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Intervention

Groundwater urgencies: what can geography offer?

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Abstract. Drawing on a conference session on groundwater embedded in distal relations, we present the outcome of an interdisciplinary discussion on conflicts and boundaries in groundwater geographies. We present five case studies illustrating key aspects of how conflicts evolve and boundaries change. We identify epistemic contestations and transition phases of adjustment as common themes across the cases. We furthermore expose a tension between the urgent needs for producing applied groundwater research and implementing findings on one hand and taking time for reflective research modes and questioning modes of knowledge production in groundwater research on the other hand. We argue that continuous epistemic boundary work is needed, bridging perspectives and disciplines, while also engaging with epistemic pluralism and conflicting assumptions. Here geography has a timely role to play in the current struggle for sustainable and just groundwater futures.

1 Groundwater in focus

Groundwater conflicts are unfolding across the globe as people and ecosystems increasingly rely on groundwater for survival (Saccò et al., 2024; Huggins et al., 2024). Attending to these conflicts involves addressing dynamics and uncertainty in groundwater flows: groundwater is in constant movement. Climate change and evolving societal water demand patterns bring in additional uncertainty about the future (Margat and van der Gun, 2013; Huggins et al., 2023; Söller et al., 2024b). Conflicts therefore also address what groundwater is, how to delineate boundaries, and how to measure and assess the state of groundwater. Contestations illustrate how societal relations to nature (Hummel et al., 2023) are undone, reconfigured and reimagined in the Anthropocene "as a period in which … environmental degradation becomes more widespread, and stakeholders search for verbal and visual language that will help them to intervene" (Adams, 2021:5). These issues highlight the necessity of addressing groundwater urgencies from a geographical perspective.

This intervention is an outcome of and reflection on a lightning talk session at the German Congress of Geography (Deutscher Kongress für Geographie, DKG) 2023 in Frankfurt. Guiding questions were the following. How do conflicts around groundwater evolve? How do boundaries manifest in how groundwater is known and managed? How can such conflicts, knowledge and management change? Departing from the individual contributions to these questions, we discuss in this intervention various approaches to studying groundwater as a matter of concern (Latour, 2004) for and its possible contributions to human geography. In bringing a diversity of perspectives on groundwater into exchange we intend to contribute to the endeavours of “pluralizing groundwater governance scholarship” (Zwarteveen et al., 2021:90) and “discipline-bridging research in the field of critical water resource geography” (Rusca and Di Baldassarre, 2019:9). Five case studies serve to illustrate the complementarity of different epistemic approaches in researching groundwater conflicts and boundaries.

2 Conflicts and boundaries as conceptual points of convergence in researching groundwater urgencies

Studying groundwater may refer to multiple ways of assessment, including measuring, taking samples, monitoring, modelling, projecting, mapping regulations and the allocation of rights, and analysing techniques and practices related to groundwater use. The different epistemic stances involved (observing resources, ecosystem reactions, practices, projecting) relate to ontological positions, i.e. what groundwater is: a natural resource, a habitat, an object of contestation and commodification, a subject in socio-hydrogeological relations, etc. (cf. Bakker, 2012; Linton and Budds, 2014; Linton and Krueger, 2020; Rusca et al., 2024). By epistemic we mean concerning ways of knowing. By ontological we mean concerning what “is”. Geographical subfields engaging with groundwater exhibit diverse epistemic and ontological perspectives on society–nature and society–water relationships. Rather than detailing each subfield’s approach, we focus on key conceptual convergences: conflicts, borders, b/ordering and boundaries in society–groundwater relations.

2.1 Conflicts

In analysing conflicts we see a productive complementarity between two different approaches: critical hydrosocial research and social hydrology. Both challenge the ontological separation of society and water but from differing starting points. While socio-hydrology considers society–water relations as external to hydrological systems, the hydrosocial perspective considers these relations as internal to the hydrosocial cycle (water as hybrid). Despite these differing starting points, there can be a productive complementarity between the two approaches in analysing conflicts.

