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Disparate Groundwater Responses to Wildfire

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ABSTRACT

Post-wildfire investigations of groundwater response reveal a range of outcomes, varying from substantial increases to notable decreases in recharge and baseflow, with some studies indicating negligible or short-lived effects. This review assesses these varied responses within five critical categories: climate, vegetation, hydrogeology, fire characteristics, and the cryosphere, examining both short-term (within 2 years) and intermediate (2–10 years post-fire) effects. Despite considerable variability, some consistent patterns emerge. For instance, in hydroclimatic settings where water input and evaporative demand cycles are out of sync, post-wildfire groundwater responses tend to be positive (i.e., increased flux or storage), whereas under low fire severity conditions or in vegetation types that quickly recover, groundwater responses tend to be negative (i.e., decreased flux or storage). We synthesize relevant findings into a compendium of testable hypotheses aimed at explaining the spatiotemporal variability in observed post-wildfire groundwater responses. A recurring theme is the critical influence of the pre-wildfire groundwater regime on expected response and recovery. We identify opportunities for specific improvements in post-wildfire monitoring and modeling that would further advance capabilities to predict groundwater response. A key area for further research is understanding how wildfire effects on snow dynamics and other cryospheric processes translate to changes in groundwater.

JEL Classification: Hydrological Processes

1 | Introduction

Forested watersheds are increasingly affected by wildfire. Potentially negative effects on water quality and shifts in water quantity have been documented worldwide (e.g., Belongia et al. 2023; Bladon et al. 2014; Hallema et al. 2017; Nunes et al. 2018; Robinne et al. 2021; Smith et al. 2011). The importance of studies aimed at understanding hydrologic effects of wildfire continues to grow as wildfire frequency and affected area increase in response to climate change, intense heat, and extended drought (Abatzoglou and Williams 2016; Parks and Abatzoglou 2020; Zhuang et al. 2021). Post-wildfire hydrologic investigations typically target immediate and short-term (< 2 year) responses in overland flow, streamflow peaks, and annual yield due to the deleterious consequences of flooding, erosion, debris flows, and surface water quality that are elevated in the near-term following fire (e.g., Coombs and Melack 2013; Lane et al. 2006; Murphy et al. 2015, 2020; Kean et al. 2019; Vieira et al. 2023). Less common are studies that address the longer-term and deeper subsurface hydrologic response to wildfire, even though groundwater interaction is increasingly recognized as playing a vital role in mediating the overall hydrologic response to wildfire (Hallema et al. 2017; Atwood et al. 2023; Rey et al. 2023;

Bush et al. 2024). Communities within and downgradient of wildfire-affected regions may utilize both surface water sources fed by groundwater as well as direct pumping from groundwater. Herein, we define the groundwater response to wildfire to include changes in recharge, groundwater storage, and baseflow (generally groundwater generated), with the acknowledgment that wildfire-affected changes in unsaturated zone water fluxes, soil moisture, and rock moisture are highly relevant and connected. Studies that address observed groundwater response to wildfire describe divergent findings, with groundwater flux and storage components increasing (e.g., Kinoshita and Hogue 2011; Giambastiani et al. 2018), decreasing (e.g., Silberstein et al. 2013), and exhibiting mixed behavior or no appreciable change (e.g., Johnk and Mays 2021; Balocchi et al. 2022). Variability in groundwater response is hypothesized to depend on burn severity and area, climate, landcover type, vegetation, topography, soils, geologic setting, and time since fire, among other possible influences, though a comprehensive understanding of factors and interrelated processes controlling groundwater response remains underdeveloped (Paul et al. 2022).

Groundwater responses to wildfire effects depend on multiple hydrologic processes that recover from fire over different timescales. Numerous studies show reduced post-wildfire infiltration due to changes in soil hydraulic properties in the upper few centimeters that promote infiltration-excess runoff generation in response to storm events (Moody et al. 2013; McGuire et al. 2021). Such changes include enhanced soil water repellency (DeBano 2000; Ferreira et al. 2005), ash storage (Woods and Balfour 2010; León et al. 2015), surface seal formation (Larsen et al. 2009), macropore collapse or infilling (Nyman et al. 2010, 2014), and soil structural changes that decrease saturated hydraulic conductivity (Moody et al. 2016). Most of these effects are transient, peaking soon after fire and tapering 1–2 years after fire (e.g., Robichaud et al. 2016; Ebel and Martin 2017), or slightly longer recovery times for saturated hydraulic conductivity (Moody et al. 2013). Though reduced infiltration generally translates to reduced recharge, it is important to consider the short-lived nature of many processes that enhance infiltration-excess runoff generation (Ebel 2020) and the potentially longer lasting effects on canopy interception and evapotranspiration (ET) from vegetation degradation and mortality (e.g., Collar et al. 2022, 2023; Ma et al. 2020; Poon and Kinoshita 2018). Of equal consideration are expected differences in hydrologic partitioning as a function of precipitation intensity and energy availability. The longer-term groundwater response to wildfire, therefore, reflects the balance of changes in ET and soil hydraulic properties during vegetation recovery as subjected to both storm events and inter-storm periods.

Process-focused hydrologic studies that devote attention to groundwater response to wildfire tend to be locally specific, which can limit the extensibility of these findings to other areas. On the other end of the spatial scale spectrum, large-scale aggregated efforts to assess patterns in groundwater-related wildfire response have been limited by data availability and hydroclimatic variability that complicate parsing the hydrologic effects that are solely from wildfire (Beyene et al. 2021). Wildfire effects on snowpack water and energy balances in snow-influenced systems can further confound untangling the overall hydrologic response to wildfire (Smoot and Gleason 2021; Kampf et al. 2022; McGrath et al. 2023; Reis et al. 2024). Evidence of snowpack response to wildfire reveals seemingly contradictory results due to the countering influences of reduced snowfall interception (favoring accumulation) and enhanced snowpack energy inputs (favoring melt). *How wildfire effects on snowpack dynamics and related cryospheric processes translate to changes in groundwater flux or storage is a largely unexplored topic.* The lack of definitive understanding of expected post-wildfire groundwater response motivates this synthesis that includes an overview of existing relevant studies, compilation and discussion of findings, and a path forward for future work including generating testable hypotheses to explain spatiotemporal variability in observed responses.

2 | Post-Wildfire Changes in Groundwater Flux and Storage

2.1 | Recharge and Groundwater Storage

Studies reporting direct measurements of pre- and post-wildfire water table levels to evaluate the effects of wildfire on groundwater storage and recharge are extremely limited at present (Table 1). In an attempt to systematically analyze groundwater level response to wildfire from 1980 to 2016 across the contiguous United States (US), Johnk and Mays (2021) found only one groundwater monitoring site that met their search criteria for wildfire proximity, data completeness 3 years before and after fire, and freedom from confounding processes expressed in the water level timeseries record. This monitoring well in Beaver County, Utah (US), showed a temporary reduction in groundwater level, following the Honey Boy fire in 1996, that lasted 2 years before resuming to pre-fire levels. The decline in groundwater recharge, adjusted for precipitation variability, was hypothesized to result from transient wildfire-induced changes in soil hydraulic properties that impede infiltration. The transient response is consistent with soil hydraulic measurements that promote peak infiltration-excess runoff generation in the first 2 years following fire, and thereby limiting recharge, with recovery of near-surface soil hydraulic properties thereafter (e.g., Ebel 2020; McGuire et al. 2021).

As an alternative to using pre- and post-wildfire groundwater monitoring data that are rarely available, some studies have implemented new groundwater monitoring in adjacent burned and unburned areas for comparison to infer wildfire-influenced groundwater response. Such groundwater level observations from a coastal aquifer in Italy reported by Giambastiani et al. (2018) show recharge rates in a burned area 4 years post wildfire that exceed those in the unburned area by three to seven times. This striking increase in estimated post-wildfire recharge is likely elevated by its site characteristics and precipitation patterns that make the system unlikely to incur a substantial wildfire-influenced change in overland flow. Specifically, the site is characterized by sandy substrate and low relief as well as a hydroclimatology characterized by low intensity rainfall, all of which tend to limit infiltration-excess runoff. Therefore, the reduction in canopy interception and tevapotranspiration resulting from fire-induced forest mortality manifest prominently

TABLE 1 | Studies with a reported post-wildfire change detection outcome in groundwater-relevant components: Recharge, soil water storage, baseflow, and low flow.

