Streamflow depletion caused by groundwater pumping: fundamental research priorities for management-relevant science

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Streamflow Depletion Caused by Groundwater Pumping: Fundamental Research Priorities for Management-Relevant Science

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Key Points:

- Changes in streamflow caused by groundwater pumping ("streamflow depletion") are a link between basic and applied hydrologic science
- Streamflow depletion science is critical to support decision making and requires advances in hydrology and transdisciplinary collaboration
- We identify key priorities for streamflow depletion research to improve hydrological process understanding and support water management

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Abstract

Reductions in streamflow caused by groundwater pumping, known as "streamflow depletion," link the hydrologic process of stream-aquifer interactions to human modifications of the water cycle. Isolating the impacts of groundwater pumping on streamflow is challenging because other climate and human activities concurrently impact streamflow, making it difficult to separate individual drivers of hydrologic change. In addition, there can be lags between when pumping occurs and when streamflow is affected. However, accurate quantification of streamflow depletion is critical to integrated groundwater and surface water management decision making. Here, we highlight research priorities to help advance fundamental hydrologic science and better serve the decision-making process. Key priorities include (a) linking streamflow depletion to decision-relevant outcomes such as ecosystem function and water users to align with partner needs; (b) enhancing partner trust and applicability of streamflow depletion methods through benchmarking and coupled model development; and (c) improving links between streamflow depletion quantification and decision-making processes. Catalyzing research efforts around the common goal of enhancing our streamflow depletion decision-support capabilities will require disciplinary advances within the water science community and a commitment to transdisciplinary collaboration with diverse water-connected disciplines, professions, governments, organizations, and communities.

Plain Language Summary

Pumping water from a well can reduce flow in surrounding streams, a phenomenon called "streamflow depletion." It is important for water managers to know when, where, and how much streamflow depletion is occurring because it can affect the amount of water available for ecosystems and other water users. However, estimating streamflow depletion is challenging because weather and other factors affect streamflow, in addition to pumping. Here, we discuss important topics related to streamflow depletion that need further research. Most importantly, scientists need to move beyond estimating changes in flow caused by pumping, and also develop improved approaches to estimate the impacts of these streamflow changes on ecosystems and water users. Additionally, it will be important to develop improved tools for estimating streamflow depletion and linking those estimates to water management decisions. Making these advances will require basic scientific research and collaboration between hydrologists and other fields; these efforts should be prioritized because streamflow depletion is occurring at a rapid pace around the world.

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1. Streamflow Depletion: A Basic Hydrological Process Central to Integrated Watershed Management

Streamflow depletion, defined as reductions in streamflow caused by groundwater pumping (Barlow et al., 2018), represents a fundamental link between stream-aquifer interactions and human impacts on the water cycle (Figure 1). However, streamflow depletion is difficult to measure in real-world stream networks because it requires comparing observed streamflow to a hypothetical counterfactual (i.e., streamflow without groundwater pumping) (Zipper, Farmer, et al., 2022). Streamflow depletion cannot be directly inferred from streamflow gaging data because streamflow reductions are dampened and lagged relative to pumping (Bredehoeft, 2011); groundwater withdrawal volumes and timing are rarely known (Brookfield, Zipper, et al., 2023); and pumping impacts are masked by variability in weather and other factors (Barlow & Leake, 2012).

Streamflow depletion has long been recognized as an issue by the hydrologic community (Theis, 1941; Winter et al., 1998), but groundwater and surface water have historically been regulated and managed separately (Winter et al., 1998). The earliest instance of this separate treatment in United States (U.S.) jurisprudence was in 1861 when the Ohio Supreme Court declined to intervene in a dispute where a surface water user was impacted by a groundwater pumping neighbor (Klein, 2022). While regulatory actions and legal rulings in recent decades address streamflow depletion in jurisdictions including California (Owen et al., 2019), Europe (Kallis & Butler, 2001), Australia (Ross, 2018), and India (Harsha, 2016), most groundwater management plans still do not address streamflow impacts of groundwater pumping (Gage & Milman, 2020), despite documented impacts of pumping on surface water users and ecosystems (Currell, 2016; Perkin et al., 2017; Zipper, Popescu, et al., 2022).