Rusca and Di Baldassarre (2019) advocate for the importance of quantitative socio-hydrology, which provides valuable insights into inequalities, vulnerabilities and hydrological risks. They emphasise how quantitative data can uncover, measure and visualise spatial inequalities, enriching the understanding of waterscapes and the hydrosocial cycle. Similarly, Zeitoun et al. (2020) advocate for integrating basic hydrology, hydrogeology and political economics into hydrosocial thinking to offer a comprehensive analysis of water conflicts. They suggest that quantitative data from technical reports can clarify discrepancies in water securitisation claims and national water needs, thereby shifting debates and enhancing transparency. Focusing on hydrosocial research Flaminio et al. (2022) identify complementary approaches to conflict: waterscapes (Swyngedouw, 1999) focus on historical development and the emergence of inequalities, while hydrosocial territories (Boelens et al., 2016) examine structural inequalities and systemic conflicts. The complementarity between these two approaches lies in their contrasting but interconnected timescales: waterscapes explore slow, historical shifts, while hydrosocial territories address sudden, systemic changes. Together, they offer a more comprehensive understanding of water-related conflicts by accounting for both historical legacies and contemporary dynamics. Deploying the notion of subterranean waterscape, Melo Zurita and Munro (2019) tease out how colonial powers shaped groundwater availability and use in the Yucatán Peninsula, Mexico, in the production of henequen for an international market in the 19th century. This historical perspective draws attention to the enduring legacy of these conflicts, with their effects still present in contemporary groundwater struggles.

2.2 Borders, b/ordering and boundaries

Borders, b/ordering and boundaries in human water relations form an integral part of groundwater analyses. Drawing management boundaries along hydrological (and hydrogeological) boundaries, including across administrative borders, is a core feature of the integrated water resource management (IWRM) paradigm. Transboundary management additionally raises questions about delineating aquifers and modelling socio-hydrogeological interactions such as the following. What are the system boundaries for these interactions? What are representative sites for sampling, categories and system boundaries for monitoring groundwater? Socio-ecological and socio-hydrology concepts show that boundaries in human–water relations extend beyond aquifers (York et al., 2019; Luetkemeier et al., 2021), and the notion of planetary boundaries (Rockström et al., 2023) adds urgency to managing groundwater for (global) water security and resilience (Falkenmark et al., 2019).

Geography provides multiple perspectives to engage in redefining boundaries and borders and in studying the effects of shifting boundaries and b/ordering. While physical geography, political geography and human geography may offer different understandings of boundaries, we follow Zurba (2022:1) in that conflicts surrounding boundaries “can be better understood through different types of research”. The (re)drawing of boundaries in groundwater studies affects the notion of territorial borders, not only where system boundaries are drawn across national borders. Where groundwater bodies are defined on maps, assigned to river basins and captured in international databases, they constitute part of borders and the orders and forms of othering they create: "[a] territorial b/order is a normative idea, a belief in the existence and continuity of a territorially binding and differentiated power that only becomes concrete, objectified and real in our own everyday social practices" (van Houtum et al., 2005:3).

Waterscape and hydrosocial territories perspectives allow for disentangling the (uneven) effects of boundary choices in human–groundwater relations. Socio-hydrological modelling aims at defining the most fitting system boundaries in order to anticipate future system behaviour and potential points of intervention. In integrating hydrosocial and socio-hydrology perspectives, critical geographical water scholars have created spaces for reflecting on boundary choices (cf. Krueger and Alba, 2022; Rusca and Di Baldassarre, 2019). Here groundwater and system boundaries became boundary objects (Jahn et al., 2012): objects that facilitate conceptual discussion across epistemic and ontological perspectives and allow for conducting research across disciplinary boundaries. "Such boundary thinking and related boundary work are necessary for future-proofing science and society but are indeed contested and fought over" (Kanesu and Bruns, 2020, translation by Fanny Frick-Trzebitzky; see also Rusca and Di Baldassarre, 2019). Participatory approaches aim at embracing uncertainty by grounding modelling data in practitioners' experiences and knowledge and enable the collaborative definition of transformative pathways. Here again the deliberate and reflexive choice of epistemic, ontological and aspirational boundaries becomes paramount (Lazurko et al., 2023).

