Journal of Hydrology 602 (2021) 126772

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review papers

Post-wildfire hydrologic recovery in Mediterranean climates: A systematic review and case study to identify current knowledge and opportunities

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ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Edoardo Daly, Associate Editor

Keywords:
Post-fire recovery
Long term
Catchment
Watershed
Burn
Recovery metric

ABSTRACT

Post-fire hydrologic research typically focuses on the first few years after a wildfire, leading to substantial uncertainty regarding the longevity of impacts. The time needed for hydrologic function to return to pre-fire conditions is critical information for post-fire land and water management decisions. This is particularly true in Mediterranean climates, where water is scarce and in high demand, and the severity and area burned by wildfires are increasing. In part, uncertainty about hydrologic recovery is due to lack of a consistent definition or interpretation of what constitutes "recovery." Here, we systematically reviewed empirical studies from Mediterranean climates with at least three years of post-fire hydrologic data with the objectives of (a) assessing the recovery period, (b) identifying a definition of post-fire hydrologic recovery, (c) demonstrating a simple analytical approach to aid in assessment of recovery, and (d) outlining research needs and opportunities to better quantify post-fire recovery. We assessed the hydrologic effects reported in 38 sites that were monitored for 3–20 years. Eighteen sites were considered recovered within seven years; however, the recovery time was inconsistent across sites and was not related to location, response variable, or study design. The likelihood of recovery within the study period also decreased with increasing proportion of the watershed area burned. Importantly, we have also proposed a standardized definition and an approach to quantifying hydrologic recovery that may facilitate cross-study comparisons and a deeper understanding of recovery. Specifically, we propose hydrologic recovery has occurred when a specific post-fire hydrologic function or condition of interest returns to the 95% confidence interval of the pre-fire condition. In support of this definition, we have demonstrated applying this simple approach to assess recovery and presented future research topics to improve our understanding of long-term post-fire catchment responses. In addition to the need for more studies that quantify hydrologic responses farther into the post-fire period, understanding post-fire changes in soil structural and hydraulic properties through time will improve our mechanistic understanding of post-fire hydrologic responses and recovery.

1. Introduction

Wildfire activity, including length of wildfire season, number of fires, area burned, and fire severity, has increased in many areas of the world in recent decades (Abatzoglou and Kolden, 2013; Reilly et al., 2017). These rising trends are projected to continue in some regions due to climate change, increasing population, and fire suppression activities (Flannigan et al., 2013; Moritz et al., 2012). Concurrently, there have been growing concerns about the economic, social, and environmental impacts of increasingly severe wildfires (Bowman et al., 2017; Schoennagel et al., 2017; Stevens-Rumann et al., 2018). Deficiencies in the literature exist concerning the magnitude, extent, and longevity of effects from wildfire on water supplies (Bladon et al., 2014; Hallema et al., 2018a; Heath et al., 2014; Leonard et al., 2017; Mirus et al., 2017; Murphy et al., 2015; Rhoades et al., 2019b). The importance of addressing these knowledge deficiencies is critical due to increased fire activity in many regions that have concurrently experienced substantial declines in both water quantity and quality (Bladon, 2018; Martin, 2016; Nunes et al., 2018). As such, several studies have noted the need to include fire in local, regional, and global assessments of catchment vulnerability to the effects of disturbances on hydrologic processes (Kinoshita et al., 2016; Martin, 2016; Robinne et al., 2018, 2021).

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https://doi.org/10.1016/j.jhydrol.2021.126772
Received 16 April 2021; Received in revised form 14 July 2021; Accepted 28 July 2021
Available online 2 August 2021
0022-1694/Published by Elsevier B.V.

A growing number of studies have investigated the effects of wildfires on water quantity, water quality, aquatic ecology, and downstream drinking water supply (e.g., Hallema et al., 2018b; Kinoshita et al., 2014; Loiselle et al., 2020; Moody et al., 2016; Moreno et al., 2020; Rust et al., 2018). Many have shown that soil hydraulic properties and runoff generation mechanisms may be altered by wildfire (Ebel and Moody, 2017; Ebel et al., 2016), leading to increased annual water yields, low flows, and peak flows for several post-fire years (Blount et al., 2020; Hallema et al., 2017a; Saxe et al., 2018) or even decades (Brookhouse et al., 2013; Kuczera, 1987; Niemeyer et al., 2020). Moreover, exposed mineral soils are highly susceptible to hillslope erosion or debris flows, which deliver sediment and other contaminants from burned hillslopes to streams (Nyman et al., 2020; Sheridan et al., 2016; Wagenbrenner and Robichaud, 2014). Combined, these and other post-fire changes in source water quantity and quality have the potential to propagate long distances downstream, impacting aquatic ecosystem health and creating substantial challenges for drinking water treatment (Chow et al., 2019; Emelko et al., 2011, 2016; Hohner et al., 2019).

Many studies have shown a peak in hydrologic impacts during the first several years after wildfire (i.e., initial response), followed by a decline at varying rates before returning to the pre-fire condition or some alternate stable state (Ebel, 2020; Ebel and Mirus, 2014; Greenbaum et al., 2021; Noske et al., 2016; Vieira et al., 2016). The longevity and trajectory of the recovery curve may be influenced by a range of factors, including fire severity, disturbance history, post-fire land management, catchment physiography, vegetation composition and regrowth, soils, geology, climate, and weather during the post-fire years (Prats et al., 2016; Vieira et al., 2015; Wittenberg and Inbar, 2009) (Fig. 1). In particular, burn severity is often considered a key control on the magnitude of post-fire hydrologic responses (Keeley, 2009; Moody et al., 2016; Vieira et al., 2015). Similarly, post-fire precipitation is another important control on hydrologic responses from burned areas, often explaining much of the variability in local responses (Benavides-Solorio and MacDonald, 2005; Hallema et al., 2017b; Moody and Martin, 2001; Murphy et al., 2015; Wu et al., 2021). Other important controls on downstream processes include the proportion of catchment burned (Bart, 2016; Hallema et al., 2018b) and the regrowth of vegetation, which often is related to the regeneration mechanism (i.e., seeding versus resprouting) and post-fire weather patterns (Keeley, 1992; Keeley and Zedler, 1978; Kinoshita and Hogue, 2011; Niemeyer et al., 2020). Evidence also shows that the recovery trajectory may be altered by the resiliency of the ecosystem in the face of increasing wildfire activity (Scheffer et al., 2001; Schoennagel et al., 2017).

The vast majority of studies investigating the effects of wildfire on water quantity or quality have focused on the initial (<5 years) effects (e.g., Florsheim et al., 2017; Saxe et al., 2018; Silins et al., 2014; Smith et al., 2012). Comparatively few studies have investigated the longer-term effects of wildfire (Rhoades et al., 2019a), despite clear evidence of the essential value of long-term research (Laudon et al., 2017; Tetzlaff et al., 2017). Further, few datasets include pre- and post-fire hydrologic responses from hillslopes or small catchments for periods long enough to statistically assess longer-term post-fire responses. Thus, the longevity of post-fire hydrologic effects is uncertain, which hinders prediction of catchment processes during the post-fire recovery period and longer-term post-fire management.

Recent assessments of global wildfire risks to water security indicate that some of the most vulnerable cities (e.g., Cape Town, Haifa, Istanbul, and San Francisco) are located in Mediterranean climates (Robinne et al., 2018, 2016). Additionally, because water demand often exceeds available resources due to tremendous variability in annual and seasonal precipitation (Dahm, 2010; Gasith and Resh, 1999; Iglesias et al., 2011; Kondolf and Batalla, 2005), many regions with Mediterranean climates rely on dams and water conveyance infrastructure (Conacher and Sala, 1998; Kondolf and Batalla, 2005; Thoms and Sheldon, 2000), which may be negatively impacted by elevated post-wildfire sediment yields (Murphy et al., 2018). Post-fire hydrologic responses in Mediterranean climates generally result from long-duration cyclonic or frontal systems, where periods of high intensity precipitation can lead to overland flow. These responses contrast with drivers or responses in other fire-dominated climate regimes, such as convective precipitation in areas with warm continental climates (Saxe et al., 2018; Wilson et al., 2018) or the impacts of fire on subsurface flow in areas with boreal climates and permafrost (Ebel et al., 2019; Koch et al., 2014; Walvoord et al., 2019). Additionally, a relatively large portion of post-fire hydrologic research has occurred in Mediterranean climates, which provides an opportunity to combine the results from experiments with similar climates and vegetation to identify commonalities.

