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Hydrologic recovery after wildfire: A framework of approaches, metrics, criteria, trajectories, and timescales

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Abstract: Deviations in hydrologic processes due to wildfire can alter streamflows across the hydrograph, spanning peak flows to low flows. Fire-enhanced changes in hydrologic processes, including infiltration, interception, and evapotranspiration, and the resulting streamflow responses can affect water supplies, through effects on the quantity, quality, and timing of water availability. Post-fire shifts in hydrologic processes can also alter the timing and magnitude of floods and debris flows. The duration of hydrologic deviations from a pre-fire condition or function, sometimes termed hydrologic recovery, is a critical concern for land, water, and emergency managers. We reviewed and summarized terminology and approaches for defining and assessing hydrologic recovery after wildfire, focusing on statistical and functional definitions. We critically examined advantages and drawbacks of current recovery assessment methods, outline challenges to determining recovery, and call attention to selected opportunities for advancement of post-fire hydrologic recovery assessment. Selected challenges included hydroclimatic variability, post-fire land management, and spatial and temporal variability. The most promising opportunities for advancing assessment of hydrologic recovery include: (1) combining statistical and functional recovery approaches, (2) using a greater diversity of post-fire observations complemented with hydrologic modeling, and (3) defining optimal assemblages of recovery metrics and criteria for common hydrologic concerns and regions.

Keywords: Recovery; Wildland fire; Hydrologic function; Statistical recovery; Functional recovery; Ecosystem services.

INTRODUCTION

Wildfire can have numerous effects on hydrological processes, water supply, and water-related hazards. Post-fire water-related hazards include increased risk of flash floods (Conedera et al., 2003; Moody and Martin, 2001a; Moody and Martin, 2001b; Tryhorn et al., 2008) and debris flows (e.g., McGuire et al., 2017; Nyman et al., 2011; Staley et al., 2013; Thomas et al., 2021). Fire can also lead to hydrologically driven alterations of water supply through shifts in the timing and magnitude of streamflow (Beyene et al., 2021; Hallema et al., 2018; Kinoshita and Hogue, 2015; Wine et al., 2018). Water quality can also be altered by wildland fire (e.g., Harper et al., 2018; Martin, 2016; Murphy et al., 2018; Nunes et al., 2018a; Rhoades et al., 2019; Roces-Díaz et al., 2022; Rust et al., 2018), including through increases in nutrients (Ferreira et al., 2016; Hosseini et al., 2017; Serpa et al., 2020) and suspended sediment (e.g., Cerdà and Lasanta, 2005; Prats et al., 2016; Wittenberg and Inbar, 2009). While the effects of fire on water quantity and quality are often substantial, fire effects on hydrologic functions and aquatic ecosystems are not always detrimental and often provide a necessary ecosystem service (Pausas and Keeley, 2019; Roces-Díaz et al., 2022; Warren et al., 2022). For example numerous studies have shown increases in water yield following fire (e.g., Hallema et al., 2018; Saxe et al., 2018; Shakesby and Doerr, 2006; Williams et al., 2022) likely as a result of reduced transpiration (Collar et al., 2021; Kinoshita and Hogue, 2015) that could be viewed as beneficial from a water supply perspective. Indeed, recent reviews of ecosystem services have documented both positive and negative changes in ecosystem services after fire (Roces-Díaz et al., 2022; Vukomanovic and Steelman, 2019).

Fire effects on streamflow and water supply are generally driven by substantial post-fire alterations in vegetation, surface cover, soil properties, and hydrologic processes. Post-fire changes in vegetation and surface cover conditions include canopy (e.g., Stoof et al., 2012) and litter/duff (e.g., Ebel, 2013b) interception, vegetation type (e.g., Cerdà et al., 2021), and ground cover (e.g., Cerdà and Doerr, 2008). These vegetation and ground cover shifts can result in more precipitation reaching the land surface (Mitsudera et al., 1984), alter snow accumulation and ablation (Gleason et al., 2013; Moeser et al., 2020), and reduce transpiration (e.g., Collar et al., 2021; Poon and Kinoshita, 2018; Wilder and Kinoshita, 2022), thus potentially increasing groundwater recharge (e.g., Cardenas and Kanarek, 2014; Ebel, 2013a). Combustion of vegetation and surface fuels can result in the generation of ash and char layers that can substantially alter surface water storage, infiltration, and runoff chemistry (e.g., Bodí et al., 2014; Pereira et al., 2015; Pereira et al., 2012). Soil hydraulic properties altered by fire include hydraulic conductivity (e.g., Ebel, 2019), sorptivity (e.g., Moody et al., 2009), soil-water repellency (e.g., Imeson et al., 1992), and soil-water retention (Stoof et al., 2010), which can alter infiltration rates (e.g., Cerdà, 1998; Plaza-Álvarez et al., 2019). Soil physical properties — including bulk density (e.g., Stoof et al., 2010), organic matter content (e.g., González-Pérez et al., 2004), soil particle size distribution (e.g., Ulery and Graham, 1993), and aggregate stability (e.g., Mataix-Solera and Doerr, 2004) — can also be changed by wildfire and can affect water storage, infiltration, and erodibility. The magnitude of the fire effects on the aforementioned system properties and processes can be amplified or dampened by numerous physical, biological, pyrologic, and anthropogenic factors, leading to uncertainty in predicting post-fire effects. For example, some factors that can modify the magnitude of post-fire effects include soil type (e.g., Mataix-Solera and Doerr, 2004), vegetation type (e.g., Cerdà et al., 2021), hydroclimatology (e.g., Florsheim et al., 2017), burn severity (e.g., González-Pelayo et al., 2006), and post-fire management activities (e.g., Barroso and Vaverková, 2020; Francos et al., 2020; Wittenberg et al., 2020).

