Bright but flickering lights of sustainable, community-based groundwater supply and management: ASADAS in Costa Rica

Róger Madrigal-Ballestero, Tom Gleeson, Mariaclara López-Ruiz, & Aaron Benhur Castillo-Cruz

2025

IOP Publishing Environ. Res. Lett. 20 (2025) 051002 https://doi.org/10.1088/1748-9326/adc58d

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
31 January 2025

REVISED
13 March 2025

ACCEPTED FOR PUBLICATION
26 March 2025

PUBLISHED
8 April 2025

PERSPECTIVE

Bright but flickering lights of sustainable, community-based groundwater supply and management: ASADAS in Costa Rica

Róger Madrigal-Ballestero[1,*], Tom Gleeson[2], Mariaclara López-Ruiz[1] and Aaron Benhur Castillo-Cruz[1]

[1] Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Cartago, Turrialba, Costa Rica
[2] Department of Civil Engineering and School of Earth and Ocean Sciences, University of Victoria, Victoria, Canada
[*] Author to whom any correspondence should be addressed.

E-mail: rmadriga@catie.ac.cr

Keywords: governance, groundwater, community-based management

1. Introduction: illuminating the management of an invisible resource

Groundwater, a quintessential invisible natural resource, is often misunderstood and mismanaged due to scale and management approaches as well as geographic and disciplinary biases (Giordano 2009, Gleeson *et al* 2020, Lall *et al* 2020). While groundwater management and sustainability discussions typically focus on large scales, such as regional aquifers and global analyses (Scanlon *et al* 2023), it is crucial to recognize that groundwater systems and sustainability occur across multiple scales (Foster *et al* 2013), from individual wells to large aquifers and even global virtual groundwater trade (Dalin *et al* 2017). Groundwater management and sustainability have often emphasized top-down approaches for controlling individuals and pumps. However, a shift towards focusing on communities and aquifers is emerging, particularly in the Global South (Zwarteveen *et al* 2021). Developing regional groundwater models and global groundwater datasets often underrepresents conditions in the Global South (Zamrsky *et al* 2025, Huggins 2025). Groundwater management has historically centered on the discipline of physical hydrology, by focusing on fluxes (e.g. recharge) and stores (e.g. water table levels or groundwater storage), minimizing the importance of governance and social or cultural aspects (Villholth and Conti 2017). To illuminate the invisible, we highlight a successful but little-known network of community-based groundwater management organizations in the Global South as an example of a bright but flickering light of groundwater sustainability. Insights from this network may be useful internationally in both the global south and leap-frogging approaches to management in the global north. This example is consistent with the goal of this Focus Issue, which is to further our understanding of groundwater supply, usage, governance, and dynamics as a social-ecological system (Huggins *et al* 2023).

In most Latin American countries and other parts of the Global South, community-based drinking water organizations (CWOs) are the leading water supply for human consumption in rural areas, significantly improving access for poor and marginalized households. In contrast to the prevalence of governmental water utilities in urban areas, CWOs, locally known in Costa Rica as ASADAS, are the main providers in rural areas (Bernedo Del Carpio *et al* 2021, Madrigal *et al* 2024). The ASADAS are locally elected organizations providing drinking water in areas where government and private companies would not be incentivized to operate. They promote democratic values and the achievement of UN Sustainable Development Goals, and are responsible for ensuring safe water quality, protecting watersheds, maintaining water infrastructure, and resolving intra-and inter-community water conflicts. However, while successful examples exist, many face challenges associated with financial sustainability, land use change, the technical capacities of local leaders, and their capacity to cope with external drivers of change (Madrigal *et al* 2024).

A substantial body of literature on environmental governance and sustainability has documented the ability of communities to govern their shared resources successfully (Baggio *et al* 2016, Ostrom 2009). This research finds that natural resource management arrangements are often more effective when local communities design rules and programs tailored to local social and environmental conditions. Many ASADAS are good examples of successful bottom-up approaches for groundwater and surface water

delivery that suggest plausible development pathways for fostering a better future in the Anthropocene (Bennett *et al* 2016). This paper illuminates ASADAS as a bright but flickering light of community-led groundwater management. We consider their performance, governance and key challenges, drawing from national datasets and our experiences. While approximately half of ASADAS demonstrate high performance, many struggle with water quality, infrastructure maintenance, and long-term leadership succession. Emerging polycentric governance structures, including federations of ASADAS, offer potential solutions by strengthening political advocacy, knowledge-sharing, and resource access. ASADAS offer valuable insights for groundwater governance, emphasizing the importance of community-driven solutions over conventional pump- and individual-focused management.

