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COMMENTARY

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Forming the Future of Agrohydrology

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Key Points:

- Agrohydrology has yet to materialize as a distinct sub-discipline in hydrology despite the importance of agriculture in the water cycle
- We propose agrohydrology as a sub-discipline that embraces tools from physical and social sciences across diverse agricultural landscapes
- Agrohydrology as a revised sub-discipline offers new opportunities for the sustainable management of water for food in a changing world

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Abstract Agricultural water management is increasingly prioritized throughout the world as producers are tasked with meeting growing crop demand while also managing environmental resources more sustainably. Likewise, agriculture is increasingly modifying the terrestrial water cycle. In response to these dynamics, the informal research discipline of agrohydrology continues to grow, fueled by a new era of rapidly evolving research tools and big data availability. While many researchers are actively invested in agrohydrology as a research topic, there remains a gap in formalizing this valuable discipline. This article aims to: (a) identify key research themes in agrohydrology, (b) conceptualize future research topics within each theme, and (c) estimate a timeframe before topics become pressing (i.e., before a topic becomes a limiting factor in advancing water management in an agricultural context). This commentary is meant to guide the trajectory of an evolving discipline of agrohydrology, the practice of agricultural water management at multiple nested scales, and the conversation of the invested public.

Plain Language Summary The study of water in agriculture is an important global research field. Water supports farming and ranching, and agriculture provides food, feed, fiber, and fuel. However, agricultural activities can also stress water resources. As a result, society faces many water challenges in agriculture. The global demand for agricultural products is increasing, but the availability of fresh water is decreasing in many places. Sometimes this is because of a lack of water, contamination, or social changes. We propose the study of such problems and their solutions be recognized as its own subdiscipline, agrohydrology. Here, we imagine the future of the discipline by giving form to research themes and topics that can rally researchers from many existing fields around this revised subdiscipline.

1. Background to Agrohydrology

Water plays a vitally important role in the world's supply of food, fiber, feed, and fuel (Chapagain & Hoekstra, 2004; Dalin et al., 2012). Not only is water a necessary input to agricultural production, but it can further be an output of varying quantity, quality, or toxicity (Chen et al., 2020; Gassman et al., 2014), a driver of local and regional

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weather patterns (Harding & Snyder, 2012; Mueller et al., 2016; Raddatz, 2014), a mechanism for increasing revenues (Smidt et al., 2019), a staple for cultural identity (Anderson et al., 2019; Fischer & Sanderson, 2022), and a centerpiece for regulatory struggle (e.g., CSGMA, 2014), among many other concepts and applications. In its simplest form, hydrology is the study of water and its movement on the earth. However, hydrology as a discipline has evolved to broader domains, including the need to embrace concepts and methods from social sciences, due to increasingly complex water challenges that need to be addressed, like those in agricultural landscapes (McLamore et al., 2023). These shifts in hydrology are highly consequential and have even prompted a recently updated water cycle diagram from the US Geological Survey (Corson-Dosch et al., 2023), complementing work that concluded standard water cycle diagrams neglected anthropogenic processes that represent a larger proportion of flux and storage than many natural processes (Abbott et al., 2019).

Despite growth in agricultural hydrology, "agrohydrology" as a sub-discipline has failed to gain formal recognition despite its ancient history, ever-relevant importance, and growing emphasis in the overall field of hydrology. Agrohydrology has been historically described as the study of the physical water processes related to irrigation, crop water uptake, drainage, and overall water use efficiency. However, agrohydrology has rapidly developed into a significantly broader research portfolio with diverse outcomes spanning both social and physical sciences (Table 1). As such, there is a growing need to better unify the direction of the discipline while further giving form to the evolving research field, especially as more interdisciplinary researchers leverage unique tools to resolve ever-changing challenges in agriculture and water management.

We have been working for several years to establish agrohydrology as a research field where interactions between the physical and social sciences coalesce across agricultural landscapes (e.g., McGill et al., 2019; Smidt & Haacker, 2022; Smidt, Haacker, & Deines, 2018). Reasons for doing so include a directed focus on research priorities and their advancements, streamlined methods and data for interdisciplinary comparisons and collaborations, and increased attention from the scientific community, among others. Even at the federal level, the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) officially recognizes that agrohydrology challenges include competing demands across agriculture, society, and ecosystems. USDA-ARS further developed a national Water Research Vision for the next 30 years highlighting the need for transdisciplinary approaches to address water issues for agricultural systems that are becoming increasingly vulnerable to biotic (e.g., invasive pests and weeds) and abiotic (e.g., floods, droughts, heat waves) stressors (USDA, 2022). The historical scope of agrohydrology fails to capture the depth and trajectory of current agrohydrology research demands, prompting the need for new discussions and a greater cross-disciplinary call to a refreshed agrohydrology discipline.