Integrating streamflow depletion into water management decision support is critical to avoid unintended consequences of groundwater extraction, such as ecosystem degradation or water conflict. As climate change and other human influences increasingly modify the water cycle, quantifying streamflow depletion is becoming more urgent, and the pace of streamflow depletion science must accelerate. Here, we share our collective view of research needs to advance streamflow depletion science and support effective water management.

2. Research Priorities to Meet Current and Emerging Management Needs

Decision support research in hydrology is typically a multi-step process (Doherty & Moore, 2020). Typical steps include: (a) identifying decision need(s), (b) determining information required to evaluate decision options, (c) selecting appropriate quantitative tool(s), (d) constructing tools and evaluating performance, (e) quantifying streamflow depletion including uncertainty, and (f) developing decision-relevant information in collaboration with partners. We identify fundamental streamflow depletion research needs to improve this process, grouping steps together where appropriate, and better serve water management (Figure 2).

Decision Support Steps: Identify decision need(s) and decision-relevant information

<u>Priority: Linking streamflow depletion to decision-relevant outcomes such as ecosystem function and water users to align with partner needs</u>.

Streamflow depletion affects diverse partners such as Federal, State, and Tribal agencies; water-using industries; and environmental conservation groups. These groups have diverse water needs that must be integrated into planning processes to ensure that stakeholder needs are protected, such as preventing wells and ecosystems from drying up (Perrone et al., 2023). While past streamflow depletion research has primarily centered on changes in water quantity, the changes that partners care about are often resulting impacts of streamflow change, such as degraded aquatic ecosystems or insufficient water for downstream users (Zipper, Farmer, et al., 2022). Due to the lags between pumping and streamflow response, streamflow depletion impacts are felt years to decades after the onset of pumping, and the balance between withdrawals and return flows can cause shifts in streamflow timing, for example, increasing winter streamflow at the expense of summer streamflow (Kendy & Bredehoeft, 2006). While these lags provide time for management actions such as managed aquifer recharge to counteract potential pumping-driven water supply challenges (Bredehoeft & Kendy, 2008; Parimalarenganayaki & Elango, 2015, 2016), balancing streamflow depletion impacts with potential remediation actions requires a clear characterization of the desired hydrologic conditions to provide the ecosystem services desired by partners.

For ecosystem impacts, there is a pressing need to develop improved links between streamflow depletion and resulting decision-relevant outcomes, such as changes in stream biodiversity or protection of culturally significant