		Published post-wildfire study	Location	Source of change detection	Δ groundwater recharge	Δ soil water storage	Δ baseflow or low flow	Water/energy asymmetry?	Time since fire (year)
Recharge focus	1	Giambastiani et al. 2018	Ravenna, Italy	Groundwater elevation	Strong Increase			No	4
	2	Johnk and Mays 2021	Beaver County, Utah, US	Groundwater elevation	Temporary Decrease			No	4
	3	Silberstein et al. 2013 *	North of Perth, Australia	Soil moisture, groundwater elevation	Slight Increase then Decrease	Temporary Increase		Yes	3
Soil water storage focus	4	Atchley et al. 2018	Bandelier National Monument, New Mexico, US	Modeled soil water storage		Mixed		No	2
	5	Atwood et al. 2023	San Gabriel Mountains, California, US	Subsurface water storage	Increase	Increase	Increase	Yes	2
	6	Cardenas and Kanarek 2014	Bastrop State Park, Texas, US	Soil moisture	Increase	Increase		No	1
	7	Ebel 2013a	Boulder, Colorado, US	Soil moisture, matric potential	Increase	Increase		No	1
	8	Silva et al. 2006	Tapada Nacional de Mafra, Portugal	Soil moisture	Increase	Increase		Yes	2
	9	Obrist et al. 2004	North of Reno, NV US	Soil moisture	Decrease	Decrease		Yes	3
Baseflow or low flow focus	10	Balocchi et al. 2022	Maule Region, central Chile	Stream discharge			Increase (2/3); Decrease (1/3)	Yes	2
	11	Bart and Tague 2017	Southern and central California, US	Stream discharge			Increase	Yes	7
	12	Beyene et al. 2021	Western US	Stream discharge			Increase (26/44); Decrease (11/44)	Mixed	≥ 5

(Continues)

TABLE 1 | (Continued)

	Published post-wildfire study	Location	Source of change detection	Δ groundwater recharge	Δ soil water storage	Δ baseflow or low flow	Water/energy asymmetry?	Time since fire (year)
13	Blount et al. 2020	Mill Creek basin, Montana, US	Stream discharge	Increase	Increase	Increase	No	10
14	Bush et al. 2024	HJ Andrews Experimental Watershed, Oregon, US	Stream discharge and chemistry			Slight Increase	Yes	3
15	Cingolani et al. 2020	Córdoba highlands, central Argentina	Stream discharge			Decrease	No	1
16	Duncan and Thomas 2004	East Otago, New Zealand	Stream discharge			Decrease; No Change	No	3
17	Jung et al. 2009	Devil Canyon, southern California, US	Stream discharge and chemistry			Increase (1/2); No Change (1/2)	Yes	4
18	Kinoshita and Hogue 2015	San Bernadino Mountains, California, US	Stream discharge			Increase	Yes	10
19	Rey et al. 2023	Western US	Stream temperature			Increase Inferred	Mixed	≥ 5
20	Saxe et al. 2018	Western US	Stream discharge			Increase	Mixed	≥ 5
21	Scott and Schulze 1992	Ntambamhlope Agricultural Research Station, South Africa	Stream discharge			Decrease	No	1
22	Stoof et al. 2014	Serra da Lousa in north-central Portugal	Stream discharge			Increase	Yes	1
23	Wine and Cadol 2016	New Mexico, US	Stream discharge			No Change		Variable

Note: Sources of change detection pertain to field observations except for study 4 (Atchley et al. 2018) that relied on modeled subsurface hydrologic data. Parenthetical ratios denote the number of sites where a trend of increase or decrease was observed relative to total sites. Asterisk (*) denotes response to a controlled burn; all other studies are associated with wildfire.

in the increase in groundwater recharge, with few counteracting processes.

Some studies have taken advantage of planned controlled burns (i.e., prescribed fire to manage fuels) to characterize recharge response to fire. Controlled burns typically do not reach the high temperatures and intensities associated with most wildfire occurrences (e.g., Alcañiz et al. 2018) making the translation to post-wildfire response open for debate, yet worth noting. In a study conducted in southwest Australia, Silberstein et al. (2013) observed an increase in recharge immediately following a controlled burn using a combination of groundwater and soil moisture monitoring, remotely sensed ET, and physically based modeling. After 3 years post-fire, vegetation recovery and the associated resumption and uptick in ET negated this initial enhanced recharge pulse, eventually leading to a net decrease in recharge. Low-relief and coarse sandy soil texture at this site contributed to the relatively uncomplicated signal of the groundwater response attributed to changes in ET from vegetation mortality and recovery, leaving initially more and then less water available, respectively, for recharge. Low severity of the controlled burn, as well as the initial post-fire enhancement in soil moisture, likely contributed to rapid vegetation regrowth and associated ET recovery.

2.2 | Soil Water Storage

In post-wildfire hydrologic studies, soil moisture data are more prevalent than data such as unsaturated zone tracer information or water table elevation timeseries that can be used to estimate recharge. Because changes in soil water storage and recharge typically follow the same trajectory, changes in deep soil moisture following fire have been used in several studies to infer post-wildfire recharge response (Table 1). Typical measurement techniques include soil moisture probes, sensors, and non-invasive geophysical methods such as electrical resistivity surveys to quantify and describe changes in soil water storage. Several observational studies report increases in soil water storage in response to wildfire disturbance through comparison of conditions at paired burned/unburned sites (e.g., Silva et al. 2006; Ebel 2013a; Cardenas and Kanarek 2014; Atwood et al. 2023). Studies reporting notable decreases in soil water storage in post-wildfire settings are also common (e.g., Obrist et al. 2004 and others in Tab. 4 of Silva et al. (2006)) highlighting the variety of competing factors controlling subsurface hydrologic response. Field investigations have been complemented by physically based modeling studies that support increased post-wildfire soil water storage in response to the reduction in canopy interception and transpiration in burned areas (Ebel 2013b; Atchley et al. 2018; Abolafia-Rosenzweig et al. 2024). Combustion of the litter/duff layer reduces above-ground water storage, and combustion of near-surface soil organic matter alters soil-water retention properties, both of which can also promote enhanced soil water storage in the deeper unsaturated zone (Ebel 2013a). In a modeling analysis extending 2 years post wildfire, Atchley et al. (2018) showed that reductions in soil water storage only occurred for high burn severity cases in which infiltration-limiting parameterization of soil hydraulic properties dominated over reductions in ET in the water balance. Though soil water storage and recharge are generally positively correlated, changes in one do not always correspond to changes in the other in post-wildfire settings. For example, in systems with deep water tables, a reduction in ET the first year following fire can lead to an early-time enhancement of soil moisture in the unsaturated zone that is depleted upon rapid, deep-rooted vegetation regrowth prior to supplying the water table, resulting in little to no effect on recharge (e.g., Silberstein et al. 2013). It is also possible to have post-wildfire increases in recharge via enhanced preferential flow with minimal observable increases in soil moisture, or with brief periods of enhanced soil moisture that could be missed depending on the frequency of observations. Augmented preferential flow through fingering in dry soils prevails in some post-wildfire settings due to water repellent soil conditions and heightened soil moisture variability (Stoof et al. 2014), thereby increasing recharge. Another potential mechanism of wildfire-induced preferential flow in arid and semiarid regions is through macropores enhanced by surficial variability in water repellency (Nyman et al. 2010) and through root pathways (Lei et al. 2021; Leslie et al. 2014).

2.3 | Baseflow

The downstream effects of wildfire-induced changes in groundwater hydrology can be manifested in baseflow magnitude, timing, temperature, isotopic signature, and streamflow chemistry. Because these effects may be subtle and occur over prolonged timeframes, studies examining wildfire disturbance need to account for interannual to longer-term climatic variability and other factors, including antecedent water storage conditions (Littell et al. 2016) and compensatory plant water uptake in unburned and riparian areas (Bart and Tague 2017; Collar et al. 2023) that can enhance or dampen baseflow response. Due to these complexities, parsing wildfire effects to baseflow remains challenging.

Several approaches have been used to infer changes in groundwater-stream exchange in response to wildfire, with results that vary from enhanced to reduced groundwater contribution to streamflow. Increases in baseflow are more common than reductions for studies with observations extending > 1 year post fire (Table 1). Wildfire effects on baseflow have been shown to vary depending on the seasonal period of investigation, with increases more typically observed during the summer dry period and more variable during the wet season (Bart and Tague 2017; Jung et al. 2009). Baseflow recession analysis yielded reduced post-wildfire recession rates that correspond to enhanced groundwater-stream exchange in central and southern California, US (Bart and Tague 2017). Atwood et al. (2023) used stable isotopes to characterize potential differences in groundwater-stream exchange between paired burned and unburned watersheds in the San Gabriel Mountains in California, US. The results pointed to a post-wildfire enhancement in shallow groundwater contributions to streams, which conceptually aligned with post-wildfire increases in soil water storage identified through time-lapse electrical resistivity surveys. Blount et al. (2020) documented a sustained (10-year) increase in baseflow together with an increase in annual yield following the Chippy Creek fire in the

Mill Creek basin of Montana, US. Water level data from two groundwater monitoring wells downgradient of the burned area indicated a post-wildfire increase in groundwater storage in support of the observed baseflow enhancement. A study by Balocchi et al. (2022) assessed post-wildfire hydrologic effects in three catchments in central Chile that were completely burned by a high severity fire in January of 2017 following an unusually dry 8-month period. By contrast, the year following the fire was unusually wet. Based on analysis of streamflow data 7 years pre fire and 2 years post fire, the ratio of baseflow to annual flow was shown to increase in two of the catchments and decrease in the remaining catchment. The study also tested the use of tritium as a tracer for evaluating changes in groundwater transit times that could be attributed to fire. The authors concluded that a monitoring period longer than their 2-year study would be required for detecting changes in transit time, given the tritium-informed mean transit times of 5–30 years. This study highlights the potential of using isotopic methods for augmented analysis and the limitations of short-term post-wildfire monitoring for understanding groundwater response.