The timescale and magnitude of fire effects on hydrologic processes and quantitative assessment of recovery are of critical interest to aquatic ecologists, forest and emergency managers, and water supply agencies. It is typically assumed there is a detectable increase or reduction in vegetation conditions, soil properties, and hydrologic fluxes (e.g., evapotranspiration, streamflow) after fire, relative to the unburned condition, and recovery is represented by a return towards a pre-fire state (e.g., Cerdà, 1998; Kinoshita and Hogue, 2011; Rulli et al., 2006; Wagenbrenner et al., 2021). The period between the wildfire and hydrologic system recovery is sometimes termed the "window of disturbance" (Prosser and Williams, 1998). Numerous studies in the fire science community have examined hydrologic recovery following wildfire. Vegetation recovery has been linked to recovery in streamflow (Brown, 1972; Heath et al., 2014; Kinoshita and Hogue, 2011; Kuczera, 1987; Nolan et al., 2015; Shin et al., 2013), infiltration (Cerda et al., 1995), erosion (Inbar et al., 1998; Swanson, 1981; Wittenberg and Inbar, 2009), and peak flows (Bolin and Ward., 1987; Kunze and Stednick, 2006). The recovery of soil-water repellency to unburned levels has also been connected to recovery of infiltration (Robichaud, 2000; Shakesby et al., 1993) and erosion (Robichaud et al., 2016; Tessler et al., 2012). Other factors including macropore flow (Nyman et al., 2014) and soil structure (Cerda et al., 1995; Mataix-Solera and Doerr, 2004) have been noted to affect the recovery of infiltration, runoff generation, and streamflow after fire. Post-fire mitigation methods can also affect hydrologic recovery times, adding more complexity (Girona-García et al., 2021; Neris et al., 2016; Prats et al., 2014; Zema, 2021).

While the collective efforts of the fire science community have provided insight into the many factors that can promote or inhibit hydrologic recovery, we lack a systematic understanding of recovery processes necessary to predict the magnitude and duration of fire effects on hydrologic responses. Terminology differences and lack of consistency in how recovery is assessed are primary barriers to synthesizing hydrologic recovery between geographic areas and types of hydrologic response (Wagenbrenner et al., 2021). The goal of our work was to examine terminology used to describe hydrologic recovery assessment and build a flexible framework for consistent assessment of hydrologic recovery after wildfire. The study of hydrologic recovery after wildfire includes (1) selecting an *approach* defining what type of recovery is of interest, such as a return to a pre-fire condition or a necessary level of hydrologic function, (2) defining *metrics* of interest that quantitatively measure the system condition or response, (3) choosing *criteria* that quantitatively determine whether recovery has been achieved, (4) identifying a recovery *trajectory* that defines the shape of the system response or condition with time since fire, and (5) estimating the recovery *timescale* that is the period from the wildfire until hydrologic recovery has been achieved. Thus, in this work, we:

- examined concepts and definitions of approaches, metrics, criteria, trajectories, and timescales to assess hydrologic recovery after fire,
- summarized uses of these definitions in the post-fire hydrologic literature and presented a framework for assessing recovery,
- considered advantages and drawbacks of the various approaches and elements of the recovery framework,
- discussed challenges associated with recovery timescales and recovery trajectories (forms), and
- highlighted opportunities for advancing assessments of post-fire hydrologic recovery.

We provide examples across multiple fire-affected systems and hydrologic processes to illustrate the broad applicability of the recovery terminology and proposed framework.

BACKGROUND AND FOUNDATION FOR NEW HYDROLOGIC RECOVERY ASSESSMENT FRAMEWORK

Assessing post-fire hydrologic recovery requires a clearly defined approach for selecting the most important hydrologic variable of concern (e.g., water supply, water quality, debris flow hazard) and objectively quantifying recovery. The approach for assessing hydrologic recovery has generally involved either an assessment of whether (1) the hydrologic variable of concern has returned to a statistically indistinguishable condition relative to a pre-fire state or (2) a hydrologic function of interest has been restored (Table 1). We summarize these two approaches below.

Recovery assessment approach: Statistical

In the statistical recovery approach, central tendencies, variances, statistical distributions, or quantitative statistical relations (e.g., linear regression) are used to define the pre-fire and post-fire states and sequential temporal comparisons are used to assess a return to the pre-fire state or condition (Cerdà, 1998; Ebel and Martin, 2017; Kinoshita and Hogue, 2015; Robichaud et al., 2016; Wagenbrenner et al., 2021). The statistical recovery definition (Figure 1A) is the most broadly used definition in the hydrologic literature. For example, Larson-Nash et al. (2018) assessed recovery by determining when the ratio of infiltration on burned sites and unburned sites had returned to one. Similarly, post-fire evapotranspiration recovery was also assessed by comparing pre- and post-fire ratios, but to an 80% rather than 100% recovery criterion (Collar et al., 2021). Wagenbrenner et al. (2021) reviewed this approach and recommended statistical recovery should be considered achieved when the hydrologic parameter of concern returned to within the 95% confidence interval of the pre-fire hydrologic response (Figure 1A).