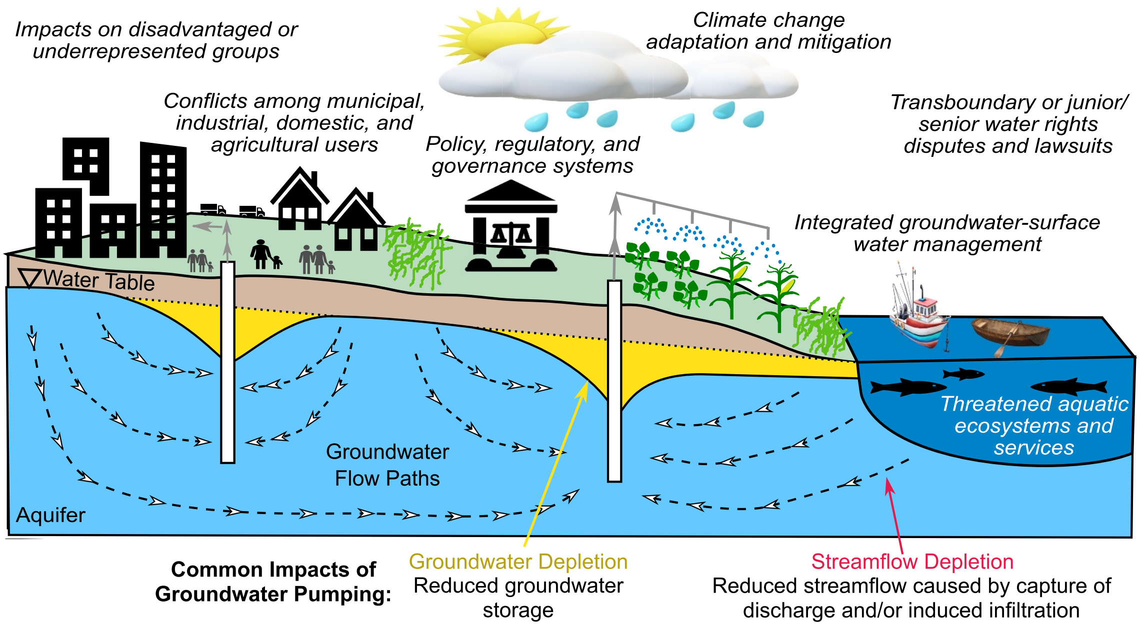

Figure 1. Streamflow depletion in an interconnected stream-aquifer system, with related governance systems and societal challenges italicized.

or legally protected species. Impacts of streamflow depletion on aquatic ecosystems may be through direct changes in streamflow or indirectly through changes in water quality or temperature caused by depletion, as in the case of salmonids which are highly dependent on cool groundwater inflows (Larsen & Woelfle-Erskine, 2018) and are a major driver of policy and management decisions in many settings (Lackey, 1999). While a variety of approaches to estimate environmental flow needs for aquatic ecosystems have been developed and proposed, these are not well-correlated with freshwater biodiversity (Mohan et al., 2022), suggesting that more information beyond just changes in water quantity is needed to link streamflow depletion to adverse ecological outcomes (Lapides et al., 2022; Yarnell et al., 2020). While recent studies have identified low-flow signatures as most

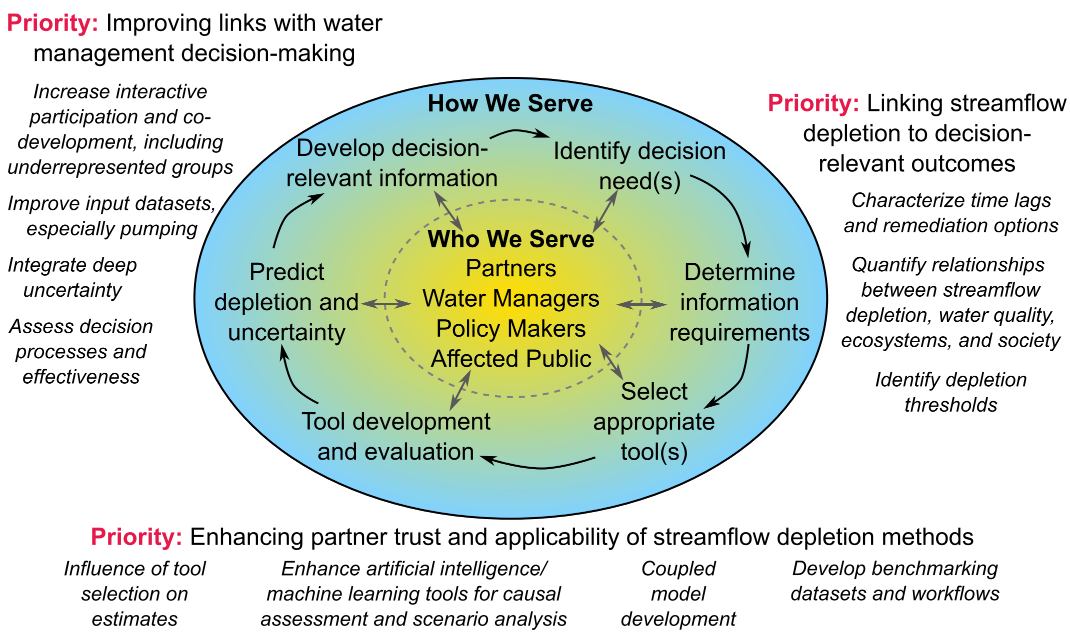

Figure 2. A vision for streamflow depletion research priorities to improve the decision making process (outer oval) and benefit society (center oval). Core priorities are located near the most relevant steps of the decision support process, and specific areas for research advancement are italicized for each priority.

