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Research papers

How does wildfire and climate variability affect streamflow in forested catchments? A regional study in eastern Australia

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ABSTRACT

The impact of wildfire on catchment water yield remains uncertain, with case studies reporting a range of observed response paths. Additionally, the impacts of fire and climate variability are often intertwined, making them difficult to evaluate separately. This study assesses how wildfire and climate influence streamflow in forested catchments. We focused on selected forested catchments in eastern Australia that have experienced both sustained drought and large fire events, but otherwise have experienced little hydrological modification. We compared the relationship between streamflow and rainfall before and after the severe fire events in the 2019/2020 season and over a longer multi-year period. We obtained historical data for streamflow, rainfall, and wildfire extent, timing, and severity for each catchment. The study found a consistent increase in streamflow with given rainfall after the 2019/2020 fire event. However, the timing of the fire aligned with the end of a prolonged major drought that affected the region. Dry conditions decrease runoff while fire increases it, which makes it difficult to attribute the flow increase to fire alone. We also assessed the relative importance of multiple potential drivers (climatic and fire-related) of changes in streamflow over a longer, multi-year historical period. We found that the impacts of historical wildfires on streamflow are generally smaller than the impacts of hydro-climatic factors such as catchment storage, which has a relative importance for the streamflow over 3 times greater than that of the fire-related factors. Our results imply that historical changes in flow in the study region are more heavily affected by climate variability than by fires at the catchment scale. They emphasize the importance for water resources management of considering regional drivers such as changing climatic conditions over wildfire, which often affects only parts of individual catchments.

1. Introduction

Streamflow in forested catchments can be influenced by multiple factors including climate, land cover, land use change and wildfire, along with other human activities such as extraction of surface water and groundwater. To facilitate effective management of forested catchments, it is important to understand the responses of streamflow to changes in these driving factors. Such understanding becomes more critical when considering the global trends of climate change, increasing deforestation and more frequent occurrence of wildfire events.

A significant body of literature has established the impact of climate change on water yield in forested catchments. Climate change may alter hydroclimatic regimes in many areas of the world (Dai, 2013) and significantly affect water availability (Milly et al., 2005). Climate change directly affects water resources by changing the amount, magnitude, duration, and timing of precipitation (Crockford and Richardson, 2000), which then influences baseflow, groundwater recharge, and runoff (Karl et al., 2009). For example, while temperatures and potential evapotranspiration are predicted to increase for the east coast of Australia, the average rainfall and runoff are projected to decrease, along with winter and spring rainfall (CSIRO and Bureau of Meteorology, 2015). Further indirect influences of climate change may include a short-term increase in plant water use due to increased temperature, thereby decreasing the amount of effective rainfall for

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recharging streamflow or groundwater (Ford et al., 2011); or changes in forest water use efficiency with elevated CO_2 levels via increasing photosynthesis and net carbon uptake (Keenan et al., 2013; Jasechko, 2018). In the long term, global warming is likely to change the composition and distribution of forest communities (Iverson et al., 2008) via alterations to hydroclimatic conditions (Sun et al., 2011; Vose & Klepzig, 2013), which can in turn affect forest water use. Finally, stochastic and extreme hydroclimatic events are projected to increase worldwide (Kelly et al., 2016). These events include extreme precipitation, flooding events and droughts, which pose greater challenges for water resources compared with historic conditions (Ford et al., 2011).

Apart from climate change, another key natural disturbance for forested catchments is wildfire. The impacts of forest wildfires are mainly related to reduced canopy interception and evapotranspiration and enhanced nutrient losses and soil erosion (Meyer et al., 2001; Nolan et al., 2014; Khaledi et al., 2022). Fires can also change soil structure, decrease soil porosity and increase hydrophobicity, thereby affecting the

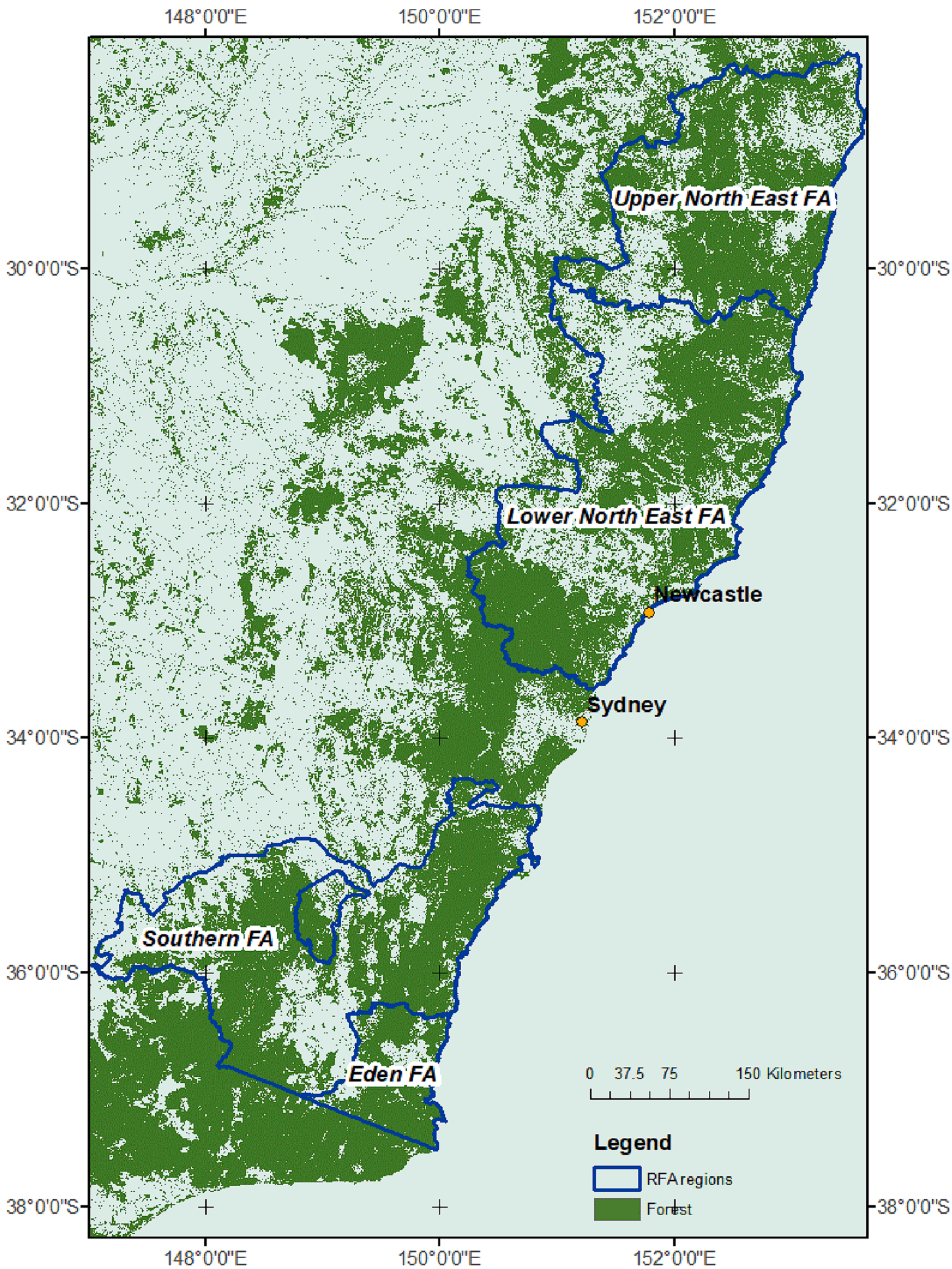

Fig. 1. Map of the study region – NSW RFA regions, comprised of the North East FA (upper and lower), Southern FA and Eden FA. Dark green in the base map indicates forested areas.

hydraulic conductivity and infiltration rates of soil. This, in turn, can increase surface runoff during rainfall or storm events (Elliott and Vose, 2006). In the longer term, some types of regenerating eucalypt forests often require more water after fire than the mature forests that they replace, thus leading to reduced water availability. This can take a decade for severely burnt resprouting eucalyptus forests (Nolan et al., 2015) or decades for tall-wet eucalyptus obligate seeder forests (Kuczera, 1987; Vertessy et al., 2001; Inbar et al., 2022).

The intertwined occurrence and impacts of climate variability and fire on forested catchments make it challenging to understand their effects separately. In eastern Australia, a region that is heavily driven by both fire and climate variability, fire is becoming more frequent and severe, especially during the droughts that often occur during El Nino conditions (Canadell et al., 2021). The summer of 2019–2020 saw eastern Australia experience fire events of unprecedented severity (Nolan et al., 2020). On the other hand, the region is also influenced by La Niña events resulting in wetter conditions. Under the influence of both fire events and climate variability, the post-fire responses of streamflow can vary substantially with the recent and long-term hydrologic and climatic conditions (e.g., Zhou et al., 2015; Feikema et al., 2013; Khaledi et al., 2022). However, the existing literature is mainly small-scale case studies, highlighting a gap in regional scale understanding on these impacts (Khaledi et al., 2022). This study aims to extend understanding of how streamflow in forested catchments responds to disturbances from climate and fire over large regions. Specifically, the study explores two research questions:

1. Focusing on the season of 2019/2020, when an unprecedented fire event occurred in the study region, has streamflow changed in response to the fire event, and if yes, how?
2. Over the longer historical period, what are the key hydroclimatic and fire-related factors that affected streamflow?