Additional studies have compared pre- and post-wildfire low flows, which under some conditions are a reasonable proxy for groundwater discharge to streams (i.e., baseflow). An important exception is that in dry settings, low flow conditions may be more reflective of water released from riparian storage rather than from the local or regional groundwater system if/when water tables are not well connected to the stream corridor. Reported low-flow response to wildfire yields mixed results. A seminal study by Wine and Cadol (2016) examining three large watersheds in New Mexico that had experienced over 100 wildfires between 1982 and 2014 found no changes in low flows that could be attributed to wildfire after accounting for local to regional hydroclimatic variability. Yet in the central Argentina highlands, dry-season post-wildfire low flows declined by 31%–48% in support of the infiltration-evapotranspiration tradeoff hypothesis that postulates that the effect of impaired infiltration exceeds the effect of reduced ET on net subsurface storage and flow in response to vegetation degradation (Cingolani et al. 2020). Scott and Schulze (1992) also reported a baseflow reduction in response to wildfire attributed to a strong soil repellency effect that enhanced infiltration-excess runoff generation and in turn reduced recharge. Both Cingolani et al. (2020) and Scott and Schulze (1992) focused on the low-flow response the year after fire. In contrast, Kinoshita and Hogue (2015) observed 118%–1090% increases in low flow volumes of ephemeral and intermittent stream systems averaged over nearly a decade following a 2003 wildfire in the semi-arid San Bernardino Mountains, California (US). These observed increases were attributed to a basin-wide reduction in transpiration resulting from plant canopy removal allowing more available water for baseflow. Elevated fall low flows (referred to as baseflow in the study) were also observed 3 years post-wildfire in the western Cascade Range, Oregon, US (Bush et al. 2024) though the increases were relatively small, due perhaps to low-moderate fire severity.

A large-sample hydrology approach to assess the aggregated response to wildfire occurrence over large spatial scales across diverse settings (after Gupta et al. 2014) can serve as an important complement to place-based studies that examine baseflow and low flow response to individual wildfires or to a series of wildfires in a common regional setting (e.g., Bart and Tague 2017; Wine and Cadol 2016). For example, Beyene et al. (2021) examined changes in pre- and 5-year post-wildfire low flows across the western US using empirical approaches. They used a bootstrap and double mass analysis followed by quantile regression approach to parse the effects of wildfire from meteorological variability over the pre- and post-wildfire time periods. The results yielded increases attributed to wildfire in flow at the 0.05th quantile by 10%–5000% at 26 of 44 stream sites evaluated and decreases attributed to wildfire at the 0.05th quantile at 11 sites. The study highlighted a notable increase in low flow response in the Pacific Northwest and California regions with contrasting responses in the Rio Grande and Lower Colorado regions. Soil permeability was found to be the most important predictor of wildfire response to flow at the 0.05th quantile, followed by slope, burned area and severity, and annual baseflow index (Beyene et al. 2021). Rey et al. (2023) also investigated baseflow response to wildfire over similar durations (5 years pre and post fire) across the western US by developing a temperature tracing approach for detecting changes in groundwater contribution to streamflow. This approach identified a substantial shift in air and stream water coupling, indicative of a post-wildfire increased groundwater contribution to streams when taken in aggregate, in line with findings in Beyene et al. (2021). Further examination revealed variability in individual post-wildfire response that was determined to some extent by source depths of pre-wildfire groundwater contributions to streamflow. Saxe et al. (2018) examined 82 fire-affected watersheds in the continental US with ≥ 10 years of continuous pre-fire daily streamflow records and ≥ 5 years of continuous post-fire daily flow records to assess effects on low flows (average daily flow at 90% exceedance) and baseflow index. Increases in low flows and baseflow indices were found for the first 2 years post-fire followed by decreases over longer time periods. First-year low flows showed larger increases when the burned area fraction was $> 23\%$, and second-year low flows showed larger increases when burned area fraction was $> 37\%$.

3 | Spatiotemporal Patterns in Post-Wildfire Groundwater Responses and Underlying Processes

3.1 | Spatial Considerations

Underlying regional (e.g., climate, vegetation) to local (e.g., hydrogeology) conditions together with wildfire characteristics play roles in determining the magnitude and directionality of the groundwater response to wildfire. Fire effects on cryospheric processes also come into play in cold regions. Based on limited available studies, as well as foundational understanding of recharge and discharge processes, we can begin to identify and interpret emerging patterns to explain disparate and spatially variable post-wildfire groundwater responses summarized in Table 2.

3.1.1 | Climate-Vegetation Interactions

Climate can influence groundwater response to wildfire in multiple ways related to (1) amount and intensity of energy and

TABLE 2 | Linkages between defining variables and expected post-wildfire groundwater response based on existing studies.

Category	Defining variable	Expected post-wildfire groundwater response: Favors positive (increased) response	Neutral response	Favors negative (decreased) response	Considerations/explanations	Support (Numbered study from Table 1)
Climate	Aridity			High aridity (?)	Counterbalancing and confounding factors. For example, high aridity equates to high potential evaporation that can compensate post-wildfire transpiration loss (negative groundwater response), yet it would also contribute to low vegetation recovery rate (positive groundwater response)	2, 12
Climate	Precipitation intensity	Low intensity (?)			Low precipitation intensity lowers infiltration-excess surface runoff, potentially favoring recharge. High precipitation intensity favors infiltration-excess runoff (and thus decreased groundwater response), but when coupled with wildfire-enhanced preferential flow could lean toward a positive recharge response	1
Climate	Water and energy synchrony	Asynchronous			Asynchronous water input and evaporative demand favor increased groundwater response for site based and aggregated studies. Yet, the opposite does not hold; the full spectrum of responses is observed for synchronous water/energy systems	5, 8, 10, 11, 12, 14, 17, 18, 22
Vegetation	Landcover type	Forest	←	Grasslands	Landcover type strongly linked to aridity and vegetation regrowth rate. Mixed groundwater response in shrublands and mixed vegetation types	9, 15, 16

(Continues)

TABLE 2 | (Continued)

		Expected post-wildfire groundwater response				Support
Category	**Defining variable**	**Favors positive (increased) response**	**Neutral response**	**Favors negative (decreased) response**	**Considerations/explanations**	**(Numbered study from Table 1)**
Vegetation	Regrowth rate	Slow recovery	←	Rapid recovery	Rapid vegetation recovery promotes compensatory uptake	3, 15, 16, 21
Hydrogeology	Permeability	High permeability		Low permeability	Highly permeable systems reflect a > 2-year post-wildfire reduction in ET with few complicating soil water processes more common in lower permeability systems	1, 13, 14, 21
Hydrogeology	Topography	Low relief			Topography should be considered together with surface permeability and precipitation intensity given their collective control on runoff generation. Low relief tends to favor positive groundwater response (though exceptions exists), and high relief settings show a mixed response	1, 6, 8
Hydrogeology	Deep groundwater in streamflow	Low fraction	High fraction		Large pre-existing groundwater contribution to streamflow from deep sources will buffer changes in baseflow induced by wildfire	18
Fire characteristic	Burn severity	High severity	←	Low severity	Groundwater response > 2-years post fire is generally positive for high severity but may be neutral (minimal effect) for low severity or even negative with denser post-fire regrowth	3, 4, 10, 23
Fire characteristic	Watershed burn extent	High % burned	←	Low % burned	Minimum watershed burned percentage threshold has not been established for expected groundwater response	12, 17, 20

(Continues)

TABLE 2 | (Continued)

Category	Defining variable	Expected post-wildfire groundwater response: Favors positive (increased) response	Neutral response	Favors negative (decreased) response	Considerations/explanations	Support (Numbered study from Table 1)
Fire characteristic	Riparian zone burned	High % riparian area burned	←	Low % riparian area burned	Low disturbance of riparian zone favors compensatory uptake to override the reduction in ET within upstream burned area	11
Cryosphere	Snow	Presence of seasonal snow (?)			Limited studies. Enhanced snow accumulation would tend to favor groundwater recharge; however increased snowmelt rate could limit recharge (dependent on infiltration capacity and frozen ground conditions), favoring runoff over recharge	7, 23
Cryosphere	Seasonal freeze/thaw	Presence of seasonal frost (?)			Limited field studies. The influence of seasonal freeze/thaw is linked to snow (above). Reduced fire-enhanced soil hydrophobicity from freeze/thaw processes in wet soils may favor positive recharge response (Rakhmatulina and Thompson 2020)	
Cryosphere	Permafrost	Presence of permafrost (?)			Limited/no field studies. Theoretical basis for positive groundwater response with wildfire-enhanced permafrost thaw (Walvoord et al. 2019)	

Note: Question mark (?) denotes uncertainty related to a paucity of relevant studies. Left pointing arrow (←) denotes that the characteristic to the right has been linked to a neutral as well as a decreased post-wildfire groundwater response.

