Earth's Future

COMMENTARY

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Special Section:
Fire in the Earth System

Key Points:

- Australia's unprecedented wildfire season 2019/2020 was part of a complex hazard cascade of partly extreme and partly moderate events
- We study the complete hazard cascade of drought, fire, rain, flood, and soil erosion in the Manning River catchment, New South Wales
- We show that hazard cascades can amplify the impacts of moderate events, which requires renewed consideration in risk management

Supporting Information:

- Supporting Information S1

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Cascading Hazards in the Aftermath of Australia's 2019/2020 Black Summer Wildfires

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Abstract Following an unprecedented drought, Australia's 2019/2020 "Black Summer" fire season caused severe damage, gravely impacting both humans and ecosystems, and increasing susceptibility to other hazards. Heavy precipitation in early 2020 led to flooding and runoff that entrained ash and soil in burned areas, increasing sediment concentration in rivers, and reducing water quality. We exemplify this hazard cascade in a catchment in New South Wales by mapping burn severity, flood, and rainfall recurrence; estimating changes in soil erosion; and comparing them with river turbidity data. We show that following the extreme drought and wildfires, even moderate rain and floods led to undue increases in soil erosion and reductions in water quality. While natural risk analysis and planning commonly focuses on a single hazard, we emphasize the need to consider the entire hazard cascade, and highlight the impacts of ongoing climate change beyond its direct effect on wildfires.

Plain Language Summary In 2019/2020, a chain of natural hazards impacted Australia's East Coast. Following the severest drought since weather records began, record-breaking wildfires known as the "Black Summer" ravaged the region for months. In early 2020, the rainfall that extinguished the last of these fires caused further damage, as the burned soils repelled much of the rain. Water took the exposed soil and charred vegetation with it on its way to the rivers, flooding streets and polluting drinking water. We show an example of this cascade of hazards in a single river catchment. We found that after the wildfires, even moderate rainfall caused floods, increased soil erosion, and reduced water quality drastically. Natural risk analyses mostly focus on single types of events in isolation. However, this hazard cascade shows that, especially in the face of ongoing climate change, scientists and decision makers need to consider events not just by themselves, but connected with each other.

1. Introduction

Australia's 2019/2020 "Black Summer" fire season was exceptional in terms of the number of fires, burned area, and fire severity (Baldwin & Ross, 2020; Deb et al., 2020; Hughes et al., 2020). The fires followed an unprecedented drought; 2019 was the driest year on record (Hughes et al., 2020; van Oldenborgh et al., 2021). Throughout the continent, the fires caused direct damages to humans and ecosystems, including at least 33 directly fire-related deaths, 3,100 homes lost, an area of at least 24 million hectares burned—the size of the United Kingdom—, and never before seen air pollution levels in major cities (Davey & Sarre, 2020; Hughes et al., 2020; Royal Commission into National Natural Disaster Arrangements, 2020; Vardoulakis et al., 2020). The wildfires led to the formation of a record number of pyrocumulonimbus clouds that reached the lower stratosphere over southeastern Australia (Kablick III et al., 2020).

Wildfires cause hydrometeorological and geomorphic changes that can heighten the susceptibility of burned areas to other hazards; for example, raised soil water repellency after a fire can lead to increased runoff (Shakesby & Doerr, 2006). This was the case with the 2019/2020 fires: following an extreme drought, the fires were the second step in an entire cascade of adverse processes (Figure 1). Next, rainfall in February 2020 triggered increased surface runoff and eroded ash and soil. Entrained ash, plant, and soil deposits enhanced sediment concentration in rivers, damaging infrastructure and compromising water quality