Quantifying the legacy impacts of wildfire also remains challenging due to varying definitions of recovery. Thus, there is a critical need to clarify the concept of post-fire hydrologic recovery and apply more rigor in testing whether post-fire responses have recovered to improve models and predictions for post-fire land and water management decisions. Our working theory is that the post-fire response, measured as a departure from the pre-fire range of variability, would return to the pre-fire condition within a predictable period constrained by some distribution of natural variability (Fig. 1). This theoretical recovery period may differ by the hydrologic process of interest, such as runoff generation, transpiration, or rainfall interception. Regardless of parameter of interest,

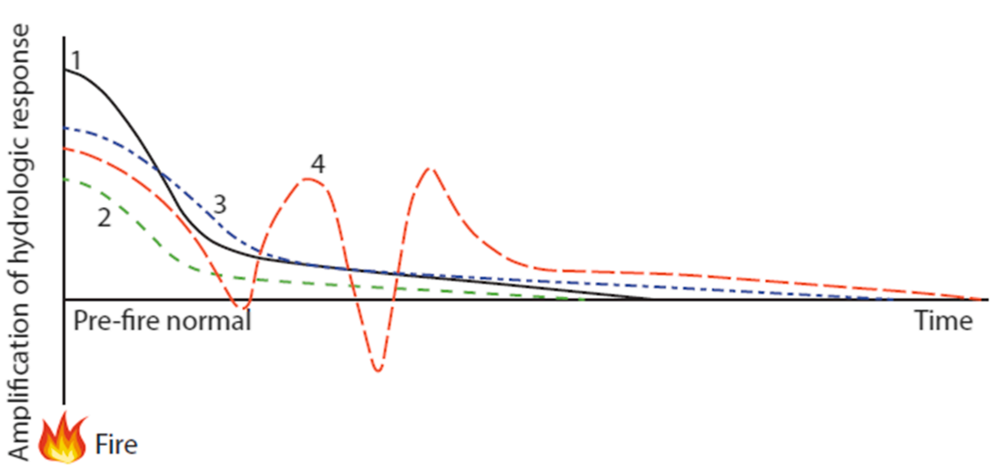

Fig. 1. Possible distribution of amplification of post-fire hydrologic responses during recovery period, showing conceptual magnitudes relative to pre-fire: (1) completely and uniformly burned at high severity and post-fire weather similar to climate during the pre-fire normal period; (2) incompletely burned at varying severity and post-fire weather similar to climate during the pre-fire normal period; (3) completely and uniformly burned at high severity, but post-fire weather is drier than climate during the pre-fire normal period resulting in slower vegetation regrowth, smaller magnitude of responses and extended recovery relative to (1); and (4) completely and uniformly burned at high severity, but post-fire weather is more variable than for the pre-fire normal period. Some responses of interest would be greater than the pre-fire norm (e.g., annual runoff or storm peak discharge), while others would produce negative relative responses (e.g., transpiration or infiltration capacity). (Available in color online).

we hypothesize that the dominant controls on post-fire recovery rates are burn severity, precipitation timing and magnitude, and vegetation regrowth—and that these factors can lead to a wide range of possible post-fire recovery trajectories (Fig. 1). We further hypothesize that with enough information about post-fire responses across a range of fire severity and post-fire weather and vegetation conditions, the recovery period can be predicted with reasonable accuracy.

Our goal was to identify and summarize past research in Mediterranean climates that could provide a sufficient level of information to quantify the likely range of post-fire recovery periods to aid post-fire management and research. Specifically, we evaluated empirical studies in Mediterranean climates to meet the following objectives: (a) synthesize results from longer-term post-fire hydrologic studies to assess the recovery period and bound the recovery timescale, (b) identify a common definition of post-fire hydrologic recovery to unify terminology, (c) demonstrate a simple analytical approach to aid in assessment of recovery across diverse catchment conditions and research or monitoring objectives, and (d) outline research needs and opportunities to better quantify and predict post-fire recovery. We focused on studies addressing surface water quantity and sediment delivery. However, the general recovery framework and principles of analysis presented here are extensible to other physical and chemical water quality metrics.

2. Materials and methods

2.1. Site characteristics

Due to the dominant influence of temperature and precipitation regimes on vegetation composition and productivity (Bailey, 1989), as well as the potential for similarities in hydrologic response and recovery (Hallema et al., 2018b), we have focused our analysis on climate type rather than ecoregion or location. Our review focused on areas with Mediterranean climates as characterized by the Köppen-Geiger classification system (Fig. 2). All three Mediterranean climates are described as temperate with dry summers and wet winters—the driest summer month produces <40 mm of precipitation and less than one-third of the precipitation of the wettest winter month (Peel et al., 2007). The Csa class has hot dry summers with maximum mean monthly temperature (T_{max}) greater than 22 °C during at least one month and all months with a mean monthly temperature above 0 °C. The Csb class has warm summers with $T_{max} < 22$ °C during all months, at least four months with a mean temperature of at least 10 °C, and all months with a mean monthly temperature above 0 °C (Peel et al., 2007). The third class (Csc) is for cold summers, where between one and four months have mean temperature of at least 10 °C, but this class is much less prevalent and was not included in our review. These climate conditions generally occur between 30° and 40° latitude (Lionello et al., 2006), extending to about 49° north latitude in western North America (Peel et al., 2007). More than half of the land area with Mediterranean climates is located in the Mediterranean Basin, with other major regions in southwestern Australia, Chile, the Cape of South Africa, and California in the U.S. (Dahm, 2010) (Fig. 2).

Although Mediterranean climate regions are geographically separated, climate-driven convergence in ecosystem structure and dynamics creates similarities in vegetation across these regions. Highly flammable sclerophyllous shrublands with regional names of maquis (Mediterranean Basin), chaparral (California), matorral (Chile), fynbos (South Africa), and mallee and kwongan (Australia) (Christensen, 1985; Syphard et al., 2009) are adapted to hot, dry summers. These systems generally support crown fires yet are resilient in terms of regrowth (Christensen, 1985; Naveh, 1975; Syphard et al., 2009).

The regions with Mediterranean climates host relatively large proportions of the world's population, tourism trade, gross domestic product per capita, and Earth's flora (Cowling et al., 1996; De Stefano, 2004; Mellinger et al., 1999), despite only covering 1.5% of the global land area (Blondel et al., 2010). The precipitation seasonality in these regions increases fire frequency (Archibald et al., 2013), and when combined with the relatively high population densities and resultant increased human ignitions (Montenegro et al., 2004; Pausas et al., 2008; van Wilgen et al., 2012), have led to increased wildfire occurrence and severity in recent decades (Bowman et al., 2017; Moritz et al., 2014).

2.2. Literature search

We focused our literature review on English-language, post-wildfire, hydrologic studies in regions with Mediterranean Köppen-Geiger Csa (hot dry-summer) or Csb (warm dry-summer) climate classifications (Peel et al., 2007). We combined prior knowledge of the literature with

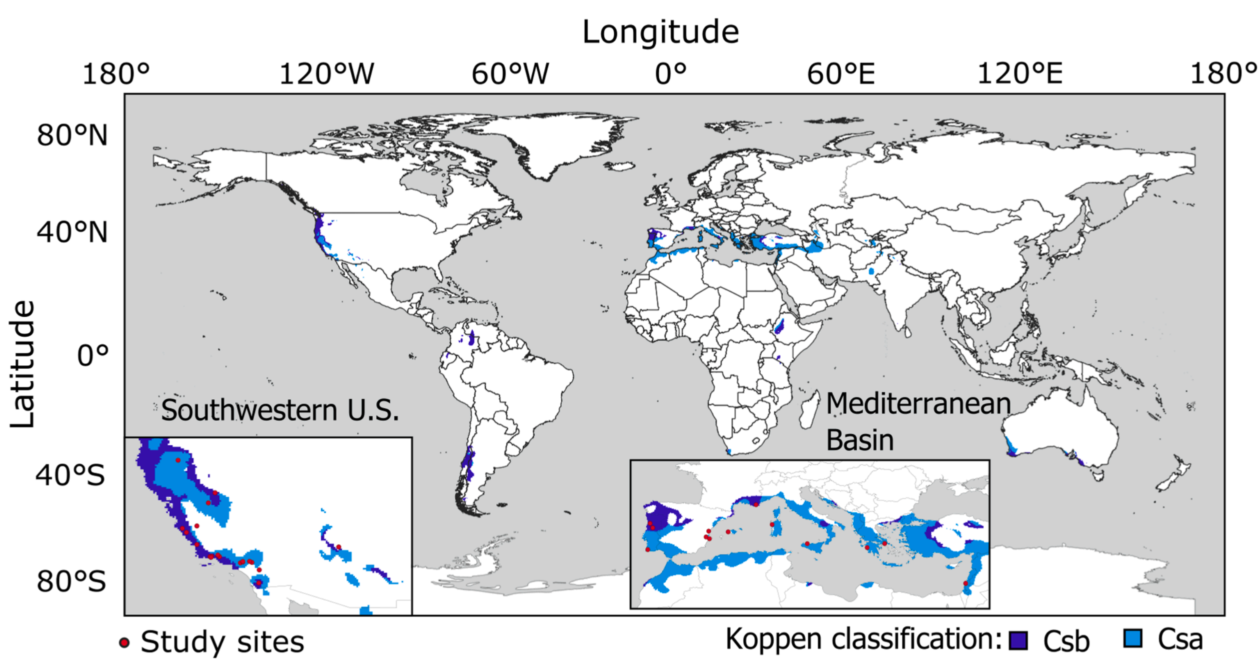

Fig. 2. Regions with Mediterranean (Köppen-Geiger Csa and Csb) climates and studies used in this systematic review. Data are from Peel et al. (2007). (Available in color in print and online).

systematic searches of databases to identify empirical studies that included at least three years of post-fire, field-based hydrologic observations. We also reviewed citations in identified articles to expand our literature search. Our search terms in Georef, Scopus, Web of Science, and Google Scholar included either "*fire" or "burn*" combined with "recovery", "hydrolog*", "runoff", "catchment", "discharge", "flow", or "water*". The asterisk (*) was used as a wildcard search character to include word fragments in a single search. We screened the articles and government reports available through January 2021 and included them if the study: (a) included sites affected by wildfire; (b) was located in a Csa or Csb climate; (c) quantified a hydrologic response, including runoff, evapotranspiration, infiltration, erosion, sediment delivery, or sediment concentration; (d) measured responses at the plot (<1–10 m^2), hillslope (10–5000 m^2), or catchment (>5000 m^2) scales; and (e) included at least three years of post-fire data.

We recorded the latitude, longitude, fire year, post-fire study duration, measurement types and spatial scales, soil texture, pre-fire vegetation, and the proportion of the experimental unit or catchment burned for each included study. We also recorded the burn severity classification when it was provided or when it could be assessed through the Monitoring Trends in Burn Severity data (Monitoring Trends in Burn Severity, 2019). We either retained the climate classification provided in the article, or, when no classification was provided, we used the approximate location and local climate maps (e.g., http://stepsa.org/climate_koppen_geiger.html) to assign one. For global consistency, we mapped the study locations using the climate classifications from Peel et al. (2007) (Fig. 2). We also recorded the stream order and whether the stream was perennial, intermittent, or ephemeral when provided in the articles or the classification could be determined by the location and Google Earth imagery (Google LLC, 2020).