Statistical tests comparing burned and unburned infiltration data and derived soil-hydraulic properties, such as the non-parametric Kruskal-Wallis test (Kruskal and Wallis, 1952), have also been used to assess recovery between repeated years after fire (Ebel et al., 2022). Similar methods for assessing statistical recovery of hydrologic processes include statistical analyses of variance (e.g., Williams et al., 2016a) and mixed-effects statistical models (e.g., Robichaud et al., 2016). Linear regression has also been used to observe statistical recovery of infiltration and derived soil-hydraulic properties across burn severity (Ebel et al., 2018). While many different statistical approaches have been used to assess hydrologic recovery, there are no currently agreed upon baseline statistical methods that serve as benchmarks for assessing whether a site has recovered, which has hindered cross-study comparisons.

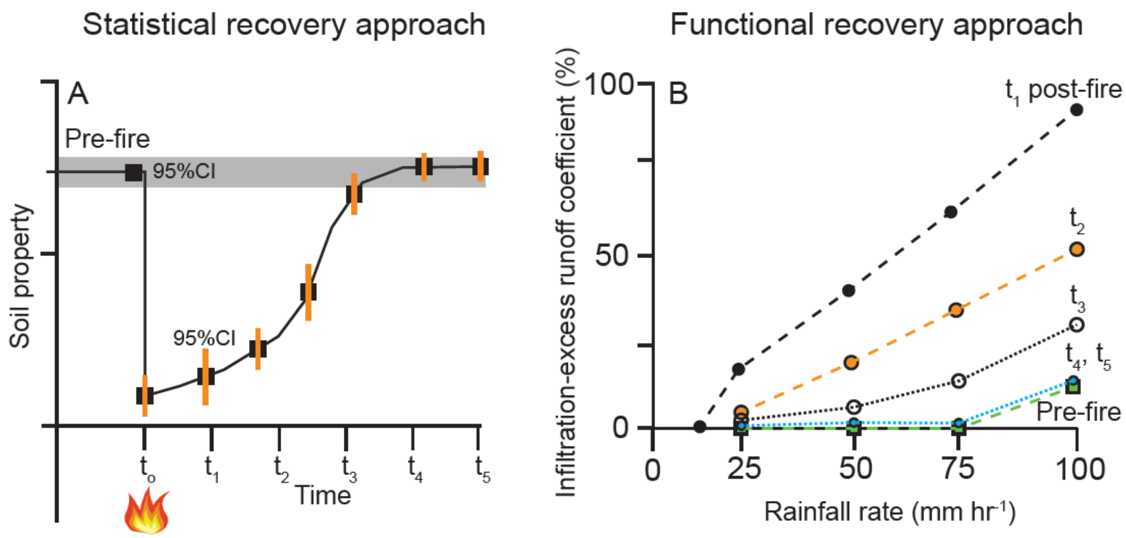

Fig. 1. Examples of the (A) statistical and (B) functional approaches for hydrologic recovery assessment following wildfire. CI = confidence interval.

Table 1. Definitions of post-fire recovery approach, metric, criteria, trajectory, and timescale for hydrologic recovery following wildfire.

Recovery term	Definition	Reference(s)	Example
Approach	Selecting the most important hydrologic concern (e.g., water supply, water quality, debris flow hazard) and then deciding what constitutes recovery	This work	Statistical recovery (return to pre-fire condition); Functional recovery (return to required hydrologic function)
Metric	Numerical value that captures some salient hydrologic property, process, condition, flux, or state	Rathburn et al. (2018); Wagenbrenner et al. (2021)	Runoff ratio, total runoff/total precipitation; Q90, the discharge with 90% exceedance probability estimated from a flow duration curve
Criteria	Quantitative analysis or comparison of a recovery metric against some standard or endpoint to decide if recovery has been achieved	Hughes et al. (1990)	Within 95% confidence interval of pre-fire data; annual watershed yield sufficient for water supply demand
Trajectory	Temporal form of the hydrologic property, state, flux, or function with elapsed time since fire	Minshall et al. (1997)	Linear recovery form; sigmoidal/logistic recovery form; humped recovery form
Timescale	Duration between the fire and the attainment of a selected recovery metric	Lamb et al. (2011)	Peak flow recovery to pre-fire levels (for similar magnitude precipitation) in 2-3 years after fire

Recovery assessment approach: Functional

Functional recovery assessment is an alternative approach to evaluating post-fire hydrologic recovery, which relies on re-establishment, or documentation of no loss, of hydrologic function following a fire rather than a statistical return to an unburned condition (Figure 1B). The concept of ecosystem services provides a framework to assess altered hydrologic function following wildfire and prescribed fire (e.g., Harper et al., 2018; Nunes et al., 2018b; Pausas and Keeley, 2019; Pereira et al., 2021; Robinne et al., 2020; Roces-Díaz et al., 2022). Recent efforts examining the effects of fire on ecosystem services (Roces-Díaz et al., 2022) have used classifications from the Common International Classification of Ecosystem Services (Haines-Young and Potschin-Young, 2018; Haines-Young and Potschin, 2018). Within this classification system, water provides many provisioning and regulating ecosystem services. Provisioning hydrologic ecosystem services include supplying sufficient quantity and quality of water for various uses (e.g., Brauman et al., 2007). Comparatively, regulating ecosystem services include those processes that benefit ecosystems, such as forests dampening hydrologic responses to rainfall, reducing flood magnitudes and the probability of debris flow initiation, and purification of source water supplies (e.g., Ebel, 2020; Roces-Díaz et al., 2022).

