This manuscript is a non-peer-reviewed preprint that has been submitted to EarthArXiv. The manuscript is submitted for peer review to *Nature Water* as a Perspective article for the special collection "Urban Fires Around the Globe."

Uncovering a hidden resource for wildfire resilience: groundwater governance solutions to social-ecological challenges in a warming world

Navya Vikraman Nair[1], Tom Gleeson[1, 2], Kristen Walters[3], Giuliano Di Baldassarre[4]

[1] Department of Civil Engineering, University of Victoria

[2] School of Earth and Ocean Sciences, University of Victoria

[3] POLIS Wildfire Resilience Project, University of Victoria

[4] Department of Earth Sciences, Uppsala Universitet, Sweden

ABSTRACT

Wildfires are intensifying worldwide and increasingly threaten cities and communities in the wildland–urban interface. While attention has focused on forests, fuels, and firefighting capacity, water systems are also under growing pressure during major fire events. Groundwater, accessed through decentralized wells across urban, peri-urban, and rural landscapes, remains largely overlooked in wildfire planning despite its potential to support firefighting, provide emergency drinking water, and buffer disruptions to surface water systems. We argue that groundwater should be treated not simply as emergency backup, but as a shared social–ecological resource requiring anticipatory governance. Using a social–ecological systems perspective, we identify key decision contexts where groundwater may be mobilized before, during, and after wildfire events. Integrating groundwater governance into wildfire resilience planning could strengthen water security, reduce inequities, and support communities learning to live with fire in a warming world.

Wildfire resilience challenges and groundwater opportunities

Wildfires are increasing in frequency, intensity, and spatial extent globally across many regions of the world, driven by climate change, land-use change, and legacies of historical fire suppression and land use (Abatzoglou & Williams, 2016; Bowman et al., 2020). Once understood as episodic disturbances, wildfires are increasingly recognized as persistent social-ecological conditions to which communities respond and adapt across uneven social, infrastructural, and environmental contexts (Paveglio et al., 2009; McWethy et al., 2019). Importantly, wildfire risks and impacts are not evenly distributed. Marginalized and resource-constrained communities often experience disproportionate exposure, slower recovery, and reduced access to reliable water supplies, particularly under conditions of hydroclimatic stress including drought, long-term water scarcity, and seasonal variability, which can magnify dependence on decentralized sources such as groundwater (Gleeson et al., 2026). This shift has prompted growing interest in 'wildfire resilience', here understood as approaches that emphasize preparedness, mitigation, emergency response, redundancy in critical infrastructure and water supply, coexistence with recurring fire regimes, and long-term recovery and adaptation rather than complete fire exclusion (Birot, 2009; Paveglio et al., 2009). Within this framing, firefighting and emergency response remain central, but are increasingly complemented by longer-term strategies that aim to reduce vulnerability and maintain essential services during repeated fire exposure. Critically, wildfire resilience is now an urban and peri-urban water challenge as fires increasingly penetrate the wildland–urban interface and threaten water supply and pressure in urbanized neighbourhoods and expanding peri-urban settlements. Despite this conceptual shift, wildfire resilience planning continues to focus primarily on vegetation management, land-use planning, cultural and prescribed burning, and emergency response capacity, with comparatively less attention to urban, peri-urban, and wildland–urban interface water systems as integrated components of wildfire resilience. Yet water plays a critical role across all phases of wildfire: it is important for certain fuel management strategies such as prescribed and cultural burning (while other fuel reduction methods such as mechanical thinning or chipping may not require water), central to active fire suppression and structural protection, and vital for drinking water security and ecological recovery following fire (Bladon et al., 2014; Martin, 2016). Recent wildfire disasters in major metropolitan regions have amplified expectations that urban water supply systems should play a stronger role in wildfire resilience, often beyond what these systems were originally designed to deliver for typical firefighting demands in urban areas (Pierce et al., 2025; Belongia et al., 2023). In this context, Pierce et al. (2025) call for an 'all-hands-on-deck' approach to strengthen urban water preparedness, while also recognizing infrastructure limits, cost trade-offs, and equity implications of expanded fire-related water demands. This Perspective responds to that call by extending the urban water discourse to groundwater, conceptualizing it not merely as emergency backup but as a governed social–ecological system (SES) embedded in wildland–urban interface and peri-urban landscapes where wildfire exposure, decentralized wells, and institutional coordination intersect (Huggins et al., 2023; McGinnis & Ostrom, 2014). As wildfire regimes intensify, disruptions to water quantity, quality, and infrastructure are becoming more frequent, exposing vulnerabilities in water governance systems that were not designed for repeated, high-severity fire events or for the cumulative pressures created by recurring emergency water demands.

Existing wildfire–water scholarship has largely focused on surface water impacts, particularly post-fire contamination, increased sediment and nutrient loading, and damage to water treatment infrastructure (Bladon et al., 2014; Smith et al., 2011). These studies have been crucial in demonstrating that wildfires affect not only forests but also downstream water users, aquatic ecosystems, and municipal water providers. However, this body of work has tended to frame water primarily as a passive recipient of wildfire impacts or as a logistical input to fire suppression, rather than as a dynamic SES whose governance is reshaped by fire, including governance challenges that emerge inside urban and peri-urban service areas when wildfire disrupts water pressure, power, treatment, and distribution. Groundwater, in particular, remains largely overlooked in wildfire resilience planning despite its potential role in supporting both emergency firefighting and drinking water security when surface systems fail. In this context, groundwater governance includes decisions about who can access groundwater during emergencies, how extraction is prioritized and monitored, what safeguards protect aquifers and groundwater-dependent ecosystems, and how risks and responsibilities are distributed across users and communities. Yet in many regions, groundwater is widely distributed, embedded in peri-urban subdivisions and rural–urban fringes, and may provide a decentralized reserve of water for fire suppression, structural protection, and emergency domestic supply, while also being less exposed than surface water to certain immediate contamination pathways during wildfire events, even though post-fire recharge, turbidity pathways, and well vulnerability can still occur (Gleeson et al., 2026). While groundwater has not been systematically documented or institutionally integrated as a primary water source for wildfire response in most jurisdictions, its decentralized presence suggests significant untapped potential for supporting resilience. In some areas, wells could provide the only reliable water source during late summer fire seasons, especially where surface water flows are intermittent or access to surface water is constrained (e.g., due to limited conveyance infrastructure, pumping capacity, or site accessibility) and high groundwater levels increase soil moisture. This may be particularly important in wildland–urban interface and peri-urban landscapes where centralized infrastructure can be limited, fragmented, or vulnerable to disruption during fire events Despite this, groundwater is typically treated as invisible infrastructure or as an emergency backup to be mobilized during crises, rather than as a system requiring anticipatory governance and long-term stewardship (Foster et al., 2016; Taylor et al., 2013).