In some cases, the original authors had indicated recovery; however, recovery was not assessed explicitly in most of the studies. For consistency, we assessed the state of recovery for the main hydrologic response variable using data presented in each original study and the same criteria. We classified the recovery of each study using one of the following criteria, depending on the available data: (a) before-after (BA) when pre-fire data were included and the post-fire response returned to the pre-fire condition; (b) control-impacted (CI) when an unburned reference condition was included and the response in the burned site was similar to the response in the unburned site; or (c) hypothetical (H) when no unburned reference data were provided and the post-fire variable of interest attained a zero response (i.e., equivalent to pre-fire response). In cases where published data and statistical analyses allowed more rigorous assessment, we used those results. In most cases such analyses were not available, which necessitated using the hypothetical criterion as it was the simplest and most conservative criterion we could apply among the diverse studies.

When a single publication discussed post-fire responses at multiple sites (e.g., Bart and Hope, 2010; Kinoshita and Hogue, 2011) or from multiple conditions, such as different vegetation types (e.g., Cerdà and Doerr, 2005; Hubbert et al., 2012), the multiple sites or conditions were treated independently. Some articles covered the same site over different periods or used different analyses (e.g., Cosandey et al., 2005; Folton et al., 2015; Lebedeva et al., 2014); we treated those cases as a single study.

Given the immense variability in spatial scale among the identified studies—over 10 orders of magnitude—we did not compare the studies in absolute terms. Also, because of the different time steps used in the studies, we did not attempt to normalize results by annual precipitation or some other index. Rather, we examined site factors for similarities as an explanation for whether the sites recovered or not.

2.3. Post-fire hydrologic recovery metrics and case studies

Hydrologic recovery following either natural or anthropogenic disturbance has been defined as the restoration of pre-disturbance hydrologic characteristics such as interception, evapotranspiration, or streamflow to near pre-disturbance conditions (Buttle et al., 2018; Hudson, 2000). Moreover, assessment of recovery depends on the specific process, output, temporal and spatial scales, and application or objective (e.g., aquatic habitat, flood protection, recreation, or community drinking water supply). These different factors complicate the assessment of recovery, yet the complexity can be reduced by metrics that simplify analysis.

Although many possible metrics exist, we suggest metrics that could be useful to various end-users interested in post-fire hydrologic recovery, grouped in Table 1 by potential use: water supply, water-related hazard, infrastructure, and ecological habitat. We used longer-term datasets of pre- and post-fire precipitation and discharge from City Creek, California, U.S. (Kinoshita and Hogue, 2015) and the Rimbaud catchment in southern France (Lavabre et al., 1993) to demonstrate the utility of metrics in assessing recovery. The October–November 2003 Old Fire burned approximately 87% of the City Creek catchment (50.8 km^2), including 13% at high severity and 57% at moderate severity (Kinoshita and Hogue, 2015). Daily precipitation data (#2860; San

Table 1
A brief description and relevant temporal scale(s) of analysis of metrics for assessing post-fire hydrologic recovery. Metrics are grouped by possible uses.

Metric	Description	Temporal scale(s)
Water Supply		
Runoff ratio	$\frac{Q}{P}$ where Q is a measure of streamflow and P is a measure of precipitation	Annual, storm
Baseflow or low flow	Q_{90}, the discharge with 90% exceedance probability estimated from a flow duration curve	Annual, seasonal
Snow accumulation	Total snow pack	Seasonal
Snow melt rate	$T_{maxsnow} - T_{minsnow}$, the difference in time between the max. and min. snowpack	Seasonal
Bedload, suspended, or total sediment load	Sediment carried in stormflows	Annual, storm
Water-Related Hazard		
Flood peak	$\frac{Q_{pk}}{X}$, where X is a measure of precipitation intensity or snow melt rate and is used to account for differences in intensity	Annual, storm
Slope of rising limb	$\frac{\Delta Q}{\Delta T}$, where ΔQ and ΔT refer to differences in discharge and time, respectively, between start of rise and peak	Storm
Slope of falling limb	$\frac{\Delta Q}{\Delta T}$, where ΔQ and ΔT refer to differences in discharge and time, respectively, between peak and end of stormflow	Storm
Duration	$T_{baseflow} - T_{rise}$, the difference in time between when discharge returns to base flow and the start of the rising limb	Storm
Ecological Conditions		
Time of peak	$T_{pk} - T_{rise}$ the difference in time between the peak discharge and the start of the rising limb. A measure of the time of concentration.	Annual, storm
High flows	Q_{10}, the discharge at 10% exceedance probability estimated from a flow duration curve	Annual
Median streamflow	Q_{50}, the median discharge estimated from a flow duration curve	Annual
Duration of low flow	Number of days with no flow or flow below a critical threshold	Annual
Slope of flow duration curve	Change between Q_{10} and Q_{90}	Annual
Stream temperature	Average stream temperature	Daily, seasonal

Bernardino County, 2018) and hourly discharge data (#11055800; U.S. Geological Survey, 2018) were obtained for water years (1 Oct–30 Sep) 1989–2017. Comparatively, a fire occurred in the Rimbaud catchment (1.46 km^2) in August 1990, burning approximately 85% of the catchment at unspecified severity (Lavabre et al., 1993). We obtained hourly precipitation and discharge data for water years 1968–2010 (N. Folton, Institut National de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture, personal communication, 14 May 2018). For statistical analysis, we used water years 1989–2003 for City Creek and 1968–1990 for the Rimbaud catchment for the pre-fire periods.

We calculated several metrics for the pre- and post-fire periods: runoff ratio, slope of the flow duration curve using an exponential fit, and flows that were exceeded 90% (Q_{90}, low flow) and 10% of the time (Q_{10}, high flow) (Table 1). We also calculated the proportion of time with no flow at Rimbaud, which had intermittent streamflow. The runoff ratios were calculated on annual timescales (water years) and the other metrics were calculated using hourly time steps consistent with the temporal resolution of the discharge data. We removed observations when there was no flow for the frequency analyses—this was more common at the Rimbaud catchment given its smaller size and intermittency. We also excluded data from Rimbaud when more than 10% of the observations were missing (water years 1986 and 2000–2002).

We applied relatively simple statistics to assess hydrologic recovery using the selected metrics with the intent that a more accessible approach would increase the utility for a diverse group of users. We calculated 95% confidence intervals for the pre-fire metrics, assuming a *t*-distribution (Helsel and Hirsch, 2002). All the City Creek metrics except the slope of the flow duration curve and the Rimbaud Q_{90} showed some skewness, so these values were $\log_{10}$-transformed before determining the confidence intervals. We then calculated and plotted the metrics from the post-fire period and considered that a state of recovery had been reached if the post-fire metrics were within the 95% confidence interval from the pre-fire period.

3. Results

3.1. Systematic review of post-fire hydrologic recovery

Our literature search and screening resulted in 28 studies covering 38 distinct sites that met our criteria for inclusion in our meta-analysis of post-fire hydrologic recovery in Mediterranean climates (Table 2). Study sites were located in the western U.S. (California and Arizona) (23 sites) or the Mediterranean Basin (Spain, Portugal, Italy, Israel, France, and Greece) (15 sites) (Table 2; Fig. 2). Our search also identified studies in South Africa (Bosch et al., 1986; Scott and Van Wyk, 1990) and South America (Morales et al., 2013), but these were not empirical studies with at least three years of observations—thus, they were not included in the meta-analysis. No studies met our inclusion criteria from Mediterranean climates in Australia, the Middle East outside of Israel, Chile, east Africa, or Asia. The studies included in our analysis represented wildfires from 1924 to 2015 with study durations from 3 to 20 years (Table 2).

The soil types in the included studies were mostly coarse-textured, except for four studies with either clay loam or clay soils (Table 3). The dominant pre-fire vegetation in 17 sites was described as one of the sclerophyll shrub communities common in Mediterranean climates (Table 3). One study included a site that had been experimentally converted from chaparral to a grassland four decades before the wildfire (Hubbert et al., 2012). The remaining 20 sites were established in areas where forests or forest plantations were the dominant vegetation type, and these were mostly pine but included other conifers, oaks, and eucalypts. The spatial scale of the study sites ranged from 0.25 m^2 plots, which were used in a rainfall simulation experiment (Cerdà and Doerr, 2005), to a 6000 km^2 region of Greece, which was used to assess the number of floods and debris flows (Diakakis et al., 2017) (Table 3). Only 20 of the 38 study sites provided some measure of burn severity (e.g., Moody et al., 2013; Vieira et al., 2015), but all studies included the fraction of the experimental unit burned (Table 3). Only four of the

Table 2
Studies identified from the systematic review. Abbreviations are: Q = discharge, Q_{pk} = peak discharge, E = erosion, S = sediment delivery, I = infiltration, N = number, B = before, A = after, C = control, I = impacted, and H = hypothetical, indicating no data from unburned condition were available for comparison and we presumed a small value as our recovery criterion. Study numbers followed by letters indicate multiple sites or conditions.

