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POST-WILDFIRE HYDROLOGIC RECOVERY IN MEDITERRANEAN CLIMATES

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ABSTRACT

Research on hydrology following wildfires typically concentrates on the initial few years, resulting in significant uncertainty regarding the duration of impacts. Knowledge of the time required for hydrologic function to return to pre-fire conditions is crucial for making informed decisions regarding post-fire land and water management. This is particularly relevant in Mediterranean climates, where water is scarce and in high demand, and the severity and extent of wildfires are on the rise. The lack of a consistent definition or interpretation of what constitutes "recovery" contributes to the uncertainty surrounding hydrologic recovery. In this study, we conducted a systematic review of empirical studies from Mediterranean climates that had at least three years of post-fire hydrologic data. Our objectives were to (a) evaluate the recovery period, (b) establish a definition of post-fire hydrologic recovery, (c) demonstrate a straightforward analytical approach to aid in recovery assessment, and (d) outline research needs and opportunities to better quantify post-fire recovery. We analyzed the hydrologic effects reported in 38 sites that were monitored for 3-20 years. Eighteen sites were deemed to have recovered within seven years; however, the recovery time varied across sites and was not linked to location, response variable, or study design. The probability of recuperation during the study period was found to decrease as the proportion of the watershed area burned increased. It is noteworthy that we have proposed a standardized definition and methodology for quantifying hydrologic recovery, which may facilitate cross-study comparisons and a more profound comprehension of recovery. Specifically, we suggest that hydrologic recovery has transpired when a particular post-fire hydrologic function or condition of interest returns to the 95% confidence interval of the pre-fire condition. To support this definition, we have demonstrated the application of this straightforward approach to evaluate recovery and presented future research areas to enhance our understanding of long-term post-fire catchment responses. Furthermore, in addition to the requirement for more studies that quantify hydrologic responses further into the post-fire period, comprehending post-fire changes in soil structural and hydraulic properties over time will

enhance our mechanistic understanding of post-fire hydrologic responses and recovery.

1. INTRODUCTION

In recent decades, there has been a notable increase in wildfire activity across various regions of the world. This includes the length of wildfire seasons, the number of fires, the area burned, and the severity of the fires. Such upward trends are expected to persist in certain areas due to climate change, population growth, and fire suppression efforts. This has led to mounting concerns regarding the economic, social, and environmental impacts of increasingly severe wildfires.

Moreover, there are significant gaps in the literature regarding the extent, magnitude, and duration of the effects of wildfires on water supplies. Given the increased frequency of wildfires in many regions, coupled with significant declines in both water quantity and quality, it is imperative to address these knowledge deficiencies. Consequently, several studies have emphasized the need to incorporate fire into local, regional, and global assessments of catchment vulnerability to disturbances on hydrologic processes.

An increasing number of studies have undertaken an investigation into the impact of wildfires on water quantity, water quality, aquatic ecology, and downstream drinking water supply. These studies have demonstrated that wildfire can alter soil hydraulic properties and runoff generation mechanisms, resulting in heightened annual water yields, low flows, and peak flows for several years or even decades following the fire. Additionally, mineral soils that are exposed are highly vulnerable to hillslope erosion or debris flows, which can transport sediment and other contaminants from burned hillslopes to streams. When combined, these and other post-fire changes in source water quantity and quality have the potential to propagate over long distances downstream, adversely affecting aquatic ecosystem health and creating significant challenges for drinking water treatment.

Numerous studies have demonstrated that there is a peak in hydrologic impacts during the initial response period, which is typically several years after a wildfire. This is followed by a decline at varying rates before returning to the pre-fire condition or some alternate stable state. The longevity and trajectory of the recovery curve can 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. Burn severity is often considered a key control on the magnitude of post-fire hydrologic responses, while post-fire precipitation is another important factor that can explain much of the variability in local responses. Other important controls on downstream processes include the proportion of catchment burned and the regrowth of vegetation, which is often related to the regeneration mechanism (i.e., seeding versus resprouting) and post-fire weather patterns. Evidence also suggests that the resiliency of the ecosystem in the face of increasing wildfire activity can alter the recovery trajectory.