2. Methods

2.1. Study region

This study focuses on the state of New South Wales (NSW) in eastern Australia, a key region of interest for forest management (Fig. 1). The study area was the three NSW Regional Forest Agreement (RFA) regions: the Eden FA, the North East FA (with upper and lower regions) and the Southern FA. These NSW RFA regions mostly have a temperate climate with a small portion of subtropical climate areas in the north. RFAs provide a national management framework and include both conservation and production forests (ref something describing RFAs). To understand how streamflow changes and link any change with wildfire and climate, we focused on catchments within the NSW RFA regions that have long-term historical records of streamflow, are primarily forested, have no or little hydrological modification, and have experienced large fire events.

2.2. Data acquisition

2.2.1. Streamflow and flow monitoring sites

Daily streamflow data were obtained from WaterNSW, which maintains and operates the largest continuous water monitoring network in NSW. All of WaterNSW's data have been collated, quality checked and made publicly available via its online portal (https://realtimedata.waternsw.com.au/).

There are 282 WaterNSW monitoring sites within the NSW RFA regions. The daily streamflow time-series of all these sites were extracted for the full record period at each site (i.e., since the start of record, up to Sep 2021 when this study commenced). Within the 282 sites, we selected 90 monitoring sites that maintained high quality long-term streamflow records, spanning longer than 35 years with at least 350 days of high-quality records each year (i.e., no more than 15 days' gap in each year). The coordinates of the 90 monitoring sites were also obtained to enable identification of the boundaries of the contributing catchment for each site (Section 2.2.2).

2.2.2. Catchment boundaries

The catchment boundaries were delineated to enable us to summarize climate conditions and the extent of wildfire at a catchment level. Further, these boundaries also enabled the extraction of land cover condition and hydrological modification at a catchment level, allowing us to select suitable study catchments.

The catchment boundaries corresponding to the 90 long-term monitoring sites were delineated using ArcMap based on the site locations. The Australian Bureau of Meteorology's (BoM) Geofabric dataset (Bureau of Meteorology, 2012) was used to identify upstream contributing areas. The delineated catchment areas were then compared against an alternative source of catchment area information provided by WaterNSW, which confirmed that any discrepancy was no larger than 10% of individual catchment areas.

2.2.3. Historical climate and forest disturbance data

To represent the climate condition at a catchment scale, we first extracted the long-term data on the catchment-scale climate conditions. Nation-wide daily gridded rainfall and potential evapotranspiration (PET) data were both available at 5 km × 5 km scale, with the former dataset provided by the BoM's Australian Water Availability Project (AWAP) (Raupach et al., 2009) and the latter provided by The Queensland Government SILO database (Queensland Government, 2022). We then used the delineated catchment boundaries to clip the gridded data to obtain the daily time-series for rainfall and PET over the period of corresponding streamflow record for each of the 90 catchments.

To answer research question 1, we focused on the 2019/2020 major wildfire event and relied on a map of fire severity of the 2019/2020 event across NSW (NSW Department of Planning and Environment (DPIE), 2020). This map shows the variation of fire severity across space with six different classes: unburnt, low severity (burnt understory, unburnt canopy), moderate severity (partial canopy scorch), high severity (complete canopy scorch, partial canopy consumption) and extreme (full canopy consumption), where 'extreme' indicates the most severe class of burn. We estimated the percentage of area affected by each fire severity class in each catchment by overlaying this fire severity map with the catchment boundaries, using ArcMap spatial analyst.

To answer research question 2, we used a long-term historical wildfire dataset for NSW (NSW Natural Resources Commission (NRC), unpublished data) which consists of spatial layers of the extent of individual fire events within NSW along with their timings, dating back to 1900. When overlaying this dataset with the boundary of individual catchments with ArcMap spatial analyst, we were able to obtain a time-series of historical percentage area burnt for each catchment. However, this long-term dataset does not contain information on the severity of individual fire events. To fill this information gap, we obtained the monthly nation-wide vegetation cover maps derived from MODIS satellite, which spans the historical period since 2001 (Guerschman, 2019). These dynamic vegetation cover maps were further processed to be used as a proxy of fire severity (Section 2.4.2).

2.2.4. Spatial data on forest cover and hydrological modification

To assist the selection of natural, forested catchments to identify any impact of fire, further spatial data were obtained to represent forest cover and the extent of hydrologic modification of each catchment. The specific datasets obtained, and their purposes were:

- NSW woody area extent for 2019 (NSW NRC, unpublished data). This identifies forested regions in NSW, and thus enabled the extraction of the percentage area covered by forest for individual catchments.

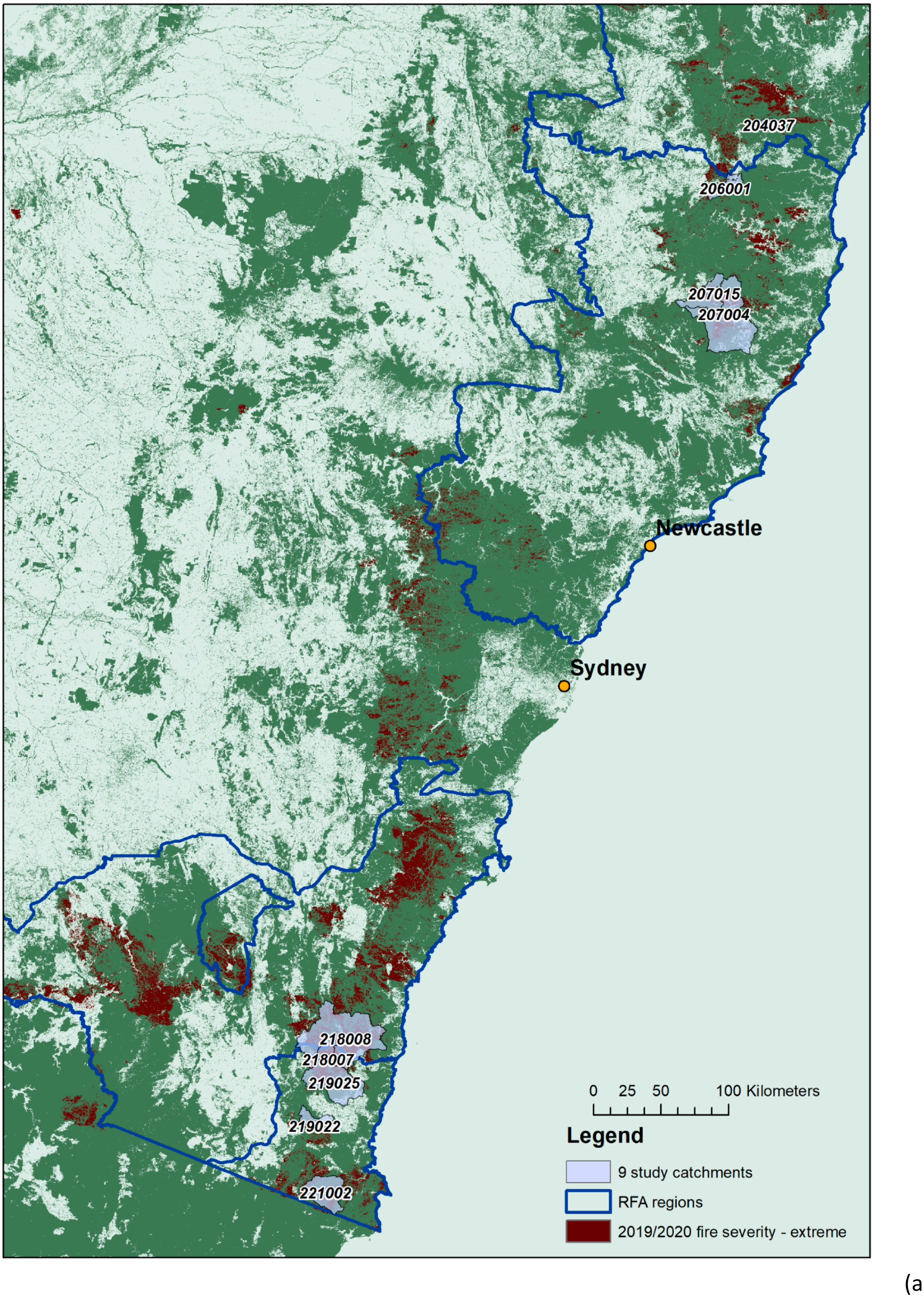

Fig. 2. Maps of a) the nine selected severely burnt catchments to address research question 1, with red shading highlights regions which experienced 'extreme' fire severity during the 2019/2020 fire event; b) the twelve selected catchments that have experienced large fire events over history to address research question 2. The background maps highlight the forested areas in dark green.