Study	Location	Latitude (°)	Longitude (°)	Fire date (s)	Study dur. (yr)	Reference (s)
United States						
1	California	34.117	−117.900	1924	6	Hoyt and Troxel (1932)
2	California	34.530	−119.690	1932–1933	14	Anderson (1955)
3	California	34.167	−117.750	1960	7	Doehring (1968)
4	Arizona	35.100	−111.800	1972	3	Campbell et al. (1977)
5 a,b,c,d,e,f	California	36.250	−121.500	1977–1985	5	Bart and Hope (2010)
6	California	34.500	−119.783	1990	3	Keller et al. (1997)
7 a,b	California	33.680	−116.730	1999; 2003	6, 4	Robichaud et al. (2008)
8 a,b	California	34.144	117.188	2003	7	Kinoshita and Hogue (2011, 2015)
9 a,b	California	34.200	−117.750	2003	4	Hubbert et al. (2012)
10	California	32.870	−116.760	2003	6	Robichaud et al. (2013b)
11	California	34.460	−119.720	2008–2009	4	Cooper et al. (2015)
12	California	40.469	−121.769	2012	4	James and Krumland (2018)
13	California	38.835	−122.701	2015	5	Cole et al. (2020)
14 a,b	California	37.828	−119.888	2013	4, 5	Olsen et al. (2021)
Mediterranean Basin						
15	Portugal	40.580	8.430	1986	4	Shakesby et al. (1993)
16	Israel	32.733	35.050	1989	4	Inbar et al. (1998); Wittenberg and Inbar (2009)
17 a,b	Spain	38.920	−0.660	1989	11	Cerdà and Doerr (2005)
18	S. France	43.23	6.217	1990	20	Cosandey et al. (2005); Folton et al. (2015); Lebedeva et al. (2014)
19	E. Spain	39.700	−0.300	1993	3	Andreu et al. (2001)
20	Sicily	38.024	13.261	1994	5	Aronica et al. (2002)
21	E. Spain	38.683	−0.200	1998	7	Mayor et al. (2007)
22	Greece	37.500	21.500	2007	9	Diakakis et al. (2017)
23	Portugal	40.146	−7.997	2008	4	Vieira et al. (2016)
24	Portugal	40.730	−8.360	2010	3	Prats et al. (2016)
25	Mallorca	39.604	−2.380	2013	3	García-Comendador et al. (2017)
26	Portugal	37.230	−8.680	2003	5	Wu et al. (2021)
27	Israel	32.733	35.050	2010	6	Greenbaum et al. (2021)
28	Greece	38.037	23.906	2009	5	Soulis et al. (2021)

Table 3
Additional site characteristics of the studies identified in the systematic review. Study numbers are the same as in Table 2, which lists the references.

Study	Location	Area (km^2)	Fraction burned (%)	Spatial scale class [a]	Stream order [b]	Stream type [c]	Soil texture[e]	Predominant vegetation
1	California	17	80	Catchment	3	Quasi-perennial		Shrub
2	California	567	31	Basin	No data	Perennial [d]		Shrub
3	California	4.5	95	Sm. catchment	5	Ephemeral	Sandy loam	Shrub
4	Arizona	0.08	100	Sm. catchment	No data	Ephemeral	Sandy loam	Conifer
5a	California	632	63	Basin	No data	Intermittent		Shrub
5b	California	119	23	Catchment	No data	Intermittent		Shrub
5c	California	54	100	Catchment	No data	Intermittent		Shrub
5d	California	562	31	Basin	No data	Intermittent		Shrub
5e	California	104	71	Catchment	No data	Intermittent		Shrub
5f	California	130	40	Catchment	No data	Intermittent		Shrub
6	California	4.5	89	Sm. catchment	2	Intermittent		Shrub
7a	California	0.01	100	Sm. catchment	1	Ephemeral	Loamy sand	Conifer
7b	California	0.13	100	Sm. catchment	1	Ephemeral	Loamy sand	Conifer
8a	California	50.8	87	Catchment	3	Intermittent	Clay and sandy loams	Shrub
8b	California	14.2	95	Catchment	3	Intermittent	Loamy sand	Shrub
9a	California	0.019	90	Sm. catchment	1-2[d]	Ephemeral[d]	Sandy loam	Shrub
9b	California	0.027	90	Sm. catchment	1-2[d]	Ephemeral[d]	Sandy loam	Grass
10	California	0.015	100	Sm. catchment	1	Ephemeral	Loamy sand	Shrub
11	California	17	71	Catchment	No data	Intermittent		Shrub
12	California	0.005	100	Sm. catchment	0	Ephemeral	Sandy loam	Plantation
13	California	0.000075	100	Hillslope	N/A	Ephemeral	Sandy loam	Conifer
14a	California	0.005	100	Sm. catchment	0	Ephemeral	Loam	Conifer
14b	California	0.002	100	Hillslope	0	Ephemeral	Gravelly loam	Conifer
15	Portugal	0.000016	100	Hillslope	N/A	Ephemeral	Sandy loam	Plantation
16	Israel	0.0002	100	Hillslope	N/A	Ephemeral		Conifer
17a	Spain	0.00000025	100	Plot	N/A	Ephemeral	Loamy sand	Shrub
17b	Spain	0.00000025	100	Plot	N/A	Ephemeral	Loamy sand	Conifer
18	France	1.46	80	Sm. catchment	No data	Intermittent		Forest
19	Spain	0.000025	100	Hillslope	N/A	Ephemeral	Sandy loam	Forest
20	Sicily	76	5	Catchment	4	Unknown		Shrub
21	Spain	0.021	100	Sm. catchment	1	Ephemeral	Silty clay loam	Conifer
22	Greece	6000	30	Region	Varied	Varied		Forest
23	Portugal	0.00000025	100	Plot	N/A	Ephemeral	Sandy loam	Eucalypt
24	Portugal	0.000095	100	Hillslope	N/A	Ephemeral	Sandy loam	Eucalypt
25	Spain	4.8	71	Sm. catchment	3	Unknown		Conifer
26	Portugal	18.5	78[f]	Catchment	3	Unknown		Plantation
27	Israel	18	30	Catchment	3	Ephemeral	Sandy clay loam	Forest
28	Greece	7.8	87	Sm. catchment	3	Unknown	Sandy loam and sandy clay loam	Conifer

[a] Spatial scale classes: <10 m^2 plot, 10–5000 m^2 hillslope, 0.005–5 km^2 small catchment, 5–500 km^2 catchment, >500 km^2 basin. Region covers parts of multiple basins.
[b] "No data" indicates studies with no stream maps. "N/A" means not applicable to hillslope or plot studies.
[c] Stream types, if not classified in original study: perennial—data show year-round flow, quasi-perennial—data show year-round flow. most years, intermittent—regular dry season with no flow, and ephemeral—flow produced only by storms or snow melt.
[d] No data available; classification based on catchment size.
[e] Empty cells indicate insufficient data provided to identify the textural class.
[f] An additional 22% of the catchment was burned at low or unburned severity (J. Wu, personal communication, 20 February 2021).

studies (five sites) provided an estimate of the fire recurrence periods, so this characteristic was not analyzed.

In all but six of the studies (Cole et al., 2020; Diakakis et al., 2017; Doehring, 1968; James and Krumland, 2018; Keller et al., 1997; Olsen et al., 2021), the authors presented some measure of streamflow or hillslope surface runoff (Table 4). Doehring (1968) studied dry ravel and the subsequent evacuation of deposited sediment and downstream sediment delivery by post-fire flows in California's San Gabriel mountains. Four studies (Cole et al., 2020; James and Krumland, 2018; Keller et al., 1997; Olsen et al., 2021) focused on sediment delivery and changes in hillslope or channel morphology, while Diakakis et al. (2017) evaluated the number of floods and debris flows. Of the 33 study sites where streamflow persistence could be assessed, only one site included a perennial stream and one included a quasi-perennial stream (perennial flow in all but the driest years) (Table 3). Eleven of the sites had intermittent streams, and the remaining 20 sites, including the hillslope studies, had ephemeral flow (Table 3). Two studies addressed erosion rates indirectly by reporting rill characteristics (James and Krumland, 2018; Olsen et al., 2021) and two studies reported sediment concentrations (Greenbaum et al., 2021; Wu et al., 2021). None of the studies quantified wildfire effects on evapotranspiration, infiltration, or subsurface flow or storage. Time steps for the studies were mostly annual ($n = 24$), followed by storm based ($n = 9$), monthly or seasonal ($n = 4$), and through a nine-year period ($n = 1$) (Diakakis et al., 2017).

There was no consensus regarding the time to achieve hydrologic recovery across the 38 study sites (Fig. 3). Three of the largest sites (54–104 km^2) (Aronica et al., 2002; Bart and Hope, 2010) identified no post-fire response, so recovery was essentially attained at year zero. Recovery was indicated during the study period at 15 sites, ranging from two to seven years with a mean of 3.8 years and a standard deviation of 1.6 years (Fig. 3).

Among the 20 sites without recovery, the longest study period extended to 11 years after the fire (Cerdà and Doerr, 2005) (Fig. 3). In this case, the authors attributed the lack of recovery to the return of soil water repellency at the soil surface ("inherent" water repellency as described by Scott and Van Wyk (1990)), resulting from pine forest regrowth and reestablishment of the litter layer. The seemingly counterintuitive role of water repellency at this site, which was greater in the

Table 4
Variables and criteria used to assess recovery and our assessment of recovery for the studies identified in the systematic review. Study numbers are the same as in Table 2, which lists the references. "N" indicates the response did not recover during the study duration, "Q" is for discharge, "Qpk" is for peak discharge, "E" is for erosion, "S" is for sediment delivery, "BA" is for before/after, "CI" is for control/impacted, and "H" is for hypothetical, which indicates no data from unburned condition were available for comparison and we presumed a small value as our recovery criterion.