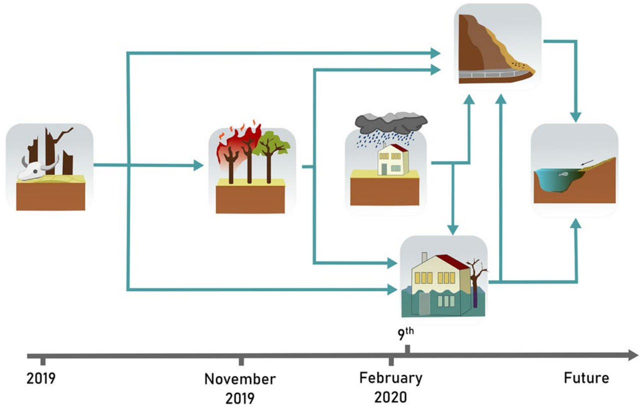

Figure 1. Australia's 2019/2020 hazard cascade. Drought increased the likelihood of wildfires, which burned vegetation and raised the likelihood of increased surface runoff, soil erosion and hillslope failures. When heavy rain fell in early 2020, runoff from burned areas led to flooding and entrained ash, soil, and organic matter, increasing sediment concentrations in rivers and negatively impacting water quality.

(Alexandra & Finlayson, 2020). In some cases, the ash-laden water contaminated water bodies such as the Lake Burragorang reservoir, Sydney's main drinking water supply (Figure S1).

Extreme impacts, like those observed in Australia in early 2020, are often caused by a combination of several drivers (Figure 1). Their linkage can lead to a so-called cascading event characterized by an initial impact that triggers other, partly unexpected, effects of potentially destructive magnitudes (Pescaroli & Alexander, 2015). However, the underlying drivers are mostly studied separately and without considering their potential interactions (AghaKouchak et al., 2018; Zscheischler et al., 2018). Appraisals of flood risk in Australia, for example, may underestimate the actual risk, if neglecting the impacts of an antecedent fire in the upstream catchment. When extreme impacts are combined, their effect can be greater than the sum of their parts, making a holistic approach crucial to analyzing event sequences (AghaKouchak et al., 2018; Gill & Malamud, 2016; Hegerl et al., 2011; Zscheischler, Martius, et al., 2020). The analysis of cascading events remains challenging because completely documented cascades are scarce, suitable indices and methods for their quantification are limited, and bulk uncertainties are often much higher than for single events (Kappes et al., 2012; Schauwecker et al., 2019; Zscheischler, Martius, et al., 2020). Here, we illustrate the stages of a hazard cascade in a catchment in New South Wales (NSW), Australia (Figure 2a). We argue that considering the hazards separately may lead to serious misestimates of magnitudes, intensities, and durations of the processes involved, all of which may reverberate on hazard and risk appraisals.