Assessing post-fire recovery of hydrologic function requires a definition of function and quantification of whether that function or ecosystem service is still provided following fire disturbance. As with the statistical definition of recovery, the functional definition also requires defining metrics to assess functional adequacy across a suite of ecosystem services or hydrologic responses. These metrics can be directly measured, such as discharge (e.g., Cosandey et al., 2005; Niemeyer et al., 2020), soil moisture (Ebel et al., 2012; Kean et al., 2011; Leighton-Boyce et al., 2005) and infiltration (e.g., Cerdà, 1998; Ebel et al., 2022; Shakesby et al., 1993), or indirectly estimated metrics, such as Budyko water balances (e.g., Hampton and Basu, 2022) or remotely sensed indices.

Recovery metrics

Quantitatively assessing post-fire hydrologic recovery using either the statistical or functional approach requires a numerical value that captures a salient hydrologic property, condition, flux, or state. The term "recovery metric" has been used (Hampton and Basu, 2022; Rathburn et al., 2018; Wagenbrenner et al., 2021) to describe the quantitative (i.e., continuous numerical scale, not categorical) measurement for which recovery was assessed, typically relating to watershed discharge, peak flow, low flow, total sediment delivery, evapotranspiration, or infiltration (Table 1). Common metrics used for post-fire system properties or hydrologic response are summarized in Table 1 of Wagenbrenner et al. (2021) and include runoff ratio, low flow, snow melt rate, suspended sediment load, flood peak, slope of rising or falling hydrograph limbs, time of peak streamflow, median streamflow, and the slope of the flow duration curve. Often, multiple aspects of a single measured variable, such as streamflow, are used as recovery metrics such as the 90th percentile exceedance discharge (or low flow) and the total annual flow normalized by basin area. In some studies, a single hydrologic recovery metric has been used (e.g., Aronica et al., 2002; Bart and Hope, 2010; Cole et al., 2020; Shakesby et al., 1993) whereas others have used multiple metrics (e.g., Cerdà and Lasanta, 2005; García-Comendador et al., 2017; Kinoshita and Hogue, 2011; Kinoshita and Hogue, 2015; Prats et al., 2016). Depending on the hydrologic parameter of concern (e.g., water supply, water-related hazards, ecological conditions) these metrics may be calculated at different timescales, such as sub-daily, monthly, or annually (Wagenbrenner et al., 2021). For example, peak flows for hazard concerns are often calculated on a sub-daily event basis whereas annual watershed yield (i.e., total annual streamflow) is often used to assess recovery for water supply purposes.

Recovery criteria

Determining whether post-fire hydrologic recovery has been achieved requires recovery criteria. Defining recovery criteria (Table 1) typically involves a quantitative analysis or comparison of a recovery metric against some standard (Hughes et al., 1990). Recovery criteria are typically defined using either the statistical (95% confidence interval of pre-fire metrics) or functional (return to pre-fire function) approaches to defining recovery, but multiple criteria could be applied using both approaches. Recovery criteria for the statistical recovery approach often involve a return of a measured metric to the central tendencies and statistical distributions that characterized the pre-fire system, such as the 95% confidence interval of the pre-fire data (Wagenbrenner et al., 2021) used for recovery metrics of runoff ratio, slope of the flow duration curve, fraction of the year with no flow, and the discharge with 10% and 90% exceedance probabilities estimated from a flow duration curve. Return of the hydrologic metric to a fraction of the pre-fire level is also used, such as a return to 80% (Collar et al., 2021) or 90% (Hampton and Basu, 2022) of the pre-fire recovery metric. The recovery criteria for the functional recovery approach signifies processes returning to a typical pre-fire hydrologic function, such as the transition from infiltration-excess hillslope runoff generation after the fire back to the pre-fire condition of subsurface storm flow hillslope runoff generation (e.g., Ebel, 2020). Functional approach criteria can also relate to the provision of an ecosystem service, such as supplying the annual water demand of a community (i.e., a minimum total annual discharge) (Table 1). Assessment of recovery criteria can be complicated by post-fire runoff and erosion mitigation efforts that may or may not accelerate the return of hydrologic function to pre-fire levels.

Recovery trajectories

The temporal evolution of the recovery of hydrologic processes after fire may take various pathways or trajectories depending on many interconnected, complex factors. The recovery trajectory (after Minshall et al., 1997) can be defined as the temporal form or shape of the system property (e.g., soil hydraulic conductivity), state (e.g., soil water content), flux (e.g., streamflow), condition (e.g., vegetation characteristics, channel form), or function (e.g., water provision) with elapsed time since fire (Figure 2, Table 1). Knowledge of the range of possible shapes describing the potential recovery trajectory with time since fire is essential to developing hypotheses and statistical relations that quantify temporal variation and trends in the post-fire hydrologic response. Several shapes of recovery trajectories have been hypothesized, including sigmoidal or logistic (e.g., Ebel and Martin, 2017), linear (e.g., Canfield et al., 2005), humped (e.g., Nolan et al., 2015, see Figure 2), cyclical or multi-humped (e.g., Cerdá and Doerr, 2005, see Figure 2), and exponential (e.g., Vertessy et al., 2001). Additionally, other shapes are possible for recovery trajectories. The relative sign (i.e., greater or less than pre-fire values) and form of the trajectory can vary between hydrologic response type (Cerdá and Doerr, 2005) and burn severity (Nolan et al., 2015).