2.3 Case overview

In the following section we explore changing groundwater conflicts and shifting boundaries in groundwater urgencies across epistemic perspectives and cases. Table 1 provides an overview of the cases, epistemic perspectives and methods involved as well as a short introduction to the relevant groundwater urgencies.

3 How do conflicts around groundwater evolve and change?

Conflicts around groundwater typically concern its use in irrigation (here, La Mancha Oriental, Spain) and as drinking water (here, rural southern Bihar, India) and involve questions of groundwater availability in both quantity and quality.

3.1 A hydrological model in irrigation and conflict management in La Mancha Oriental, Spain

The socio-economic development of the La Mancha Oriental region largely builds on the extensive use of the aquifer of the same name for irrigation in agriculture. Combined with drought periods the intensive use has created significant challenges. Most importantly, sinking groundwater tables led to a shift in the point of intersection between the groundwater table and the riverbed of the Júcar River. As a result, larger parts of the river now feed aquifers and smaller parts of the river are being fed by groundwater – both effects result in reduced water availability for irrigation in downstream Valencia. In consequence, farmers around Valencia irrigating with water from the Júcar River contest the increased groundwater extractions in La Mancha Oriental upstream. Decreasing water quality and decentralised and patchy groundwater add to conflicts between users (upstream–downstream), water managers and conservation groups.

Both catchment managers and water users established several measures to reverse the deterioration of the La Mancha Oriental aquifer. Priorities were (a) regularising water rights and control of extractions through the design of an annual exploitation plan based on an agreement between stakeholders, (b) improving efficiency of the irrigation systems, and (c) replacing groundwater pumping in several areas with surface water from outside the system. To study and monitor the correct and best implementation of these measures, managers and users established a collaboration agreement with the Universidad de Castilla-La Mancha (UCLM) and Politècnica de València (UPV) (these two universities belong to the Júcar River basin – upstream–downstream) to develop a groundwater flow model. This model is updated annually based on modelling needs and has allowed for more detailed knowledge of the behaviour of the aquifer and the spatiotemporal distribution of its relationships with the Júcar River, as well as future predictions of the water resources of the region, being a fundamental element in water resource management. In light of its utility as a conflict-mediating monitoring tool, the model's many limitations and uncertainties have been downplayed by water authorities, who present its outcomes as objective facts to legitimise policies, thereby reducing stakeholder resistance (Sanz et al., 2019).

The case illustrates three ways in which conflicts around groundwater arise and develop: firstly, when a stakeholder is considered affected by negative impacts on groundwater or groundwater management, e.g. decrease in downstream contributions (Esteban and Albiac, 2012); secondly, when a deterioration becomes visible, e.g. the decrease in the groundwater level by up to 80 m within 2 decades, which led to a decrease in the water volume transported by the Júcar River towards Valencia (Cassiraga et al., 2019); and thirdly, when knowledge is contested about the aquifer system (Sanz et al., 2016). Many uncertainties and contestations relate to management tools based exclusively on surface water models. Traditional surface water management systems are difficult to integrate into the spatial distribution model of groundwater due to their own characteristics (large surface area, high number of pumping wells without flowmeters, etc.). New management models are necessary that consider the drought impacts affecting surface water, which put severe pressure on the groundwater resources and availability of groundwater impacts in the Júcar River basin (Dountcheva et al.,

Table 1. Overview of cases, epistemic perspectives, methods and groundwater urgencies.