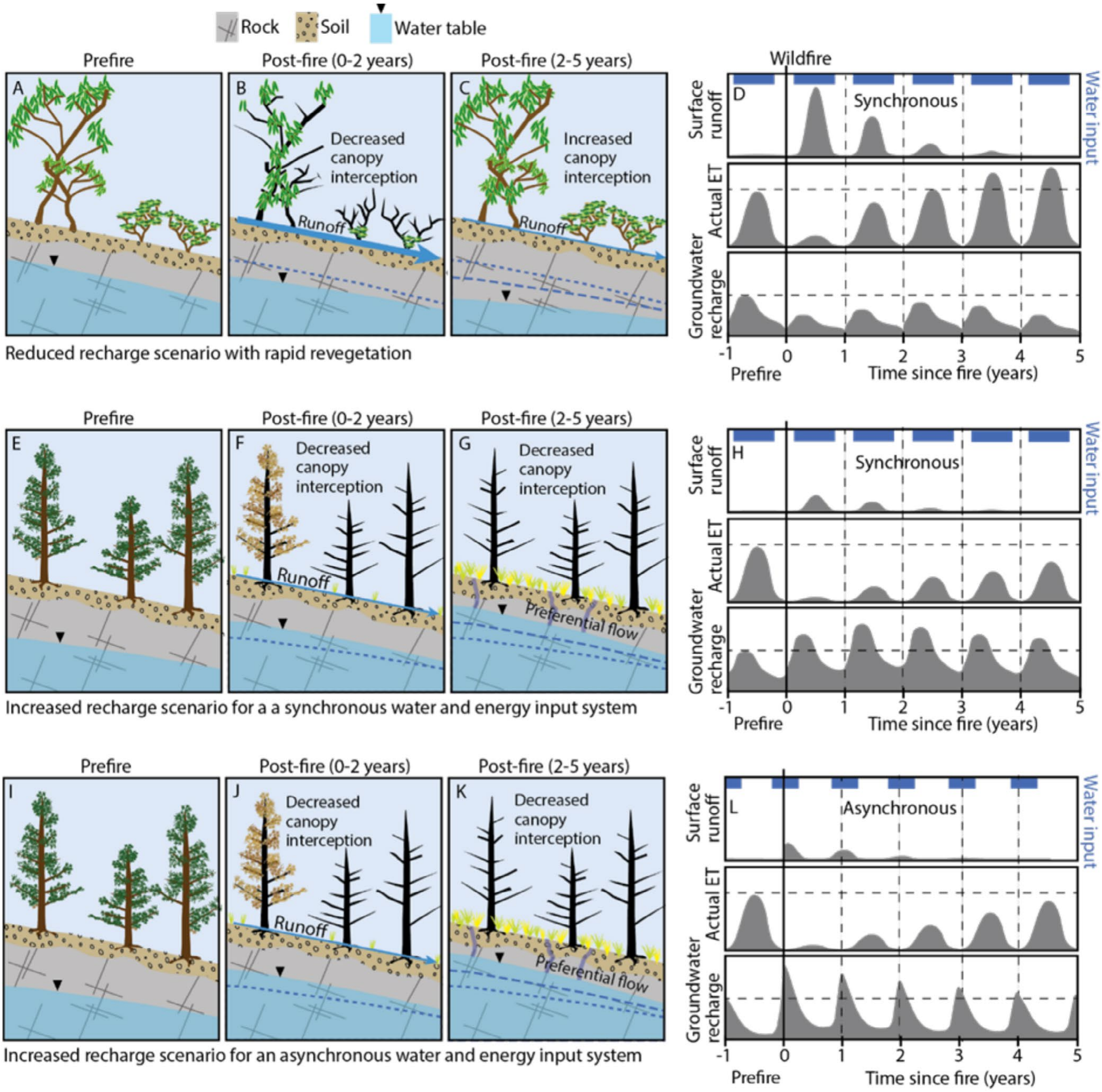

FIGURE 1 | Schematic depiction of pre-fire, early-time post-fire, and intermediate-time post-fire conditions with accompanying surface runoff, actual ET, and recharge timeseries for a reduced recharge scenario with rapid revegetation (A–D), and increased recharge scenario for a synchronous water and energy input system (E–H), and an asynschronous water and energy input system (I–L). Dotted line in B, C, F, G, J, and K represents the prefire water table. Dashed line in C, G, and K represents the early-time (0–2 years) post-fire water table. Horizontal dashed lines in D, H, and L denote pre-fire actual ET and groundwater recharge for comparison in the post-fire time series. Annual guidelines (vertical dashed lines) highlight water/energy synchrony (D and H) and asynchrony (L).

water inputs, (2) timing of atmospheric demand vs. water inputs, and (3) cryospheric processes (discussed in Section 3.1.4) (Figure 1). Embedded within these primary considerations are additional and cross-cutting factors, including the land-cover types and vegetation recovery rates supported by climatic conditions.

The typical rainfall regime of an area is expected to play a role in groundwater response to wildfire as well as the specific precipitation conditions before and after the fire within the burned area. The latter, however, comes into play more prominently for the short-term rather than the long-term response. Regions prone to high intensity storms are likely to experience increased infiltration-excess runoff following wildfire, potentially leaving less available water for groundwater recharge, especially shortly after fire when wildfire-effects that reduce infiltration are strongest (Moody et al. 2013; Balfour et al. 2014) (Figure 1). However, high intensity precipitation events in arid and semi-arid regimes with dry soils can promote preferential flow, through wetting front instability, fingering and macropore channeling, as a mechanism for recharge that may be enhanced in post-wildfire settings (Stoof et al. 2014).

In climates with relatively synchronous energy and water delivery cycles (evaporative demands and precipitation input are high during the same season), some recharge during the growing season can be expected though seasonal variability may also be present. Here, compensatory uptake during the summer/growing season may offset wildfire-induced reductions in canopy interception and transpiration in climatic conditions that support summer recharge (Collar et al. 2023). Thus, compensatory measures become major factors in determining groundwater response, and mixed outcomes are observed in systems with synchronous energy and water inputs. Landcover type and vegetation recovery rate are also key variables in groundwater response. Primary differences in response are observed among forests, shrublands, and grasslands due to variations in the capacity of these landcover types to intercept precipitation, alter the surface energy balance, access groundwater through deep rooting structures, and revegetate after wildfire (Ahmad et al. 2024). Negative (decreased) or negligible groundwater responses to wildfire are most common in regions with rapid revegetation rates such as grasslands (Duncan and Thomas 2004; Cingolani et al. 2020) or vegetation that regenerates by basal or epicormic resprouting (e.g., Nolan et al. 2014) (Figure 1A–D), whereas positive (increased) groundwater responses are more typical of forested landcover types (Ebel 2013a; Giambastiani et al. 2018) (Figure 1E–H). Though landcover type at the time of the wildfire is a key groundwater response variable, post-wildfire vegetation shifts from forest to shrubs and grassland (Blount et al. 2020; Collar et al. 2023) can also be important because of shifts in vegetation phenology, rooting depth, and total plant-water use (Figure 1E–H). Another consideration of increasing importance is the additional stressor of drought conditions that contribute to slow recovery in non-forested vegetation types with shallow rooting structures (Ahmad et al. 2024).

In climate regimes with warm dry summers and cool wet winters, evaporative demands and water inputs are not in phase (i.e., asynchronous; Figure 1I–L). Post-wildfire studies conducted in Mediterranean climates, for example, tend to exhibit positive (increased) groundwater responses (Table 2). The asynchrony of energy and water inputs imparts a strong seasonal dimension to recharge (winter-dominated recharge), which likely bears critical context for assessing the post-wildfire groundwater response. During the winter/non-growing season when the potential for compensatory uptake of increased available soil water is low, reductions in precipitation interception from wildfire may be crucial for determining changes in recharge.

3.1.2 | Hydrogeologic Conditions

Just as the underlying climate-vegetation interactions supporting seasonal recharge are critical for predicting wildfire disturbance, so too are the existing hydrogeologic conditions. Soil permeability and topography are key variables that define hydrogeologic setting. These hydrogeologic variables were identified as the top two predictors of low flow wildfire response in the large-scale investigation by Beyene et al. (2021). In systems with highly permeable near-surface soil, post-wildfire reductions in transpiration and canopy interception may be more likely to outweigh and outlast short-lived increases in infiltration-excess runoff resulting from soil water repellency and soil seal formation over longer (> 2 years post fire) timescales. The expected 2–5-year net result in highly permeable near-surface soil systems is a post-wildfire increase in recharge as was observed by Giambastiani et al. (2018) and inferred by Cardenas and Kanarek (2014) and Blount et al. (2020). The scientific community currently lacks quantitative methodologies to deterministically estimate post-wildfire effects on soil permeability and timescales of recovery. This knowledge gap poses challenges to predicting post-wildfire groundwater response regionally. An additional challenge for prediction is the lack of high quality hydrogeologic characterization to describe groundwater-surface water connectivity and dynamic groundwater storage that goes beyond topography and available soils maps.

Systems with steep slopes have been shown to bear the strongest response to wildfire in infiltration-excess runoff generation (e.g., Ebel 2013a, 2013b; Moody et al. 2013). Although slope plays a role in recharge response following fire, no clear association has been established. Studies conducted in watersheds with high and low relief also show mixed post-wildfire groundwater responses suggesting that slope is just one of several controlling factors.