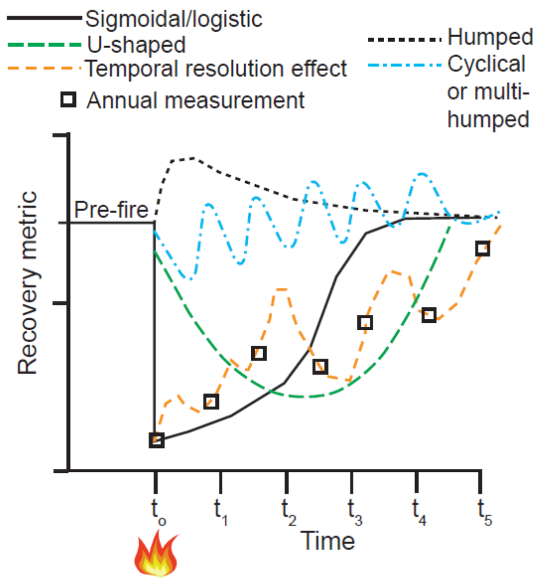

Fig. 2. Different potential hydrologic recovery trajectories following wildfire.

Recovery trajectories have often been conceptualized as monotonic in time; however, numerous exceptions have been observed. For example, seasonal variations in soil moisture, potentially linked with soil-water repellency, influenced infiltration recovery trajectories after fires in the Mediterranean climates of Spain and California, which led to cyclical or multi-humped (Figure 2) trajectories that varied seasonally (Cerdá and Doerr, 2005; Ferreira et al., 2000; Leighton-Boyce et al., 2005; Perkins et al., 2022). U-shaped post-fire infiltration recovery trajectories (Figure 2) were observed after the 2003 Hot Creek Fire in Idaho for steep (60%) slopes, in contrast to more linear infiltration recovery trajectories for gentler (20%) slopes (Larson-Nash et al., 2018). After a wildfire in eastern Spain, surface runoff followed a non-monotonic (multi-humped) recovery trajectory in an area with tree species overstory, whereas shrub and herbaceous vegetation overstory followed a sigmoidal recovery trajectory (Cerdá and Doerr, 2005). In some environments, such as cold regions where permafrost plays an important hydrologic role, the effects of fire can have a delayed, slow onset; in these environments a decade or longer can pass before fire effects on soil-hydraulic properties and subsurface hydrologic conditions are evident, followed by decades to recover to a long-unburned condition (Ebel et al., 2019; Rey et al., 2020). This complexity in recovery trajectories creates substantial challenges for predicting the effects of wildfires, especially in regions where the wildfire regime is changing rapidly.

In part, assessment of post-fire recovery trajectories could be affected by the temporal resolution of the data. For example, in Figure 2 we show a hypothetical situation where annual data indicate a possible linear recovery trajectory (square symbols) whereas sub-annual data show a multi-humped trajectory (temporal resolution effect line), revealing seasonal variations in the hydrologic parameter of concern. In some cases, temporal resolution may result in the appearance of abrupt recovery (or regression) of the observed metric (Ebel, 2020; Hoch et al., 2021), whereas a finer timescale of measurement might reveal more nuanced temporal trends (Thomas et al., 2021). As with recovery timescales, hydroclimatic variability, such as drought or extreme precipitation events, can alter the recovery trajectory and prevent comparisons with typical post-fire recovery trajectories that may be hypothesized for specific regions, vegetation types, or hydrologic processes (Figure 2). The spatial scale of assessment can also affect the recovery timescale (e.g., Ferreira et al., 2005; Prats et al., 2016; Wilson et al., 2018).

Recovery timescales

Knowledge of the duration of fire effects on the hydrologic response is important for prioritizing post-fire forest management activities and informing water and emergency management decisions. The cumulative effects of multiple activities in a watershed may lead to greater impacts on a given hydrologic response than any single activity (MacDonald, 2000) and understanding the post-fire recovery trajectory of a given hydrologic response would help describe the possible combined effects of the fire and another proposed activity on that response. The duration of fire effects, or recovery timescale (after Lamb et al., 2011), can be defined as the time between the occurrence of fire and the attainment of a value chosen to represent recovery (i.e., the recovery criteria; Figure 3, Table 1). However, recovery timescales of fire effects on hydrologic processes have been noted to vary substantially between regions (Cerdà and Robichaud, 2009). For example, various post-fire recovery timescales for infiltration have been observed such as <1 year (Nyman et al., 2014), 4 years (Cerdà, 1998; Ebel et al., 2022), 4–5 years (Ebel, 2020), 6 years (Robichaud et al., 2016), 7–8 years (Shakesby et al., 1993), and >10 years (Canfield et al., 2005). These vast differences in post-fire infiltration recovery timescales likely occur due to complex and differing effects of wildfire on the various factors contributing to infiltration recovery, such as macropore regeneration (Nyman et al., 2014), vegetation regrowth and ground cover (Canfield et al., 2005; Cerdà, 1998; Ebel, 2020; Robichaud et al., 2016), soil structure (Ebel et al., 2022), and soil water repellency (Shakesby et al., 1993), which vary by watershed conditions and location. The individual soil-hydraulic properties contributing to infiltration can have different recovery timescales, such as the shorter recovery timescale for sorptivity (≤2 years) and longer recovery timescale for hydraulic conductivity (≥4 years) (Ebel, 2020; Ebel et al., 2022).

Streamflow recovery timescales can diverge substantially from infiltration recovery timescales because of the additional dependence on precipitation, evapotranspiration, groundwater recharge, and baseflow. Long groundwater residence times may delay the recovery timescales compared to hydrologic systems where streamflow generation is dominated by shorter timescale mechanisms such as shallow subsurface flow. Streamflow recovery timescales can also vary substantially. For example, there have been observations of wildfire effects on mean annual streamflow persisting for 8–12 years (Nolan et al., 2015), <10 years (Brown, 1972), >30 years (Webb and Jarrett, 2013), and >40 years (Niemeyer et al., 2020). Comparatively, peak streamflow recovery timescales are generally shorter, such as the 2 to 3-year timescales observed in the western USA in several studies (e.g., Bolin and Ward., 1987; Kunze and Stednick, 2006; Moody and Martin, 2001a).

