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Groundwater use to reduce natural hazard susceptibilities and inequities in the metacrisis

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Preface

Long-term thinking is broadly advocated for groundwater - the largest available freshwater resource that is essential for drinking water, irrigation and ecosystems around the world. Long-term thinking is crucial to support sustainability of this slowly renewed resource, but here we propose another crucial, novel and emerging approach for groundwater: short-term use over days and months during or after various natural hazards such as earthquakes, wildfires, floods and droughts. As natural hazards are compounded by other social, political and economic crises in the metacrisis, groundwater is emerging as a strategic solution that is inexpensive, speedy and distributed. We review emerging risks and successes while arguing for a shift of mindset, policy and planning as well as a deeply interdisciplinary and equity-driven approach incorporating disaster sociology, environmental justice, sustainability science and sociohydrology. We offer examples of hope, thought leadership and policy direction for hazards around the world that share a common solution: groundwater.

Natural hazards in the metacrisis: could groundwater help?

The negative impacts of natural hazards are compounded in the metacrisis by other social, political and economic challenges [1–5], including political polarization, racism, misinformation, and economic challenges. Yet one possible strategy to reduce the impacts of natural hazards is lying right beneath our feet, waiting to be considered more deeply. Four natural hazard events from around the world hint at the possibilities:

- The 2024 Noto, Japan earthquake (magnitude 7.6) caused extensive infrastructure damage such that 110,000 households lost water supplies. Severe road damage limited access to water trucks, but private well owners immediately provided groundwater to neighbors mainly for non-potable uses similar to past earthquake events in Japan[6].
- The 2020 wildfire near Santa Cruz, California, USA extensively damaged water infrastructure including damaging 12 km of pipes supplying surface water. This resulted in the San Lorenzo

Valley Water District relying largely on groundwater for months after the wildfire until surface water infrastructure could be repaired[7].

- A 2015-2018 multi-year drought in South Africa culminated with the Day Zero water crisis in the city of Cape Town [8,9]. Groundwater was used to cope during this event but only wealthier people located close to an aquifer were able to benefit by drilling wells to replace or integrate municipal water supply with groundwater.
- Catastrophic floods of the Elbe River, Czech Republic in August 2002 contaminated several sources of drinking water supply. Pumping groundwater from confined aquifers that are resistant to natural hazards was recommended for emergency water supply[10].

Although groundwater depletion and contamination are widespread [11,12], these four different natural hazards point to a crucial and emerging approach in the metacrisis: short-term groundwater use over days and months during and after a natural hazard. In this manuscript we extend important previous work led by UNESCO over ten years ago [13,14] with emerging risks and successes (Box 1). We argue for a shift of mindset, policy and planning as well as a deeply interdisciplinary and equity-driven approach. Specifically, we 1) visualize susceptibility to a variety of natural hazards and how susceptibility can be reduced through a myriad of tools and approaches; 2) differentiate short-term groundwater use during or after natural hazards compared to normal long-term use; and 3) highlight how considering groundwater use along with disaster and environmental justice, disaster sociology, sustainability science and sociohydrology could help reduce the impacts of natural disasters.

Box: Novelty, scope and terminology

Novelty: The 2002-2013 UNESCO project 'Groundwater for Emergency Situations' first identified methodologies, examples and challenges of groundwater use during natural hazards considering diverse geoscience methods [13,14] , international case studies, and governance[15]. This work has few citations academically or in natural hazard mitigation plans, and is not incorporated into recent flagship UN groundwater report[16] or the Sendai Framework for Disaster Risk Reduction[17], suggesting this important work has not significantly impacted regional, national or international natural hazard mitigation. We elevate and extend this previous work through a more interdisciplinary and social-science oriented approach (beyond primarily geoscience), consistently and explicitly considering equity, describing recent case studies from around the world, and including wildfires that have emerged as a more common natural hazard. Specifically, we develop a new visualization for how susceptibility can be considered (Figure 1) and reduced through a myriad of tools and approaches (Figure 3), as well as a new way of thinking about groundwater use for natural hazards inspired by a recent, popular approach[18] to groundwater governance (Figure 2). For groundwater governance during emergencies, Vrba[15] proposed a framework of institutional and technical capacities, and identified serious gaps including low compatibility between governmental and community level organizations, and the lack of legal frameworks for water rights in emergency situations. Figure 3 is a concrete way of visualizing how technical and institutional capacities can reduce susceptibility; we draw on disaster hydrology, and recent policies in British Columbia to start to address these two gaps, respectively.