2. Bright lights: ASADAS' characteristics and performance

From the 1960s to the 1990s, there was a boom in the construction of public drinking water infrastructure in Costa Rica. In most cases, the government delegated the administration to ASADAS. Therefore, many of these organizations have been operating for approximately 60 years, with ongoing strong endorsement and financial support from various generations from local communities. This management model is one of the major reasons why Costa Rica has a very high coverage of safe drinking water in rural areas compared to neighboring countries (Madrigal *et al* 2011).

Although Costa Rica is a relatively small country (51 100 km^2), one distinctive feature of ASADAS is its diversity of size, water sources, delivery approaches, and governance structures. There are approximately 1200 ASADAS nationwide, serving ∼300 households on average (see figure 1(a) and table 1 for details). These providers rely on a combination of groundwater and surface water to feed piped water systems with in-house connections. Pumped groundwater plays a more prominent role, especially in Guanacaste Province, in the northwest on the Pacific coast (see figure 1(b)). In this region, the dry season (Dec–April) is more pronounced, and the topography is flatter and lower than the central mountainous range that crosses the country from north to south. In other regions of Costa Rica, gravity-fed systems from surface water are the most common water source. They are generally less expensive to operate since they do not require electricity for pumping.

Table 1 summarizes some key features of CWOs in Costa Rica, according to the type of water-feeding technology. Micro-metering seems to be more prevalent in pumped systems, which could be due to higher incentives to rationalize water consumption through fees, especially during the dry season in Guanacaste Province. Fewer hours of wells pumping reduce total water withdrawal but also electrical consumption, which is a financial relief for CWOs relying on groundwater.

Costa Rica is renowned for its extensive terrestrial protected area system, which covers approximately 30% of the nation. Despite this, ASADAS are filling the conservation gaps that the government or private owners cannot or choose not to address, particularly concerning lands for the protection of water resources. As shown in table 1, 18% of ASADAS that rely on gravity-fed systems have invested in land for conservation purposes. These communities primarily acquire land around or near springs to fence off and exclude human activities that could potentially contaminate surface water and promote water infiltration. In contrast, given the complexity of groundwater dynamics, ASADAS relying on pumped systems probably have lower incentives to acquire conservation land because of the difficulties in identifying areas with potential for recharging aquifers or the lack of capacity to distinguish the direct effect on minimizing some productive activities (e.g. cattle) on water quality. Notably, ASADAS with pumped systems are predominantly found in Guanacaste province (figure 1(b)), part of the Central American dry corridor, one of the most vulnerable and exposed regions to severe droughts and water scarcity caused by climate change (Pörtner *et al* 2022).

Evaluating the performance of ASADAS is complex due to the multidimensional nature of performance and the limitations of available data (Madrigal *et al* 2011). Despite this, government authorities have attempted to measure performance through an index that categorizes these organizations based on water quality indicators, watershed protection activities and having various organizational features, such as legal status and audited financial reports. This index shows that approximately half of the ASADAS exhibit relatively high-performance levels regardless of feeding technology (see table 1). In addition, figure 1(c) shows that high- and low-performing ASADAS are scattered throughout the country with no precise spatial location or agglomeration by regions. It is worth mentioning that the relatively high number of underperforming ASADAS suggests considerable room for improvement in rural water management in most areas of the country, potentially enhancing the sustainability of these systems and improving the quality of the water service delivered.