This emergency framing creates a paradox. In many wildland–urban interface and peri-urban landscapes, wildfire risk is rising and decentralized wells could be relied upon, yet institutional pathways for using groundwater safely, equitably, and sustainably during emergencies remain underdeveloped. On one hand, groundwater aligns well with emerging notions of wildfire resilience: it is decentralized, less susceptible to single-point failures, and already embedded in many communities. On the other hand, unmanaged or poorly governed emergency groundwater use could exacerbate long-term risks, including aquifer depletion, harm to groundwater-dependent ecosystems, and inequitable access during crises (Aeschbach-Hertig & Gleeson, 2012; Zwarteveen & Boelens, 2017). These concerns may be especially acute in slow-recharge or fossil aquifers, where emergency extraction can create long recovery times and intensify intergenerational sustainability trade-offs. These risks to specific action situations and governance responses are explored further below. As wildfire events become more frequent, there is a growing risk that emergency groundwater extraction becomes normalized, shifting groundwater governance from planned allocation toward reactive crisis management. Importantly, the absence of proactive governance does not prevent groundwater from being used during wildfire emergencies rather, it increases the likelihood that extraction occurs informally, unevenly, and without adequate safeguards, monitoring, or long-term planning. While documented examples of ad hoc groundwater use for wildfire response remain limited, anecdotal and emerging evidence from wildfire-prone regions (e.g., western North America and Australia) suggests localized, informal usage of private wells during emergencies, highlighting the need for systematic study and governance attention (Concerns-Wells, 2012; Government of Newfoundland and Labrador, 2024). This shift is not equity-neutral, wildfire-driven groundwater decisions can redistribute risks and responsibilities across households and communities, often amplifying pre-existing inequities in access, voice, and capacity (Zwarteveen & Boelens, 2017; Hanrahan et al., 2014; Gleeson et al., 2026). Similar dynamics have been observed during climate-related water crises. During the 2015–2018 Cape Town 'Day Zero' drought, wealthier households increasingly buffered municipal shortages through private groundwater access, while more vulnerable populations remained disproportionately exposed to water insecurity (Savelli et al., 2021; Savelli et al., 2023). Without coordinated planning and monitoring, wildfire-related groundwater use could reproduce similar inequities, with communities that have fewer water alternatives or lower institutional capacity bearing a disproportionate share of long-term risks.

SES scholarship offers a useful lens for addressing this gap. Groundwater is a classic common pool resource, characterized by difficulties of exclusion and subtractability, and shaped by interactions among biophysical processes, social actors, and governance arrangements (Ostrom, 1990; McGinnis & Ostrom, 2014). The recent 'groundwater-connected systems' framing considers groundwater as SES with feedbacks, nonlinearities, multiple stable states, and path dependency, properties that only become visible when groundwater is framed as embedded in social, ecological, and Earth systems rather than treated as isolated physical storage (Huggins et al., 2023). SES frameworks emphasize relational interactions among ecological conditions, governance arrangements, social actors, and power relations, rather than treating resource outcomes as determined solely by physical availability. In this context, wildfire can be understood not simply as an external disturbance to groundwater systems or merely a resource for wildfire management, but as part of an interconnected governance challenge in which fire regimes, water systems, emergency response, and social institutions shape one another. Wildfire events can temporarily alter groundwater governance arrangements by reshaping who can access water, under what conditions, and for what purposes. Building on this insight, the concept of 'action situations' is particularly valuable for examining groundwater–wildfire interactions. Action situations refer to contexts in which actors interact, make decisions, and generate outcomes under specific institutional and environmental conditions (McGinnis & Ostrom, 2014). Wildfires can activate multiple, overlapping groundwater-related action situations, before, during, and after fire events, each with distinct actors, stakes, and trade-offs. These include groundwater use for preparedness and risk reduction (e.g., cultural and prescribed burning), emergency use for active fire suppression and structural protection, emergency drinking water supply when surface water systems fail, and longer-term recovery and adaptation processes that shape future vulnerability.

Viewing groundwater through the lens of wildfire-activated action situations helps move beyond narrow questions of whether groundwater can technically support firefighting. Instead, it foregrounds broader governance questions: Who has the authority to access groundwater during emergencies? How are risks and benefits distributed across users? What safeguards exist to protect aquifers and groundwater-dependent ecosystems? And how do repeated wildfire events alter the long-term social and ecological functions of groundwater systems? Equity and justice are embedded within these governance processes through decisions about participation, recognition, monitoring, allocation, and burden-sharing. This includes distributive equity (who bears depletion risk), procedural equity (who participates in decisions), and recognition justice (whose rights, values, and knowledge systems are acknowledged, including Indigenous governance) (Zwarteveen & Boelens, 2017; Whyte, 2017). This aligns with the commitment of *Nature Water* to work that reimagines humanity's relationship with water while advancing sustainability and equity, an especially urgent remit where wildfire drives cascading and unequal impacts on urban and peri-urban water systems (Pierce et al., 2025).

We argue that wildfire resilience is increasingly a water governance challenge, and that groundwater should be explicitly conceptualized and governed as a SES within fire-prone landscapes. We apply a SES framework and the concept of action situations that illustrate how wildfires reconfigure groundwater systems, governance arrangements, and outcomes. We use British Columbia as an illustrative example of broader wildfire–groundwater governance challenges emerging across fire-prone regions (e.g., Gleeson et al., 2020; BC Wildfire Service, 2023; Daniels et al., 2024). Specifically, this paper addresses the following research questions: 1) how could groundwater as SES enhance wildfire resilience? and 2) which groundwater-related action situations are possible before, during and after wildfire? This paper contributes to emerging debates on climate adaptation, common pool resource governance, and social-ecological resilience that builds on the recent argument that short-term groundwater use could reduce natural hazard susceptibilities and inequities (Gleeson et al. 2026). This paper contributes a governance perspective that reframes groundwater as an integral component of wildfire resilience and highlights wildfire-activated groundwater action situations as critical sites of adaptation, coordination, and stewardship.

Conceptualizing groundwater and wildfire as a social–ecological system

Groundwater as a common pool resource in fire-prone landscapes

Groundwater is a quintessential common pool resource, characterized by difficulties of exclusion and subtractability among users (Ostrom, 1990; Aeschbach-Hertig & Gleeson, 2012). Unlike centralized surface water infrastructure, groundwater is typically accessed through decentralized wells embedded within households, farms, and communities (Foster & Garduño, 2013). This decentralization can enhance resilience by reducing reliance on centralized infrastructure and enabling local self-sufficiency, particularly in rural and peri-urban contexts (Gleeson et al., 2020). At the same time, it complicates governance because monitoring, coordination, and enforcement are inherently challenging, particularly during crises when demand escalates rapidly and institutional rules are tested or temporarily suspended (Ostrom, 2009; Foster & van der Gun, 2016). However, the resilience potential of groundwater is highly uneven. Not all aquifers are sufficiently productive, permeable, or accessible to support emergency extraction, and many wells may be too shallow, too low-yielding, poorly maintained, or physically inaccessible during wildfire events. In some places, groundwater systems may already be stressed by overuse, drought, or seasonal decline, limiting their capacity to function as a reliable emergency source (Wada et al., 2010; Aeschbach-Hertig & Gleeson, 2012).