Scope: Groundwater use for natural hazards can be considered across the whole 'disaster cycle' from mitigation, preparedness, response, and recovery [15,19]. The impact of natural hazards on water infrastructure and supply can be direct such as water pipes breaking in earthquakes or it can be indirect such as electrical systems damage. Herein we focus on the direct impacts but allude to the more complex indirect impacts below by considering how natural hazards relate to the food-energy-water nexus. We focus herein on earthquakes, wildfires, droughts and floods which represent different causes, potential warning times and water impacts. There is scant current literature that is focused on groundwater use with the other types of natural hazards or on combining groundwater and surface water use after natural hazards, both areas for future research (Section 6).

Terminology: Although some natural hazards are directly exacerbated by human activities such as climate change or urbanization, all 'natural' hazards are interwoven with social dynamics. Herein we emphasize the importance of social dynamics and avoid the term 'natural disaster' which is highly contested since disasters happen only when natural hazards impact vulnerable and exposed populations[20]. We only use the term 'disaster' when used predominantly in related literature (Section 5). We use the term 'susceptibility' to natural hazards of water infrastructure or supplies rather than vulnerability, as the latter has a much broader meaning in the scientific literature[21].

Natural hazards impact water infrastructure and supplies differently

A variety of natural hazards can impact water infrastructure (engineered water distribution and purification systems) and/or water supplies (natural groundwater or surface water). We consider the nine different natural hazards tracked by the Centre for Research on the Epidemiology of Disasters [22] which represent a range of causes and consequences for water infrastructure and supplies (Figure 1). Two crucial factors determine if or how groundwater could be useful during or after natural hazards: the potential warning before the natural hazard and the potential for the natural hazard to impact water infrastructure or supplies (Figure 1). The potential warning ranges from seconds (for rapid onset natural hazards such as earthquakes) to years (for slow onset natural hazards such as droughts) and determines the time available for prediction and deliberation about how to react. The potential impact on water infrastructure or supplies also ranges from low impact (negligible change in water infrastructure or supplies) to high impacts (water infrastructure or supplies temporarily lost in a 'water outage'). Combining these two factors conceptually results in a susceptibility of water infrastructure or supplies to natural hazards. Natural hazards with a generally lower susceptibility (lower left corner of Figure 1) does not imply or mean that groundwater is not important but rather that the groundwater supply is less likely to be impacted and possibly that short-term thinking (Section 4) is less important.

Groundwater is less likely to be impacted by natural hazards than surface water [13,14]. Natural hazards such as earthquake, volcanic activity, flood, storm or wildfire often impact centralized water infrastructure that are more often surface water. These infrastructure impacts such as breaking pipes are more likely to be single point failures. Groundwater is generally more decentralized[18] so less likely to be impacted by single point failures. Second, surface water can be contaminated or salinized rapidly and extensively by natural hazards such as floods, wildfires, tsunamis or storm surges. Groundwater is less likely to be contaminated rapidly and extensively although this depends on the aquifer type as well as other factors such as land use, natural hazard, connectivity to surface water etc. Generally, contamination of unconfined aquifers (those directly connected to surface water and atmosphere) will be slow. For example, salinization after a tsunami or storm surge can take months to move downwards[23]. Confined aquifers are separated from surface water and atmosphere by a low permeability confining layer that makes contamination or salinization from the surface much less likely. For these reasons, we argue that groundwater can and should be used strategically during or after natural hazards, sometimes in conjunction with surface water.