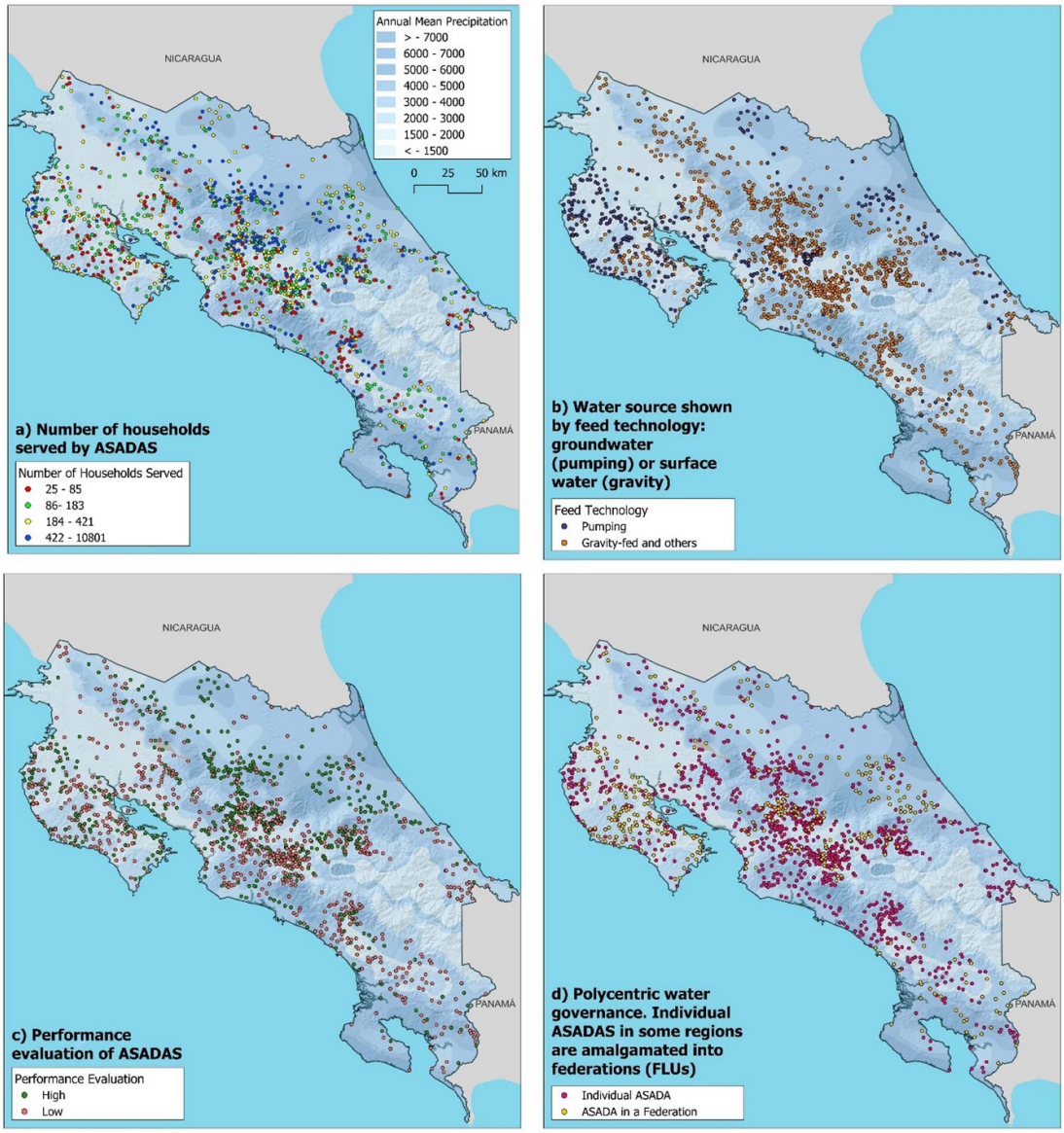

Figure 1. Characteristics of ASADAS in Costa Rica including (a) number of households served; (b) water source shown by feed technology; (c) performance evaluation; and (d) polycentric water governance.

3. Flickering lights: current challenges and emerging approaches, including polycentric governance

Costa Rica's legal framework acknowledges water as a public good and access to clean water as a fundamental human right[3]. While the state owns the water, it can provide use rights to organized communities and other users. The ICAA (Costa Rican Institute of Water and Sewerage) was established in 1961 by the government to oversee and manage drinking water infrastructure. Since water is a public good by law, the ICAA signs delegation agreements with ASADAS to transfer temporary rights (water withdrawal and infrastructure management) to supply drinking water.

Despite this governance context, sustainable management of water resources for all uses is hindered by government organizations that

Table 1. CWOs' descriptive statistics, according to feeding technology.