Study	Location	Variables reported	Recovery variable	Criterion	Recovery period (years)
1	California	Q, Q_{pk}	Q	BACI	N
2	California	Q, Q_{pk}, S	Q_{pk}	BA	7
3	California	S	S	BA	N
4	Arizona	Q, Q_{pk}	Q, Qpk	CI	N
5a	California	Q	Q	CI	N
5b	California	Q	Q	CI	2
5c	California	Q	Q	CI	0
5d	California	Q	Q	CI	2
5e	California	Q	Q	CI	0
5f	California	Q	Q	CI	2
6	California	S	S	H	N
7a	California	Q, Q_{pk}, S	Q, S	H	N
7b	California	Q, Q_{pk}, S	Q, S	H	N
8a	California	Q	Q, Q_{90}	BA	N
8b	California	Q	Q, Q_{90}	BA	N
9a	California	Qpk, S	Qpk, S	H	4
9b	California	Q_{pk}, S	Qpk, S	H	4
10	California	Q, Q_{pk}, S	S	H	N
11	California	Q	Q	BA	2
12	California	E,S	S	H	4
13	California	S	S	H	5
14a	California	E,S	S	H	N
14b	California	E,S	S	H	3
15	Portugal	Q	Q	CI	N
16	Israel	Q, S	S	CI	N
17a	Spain	Q, S	Q	CI	3
17b	Spain	Q, S	Q	CI	N
18	France	Q, Q_{pk}	Q	BACI	6
19	Spain	Q, S	Q, S	H	N
20	Sicily	Q	Q	BA	0
21	Spain	Q, S	Q, S	CI	5
22	Greece	N floods[a]	[a]	BA	N
23	Portugal	Q, S	Q, S	H	N
24	Portugal	Q, S	Q, S	H	N
25	Spain	Q, S	Q, S	H	3
26	Portugal	Qpk, S	Qpk	BA	N
27	Israel	Q,Qpk, S	Qpk	BA	5[b]
28	Greece	Qpk	Qpk	BA	N

[a] This study reported the number of floods and the number of debris flows.
[b] This study reported combined results for 4–6 years post-fire. We assigned the value of 5 years for our analysis.

11th year than immediately after the fire, suggests that fire-affected soil water repellency can have a complex effect on post-fire hydrologic responses.

Sites reporting data for annual or longer periods were more likely to indicate recovery (14 of 25 sites) than sites reporting data at storm, monthly, or seasonal resolution (4 of 13 sites) (Fig. 3). Interestingly, sites with shrubs as the dominant vegetation recovered during the study period more often (59% of 17 sites recovered) than sites where trees dominated (37% of 19 sites recovered). Half of the two sites where grasses dominated or there was a mixture of tree, shrub, and grass cover had recovered. When the shrub sites recovered, the median recovery time was two years compared to five years for the treed sites ($n = 7$) and four years for the grass site. In contrast, the median duration of the studies where sites did not recover was six years when shrubs dominated ($n = 7$) and four years where trees, grasses, or a combination of trees, shrubs, and grasses were the dominant vegetation ($n = 13$). The recovered sites in the western U.S. were in either chaparral ($n = 8$), forest or plantation ($n = 3$), or grass ($n = 1$) sites. Comparatively, the recovered sites in the Mediterranean Basin were located in forests ($n =$ 4) or shrublands ($n = 2$). Only one of the four sites in forest plantations recovered within the respective study periods (James and Krumland, 2018). We found no relationship between fire year or soil texture and post-fire recovery condition or recovery time.

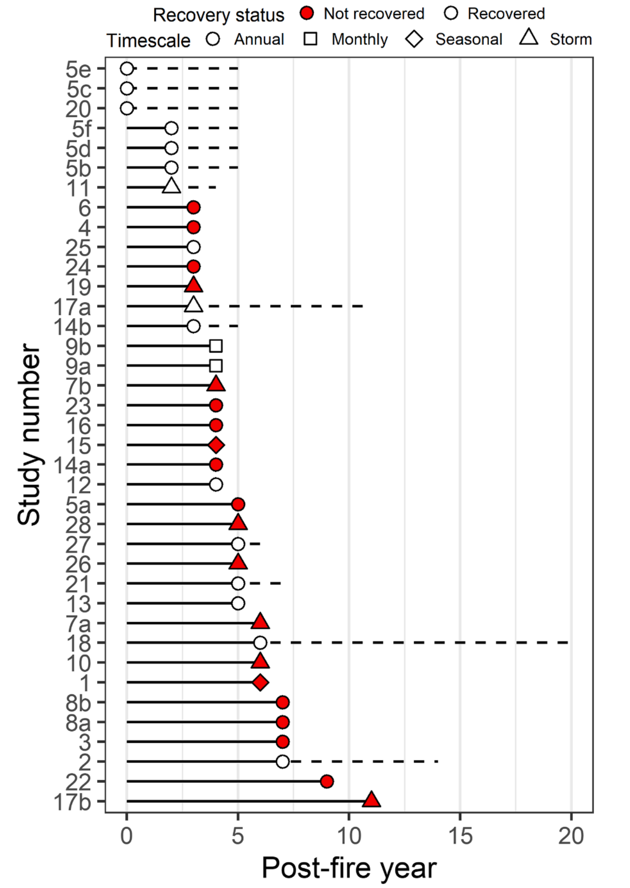

Fig. 3. Our assessment of recovery versus post-fire year for each study. Study number is the same as in Table 2. Dashed lines indicate duration of study if it exceeded the time of the recovery assessment. (Available in color online).

Burn severity is an important composite measure of the complex and heterogeneous effects of fire on soil properties and surface cover that may influence recovery rate. Burn severity classification was identified for only 20 of the 38 sites. There was no apparent relationship between recovery and burn severity within this subset of studies. However, as the proportion of the experimental unit or catchment that burned increased, the likelihood of recovery within the study duration decreased (Fig. 4). Of the 31 sites with more than 60% of the area impacted by fire, only 12 appeared to have recovered. Excluding the Diakakis et al. (2017) regional-scale study, all six of the sites with <60% of the catchment area impacted by fire recovered (Fig. 4). As the area of the study site increased, the likelihood of recovery increased (Fig. 4). We posit this was due to a greater probability of the smaller experimental units burning with uniform severity and the dilution of the immediate and long-term post-fire responses across the larger units with more complex burn severity mosaics. At the extreme spatial scales in our meta-analysis, the lack of recovery after 11 years in the 0.25 m^2 plots (Cerdà and Doerr, 2005) and the lack of immediate response in the 632 km^2 catchment (Bart and Hope (2010) exemplify the influence of homogeneity of burning at small scales and the dilution effect at larger scales.

3.2. Definition of recovery

Across the studies in our review, we were unable to find a definition of recovery despite 13 of the studies including an assessment of

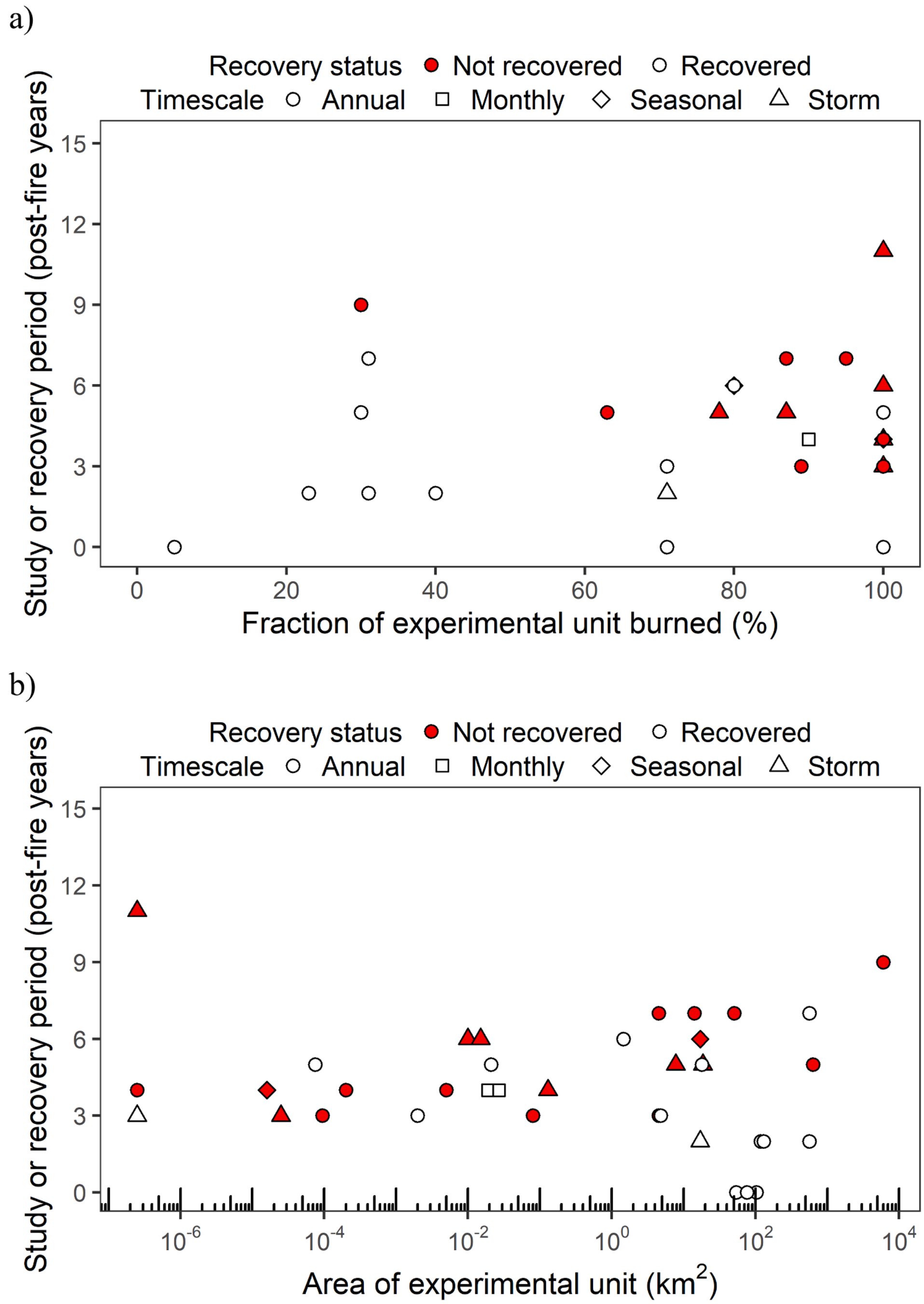

Fig. 4. Study duration for sites not recovered or recovery period vs. fraction of the area burned (a) and area of the experimental unit (b).

recovery. Several studies related the hydrologic recovery, at least in part, to the burn severity (Kinoshita and Hogue, 2011; Olsen et al., 2021; Robichaud et al., 2013a, 2008) or relatively rapid recovery of vegetation (Bart and Hope, 2010; Cerdà and Doerr, 2005; Cooper et al., 2015; Hubbert et al., 2012; Inbar et al., 1998; Kinoshita and Hogue, 2011; Wu et al., 2021). One study presented a conceptual model that suggested the recovery period varied with post-fire precipitation (Keller et al., 1997), and precipitation was indicated as a control on recovery in at least four other studies (Mayor et al., 2007; Robichaud et al., 2013b; Shakesby et al., 1993; Vieira et al., 2016). Only one study addressed changes in soil properties as a control on hydrologic recovery (Andreu et al., 2001), while another study suggested pre-fire disturbance may affect post-fire recovery rates (Vieira et al., 2016).