From hazard risk to reduced susceptibility

Policies and practices for earthquakes, wildfires, droughts and floods in a variety of countries provide clues of how groundwater could be strategically used to reduce susceptibility to natural hazards.

Earthquakes in Japan where privately owned wells change into public assets in emergency situations are the most closely studied example[6,24,25]. The 1995 Hanshin-Awaji earthquake struck highly urbanized Kobe and adjacent cities highlighting both the susceptibility of modern water infrastructure and the resilience of local groundwater as an emergency water supply prompting the establishment of 'disaster emergency well' programs. Private wells owners pre-register and are expected to provide groundwater voluntarily after an earthquake. Currently 1316 of the 1741 municipalities in Japan have plans to use groundwater during emergencies including major cities such as Kyoto, Sapporo, and Sendai[24]. Key policies include enhancing social capital, pre-registering local wells for emergency use, and facilitating information sharing and collaboration between well owners and public relief organizations. Marginalized communities can be disproportionately impacted by earthquakes in Japan[26] and elsewhere[27], and although the disaster emergency wells could ensure that water is accessible for marginalized communities, to date municipal plans do not explicitly consider equity or marginalized communities.

Groundwater is a useful water source before (prevention and protection), during (suppression) or after (recovery) **wildfires**, while also helping to maintain soil moisture. Wildfires can have disproportionate impacts on marginalized communities [28–31]; climate change is increasing the frequency and intensity of weather conducive to fire ignition and spread [32]; and the importance of groundwater for wildfires is magnified by drought, water scarcity or seasonal water availability. Policies in various jurisdictions such as British Columbia[33] clarify the importance of groundwater use for wildfires but do not explicitly consider equity and could consider the use of non-potable groundwater before or during wildfires. The literature [34–37] on water supply and wildfires is dominated by examples and warnings of erosion, mudslides and contamination of water supplies and infrastructure. It is crucial to rapidly test and repair water supplies and infrastructure after fires, while also elevating the crucial role of groundwater use before, during and after fires as a source of potable water, less likely to be contaminated or affected by erosion or landslides. For example, two large wildfires in California damaged thousands of structures, and had extensive damage to the water distribution systems but the potable water sources including wells were not impacted[37].

Droughts are slower onset events usually with more warning than other natural hazards (Figure 1). Short-term strategic groundwater use can be important when surface water resources are limited or unavailable. Droughts can exacerbate groundwater use and depletion [11,38,39], so it is key groundwater use during droughts be strategic aquifer depletion, which does not exacerbate long-term groundwater depletion and to consider equity[40]. A case in point is the 2015-2018 drought in South Africa that culminated with the Day Zero water crisis in the city of Cape Town where drought impacts were unevenly distributed because of stark social inequalities characterized by unsustainable high levels of water consumption by the city elites [8,9]. During drought restrictions, wealthier households drilled wells and integrated municipal water supply with groundwater.

Flood events often contaminate surface water and thus can severely affect water supply. Groundwater resources resistant to natural hazards can be used as a substituting supply during flood emergencies [41]. The aforementioned example of 2002 flooding in the Czech Republic is a case in point. Isotope groundwater dating was applied in the flooded region to identify aquifers with the longest groundwater residence recommended as alternative supply in case of major flooding[10]. Similar to the other hazards, flood risk is unevenly distributed across societies [1,2]. The unequal impacts of the 2005 flooding in New Orleans, for example, are emblematic of how marginalized communities often have less resources to prevent, cope with and recover from floods [42,43]. Lastly it is important to integrate the response to floods and droughts in relation to groundwater, for example by alleviating droughts by strategically recharging aquifers during floods as argued in a recent California policy water policy white paper [44].

Importantly, in each of these types of natural hazards, we are not discussing or proposing entirely different technology or groundwater resources - generally the same wells, pumps and aquifers would be used (although in some cases strategic well drilling may be useful). But really what we are proposing is a shift of thinking, policy and planning which is what we explore next.