Pre-wildfire hydrogeologic conditions have been shown to exert influence in determining the groundwater response to wildfire. For example, an investigation examining hydrologic response in the western US detected notable post-wildfire changes in thermal signals suggestive of increases in shallow groundwater input to streamflow primarily in streams that lacked a substantial connection to a deep groundwater source pre-wildfire (Rey et al. 2023). Streams with a strong pre-wildfire deep groundwater contribution were least likely to exhibit a change in the annual thermal signal. Similar findings were derived using a geochemical end member mixing analysis that revealed a post-wildfire increase in the groundwater component of inter-storm stream water for a small basin in southern California, US, with an initial low groundwater fraction compared with a larger baseflow-dominated system that appeared minimally affected with respect to source water partitioning (Jung et al. 2009). Prior synthesis of vegetation disturbance effects on streamflow noted that groundwater responses depended on the strength of connectivity to deep groundwater systems (Adams et al. 2012; Bruijnzeel 2004; Knighton et al. 2020).

3.1.3 | Wildfire Characteristics

Factors pertaining to the wildfire itself are expected to influence the groundwater response. Higher burn severity has been shown to correlate with greater reductions in infiltration (Moody et al. 2016) from event-based precipitation, effectively limiting recharge in favor of overland flow. Burn severity also affects the post-wildfire ET response as forests burned at low severity may continue to transpire immediately following fire, whereas transpirational leaf surface area plummets in high severity burns, potentially allowing more water for recharge. Atchley et al. (2018) used a physically based modeling approach to isolate the influence of burn severity, as parameterized in a hydrologic model, on the soil water balance tipping point between increased runoff and decreased transpiration induced by fire over the first 2 years following wildfire. For low severity cases, reductions in transpiration outweighed enhanced surface runoff in the water budget, leading to increased soil water storage and potential for recharge. In contrast, model results for high severity sites surpass an infiltration threshold where enhanced surface runoff dominates the post-fire water budget, leading to reduced soil water storage and potential for recharge. Over longer timescales (> 2 years), burn severity may have an opposing effect to that described above. Higher burn severity corresponds to greater vegetation mortality and slower vegetation regrowth resulting in reduced transpiration (Poon and Kinoshita 2018; Cooper et al. 2019), reduced canopy interception (Su et al. 2022), and enhanced potential for macropore development from tree root decay (Stoof et al. 2014; Leslie et al. 2014), all of which would promote increased recharge. Burn severity in riparian corridors may be especially important in determining baseflow response to fire (Bart and Tague 2017). Based on available studies, we infer burn severity to be positively correlated to groundwater recharge and baseflow over intermediate post-fire timescales (2–10 years) when ash effects and soil repellency have diminished.

The fraction of the watershed that has burned likely plays a role in determining a wildfire effect on the groundwater system, though no established minimum percent watershed threshold exists for an expected groundwater response. Typical reported minimum thresholds of percent watershed burned for expected post-wildfire changes in annual yields in streamflow are on the order of 20% (Hallema et al. 2017; Saxe et al. 2018). Aggregated large-scale studies examining low flow and baseflow response to wildfire have used criteria of > 5% (Beyene et al. 2021) and > 10% (Rey et al. 2023) watershed burned for inclusion in analysis. Results from Beyene et al. (2021) show that significant post-wildfire changes in annual baseflow yield ratio were more common in sites with > 25% watershed burned than sites with 10%–15% watershed burned, suggesting a groundwater-response dependence on burned area proportion. Saxe et al. (2018) showed low flow increases were more pronounced with > 23% watershed burned. An additional consideration noted as relevant for compensatory uptake, especially in baseflow analysis, is the percent of the burned area that encompasses the riparian zone (Bart and Tague 2017).

3.1.4 | Cryospheric Processes

In cold regions, cryospheric processes can provide an additional layer of complexity in contributing to the net effect of wildfire on groundwater recharge and baseflow. Relevant cryospheric processes include snow dynamics, seasonal freeze/thaw, the interaction between snow and seasonally frozen ground, and permafrost dynamics (Figure 2). The complete or partial loss of forest canopy resulting from wildfire can lead to a notable reduction in snow interception and changes to the surface energy balance (Moeser et al. 2020), the latter of which can also be affected by ash-induced decreases in snow albedo soon after fire (Gleason et al. 2019; Koshkin et al. 2022). Studies have shown increases (Seibert et al. 2010; Maxwell et al. 2019), decreases (Smoot and Gleason 2021; McGrath et al. 2023; Hatchett et al. 2023; Reis et al. 2024; Surunis and Gleason 2024), and no change (Goeking and Tarboton 2020) in snowpack accumulation in response to wildfire. Despite these key differences, there has been greater agreement that wildfire-affected areas in snow-dominated systems exhibit enhanced snowmelt rates and earlier snow disappearance as a result of a positive net shortwave radiation balance (Seibert et al. 2010; Gleason et al. 2019; Smoot and Gleason 2021; Kampf et al. 2022; McGrath et al. 2023). The effect of post-wildfire changes in snow accumulation and ablation on groundwater recharge and discharge remains understudied. Cold, snow-dominated systems are prone to seasonally frozen ground that can play a role in snowmelt partitioning as a solid ice-rich layer can act as a barrier to flow (and recharge) if laterally continuous (Ala-Aho et al. 2021). Thicker snowpacks that impart greater thermal insulation during the winter and thus warmer soils could lead to thinner seasonal frost, earlier soil thawing in the spring, and enhanced groundwater recharge in response to a larger and earlier post-fire snowmelt pulse (Ebel et al. 2012; Figure 2A–D). Alternatively, the mid-winter or early season snow melt events, potentially more common under burned conditions (Hatchett et al. 2023), could lead to reduced groundwater recharge due to reduced snowpacks, thicker seasonal frost, and impeded infiltration into frozen soils early in the season (Figure 2E–H). Soil freeze/thaw may have an additional impact on hydrologic partitioning following wildfire by limiting the short-term effects of wildfire-enhanced soil repellency (Rakhmatulina and Thompson 2020), thereby favoring a positive recharge response. This reduction in repellency from freeze/thaw soil mechanics has been observed in wet soils. There is little comparable effect in dry soils due to the low volume of pore water changing phase.

Wildfire promotes permafrost thaw in some sub-arctic environments (Minsley et al. 2016; Gibson et al. 2018; Rey et al. 2020) that may also impact groundwater processes. Archetypal physically based modeling analyses have demonstrated how wildfire-induced thaw in permafrost settings can increase baseflow and extend shoulder season groundwater discharge with thaw-induced opening and expansion of subsurface flowpaths (Walvoord et al. 2019) and conversely can decrease baseflow magnitude if increased ET dominates the post-wildfire response (Zipper et al. 2018). Wildfire-induced thaw is commonly attributed to combustion of near-surface organic matter and loss of canopy cover that provide key thermal insulation and soil shading, respectively, during the summer season. In addition, reduced snow interception from canopy loss can yield a thicker snowpack offering enhanced insulation from frigid winter air temperatures, further promoting permafrost thaw (Figure 2I–L).

3.2 | Temporal Considerations

Hydrologic response to wildfire evolves through time as fire-enhanced soil water repellency diminishes and vegetation regrowth occurs (Partington et al. 2022), both of which affect the temporal component of the expected groundwater response to fire. Repellency effects have been shown to taper notably the first year following fire even under high severity burns (DeBano 2000), thereby creating a transient effect that may explain findings that suggest early post-wildfire reductions in recharge followed by mid-to longer-term increases (Johnk and