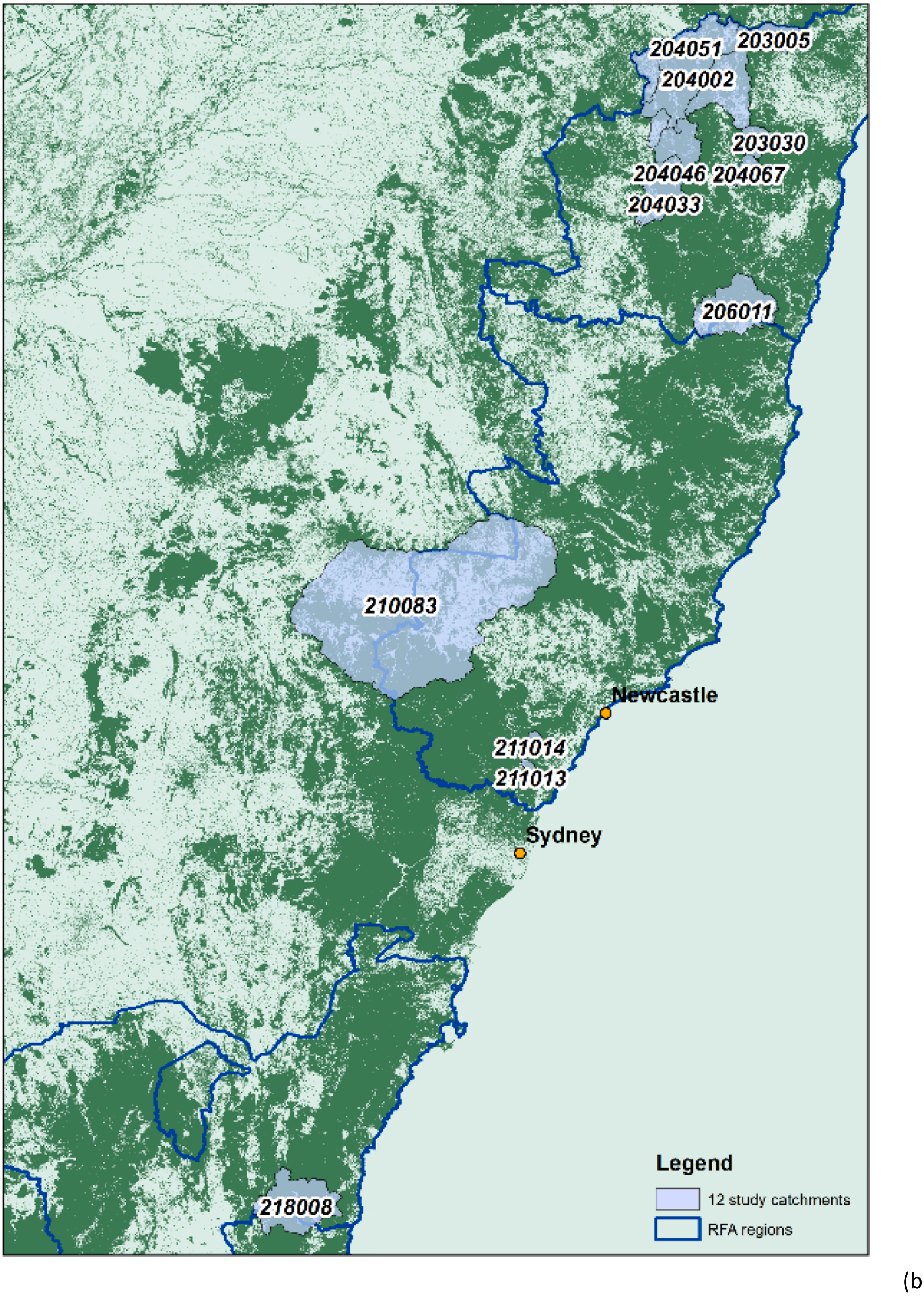

Fig. 2. (*continued*).

- Australian dams and water storages (Geosciences Australia, 2009; publicly available at: https://koordinates.com/layer/739-australian-dams-and-water-storages/data/). This dataset on the locations and characteristics of Australian dams and water storages was used to infer hydrological modification. Here we consider the hydrology of a catchment being substantially modified where large dams are present within the boundary of this catchment. A large dam was defined as any dams that is more than 15 m in height, or a dam that is more than 10 m in height, with the crest length over 500 m and the capacity over 1 million m^3 (Australian National Committee on Large Dams Incorporated (ANCOLD), 2012).

2.3. Study catchment selection

We focused the analyses on natural catchments primarily covered by forest to avoid potential confounding effects of other land uses and human activities on streamflow. We only considered catchments with more than 50% of total catchment area covered by forest (Section 2.2.4). To ensure that catchments were free from hydrological modification, catchments with large dams (Section 2.2.4) were excluded from further analysis.

A final consideration for the selection of study catchments was the disturbance by wildfire. Since the effect of wildfire can be highly localized, we expected that fire events only affecting a small portion of a catchment would make it difficult to detect clear responses of streamflow to fires. Therefore, we focused only on catchments that experienced large fire events, for which different selection criteria were applied in answering the two research questions (which explore fire impacts over the single fire season in 2019/2020 and the full historical record, respectively). The fire map for the 2019/2020 season included the spatial distribution of fire severity (Section 2.2.3). For this single-season analysis, we only retained catchments with at least 10% of the catchment area labelled as being ‘extremely’ burnt, regardless of additional areas with lower fire severity; this enabled us to focus on the most severely burnt catchments only. For the long-term analysis, considering that the historical fire maps did not contain information on fire severity, we retained catchments with at least 10% catchment area burnt within at least one year of the record. The percentage of catchment area burnt was derived by summing the burnt extent time-series (Section 2.2.3) for each year and then dividing it by the corresponding catchment area. Note that this threshold is lower than 20%, which the current literature typically suggests is the threshold of percentage burning area required to lead to significant post-fire flow responses (Hallema et al., 2018; Saxe et al., 2018; Wine et al., 2018). Our threshold was chosen considering the generally limited extent of historical fires in the region, with only three catchments having had any year with fires burning over 20% of the catchment area.

Overall, the selection process identified nine and twelve catchments within RFA to investigate research questions one and two, respectively (Fig. 2, Summary data for the selected catchments are provided in Tables S1 and S2 in the Supplementary Material). The detailed analytical approaches for the two research questions are described in Sections 2.4.1 and 2.4.2.

2.4. Attributing flow changes to climate and fire

2.4.1. Understanding flow responses to the single 2019/2020 fire event

To understand the responses of streamflow after the 2019/2020 fire event, we used both direct data-interpretation and a model-based approach to identify changes in rainfall-runoff relationship across pre-fire and post-fire periods. These analyses were run on a monthly time-step so that they were less influenced by the natural variability of daily flow, which otherwise could potentially mask any impact of fire.

The direct data interpretation was done by plotting the monthly flow against the monthly rainfall. This enables identification of significant change of the rainfall-runoff relationship after the 2019/2020 fire event and linking with the potential impact of the fire. Considering that the change after fire can be sensitive to the baseline, we assessed how the post-fire relationship changed from two different pre-fire baseline periods: 1) starting from 10 years before the fire i.e., using only the recent data since 2010; 2) of the full pre-fire historical record period (see Table S1 in the Supplementary Materials). The rainfall-runoff relationships were first assessed with visual interpretation. To quantify the extent and significance of the change in streamflow in reaction to the 2019/2020 fire event, the regression lines between streamflow and rainfall for the pre/post fire data were estimated; this was achieved by running an analysis of variance (ANOVA) to test for significant difference in the slopes of these regressions, which represent the rainfall-runoff relationship.

To complement the above analyses and further attribute any post-fire change in flow, a model-based analysis was formed based on simulations of a five-parameter, monthly conceptual rainfall-runoff model, WAPABA (Wang et al., 2011). WAPABA has demonstrated comparable to or better performances in simulating monthly water balance, when benchmarked against two other widely used conceptual rainfall-runoff models in Australia, the Australian Water Balance Model (AWBM) and SimHyd across 331 catchments in Australia. Therefore, the WAPABA model is suitable for the purpose of this analysis while being parsimonious.

The monthly water partition and balance (Wapaba) model partitions total rainfall at each time step into: 1) catchment water consumption via replenishing the soil water store and returning to the atmosphere through evapotranspiration, and 2) catchment water yield to replenish the groundwater store and to produce runoff within the month. The groundwater store is drained to produce baseflow in subsequent months. The sum of surface runoff and baseflow are accounted as total monthly flow.

The total catchment water consumption in a month is dependent on the rainfall, the potential evapotranspiration, the soil water storage deficit in the previous time step, and a model parameter α_1, the catchment consumption curve parameter. The soil water storage deficit is calculated as the difference between the soil water store level and the maximum capacity of the soil store, which is another model parameter, S_{max}. The water available for evapotranspiration in a month is the sum of total catchment water consumption and the level of soil water store in the previous time step. The actual evapotranspiration is then determined by this water available for evapotranspiration and model parameter α_2, the evaporative curve parameter. The catchment water yield (i.e., the part of rainfall after the catchment water consumption is allocated) is partitioned into surface runoff and water recharging the groundwater, for which the split is determined by model parameter β (proportion of catchment yield as groundwater). Baseflow production follows a linear storage-outflow relationship, which is regulated by the model parameter K (time constant). All parameters were calibrated as outline below.

The model was calibrated to the monthly flow using the mean squared error as the objective function and differential evolution as the optimization algorithm. The calibration period spans over 20 years of historical data from 1975 to 1996 at each catchment, which represents the average normal climate condition over the region. The period between 1997 and 2019 was a dry period. It spans the Millennium drought from 1997 to 2009 (van Dijk et al., 2013; Bureau of Meteorology, 2022), which mainly affected the southern part of the state, followed by another drought between 2017 and early 2020, which affected the entire state (Bureau of Meteorology, 2022). The period after the 2019/2020 fire event for each catchment was considered as the post-fire period. The calibrated model was then used to simulate flow for: 1) 1975–1996 average conditions; 2) 1997–2019 drought conditions and 3) the post-fire condition. We assumed that the model is capable of capturing flow under average long-term conditions, while flow signals are influenced by wetter/drier weather conditions as well as the 2019/2020 fire event. Therefore, by studying the model residuals (difference between the modelled and actual flow), we can identify any ‘unexpected’ flow response that can be attributed to climate variability or the 2019/2020 fire event. Specifically, we used the pairwise Wilcoxon test to check for any statistically significant difference in the distribution of model residuals between 1) and 3), and 2) and 3), with the aim to understand the potential impact of the 2019/2020 fire on flow with respect to the average and drought conditions.