The value of short-term thinking

Here we differentiate short-term groundwater use during or after natural hazards compared to normal long-term use. Long-term thinking is broadly advocated for groundwater - the largest available freshwater resource that is essential for drinking water, irrigation and ecosystems around the world [40]. Long-term thinking over years to decades is crucial to support sustainability of this slowly renewed resource, but here we propose short-term use over days and months during various natural and human-made disasters. For natural hazards, the timescales are likely hours to months, the primary uses likely domestic water, fire suppression etc. and key challenges include rapid and equitable access and contamination (Figure 2). Groundwater resources in normal times have three distinctive characteristics (invisible, slow and distributed or ISD) which challenge resource management of this common pool resource[18]. Invisibility leads to under prioritization; slowness makes it challenging to observe management changes; and distributed means there are many well owners spread over great distances.

However, short-term thinking is more important during or after natural hazards which suggests considering other ISD characteristics (inexpensive, speedy and distributed). Groundwater sharing at community level after natural hazard can be inexpensive because it does not need new equipment or facilities. Wells can quickly supply water to a community, potentially faster than water trucks or other means depending on the organizational response or damage to infrastructure. Finally, the distributed characteristic has a positive meaning during or after natural hazards since a broader population can access water supplies. Importantly, inexpensive, speedy and distributed may also lead to more equitable outcomes in that more people have water access regardless of socio-economic, race, geographic location etc. Adopting such 'short-term thinking' has various barriers including deciding quickly, having systems and plans in place before the natural hazard, legal barriers of water use (e.g. changing private wells into public usage) and concerns about water quality (wildfires, tsunamis, storm surges). Next we draw on insights and practices from other disciplines to enable this short term thinking.

Interdisciplinary and transdisciplinary practices

We can highlight interdisciplinary literature and transdisciplinary practices including disaster and environmental justice, disaster sociology, sustainability science and sociohydrology to frame or better understand the potential of groundwater use for natural hazards or possibly accelerate the adoption of this new approach. Geoscientific methods (such as geology, hydrogeology, hydrogeochemistry, geophysics, remote sensing, numerical modeling and geospatial analysis) and groundwater governance (institutional and technical capacities during and after natural hazards) are also important but have been previously summarized [13–15]. Due to limited space, Figure 3 highlights how scientific analysis and communication could possibly increase the warning before earthquakes, floods, storms and wildfires while a host of interdisciplinary and transdisciplinary practices and approaches introduced below could reduce the impact of natural hazards on water infrastructure and/or supplies.

Marginalized communities are often disproportionately impacted by all four types of natural hazards described above, highlighting the importance of equity, specifically **disaster and environmental justice**. Disaster and environmental justice emphasize the importance of equitable treatment and involvement of all communities, particularly those that are historically marginalized in interwoven processes related to disasters and the environment [43,45,46]. Marginalized communities are better included after disasters by removing challenges, recognizing diversity, participating in decision-making, and tailoring approaches[47]. Additionally, established environmental justice tools could be applied such as geospatial, statistical or demographic analysis [48–50] as well as community based research and knowledge co-production [51,52]. For example, to equitably include groundwater use more explicitly in California earthquake or wildfire planning, it could be important to consistently include all stakeholders which have been largely excluded from groundwater sustainability planning to date [53]. For groundwater's inexpensive, speedy and distributed characteristics to reduce the differential impacts on marginalized communities, hazard planning needs to better incorporate disaster and environmental justice.