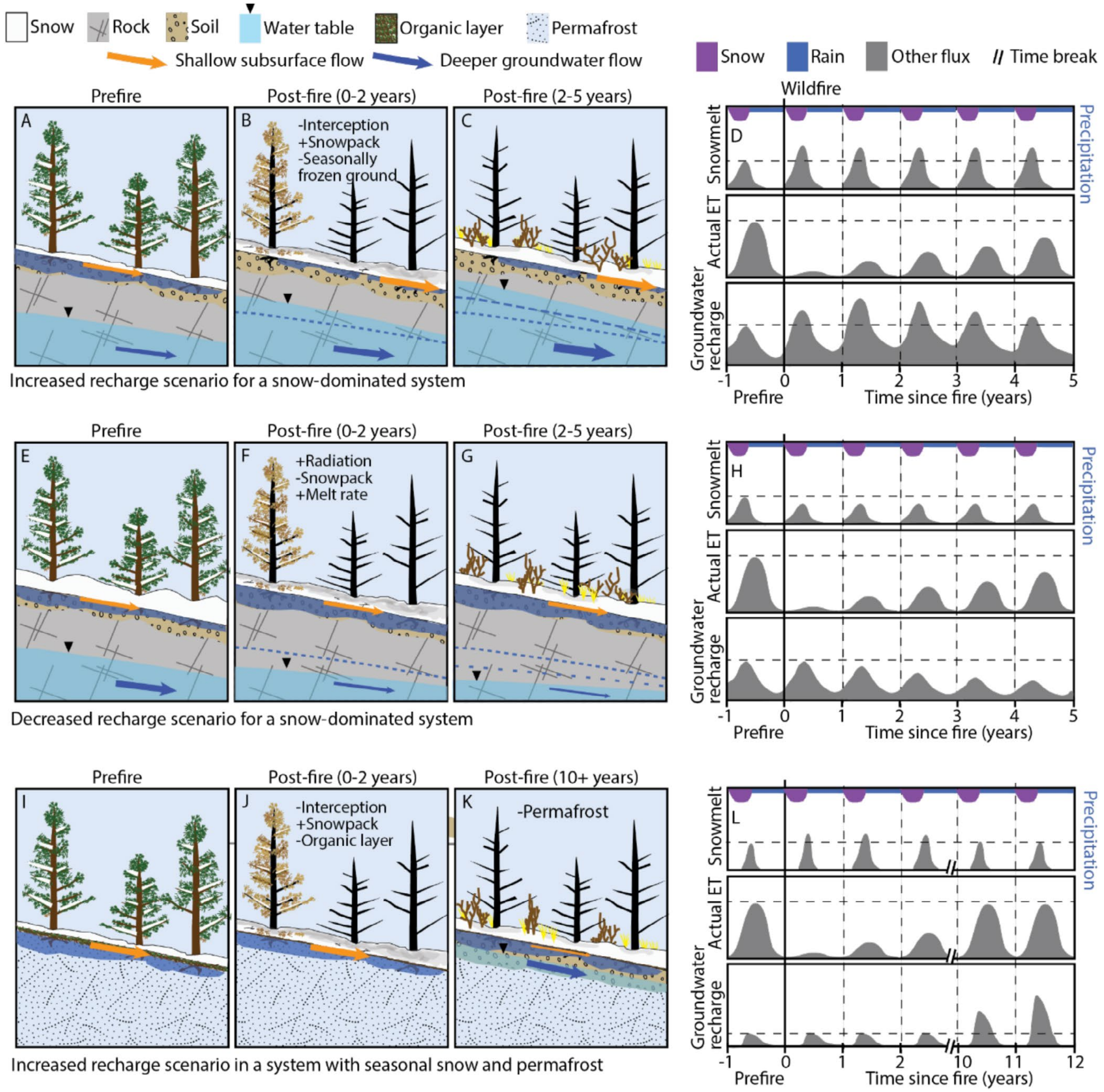

FIGURE 2 | Schematic depiction of pre-fire, early-time post-fire, and intermediate-time post-fire conditions with accompanying snowmelt input, actual ET, and recharge timeseries for an increased recharge scenario in a snow-dominated system (A–D), decreased recharge scenario in a snow-dominated system (E–H), and increased recharge scenario for a system with seasonal snow and permafrost (I–L). Note time post-fire difference in K vs. C and G in accordance with timescales of permafrost thaw. Thickness of subsurface orange and blue arrows correlates to relative flux magnitude. Dotted line in B, C, F, and G, represents the prefire water table. Dashed line in C and G represents the early-time (0–2 years) post-fire water table. Horizontal dashed lines in D, H, and L denote pre-fire snowmelt input, actual ET, and groundwater recharge for comparison in the post-fire time series.

Mays 2021; Giambastiani et al. 2018). Vegetation recovery rates vary substantially among climate settings and ecotypes; they can also depend on burn severity and pre-fire drought conditions. Rapid understory vegetation regrowth can shift the near-surface water balance to pre-wildfire conditions in just a year or two, potentially imparting a negligible or reduced post-wildfire groundwater response. In contrast, ecosystems that support low growth rates and/or have undergone high severity fires may take a decade or more to resume ET rates that are comparable to pre-wildfire conditions (Ahmad et al. 2024). In the latter case, long-term monitoring is needed to capture the complete groundwater response.

A lagged post-wildfire groundwater recharge response may be expected in systems with deep water tables and long transit times through the vadose zone. A lagged response may also occur in situations in which tree mortality is not immediate following fire or when drought conditions suppress precipitation (Newcomer et al. 2023). Another temporal consideration that may impart a lagged response is the time required for decaying root networks to develop macropores that serve as a mechanism for wildfire-enhanced preferential flow (e.g., Lei et al. 2021).

4 | Implications for Water Quality

Understanding expected changes in groundwater fluxes following wildfire has important implications for stream water quality due to inherent differences in chemical composition, residence time, and temperature of groundwater as compared with surface runoff and soil water (Paul et al. 2022; Elliott et al. 2024). Increased baseflow and associated hydrologic connectivity following fire can mediate some of the expected deleterious post-wildfire water quality impacts to streams (Bush et al. 2024). Streams with a substantial groundwater contribution serving as a relatively cool and consistent baseflow source have an annual thermal signature that is attenuated in amplitude compared to streams with minimal groundwater input (Rey et al. 2023). Groundwater-influenced streams that support conditions near the summer water temperature tolerance limit for cold water aquatic species are therefore particularly vulnerable to wildfire effects on baseflow. Here, reductions in baseflow alone or coupled with increases in net surface energy inputs to the stream due to the loss of riparian vegetation and stream shading could result in maximum summer stream temperature threshold exceedance for some aquatic species (Dunham et al. 2007). In contrast, increases in baseflow may help counter stream temperature rises from the loss of solar radiation blocking from riparian vegetation (e.g., Wagner et al. 2014; Beyene and Leibowitz 2024). Though thermal conditions in streams with substantial deep groundwater contributions pre-fire may be largely unaffected by wildfire due to the inherent buffering effect of deep groundwater, streams with minimal or shallow groundwater inputs may be most sensitive to wildfire-induced changes in stream temperature regime (Rey et al. 2023). Similarly, stream systems with substantial groundwater input may be less prone to changes in source water components (with distinct geochemistry) than streams with low pre-fire baseflow (Jung et al. 2009).

In addition to water quality effects to streams induced by changes in groundwater fluxes, wildfire can impart direct effects to groundwater chemistry. Preferential and diffuse flow through the unsaturated zone can deliver chemical constituents including ash, fire retardants, nutrients, metals, and other chemicals of concern to groundwater following fire (Elliott et al. 2024; Rodríguez-Jiménez et al. 2024). Post-wildfire groundwater contamination has implications for human and aquatic health. A study by Mansilha et al. (2020) in northwest Portugal found elevated post-wildfire concentrations of major ions, metals, and carcinogenic polycyclic aromatic hydrocarbons in springs that support local public water supply. Elevated nitrate concentrations in groundwater-sourced drinking water were detected downgradient of major wildfire-affected areas in a US study by Pennino et al. (2022). Following the rainy season after the most severe wildfires on record in Spain, Rodríguez-Jiménez et al. (2024) observed an overall decline in groundwater pH compared with pre-fire levels that was attributed to leaching of organic acids from burned biomass. Increases in groundwater concentrations of sulfate, nitrate, and cations linked to ash residue were also observed.

Though the effects of wildfire on groundwater quality tend to be negative, examples of *improved* groundwater quality in response to wildfire exist. Most notably, increases in recharge, can flush pre-wildfire groundwater chemical constituents, or even influence groundwater flow fields if water table rises are substantial. For example, in the study by Giambastiani et al. (2018) mentioned previously, major increases in post-wildfire recharge were shown to reduce groundwater salinity levels in the coastal aquifer through a dilution effect and suppression of the sea to inland hydraulic gradient thereby reducing seawater intrusion.

Transmission of chemical constituents to connected streams via groundwater pathways is a secondary, but potentially important and longer lasting, mode of post-wildfire surface water quality degradation compared with surface runoff as a primary mode (Nunes et al. 2018; Paul et al. 2022). Contaminated groundwater can extend stream water quality recovery times following fire, providing a muted, but prolonged, release of constituents in comparison to the pulse-like delivery of near-surface contaminants accompanying precipitation events soon after fire (Murphy et al. 2015). A study by Murphy et al. (2020) reported enhanced groundwater flow through underground mine workings as a mechanism contributing to elevated arsenic and metals in streams following wildfire. Direct wildfire effects on water distribution systems have included well damage and groundwater contamination at the wildland-urban interface (e.g., Jankowski et al. 2023; Schulze and Fischer 2020), which is an important topic as fires increasingly affect the built environment (e.g., Radeloff et al. 2018; Tang et al. 2025).

5 | Needs for Future Work

5.1 | Capturing Post-Wildfire Groundwater Response

The empirical knowledge base of groundwater response to wildfire is growing, but still lacking in overall data coverage, post-wildfire monitoring duration, direct pre- and post-wildfire measurements of groundwater recharge, auxiliary measurements of cryospheric components (where applicable), groundwater chemistry measurements, and consistent observational approaches. Key ideas for expanding the knowledge base through monitoring are summarized in Figure 3A.

Post-wildfire groundwater responses evolve over time with vegetation recovery and soil hydrophobicity degradation; monitoring approaches could take this temporal component into consideration when designing sampling campaigns. Efforts to sample with less frequency than during the first year after fire but over a long duration (5–10 years) can be helpful in improving post-wildfire assessments. Short-term funding availability coupled with added pressure to publish on early-career researchers in particular fuels a systemic dynamic that is not conducive for such long-term studies.