Case	Epistemic perspectives	Methods	Groundwater urgencies
La Mancha Oriental, Spain	Social hydrology, hydrosocial territories	Hydrogeological modelling, qualitative interviews	– Significant drop in groundwater levels due to irrigated agriculture since the 1980s – Altered hydrological flow affects traditional agriculture systems downstream – Climate and land use changes exacerbating water quality and quantity effects in upstream–downstream interactions
Rural southern Bihar, India	Political ecology of water infrastructures	Quantitative and qualitative interviews	– Seasonal drying of rivers after monsoons – Excessive fluoride levels in groundwater causing severe impairment of human health – Long-standing deficiencies in the supply of safe drinking water
Klokot, Croatia, Bosnia and Herzegovina	Knowledge practices	Ethnographic research	– Transboundary groundwater catchment impacted by tourism and contamination – Karst conditions (high flow rates, low filtration and unknown flow directions) posing challenges to monitoring and management
Strategic Pipeline Alliance in East Anglia, UK	Political ecology, science and technology studies	Qualitative interviews, discourse analysis	– Region classified as water-stressed with risks exacerbated by climate change – Large-scale water pipeline network constructed to redistribute water from wetter to drier areas – Digital technologies in the new network colliding with conventional water management practices
Krk, Croatia	Social hydrology, socio-ecological systems	Hydrological modelling, participatory scenario development	– Summer tourism peaks leading to manifold increases in water consumption – Local groundwater insufficiencies met by water transfer from mainland – Rising temperatures and drier conditions (Söller et al., 2024b) placing additional strain on mainland water catchments

2020). While limitations are acknowledged by modellers, the presentation of the model's outcomes as objective facts by the authorities masks inherent uncertainties and limitations, transforming the model into a tool of epistemic authority. This can marginalise alternative perspectives, thus highlighting the conflict over whose knowledge counts in managing shared resources (ter Horst et al., 2024).

3.2 Visibility as a measure of crisis: rural southern Bihar, India

The village of Hardiya and associated regions in rural southern Bihar, India, suffer from excessive fluoride contamination in groundwater, primarily due to geogenic conditions. The nearby mica mines contain natural fluorite minerals, and both natural and human activities contribute to the dispersion of fluoride at the ground and surface levels. This contamination has led to widespread fluorosis, affecting people's health, livelihoods and socio-economic reproduction. In response, governmental, non-governmental and international organisations have launched programmes to manage groundwater resources and mitigate fluorosis. These initiatives include building infrastructure, deploying fluoride removal technologies and providing expertise.

However, the understanding of fluoride and fluorosis by scientists and experts has led to socio-spatial inequalities in the design and implementation of these mitigation programmes. Organisations initially focused only on areas with extremely high fluoride levels (4.5–6.0 $\mathrm{mg\,L^{-1}}$) where visible physical deformities from skeletal fluorosis were apparent. This led to the exclusion of other forms of fluorosis, such as dental and non-skeletal fluorosis, which also arise from contaminated groundwater. Many settlements with fluoride levels between 1.5–5.0 $\mathrm{mg\,L^{-1}}$, including those in dam-induced resettlement areas, were left without access to mitigation efforts, despite a significant number of cases of skeletal fluorosis. In Hardiya's case, even though incidences of fluorosis prevail in visible and invisible forms, institutions and actors only accept visibility (bodily effect of fluorosis) as a measure of the crisis. Local technical actors further exacerbate these inequalities by influencing access to mitigation programmes. The uneven distribution of knowledge and resources within organisations and administrative bodies hampers effective groundwater management in Bihar. As a result, the management of groundwater and fluorosis has become entangled with biopolitics and techno-political imaginaries, affecting the social-reproduction capacities of the affected communities. We therein detect similar ways in which conflicts change and unfold: residents of Hardiya are initially affected by fluoride concentration and subsequently affected by issues that are unattended to in infrastructure and health management.