Important social dynamics examined by **disaster sociology** during or after natural hazards include emergent groups and temporary altruism**.** Organizations are classified [54,55] as established, extending, expanding and emergent based on whether the tasks conducted by an organization during and after disasters are regular or not, and whether the organizational structure is existing or new. Figure 4 highlights how groundwater use after earthquakes could be enabled by these different types of organizations, and due to limited space herein we focus on emergent groups (an ad hoc association of volunteers who appear spontaneously after a disaster) since we envision these organizations catalyzing and enabling groundwater use in different natural hazards. The disaster emergency wells in Japan are an example of such an emergent organization, and we need to develop strategies to seed and support such organizations for other types of natural hazards, as well as coordinate emergent organizations with the other organizational types. Additionally, temporary altruism is common to people affected by natural hazards and is important to consider and amplify since this can extend and strengthen the impact of the different types of organizations [56–58].

Using or adopting approaches from **sustainability science** could enable groundwater use during natural hazards. Groundwater sustainability [40,59] and the groundwater connected systems framing [60] argues for the importance of equity (intra- and intergenerational), adaptive management and groundwater as a socio-ecological system. Groundwater is a common-pool resource, so principles for how commons can be governed sustainably and equitably by communities[61], could complement insights from disaster sociology further enabling emergent groups. Instead of considering groundwater only as a physical resource, the groundwater connected systems framing suggests identifying the ecological (e.g. groundwater dependent ecosystems), Earth system (e.g. groundwater-climate interactions) and social (e.g. food security) functions to prioritize. These key functions could maintain resilience through natural hazards and/or be important to recovery after natural hazards. Two additional concepts from the broad sustainability science domain could be important: nature-based solutions[62] and the food-energy-water nexus [63,64]. Nature-based solutions include a broad set of green infrastructure that can complement or replace traditional gray infrastructure [12] to reduce hazard impact (for example increase slope stability after wildfires). The food-energy-water nexus reminds that the direct impacts of natural hazards on water discussed in section 2 can be magnified when natural hazards damage and disrupt energy systems and reduce food production [65].

Sociohydrology focuses on the complex web of interactions and feedbacks between hydrological and social processes[66] to advance the understanding of complex human-water systems, and inform sustainable water resource management. Qualitative and quantitative methods including historical analyses and system dynamics models draw on diverse fields including[67] water resources systems[68], integrated water resources management [69] and social-ecological systems[70]. Sociohydrological approaches are important since they analyze how community resilience and social networks can help mitigate the negative impacts of natural hazards. Sociohydrological methods also emphasize the potential for unexpected cascading effects or unintended consequences, such as how groundwater use in the short term can backfire on long-term goals such as reduced groundwater depletion[39]. Social capital, the networks and resources available to people through their connection to others[58], is important but yet to be included in the sociohydrology literature related to natural hazards. It is crucial to consider equity along with social capital, since social capital can ameliorate or exacerbate the impacts of natural hazards depending on social dynamics[58]. Finally, in relation to groundwater, socio-hydrogeology specifically includes social sciences into hydrogeological assessments and elevates the importance of reciprocity and responsibilities, as well as the ethical, social, and cultural implications of groundwater-related research[71].

Future challenges

Short-term groundwater use is one possible strategy to reduce susceptibility to some natural hazards in the metacrisis. But groundwater use is certainly not a panacea. Unfortunately, aspects of the metacrisis could challenge some of the suggestions above: political polarization and misinformation could undermine efforts to improve scientific prediction; economic challenges to reduce funding of such efforts; and systemic racism could challenge reducing these impacts on marginalized communities. However, we argue this crucial, novel and emerging approach of short-term groundwater use during or after natural hazards leads is important and has a number of emerging research questions:

- What are the time scales, spatial scales and regional differences between impacts of different natural hazards on both surface and groundwater supplies?
- Where, when and how does groundwater most significantly reduce the impact of natural hazards, especially on marginalized peoples?
- How can groundwater policies be changed to proactively ensure that groundwater can immediately be used after natural hazards?
- How can scientific analysis, modeling and prediction improve the warning for time different types of natural hazards, and how can this best be communicated with impacted communities?
- How can the science-policy interface strategically be improved to enable knowledge sharing and targeted policy development?
- How can social capital etc. be improved to reduce impact?
- How can disaster sociology and social-ecological systems knowledge be combined to reduce harms to marginalized peoples from natural hazards?
- How do the examples and dynamics discussed earthquake, wildfire, flood and drought hazards be extended to other natural hazards such as volcanic activity, storm, landslide and mass movement?
- How can we ensure that any groundwater supplies or infrastructure specifically developed for natural hazards is not used in normal times?