In fire-prone landscapes, groundwater governance tensions associated with subtractability, access and emergency allocation may become more visible and contested. Wildfires introduce acute, episodic, and spatially uneven demand for water (Bladon et al., 2014; Martin, 2016). During active fire response, groundwater may be mobilized for suppression and structural protection when surface water is unavailable, unsafe, or inaccessible due to contamination, infrastructure failure, or seasonal low flows (Smith et al., 2011; Burke et al., 2021). During and after fire events, groundwater could become the primary source of drinking water for communities affected by surface water contamination or treatment disruptions (Bladon et al., 2014). Yet groundwater governance regimes are rarely designed to manage such short-term, high-intensity extraction events. Most licensing and allocation systems assume relatively stable patterns of use and incremental change, creating a mismatch between governance design and wildfire-driven realities (Foster & van der Gun, 2016; OECD, 2015). At the same time, the physical feasibility of groundwater use during wildfire cannot be assumed such as aquifers with low transmissivity may not sustain high pumping rates, wells may not generate sufficient flow or pressure for firefighting, and damaged infrastructure, power outages, or limited site access can render groundwater unusable in practice.

This mismatch creates governance tensions that extend well beyond technical questions of hydrological capacity. Emergency groundwater use raises fundamental questions about authority, consent, liability, equity, and long-term stewardship (Zwarteveen & Boelens, 2017). Who has the right to access private or community wells during emergencies? How are risks to aquifers and groundwater-dependent ecosystems assessed and mitigated? Who bears responsibility if emergency pumping damages wells, reduces yields, or depletes local supplies? And how do repeated wildfire events alter social norms, expectations, and institutional arrangements surrounding groundwater use? These questions highlight that groundwater governance is shaped not only by biophysical availability, but also by social institutional arrangements, and political priorities. (Ostrom, 1990; Berkes et al., 2008). They also underscore that groundwater is not a universally reliable solution. Its contribution to wildfire resilience depends on hydrogeological conditions, infrastructure functionality, and prior stewardship, as well as governance (Taylor et al., 2013; Gleeson et al., 2020).

In regions such as British Columbia, these governance challenges are particularly salient. Wells are widespread across fire-prone landscapes, including within peri-urban and wildland–urban interface zones where wildfire risk is high and surface water availability is often seasonally constrained (BC Wildfire Service, 2023). A significant proportion of these wells are technically capable of supplying water for firefighting or emergency domestic use, especially during late summer fire seasons when surface water sources may be intermittent or inaccessible. However, even where groundwater is present, physical capacity does not necessarily equate to operational or institutional readiness. Some wells may not provide sufficient yield or pressure, some aquifers may be too depleted or slow to recover, and some sites may be inaccessible to firefighting crews during emergencies. The ability to mobilize groundwater during wildfire depends not only on hydrogeological conditions, but also on governance arrangements that determine access rights, emergency powers, monitoring requirements, and social acceptance (Megdal et al., 2017). Provincial policy recognizes the importance of water for wildfire response, including provisions for emergency water use (Province of British Columbia, 2022), but these are not embedded with any coordinated, anticipatory wildfire or groundwater governance. Without anticipatory governance, there is a risk that emergency groundwater extraction becomes normalized, shifting groundwater governance from planned allocation toward reactive crisis management and reinforcing path-dependent vulnerabilities for aquifers, ecosystems, infrastructure systems, and communities. Groundwater should therefore be understood as a context-dependent resilience resource whose usefulness varies across landscapes, rather than as a universally available substitute for surface water systems.

Applying a social–ecological systems (SES) framework

The SES framework developed by McGinnis and Ostrom (2014) provides a structured way to analyze complex resource systems shaped by interactions among ecological processes, social actors, and governance institutions. Rather than treating environmental resources as external to society, the SES framework conceptualizes them as co-produced through human–environment interactions, with outcomes emerging from feedbacks across multiple system components (Ostrom, 2009; Berkes et al., 2008). In its canonical form, the SES framework includes several interacting components: resource systems, resource units, governance systems, actors, action situations, related ecosystems, and broader social, economic, and political contexts. Outcomes emerge from interactions within action situations and feed back into other system components over time. We use Ostrom's SES framework as a diagnostic governance framework because groundwater–wildfire interactions are fundamentally coupled human–environment systems characterized by feedbacks, governance complexity, and disturbance-driven change (Huggins et al., 2023; McGinnis & Ostrom, 2014; Ostrom, 1990). Recent wildfire scholarship increasingly conceptualizes fire-prone landscapes as dynamic SES where adaptive and transformative resilience, rather than simple recovery, are required (McWethy et al., 2019). This framing aligns with emerging water research highlighting cascading wildfire risks across water quantity, quality, and infrastructure systems (Belongia et al., 2023). Moreover, SES applications in groundwater governance demonstrate that aquifers, communities, and ecosystems operate as interdependent subsystems shaped by institutions, rights, and collective action (Bouchet et al., 2019; Rica et al., 2017). Alternative and complementary SES-oriented frameworks (e.g., network governance and social cohesion models) may further refine analysis in future empirical work (Hamilton et al., 2018; Prior & Eriksen, 2013). In addition, wildfire and climate-driven water crises can also be interpreted through the lens of hyperobjects, which are large-scale, temporally extended phenomena that exceed conventional spatial, temporal, and governance boundaries (Morton, 2013). From this perspective, wildfire-groundwater interactions are not isolated events, but components of a distributed social-hydrological disturbance shaped by climate change, land use, and infrastructure systems. These dynamics becoming visible through recurring groundwater-related action situations before, during, and after wildfire events.

Applying the SES framework to wildfire–groundwater interactions require contextual reinterpretation across wildfire temporal phases and governance contexts. First, wildfire must be treated not as an external shock, but as a recurring disturbance regime that repeatedly activates and reshapes groundwater-related action situations (Bowman et al., 2020; Martin, 2016). Second, groundwater governance must be understood as operating across multiple temporal phases, from preparedness and response to recovery and long-term adaptation (Pahl-Wostl, 2009; Foster & van der Gun, 2016). Third, outcomes must be understood as cumulative and path-dependent, influencing future governance arrangements, social norms, and resource availability (Pierson, 2004). The framework presented here centers on a composite action situation: groundwater use for wildfire resilience. Then below we describe more specific action situations activated before, during, and after wildfire events including groundwater use for preparedness and risk reduction, active wildfire response, emergency drinking water supply, recovery and adaptation, and prescribed and cultural burning (Lake et al., 2017; Paveglio et al., 2009). While these contexts differ in timing, intensity, and actors, they share underlying governance challenges related to access, authority, accountability, and sustainability.

