Introduction to Special Section: The Quest for Sustainability of Heavily Stressed Aquifers at Regional to Global Scales

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1. **Introduction**

Groundwater is a critical resource for drinking water and food production, yet limited management amid intensive use has led to aquifer depletion across the globe (Alley and Alley, 2017; Bierkens and Wada, 2019). Efforts to address this depletion have been stymied by an incomplete understanding of aquifer dynamics, data limitations, a mismatch between law and science, along with socio-economic, cultural, and political factors. The AGU Chapman Conference "The Quest for Sustainability of Heavily Stressed Aquifers at Regional to Global Scales" was held in October 2019 at the Universitat Politècnica de València in Spain to address these barriers to progress and explore promising paths forward. Presentations by researchers from the hydrology, law, economics, and social science communities provided the basis for wide-ranging discussions of the most critical data needs; the appropriate scale for aquifer analyses; assessments of supply and demand from local to global scales; and proposals for future directions that incorporate governance, the likely trajectory of anthropogenic stresses, the protection of ecosystems, and the evolution of modeling and analysis tools.

The conference's presentations and discussions prompted the preparation of this special section focused on the prospects for a more sustainable future for the world's heavily stressed aquifers. The special section consists of seventeen papers contributed by conference attendees and others with similar interests. Although these papers only present a partial picture of the topics covered in the conference's wide-ranging presentations and discussions, they aptly demonstrate the interest of the broader hydrological community in the future of the world's critically important groundwater resources.

2. **Summary of Papers**

The seventeen papers can be divided into three general categories: assessing or addressing data needs (eight papers), groundwater governance (three papers), and modeling methods and applications from farm to continental scales (six papers). These papers primarily describe conditions in the United States (US), but the conference's presentations and discussions extended far beyond that country.

Data Needs

Groundwater pumping is the primary driver of aquifer depletion. However, most countries do not have adequate data to quantify the annual pumping stress placed on their aquifers. For example, in the US, only 36% of all irrigation wells are metered; many of the most heavily stressed areas in the central and western US have yet to adopt widespread metering practices (NASS, 2018). The state of Kansas is the most prominent exception with over 95% of its approximately 18,900 irrigation wells metered and subject to regulatory verification (Butler et al., 2016; NASS, 2018). Bohling et al. (2021), Lamb et al. (2021), and Majumdar et al. (2020) use the Kansas pumping data to evaluate how many wells need to be metered, the major influences on pumping volume, and the effectiveness of a new machine learning approach for estimating pumping volumes, respectively. Foster et al. (2020) use the pumping data from a heavily monitored area in the state of Nebraska to assess the effectiveness of remote-sensing methods for estimating irrigation water use and to explore the policy implications of adopting those methods.

Recharge is an important but often highly uncertain component of an aquifer's water budget that can be extremely variable in space and time (Healy, 2010). Neely et al. (2021) use remotely sensed surface displacement data to identify possible recharge zones in the Central Valley aquifer in the state of California. Managed aquifer recharge (MAR) is considered an important technology to moderate and reverse the depletion of heavily stressed aquifers in California and elsewhere. Marwaha et al. (2021) present a multi-criteria decision analysis approach, which is supported by flow and transport modeling, to identify locations for MAR that increase the resilience of rural communities that are dependent on groundwater from the Central Valley aquifer.

Water-storage estimates based on the Gravity Recovery and Climate Experiment (GRACE) satellite mission have revealed the severity of groundwater depletion challenges that face countries across the globe (Rodell et al., 2018). However, studies comparing GRACE water-storage estimates with those based on other information have been limited. Rateb et al. (2020) compare the GRACE water-storage estimates with those derived from water-level monitoring data and regional and global models for 14 major aquifers in the US.

Pumping-induced land subsidence has wreaked havoc in coastal regions (e.g., increased salt-water intrusion and flood frequency) and, more generally, with infrastructure across the globe (Hyndman and Hyndman, 2016). A major challenge is identifying where and when irreversible formation compaction will likely occur. Hung et al. (2021) describe a specially constructed well that allows compaction potential to be assessed over multiple vertical intervals and they demonstrate the tool's capabilities with a field application.

Groundwater Governance

There is no standard approach for management of groundwater resources; regulatory frameworks can vary tremendously between, and even within, countries. For example, in the US, groundwater management is a state responsibility, so adjacent states overlying the same aquifer can have vastly different approaches (Griggs, 2014). A key question is: How are management mechanisms evolving to address the overdrafting of groundwater resources? Rouillard et al.