We hope to galvanize new research, policy and practice with this vision of a deeply interdisciplinary and equity-driven approach incorporating disaster and environmental justice, disaster sociology, sustainability science and sociohydrology. Groundwater to the rescue!

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Figures

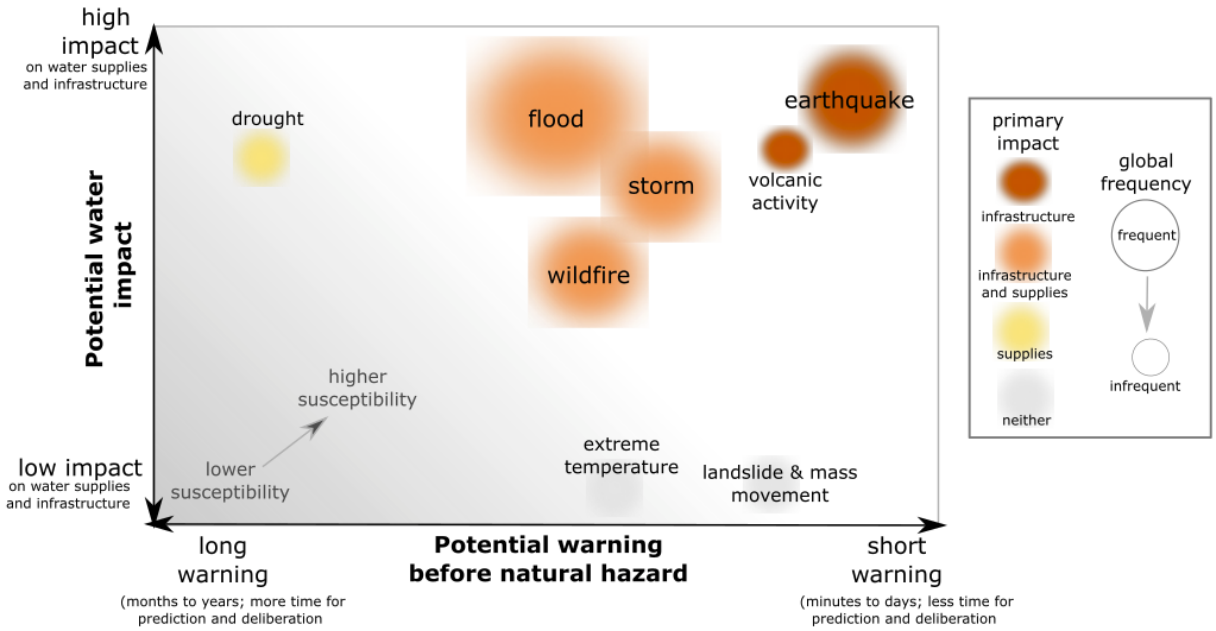

Fig.1. Classifying natural hazards by the potential warning before the natural hazard and the potential to impact water supplies.

Disasters are divided based on whether the primary impact is on water infrastructure and/or supplies, and the symbol for each disaster is scaled based on the global frequency of each type of natural hazard[22]. The size and location of 'drought' on this graph does not consider flash droughts[72].