2. Future Topics in Agrohydrology

We divided our vision of agrohydrology into six driving research themes, each covering both human and natural systems while focusing on the hydrological optimization of these systems to maximize agricultural and stewardship outcomes (Figure 1). Within each theme, we identified example future topics that allow for the overall advancement of agricultural water management through a hydrological lens. We grouped these topics into relative time categories of Near Future, Mid Future, and Far Future based on when we believe that topic, if left unaddressed, is likely to become a limiting factor to advancing the discipline. In general, we viewed Near Future topics as operating on a 0–5 years timescale, Mid Future as 5–25 years, and Far Future as 25 years and beyond. Overall, these topics demonstrate the need for collaboration across stakeholders and scales (e.g., local producers, regional, and federal organizations), all with the belief that socially responsible knowledge transfer and aligning of shared agrohydrological interests can ultimately lead to improved agricultural water management and environmental outcomes. Additionally, within these topics was the utilization of advanced technologies that can continue to improve data accessibility and knowledge generation across both space and time. The establishment of these disciplinary directions can help the field coalesce into a formal, distinct community and body of work; coalescence has implications for societal challenges, funding needs, and the direction of foundational work in the very near term.

3. Guiding Outcomes

Categories of Near Future, Mid Future, and Far Future groups can largely be further summarized into eras of equipping researchers and stakeholders with the tools and partnerships necessary for advancing the field (Near

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Table 1
Historical Agrohydrology Definitions Compared to the Broader Applications by Recent Agrohydrological Researchers

Historical Definitions	Recent Applications
"Agrohydrology is a study of interactions. It seeks not only to evaluate the influence of available water on the agricultural potential of a region, but conversely to determine the influence of land management practices on the water resources of that region. Both these phases of study have a common objective, viz., to promote maximum efficiency in the use of water."[1]	Climate variability and extreme weather[3,4,5]
	Environmental degradation[6]
	Decreased water supply[7,8,9]
	Increased access to data[10]
	Crop water use and earth system interactions[11,12,13,14]
	Recognition of the embedded complexity of food, energy, and water[15,16,17]
"The study of hydrological processes and the collection of hydrological data, aimed at increasing the efficiency of crop production, largely by providing beneficial soil moisture conditions."[2]	Watershed-scale implications of agricultural and conservation practices under varying land cover and land use[18,19,20,21]
	Increased demand for maximizing crop production and livestock[22]
	Advanced technology and related consequences of increased water use[23,24,25]
	Artificial intelligence and machine learning methods[26]
	Changing social behaviors of growers[27,28]
	Evolving regulatory frameworks[29]

[1]Whitmore (1961). [2]Miller (1994). [3]Beillouin et al. (2020). [4]Frieler et al. (2017). [5]Groh et al. (2022). [6]Jha et al. (2021). [7]Deines et al. (2020). [8]Forstner et al. (2021). [9]Haacker et al. (2016). [10]Wulder et al. (2022). [11]Jarvis et al. (2022). [12]Melton et al. (2021). [13]McDermid et al. (2023). [14]Nocco et al. (2019). [15]Groh et al. (2020). [16]McGill et al. (2018). [17]Smidt et al. (2016). [18]Aliyari et al. (2019). [19]Mojid and Mainuddin (2021). [20]Smidt, Tayyebi, et al. (2018). [21]Weldegebriel et al. (2020). [22]Heinke et al. (2020). [23]Ebert et al. (2022). [24]Glose et al. (2022). [25]Scott et al. (2014). [26]Lamb et al. (2021). [27]Deines et al. (2019). [28]Nocco et al. (2020). [29]Schoengold and Brozovic (2018).