3.3 Epistemic contestation and violence

The two cases reveal a particularity of groundwater conflicts related to the spatial and temporal distances between the source and impact of pollution and exploitation: both conceptually and empirically, the fact that the polluter and the polluted and the exploiter and the exploited might never meet creates a challenge in the definition of conflict parties. In addition, epistemic perspectives are crucial in both cases in determining whether water rights have been violated and in guiding future groundwater management. In La Mancha Oriental, it is the scientific model and remote sensing technology that render certain groundwater abstractions visible and are used to grant access to (organised) irrigators. In Bihar, the visibility of groundwater pollution impacts in water and in people's bodies is a key indicator of groundwater quality in local monitoring. Both ways of measuring rely heavily on "seeing" the "invisible" resource and are blind to abstractions and impairments that would be detectable using alternative methods, models and epistemic perspectives. Embracing epistemic pluralism by including differentiated perspectives would challenge truth claims and open alternative development pathways. The mapping of social groups and their exposure to contaminated waters and the collection of qualitative data on invisible forms of fluorosis in Bihar, for instance, reveal structural inequalities regarding exposure to toxic (ground)water and related disease (Srivastwa and Kabra, 2023) and are valuable to overcoming inherent forms of violence (cf. Korf, 2005). However, embracing multiple epistemologies "should not be seen as a technical problem to be solved, but should rather increase reflexivity in the choice of narratives leading to new modes of adaptive and systemic governance" (Cabello et al., 2018). This involves reflecting on how boundaries shift in how groundwater is known and managed in the course of questioning and contesting epistemic claims. We turn to this in the following section.

4 How do boundaries change in how groundwater is known and managed?

Delineations of boundaries in how groundwater is known and managed concern multiple aspects. In this section we draw attention to cases of shifting territorial borders in aquifer management (Klokot, Croatia, and Bosnia and Herzegovina), of new administrative boundaries introduced by digital technologies (East Anglia, UK) and of seasonal expansion of infrastructural networks across hydrogeological boundaries (Krk, Croatia).

4.1 Shifting territorial borders in Klokot, Croatia, and Bosnia and Herzegovina

The case of Klokot's transboundary groundwater catchment in Croatia and Bosnia and Herzegovina illustrates poignantly how groundwater appears as a site where different boundaries meet and are already entangled and negotiated. In this sense, boundaries can shift management and knowledge practices just as management and knowledge practice shift boundaries.

Klokot's groundwater catchment has been a site of multilayered contestations of shifting territorial borders for centuries, most recently during the Yugoslav dissolution wars in the 1990s. While these shifts carried fundamental consequences for geopolitical orders and alliances, economic prosperity, and public life, they also reached underground. Croatia's and Bosnia and Herzegovina's independence from Yugoslavia co-produced many transboundary aquifers that were not considered transboundary some 30 years ago. So, how do shifting political and administrative boundaries affect how groundwater can be known and managed? Today's Croatia shares the majority of its aquifers with its neighbouring states, mostly with Bosnia and Herzegovina. In Yugoslavia, management activities overlooked groundwater use on a catchment level. During that time, the Klokot spring supplied not only the city of Bihać with drinking water but also the underground military air base of Željava, at that time one of Europe's biggest military airports.

Today, the border between Croatia and Bosnia and Herzegovina runs right through the now transboundary airport and through the entire catchment area, posing complex management challenges. For one, since Croatia's formal accession to the European Union (EU) in 2013, in addition to the state border, the EU external border now divides the groundwater catchment. Newly b/ordering the groundwater catchment as transboundary in order to make it legible to techno-managerial regimes (including transposing EU acquis) included a number of measures: forming an international commission on shared water resources, securing donor funds for scientifically driven policy projects tasked with defining the groundwater catchment's boundaries, tracing and identifying pollutants, and formulating policy recommendations that have not yet come to fruition. The concomitant new delineation of drinking water jurisdictions, transboundary sanitary protection zones that are not harmonised between the two countries, contestation of who is responsible for (what kind of) pollution, and attempts at technical fixes are materialised effects of the contemporary nation-state boundaries that, in turn, push boundaries of management, monitoring and maintenance. Dealing with shifting boundaries in such dynamic and politically sensitive contexts that involve contradicting sets of regulations is extremely challenging and heavily relies on embedded practices and care (Hodžić, 2025).