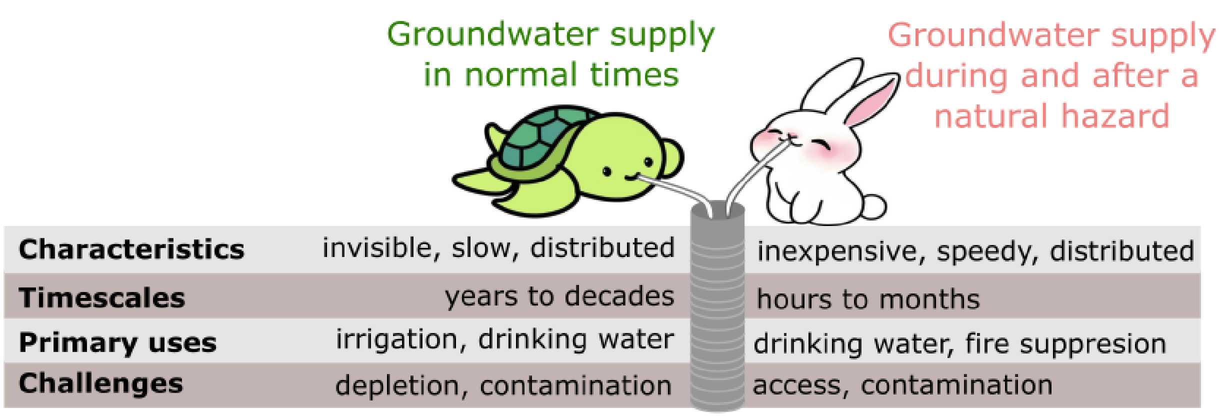

Figure 2. The characteristics, timescales, primary uses and challenges of groundwater supplies in normal times and during or after natural hazards are different.

Groundwater in normal times (represented by a turtle) and groundwater during or after natural hazards (represented by a rabbit), both drink from the same well representing that the same

technology and aquifers are used. The rows of characteristics, timescales, primary uses and challenges represent different layers in the same aquifer system.