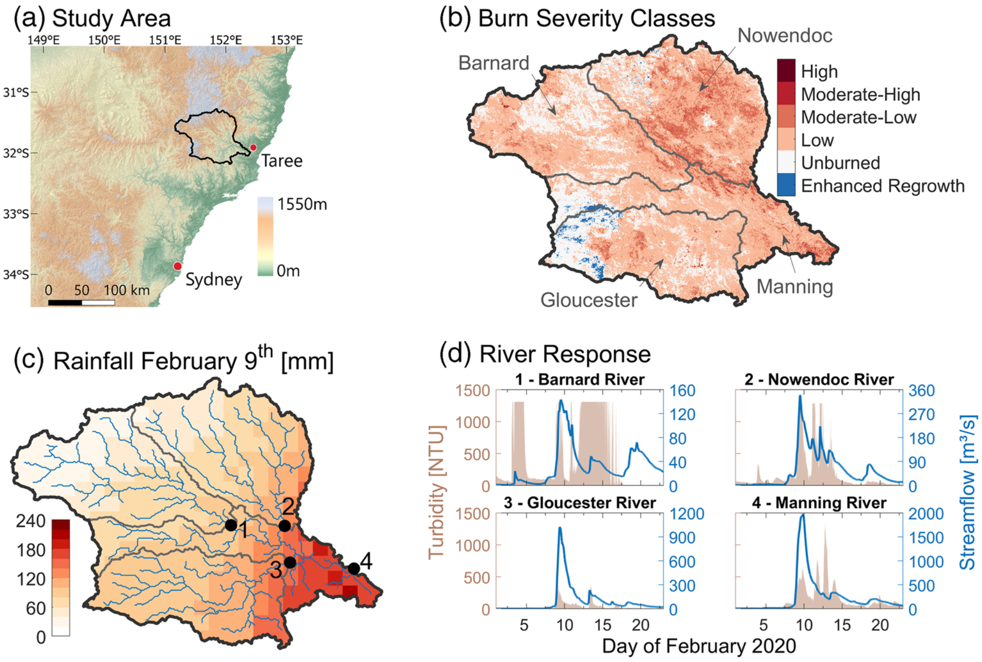

Figure 2. Study area. (a) The Manning River catchment is located 250 km north of Sydney in one of the steepest regions of New South Wales, Australia. (b) Fires affected the tributaries of the Manning River differently, with the highest burn severities occurring in the Nowendoc catchment. (c) Gridded rainfall data for February 9th, 2020, show increasing rainfall totals toward the coast. 1-Barnard River (Mackay), 2-Nowendoc River (Rock's Crossing), 3-Gloucester River (Doon Ayre), 4-Manning River (Killawarra). (d) Turbidity in brown and discharge in blue for Manning River and its tributaries between February 1st and 22nd.

During 2019/2020, the Manning River catchment was affected by drought, fires, heavy rainfall, and high sediment fluxes. Three of its tributaries experienced different degrees of burn severity (Figure 2b) and rainfall amounts (Figure 2c), allowing us to compare the postfire impacts on streamflow and soil erosion (Figure 2d). By moving through the sequence of hazards, we explore how certain events triggered and influenced each other, changing their susceptibility as the event chain developed and its effects propagated throughout the catchment.

2. Cascade Onset: Drought and Heat

2019 was the driest year on record in Australia (van Oldenborgh et al., 2021), with the lowest rainfall on record from July to December in many parts of southeastern Australia (Nolan et al., 2020; data accessible from http://www.bom.gov.au/climate/history/rainfall/). Neutral El Niño-Southern Oscillation conditions and a positive Indian Ocean dipole were the main causes for the drought (King et al., 2020; van Oldenborgh et al., 2021). In summer 2019, this event was accompanied by the highest mean maximum temperatures since recording began in 1910, with the highest anomalies in December 2019 surpassing those of the "Angry Summer" of 2012/2013 (van Oldenborgh et al., 2021). This extraordinary drought was a key driver of the wildfires, whereas the role of fuel accumulation due to fire suppression is still disputed (Bradstock et al., 2020).

Based on gridded rainfall data (Jones et al., 2009, see supplements) we find that 2019 was the driest year in the Manning River catchment since at least 1970 with a catchment average of only 440 mm of rainfall, or 42% of the average annual rainfall of 1,040 mm from 1970 to 2018. In December 2019, the river ran completely dry at Killawarra (Figure 2d) for the first time on record (since 1945), where it has a daily average streamflow of 55 m^3/s.

3. Initial Impact: Extreme Wildfire

Wildfires are a frequent natural hazard in Australia and have caused substantial economic and environmental impacts in the past. Yet the 2019/2020 fires were exceptional in scale, and likely linked to anomalous weather conditions driven by climate change (Bowman et al., 2020; Deb et al., 2020; van Oldenborgh et al., 2021). They burned the largest continental fraction of any forest biome in at least 2 decades (Boer et al., 2020). Insurance claims from these fires totaled $2.34 billion AUD, making up 44% of all natural disaster claims for the entire fire season (Whelan, 2020). In comparison, wildfires accounted for 12% of normalized insurance losses from natural hazards between 1966 and 2017 (McAneney et al., 2019). The total loss also far exceeds that incurred by the 2009 "Black Saturday" fires, when insurance claims totaled $1.2 billion AUD (Victorian Bushfires Royal Commission, 2010). In NSW the fires caused the largest area burned and highest property loss ever recorded (Hughes et al., 2020).