In both the above analyses, the rainfall-runoff relationship prior to the 2019/2020 fire event may be influenced by other historical fire events. To ensure that the pre-fire data accurately represent the baseline rainfall-runoff relationship, we checked the fire history of each catchment in the pre-fire period. None of the catchments had experienced a historic fire event that burnt greater than 10% catchment area. We therefore assumed that any impact of fire on the rainfall-runoff relationship is minimal compared to that of the 2019/2020 fire, which enabled us to retain the full historic pre-fire data period in each catchment to calculate the baseline rainfall-runoff relationship.

2.4.2. Linking flow changes to historical fire and climatic variability

To explain historical changes in flow in response to climate and fire, we used the residuals of a linear regression between annual rainfall and annual runoff as the response variable. This allowed the analysis to focus on any unexpected change in runoff after excluding the effects of rainfall variability. These residuals represent the deviations of annual flow from expectation for the corresponding rainfall, and can thus inform whether changes in streamflow are due to changes in rainfall or other potential drivers. The flow data were Box-Cox transformed to removed skewness from the data and improve the fit of the linear regression.

For the potential climatic drivers of flow, we considered the potential evapotranspiration (PET) of the current year, the lowest seven-day average flow in the previous year, along with a number of attributes that capture the seasonality and variability of rainfall within the current year (Table 1). Annual rainfall was not included as a potential predictor as our focus on the rainfall-runoff residuals inherently assumes that any influence of annual rainfall has already been considered.

In addition to climate, two further potential drivers were considered to represent the extent and severity of wildfire. To represent the former, the time-series of percentage area burnt for each catchment (Section 2.2.3) was aggregated to an annual scale by summing the percentage area burnt within each hydrologic year. A preliminary data exploration was performed to compare the start of hydrologic year and fire season in each catchment with the historical records of flow and fire; for catchments where the start of water year cuts through the fire season, an appropriate offset before each hydrologic year starts was used as the start of the summation period for the annual fire-affected area. This ensures that any fire disturbance and flow response captured in our analyses are representative of the current year.

To represent the severity of wildfire in individual catchments over time, the monthly MODIS satellite-derived vegetation cover maps (Section 2.2.3) were further processed. Since the fire events often only affect a proportion of the catchment, we focused on the vegetation cover change before and after each fire event only within the burnt region of the catchment. This was used as a proxy of fire severity and ensured that only the most relevant vegetation responses to fire were captured. Further, vegetation cover can potentially change even without fire, due to seasonality, climate and catchment wetness, etc. Therefore, the change in vegetation cover within the unburnt region of the catchment was also considered to represent the background vegetation change. Thus, we extracted two time-series for each catchment to capture the difference of vegetation cover before and after fire, for areas both within the burnt area of individual fire events and within the unburnt area corresponding to these fire events. Each time-series was generated by clipping the monthly nation-wide vegetation cover maps to the corresponding burnt/unburnt regions resulting from individual fire events in the catchment, where the latter were obtained from the long-term historical fire extent maps (Section 2.2.3). We then used the difference of the two time-series to obtain a time-series of the relative change in vegetation cover in the catchment, which represents the vegetation cover change in response to fire, after excluding any background noise due to other vegetation changes such as responses to seasonality, climate and catchment wetness (Fig. 3). This time-series of the relative vegetation cover change was then aggregated to an annual scale using a weighted sum within each hydrologic year; the weights were assigned based on the burnt area of individual fire events within the year, so that

Table 1
Potential climatic and fire-related drivers considered to explain temporal changes in flow, and their corresponding data sources and available record period. The 'full period' means that the dataset covered the full historical period when flow data was available.

Potential driver and acronym used			Data source and available record period	Definition and derivation
Climate	Annual PET	*AnnPET*	Queensland Government SILO database (Queensland Government, 2022) Available for full period	Annual PET of the current year.
	7d low flow (previous year)	*low7dPrev*	WaterNSW flow data (same as used for water quantity trend analysis) Available for full period	The average flow over the 7 days with lowest flow in the previous year. This is an indication of catchment storage.
	Rainfall seasonality	*Seasonality*	BoM AWAP dataset (Raupach et al., 2009) Available for full period	The seasonal incidence of rainfall, determined from the ratio of median rainfall for two periods 1) May to October and 2) November to April, within each water year (Bureau of Meteorology, 2016; Gaffney, 1971).
	Annual maximum dry spell length	*maxDry*		The annual (within each water year) maximum number of consecutive days with daily precipitation < 1 mm (Bureau of Meteorology, 2019).
	Annual median dry spell length	*medDry*		The annual (within each water year) median number of consecutive days with daily precipitation < 1 mm (Bureau of Meteorology, 2019).
	Extreme rainfall frequency	*extremeFreq*		The annual number of days with rainfall exceeding the long-term 95th percentile of all daily rainfall (Haylock and Neville, 2000).
	Extreme rainfall intensity	*extremeInt*		The annual average daily rainfall for days with rainfall exceeding the long-term 95th percentile of all daily rainfall (

(continued on next page)

Table 1 (*continued*)

Potential driver and acronym used			Data source and available record period	Definition and derivation
				Haylock and Neville, 2000).
	Extreme rainfall proportion	*extremeProp*		The extreme intensity divided by the year's total rainfall (Haylock and Neville, 2000).
Wildfire	Fire extent	*burnt_perc*	Long-term historical maps of wildfire over NSW (NSW NRC, unpublished data) Available for full period	Total percentage catchment area burnt each year.
	Fire severity inferred by vegetation cover difference	*vegDiff*	MODIS monthly nation-wide fractional vegetation cover maps (Guerschman, 2019) Available 2001–2021	Total relative difference in fractional vegetation cover before/after fire events each year.

a fire event with larger extent was weighted higher in the summation. The relative vegetation cover change then became a continuous estimate of fire severity, as opposed to the categorical definition as used for the 2019/2020 fire (Section 2.4.1). The vegetation cover dataset was only available from 2001, which limited the period of this analysis of explaining historical flow changes to post 2001.

Combining the above potential drivers of flow on climate and wildfire, we assessed importance and impact of individual drivers using a Random Forest model with bootstrapping. Random Forests are a widely-used machine-learning model (Breiman, 2001; Geurts et al., 2006) that evaluate a large number of different combinations of potential predictors to explain changes in the response variable, with different model structures including non-linearity and lagged effects. The best combination of predictors and model structure are selected, and from this the importance of individual predictors can be evaluated.

3. Results

3.1. The impact of the 2019/2020 fire on flow

The relationships between streamflow and rainfall for the 10 years before the 2019/2020 fire and up to 30 months after the fire are shown for 9 forested catchments that were most severely burnt during the event (Fig. 4), which highlights a general increase in flow for a given amount of rainfall following the 2019/2020 fire event. Comparing the linear regression slopes going through the pre-fire and post-fire data, the post-fire slopes are steeper than the pre-fire slopes for all catchments, with increase in slope ranging from 29% to 145% (Table 2). Six out of the nine catchments show a statistically significant (at $p < 0.05$) increase in the slopes of rainfall-runoff relationships from pre- to post-fire. Most catchments that show a significant change in these slopes are in the southern part of the state (218007, 218008, 219022, 219,025 and 221002), which generally also have lower elevations (Tables S1).

The same analysis was extended over the full historical period for which rainfall and streamflow data were available (Fig. 5). The post-fire slopes between streamflow and rainfall are again steeper than the pre-fire slopes for all catchments with a 43% to 61% difference in the regression slopes (Table 2, Fig. 5). The differences in the pre-/post-fire slopes are less evident compared with those in Fig. 4, with statistically significant differences only found at three catchments (206001, 219,022 and 219025),

The above results suggest an overall increase in post-fire flow for given rainfall; more insights on attributing this flow increase were obtained from analysing the results of a conceptual rainfall-runoff model, WAPABA (as detailed in Section 3.1). We assessed the model residuals and compared them across the three simulation periods, which can help informing the relative change in flow and whether the flow is as expected (Fig. 6). The pre-fire model simulations for normal climate condition have well-behaved residuals that are symmetrically distributed both above and below zero, which suggests that the model generally well captures the flow under normal climate conditions (i.e., with no systematic underestimation or overestimation). The pre-fire drought simulations are generally more biased towards negative values; this highlights that the model generally overestimates flow for the drought period. For catchment 206001, the post-fire flow is significantly lower than that during average conditions and similar to the drought condition. Although the slope of flow to rainfall significantly increases after the fire in our previous results (Fig. 5), the negative residuals in the post-fire flow observed in Fig. 6 suggest that it was still lower than expected. For 207,004 and 207015, the flow during the post-fire period is significantly lower than that for both the drought and average conditions. The low post-fire flow of these catchments might be result of shifting rainfall-runoff relationships during the prolonged drought between 1997 and 2010, leading to reduced flow for given amount of rainfall, and with non-recovery of the rainfall-runoff relationship continuing till after the drought period concluded and into the wetter post-fire period (Saft et al., 2015; Peterson et al., 2021).