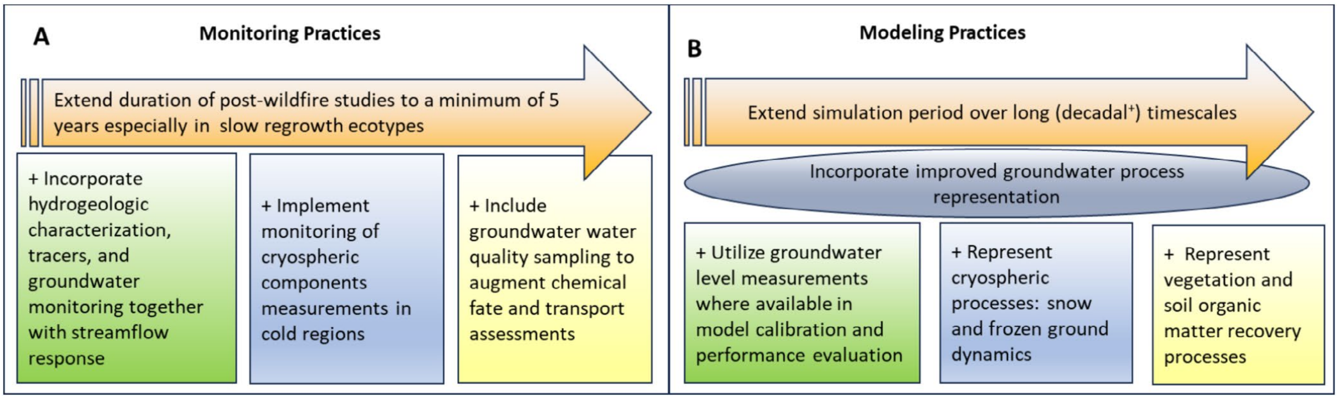

FIGURE 3 | Summary of needs for monitoring (A) and modeling (B) in post-wildfire studies to better capture groundwater response.

Overall, there is a current deficiency of information on changes in water table elevation in response to wildfire (Table 1). Where available, groundwater monitoring sites are typically far downgradient of fire-affected headwaters, which introduces ambiguity in tying groundwater responses to fire-induced water balance shifts in recharge areas. Definitive understanding of groundwater response to wildfire requires expanded well and piezometric data that may be complemented with environmental tracers and non-invasive geophysical techniques for groundwater change detection (e.g., Cardenas and Kanarek 2014; Atwood et al. 2023). Developing the use of fire tracers, or compounds that form during plant matter burning, may be a fruitful direction for characterizing post-wildfire recharge, though microbial degradation of some pyrolysis products through thick unsaturated zones may limit this technique (Silberstein et al. 2013). Mechanisms of preferential flow that may be invoked or enhanced in post-wildfire settings are understudied yet potentially important processes for increasing groundwater recharge and storage that warrant further study.

Though comparison of pre- and post-wildfire low flow and baseflow analyses using streamflow records can provide insight on groundwater response integrated over burned watersheds, most studies are conducted in the absence of subsurface data at appropriate depths to fully investigate mechanistic processes responsible for observed changes. Interpretations that rely on streamflow records pre- and post-wildfire could be enhanced through the incorporation of strategic groundwater monitoring and subsurface characterization efforts.

The effects of wildfire on snow accumulation and melt are an area of active research (Smoot and Gleason 2021; Kampf et al. 2022), and how these effects translate to potential changes in groundwater recharge and discharge (baseflow) is not well known. Even less studied are the intertwined effects of snow and frozen ground on groundwater in wildfire-affected landscapes. Useful monitoring of cryospheric components includes water and energy measurements of snowpack together with seasonally frozen ground temperature and soil moisture estimates through direct borehole measurements and non-invasive geophysical techniques (e.g., Minsley et al. 2016; Rey et al. 2021).

Groundwater pathways pose a risk for prolonged contaminant loading to streams following wildfire. Yet, few examples of post-wildfire groundwater chemistry studies exist. Building on post-wildfire water quality monitoring recommendations described by Murphy et al. (2023), groundwater quality monitoring can serve as a bridge for tracing and predicting near-surface contaminant (source) to stream (sink) transport.

To help address in situ pre- and post-wildfire measurement limitations, satellite data, including optical and thermal imaging (Moreno et al. 2020), radar (Hrysiewicz et al. 2023), and gravitational measurements (Cui et al. 2023) could offer additional insight into the groundwater response. Direct approaches are currently underdeveloped due to limitations in depth of interrogation and spatial resolution; satellite data tend to be shallower and coarser than needed for detecting localized subsurface hydrologic change. However, satellite-based methods for estimating water balance components, including ET and snow, can be useful for inferring post-wildfire changes in recharge (Poon and Kinoshita 2018; Ma et al. 2020). In addition, advances in remote sensing techniques, including airborne and UAS methods for more directly capturing subsurface hydrologic change, may pave the way for more prolific and efficient research on the topic of post-wildfire groundwater response.

5.2 | Post-Wildfire Groundwater Modeling

Physically based distributed hydrologic modeling applications to simulate the effects of wildfire tend to ignore groundwater processes or represent groundwater dynamics in a simplified way. In a review of such relevant model applications, Ebel et al. (2023) identified only 16% (33 of 206) that included groundwater flow (baseflow) as a mechanism for streamflow generation. Of these applications, none utilized groundwater levels as a basis for model calibration or performance evaluation. In most model applications, recharge is estimated as a water balance residual that is instantaneously routed to the adjacent stream as baseflow. However, more robust integrated modeling approaches for evaluating post-wildfire hydrologic response that include groundwater processes have been conducted, offering a foundation for additional applications and hypothesis testing. For example, Maina and Siirila-Woodburn (2020) use ParFlow-Community Land Model (CLM), a physics-based subsurface model with fluid flow and energy transport coupled to a land surface model to simulate the complex interactions between vegetation, snow, and subsurface hydrology in response to post-wildfire land coverage changes. The approach identified counterintuitive feedbacks and variations in groundwater storage response to wildfire in a California test basin. Results from Maina and Siirila-Woodburn (2020) show non-uniform increases in snow accumulation and overall increases in groundwater storage. Atchley et al. (2018) also use ParFlow-CLM to explore the integrated surface and subsurface hydrologic response to fire guided by data from the 2011 Las Conchas Fire in New Mexico, US. Results demonstrate a high sensitivity to burn severity underscoring the importance of the parameterization schemes used to invoke fire effects. In a review of post-fire recharge modeling, Guzmán-Rojo et al. (2024) further emphasized hydrologic parameterization commensurate with fire severity with relevance to recharge. They noted highly sensitive hydrologic parameters to recharge include curve number and saturated hydraulic conductivity, while leaf area index and albedo presented moderate and low impact on long-term recharge, respectively.

Because of the long timescales of interest for groundwater response to wildfire, modeling approaches that account for ecosystem recovery processes such as vegetation regrowth (Partington et al. 2022) and the regeneration of near-surface organic matter, of particular importance for systems undergoing seasonal freezing due to the thermal properties of organic matter, will be particularly useful. Understanding snow dynamics and subsurface freeze/thaw processes in influencing the groundwater response to wildfire are also areas ripe for further exploration using modeling approaches (Figure 3B) in conjunction with enhanced monitoring described in the previous section.

5.3 | Considerations for Change Detection and Attribution

Though currently limited by pre- and post-wildfire groundwater-relevant data availability, some large-scale aggregated efforts have been made to broadly characterize groundwater response to wildfire with some attention toward attribution. To overcome the inherent challenges of distinguishing post-wildfire effects from those derived from interannual climate variability and long-term trends in climate, several methods of analysis applied to streamflow and meteorological records have been proposed and applied (e.g., Beyene et al. 2021; Williams et al. 2022; Wine et al. 2018). Still, limitations exist that include accounting for lags in wildfire-induced hydrologic response, anthropogenic alterations to the natural system, and additional complexity in seasonal weather variations. Analyses that use auxiliary temporal data records to infer groundwater response to wildfire have also been shown to be data limited. For example, the paired air water temperature study by Rey et al. (2023) was constrained to western US sites with pre and post fire seasonal stream temperature records to evaluate against local seasonal air temperature. As a result, only 17 sites met the data record criteria. Ongoing expansion of stream temperature monitoring may help expand the utility of paired air water temperature approaches for characterizing groundwater response to wildfire.

