, recent advancements in remote sensing and modeling techniques have enabled more accurate quantification of green water flows, further underscoring its importance in water resource management (Atmaja & Yasa, 2020; Feng et al., 2021; Olusanmi et al., 2021).

Despite these advancements, challenges remain in fully integrating green water into water accounting systems. The complexity of measuring soil moisture, the spatial and temporal variability of green water flows, and the lack of standardized methodologies are some of the key hurdles identified in the literature (Hoekstra et al., 2011).

METHODOLOGY

This study adopts a mixed-method approach to green water accounting, combining both qualitative and quantitative methods (Creswell, 2014; Sekaran & Bougie, 2016). The research is conducted in three stages.

Data Collection (W et al., 2023):

1. Remote Sensing: Satellite imagery is used to estimate soil moisture levels across different land-use types (Renaldo, Andi, et al., 2023), including agricultural fields, forests, and grasslands. The Normalized Difference Vegetation Index (NDVI) is employed to assess vegetation health, which is closely linked to green water availability.
2. Field Surveys: Soil samples are collected from selected sites to measure soil moisture content directly. These measurements are used to validate the remote sensing data.
3. Literature Review: A thorough review of existing studies on green water accounting is conducted to identify best practices and methodologies.

Data Analysis:

1. Water Balance Model (Nyoto, Sudarno, et al., 2023): A water balance model is developed to quantify green water flows, considering factors such as precipitation, evapotranspiration, and soil characteristics. The model is calibrated using the data obtained from remote sensing and field surveys.
2. Scenario Analysis: Different land-use scenarios are simulated to assess the impact of changes in vegetation cover, climate, and agricultural practices on green water availability.

Validation: The model's accuracy is evaluated by comparing its outputs with observed data from field surveys and other independent studies. Sensitivity analysis is conducted to identify the most critical factors influencing green water flows.

RESULT AND DISCUSSION

The results of this study underscore the importance of green water in sustaining agricultural productivity and ecosystem services. The water balance model reveals that green water accounts for a significant proportion of the total water used by crops in the study area, particularly in regions with limited access to blue water resources. The scenario analysis indicates that changes in land use, such as deforestation or conversion of natural ecosystems to agriculture, can lead to a substantial reduction in green water availability, with adverse effects on crop yields and ecosystem health.

The findings also highlight the spatial variability of green water flows (Fakoya & Imuezerua, 2021; Fatxulloyev et al., 2021), with some regions experiencing higher soil moisture levels due to favorable climatic conditions or sustainable land management practices. The study emphasizes the need for context-specific strategies to enhance green water use, such as optimizing crop selection, improving soil management, and promoting agroforestry practices.

Measuring green water is essential for several reasons, particularly in the context of sustainable water management, agriculture, and ecosystem preservation. Here are the key reasons for measuring green water:

1. Agricultural Productivity and Food Security (Es'haghi et al., 2022; Holyoak et al., 2019; Jamshidi, 2021):
   - Green water is the primary source of water for rain-fed agriculture, which accounts for a significant portion of global food production. By measuring green water, we can better understand the soil moisture available to crops, leading to more accurate predictions of agricultural yields and better planning for food security.
   - In regions where irrigation infrastructure is limited, understanding green water availability can help farmers optimize planting schedules, select appropriate crop varieties, and implement soil management practices that enhance water retention and crop growth.
2. Sustainable Water Resource Management (Correia, 2019; Feng et al., 2021; Olusanmi et al., 2021):
   - Traditional water management focuses heavily on blue water (surface and groundwater), often neglecting the contribution of green water to the overall hydrological cycle. Measuring green water allows for a more comprehensive understanding of water resources, ensuring that water management strategies account for the full spectrum of water use, including the vital role of soil moisture.
   - This holistic approach is crucial for developing sustainable water policies that balance the needs of agriculture, industry, and natural ecosystems.
3. Climate Change Adaptation (Fort & Freschet, 2020; Holyoak et al., 2019; Turner et al., 2010):
   - Climate change is altering precipitation patterns, leading to more frequent droughts and shifts in the availability of water resources. By measuring green water, we can assess how these changes impact soil moisture and plant water use, enabling better adaptation strategies for agriculture and natural resource management.
   - Understanding green water dynamics is particularly important for regions that rely on rain-fed agriculture, where changes in green water availability directly affect food security and livelihoods.
4. Ecosystem Health and Biodiversity (Curry & Donnellan, 2015):
   - Green water is essential for maintaining the health of natural ecosystems, such as forests, grasslands, and wetlands. These ecosystems provide critical services, including carbon sequestration, habitat for biodiversity, and regulation of local climates.
   - By measuring green water, we can monitor the health of these ecosystems, assess the impacts of land-use changes, and develop conservation strategies that maintain or enhance green water availability for these critical environments.
5. Informed Land-Use Planning (Atmaja & Yasa, 2020; Gazal et al., 2022; Schoonover & Crim, 2015):
   - Land-use decisions (S. Chandra et al., 2023), such as deforestation, urbanization, and agricultural expansion, can significantly alter green water flows. Measuring green water helps land managers understand the implications of these changes on soil moisture and ecosystem services.