For catchments 204037, 219,022 and 219025, we see the post-fire flow being significantly higher than during drought conditions, but not showing a significant difference from the average long-term climate condition. Therefore, the flow of these three catchments seems to have recovered from the drought after fire. The potential interactions between the 2019/2020 fire with the prolonged drought and its recovery

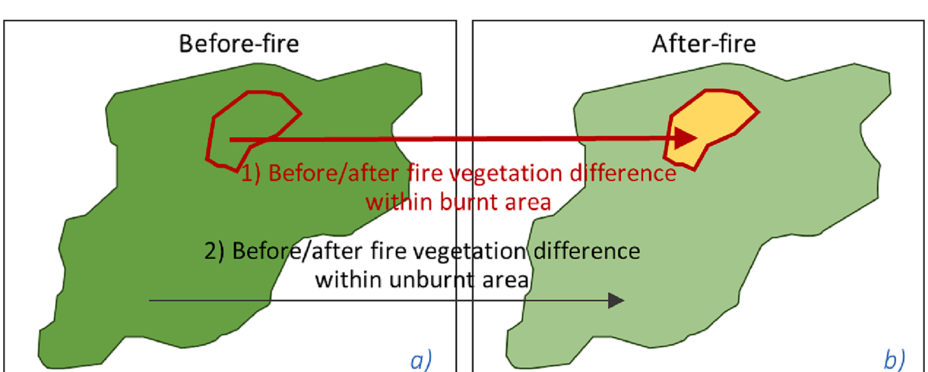

Fig. 3. An illustration of the process we used to calculate vegetation change for Question 2. Each panel shows a map of a catchment (bounded by green border), and the area affected by a single fire event (bounded by red border) for a) before fire and b) after fire. Vegetation cover is illustrated with shaded colours. The relative change in vegetation cover that we extracted is the difference between the burnt area and the unburnt area in the vegetation cover change before/after fire. This is intended to capture the vegetation cover change in response to fire, after excluding any background noise due to other catchment changes such as seasonality, climate and catchment wetness.

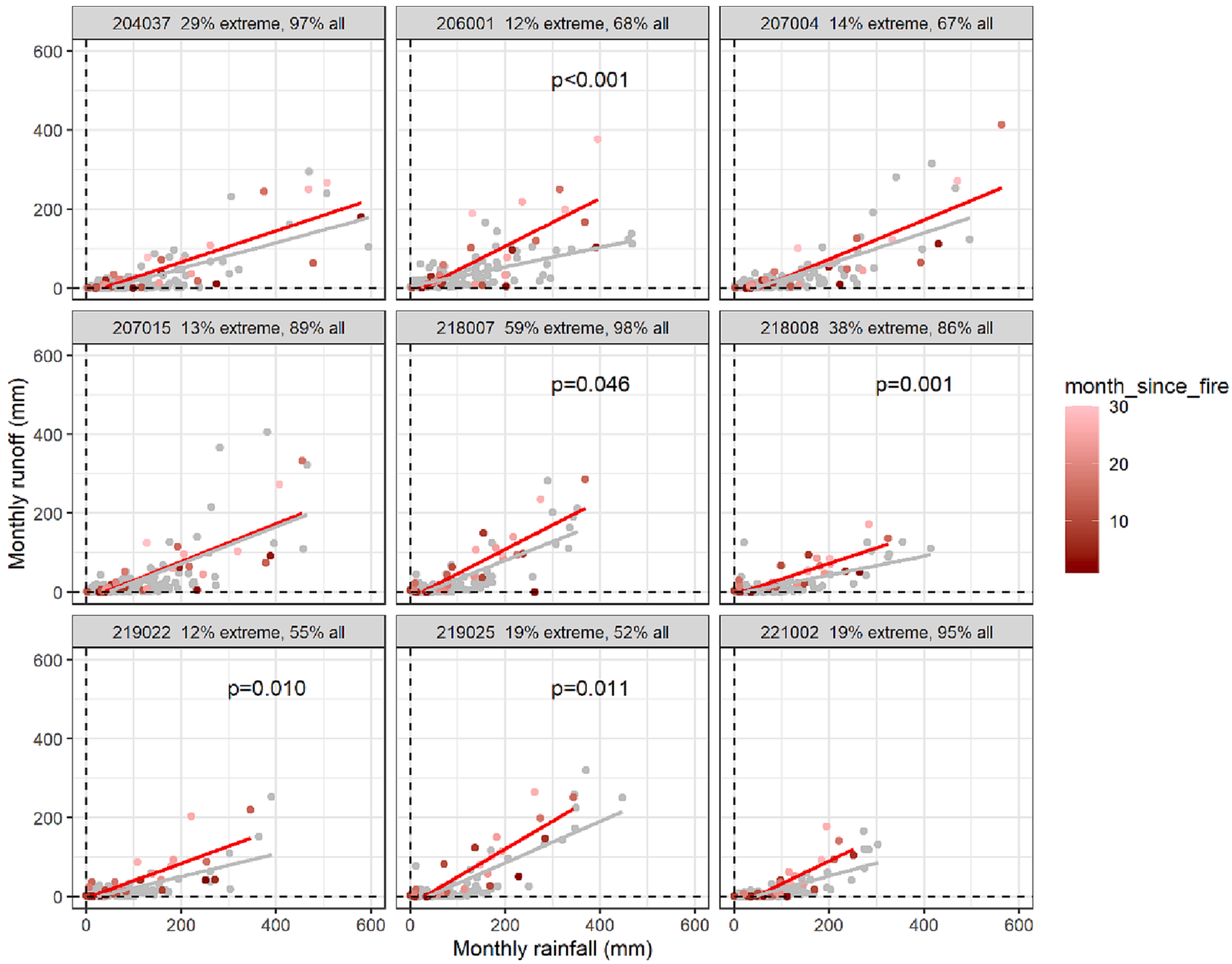

Fig. 4. Comparison of the monthly runoff against the monthly rainfall before and up to 30 months after the 2019/20 fire event (as grey and red dots, respectively) at 9 catchments that were most severely burnt – see the percentage of each catchment as 'extremely burnt' (full canopy consumption) labelled above each panel; the percentage burnt regardless of severity is also included in the labels. A darker red dot indicates a date closer to the fire occurrence. The linear regression lines for the post-fire (red line) and pre-fire (grey line) data are shown in solid lines. They represent the post-fire and pre-fire regression lines between streamflow and rainfall. The p-values of the ANOVA are shown for catchments that display statistically significant differences in the slopes of pre- and post-fire regression lines at a 0.05 level based on an ANOVA test. The comparison includes all data from Jan 2010 (10 years before the 2019/2020 fire) to Sep 2021.

Table 2
The slopes of the regression between the monthly flow and rainfall, fitted to the pre-fire and post-fire data for each catchment, the percentage difference from the pre-fire to post-fire slope, the corresponding p-value of the ANOVA test between the pre/post fire slopes and the residual degree of freedom. Each regression was fitted twice to two different sets of pre-fire data for the recent 10 years only and the full historical record period. Bold texts highlight the statistically significant differences (at $p < 0.05$) between the pre/post fire slopes. The post-fire period included up to 30 months after the major fire occurred in each catchment. Column 2 specifies the percentages of catchment area burnt with extreme severity and burnt with any severity.

Catchment	% extremely burnt / % burnt	Post-fire slope	Recent 10 years				All records			
			Pre-fire slope	% difference from pre-fire	p-value	Degrees of freedom	Pre-fire slope	% difference from pre-fire	p-value	Degrees of freedom
204,037	29%/97%	0.396	0.325	22%	0.153	144	0.334	19%	0.132	611
206,001	12%/68%	0.605	**0.247**	**145%**	**<0.001**	144	**0.376**	**61%**	**0.001**	523
207,004	14%/67%	0.496	0.392	26%	0.075	144	0.440	13%	0.228	593
207,015	13%/89%	0.478	0.469	2%	0.913	144	0.441	8%	0.552	452
218,007	59%/98%	0.616	**0.476**	**29%**	**0.046**	144	0.550	12%	0.254	571
218,008	38%/86%	0.394	**0.242**	**63%**	**0.001**	144	0.339	16%	0.287	537
219,022	12%/55%	0.437	**0.286**	**53%**	**0.010**	144	**0.305**	**43%**	**0.005**	602
219,025	19%/52%	0.707	**0.525**	**35%**	**0.011**	144	**0.494**	**43%**	**<0.001**	542
221,002	19%/95%	0.579	**0.328**	**76%**	**<0.001**	144	0.579	20%	0.221	602