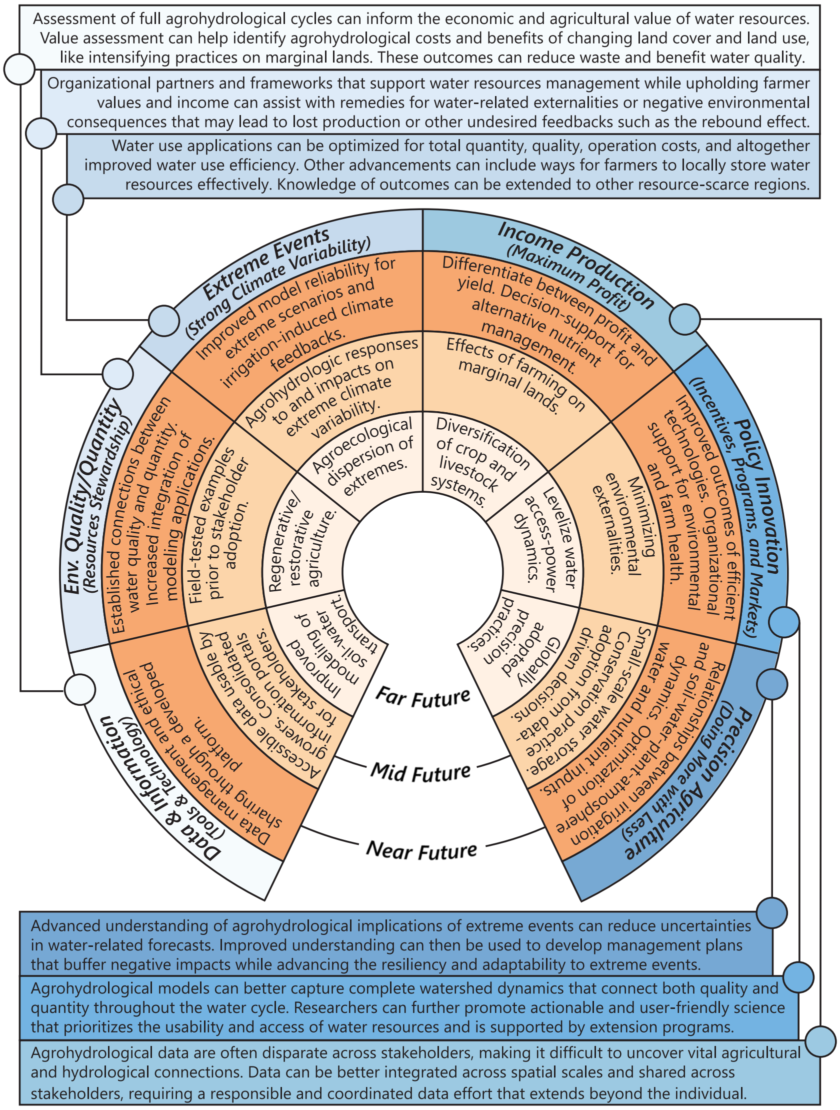

Figure 1. Summarized agrohydrological research themes driving future topics and outcomes across timescales.

Future), employing new operational capabilities to revitalize farming strategies (Mid Future), and transforming regional farming systems to realize global benefits over extended time and spatial scales. Each plays a unique role in forming the future of agrohydrology.

3.1. Near Future

Near Future topics largely focus on establishing water-related stakeholder collaborations and equipping end users (growers, ranchers, and resource managers) with improved decision-making tools. These tools will lead to an improved understanding of water systems, so end users are more likely to adopt new water-focused practices (e.g., water conservation strategies, valuation of food production; Michalke et al., 2023). Researchers and other stakeholders are at an interesting confluence of conventional agricultural practices and advanced data analytics. However, these analytics have yet to capture full water cycle dynamics in a way that can comprehensively advance farming practices, or even fully characterize the farm water balance. In short, modern agriculture has demonstrated interest and engagement with emerging water management practices, so demand for data-driven decisions is likely to increase and transform operational transitions. Operational changes based on the agricultural information gained from these data has already progressed in some agricultural technology (e.g., Melton et al., 2021), but more are likely to flood the industry in the near future as new water-related applications are developed and field-tested. Economists and sociologists, particularly those interested in the role of technology and its adoption, are necessary to realize this near-future vision. The success and social acceptability of such innovations depends on the ability to engage end users making it critical to understand how farmers perceive agrohydrological programs and associated new tools (e.g., Teff-Seker et al., 2022). This research program may also provide opportunities for public-private partnerships given the role of the private sector in the development of decision-making tools and equipment for data collection and analytics.