Core components of a SES framework

Resource Systems: In the wildfire–groundwater context, the resource system includes both groundwater and its interaction with surface water, forests, and climatic conditions. Aquifers are embedded within broader hydrological and ecological systems that are influenced by wildfire through changes in recharge, runoff, sedimentation, and contamination pathways (Bladon et al., 2014; Smith et al., 2011). Wildfires can alter infiltration patterns, increase erosion, and affect the quality and availability of groundwater over time, particularly through post-fire soil hydrophobicity and landscape disturbance (Martin, 2016). These biophysical dynamics set the conditions under which groundwater can be mobilized during fire events and shape longer-term recovery trajectories.

Resource Units: Resource units refer to the groundwater volumes and flows that are accessible to users, as well as the spatial units through which wildfire and water interactions are mediated. These include aquifer storage, well yields, source water protection areas, forest blocks, and wildland–urban interface zones. Importantly, resource units are not static; their availability and reliability can change as a result of cumulative extraction, infrastructure damage, climate variability, or ecological impacts (Aeschbach-Hertig & Gleeson, 2012). In wildfire contexts, resource units become particularly salient as communities and agencies seek to mobilize groundwater rapidly under conditions of urgency and uncertainty.

Actors: Actors in the wildfire–groundwater SES include firefighters and wildfire agencies, emergency responders, private and community well owners, Indigenous, local, regional, provincial/state and national governments, non-governmental organizations, water utilities, and communities. These actors bring diverse priorities, knowledge systems, and power relations into groundwater-related decision-making (Berkes, 2018; Zwarteveen & Boelens, 2017). Private well owners, in particular, occupy a critical position as both rights holders and potential contributors to collective wildfire response potentially negotiating access informally during emergencies. Indigenous actors bring long-standing knowledge of fire and water stewardship and play a central role in cultural and prescribed burning, yet their authority and rights are frequently marginalized or constrained within dominant governance systems (Lake et al., 2017; Whyte, 2017). Equity considerations cut across actor roles and capacities, rural and remote well users may face higher exposure to depletion risks and lower access to monitoring, financial buffers, or political voice, while Indigenous Nations may confront recognition gaps where stewardship authority and water rights are not operationalized in emergency governance. These inequities shape who can contribute groundwater to collective response and who bears the long-term costs (Hanrahan et al., 2014; Whyte, 2017; Zwarteveen & Boelens, 2017).

Governance Systems: Governance systems encompass the formal and informal rules that structure groundwater use during wildfire. These include water allocation and licensing regimes, emergency powers and wildfire response protocols, land-use and forestry regulations, Indigenous and local governance systems, monitoring and reporting requirements, and informal norms or ad hoc agreements (Foster & van der Gun, 2016; OECD, 2015). In wildfire contexts, governance systems are often characterized by rule switching, as emergency powers temporarily override standard allocation regimes (Ostrom, 2009). How these temporary measures are implemented, monitored, and institutionalized has profound implications for long-term groundwater sustainability, equity, and legitimacy. An equity-oriented wildfire resilience approach requires that emergency groundwater rules include procedural safeguards (participation and transparency), distributive protections (burden-sharing and compensation), and recognition of Indigenous rights and knowledge systems (Whyte, 2017; Zwarteveen & Boelens, 2017).

Related Ecosystems: Related ecosystems include forests, groundwater-dependent ecosystems, surface waters, soils, and post-fire landscapes. These ecosystems both influence and are influenced by groundwater use and wildfire dynamics (Eamus et al., 2015). For example, groundwater extraction can affect baseflows, wetlands, and riparian ecosystems, while post-fire changes in vegetation cover and soil structure can alter recharge patterns and hydrological connectivity (Bladon et al., 2014). Recognizing these interdependencies is essential for avoiding maladaptive responses that protect one component of the system, such as emergency water supply, at the expense of ecological integrity and long-term resilience (Folke et al., 2010).

Related Social, Economic, and Political Contexts: Groundwater use for wildfire resilience is also shaped by broader social, economic, and political conditions, including climate change, land-use change, colonial and legal histories, rural–urban development patterns, infrastructure investment, and Indigenous rights and governance (McGinnis & Ostrom, 2014; Whyte, 2017). These contextual factors influence exposure to wildfire risk, access to groundwater infrastructure, institutional capacity, and the distribution of benefits and burdens associated with emergency groundwater use. They also shape whose knowledge systems, priorities, and governance approaches are recognized in wildfire resilience planning. Recognizing these broader contexts is critical because wildfire–groundwater interactions are embedded within unequal social and political landscapes rather than operating as purely technical or hydrological systems.

Action Situations for groundwater use in wildfire resilience

Central to the SES framework is the concept of action situations, defined as contexts in which actors interact under specific institutional and environmental conditions to produce outcomes (McGinnis & Ostrom, 2014). Wildfires activate multiple groundwater-related action situations across temporal phases, each with distinct actors, stakes, and governance questions. These action situations are not isolated events but recurring decision contexts that emerge before, during, and after wildfire disturbance (Paveglio et al., 2009). Table 1 synthesizes five such action situations: preparedness and risk reduction, active wildfire response, drinking water security during wildfire, recovery and rehabilitation, and cultural and prescribed burns. Across action situations, equity outcomes are produced through both formal rules (licensing, emergency authorities) and informal relationships (trust, reciprocity, social pressure), making distributive, procedural, and recognition justice integral to wildfire resilience governance (Zwarteveen & Boelens, 2017; Hanrahan et al., 2014). Importantly, these action situations are interconnected rather than independent. Decisions made during preparedness influence emergency response capacity; crisis-driven extraction during wildfire response can reshape recovery trajectories; and repeated emergency practices may become institutionalized over time. These interactions create trade-offs between short-term emergency needs and long-term groundwater sustainability, equity, and ecosystem protection.

During **preparedness and risk reduction**, groundwater may support prescribed and cultural burning, fuel management, and the development of redundant water infrastructure for resilience planning (Lake et al., 2017; Paveglio et al., 2009). Governance questions in this phase center on planning authority, cost sharing, and collective risk reduction, particularly where groundwater is privately owned but wildfire risk is shared across communities. If these governance arrangements remain underdeveloped, opportunities for prevention may be missed, increasing wildfire severity and downstream impacts (Bowman et al., 2020).