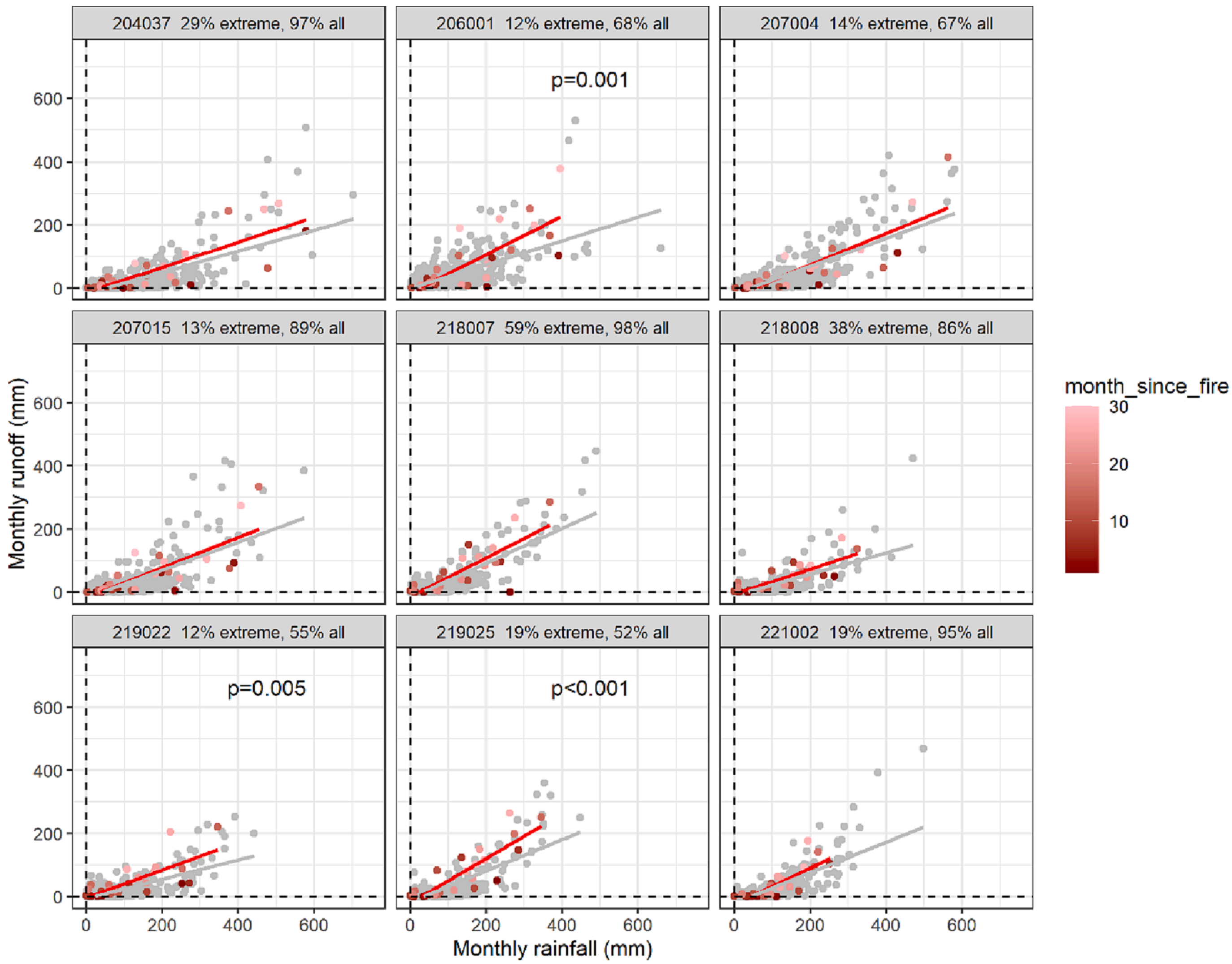

Fig. 5. Comparison of the monthly runoff against the monthly rainfall before and up to 30 months after the 2019/20 fire event, including all data over the full historical record period. Catchments and presentation of pre- and post-fire data is as for Fig. 4.

period make it difficult to distinguish whether such flow recovery is an effect of the fire, the weather conditions, or a combination of both. Section 4.1 further discusses the potential interplay between drought and fire.

3.2. The impact of fire and climate factors on historical flow

For the Random Forest analysis of important drivers of flow at twelve selected catchments, we see historical fire events having some influences on flow, but these influences are generally not as large as those of the catchment storage and climatic drivers (Fig. 7). There is also a considerable variability between the catchments. Overall, the most important driving factor for flow is the catchment storage from previous year (as indicated by 7-day low flow, *low7dPrev*) with median importance of 0.3 and reaching 0.5–0.6 in selected catchments. Some other predictors related to climate, namely the annual median dry spell length (*medDry*) and the proportion of rainfall above 95th percentile compared to annual rainfall (*extremeProp*) also have marked impact in selected catchments with feature importance exceeding 0.2. In contrast, indicators related to fire, i.e., change in catchment vegetation cover before/after fire (*vegDiff*) and percentage catchment area burnt in each fire event (*burnt_perc*) show relatively minor effects, with median importance of only around 0.1 and 0.05, respectively. The effect of fire appears similar to a number of the other climatic predictors considered (*Seasonality*, *maxDry*, *extremeProp*). The results complement those in Section 3.1 which concentrated on a single fire event, further syntheses of these two sets of results are discussed in Section 4.1.

4. Discussion

4.1. Comparison of post-fire flow responses with literature

Our assessment of the flow responses post the 2019/2020 fire was partly based on comparing the pre-fire and post-fire rainfall-runoff relationships (Section 3.1). Similar approaches (but referred to as either runoff ratio, runoff coefficient or precipitation-runoff ratio) have also been employed by a number of previous studies. They generally found increases in flow per unit rainfall in the short-term (within 10 years) following fire events. The majority of these studies were in the United States of America. For example, Hallema et al. (2017) found a −27% to 198% change in the rainfall-runoff slope in two temperate and one Mediterranean catchments with various burnt proportional areas and severities. Hampton and Basu (2022) reported a −63% to + 200% change in the rainfall-runoff slope in 7 Mediterranean catchments in Southern California with 12% to 71% catchment area being moderately or highly burnt. Blount et al. (2020) found a 131% increase in the slope

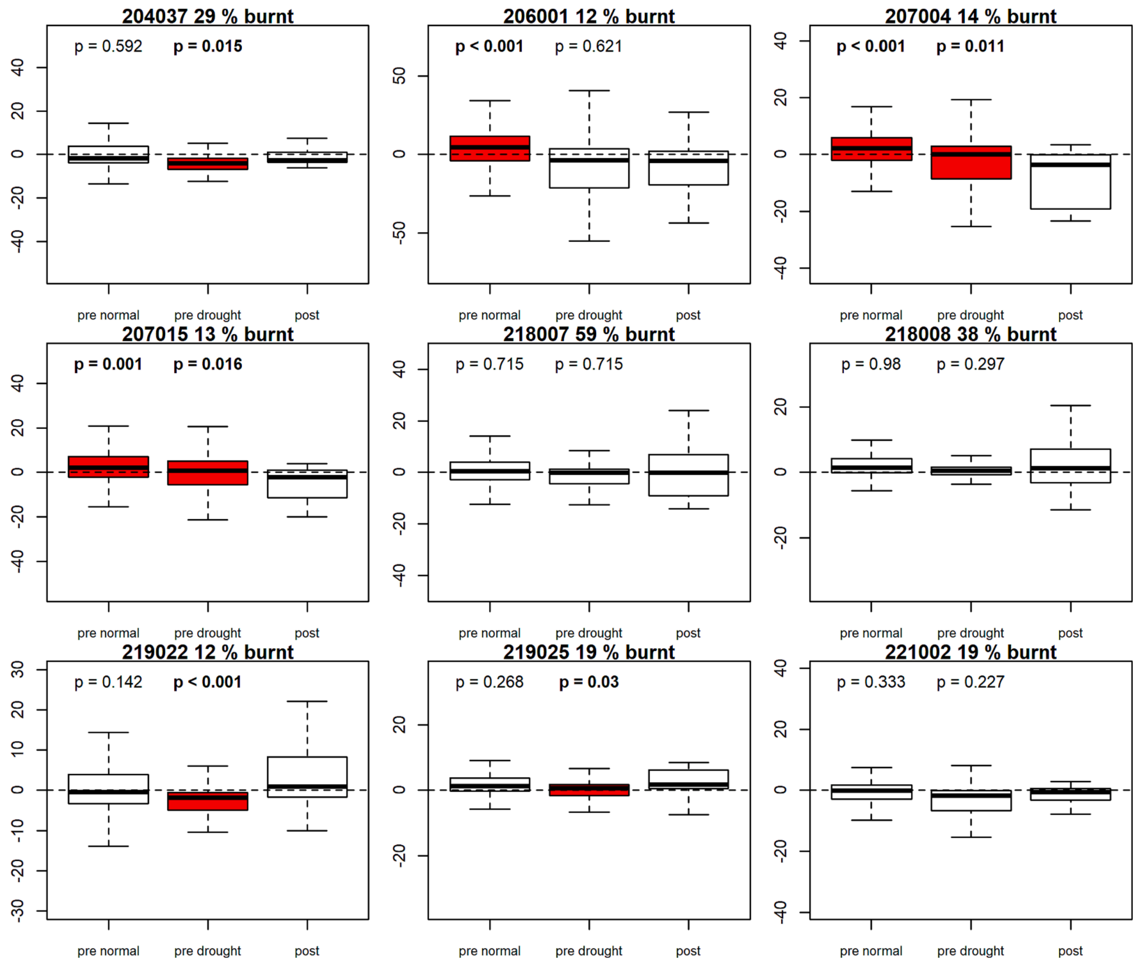

Fig. 6. Comparison of the runoff model residuals (monthly flow observed – monthly flow modelled in mm) for three periods: 1) the 1981–1996 period, representing the average climate condition; 2) the 1997–2019 period, representing drought conditions and 3) the period post the 2019/2020 fire event. The two 'p-values' within each panel are from the pairwise Wilcoxon text at a 0.05 significance level between 1) and 3), and 2) and 3), respectively, where bolded text along with a red box indicates significant difference between residuals for the specific period and those for the post-fire period. A positive residual above the dotted zero line indicates that the actual flow observed is higher than expected, and vice versa. The individual panels show the 9 catchments that were most severely burnt – see the percentage of each catchment as 'extremely burnt' labelled above each panel.

for a semi-arid catchment in Western US that was 95% forested and with 88% of the area having experienced moderate to high severity of fire.