3.2. Mid Future

Mid Future topics see a transition to improved farming practices with clear, quantitative influences on and responses to water use, distribution, and conservation. Example topics include shifts in crop selection based on both water needs and income generation (e.g., commodity diversification, new planting locations) and improved access to centralized data-driven decision-making and support tools. These activities employ the Near Future outcomes to empower farmers to maximize profit through lower-risk adaptations in water use during growing practices. Likewise, this period captures a time when the use of data integration will no longer be novel but rather commonplace in a new culture for water management. As a result, we envision that smallholder farmers will gain opportunities for water resources success (e.g., reduced watershed burden) in ways that are simultaneously innovative, individualized, and lower in risk both economically and environmentally. Success at this stage will rely on the integration of water management with many other aspects of farming and ranching and their larger sociohydrological systems, including government programs such as crop insurance, equipment suppliers, and commodity buyers who have a vested interest in a sustainable and transparent supply chain. These facets of production have historically been treated as the domain of different disciplines except in formal life cycle analyses, but agrohydrology holds the promise of unification into a single field.

3.3. Far Future

Far Future topics encompass a holistic reimagining of the global agrohydrologic cycle at many nested spatial scales. Regenerative agriculture is a targeted avenue for meeting increased global food demands through improved soil structure, infiltration, water-holding capacity, and other measurable soil health outcomes. Livestock or aquaculture integration into cropping systems can further unlock valuable long-term soil health and water conservation benefits. Agricultural waste may be minimized through the optimization of growing practices or put to use in novel ways, and managing for resilience to water-related extreme events will be normalized throughout all of agriculture. Infrastructure for local water resources conservation and storage will allow growers to become more resilient to hydrological extremes, including the improved utilization of soil-water transport models. Decades of agrohydrological progress will permeate all regions of the world, and agricultural water use and management in developing countries will progress in a way that will help tackle global challenges related to poverty, hunger, and overall human well-being. Realizing this vision relies on advances in the physical sciences, such as sub-seasonal forecasting and mechanistic understanding of extreme hydrological events and irrigation-induced climate change. It also relies on fields including human geography and political science in order to explicate and level the relationship between power dynamics and access to water. Much of this will require large-scale investments from governments at the local, regional, and national levels. By establishing the field of agrohydrology, researchers have the potential to contribute to global well-being by maximizing the efficacy of state and private interventions.

3.4. Gaps and Opportunities

We believe that future water demands and hydrological impacts of agriculture can be balanced in a way that is more integrated, holistic, and meets the needs of an ever-evolving global demand for water to produce food, feed, fiber, and fuel. Specifically, there remains a growing need for frequent and direct interactions with farmers, ranchers, and other representatives of the agricultural supply chain, which further justifies the support and demand for cooperative extension scientists (Nocco et al., 2020), social science integration (Sanderson et al., 2017), and the demand for an updated discipline that spans beyond traditional water processes (Davidson, 2016; Grafton et al., 2018; McDermid et al., 2023). Better connecting disparate agrohydrological data across both space and time will further allow for united research and application efforts across the physical and social sciences; this notion is further echoed by other interdisciplinary hydrologists (Pande et al., 2022). For example, such efforts are being implemented by the USDA-Agricultural Research Service through the establishment of a Long Term Agroecosystem Research (LTAR) network, which can help to address Near Future, Mid Future, and Far Future topics. Improved understanding can then lead to the creation of interdisciplinary, holistic, and adaptable management plans that incorporate societal and consumer interests. Capturing these opportunities requires open data sharing and ethical data management across all stakeholders, which can fundamentally advance the discipline and improve the hydrological outcomes for both human and natural systems. Over time, these activities can be implemented more broadly so that positive agrohydrological impacts can be realized worldwide over the near, mid-, and long-term. Agrohydrology demands a meeting of minds across established disciplines, and the historical agrohydrological framework does not fully capture the evolution of the subdiscipline.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The raw FIHM session data (i.e., recorded notes) used to help form the future of agrohydrology are openly available through CUAHSI Hydroshare (Smidt et al., 2022) via http://www.hydroshare.org/resource/1d52161761a24e24a38020d9c73bb18e.

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