- This information is vital for making informed decisions that balance development (Sevendy et al., 2023) needs with the preservation of natural resources and ecosystem functions.

6. Water Accounting and Policy Development:

   - Incorporating green water into water accounting frameworks allows for a more accurate representation of total water resources. This is critical for developing water policies that reflect the true availability and distribution of water, ensuring that all sources of water, including soil moisture, are managed sustainably.

   - Policies informed by comprehensive water accounting, including green water, are better equipped to address water scarcity, support agricultural sustainability, and protect ecosystems.

7. Improved Hydrological Models: Measuring green water contributes to the development of more accurate hydrological models that can simulate water movement through soil, vegetation, and the atmosphere. These models are essential for predicting the impacts of climate change, land-use changes, and water management practices on water availability and distribution (Turner et al., 2010).

Furthermore, the research identifies several challenges in green water accounting, including the difficulty of accurately measuring soil moisture and the need for more robust models to capture the complex interactions between vegetation, soil, and climate. These challenges suggest that there is still considerable scope for further research and methodological refinement in this field.

CONCLUSION

Conclusion

Green water accounting offers a valuable framework for understanding the role of soil moisture in supporting agricultural production and maintaining ecosystem services. The study demonstrates that green water is a critical but often overlooked component of the hydrological cycle, particularly in regions dependent on rain-fed agriculture. By integrating green water into water accounting systems, policymakers and water managers can make more informed decisions to promote sustainable water use (Goh et al., 2022) and enhance food security.

However, the study also highlights several challenges in implementing green water accounting, including the need for standardized methodologies and better data on soil moisture. Addressing these challenges will require continued research, capacity building, and collaboration between researchers, policymakers, and practitioners.

Recommendations

Based on the findings of this study, several recommendations are proposed:

1. Policy Integration: Governments and international organizations should incorporate green water accounting into national water management policies and frameworks to ensure a more holistic approach to water resource management.

2. Capacity Building: Training programs should be developed to equip water managers, agricultural practitioners, and policymakers with the skills and knowledge needed to implement green water accounting effectively.

3. Research and Development: Further research is needed to refine methodologies for measuring and modeling green water flows, particularly in diverse climatic and land-use contexts.

4. Sustainable Land Management: Practices such as agroforestry, conservation agriculture, and soil moisture conservation should be promoted to enhance green water availability and optimize its use in agriculture and ecosystem management.

5. Public Awareness: Efforts should be made to raise awareness among stakeholders about the importance of green water in sustaining agricultural productivity and ecosystem health, encouraging the adoption of practices that enhance green water use.

Future Research

Future research on green water accounting could focus on several key areas to advance our understanding and improve the application of this critical concept in sustainable water management. Here are some potential directions for future research:

1. Integration of Green and Blue Water Accounting

   - Holistic Water Accounting Models: Future research should focus on developing integrated water accounting models that combine green and blue water resources. These models would provide a more comprehensive understanding of the entire hydrological cycle and improve water management strategies at both regional and global scales.