During **active wildfire response**, groundwater may be mobilized for emergency pumping to support ground crews and structural protection when surface water sources are unavailable or unsafe (Bladon et al., 2014; Martin, 2016). Governance challenges include access to private and community wells, liability for damage or depletion, consent under emergency conditions, and equity in the distribution of impacts and benefits (Foster & van der Gun, 2016; Megdal et al., 2017). Repeated reliance on emergency extraction risks aquifer stress and the normalization of crisis-driven governance, particularly in regions experiencing increasingly frequent fire seasons.

During **drinking water security** action situations, groundwater becomes a critical backup when surface water systems are compromised by contamination, infrastructure failure, or power outages (Smith et al., 2011; Bladon et al., 2014). Governance questions focus on water quality monitoring, public health protection, emergency prioritization, and responsibility for ensuring safe supply (OECD, 2015). Inadequate planning in this phase can disproportionately affect rural, Indigenous, and remote communities that already face structural inequities in water access and infrastructure (Hanrahan et al., 2014; Zwarteveen & Boelens, 2017).

During **recovery and adaptation**, groundwater supports rebuilding, altered land-use practices, and longer-term resilience to future fire events (Pahl-Wostl, 2009). Key governance challenges include institutionalizing lessons learned from emergency use, preventing chronic over-extraction, and protecting groundwater-dependent ecosystems as fire regimes intensify (Eamus et al., 2015; Gleeson et al., 2020).

Finally, **cultural and prescribed burns** highlight the role of groundwater in enabling Indigenous fire stewardship and the implementation of low-intensity fire regimes that reduce catastrophic wildfire risk (Lake et al., 2017). Governance questions in this action situation center on recognition of Indigenous water rights, authority over groundwater access, and the integration of cultural values and Indigenous knowledge into dominant water governance systems (Berkes, 2017; Whyte, 2017). Failure to address these questions risks marginalizing Indigenous stewardship practices and undermining fire resilience at broader landscape scales.

Wildfire-activated action situations generate outcomes that extend well beyond immediate fire suppression or water provision. These outcomes include water security and reliability, public health protection, aquifer stress or sustainability, ecosystem impacts, equity outcomes, and processes of institutional learning or maladaptation (Folke et al., 2010; Ostrom, 2009). Importantly, outcomes feed back into governance systems, actor behavior, and resource availability over time, shaping future action situations and governance trajectories (McGinnis & Ostrom, 2014). Repeated wildfire events can lead to path-dependent governance trajectories, where emergency measures become normalized and integrated into standard practice without adequate safeguards or monitoring (Pierson, 2004; Foster & van der Gun, 2016). Conversely, wildfire-driven crises can catalyze learning, coordination, and institutional reform that strengthen anticipatory and adaptive governance (Pahl-Wostl, 2009). Whether groundwater use for wildfire resilience becomes a source of long-term resilience or vulnerability depends on how these feedbacks are recognized, governed, and institutionalized. If crisis-driven extraction becomes normalized without safeguards, inequities can become path-dependent, where communities with fewer alternatives repeatedly shoulder depletion and reliability risks while others externalize costs (Pierson, 2004; Gleeson et al., 2026).

This SES framework advances understanding of wildfire resilience as a fundamentally governance-driven challenge, rather than a purely technical or ecological one by adapting the SES framework to wildfire–groundwater interactions (Paveglio et al., 2009). It demonstrates that groundwater is not merely emergency infrastructure, but a common pool resource whose sustainability depends on institutions, power relations, and social norms (Ostrom, 1990; Zwarteveen & Boelens, 2017). Integrating groundwater into wildfire resilience planning therefore requires anticipatory governance that explicitly recognizes multiple action situations, respects Indigenous rights and authority, and balances short-term emergency needs with long-term stewardship. This framework also has broader relevance beyond British Columbia. As wildfire regimes intensify globally, many regions will confront similar challenges at the intersection of water governance and fire resilience (Bowman et al., 2020; IPCC, 2022). Applying an SES lens to groundwater use under wildfire disturbance offers a pathway toward more integrated, equitable, and sustainable climate adaptation strategies in a warming world.

From local to global fire resilience: why this matters?

Wildfire–groundwater interactions are not unique to British Columbia. Across fire-prone regions of Australia, the western United States, the Mediterranean, southern Africa, Latin America, and parts of Asia, groundwater could increasingly function as an invisible backbone of wildfire response and post-fire recovery (Bladon et al., 2014; Martin, 2016; Gleeson et al., 2026). As surface water systems become more vulnerable to drought, contamination, and infrastructure failure under climate change, reliance on groundwater during wildfire events is likely to intensify globally (Abatzoglou & Williams, 2016; IPCC, 2022). Climate uncertainty may further complicate these action situations by altering recharge dynamics, seasonal water availability, and long-term groundwater reliability across fire-prone regions. Yet in many of these regions, groundwater governance remains fragmented, reactive, and poorly aligned with emergency management and climate adaptation planning (Foster & van der Gun, 2016; OECD, 2015). This SES framework offers a transferable way to recognize groundwater as a shared common pool resource activated by fire disturbance (Ostrom, 1990; McGinnis & Ostrom, 2014). It highlights how localized emergency decisions, often negotiated informally between responders and private well owners, accumulate into broader governance outcomes that shape equity, ecosystem health, and long-term water security. Without anticipatory governance, repeated wildfire events risk normalizing crisis-driven extraction and exacerbating groundwater depletion, institutional fragility, and social inequities. The call to action is clear: wildfire resilience strategies should explicitly integrate groundwater governance, emergency protocols, and Indigenous stewardship into climate adaptation planning (Berkes, 2017; Lake et al., 2017). Treating groundwater as a SES, rather than invisible emergency infrastructure, is essential for learning to live with fire in a warming world. Several important questions remain unresolved at the groundwater–wildfire interface. Future research should examine how emergency groundwater governance can balance short-term fire response with long-term aquifer sustainability; how liability, compensation, and consent mechanisms should operate during crises; and how Indigenous governance systems and relational stewardship approaches can be meaningfully integrated into wildfire adaptation planning. More broadly, wildfire-driven groundwater governance raises unresolved ethical and political questions regarding whose water is mobilized during emergencies, whose risks are prioritized, and how climate adaptation burdens are distributed across communities. Addressing these challenges will require stronger integration between groundwater governance, emergency management, climate adaptation, and justice-oriented resilience planning.

Acknowledgements

We appreciate Jesse Wallace-Webb from the BC Wildfire Service, Xander Huggins, Tristan Pearce, Gerald Singh for discussions and suggestions on this manuscript. Graphic design for Figure 1 by Marci Janecek of Marsupial Design based on original sketches from TG and NV; farm buildings, people and airplane generated with Adobe Firefly AI in Illustrator and artist-modified.