	Pumped	Gravity-fed	Mixed
Number of CWOs	316	722	151
Households served (average)	248	376	367
% Micro-metering	95	81	94
% High performance	49	44	49
% Own land for protection	7	18	10

Source: AyA (2024), Registro Nacional (2024).

[3] As per Environmental Law (Asamblea Legislativa 1995) and an amendment to article 50 of the Political Constitution of Costa Rica (Asamblea Legislativa 2020).

often have unclear mandates, insufficient staff, and inadequate budgets. In general, groundwater regulations have been less well developed than surface water, and their implementation remains a significant challenge due to the governmental constraints that characterize water management in the country (Cuadrado-Quesada *et al* 2018). As a result, some ASADAS and other stakeholders have been providing ad hoc responses to particular and urgent problems in water management but not in a holistic and planned manner (Cuadrado-Quesada *et al* 2018).

An interesting feature of rural water governance in Costa Rica is its emerging polycentric approach. Ideally, polycentricity means that governance involves multiple independent decision-making centers that interact with each other within a system (Ostrom 2010). While many ASADAS have successfully delivered water to their communities for over sixty years, there is growing concern about their ability to address external threats such as climate change, urbanization, and agricultural expansion (Fundación Avina 2024). In response to these challenges, some CWOs are considering how they can work together by organizing into federations (networks or second-level organizations of polycentric governance), typically made up of 10–20 ASADAS. Federations aim to strengthen communities' political voices and are hubs where local leaders can receive training and resources needed to support local governance.

The number of networks has been growing rapidly over the last decade. There are 26 federations representing ∼25% of ASADAS nationwide (see figure 1(d)). Also, there is an increasing shift towards networking at the national level (third-level organization of polycentric governance) to unite all federations (UTN 2020). Today, Costa Rica has some of Latin America's largest network of community water organizations. Figure 1(d) shows that these networks tend to be concentrated on the North Pacific and North Atlantic coasts. In addition, a comparison with figure 1(b) suggests that most individual ASADAS within these networks rely on groundwater technology. However, these basic observations, along with others that could lead to interesting policy-relevant conclusions, need to be further explored and tested by rigorous analytical methods. Bridging these knowledge gaps is crucial to provide a more comprehensive understanding and support the development of effective policies and strategies. Furthermore, the networks or federations of ASADAS are an exciting experiment by which communities are attempting to 'scale up' their locally devised rules or arrangements. However, there is no scientific evidence on whether and how these networks will effectively address their systems' internal needs and external threats or how they could achieve their intended objectives effectively. Additional concerns are that some federations might crowd out local CWOs, particularly the poorer and smaller organizations. Although federation leaders seek advice on the best ways to advocate for their communities, and governmental and non-governmental organizations ask how they can support these grassroots efforts, there is no comprehensive approach to support the strengthening of this novel polycentric governance approach.

Although ASADAS are often seen as a successful management model, they face challenges that could threaten this community governance structure. Regarding their human capital, despite the strong willingness to contribute *ad honorem* to the well-being of their communities, most community leaders lack sufficient technical training in fundamental aspects of hydrology, climate, technical operation of water infrastructure, and administrative management, among others. Additionally, there is significant uncertainty regarding the replacement of long-term leaders. Although many ASADAS attempt to engage youth from the communities through various means, their direct involvement is challenging, greatly complicating the succession of board members and the sense of ownership by the new generations.

Additionally, ASADAS's financial sustainability is weak in many cases. Although the initial water supply infrastructure was built by the government, in recent years, governmental support regarding training and financial resources has been minimal. Therefore, ASADAS rely heavily on the fees they charge, which the national public services regulator sets. Unfortunately, while these fees are generally sufficient to cover operational expenses, in many cases, they are insufficient to replace infrastructure that has exceeded its useful life or to efficiently address adverse natural events such as earthquakes or hurricanes, which are frequent in the country.

Finally, one of the major shortcomings in managing ASADAS is the quality of the water provided and its potential negative impact on human health. Approximately one-third of ASADAS cannot meet national water quality standards for human consumption. While this is often due to inadequate chlorination of the systems, the health risk is also significantly influenced by the impact of agricultural activities and uncontrolled urban growth. Given the government's limited capacity to effectively mitigate these threats, some ASADAS have opted to purchase areas near water sources for conservation purposes. However, as mentioned earlier, the percentage of ASADAS that manage to acquire land is relatively low. Moreover, in most cases, these purchases are not supported by technical criteria indicating which areas

are ideal for protection or the minimum area required to achieve a significant impact.