- Policy Implications: Investigating how integrated green and blue water accounting can influence policy development, particularly in water-scarce regions, is essential. Research could explore the impact of including green water in water allocation frameworks and how it might influence land-use planning, agricultural policies, and climate adaptation strategies.

2. Advancements in Remote Sensing and Data Analytics

- Enhanced Remote Sensing Technologies (Junaedi et al., 2023; Nyoto et al., 2024): Future research could explore advancements in remote sensing technologies to improve the accuracy and resolution of green water measurements. This includes the development of new satellite sensors, drone-based remote sensing, and the use of artificial intelligence to analyze large datasets.
- Big Data and Machine Learning: Leveraging big data and machine learning techniques to analyze complex datasets from multiple sources (e.g., satellite imagery, climate models, soil sensors) could enhance the precision of green water assessments. Research could focus on creating predictive models that account for climate variability and its impact on green water availability.

3. Climate Change Impacts on Green Water

- Modeling Climate Scenarios: Research could explore how different climate change scenarios will affect green water resources, particularly in vulnerable regions. This includes studying changes in precipitation patterns, soil moisture dynamics, and vegetation responses to climate stressors.
- Adaptation Strategies: Investigating adaptive strategies that optimize green water use in agriculture and natural ecosystems under changing climate conditions is crucial. Future research could focus on developing resilient crop varieties, improving soil management practices, and enhancing water retention in soils.

4. Economic Valuation of Green Water

- Valuing Ecosystem Services: Future research could explore methods for quantifying the economic value (Sudarno et al., 2022) of green water in supporting ecosystem services, such as carbon sequestration, biodiversity, and local climate regulation. This could inform cost-benefit analyses of conservation strategies and guide investments in ecosystem restoration.
- Green Water in Agricultural Economics: Investigating the role of green water in agricultural productivity and its contribution to the economy could provide insights into the economic benefits of sustainable water management practices. This research could also explore the potential for green water markets and incentives for farmers to adopt green water-efficient practices.

5. Social and Institutional Dimensions (Renaldo, Junaedi, et al., 2022)

- Community-Based Water Management: Research could explore the role of local communities in managing green water resources, particularly in rain-fed agricultural systems. Understanding how traditional knowledge (Andi et al., 2023) and practices can be integrated with modern water management strategies is important for fostering sustainable practices at the grassroots level.
- Institutional Frameworks: Investigating the institutional frameworks needed to support green water accounting and management could provide insights into the governance structures (Renaldo, Suhardjo, et al., 2022; Yusrizal et al., 2021), policies, and regulations required to ensure sustainable water use. This includes exploring how international cooperation and transboundary water management can incorporate green water considerations.

6. Green Water in Urban Environments

- Urban Green Spaces: Future research could explore the role of green water in urban environments, particularly in maintaining green spaces, reducing urban heat islands, and managing stormwater. This research could inform urban planning and the design of sustainable cities that incorporate green water management into their infrastructure.
- Water-Sensitive Urban Design: Investigating how water-sensitive urban design (WSUD) principles can be applied to enhance green water use in cities could lead to innovations (Renaldo et al., 2024) in urban water management. This includes exploring the potential for green roofs, permeable pavements, and urban wetlands to optimize green water retention and use.

7. Educational and Capacity-Building Initiatives

- Educational Programs (Cahyanto et al., 2023): Research could focus on developing educational programs and training materials to raise awareness about the importance of green water among policymakers, water managers, and the general public. This includes creating curricula for schools and universities that emphasize the role of green water in sustainable development (Nyoto, Effendi, et al., 2023).

- Capacity Building in Developing Countries: Future research could explore strategies for building capacity in developing countries to measure, manage, and utilize green water resources effectively. This includes training in the use of remote sensing technologies, data analysis, and the implementation of green water accounting in water management practices.

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