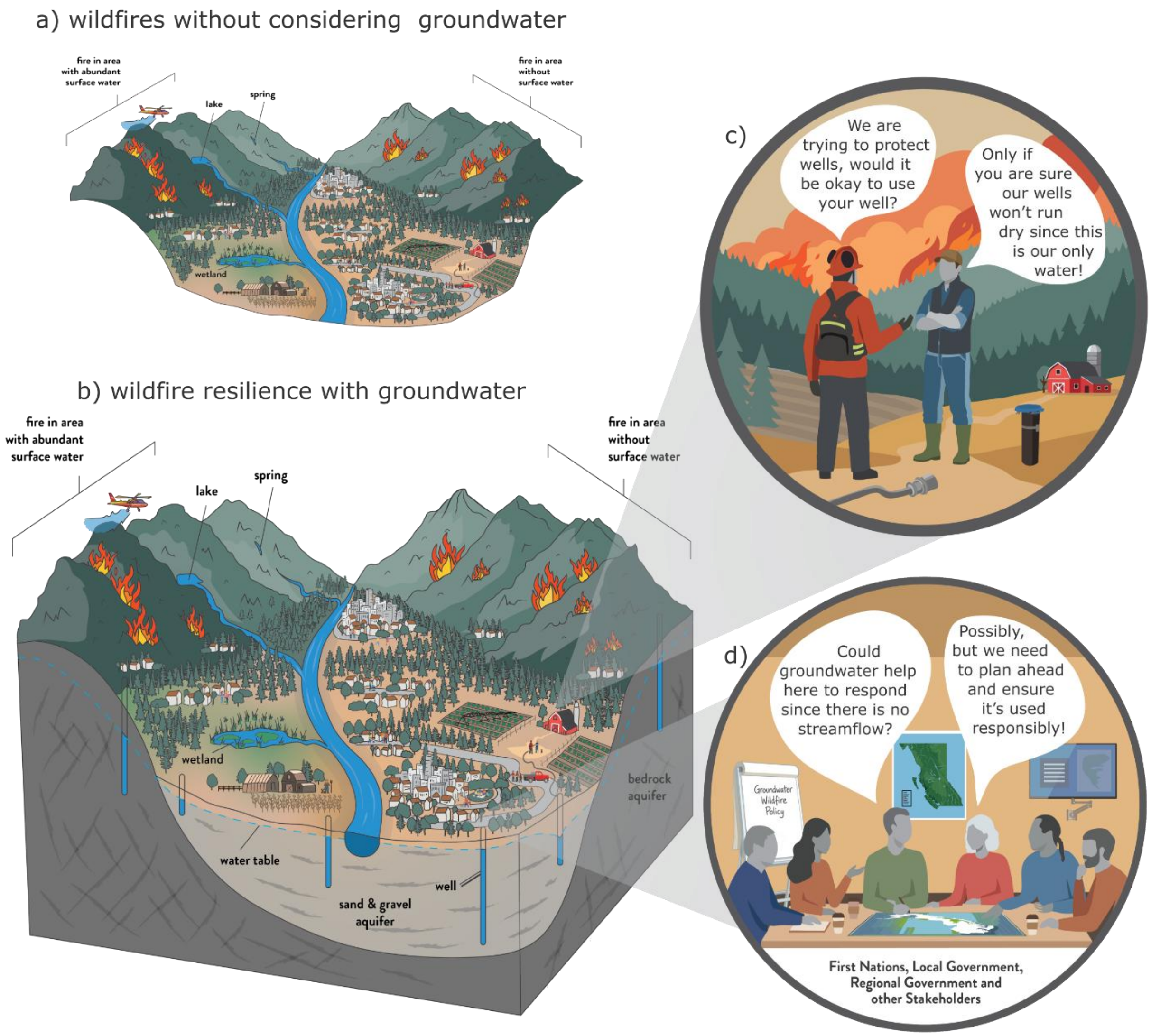

Figure 1. Conceptual landscape of wildfire resilience if a) without explicit integration of groundwater governance or b) with coordinated groundwater integration. Two conceptual vignettes illustrate relationship-centered action situations: (c) an emergency negotiation at a private well during wildfire response, and (d) a multi-stakeholder decision meeting shaping governance safeguards, equity, and long-term stewardship.

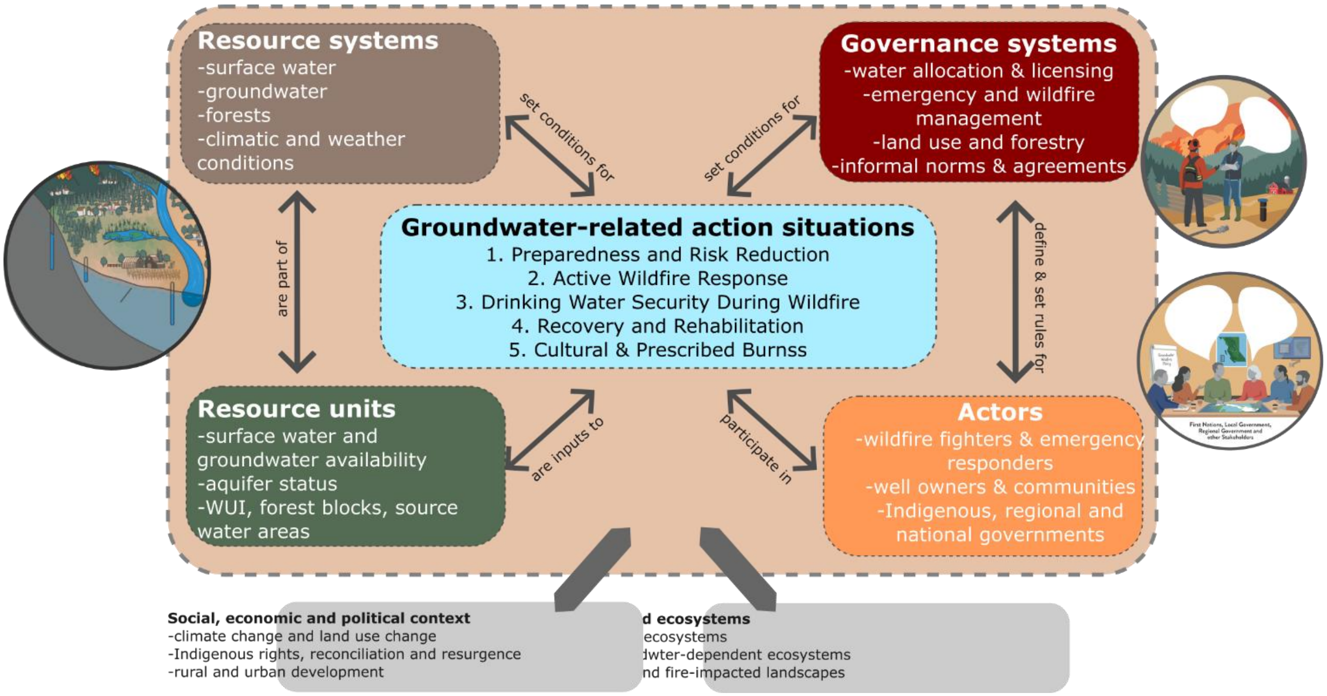

Figure 2. Social-ecological systems framework for the composite action situation of groundwater use for wildfire resilience.