Khaledi et al. (2022) performed a more extensive study of the post-fire responses in 92 temperate Australian catchments with flow and wildfire records between 1975 and 2018. The authors generally found no change in the rainfall-runoff slope post wildfires that burnt<25% of catchment area. The average percentage changes in the slope are between −1% to + 6% within 5 years following wildfires that burnt 25–50% of the catchment area. However, the authors also found high between-catchment variation relative to the average magnitude of change, making the overall changes across all catchments statistically insignificant.

In this study, we focused on catchments with a substantial proportion of extreme burning. the total proportion of area burnt ranging from 52% to 98% (Table 2). We found an increase in the rainfall-runoff slope compared to the recent 10 years' condition in all 9 catchments studied, with magnitudes of increase ranging from 2% to 145%; statistically significant increases were found in 5 out of the 9 catchments with magnitudes between 29% and 145%. Compared to the long-term (greater than35 years) average conditions, the slopes of all 9 catchments increase between 8% and 61% from pre- to post-fire, while significant increases between 43% and 61% were seen in 3 out of 9 catchments. These directions and magnitudes of change are in line with those reported in the literature. It is worth noting that the changes were generally larger than those in the continental study of Khaledi et al. (2022). This might be because our analysis focuses on a single fire season within a region with relatively similar climate conditions, while the estimated changes in Khaledi et al. (2022) were averaged over 92 catchments across Australian continent, which included a wider range of climate, land cover and fire conditions, and are thus likely to display higher variability in the post-fire flow responses and make it difficult to identify strong general trend in these responses.

4.2. Synthesizing the impacts of climate variability and fire on streamflow

Our results in Section 3.1 suggest that post-fire streamflow has increased for a given rainfall, and such increase is more evident when compared to only the most recent 10 years before the fire. Further, from a statistical perspective, the data for the recent 10 years before the fire should have lower power to detect a significant difference as it has smaller sample size and thus lower degrees of freedom (column 'Degrees of freedom' in Table 2). The fact that we detected more significant differences in the more recent data emphasizes the evident increase in flow after the 2019/2020 fire.

There are several different potential factors contributing to such flow increases. Firstly, the rainfall-runoff pattern for the pre-fire reference period of this analysis (2009–2019) is likely heavily dominated by prior severe droughts in the region (1997–2009 and then 2017–2019, see

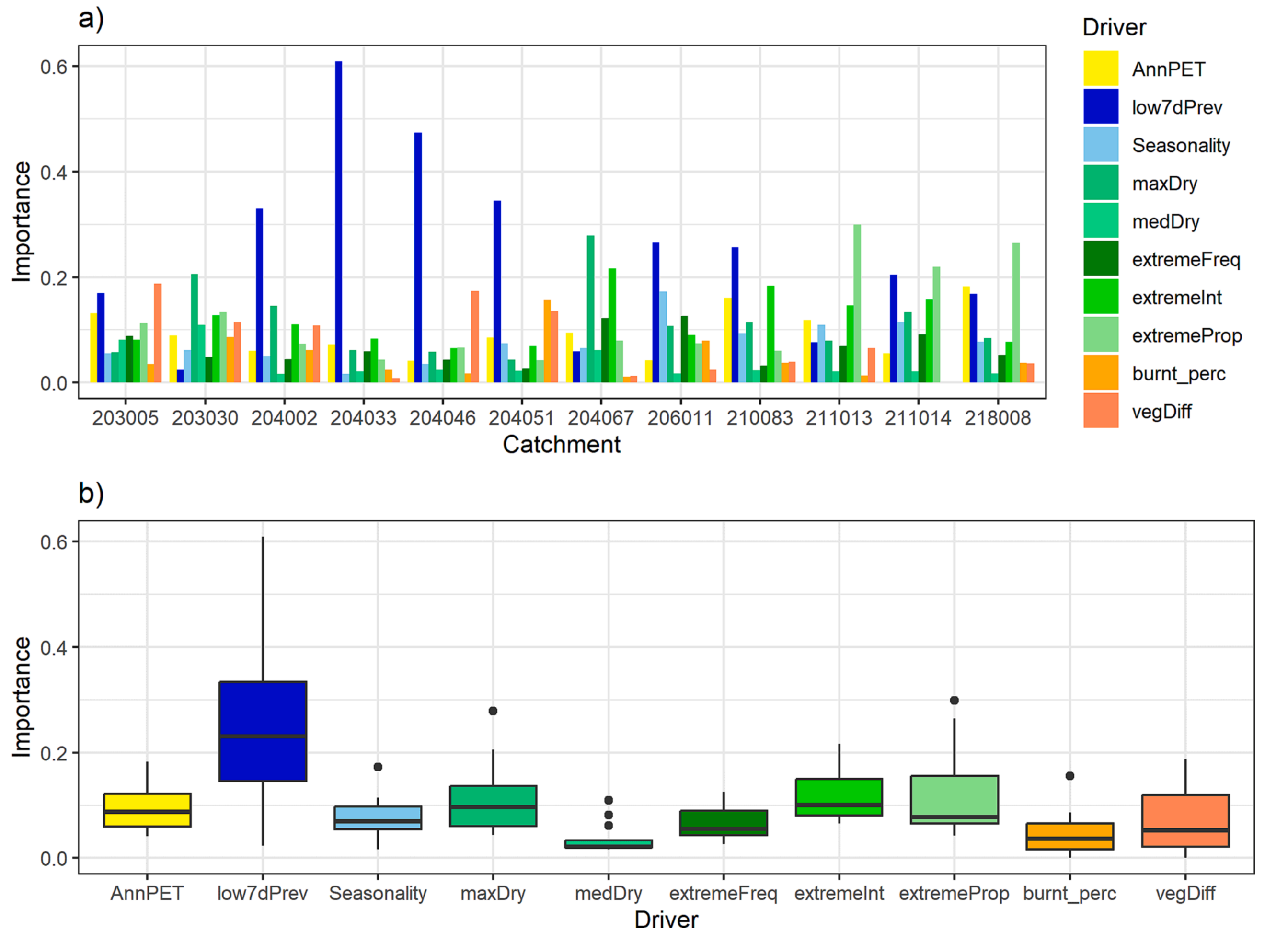

Fig. 7. A) the importance of key drivers for flow at 12 individual catchments over 2001–2021; b) the distribution of the importance of each key driver across 12 catchments. The key drivers included are, namely: AnnPET: annual PET (mm); low7dPrev: 7d low flow in previous year (mm); vegDiff: fire severity represented by vegetation cover difference (%); burnt_perc: fire extent as percentage catchment area burnt (%); Seasonality: rainfall seasonality; maxDry: annual maximum dry spell length (days); medDry: annual median dry spell length (days); extremeFreq: extreme rainfall frequency (days); extremeInt: extreme rainfall intensity (mm); extremeProp: extreme rainfall proportion. See Table 5 for the full definition of individual predictors. For each catchment, the importance of individual drivers sum to 1.

Bureau of Meteorology, 2022). Following the prolonged 1997–2009 drought, there have been shifts in the rainfall-runoff relationships observed in multiple catchments in south-eastern Australia, where streamflow for a given rainfall declined during the drought, but then persisted after the drought ended (Saft et al., 2015; Fowler et al., 2020). Such shifts in rainfall-runoff relationships can last multiple years beyond the end of the drought due to long-term changes in the mechanisms driving the relationship (Fowler et al., 2022; Peterson et al., 2021). The residual impacts of the two drought periods are likely to result in a decline in streamflow for a given rainfall that persists for multiple years, which thus overlaps with the post-fire period analysed here.

Secondly, following the unprecedented fires in 2019/2020, there would have been a substantial decrease in the leaf area, causing reduced evapotranspiration and a subsequent increase in streamflow. Such a response has previously been seen in mixed species eucalypt forested catchments in south-eastern Australia following high-severity wildfire events (Webb and Jarrett, 2013; Nolan et al., 2015). Fire induced hydrophobicity, resulting in decreased soil infiltration capacity and thus an increase in infiltration-excess runoff (Nyman et al., 2010; Nyman et al., 2014). The other factor that can potentially affect the post-fire flow is that south-eastern Australia has experienced a shift from a dry, warm phase to a wet and cold climate since 2020 (i.e., around the same time as the post-fire period), which was associated with a La Niña and negative Indian Ocean Dipole (Wang and Cai, 2020; Cassidy, 2022). Combining these together, although we saw a consistent post-fire increase in flow for given rainfall across all catchments, the flow responses in individual catchments are likely results of different combinations of the effects of the prolonged drought with recent fire and weather conditions. Unfortunately, for this study, we have limited data available post-fire that are free of other climatic disturbances, and thus insufficient evidence to attribute the flow increases to the effect of fire alone. A further decade of data when available might enabling us to gain additional insights on this issue.