4. Future outlook, fit into global context and policy recommendations

This perspective article showcases a bright light (the promising efforts in community-based groundwater and surface water management in Costa Rica) that is also flickering (with significant challenges that must be addressed to strengthen and upscale these efforts), which furthers our understanding of groundwater supply, usage, governance, and dynamics as a social-ecological system, a goal of this Focus Issue. Following other important work on ASADAS, we humbly hope this article elevates CWOs in Costa Rica as one more example of focusing groundwater management on communities, rather than pumps and individuals (Zwarteveen *et al* 2021). We contribute to the groundwater sustainability literature in two additional ways: by elevating the importance of governance (Villholth and Conti 2017) of groundwater sustainability as a social-ecological system (Huggins *et al* 2023) and by better representing conditions in one country in the Global South. We conclude by discussing policy implications or recommendations as well as future research directions.

Current challenges ASADAS are facing include human capital, financial sustainability, and water quality. For this model to address current problems and medium- to long-term threats and become a bright example of seeds of a good Anthropocene, a concerted effort is required among communities, various central government authorities, academia, and others. Initiatives should focus on effectively implementing water laws and governance into a polycentric approach, improving access to financing, enhancing capacity building, generating accessible and timely relevant information, and improving the uptake of modern technologies, among other aspects. Although these recommendations apply to the Costa Rican case, they can be considered principles or good practices that could support other countries in the Global South improve groundwater management. However, caution must be exercised when extrapolating lessons from this case due to the ecological, cultural, socio-economic, and political differences that influence water governance.

Promising future research directions include work within Costa Rica, as well as internationally. Costa Rica is a useful location for future research because of some distinct aspects compared to other parts of the Global South, including the prevalence and culture of nature preservation and the polycentric governance of community water organizations. For example, how do CWOs benefit from or contribute to the prevalence and culture of nature preservation in Costa Rica? And how do the polycentric governance networks address ASADAS' internal needs and external threats, or how could they achieve their intended objectives effectively? This research could strengthen this novel polycentric governance approach as well as synergies with nature conservation and water management. Another interesting research direction is considering if or how ASADAS are an example of a transformation of groundwater sustainability practices of situating, tinkering, and caring for groundwater (Dominguez Guzmán *et al* 2023). Since many other regions have less emphasis on nature preservation and polycentric governance, important research questions are: How can approaches or lessons learnt in Costa Rica be helpful (or not) in other regions? Finally, it would be interesting to explore how approaches or lessons learnt in Costa Rica could be useful (or not) to leap-frog approaches to management in other regions, especially in the context of climate change and increasing competition across traditional and emergent water users.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgment

Financial support from SIDA through the Environment for Development (EfD) Initiative and the National Institute of Forest Science (NIFoS) are gratefully acknowledged. All errors and omissions remain the full responsibility of the authors.

ORCID iDs

Róger Madrigal-Ballestero https://orcid.org/0000-0002-5637-0129
Tom Gleeson https://orcid.org/0000-0001-9493-7707
Aaron Benhur Castillo-Cruz https://orcid.org/0009-0006-1736-905X

References

Asamblea Legislativa de Costa Rica 2020 Constitución Política de la República de Costa Rica
Baggio J A *et al* 2016 Explaining success and failure in the commons: the configural nature of Ostrom's institutional design principles *Int. J. Commons* **10** 417–39
Bennett E M *et al* 2016 Bright spots: seeds of a good Anthropocene *Front. Ecol. Environ.* **14** 441–8

Bernedo Del Carpio M, Alpizar F and Ferraro P J 2021 Community-based monitoring to facilitate water management by local institutions in Costa Rica *Proc. Natl Acad. Sci.* **118** e2015177118

Cuadrado-Quesada G, Holley C and Guptac J 2018 Groundwater governance in the Anthropocene: a close look at Costa Rica *Water Policy* **20** 475–89