The majority of studies that have examined the impact of wildfires on water quantity or quality have primarily concentrated on the initial effects, which span a period of less than five years. However, there exists a dearth of research that has investigated the longer-term effects of wildfires, despite the clear evidence of the crucial importance of conducting long-term studies. Additionally, only a limited number of datasets have incorporated pre- and post-fire hydrologic responses from hillslopes or small catchments for a duration that is sufficient to enable statistical evaluation of longer-term post-fire responses. Consequently, the longevity of post-fire hydrologic effects remains uncertain, thereby impeding the ability to predict catchment processes during the post-fire recovery phase and the longer-term management of post-fire conditions.

Recent evaluations of global wildfire hazards to water security have revealed that some of the most vulnerable cities are situated in Mediterranean climates. Furthermore, due to the significant variability in annual and seasonal precipitation, water demand often surpasses available resources in many regions with Mediterranean climates, necessitating the use of dams and water conveyance infrastructure. However, these structures may be adversely affected by increased post-wildfire sediment yields. In Mediterranean climates, post-fire hydrologic responses are typically caused by long-duration cyclonic or frontal systems, resulting in periods of high-intensity precipitation that can lead to overland flow. These responses differ from those in other fire-dominated climate regimes, such as convective precipitation in areas with warm continental climates or the effects of fire on subsurface flow in areas with boreal climates and permafrost. Additionally, a significant portion of post-fire hydrologic research has been conducted in Mediterranean climates, providing an opportunity to combine findings from experiments with comparable climates and vegetation to identify commonalities.

The quantification of the lasting impacts of wildfires remains a challenging task, primarily due to the varying definitions of recovery. Therefore, it is imperative to clarify the concept of post-fire hydrologic recovery and apply a more rigorous approach to test whether post-fire responses have recovered. This will aid in improving models and predictions for post-fire land and water management decisions. Our working hypothesis is that the post-fire response, measured as a deviation from the pre-fire range of variability, will return to the pre-fire condition within a predictable period, constrained by a distribution of natural variability. This theoretical recovery period may differ depending on the hydrologic process of interest, such as runoff generation, transpiration, or rainfall interception. Regardless of the parameter of interest, we hypothesize that the dominant controls on post-fire recovery rates are burn severity, precipitation timing and magnitude, and vegetation regrowth. These factors can lead to a wide range of possible post-fire recovery trajectories. We further hypothesize that with sufficient 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 objective was to identify and summarize previous research conducted in Mediterranean climates that could provide a sufficient level of information to quantify the probable range of post-fire recovery periods, with the aim of aiding post-fire management and research. Specifically, we evaluated empirical studies in Mediterranean climates to achieve the following objectives: (a) synthesize results from longer-term post-fire hydrologic studies to assess the recovery period and bound the recovery timescale, (b) establish a common definition of post-fire hydrologic recovery to unify terminology, (c) demonstrate a straightforward analytical approach to aid in the 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. Our focus was on studies that addressed surface water quantity and sediment delivery. However, the general recovery framework and principles of analysis presented here are applicable to other physical and chemical water quality metrics.