4.2 Breaking down administrative boundaries in East Anglia

In the Strategic Pipeline Alliance in the UK, knowing groundwater through data and AI models involves advanced informatics, computation skills and comprehensive adjustments of datasets to be integrated. To secure water supplies for future generations as well as creating more drought resilience in the East of England, Anglian Water started the Strategic Pipeline Alliance project. It is a large-scale, holistically linked water transfer system aiming to tackle future water shortages in the East of England by transferring water from “wetter to drier areas” (Anglian Water, 2023). Whereas the introduction of a digital twin – a virtual representation of a physical object or process – for monitoring the water along a 320 km pipeline promises comprehensive integration, data are currently still mainly managed in silos: they are not largely shared between teams and departments (Anglian Water, 2023). Formation of technical knowledge, facilities and expertise by different organisations may or may not perform as expected.

In the Strategic Pipeline Alliance, the introduction of digital water technologies aims to change the existing water management structure which created boundaries between the administrative units within the utility, even though they work in the same network and on the same resource. In anticipation of the digital twin, data and their computation with artificial intelligence are seen as an ideal way of managing water and breaking down administrative boundaries along remote water transfer across aquifers and sharing the data throughout the utility to allow for more informed water management in the region. The digital management of water (data) dissolves the boundaries and aims to represent the flow of the water as it is in the physical world. However, this still presents a lot of challenges for the utility as data interoperability is key for these new networks to work, as digital twins can only operate successfully if all the data are available and all systems are connected at the same time. Changing boundaries include for instance administrative boundaries as changes regarding management zones are introduced, affecting the decision-making processes. These strategic decisions will increasingly be supported with AI tools. This also creates new boundaries between reality (e.g. the physical flow of water in the system) and its digital representation (e.g. the digitalised version of these flows) and affects people’s relation to water due to the new relations with and through the digital technologies (Walter, 2024).

4.3 Seasonal fluctuation in infrastructural and managerial boundaries on Krk, Croatia

In Croatia’s coastal regions, particularly on Krk Island, the hydrological impact of water use and transfer, notably in relation to tourism, is significant. During summer months, water consumption surges 5-fold (Silvio Giorgolo, personal communication, 2022), necessitating the activation of secondary infrastructure networks like a scalable desalination plant and a long-distance water transfer scheme to the mainland to meet peak season demands. In the off-season, the island’s water supply is met by local groundwater. Thus the infrastructural and managerial boundaries for managing drinking water supply fluctuate seasonally, aligning with peaks in tourist flows. This challenge is emblematic of the broader issue facing Croatia’s tourism sector. Efforts to address this imbalance, such as connecting Krk’s northern half to the mainland’s water supply in 2008, underscore the complexity of water resource management in tourism-dominated contexts (Söller et al., 2024a). Previously independent hydrological catchment areas are being altered by management strategies and adaptation to high tourist numbers. Water is now being transported beyond its natural hydrological boundaries (Grbac Žikovic et al., 2009), which may also impact ecosystems and the drinking water supply in the sending system on the mainland. Additionally, climate change exacerbates existing challenges, with projections indicating potential decreases in groundwater recharge by the century’s end (Söller et al., 2024b).

4.4 Transition phases of adjustment

Boundaries shift in different realms. On the one hand, post-Yugoslav and EU b/ordering practices have introduced and fortified administrative boundaries regarding how groundwater is managed and known within the same groundwater catchment in the Klokot case. On the other hand, management and knowledge practices have extended boundaries to comprise multiple catchments as part of one water supply system (East Anglia, UK, and Krk, Croatia). The examples show that managing shifting boundaries is challenging. In Klokot and East Anglia, legacies of boundary setting persist in how groundwater is monitored, used and protected and how infrastructure is designed, maintained and managed, even though administrative regulation had formally been changed. New delineations of boundaries (b/orders) by regulatory frames (Klokot case) or information technology (East Anglia case) create disruption in workflows, are at odds with established practices and initiate transition phases of adjustment that are likely to span over longer periods in time. The Krk case illustrates the particular challenge involved in managing periodically shifting boundaries: here seasonal peaks in water demand require a double set of infrastructures that work in the tourist off-season and in the tourist season, respectively. Not only does this represent a burden on management and maintenance activities, but it also implies that different arrangements of stakeholders and administrative and hydrogeological entities and infrastructures form part of Krk Island's groundwater system in the tourist season and off-season.