Of the 19 study sites where hydrologic recovery had occurred or there was no post-fire response, we found only one study (Cosandey et al., 2005) that presented a robust before-after control-impact (BACI) analysis. Four other studies used before-after analysis with no post-fire control (Table 4), which also provides a relatively robust assessment of recovery when adequate pre-fire data are available. Given the low number of long-term gauging stations in catchments likely to be heavily impacted by wildfire, control-impact analyses using an unburned reference site as the control were most common, and we deemed seven sites as recovered using data presented in this type of design. Bart and Hope (2010) used prediction intervals from control and impacted catchments to identify post-fire streamflow that exceeded the reference, unburned condition. Of their six burned catchments, only one (Arroyo Seco) exceeded the pre-fire prediction intervals for annual, monthly, or seasonal flows during years three through five after the fire. However, the response had not yet recovered at the end of the five-year study. Even when the simpler hypothetical criterion for recovery was applied, there was no clear consensus about the length of time needed for hydrologic responses to return to pre-fire conditions.

Many of the studies used runoff measures relevant to the specific sites or objectives, such as storm, monthly, or annual runoff rates or peak discharge rates. However, the variety of measurement methods and data reporting approaches made comparisons across sites difficult. Thus, we suggest the use of metrics (e.g., Table 1) to help quantify recovery among diverse locations in future studies, wherein recovery would be indicated when the post-fire metrics fall within the confidence intervals of the pre-fire metrics.

3.3. Demonstration of recovery metrics

We used the unique, longer-term data from the City Creek (California) and Rimbaud (France) sites to test five metrics of streamflow to identify post-fire recovery. Specifically, we quantified runoff ratio, slope of the flow duration curve, low flow (Q_{90}), the proportion of time with no flow, and high flow (Q_{10}). At both locations, the annual runoff ratios appeared cyclical and followed precipitation patterns (Fig. 5a and e). Both sites experienced dry conditions in the period just before the fire, leading to lower pre-fire runoff ratios. Based on the 95% confidence interval analysis, City Creek showed a clearer pattern of response and recovery than the Rimbaud catchment (Fig. 5).

The City Creek runoff ratios were higher than the pre-fire period for the first three years after burning (Fig. 5a). When we analyzed only the first five or six years of post-fire data it appeared like hydrologic recovery had occurred. However, the runoff ratio in the seventh and eighth years again exceeded the confidence limits from the pre-fire condition, illustrating the importance of longer-term studies. Similarly, the slopes of the flow duration curves and Q_{90} (low flows) for City Creek remained elevated for 10–11 years after the fire and showed only a gradual declining trend over this period (Fig. 5b and c). These results affirm previous analyses on this catchment (Kinoshita and Hogue, 2015).

Interestingly, we did not observe a dramatic increase in the high flows (Q_{10}) at City Creek in the first several years after the fire, followed by a slow decline over time (Fig. 5d). Rather, the response in Q_{10} was somewhat cyclical and followed the pattern identified in the annual runoff ratio. This observation was counter to the high flows reported in most of the studies in our review, which were generally elevated for the first two years after the fire and then decreased over time (Anderson, 1955; Cooper et al., 2015; García-Comendador et al., 2017; Robichaud et al., 2013b).

In contrast to City Creek, the runoff ratios in the Rimbaud catchment showed a muted response after the fire in 1990 (Fig. 5e). This response was somewhat cyclical and related to the post-fire precipitation pattern. Like City Creek, the runoff ratios appeared to trend down over the study period (Fig. 5e). The slopes of the flow duration curves were elevated above the pre-fire confidence interval for the first five years and for a subsequent seven-year period after the fire (Fig. 5f). The Q_{90} low flows followed a similar pattern as the slopes, but with fewer points above the upper confidence limit (Fig. 5g). The Rimbaud catchment demonstrates typical intermittent stream behavior, where there was no flow 20% of the time before the fire. The proportion of time with no flow averaged 21% after the fire, but there was a distinct increasing trend in the fraction of time with no flow in the post-fire period (Fig. 5h). We did not find a trend in the high flows (Q_{10}) after the wildfire at Rimbaud; however, there were many streamflow values below the lower pre-fire confidence limit (Fig. 5i). In contrast to the original authors' assessment of recovery after four years, we considered the Rimbaud site to have recovered after six years (Table 4) using the earlier analyses and finer resolution timescale (Cosandey et al., 2005; Folton et al., 2015; Lebedeva et al., 2014).

4. Discussion

4.1. The influence of site physical factors on recovery

We initially hypothesized that burn severity, post-fire precipitation, and vegetation regrowth would be important factors in assessing post-fire hydrologic recovery and that interactions among these factors can lead to a wide range of possible post-fire recovery responses (Fig. 1). In our synthesis of 28 studies spanning 38 sites from Mediterranean climates we were unable to find consensus about the longevity of fire effects on local or regional hydrology. In the 15 studies that showed a post-fire response and then recovered, the elevated post-fire hydrologic effects persisted from two to seven years, with longer recovery times generally occurring in catchments with a greater proportion of area burned. There were too few studies that reported burn severity to support a general conclusion about this factor. However, the scale of inference combined with the area burned led to the important finding that a higher proportion of area burned resulted in a lower likelihood of recovery in the study period.

The spatial scales of the sites in our review were divided among hillslopes (<0.005 km^2; $n = 9$), small catchments (0.005–5 km^2; $n = 14$), and medium or large catchments (>5 km^2; $n = 15$). In general, there was less variability in fire effects or other site characteristics at the smaller scales (e.g., hillslopes). The catchment scale provided spatial integration of the effects from heterogeneous catchment characteristics, including burn severity. Larger catchments generally require greater infrastructure to quantify streamflow responses, but larger catchments are also more likely to have long-term gauging records that allow for more robust assessment of pre-fire responses and hence post-fire hydrologic recovery. Also, as the size of the catchment increases, the fraction of the area impacted by fire tends to decrease and the fire impacts become muted (Table 3) and harder to detect (e.g., Bart and Hope, 2010; Wagenbrenner and Robichaud, 2014), which may confound the assessment of recovery (Fig. 4).

Our analysis identified differential responses and recovery trajectories that were strongly related to the local precipitation patterns in the post-fire period. For example, in our City Creek analysis, water year 2005 had higher than normal precipitation, which led to greater vegetation cover (Kinoshita and Hogue, 2011). However, the slope of the flow duration curve and the Q_{90} low flows remained elevated compared to pre-fire conditions (Fig. 5b and c). Additionally, wildfires often occur during dry periods or meteorological droughts (Pausas and Fernandez-Munoz, 2012), which can extend into the post-fire period. Mayor et al. (2007) and others (e.g., Florsheim et al., 2017) reported dry periods after the wildfire, which delayed the regrowth of vegetation in the burned area and may have led to longer recovery periods. These complexities in the post-fire period suggest that site-specific assessments of recovery are needed and that many studies using similar metrics will be necessary to develop a general rule for post-fire hydrologic recovery.

Interestingly, our review illustrated that on sites where vegetation recovered rapidly (18 studies) there was either no post-fire response or hydrologic recovery occurred during the study. In part, this was related to the Mediterranean climates, where the year-round growing season and mild winter weather can facilitate rapid vegetation regrowth and facilitate post-fire recovery. However, the relation between vegetation and hydrology is complex, and vegetation regrowth alone may not serve as a clear indicator of hydrologic recovery. Evapotranspiration rates from early succession forests can be greater than rates in established forests, leading to a lagged post-fire decline in flows, especially during dry periods (Brown et al., 2005; Langford, 1976; Watson et al., 1999). This is a plausible explanation for the partial declines in streamflow relative to pre-fire conditions in two studies (Kinoshita and Hogue, 2011; Wittenberg and Inbar, 2009) as well as the increased proportion of time with no flow in the Rimbaud catchment in the post-fire period (Fig. 5h). Further, the recovery of understory vegetation is a critical component in re-establishing pre-fire hydrologic conditions. Increasing