Table 1. Groundwater–Wildfire Action Situations in a Social–Ecological Systems Perspective

Action Situation	*Opportunities of groundwater use*	*Challenges of groundwater use*	*Key Actors*	*Governance Questions*
1. Preparedness and Risk Reduction	• Water supply for prescribed and cultural burning • Fuel management support • Redundant water infrastructure for resilience planning	• Under-use of groundwater for prevention • Reliance on informal or ad hoc access • Conflict over pre-fire extraction • Missed opportunities for risk reduction	• Forestry and wildfire agencies • Indigenous fire stewards • Land managers • Private well owners • Local governments	• Who plans for groundwater use in fire preparedness? • Who pays for infrastructure and monitoring? • Whose groundwater is used for collective risk reduction?
2. Active Wildfire Response	• Emergency pumping for ground crews • Structural protection • Supplement or substitute for surface water	• Aquifer stress from repeated emergency pumping • Legal ambiguity and liability disputes • Unequal access across communities • Normalization of crisis-driven extraction	• Firefighters and wildfire agencies • Emergency managers • Private, irrigation, and community well owners • Utilities	• Can public agencies access private groundwater? • Who bears liability for damage or depletion? • How is consent obtained under emergency conditions? • Are impacts distributed equitably?
3. Drinking Water Security During Wildfire	• Emergency drinking water supply • Backup when surface water is contaminated or infrastructure fails	• Public health risks from inadequate monitoring • Disproportionate impacts on rural, Indigenous, and remote communities • Short-term fixes replacing long-term planning • Procedural inequities in emergency prioritization and communication	• Rural and urban communities • Indigenous Nations • Water utilities • Public health agencies	• Is groundwater quality adequately monitored? • Who ensures water safety during emergencies? • Which communities receive priority access?
4. Recovery and Rehabilitation	• Sustained water supply during rebuilding • Support for altered land use and livelihoods • Buffer against future fire-related disruptions	• Chronic groundwater depletion • Ecosystem degradation • Entrenchment of maladaptive practices • Escalating conflict over water allocation	• Communities and households • Agricultural users • Policymakers and regulators • Researchers and planners	• How are lessons from emergency use institutionalized? • What limits prevent long-term over-extraction? • How are groundwater-dependent ecosystems protected?
5. Cultural & Prescribed Burns	• Reliable water supply for controlled and cultural burning • Enabling Indigenous fire stewardship • Safer implementation of low-intensity fire regimes	• Undermining Indigenous fire stewardship • Marginalization of cultural burning practices • Increased wildfire severity due to limited prescribed fire • Recognition gaps for Indigenous authority and water rights in emergency planning	• Indigenous fire stewards and knowledge holders • Forestry and wildfire agencies • Landowners and land managers • Local and regional governments	• How are Indigenous water rights and authority recognized? • Who controls access to groundwater for prescribed fire? • How are cultural values integrated into water governance?

References

Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of sciences, 113(42), 11770-11775. https://doi.org/10.1073/pnas.1607171113

Concerns-Wells, D. W. (2012). Your Well and Septic System–After a wildfire. https://glwqd.org/wp-content/uploads/2016/02/your-well-and-septic-system-after-a-wildfire.pdf

Government of Newfoundland and Labrador. (2024). Well water safety after wildfires. https://www.gov.nl.ca/eccc/files/Wildfires-Wells-1.pdf

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. Nature Geoscience, 5(12), 853-861. https://doi.org/10.1038/ngeo1617

BC Wildfire Service. (2023) Wildfire Season Summary. BC Ministry of Forests, Victoria, BC. Available from https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-history/wildfire-season-summary.

Belongia, M. F., Hammond Wagner, C., Seipp, K. Q., & Ajami, N. K. (2023). Building water resilience in the face of cascading wildfire risks. Science advances, 9(37), eadf9534. https://doi.org/10.1126/sciadv.adf9534

Berkes, F. (2017). Sacred ecology. Routledge.

Berkes, F., Colding, J., & Folke, C. (Eds.). (2008). Navigating social-ecological systems: building resilience for complexity and change. Cambridge university press.

Birot, Y. (2009). Living with wildfires: what science can tell us-a contribution to the science-policy dialogue (No. 15, pp. 82-pp). https://efi.int/sites/default/files/files/efimed/resources/Living%20with%20Fire%20-%20What%20Science%20Can%20Tell%20Us.pdf

Bladon, K. D., Emelko, M. B., Silins, U., & Stone, M. (2014). Wildfire and the future of water supply. http://dx.doi.org/10.1021/es500130g

Bouchet, L., Thoms, M. C., & Parsons, M. (2019). Groundwater as a social-ecological system: A framework for managing groundwater in Pacific Small Island Developing States. Groundwater for Sustainable Development, 8, 579-589. https://doi.org/10.1016/j.gsd.2019.02.008

Bowman, D. M., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., ... & Pyne, S. J. (2009). Fire in the Earth system. science, 324(5926), 481-484. https://doi.org/10.1126/science.1163886

Bowman, D. M., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., van der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the Anthropocene. Nature Reviews Earth & Environment, 1(10), 500-515. https://doi.org/10.1038/s43017-020-0085-3

Burke, M., Driscoll, A., Heft-Neal, S., Xue, J., Burney, J., & Wara, M. (2021). The changing risk and burden of wildfire in the United States. Proceedings of the National Academy of Sciences, 118(2), e2011048118. https://doi.org/10.1073/pnas.2011048118

Daniels, L. D., Dickson-Hoyle, S., Baron, J. N., Copes-Gerbitz, K., Flannigan, M. D., Castellanos-Acuna, D., ... & Gray, R. W. (2024). The 2023 wildfires in British Columbia, Canada: impacts, drivers, and transformations to coexist with wildfire. Canadian Journal of Forest Research, 55, 1-18. https://doi.org/10.1139/cjfr-2024-0092

Eamus, D., Zolfaghar, S., Villalobos-Vega, R., Cleverly, J., & Huete, A. (2015). Groundwater-dependent ecosystems: recent insights from satellite and field-based studies. Hydrology and Earth System Sciences, 19(10), 4229-4256. https://doi.org/10.5194/hess-19-4229-2015

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. Ecology and society, 15(4). http://www.ecologyandsociety.org/vol15/iss4/art20/

Foster, S., & Garduño, H. (2013). Groundwater-resource governance: are governments and stakeholders responding to the challenge?. Hydrogeology Journal, 21(2), 317-320. https://doi.org/10.1007/s10040-012-0904-9

BC Wildfire Service. (2023). 2023 Wildfire Season Summary. BC Ministry of Forests, Victoria, BC. Available from https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-history/wildfire-season-summary.