Process-based hydrologic modeling and process-guided machine learning hold tremendous promise to parse out the predominance of different hydrologic processes contributing to groundwater recharge and baseflow following wildfire. Modeling studies that incorporate subsurface processes and groundwater have produced important insight on primary drivers of post-wildfire hydrologic response (e.g., Ebel 2013b; Ebel et al. 2016; Atchley et al. 2018; Maina and Siirila-Woodburn 2020). Groundwater responses in post-wildfire process based hydrologic modeling have not been prioritized, however, as studies have focused more on immediate post-wildfire hazard modeling emphasizing surface runoff responses (Ebel et al. 2023). Model-based numerical experiments allow examining testable hypotheses to quantify the relative importance of hydroclimatic, pyrologic, ecologic, and hydrogeologic factors to fill in knowledge gaps remaining from observation-based studies. Modeling approaches also provide a basis for assessing how groundwater dynamics may evolve with climate change and enhanced wildfire activity. Combined wildfire and climate effects could enhance the potential for vegetation type conversion, such as from forest to shrubland to grassland, favoring a positive recharge response (Collar et al. 2023). Wildfire-induced effects on groundwater quantity and quality tend to be localized, but with projected expansion of the wildfire footprint, such effects may become more widespread and regionally important to water supply (Bladon et al. 2014; Nunes et al. 2018). Expected hydroclimatic shifts toward “wet gets wetter, dry gets drier” (e.g., Meixner et al. 2016) may widen the disparity observed in groundwater responses to wildfire and recovery times given the strong influence of aridity (Goeking and Tarboton 2022).

5.4 | Testable Hypotheses

Efforts specifically designed to evaluate the groundwater response to wildfire are not common in post-wildfire hydrologic response studies. Yet, this review identified a number of studies that have focused on quantifying post-wildfire subsurface hydrologic response including changes in groundwater recharge, storage, baseflow, and low flow. Though some consistent relationships emerge, considerable spatiotemporal variability excludes a one-size-fits-all conceptual model for the groundwater response to wildfire. The low number, minimal spatial coverage, and short durations of such studies preclude a detailed empirical investigation into all plausible factors controlling observed variability. In light of these limitations, we provide a list of hypotheses aligned with the synthesis described in Table 2 and summarized in Figure 4, as a basis for developing a comprehensive paradigm for the groundwater response to wildfire with an emphasis on intermediate (2–10 year) post-fire timescales. The list is roughly ordered from most to least well-established concepts in the current literature. A common thread is the importance of the pre-wildfire groundwater regime in imparting critical context for expected groundwater response and/or wildfire recovery.

Post-wildfire groundwater response hypotheses:

- Climate (most importantly precipitation regime, aridity, water/energy synchrony, and interannual variability) plays a determining role in groundwater response to wildfire. Asynchrony between water inputs and atmospheric demand (such as found in a Mediterranean dry summer/wet winter climate) raises the likelihood of an increased groundwater (recharge, storage, or baseflow) response to wildfire. In contrast, systems subject to relatively synchronous water and

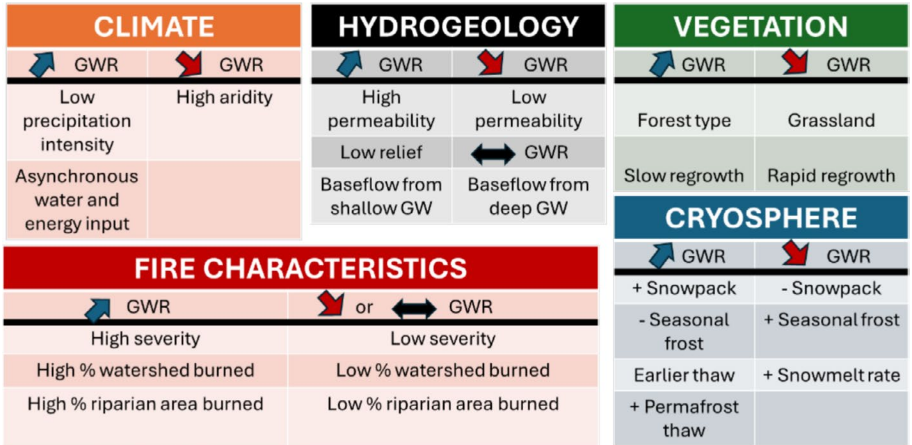

FIGURE 4 | Summary of variables within the five critical categories that have been linked to increased (blue up arrow), decreased (red down arrow), and neutral (black bi-directional arrow) groundwater response (GWR) in the available literature.

energy input experience minimal or reduced groundwater response to wildfire due to compensatory uptake processes. High aridity reduces the magnitude of water balance shifts and consequently suppresses groundwater recharge shifts or even reduces baseflow contributions. Annual variations in aridity may be more important than long-term climate averages for determining the groundwater response to fire, commensurate with findings for post-wildfire watershed yield (Goeking and Tarboton 2022; Biederman et al. 2022).

- An increased groundwater recharge response to wildfire is expected in settings with subsurface conditions that favor high rates of percolation through the vadose zone, such as deep permeable soils and systems prone to preferential flow.
- Decreased baseflow response to wildfire is expected in conditions that favor rapid vegetation regrowth post-wildfire of the same vegetation type present before the fire (e.g., low severity burn scars; grasslands; resprouting vegetation) and compensatory uptake (e.g., low riparian area burn percentage, low burn area fraction). In contrast, increased baseflow responses are expected in conditions of post-wildfire vegetation type conversion from forest to shrub or grass vegetation types.
- Pre-wildfire groundwater-stream connectivity serves as an important determinant for the post-wildfire baseflow response. Specifically, a detectable increase in shallow groundwater discharge to streams is most likely to occur in systems with minimal pre-wildfire groundwater influence. In contrast, watersheds with strong pre-wildfire groundwater influence are buffered from changes in baseflow and/or source water contributions.
- A positive (increased) groundwater response to wildfire is expected in watersheds with considerable high severity burned area.
- A positive (increased) groundwater response to wildfire is expected in snow-dominated systems that favor greater snow accumulation (reduced interception prevails over changes in energy balance), earlier melt, and reduced seasonally frozen ground, whereas a negative (decreased) response is expected in snow-dominated systems that favor reduced snow accumulation (net positive shortwave radiation balance prevails over reductions in canopy interception), faster melt rate, and enhanced seasonally frozen ground.
- A positive (increased) groundwater and baseflow response to wildfire is expected in settings with underlying permafrost resulting from thaw-induced opening and expansion of groundwater pathways.
- Pre-wildfire ecohydrological conditions, specifically water table depth relative to vegetation rooting depths and drought stressors, influence water balance recovery times from wildfire, thus affecting groundwater. Drought conditions will slow post-wildfire recovery rates most notably in non-forested vegetation with shallow rooting structures, favoring increased recharge.
- Seasonal freeze/thaw processes influence post-wildfire recharge response. Areas that undergo seasonal soil freeze/thaw and catchments with high soil moisture will show shortened effects of fire-enhanced soil hydrophobicity relative to areas with soils that do not undergo seasonal freeze/thaw. As a result, fire-affected areas in cold regions with relatively wet soils are not expected to show a wildfire-induced decrease in recharge that persists beyond the first winter post fire. Furthermore, enhanced post-fire early season snow accumulation insulates soils and reduces the likelihood of seasonal frozen ground as an inhibiting agent of snowmelt infiltration, thereby increasing winter–spring recharge.

6 | Conclusion

As demonstrated by the studies highlighted here, wildfire can have varied effects on groundwater recharge, storage, and baseflow. Many observational studies reporting on groundwater response extend for just 2 years or less post wildfire due to funding limitations and pressure to publish early, though it is recognized that longer studies would be beneficial. Fire-enhanced soil water repellency diminishes over the first year or two following fire, resulting in reduced infiltration impedance. The corresponding effect on groundwater hydrology could result in a short-term post-wildfire reduction in recharge that may be reversed over time in response to reduced canopy interception and evapotranspiration prior to vegetation recovery.

Efforts to address spatiotemporal variability in the groundwater response to wildfire are ripe for extended investigation. Pre-fire regional (climate, vegetation) and local (hydrogeologic) conditions together with wildfire characteristics are thought to mediate groundwater responses, yet precisely how these multi-scale interactions play out over time in different settings and geographic areas, including those influenced by cryospheric processes, is not well characterized. More post-wildfire measurements of groundwater levels are a clear need to improve understanding of groundwater effects from wildfire especially in areas with existing pre-fire groundwater data. Some promising methods of analysis that can also be used to determine groundwater response to wildfire across large scales and heterogeneous landscapes include: (1) tracer-based approaches such as water isotopes, geochemical indicators, and paired air and water temperature analyses; (2) time-lapse geophysical characterization; (3) process-based and process-guided modeling. Currently, data availability constrains the full potential of these methods. Because of the important implications for vegetation recovery rate and low flow conditions, water temperatures and water quality in groundwater-influenced streams, it is imperative to better understand groundwater response to wildfire. Collective hypotheses offer a path forward for advanced conceptualization on this topic.

Author Contributions

Michelle A. Walvoord: conceptualization (lead), visualization (equal), writing – original draft (lead), writing – review and editing (lead). **Brian A. Ebel:** conceptualization (equal), project administration (lead), visualization (equal), writing – original draft (equal), writing – review and editing (equal). **Trevor F. Partridge:** conceptualization (equal), writing – original draft (equal), writing – review and editing (equal). **David M. Rey:** conceptualization (equal), writing – original draft (equal), writing – review and editing (equal). **Donald O. Rosenberry:** conceptualization (equal), writing – original draft (equal), writing – review and editing (equal).

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Disclosure

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing are not applicable to this article as no new data were created or analyzed in this study.

Related WIREs Articles

Predicting wildfire induced changes to runoff: A review and synthesis of modeling approaches

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