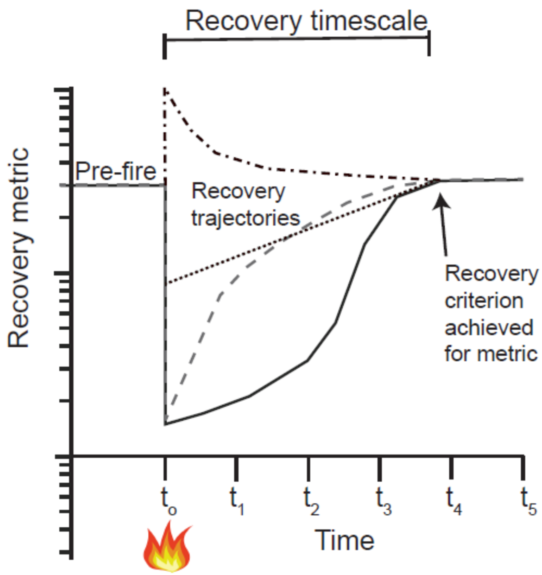

Fig. 3. Recovery timescale example for different hydrologic recovery trajectories following wildfire.

While post-fire recovery timescales vary widely, an additional challenge for comparing recovery timescales is due to differences in the statistical metrics and criteria chosen to quantitatively assess hydrologic recovery. Authors may only qualitatively assess recovery rather than use a specific quantitative metric, as noted by Wagenbrenner et al. (2021), which prevents objective comparison of recovery timescales. As pointed out by Niemeyer et al. (2020), the timescale of recovery is influenced by a broad range of factors including burn severity (e.g., Kinoshita and Hogue, 2011), prior disturbance (e.g., Murphy et al., 2020), pre- and post-fire land management (e.g., García-Orenes et al., 2017), slope aspect (e.g., Cerda et al., 1995), vegetation type (e.g., Nolan et al., 2015), and hydroclimatology in the years after the fire (e.g., Nolan et al., 2015; Wittenberg and Inbar, 2009). Consistent recovery timescale assessment across the scientific community may help site intercomparisons and improve discerning the regional differences in landscape (e.g., edaphic, geologic, vegetation), pyrologic (e.g., percent burned, burn severity, time since last fire), and climatic/hydrologic (e.g., hydroclimatology, dominant runoff generation mechanisms) factors that affect recovery. Variations in recovery timescales for different recovery metrics also highlight the benefit of multiple-metric assessments when estimating recovery timescales.

NEW PROPOSED HYDROLOGIC RECOVERY ASSESSMENT FRAMEWORK

A sequential application of the terminology for hydrologic recovery, identified in this review, can facilitate a new framework for recovery assessment that will enable comparisons across sites. This framework (Figure 4, Table 1) starts with selecting a recovery approach (step 1): statistical, functional, or a combination of both. The second step is to select and calculate the recovery metrics for the system property or hydrologic variable(s) of greatest importance. Next, a user evaluates the recovery criteria (step 3) to determine if recovery has occurred at each of the timesteps. If the hydrologic system has achieved recovery, then trajectories and timescales are determined (step 4). If recovery is not yet achieved, then recovery criteria are re-evaluated at the next timestep (Figure 4).

DISCUSSION

Recovery approaches: A comparison of statistical and functional approaches

Statistical and functional approaches to assessing hydrologic recovery after fire have numerous similarities. For example, metrics for assessment need to be defined for both approaches. Similarly, some quantitative criteria are needed for both approaches to confirm or refute that the selected metrics have achieved recovery. As such, one could argue that if a metric related to hydrologic function and ecosystem services is used, that both the statistical and functional recovery approaches will produce the same results. However, the statistical approach typically requires achieving a quantitative recovery criterion relative to the long-unburned condition. Comparatively, the functional approach has a less stringent quantitative recovery criterion of achieving an acceptable level of hydrologic function, even if it is considerably different from the pre-fire condition. Given these slight differences, if a pre-fire or reference-impacted (i.e., adjacent, similar unburned site) comparison is possible, the statistical and functional recovery approaches could be used in combination (Ebel, 2020; Ebel et al., 2022), potentially leading to a more robust assessment of recovery (two-way arrow in Figure 4).

Advantages and drawbacks of recovery approaches

The statistical recovery approach has the advantage of being a relatively simple and objective analytical approach, which requires defined quantitative criteria to evaluate recovery. A criterion, such as the 95% confidence interval of the pre-fire metric (Wagenbrenner et al., 2021), provides a clear metric to assess recovery. However, the statistical recovery approach has the disadvantage of requiring pre-fire data from the same field site (before-after design) and/or a comparable nearby site (control-impacted design) and also the additional expense of data collection before the fire or in a paired plot or watershed. In their review of post-fire hydrologic recovery in Mediterranean ecosystems, Wagenbrenner et al. (2021) documented that only 2 out of 38 sites had used the most stringent criteria, which combined before-after and control-impact study design (Cosandey et al., 2005; Hoyt and Troxell, 1934). A third type of criterion noted by