Dalin C, Wada Y, Kastner T and Puma M J 2017 Groundwater depletion embedded in international food trade *Nature* **543** 700–4

del Ambiente L P 1995 Asamblea Legislativa de Costa Rica

Dominguez Guzmán C, Zwarteveen M and Kuper M 2023 Transformation as practice: learning from everyday dealings with groundwater *Water Altern.* **16** 1–12 (available at: https://www.water-alternatives.org/index.php/alldoc/articles/vol16/v16issue1/697-a16-1-14)

Foster S, Chilton J, Nijsten G J and Richts A 2013 Groundwater—a global focus on the 'local resource' *Curr. Opin. Environ. Sustain.* **5** 685–95

Fundación Avina 2024 Centros de Sostenibilidad: una innovación para los acueductos comunales de Costa Rica *Historia, impactos y desafíos Fundación Avina* Disponible en p 82 (available at: https://biblioteca.avina.net/biblioteca/centros-de-sostenibilidad-una-innovacion-para-el-fortalecimiento-de-los-acueductos-comunales-de-costa-rica/)

Giordano M 2009 Global groundwater? Issues and solutions *Annu. Rev. Environ. Resour.* **34** 153–78

Gleeson T, Cuthbert M, Ferguson G and Perrone D 2020 Global groundwater sustainability, resources, and systems in the Anthropocene *Annu. Rev. Earth Planet. Sci.* **48** 431–63

Huggins X *et al* 2025 The open data landscape to study groundwater dynamics in social-ecological systems: a scoping review of global datasets and an aspirational future outlook *Environ. Res. Lett.* submitted to this Focus Issue

Huggins X, Gleeson T, Castilla-Rho J, Holley C, Re V and Famiglietti J S 2023 Groundwater connections and sustainability in social-ecological systems *Groundwater* **61** 463–78

Instituto Costarricense de Acueductos y Alcantarillados (AyA) 2024 Official ASADAS dataset (Accessed May 2024) Dirección de Evaluación y Mejoramiento de la Subgerencia de Sistemas Delegados AyA

Lall U, Josset L and Russo T 2020 A snapshot of the world's groundwater challenges *Annu. Rev. Environ. Resour.* **45** 171–94

Madrigal R, Alpízar F and Schlüter A 2011 Determinants of performance in rural water community organizations in Costa Rica *World Dev.* **39** 1663–75

Madrigal R, Mullan K, Pacay E, Pattanayak S K, Robalino J and Evia P 2024 Volumetric pricing in rural Central America: drivers of adoption and potential effects on water delivery *World Dev. Sustain.* **4** 100163

Ostrom E 2009 A general framework for analyzing sustainability of social-ecological systems *Science* **325** 419–22

Ostrom E 2010 Beyond markets and states: polycentric governance of complex economic systems *Am. Econ. Rev.* **100** 641–72

Pörtner H-O 2022 Climate change 2022: impacts, adaptation and vulnerability *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* The Intergovernmental Panel on Climate Change (IPCC) ed H-O Pörtner (Cambridge University Press. Cambridge University Press) p 3056

Registro Nacional de Costa Rica 2024 Official ASADAS's property records (available at: www.rnpdigital.com/shopping/login.jspx) (Accessed November 2024)

Scanlon B R, Fakhreddine S, Rateb A, de Graaf I, Famiglietti J, Gleeson T and Zheng C 2023 Global water resources and the role of groundwater in a resilient water future *Nat. Rev. Earth Environ.* **4** 87–101

Universidad Técnica Nacional (UTN) 2020 Asociatividad de la Gestión Comunitaria del Agua en Costa Rica: estado de las Federaciones, Ligas y Uniones (FLUs) Costa Rica, UTN—Fundación Avina—Fundación Suwo DI 47 Disponible en (available at: https://biblioteca.avina.net/biblioteca/asociatividad-de-la-gestion-comunitaria-del-agua-en-costa-rica/)

Villholth K G and Conti K I 2017 Groundwater governance: rationale, definition, current state and heuristic framework *Advances in Groundwater Governance* (CRC Press) pp 3–31

Zamrsky D *et al* 2025 Current trends and biases in groundwater modelling using the community-driven groundwater model portal (GroMoPo) *Hydrogeol. J.* (https://doi.org/10.1007/s10040-025-02882-7)

Zwarteveen M *et al* 2021 Transformations to groundwater sustainability: from individuals and pumps to communities and aquifers *Curr. Opin. Environ. Sustain.* **49** 88–97