Foster, S., & van der Gun, J. (2016). Groundwater governance: key challenges in applying the global framework for action. Hydrogeology Journal, 24(4), 749-752. https://doi.org/10.1007/s10040-016-1376-0

Gleeson, T., Cuthbert, M., Ferguson, G., & Perrone, D. (2020). Global groundwater sustainability, resources, and systems in the Anthropocene. Annual review of earth and planetary sciences, 48(2020), 431-463. https://doi.org/10.1146/annurev-earth-071719-055251

Gleeson, T., Endo, T., Taniguchi, M., & Di Baldassarre, G. (2026). Natural hazard susceptibilities and inequities reduced by short-term groundwater use. Nature Geoscience, 1-7. https://doi.org/10.1038/s41561-025-01884-0

Gleeson, T., VanderSteen, J., Sophocleous, M. A., Taniguchi, M., Alley, W. M., Allen, D. M., & Zhou, Y. (2010). Groundwater sustainability strategies. Nature geoscience, 3(6), 378-379. https://doi.org/10.1038/ngeo881

Hamilton, M., Fischer, A. P., & Ager, A. (2019). A social-ecological network approach for understanding wildfire risk governance. Global Environmental Change, 54, 113-123. https://doi.org/10.1016/j.gloenvcha.2018.11.007

Hanrahan, M. C., Sarkar, A., & Hudson, A. M. (2014). Water insecurity in Indigenous Canada: a case study of illness, neglect, and urgency. In Proceedings of the International Conference on Marine and Freshwater Environments (iMFE 2014)-Our Water, Our Future. https://journals.library.mun.ca/index.php/IMFE/article/view/1107/987

Huggins, X., Gleeson, T., Castilla-Rho, J., Holley, C., Re, V., & Famiglietti, J. S. (2023). Groundwater connections and sustainability in social-ecological systems. Groundwater, 61(4), 463-478. https://doi.org/10.1111/gwat.13305

IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/

Lake, F. K., Wright, V., Morgan, P., McFadzen, M., McWethy, D., & Stevens-Rumann, C. (2017). Returning fire to the land: celebrating traditional knowledge and fire. Journal of Forestry, 115(5), 343-353. https://doi.org/10.5849/jof.2016-043R2

Martin, D. A. (2016). At the nexus of fire, water and society. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 20150172. https://doi.org/10.1098/rstb.2015.0172

McFarlane, B. L. (2006). Human dimensions of fire management in the wildland-urban interface: a literature review. Canadian Wildland Fire Strategy: background syntheses, analyses, and perspectives, 27.

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. Ecology and society, 19(2). http://dx.doi.org/10.5751/ES-06387-190230

McWethy, D. B., Schoennagel, T., Higuera, P. E., Krawchuk, M., Harvey, B. J., Metcalf, E. C., ... & Kolden, C. (2019). Rethinking resilience to wildfire. Nature Sustainability, 2(9), 797-804. https://doi.org/10.1038/s41893-019-0353-8

Megdal, S. B., Gerlak, A. K., Huang, L. Y., Delano, N., Varady, R. G., & Petersen-Perlman, J. D. (2017). Innovative approaches to collaborative groundwater governance in the United States: Case studies from three high-growth regions in the Sun Belt. Environmental management, 59(5), 718-735. https://doi.org/10.1007/s00267-017-0830-7

Megdal, S. B., Gerlak, A. K., Varady, R. G., & Huang, L. Y. (2015). Groundwater governance in the United States: Common priorities and challenges. Groundwater, 53(5), 677-684. https://doi.org/10.1111/gwat.12294

Morton, T. (2013). Hyperobjects: Philosophy and Ecology after the End of the World. U of Minnesota Press. https://www.jstor.org/stable/10.5749/j.ctt4cggm7

OECD (2015). OECD principles on water governance. Paris: OECD Publishing. http://www.oecd.org/governance/regional-policy/OECD-Principles-on-Water-Governance.pdf

Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. Cambridge university press.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419-422. https://doi.org/10.1126/science.1172133

Ostrom, E. (2009). Understanding institutional diversity. Princeton university press.

Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global environmental change, 19(3), 354-365. https://doi.org/10.1016/j.gloenvcha.2009.06.001

Paveglio, T. B., Jakes, P. J., Carroll, M. S., & Williams, D. R. (2009). Understanding social complexity within the wildland–urban interface: a new species of human habitation?. *Environmental management*, *43*(6), 1085-1095. https://doi.org/10.1007/s00267-009-9282-z

Pierce, G., de Guzman, E., & Mullin, M. (2025). Redefining expectations for urban water supply systems to fight wildfires. Nature Water, 3(3), 248-250. https://doi.org/10.1038/s44221-025-00405-y

Pierson, P. (2004). Politics in time: History, institutions, and social analysis. Princeton University Press.

Prior, T., & Eriksen, C. (2013). Wildfire preparedness, community cohesion and social–ecological systems. Global environmental change, 23(6), 1575-1586. https://doi.org/10.1016/j.gloenvcha.2013.09.016

Province of British Columbia. Interim Guidance for Water Authorizations: Water Use for Fire Prevention and Suppression. (2022).

Rica, M., Petit, O., & Elena, L. G. (2017). Understanding groundwater governance through a social ecological system framework–relevance and limits. In Advances in groundwater governance (pp. 55-72). CRC Press.

Smith, H. G., Sheridan, G. J., Lane, P. N., Nyman, P., & Haydon, S. (2011). Wildfire effects on water quality in forest catchments: A review with implications for water supply. Journal of Hydrology, 396(1-2), 170-192. https://doi.org/10.1016/j.jhydrol.2010.10.043

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., ... & Treidel, H. (2013). Ground water and climate change. Nature climate change, 3(4), 322-329. https://doi.org/10.1038/nclimate1744

Wada, Y., Van Beek, L. P., Van Kempen, C. M., Reckman, J. W., Vasak, S., & Bierkens, M. F. (2010). Global depletion of groundwater resources. Geophysical research letters, 37(20). https://doi.org/10.1029/2010GL044571

Whyte, K. (2017). Indigenous climate change studies: Indigenizing futures, decolonizing the Anthropocene. English language notes, 55(1), 153-162. https://muse.jhu.edu/article/711473

Zwarteveen, M. Z., & Boelens, R. (2017). Defining, researching and struggling for water justice: some conceptual building blocks for research and action. In Hydrosocial Territories and Water Equity (pp. 8-23). Routledge.