2. MATERIALS AND METHODS

2.1 Site Characteristics

As a result of the significant impact of temperature and precipitation patterns on vegetation composition and productivity, as noted by Bailey (1989), and the potential for similarities in hydrologic response and recovery, as highlighted by Hallema et al. (2018b), our analysis has been focused on climate type rather than ecoregion or location. Specifically, our review has centered on areas with Mediterranean climates, as defined by the Koppen-Geiger classification system. These climates are characterized by temperate conditions with dry summers and wet winters, with the driest summer month producing less than 40 mm of precipitation and less than one-third of the precipitation of the wettest winter month, as described by Peel et al. (2007). Within this classification system, the Csa class is characterized by hot, dry summers with a maximum mean monthly temperature (Tmax) greater than 22 ◦C during at least one month and all months with a mean monthly temperature above 0 ◦C. The Csb class, on the other hand, has warm summers with Tmax < 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). While a third class (Csc) exists for cold summers, where between one and four months have a mean temperature of at least 10 ◦C, this class is less prevalent and was not included in our review. These climate conditions are typically found between 30◦ and 40◦ latitude (Lionello et al., 2006), extending to about 49◦ north latitude in western North America (Peel et al., 2007). The majority of land area with Mediterranean climates is located in the Mediterranean Basin, with other significant regions in southwestern Australia, Chile, the Cape of South Africa, and California in the United States (Dahm, 2010).

Despite their geographical separation, Mediterranean climate regions exhibit similarities in vegetation due to climate-driven convergence in ecosystem structure and dynamics. These regions are characterized by highly flammable sclerophyllous shrublands, known as maquis in the Mediterranean Basin, chaparral in California, matorral in Chile, fynbos in South Africa, and mallee and kwongan in Australia. These ecosystems are adapted to hot, dry summers and generally support crown fires, yet are resilient in terms of regrowth.

Regions with Mediterranean climates are home to a relatively large proportion of the world's population, tourism trade, gross domestic product per capita, and Earth's flora, despite covering only 1.5% of the global land area. The precipitation seasonality in these regions increases fire frequency, and when combined with relatively high population densities and resultant increased human ignitions, has led to increased wildfire occurrence and severity in recent decades.

2.2 Post-fire hydrologic recovery metrics

Hydrological recovery following either natural or anthropogenic disturbance has been defined as the restoration of pre-disturbance hydrological characteristics, such as interception, evapotranspiration, or streamflow, to near pre-disturbance conditions (Buttle et al., 2018; Hudson, 2000). Furthermore, the assessment of recovery is dependent on specific processes, outputs, temporal and spatial scales, and applications or objectives, such as aquatic habitat, flood protection, recreation, or community drinking water supply. These various factors complicate the assessment of recovery; however, the complexity can be reduced by metrics that simplify analysis.

Although numerous metrics are available, we propose metrics that could be beneficial to various end-users interested in post-fire hydrological recovery, by potential use: water supply, water-related hazard, infrastructure, and ecological habitat. We utilized 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 usefulness of metrics in assessing recovery. The October-November 2003 Old Fire burned approximately 87% of the City Creek catchment (50.8 km2), including 13% at high severity and 57% at moderate severity (Kinoshita and Hogue, 2015). Daily precipitation data were used.

Hourly discharge and precipitation data were acquired for the water years spanning from 1 October 1989 to 30 September 2017. In August 1990, a fire took place in the Rimbaud catchment, covering approximately 85% of the catchment at an unspecified severity (Lavabre et al., 1993). Hourly precipitation and discharge data were obtained for the water years 1968-2010 through personal communication with N. Folton from the Institut National de Recherche en Sciences et Technologies pour l’Environnement et l’Agriculture on 14 May 2018. For statistical analysis, we utilized water years 1989-2003 for City Creek and 1968-1990 for the Rimbaud catchment for the pre-fire periods. We calculated various metrics for both the pre- and post-fire periods, including the runoff ratio, slope of the flow duration curve using an exponential fit, and flows that were exceeded 90% (Q90, low flow) and 10% of the time (Q10, high flow). Additionally, we determined the proportion of time with no flow at Rimbaud, which had intermittent streamflow. The runoff ratios were calculated on an annual timescale (water years), and the other metrics were calculated using hourly time steps consistent with the temporal resolution of the discharge data. We excluded observations when there was no flow for the frequency analyses, which was more common at the Rimbaud catchment due to its smaller size and intermittency. Furthermore, we excluded data from Rimbaud when more than 10% of the observations were missing.