sensitive to streamflow depletion across diverse hydrologic regions (Lapides et al., 2023), links between hydrologic change and ecological outcomes have predominantly been local (Liu et al., 2020; Perkin et al., 2017). Ultimately, the link between streamflow depletion and actual impacts remains poorly characterized, and further research is needed to link depletion-induced changes in water quantity to changes in water quality and social and ecological outcomes.

Decision Support Steps: Select, develop, and evaluate needed quantitative tool(s)

Priority: Enhancing partner trust and applicability of streamflow depletion methods through benchmarking and coupled model development.

Historically, streamflow depletion has been quantified using analytical or numerical models, with process-based numerical models like MODFLOW considered most reliable (Barlow & Leake, 2012; Zipper, Farmer, et al., 2022). However, little is known about the impacts of tool selection on streamflow depletion estimates. Since most hydrological investigations select models based on past experience ("model legacy") rather than choosing the best-suited tool for the question ("model adequacy"), there is a risk that streamflow depletion studies may be neglecting better-suited tools (Addor & Melsen, 2019). Also, a lack of state and national governmental support for modeling tools has placed the burden of model development to local authorities in many jurisdictions, often creating financial struggles and inconsistent model development between watersheds (Perrone et al., 2023). Streamflow depletion model intercomparison studies showed mixed agreement among analytical and numerical models (Jayawan et al., 2016; Li et al., 2022; Zipper et al., 2021), suggesting that properties like climate, land use, and physiography influence model performance. Clear guidance on the potential influence of model selection on estimated streamflow depletion, and associated best practices for model selection, are needed.

Trust in environmental model estimates is critical to partner buy-in (Vazire, 2017), but demonstrating model relevance and accuracy is problematic because there are no regional-scale streamflow depletion data sets and testing the ability of models to separate streamflow depletion from other change drivers is challenging. In practice, mismatches between model predictions and actual system responses can erode trust in model-predicted outcomes. Therefore, there is a critical need to develop benchmarking data sets, reproducible workflows, and tools to facilitate standardized model intercomparison. These resources will provide improved opportunities to evaluate and intercompare the performance of existing tools and help rapidly develop and test new tools (Hughes et al., 2023). For instance, the recent proliferation of artificial intelligence/machine learning (AI/ML) shows promise for hydrologic simulation (Kratzert et al., 2019), but causal AI/ML methods (e.g., Althoff et al., 2021; Tsai et al., 2021) that link changes in drivers, like pumping, to outputs, like streamflow, have not yet been explored for streamflow depletion applications. The development of an international network of community streamflow depletion benchmarking data sets and computational resources (i.e., Castronova et al., 2023) would allow rigorous quantification of model selection impacts on streamflow depletion estimates and the rapid testing and development of new approaches, thus improving both model capabilities and partner trust in model outputs.

There is rapid evolution in the number and capabilities of hydrological models, particularly those that integrate other Earth system processes (Brookfield, Ajami, et al., 2023), and these coupled models hold promise for linking streamflow depletion to decision-relevant social and ecological outcomes. Examples of potentially relevant coupled processes include pumping impacts on streamflow across watershed boundaries through changes to atmospheric moisture circulation (Jódar et al., 2010; Keune et al., 2018); linking streamflow depletion with water quality or stream ecosystem models (Bradley et al., 2014; Liu et al., 2020); and characterizing social dynamics that lead to collective shifts in water use (Castilla-Rho et al., 2017). Interrogating these types of cross-system linkages will require developing and deploying coupled models to streamflow depletion questions. Developing these models should be supported by increased data collection efforts targeted at linkages between streamflow depletion and social-ecological outcomes to avoid potential increases in uncertainty associated with increased model parameterization and complexity (Saltelli, 2019). For example, improved coordination between monitoring of groundwater, streamflow (including water quantity and quality), and ecological resilience would provide the basis to strengthen links between streamflow depletion and decision-relevant outcomes (Rohde et al., 2019).