The 2019/2020 fires also had detrimental health effects. Most prominently, smoke-related air pollution had an unprecedented burden on public health, with 417 total pollution-related excess deaths in eastern Australia (Queensland, NSW, Australian Capital Territory, Victoria) of which 219 were recorded in NSW (Borchers Arriagada et al., 2020). Smoke-related hospital admissions for cardiovascular and respiratory conditions totaled 3,151, with 1,627 cases in NSW (Borchers Arriagada et al., 2020).

To assess the overall scope of burning in the Manning River catchment, we classified burn severity by calculating the differential Normalized Burned Ratio (dNBR) from pre and postfire satellite imagery from February 2019 and January 2020 respectively (Figure 2b) (Key and Benson, 2002, 2006); methods are described in the supplements (Alleaume et al., 2005; Barrett, 2006; French et al., 2008; Kinnell, 2010; Lentile et al., 2006; Soverel et al., 2010; Walz et al., 2007). While dNBR-derived burn severity levels solely define burn-induced magnitude of radiometric change, Chafer (2008) conducted field studies in NSW to provide a calibration to fire effects on vegetation community strata observed on the ground. They reported that low severities signify burned grass and herbs; moderate severities imply consumed shrubs; high severities indicate scorching of the lower canopy; and very high severities denote the consumption of stems with diameters <10 mm (Chafer, 2008). We found that wildfires in the Manning River catchment, which occurred from mid-November to mid-December 2019 (Data.NWS NPWS, https://data.nsw.gov.au/data/dataset/fire-history-wildfires-and-prescribed-burns-1e8b6), burned (dNBR > 0.1) a total area of 4,765 km^2 or some 72% of the catchment (Figure 2b). Moderate to high burn severities (dNBR > 0.27) mostly occurred in the Nowendoc tributary, where 57% (463 km^2) of the catchment area burned with this intensity at least (Table S1).

4. Subsequent Effects: Floods, Soil Erosion, and Water Quality

Heavy rainfall eventually extinguished fires throughout NSW in February 2020. The rain replenished depleted water reservoirs, but also led to the next hazard in the cascade. The resulting runoff flooded parts of Sydney and other cities in NSW, caused mass movements which disrupted infrastructure, and washed soil, ash, and debris into water bodies (Figure S1). Insurance claims of $896 million AUD were lodged in response to the rainstorms and associated floods (Insurance Council of Australia, 2020).

According to gridded rainfall data between 1970 and 2018 (see supplements), the Manning river catchment averaged 78 mm of rainfall on February 9th alone (Figure 2c), which is about 58% of an average February rainfall total in 1 day. On the scale of the entire catchment, such rainfall totals occur once in $5.6\,\frac{+17.3}{-2.4}$ years on average (Tables S2–S3). Rainfall was most intense in the southern part of the catchment (Figure S2), where two rain gauges measured their second highest values in records of at least 43 years (see supplements).

Although parts of the Manning River catchment witnessed heavy rainfall in February 2020, the resulting floods, which we define here as the peak streamflow following the February 9th rainfall event, were only minor. The return periods of the February 9th floods range from $1.8\,\frac{+0.6}{-0.3}$ years (Nowendoc catchment) to $4.7\,\frac{+9.8}{-1.7}$ years (Gloucester catchment), and are thus lower than those of the preceding rainfall (Tables S3–S4). We hypothesize that low soil moisture in the catchment following the drought led to decreased streamflow (Sharma et al., 2018; Wasko et al., 2019). The hydrographs (Figure 2d) show no signs of extensive surface runoff, which would form a narrow sharp spike minutes to a few hours before the main flood peak (Shakesby & Doerr, 2006).