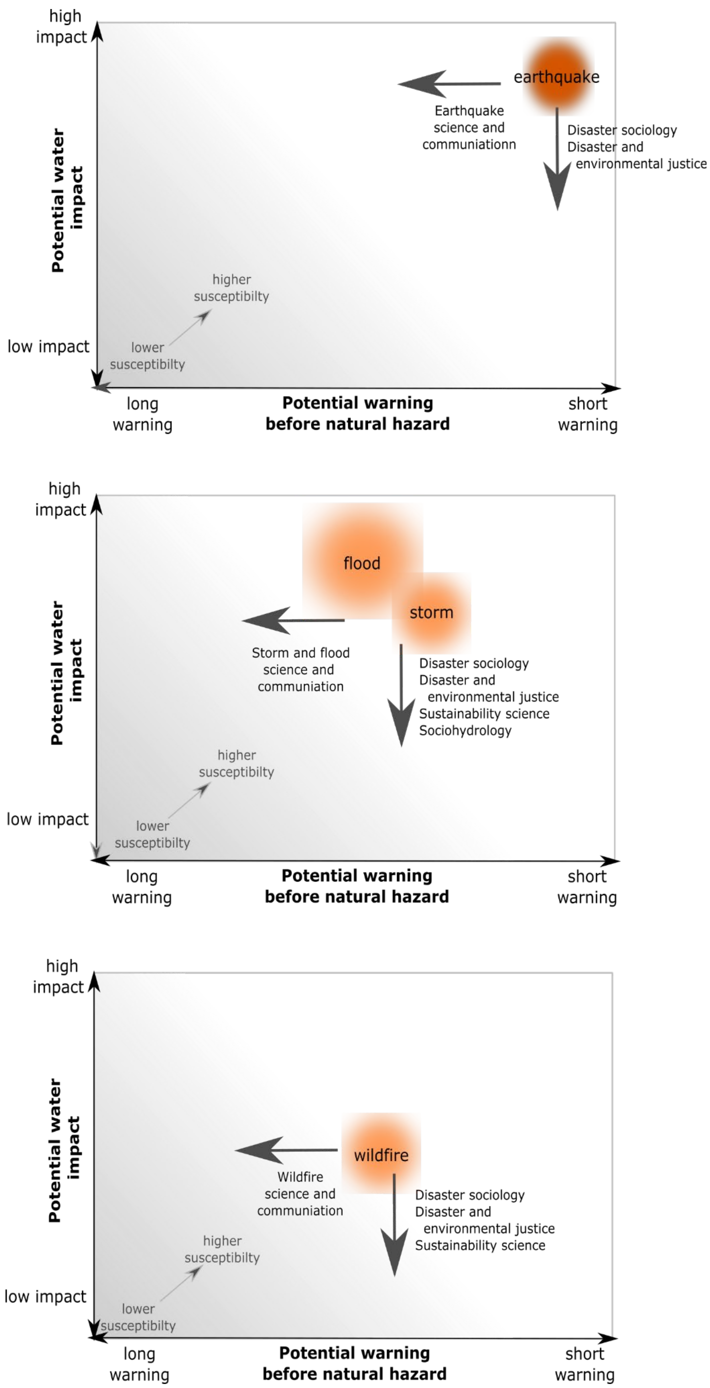

Figure 3. The potential to reduce vulnerabilities to different types of natural hazards.

We can draw on approaches and insights from other disciplines while using groundwater in the short-term during or after natural hazards.

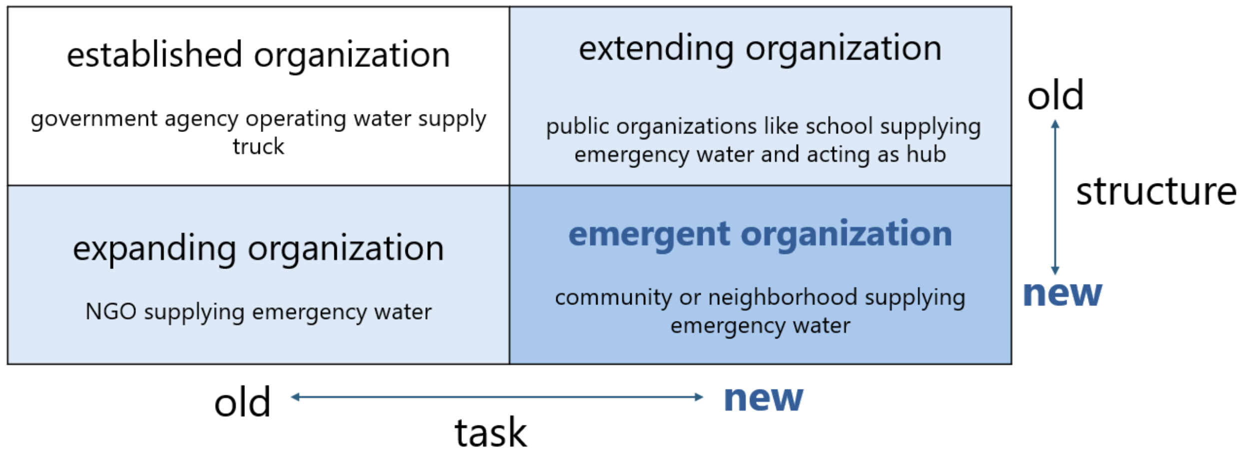

Figure 4. Disaster sociology classification of how different types of organizations respond to natural hazards.

This has not previously applied to water, but here we suggest how these insights could be applied to using groundwater in emergencies using the example of earthquakes in Japan. Established organizations (e.g., police) are engaged in disaster management as a routine task, and their organizational structure remains the same before and after a disaster event. Expanding organizations (e.g., disaster relief NGOs) prepare disaster relief activities during non-disaster periods and implement them more explicitly when a disaster happens. Although the main task (disaster relief) remains the same, they often expand the group size by inviting volunteers to cope with the increasing size of the operation. Extending organizations keep their pre-disaster organizational structure but engage in new tasks. In Japan, a schoolteacher is often appointed as the manager of public evacuation shelters established at schools. Lastly, an emergent organization is a newly formed, typically informal group, which often comprises ordinary citizens who have little experience in disaster relief activities.