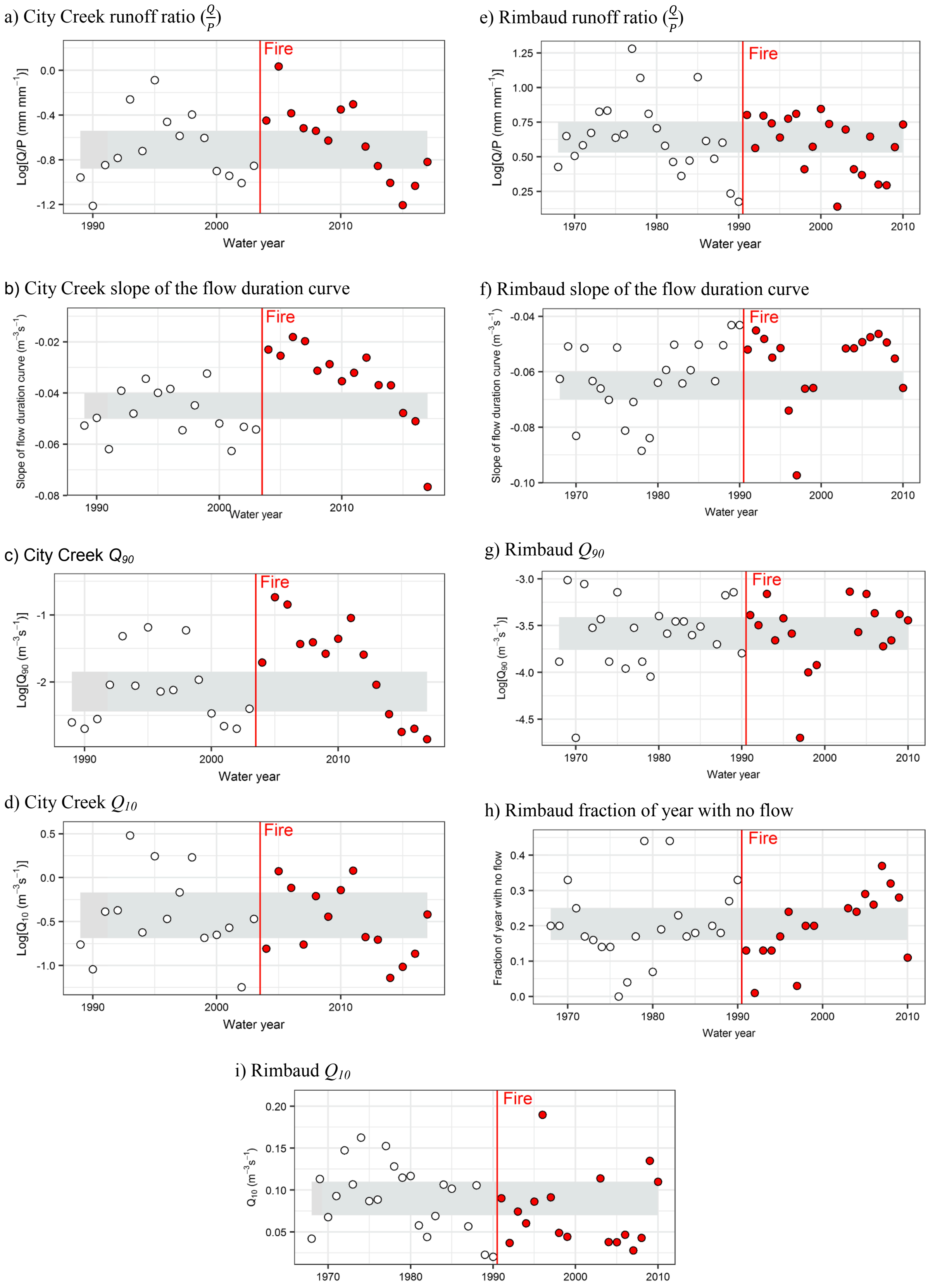

Fig. 5. Demonstration of recovery metrics using data from City Creek (a–d) and the Rimbaud catchment (e–i): runoff ratio (annual discharge divided by annual precipitation (Q/P)) (a, e); slope of exponential fit of the flow duration curve (b, f); Q_{90} (90% exceedance discharge) (c, g); fraction of year with no flow at Rimbaud (h); and Q_{10} (10% exceedance discharge) (d, i). Post-fire years are shown with filled symbols. Shaded areas represent 95% confidence intervals for the pre-fire metrics. (Available in color online).

leaf area in trees, shrubs, forbs, and grasses not only increases evapotranspiration rates, it also increases the leaf litter associated with seasonal vegetation changes, leading to greater interception and less runoff and erosion.

Although we did not include soils in our initial hypothesis, we recognize that temporal changes in post-fire soil properties likely contribute to post-fire recovery. The time needed for soil structure redevelopment after severe wildfire is largely unknown. The replacement of organic matter consumed by the fire, reestablishment of the root network, and other changes in soil properties such as re-establishment of "inherent" water repellency found in unburned hillslopes (Doerr et al., 2006; Robichaud et al., 2016) can lead to improved soil structure in burned soils over varying timescales. These and other critical factors such as soil moisture status (Ebel, 2013), geology (Robichaud et al., 2013b), climate regime (Wine and Cadol, 2016), and biological activity likely contribute to the changes in soil structure and the reestablishment of infiltration capacity. Considering the complexities that contribute to the occasionally ambiguous signals of recovery (Fig. 1, Fig. 3, Fig. 4) additional research on the influence of vegetation regrowth and changes in soil hydraulic properties are needed to assess hydrologic recovery more completely.

4.2. Effects of climate on recovery

The site specificity in hydrologic response and recovery observed across our review studies suggests even greater challenges for identifying trends in recovery among regions or climate types. For example, the American Southwest with its monsoonal convective storms may produce post-fire responses with larger magnitudes than other areas (Moody and Martin, 2009), and the occasional exceptional rainfall intensity in this region may confound assessments of recovery (Robichaud et al., 2013b). Similarly, despite more uniform precipitation conditions (Moody and Martin, 2009), areas with continental climates in the western U.S. can have recovery periods that can extend longer than five years (Larson-Nash et al., 2018; Robichaud et al., 2013a, 2016).

Defining a typical period for hydrologic recovery is also complicated by the temporal variability of high-intensity rainfall and soil moisture status within Mediterranean climates. Several studies related the observed rainfall intensity or erosivity to generation of post-fire peak discharges or sediment delivery (Cosandey et al., 2005; Inbar et al., 1998; Mayor et al., 2007; Robichaud et al., 2008). A substantial hydrologic or sediment delivery response can occur later in the post-fire period if a high-intensity rainfall event occurs on catchments where the vegetation, surface litter, and soil structure have not returned to pre-fire conditions (Inbar et al., 1998; Robichaud et al., 2008). The delayed responses can disrupt the apparent recovery trend and result in an erroneous assessment of recovery. Also, the events may fall outside the typical two to three-year window of post-fire hydrologic monitoring, and rigorous observation of these events may be missed altogether. Unusually large storms or extremely wet periods can cause large hydrologic responses regardless of the time since fire, and the timing of these storms can also influence the assessment of whether a site has recovered (Inbar et al., 1998; Schmeer et al., 2018). Due to the risk of large responses, recovery probably takes longer than is commonly understood, which is an important consideration when planning research, watershed monitoring, or emergency management after large fires.

Several studies in our systematic review refer to the likely effects of climate change on future fires, and hence post-fire hydrologic responses (Bart and Hope, 2010; Cerdà and Doerr, 2005; Cooper et al., 2015; Diakakis et al., 2017; Kinoshita and Hogue, 2015; Mayor et al., 2007; Olsen et al., 2021; Vieira et al., 2016; Wittenberg and Inbar, 2009). Any links between climate change and specific post-fire responses are highly uncertain. However, climate change is expected to increase the length of fire seasons, extent of fires, and burn severity (Abatzoglou et al., 2018; Holden et al., 2018; Littell et al., 2009; Pausas and Fernandez-Munoz, 2012). Furthermore, climate models predict increases in variability in weather patterns in general, including the possibility of more frequent droughts (Berg and Hall, 2015; Polade et al., 2014) and more frequent extreme precipitation (IPCC, 2014; Pierce et al., 2013; Polade et al., 2017) over some Mediterranean regions, including California and the Mediterranean Basin. These combined factors will likely exacerbate post-fire hydro-geomorphic responses and increase variability in post-fire hydrologic recovery (Fig. 1). Field campaign and modeling efforts that account for sources of variability in weather patterns and address the hydrologic changes related to post-fire regeneration are needed to understand the array of possible post-fire hydrologic recovery trajectories. One critical step in this direction would be to improve our ability to scale inferences from hillslope-scale studies to catchment-scale responses (Wagenbrenner and Robichaud, 2014). An additional concern with shifting wildfire regimes under current and future climates (Livneh et al., 2013; Williams et al., 2019) is the increasing potential for entire watersheds to burn. When combined with our observation that the likelihood of post-fire hydrologic recovery within the study period decreased as the proportion of area burned increased, it follows that catchments will be more likely to be in a fire-effected state (i.e., not recovered) under future climate conditions.

4.3. Toward a consistent interpretation of post-fire hydrologic recovery

We propose that applying a standardized approach to describing and identifying recovery will help researchers, policy makers, and land managers understand the complexities of post-fire hydrologic recovery and communicate recovery in more absolute terms. The basis for our recommended approach is to adapt a common definition of recovery, identify metrics (e.g., Table 1) relevant to specific needs (Fig. 6), and apply a quantitative analysis to the selected metric using pre-fire and post-fire responses.

We suggest that hydrologic recovery has occurred when a specific post-fire function or condition of interest returns to within the 95% confidence interval established for the pre-fire period (Buttle et al., 2018; Gouveia et al., 2010; Hudson, 2000). Given sufficient data, this approach can be transformed into a statistical test using varying degrees of rigor, from a simple comparison of confidence limits in a BACI experimental design as in our analysis, to advanced statistical modeling. Only 12 of 38 sites in our literature search included pre- and post-fire data (Table 4), and only two of them included unburned controls in a BACI design. Before-after analysis provides a rigorous approach and can be informative in identifying possible post-fire responses and recovery trends (Fig. 5). However, given the sparse distribution of monitored catchments, especially at small spatial scales and in parts of the world where support for monitoring is less available, using reference conditions (e.g., control/impacted in Table 4) or experimental fire (e.g., Stoof et al., 2012) can also advance our understanding of post-fire hydrological effects and recovery. In cases where sufficient hydrologic data are not available the analyst can use the tools and data that are available, including personal experience and local knowledge, and clearly state the uncertainty of their analysis in their assessment of hydrologic recovery. We also recognize that external forcing from climate change, changes in land use, or invasion by non-native species may preclude a landscape's return to the pre-fire condition. Given the site-specificity of these confounding factors, we did not attempt to address these broad and complex issues in this systematic review.