Decision Support Steps: Quantify streamflow depletion and develop decision-relevant information with partners

Priority: Improving links between streamflow depletion quantification and decision-making processes.

Effective decision support requires alignment between partner decision needs and the information-sharing mechanism, which requires placing streamflow depletion within decision-relevant contexts such as agricultural productivity, industrial needs, ecosystem services, and economic cost (Fienen et al., 2018; White et al., 2018). To adequately meet partner needs, hydrologists must improve links between streamflow depletion estimation and decision-making, guided by social research efforts to evaluate perceptions and interpretations of partners to design effective decision support systems. We have an insufficient understanding of how decision processes differ across groups of streamflow depletion information users, for example, information creators (e.g., hydrologists), policymakers (e.g., state water office staff), and water users (e.g., agricultural producers who irrigate), which limits our ability to translate scientific knowledge into actionable information (Ranjan et al., 2020; Wardropper & Brookfield, 2022). Further, social research can determine how streamflow depletion might trigger conflict among different water users and/or catalyze policy action to facilitate decision-need evaluation and decision support tools (Church et al., 2021; Prokopy et al., 2014).

Quantification and communication of uncertainty is a particular challenge. Since all tools and their input data are subject to uncertainties and errors, incorporating uncertainty into depletion estimates is critical for partners to weigh risks and tradeoffs among alternatives during decision-making (Doherty & Simmons, 2013). Parameter and model uncertainty quantification methods are well-developed (Hill & Tiedeman, 2006; Hugman et al., 2022), but streamflow depletion is particularly prone to "deep uncertainty" (Walker et al., 2013) from unknown human factors such as water use and how it may change in the future. A key source of uncertainty can be addressed by developing improved data sets for streamflow depletion quantification, especially water use data sets with fine spatial and temporal resolution to facilitate quantifying links between groundwater use and streamflow change (Marston et al., 2022). While pumping well location data are available in some countries (Jasechko & Perrone, 2021), even in these settings information about pumping volume, timing, and rate are rarely available (Brookfield, Zipper, et al., 2023). Modeling and remote sensing approaches for estimating water use are promising (e.g., Majumdar et al., 2020; Melton et al., 2021; Shapoori et al., 2015), but require additional development and verification against measured pumping rates to reduce measurement errors and uncertainties to the point where they can be used operationally (Foster et al., 2020; Zipper et al., 2024). However, future uncertainty (particularly in the realm of management scenario assessment) is inevitable and unavoidable, and therefore impact monitoring and mitigation planning should be established as a precaution (Saito et al., 2021). While communicating uncertainty has been found to slightly decrease trust in scientific data, the risk of decreased trust is outweighed by the importance of transparency (van der Bles et al., 2020).

3. Moving Forward

Streamflow depletion is a critical management issue that needs continued scientific advances to facilitate improved process understanding and support management decisions. We identify core research priorities, most notably (a) linking streamflow depletion to decision-relevant outcomes such as ecosystem function and water users to align with partner needs; (b) enhancing partner trust and applicability of streamflow depletion methods through benchmarking and coupled model development; and (c) improving links between streamflow depletion quantification and decision-making processes. Pursuing these topics will require collaboration with diverse groundwater-connected disciplines and dedicated transdisciplinary coordination to catalyze streamflow depletion research around the common goal of guiding improved water management amidst global challenges such as climate change and biodiversity loss.

Data Availability Statement

Data were not used, nor created for this research.

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