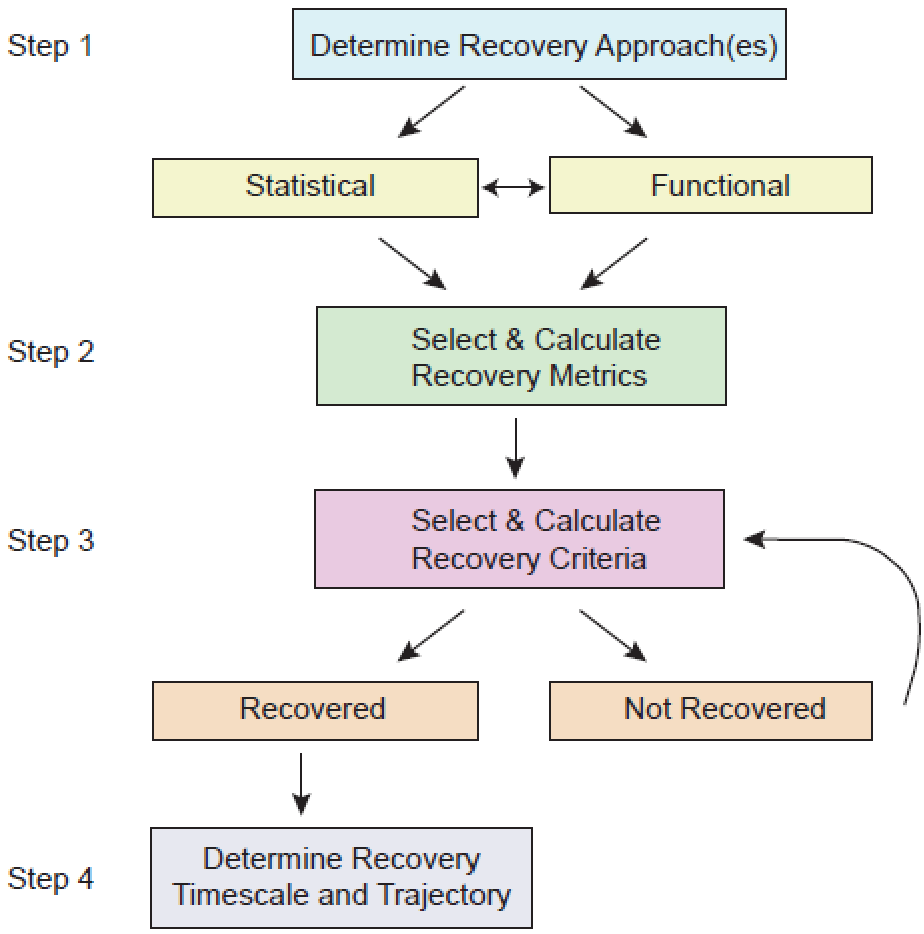

Fig. 4. Proposed hydrologic recovery assessment framework following wildfire. The two-way arrow between statistical and functional recovery assessments indicates that the approaches are not mutually exclusive and can be used in concert.

Wagenbrenner et al. (2021) was the hypothetical design, where it was assumed that the pre-fire condition would result in little to no observed response in the hydrological variable of concern. As such, if there is little to no hydrologic or sediment response to precipitation after the site burns, it was deemed hydrologically recovered (e.g., Andreu et al., 2001; Cole et al., 2020; Hubbert et al., 2012; Keller et al., 1997; Prats et al., 2016). This approach was used in 14 of the 38 sites in Wagenbrenner et al. (2021). Arguably, this type of hypothetical criterion represents functional rather than statistical recovery.

The functional recovery approach has the benefit of not necessarily requiring pre-fire data or a paired site for comparison to the burned hydrologic response. However, the functional approach has the limitation of needing to accurately quantify the hydrologic function requirements for a given purpose or multiple purposes (e.g., De Graff, 2018; Ebel, 2020; Pereira et al., 2021). Additionally, assessment of functional recovery may need to project hydrologic functional adequacy into the future to account for vegetation or climate shifts (e.g., Halofsky et al., 2020). Many functional recovery approaches may be more robust when a hydrologic model is used in combination with observed data using before-after or control-impacted study designs to assess the hydrologic functional recovery. Some recent functional recovery assessments have relied on empirical data supplemented with hydrologic modeling (e.g., Ebel, 2020; Ebel et al., 2022; Flerchinger et al., 2016). The functional recovery approach may also be more intuitive to the public or community organizations and thus lead to greater engagement and support for recovery assessments (e.g., Badik et al., 2022; Gannon et al., 2019; Pereira et al., 2016).

Barriers and challenges for assessing post-fire hydrologic recovery

The influences of climate, vegetation (including variability in pre- and post-fire conditions), landscape position or condition, post-fire land-management, and anthropogenic stressors are major challenges to assess the hydrologic recovery. Numerous efforts assessing recovery have shown that the duration of monitoring greatly affects recovery assessment, and with longer monitoring periods tending to show that sites can oscillate in and out of the recovered state (Cerdá and Doerr, 2005; Niemeyer et al., 2020; Wagenbrenner et al., 2021). In many regions, pre-fire data to assess recovery using a before-after experimental design are unavailable, complicating recovery assessment using a statistical approach. Post-fire drought can delay recovery or give a false impression of recovery. Vegetation change following fire may also alter hydrologic states, fluxes, and function when a type conversion takes place, which could confound achievement of recovery criteria for a given recovery metric (e.g., Collar et al., 2021; Mayor et al., 2016). Recovery trajectories and timescales can also vary widely between vegetation types, complicating selection of recovery metrics and criteria for large regions (Cerdà et al., 2021; Meyn et al., 2007; Novák et al., 2009). Landscape position or condition can also affect the determination of hydrologic recovery, with some slope aspects having different recovery trajectories and timescales (e.g., Cerda et al., 1995; Kinoshita and Hogue, 2011). Post-fire land management, including treatments to reduce runoff and erosion as well as post-fire logging or site preparation for planting can substantially affect recovery trajectories (e.g., Barroso et al., 2021; Cole et al., 2020; Di Prima et al., 2017; García-Orenes et al., 2017; Kim et al., 2021; Leverkus et al., 2021; Vieira et al., 2018; Wagenbrenner et al., 2015) and may influence the selection of a recovery determination approach. Incorporating anthropogenic stressors (e.g., altered disturbance regimes, habitat conversion and degradation, invasive vegetation species, pollution, see Maxwell et al. (2016)) may be essential when assessing functional recovery, especially when projecting hydrologic function of fire-affected watersheds into the future (Kinoshita et al., 2016).