Adapting this approach will not only improve our ability to make rigorous assessments of recovery within a specific study, it will also increase our ability to summarize responses and communicate across diverse fires and catchments. As the depth and breadth of post-fire hydrologic research continues to expand, this approach will increase our understanding of long-term effects and ability to be more conclusive regarding the timescale and controls on post-fire hydrologic recovery.

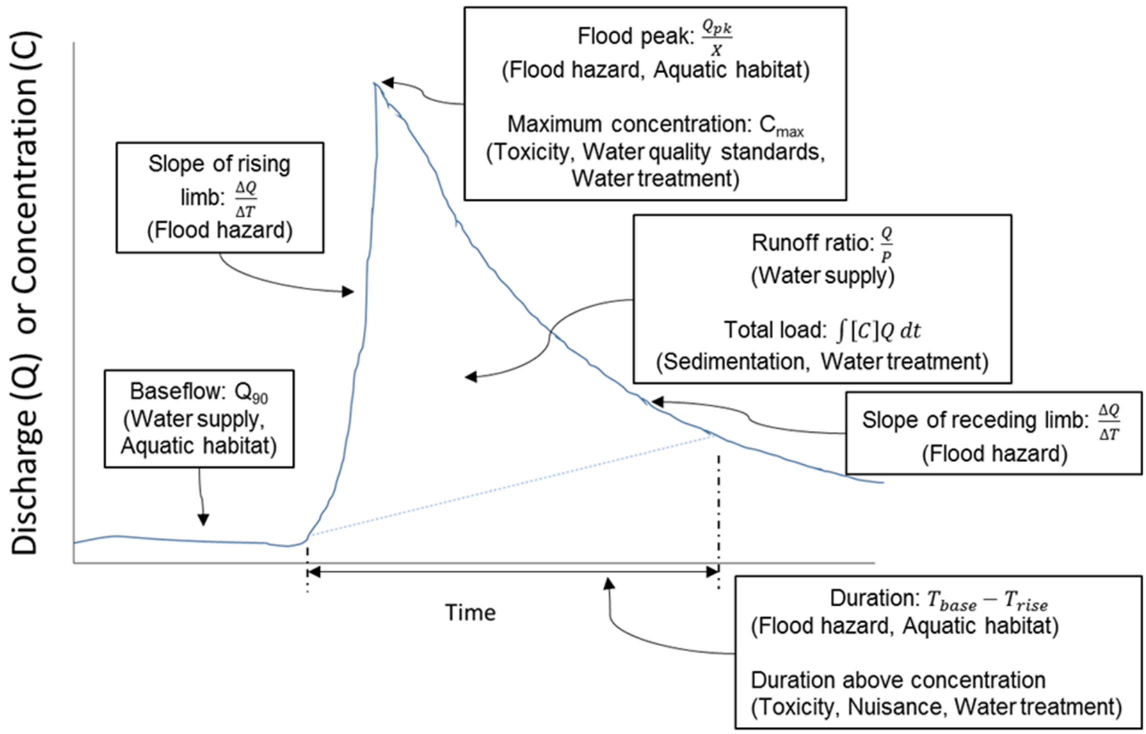

Fig. 6. Hydrograph showing some of the metrics of interest to various stakeholders. Abbreviations are the same as in Table 1. (Available in color online).

4.4. Hydrologic response metrics

We identified several possible metrics derived from commonly collected hydrologic data and related to impacts on water supply or human safety (Table 1). Our relatively simple analysis using a subset of these metrics (Fig. 5) highlights the importance of selecting an appropriate metric based on specific needs (Table 1, Fig. 6). For example, while Q_{90} can be important for long-term water supply planning and for aquatic habitat, it may be less relevant for immediate post-fire flood hazard, which is more appropriately assessed with Q_{10} or the peak discharge. In addition, the selection of a specific metric should consider the temporal scale of the data and the response. An example would be selecting peak discharge as a metric without considering whether the peak is rainfall or snow melt dominated, and therefore mostly influenced by the form and intensity of the precipitation (Moody et al. 2013) or snow melt rate.

Analyzing the metrics using data at different timescales, such as seasonal or storm flows, may also have yielded more conclusive assessments of impact and recovery. Three studies at the Rimbaud catchment in southern France (Cosandey et al., 2005; Folton et al., 2015; Lebedeva et al., 2014) showed that post-fire streamflow analyzed at the daily time step departed from the pre-fire flow, while seasonal and annual time steps did not show an effect of the fire on streamflow.

We chose a simple framework for assessing recovery of comparing pre- and post-wildfire 95% confidence intervals for hydrologic metrics because this approach is accessible to a broad range of potential users. Moreover, this framework has the potential and flexibility to be expanded upon with more complicated analyses, such as normalization by a standard pre-fire value or use of mixed-effects statistical modeling, which may also allow a more distinct signal of the catchment response and recovery.

4.5. Research opportunities

Understanding responses across temporal scales is one of the key knowledge gaps currently facing the field of post-fire hydrology. It was surprisingly difficult to find studies that continued at least three years post-fire. While longer-term studies necessitate substantial long-term investment and commitment (Tetzlaff et al., 2017), such efforts are likely to provide unexpected and critical knowledge to facilitate sustainable ecosystem and water management decisions. For example, long-term data sets have recently provided unique insights about forest disturbance effects on summer low flows (Coble et al., 2020; Niemeyer et al., 2020; Perry and Jones, 2017; Segura et al., 2020). Alternatively, a lack of long-term post-fire studies may lead to an unintentional bias toward presumed short-term effects and recovery in the early post-fire period (Fig. 3). As such, investments in long-term post-fire research sites or resampling previously studied post-fire sites would provide much-needed information for understanding hydrologic recovery and resilience of fire-prone ecosystems. Making data from monitoring and research studies publicly accessible would also allow greater synthesis and broader understanding of the variability in post-fire recovery.

Additionally, our review highlighted the importance of consistent measurement of key parameters to facilitate cross-site comparisons (Robinne et al., 2020). We propose the following measurements be included in future post-fire hydrologic studies: percentages of the area of the experimental unit in different classes of an established burn severity classification system; total precipitation and precipitation intensity; fraction of bare soil or ground cover, particularly for sediment delivery studies; and vegetation cover fraction and type. Except for burn severity, these measurements would be most useful in assessing temporal trends and recovery if continued for a period of at least 10 years. Additional studies of 10-year duration would greatly improve our understanding of medium- to long-term post-fire catchment dynamics and better inform our ability to assess and predict post-fire hydrologic recovery.

Despite the critical importance of long-term experimental watersheds for data-based decisions by water suppliers, land managers, and emergency managers (Tetzlaff et al., 2017), we are unaware of a long-term experimental watershed study designed to improve our understanding of the range of effects from wildfire. We recognize that long-term post-fire data are difficult to obtain, especially given short-term funding cycles, the logistics of sustaining measurements over long periods, and the inherent unpredictability of wildfire. However, from our experience, it is much easier and less costly to continue monitoring an existing site, or resample a previously used site, than to implement a new research endeavor. For example, measurement intervals can be reduced over time without loss of important information as the rate of regrowth or the relative magnitude of the response decreases.

Spatial scale is another important consideration in future research. The fact that all but one of the distinct sites in our systematic review were intermittent or ephemeral underscores the need for additional research on non-perennial streams, which in general are in smaller catchments, to better understand post-fire hydrologic responses and recovery. On the other hand, future assessments of recovery at large catchment or ecosystem scales may become more prevalent by combining field-based and remotely sensed data with numerical modeling to determine the impacts of geology, climate, vegetation, and changes in soil structure on recovery of hydrologic processes. Coupling of spatially explicit data with hydrologic modeling has been applied in a number of recent problems across a range of modeling platforms (e.g., Bales et al., 2018; Miller et al., 2011; Tague et al., 2004). These approaches are likely to become more sophisticated and more widely adapted by researchers and managers as technology such as airborne imaging advances and we continue to increase our understanding of post-fire hydrological impacts.

5. Conclusions

We applied a systematic approach to synthesize research on post-fire hydrologic recovery in areas with Mediterranean climates. Despite many studies on post-fire hydrologic responses, we identified only 28 studies, covering 38 sites, which met our criteria for inclusion in a systematic review. These sites were in the western United States and the Mediterranean Basin and were used to study responses to fires that occurred between 1924 and 2015. In the 18 studies whose original data met our criteria for recovery, timescales for hydrologic recovery ranged from zero (i.e., no post-fire response) to seven years. There was no clear pattern between recovery time and location or spatial scale of inference. Annual time steps were more likely to indicate recovery than shorter time steps and sites with a higher proportion of area burned were less likely to recover. These findings suggest that responses that were aggregated through time or across space where unburned area occurred within the experimental unit dampened the more discrete responses from areas with homogenous fire impacts, and that these dampening effects may be interpreted as recovery.

We propose a common definition of post-fire hydrologic recovery: when a specific post-fire function or condition of interest returns to the 95% confidence interval of the pre-fire condition. We also note metrics that can be adjusted to meet the specific needs of various stakeholders and tested with different degrees of statistical rigor, which we demonstrated using confidence interval testing. Following this approach may improve our ability to compare post-fire hydrologic recovery across future studies. The few studies available were insufficient to support or contradict our conceptual model of the recovery time needed for specific burn severity and post-fire weather patterns. We suggest some guidelines to help address this apparent deficiency in future post-fire hydrologic studies. We also identified several opportunities for additional research, including increasing the duration of planned and ongoing post-fire hydrologic studies in general, as well as initiating studies that will provide a better understanding of the reestablishment of soil structure and related hydrologic properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. We thank Sheila Murphy (U.S. Geological Survey) for her comments that helped improve the manuscript. Paul Richardson (U.S. Forest Service) helped with the flow duration curve analysis and Fig. 5. We are grateful for the comments from three anonymous reviewers, which helped us improve the paper. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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