Water quality was drastically affected by this flood. In the Manning, Barnard and Nowendoc Rivers, turbidity data logged in February 2020 show sharp peaks with no precedence in the 5–7 years on record (Figure 2d). In some cases, the turbidity exceeded the sensor measurement scale. The uncalibrated turbidity values only allow a relative comparison of sediment loads in the tributaries. In the 6 years of shared record prior to the 2019 fire season, synchronous turbidity peaks for the Gloucester and Nowendoc River were of almost equal magnitude (see supplements). In the more severely burned Nowendoc catchment the magnitude of the turbidity peak associated with the February 2020 flood was six times higher than in the less severely burned Gloucester catchment.

We apply the RUSLE model (Kinnel, 2010; Renard et al., 1991) to estimate first order the pre and postfire soil erosion rates within the Manning River catchment based on rainfall erosivity, soil erodibility, steepness, land cover and management, using input parameters from preexisting datasets (Yang et al., 2015, 2018) (see supplements). The dNBR burn severity is included by adjusting the postfire land cover-factor accordingly (Blake et al., 2020; Larsen & MacDonald, 2007) based on satellite data from February 2019 and 2020. The estimated postfire soil erosion rates range from 11-27 t h^{-1} y^{-1} (Table S1), reflecting an increase of over 200%. The absolute values and relative changes are consistent with field measurements from severely burned catchments in NSW (Atkinson, 2012; Blake et al., 2020; Shakesby & Doerr, 2006). The increases in estimated soil erosion in the three tributaries range from 88% in the Gloucester catchment to 358% in the Nowendoc catchment (Figure S3 and Table S1). The difference in the increase of erosion rates between these two tributaries is consistent with the respective increase in turbidity values, and likely linked to commensurate differences in burn severity.

5. Conclusions and Outlook

The 2019/2020 hazard cascade observed in the Manning River catchment in southeast Australia highlights how the impact of ongoing climate change on wildfires affects the likelihood and magnitude of adverse consequences from other hazards that are in parts physically linked to each other. We show that following extreme drought and wildfires, moderate rainfall and flood events were sufficient to increase estimated soil erosion and reduce water quality far beyond expected levels in the absence of fires. These amplifying effects of individual impacts within hazard cascades are still insufficiently considered in risk analysis. It is crucial to fill this knowledge gap in hazard and risk appraisals, as moderate processes in hazard cascades can incur much more damage than when they occur on their own.

Climate change is projected to increase the frequency of compounding extreme warm and dry periods in Australia and beyond (Kharin & Zwiers, 2005; Zscheischler et al., 2017), which could lead to further event cascades like the one in 2019/2020 (Zscheischler, van den Hurk, et al., 2020). Indeed, in 2020, following Australia's "Black Summer," the western United States experienced its most-extensive fire season in 70 years, while extensive fires burned across Siberia (Irannezhad et al., 2020; Pickrell & Pennisi, 2020). So far, however, we can draw on only few examples of thoroughly studied hazard cascades. Mitigating the effects of climate change will require investigating these complex interactions, including these events in risk analysis and planning, establishing consistent monitoring systems to be better prepared for future hazard cascades (Bowman et al., 2020; Royal Commission into National Natural Disaster Arrangements, 2020), and increasing adaptive capacity in affected regions.

Data Availability Statement

Gridded rainfall data were obtained from the Australian Bureau of Meteorology and is available at http://www.bom.gov.au/climate/maps/rainfall. Station rainfall data were obtained from the Australian Bureau of Meteorology and is available at http://www.bom.gov.au/climate/data. Discharge and turbidity data were obtained from the State of NSW (Lands and Water) and is available at http://www.bom.gov.au/waterdata. The soil erosion data from the State Government of NSW and Department of Planning, Industry and Environment is available at https://datasets.seed.nsw.gov.au/dataset/modelled-hillslope-erosion-over-new-south-wales. Landsat OLI imagery is available from the US Geological Survey (https://www.earthexplorer.usgs.gov). Images from Sentinel are from Sentinel Playground, https://apps.sentinel-hub.com/sentinel-playground, Sinergise Ltd.

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