5 Conclusion: navigating tensions between urgency and justice in groundwater research

The insights and discussions about conflicts and boundaries exposed a major issue in research on sustainability issues: working across epistemic differences gets delicate where definitions have vital consequences. What are the perspectives, datasets and projections needed to prevent child mortality and lifelong disability from fluorosis and other diseases? Could extensive irrigation in export-oriented food production endanger local livelihoods? How path-dependent are groundwater governance arrangements, and (how) can they ever be fit for preventing unhealthy, unsafe and unjust development? This set of questions comes with a sense of urgency: groundwater is essential to the lives of human and non-human species, has long been understudied and mismanaged as a taken-for-granted resource from the underground, and requires timely attention in research and management to prevent a further threat to lives.

Yet the cases discussed also provoked a different set of questions. How do people, infrastructures and technologies shape the scope of intervention in groundwater management? How do we know what unhealthy, unsafe and unjust groundwater management is? This line of questions tackles epistemic work that is part of how boundaries are drawn and redrawn and made visible and concealed, how threshold values become established and implemented as regulation and enforced, etc. In highlighting the incompatibilities and unintended effects of decisions entailed in modelling hydrogeology, projecting impacts and monitoring change, the research presented puts up a warning sign. Where we attend to the urgencies in groundwater research, we will inevitably become complicit in the (uneven, often unjust) structures of knowledge production for groundwater management. We therefore need to allocate time and resources to studying knowledge politics in groundwater geographies. In our view, it is not helpful to pit the two trajectories of learning from the cases against one another. Instead, we ask the following. How can we make sense of how new spatial and temporal relations are unfolding, and how can we imagine transformative pathways?

Firstly, we see a need to acknowledge the transition phase many groundwater managers and policy-makers find themselves in as epistemic and administrative boundaries shift. Knowing, managing and administering groundwater in shifting spatial relations challenges established practices and ways of relating to groundwater knowledge. This calls for modesty in proposing new approaches (Krueger and Alba, 2022) and for attending to orientation knowledge (Schneider et al., 2019). The example of water supply on Krk Island illustrates how focusing on flows of water and tourists allows for taking stock of volumetric changes in water budgets, stakeholders in local groundwater management, and perceptions and interests involved in decision-making towards the goal of sustainability. Here the flexibility of the concept of telecoupling (Liu et al., 2013) appears as a strength, offering entry points for different epistemic approaches and practical needs (Cotta et al., 2022; Luetkemeier et al., 2021).

Secondly, we see the need to identify tensions and engage with pluralism in knowledge carefully. Tension exists between the urgency to address injustices, e.g. in the intoxication of people with fluoride in Bihar on one hand, and the impulse to halt, pause and reflect on the unintended effects of techno-managerial solutions, as well as how data, models and regulations are produced, on the other hand. More than being a contributing factor to the conflicts explored in the case studies, this tension appears to challenge established ways of posing research questions and designing research in physical and human geography, respectively. In light of our observations from case analyses and the questions raised, we argue (a) that the plurality of geographical research (and neighbouring disciplines) provides a large potential for understanding societal relations of groundwater and exploring transformative pathways and (b) that the plurality is most fruitful when carefully engaged with (see also Zwarteveen et al., 2024). Consequently, bringing concepts, approaches, questions and data into careful conversation while allowing through epistemic disconcertment for space for conflict and tension would foster generative critique (Verran, 2013). Here, boundary work (Zurba, 2022; Star, 2010) can help to mediate.

Thirdly, as our concluding point, we are convinced that geography as a discipline is fit to address this tension between urgency and justice in transition phases of adjustment to new boundaries if it opens up inter- and transdisciplinary knowledge production and reflects on its own position (Schneider et al., 2019). Given the long history of boundary work in and between subdisciplines and neighbouring disciplines (e.g. Castree et al., 2009; Schurr and Weichhart, 2020) in geography more generally and in critical water resource geography (Rusca and Di Baldassarre, 2019) in particular, we are convinced that geographical research on groundwater has an important role to play in addressing groundwater urgencies.

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