Temporal and spatial variability in post-fire soil properties and hydrologic processes can be an impediment to recovery determination. Spatial variability in post-fire infiltration (Kinner and Moody, 2010; Moody et al., 2019; Pierson et al., 2001), runoff and debris flows (e.g., McGuire and Youberg, 2020; Valeron and Meixner, 2010), and soil moisture (e.g., Cerdà, 1998; Ebel et al., 2012), along with links between soil-water repellency and runoff generation (e.g., Woods et al., 2007), and spatial scale dependency (Ferreira et al., 2005; Wilson et al., 2018) can complicate recovery assessment and potentially require a cost-prohibitive number of measurements to quantify differences in burned and unburned locations (Ebel, 2022). Temporal variability in post-fire measurements, including oscillating recovery trajectories (see Figure 2 and Cerdá and Doerr, 2005; Perkins et al., 2022), can also serve as a barrier to reliable assessment of hydrologic recovery (Pierson et al., 2001).

The assumed inevitability of return to a hydrologically stable condition is not guaranteed and is a potential conceptual barrier to functional post-fire recovery assessment. Hydrologically or ecologically sound endpoints, defined as a set of conditions or functions that benchmark recovery (Hughes et al., 1990), are not singular, and instead multiple stable states may be present after fire (Lasslop et al., 2016; Mirus et al., 2017; Williams et al., 2016b; Wolf et al., 2007). Some of these multi-stable-state systems experience abrupt and rapid transitions between states, such that a system could be assessed as close to, or has achieved, functional hydrologic recovery and then quickly shift to an alternate state with reduced hydrologic function that could cause substantial land and water management challenges (e.g., May, 1977; Scheffer et al., 2001).

Furthermore, many recovery timescales and trajectories are possible depending on the landscape and pyrologic factors (see Figures 2, 3). This makes global or even regional standardization of recovery criteria potentially impractical; however, defining similar regions (such as the U.S. Environmental Protection Agency ecoregions, Omernik (1987)) may aid in developing recovery criteria that are regionally extensible (Hughes et al., 1990). Concepts such as pyromes (Archibald et al., 2013; Boer et al., 2021), combined with biome or ecoregion classifications may aid in developing consistent regional metrics and criteria to assess recovery.

A substantial barrier when comparing statistical recovery of post-fire hydrologic response across sites is an absence of standardization of metrics and criteria, including lack of information regarding what recovery approach, metric, or criteria were used. This barrier could prevent inter-site comparisons of recovery timescales and the factors that most greatly affected hydrologic recovery (Moody et al., 2013; Robinne et al., 2020; Wagenbrenner et al., 2021). Development of suites of metrics and criteria (e.g., Rojas et al., 2022) may advance standardization of recovery assessment after fire. Application of data sources with readily comparable values and widespread geographic availability could also help surmount the barrier of metric standardization. Remotely-sensed data are an example of such widely available data sources that could facilitate common metrics and criteria across study sites for recovery assessment and satellite products such as the change in the normalized burn ratio (dNBR) and leaf-area index (LAI) have been used successfully in post-fire hydrologic recovery assessments (e.g., Ebel et al., 2022; Liu et al., 2021; Moreno et al., 2019; Thomas et al., 2021).

Opportunities to advance hydrologic recovery assessment after wildfire

In this review and synthesis of post-wildfire hydrologic recovery, we highlighted five promising opportunities for advancement. These five identified opportunities were: (1) concurrently using and fusing statistical and functional recovery approaches when feasible, (2) collecting longer-term data with a greater variety of measurement types to facilitate broader ensembles of recovery metrics for more robust recovery assessments, (3) conjunctively using observation and modeling-based hydrologic recovery assessments, (4) developing suites of recovery metrics and criteria for common hydrologic concerns and regions that facilitate comparison of recovery timescales and trajectories across studies, and (5) promoting the use of commonly available data such as remotely sensed metrics of recovery.

SUMMARY

The hydrologic recovery of watersheds is critical for guiding land and resource management both before and after wildfire. We reviewed research focused on hydrologic recovery after wildfire and identified concepts and terminology. We also synthesized a framework to guide hydrologic recovery assessment. The framework links statistical and functional recovery approaches, metrics, and criteria to identify recovery timescales and trajectories. Principal challenges to post-fire hydrologic recovery assessment are the potentially confounding influences of vegetation and climate shifts along with post-fire land management, spatial and temporal variability in measurements, lack of standardization of metrics and criteria, and multiple stable ecosystem states. Five potential opportunities to advance post-fire hydrologic recovery assessments were highlighted and focus on combining statistical and functional recovery approaches, broadening data streams for recovery assessment, and applying more consistent suites of recovery metrics and criteria.

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