We utilized relatively uncomplicated statistical methods to evaluate the restoration of hydrological conditions, employing selected metrics. Our aim was to enhance the practicality of our approach for a diverse range of users. We computed 95% confidence intervals for the pre-fire metrics, assuming a t-distribution (Helsel and Hirsch, 2002). With the exception of the slope of the flow duration curve and the Rimbaud Q90, all City Creek metrics exhibited some degree of skewness, and thus, we log10-transformed these values prior to determining the confidence intervals. Subsequently, we calculated and graphed the metrics from the post-fire period, and deemed that a state of recovery had been achieved if the post-fire metrics fell within the 95% confidence interval of the pre-fire period.

3. DEFINITION OF RECOVERY

Throughout our review, we encountered a lack of a definitive definition of recovery, despite 13 of the studies we examined including an evaluation of recovery. A number of studies linked hydrologic recovery, at least in part, to burn severity or the relatively rapid recovery of vegetation. One study presented a conceptual model that posited the recovery period varied with post-fire precipitation (Keller et al., 1997), and precipitation was identified as a controlling factor in 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 controlling factor in hydrologic recovery (Andreu et al., 2001), while another study suggested that pre-fire disturbance may impact post-fire recovery rates (Vieira et al., 2016).

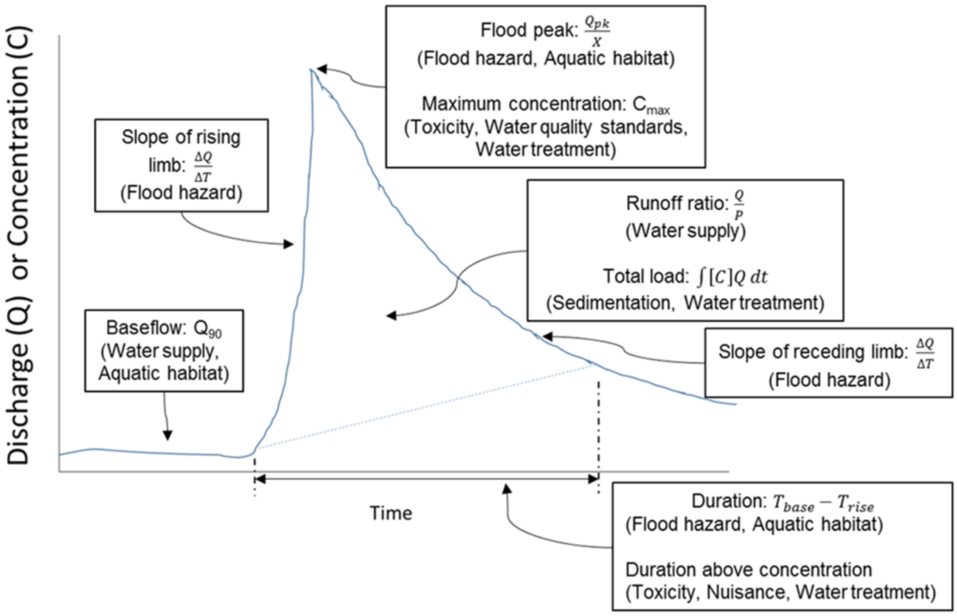
Nonetheless, by the conclusion of the five-year study, it was evident that the response had not yet undergone a full recovery. Even when employing a simpler hypothetical criterion for recovery, there was no definitive consensus regarding the duration required for hydrologic responses to revert to pre-fire conditions. Numerous studies utilized runoff measures that were pertinent to specific sites or objectives, such as storm, monthly, or annual runoff rates, or peak discharge rates. However, the diverse range of measurement techniques and data reporting approaches rendered comparisons across sites challenging. Consequently, we propose the utilization of metrics to aid in quantifying recovery across varied locations in future studies. Recovery would be deemed to have occurred when the post-fire metrics fall within the confidence intervals of the pre-fire metrics.