(2021) present a comparative analysis of co-management mechanisms that have been independently developed in France, Spain, and the state of California.

Restrictions on groundwater use are common in interconnected stream-aquifer systems. These restrictions are typically applied as part of efforts to protect higher priority surface water users and maintain environmental flows, but defining appropriate implementation strategies is difficult (Bredehoeft, 2011). Young et al. (2021) use agronomic, economic, and hydrologic models to examine the impacts of various strategies for implementing restrictions on groundwater use in aquifers in hydraulic connection with streams.

The state of California passed the Sustainable Groundwater Management Act in 2014 to address the widespread depletion of many of the state's aquifers (Water Education Foundation, 2015). Managed aquifer recharge is slated to be one of the most important tools for bringing these aquifers to a more sustainable condition. Ulibarri et al. (2021) assess the hydrological, legal, institutional, and operational challenges that threaten the feasibility of the MAR projects proposed to achieve the goals of this new management framework.

Modeling Methods and Applications

The dominant use of groundwater globally is for irrigated agriculture. In the US, close to 70% of the total groundwater pumped is used for this purpose (Dieter et al., 2018), a percentage that is likely reflective of conditions in many countries that depend on groundwater for support of irrigated agriculture. Efforts to address aquifer depletion must therefore consider their potential for success in an agricultural setting. Butler et al. (2020) present a lumped water-balance approach to assess pathways toward sustainability for aquifers supporting irrigated agriculture. Deines et al. (2021) combine a crop model and remote sensing to examine the agronomic and hydrologic impacts of an ongoing groundwater conservation effort utilizing pumping reductions in the High Plains aquifer in Kansas.

Continental- to global-scale models are undergoing continual development (Bierkens et al., 2015; Doll et al., 2016). Felfelani et al. (2020) describe the results of incorporating pumping, conjunctive-use, and lateral-flow capabilities into a widely used land surface model. Hartick et al. (2021) present a terrestrial modeling approach that incorporates atmospheric, land surface, and subsurface flow models to assess near-term changes in subsurface storage using a probabilistic methodology similar to that for weather forecasting.

Climate-induced pumping (groundwater extractions driven by climatic conditions) has been demonstrated in previous studies (Whittemore et al., 2016; Russo and Lall, 2017). Precipitation is clearly a major control on pumping schedules, but other climatic factors may also play a role. Nie et al. (2021) use a modified land surface model to explore the influence of precipitation and temperature on simulated and reported pumping from regions across the US.

Pumping in interconnected stream-aquifer systems can have large, but often difficult to quantify, impacts on stream flow (Barlow and Leake, 2012). Those impacts are typically lumped together and characterized as stream depletion. Zipper et al. (2021) compare stream depletion estimates obtained using a new approach, analytical depletion functions, with those obtained from a calibrated numerical model of a basin in the High Plains region of the US.

3. **Concluding Remarks**

Aquifers are under severe stress worldwide as a result of large water-budget imbalances created by the excessive pumping of groundwater. Although the challenges posed to irrigation and drinking water supplies by groundwater depletion are immense, they are not insurmountable.

The wide-ranging discussions at the Chapman conference in Valencia emphasized some basic principles for guiding efforts to reduce the stress on groundwater resources:

1. We must do a much better job of monitoring groundwater withdrawals, as it is difficult to manage or model a quantity that is so poorly known;
2. We must better align regulatory and legal frameworks with science; precedence may be a bedrock principle of many legal systems, but it rarely meshes well with the evolution of scientific understanding;
3. Multidisciplinary investigations that incorporate the human response to groundwater depletion are critical to reduce the stress on aquifers; those investigations must be firmly grounded in reality if significant progress is to be made;
4. New data acquisition and analysis approaches hold great promise to better quantify conditions across a range of scales; in particular, the combination of in-situ data and remote-sensing approaches appears to hold considerable potential; and
5. Aquifer modeling cannot be done in isolation, as expertise from multiple disciplines is required to improve the reliability of predictions of what the future holds for the world's aquifers.

We hope that this collection of papers will not only capture the excitement we felt during the presentations and discussions in Valencia but also help clarify the impediments to, and opportunities for, charting more sustainable paths for the world's heavily stressed aquifers.

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