4. EFFECTS OF CLIMATE ON RECOVERY

The observation of site specificity in hydrologic response and recovery, as evidenced by our review studies, presents significant challenges in identifying recovery trends across regions or climate types. For instance, the American Southwest, with its Monsoonal convective storms, may exhibit post-fire responses with greater magnitudes than other regions (Moody and Martin, 2009). Furthermore, the occasional occurrence of exceptional rainfall intensity in this area may complicate assessments of recovery. Similarly, despite more consistent precipitation conditions (Moody and Martin, 2009), regions with continental climates in the western United States may experience recovery periods lasting longer than five years.

The process of defining a typical period for hydrologic recovery is a complex task, particularly in Mediterranean climates, due to the temporal variability of high-intensity rainfall and soil moisture status. Numerous studies have linked observed rainfall intensity or erosivity to the generation of post-fire peak discharges or sediment delivery. If a high-intensity rainfall event occurs on catchments where the vegetation, surface litter, and soil structure have not returned to pre-fire conditions, a significant hydrologic or sediment delivery response may occur later in the post-fire period. These delayed responses can disrupt the apparent recovery trend and lead to an erroneous assessment of recovery. Furthermore, these 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 significant 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. Given the risk of large responses, recovery likely takes longer than commonly understood, which is a crucial consideration when planning research, watershed monitoring, or emergency management after large fires.

Numerous studies within our systematic review have examined the probable impacts of climate change on future fires and, consequently, post-fire hydrologic responses. However, any connections between climate change and specific post-fire responses remain highly uncertain. Nevertheless, it is anticipated that climate change will result in longer fire seasons, larger fires, and increased burn severity. Additionally, climate models predict greater variability in weather patterns, including the possibility of more frequent droughts and extreme precipitation events in certain Mediterranean regions, such as California and the Mediterranean Basin. These combined factors are likely to exacerbate post-fire hydro-geomorphic responses and increase variability in post-fire hydrologic recovery. To comprehend the range of possible post-fire hydrologic recovery trajectories, it is necessary to undertake field campaigns and modeling efforts that account for sources of variability in weather patterns and address the hydrologic changes associated with post-fire regeneration. A crucial step in this direction would be to enhance our ability to scale inferences from hillslope-scale studies to catchment-scale responses. Another concern regarding shifting wildfire regimes under current and future climates is the growing 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-affected state (i.e., not recovered) under future climate conditions.



5. CONCLUSION

A systematic approach was employed to synthesize research on post-fire hydrologic recovery in regions with Mediterranean climates. Despite the existence of numerous studies on post-fire hydrologic responses, only 28 studies, covering 38 sites, were identified as meeting the inclusion criteria for a systematic review. These sites were located in the western United States and the Mediterranean Basin and were utilized to investigate responses to fires that occurred between 1924 and 2015. Of the 18 studies whose original data met the criteria for recovery, the timescales for hydrologic recovery ranged from zero (i.e., no post-fire response) to seven years. There was no discernible 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 present a proposal for a standardized definition of post-fire hydrologic recovery, which entails the return of a particular post-fire function or condition of interest to the 95% confidence interval of the pre-fire state. We acknowledge that metrics can be tailored to meet the specific requirements of diverse stakeholders and subjected to varying degrees of statistical rigor, as demonstrated through confidence interval testing. Adopting this approach could enhance our capacity to compare post-fire hydrologic recovery across future investigations. However, the limited number of available studies precluded the validation or refutation of our conceptual model regarding the recovery time necessary for specific burn severity and post-fire weather patterns. To address this apparent gap in future post-fire hydrologic research, we propose guidelines and identify several opportunities for further inquiry, including extending the duration of planned and ongoing post-fire hydrologic studies and initiating investigations that elucidate the reestablishment of soil structure and associated hydrologic properties.

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