Looking at the longer historical period (2001–2020), our results in Section 3.2 suggest that changes in flow at the catchment scale is more strongly driven by changes in hydro-climatic conditions than the response to fire events. This highlights the substantial role that climate plays in driving water availability. Since 1910, the study region has warmed by around 1 °C with more hot days and fewer cold days. This would have led to higher potential evapotranspiration and thus higher water use in forested catchments (Whetton and Chiew, 2020). In addition, over the past several decades, streamflow in the region has decreased significantly in response to the drier cool seasons compared to the long-term average conditions (Whetton and Chiew, 2020) and the changes in catchment functioning in addition to the changed climate forcing (Saft et al., 2015). Climate is likely exhibiting stronger, long-term effects at a landscape scale, while the effects of fire are more likely localized (e.g. Nolan et al., 2015). This highlights the need to prioritize: 1) response to large-scale climatic patterns for forest and water resources management; and 2) investigation of fire impacts at smaller scales (Section 4.2.1).

4.3. Limitations and future research directions

4.3.1. Spatial and temporal scale of understanding

Our conclusion on the influence of wildfire events on the streamflow in forested catchments is limited to the scale of whole catchments. Catchments are typically only partially burnt in any particular fire event. For example, the nine selected catchments experienced different extents of severe burn during the 2019/2020 fire, with 12% to 59% of their individual areas being extremely burnt. Therefore, it is possible that large changes in streamflow have occurred within the smaller portions of the catchments directly affected by fire, but these changes are not large enough to result in significant responses in the streamflow at the full catchment scale. The limited catchment-level influence of wildfire that we observe highlights the need to better understand the linkage between processes at different scales within catchments. To this end, we recommend future research focusing on improving the long-term monitoring and analysis of fire and streamflow at the sub-catchment scale.

Regarding the temporal scale, this study focuses on the immediate to short-term response of flow to fire, specifically due to: 1) the limited records (up to 30 months) after the 2019/2020 fire analysed for Question 1; and 2) the 1-year post-fire recovery period assumed with no lagged predictor variables considered in Question 2. The flow response in the longer term might show very different patterns, as suggested in a number of previous studies that suggested multi-year to decadal response periods to fire (Kuczera, 1987; Vertessy et al., 2001; Nolan et al., 2015; Inbar et al., 2022).

4.3.2. Interactions between climate and fire

In question 2, we attempted to separate the effects of climate from wildfire to understand their individual contributions to changes in stream flow (Sections 3.2.2 and 3.2.3). However, climate will likely interact with wildfire, particularly under a changing climate.

Climatic change has been related to a non-linear escalation of both the extent and severity of fire (Canadell et al., 2021). As such, fire events are likely to continue to intensify in southeast Australia into the future (Abram et al., 2021). Such interactions have been reported in south-eastern Australia as well as other parts of the world. The unprecedented 2019/2020 Black Summer wildfire in southeast Australia was caused by a combination of climate variability and long-term climate trends, with an increased probability of large forest fire occurrence due to the multiple aspects of climate variability (Abram et al., 2021). In recent decades, fires have increased in the forested regions along the coast and mountains of south-eastern Australia. This has been attributed to the influence of climatic warming and drying, as well as lightning and human ignitions (Blanchi et al., 2010; Gibbons et al., 2012; Bradstock et al., 2014). The responses of wildfires to climate change may differ by vegetation types. For example, Bradstock et al. (2014) studied the fire response to climate warming and drying in south-eastern Australia, and predicted that an increase in fire response more is likely to occur in moist coastal forests than in arid and semiarid woodlands, due the different dominant fuel types (woody litter vs. herbaceous fuels).

A combination of fire and a changing climate will likely cause long-term changes in vegetation communities, which will potentially lead to changes in evapotranspiration and hence rainfall-runoff responses, as well as fire behaviour, into the future (Lakmali et al., 2022). The hydrological impacts of such changes are yet to be understood and remain one of several sources of uncertainty regarding future hydrological behaviour of catchments.

4.3.3. CO_2 fertilisation effect

Increasing levels of CO_2 in the atmosphere is another potential factor that can influence catchment hydrology. Increased atmospheric CO_2 can affect both vegetation growth and water use (Leakey et al., 2009). Rising CO_2 concentrations can enhance photosynthesis by stimulating carbon assimilation in plants (Farquhar, 1997). This CO_2 fertilisation effect increases biomass and green vegetation cover ('greening') (Morgan et al., 2007; Donohue et al., 2009; Buitenwerf et al., 2012). Moreover, elevated CO_2 levels lower stomatal conductance and thereby reduce water loss through leaves. Therefore, water use efficiency of photosynthesis increases with rising CO_2 concentrations and leads to an increase in foliage cover. A recent study on eastern Australia (where the current study region is located in) found that CO2 increases between 1982 and 2019 has led to increases in vegetation greenness by 5% in arid inland regions and by over 20% in the wet tropics and temperate regions (Rifai et al., 2022). This is in line with an earlier global study which reported a 5–10% increase in green foliage cover in warm, arid environment between 1982 and 2010, due to the CO^2 fertilisation effect (Donohue et al., 2013). Similarly, Ukkola et al. (2016) found that in response to increasing CO_2 concentration between 1982 and 2010, the sub-humid (corresponding to the current study region) and semi-arid regions are not only 'greening' but also consuming more water, which has led to a significant 24–28% reduction in streamflow. These results suggest that potential increases in vegetation water use, together with the projected decreases in future precipitation (Collins et al., 2013) may lead to further reduction in streamflow. In the context of fire impact, the expected flow reduction due to the CO_2 fertilisation effect may offset any expected increase in flow in the short term post-fire period, which requires further investigation.

4.3.4. Long-term hydrological responses and the role of groundwater

There is a widely observed downward trends in runoff for a given amount of rainfall in south-eastern Australia (Saft et al., 2015). Groundwater levels are a key indicator of the observed flow responses, as the trends in annual flow closely follow those in various measures of groundwater levels, including 7-day low flow, durations of cease-to-flow and large-scale changes in terrestrial water store (Fowler et al., 2020; Fowler et al., 2022). Further, the association between flow and groundwater trends have been stronger in catchment that are drier, flatter, and have low forest cover (Saft et al., 2015). There may be an indication of this in our results as well; lowland catchments showed more significant increases in streamflow following the 2019/2020 fire, and this may be due to greater changes in rainfall-runoff relationships linked to groundwater decline. The interplay between climate change, fire, changing groundwater level, and rainfall-runoff process remain unclear for the study catchments. Were such effects to become more widespread, declines in runoff are likely to be exacerbated, with major implications for streamflow at large scales.

5. Conclusions

A data-driven analysis was performed to attribute changes in long-term streamflow in forested catchments to climate and fire. The regional scale analysis focused on selected catchments in New South Wales, eastern Australia. Our key findings are:

- At a catchment scale, following the 2019/2020 fire there was a significant increase in streamflow when compared with the recent 10 years before fire. This is likely a combined result of an immediate flow response to both the fire event and the concurrent wetter weather condition that occurred with the breaking of droughts conditions.
- Over a longer historical period (2001–2021), fire events have had some influence on streamflow, but the impacts are generally not as large as those of climatic drivers. Across multiple study catchments,

rainfall and catchment storage are generally the most important drivers of annual flow.

Our results highlight hydro-climatic drivers as more important long-term drivers of streamflow than fire events in forested catchments within the study region. This emphasizes the need to better understand the effect of catchment responses to climate variability for managing water resources in forested catchments.

This study is novel because it analyses a regional data set. Most previous studies that assessed the impact of fire on forested catchments are field based investigations of individual plots or catchments aiming to investigate local effects and detailed processes. A key strength of our approach is its ability to use existing datasets to understand landscape responses over regions. Our study is essentially in line with the spirit of 'large-sample hydrology' (Gupta et al., 2014), starting with a large dataset of multiple catchments, from which suitable catchments were selected to answer our research questions. Identifying the suitable case study catchments is key to facilitating focused and meaningful analysis. This catchment selection process for this study was made possible by the availability of a large amount of information, especially the long-term records on streamflow and spatial data on land cover, climate and fire disturbances. The increasing availability of monitoring data and spatial datasets obtained from remote sensing will enable more data-driven studies of this kind, highlighting a promising alternative approach to obtain a more systematic understanding of fire responses in forested catchments.

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.

Data availability

All sources of public data have been specified in text; the authods fo not have permission to share the remaining data.

Acknowledgement

This study is part of a larger project between the Natural Resources Commission of New South Wales (NSW NRC) Australia and the University of Melbourne. NSW NRC is responsible for independently overseeing the design, implementation, review and improvement of a statewide Forest Monitoring and Improvement Program. Between 2020 and 2022, NRC commissioned the University of Melbourne to deliver baselines and trends for environmental values related to water quality and quantity, for the NSW Forest Monitoring and Improvement Program and the Coastal IFOA Monitoring of Landscape-scale Trends. The project aimed to understand trends in water quality and quantity in the forested regions in the state of NSW in eastern Australia.

We would like to thank NSW NRC, especially Dr Ross Peacock, Mr Jeffery Bell, Mr Liam Hogg, Mr Matt De Jongh and Mr Todd Maher for their guidance and assistance throughout the Project. NSW NRC, together with other agencies, especially WaterNSW and Forestry Corporation of NSW assisted with data access in this project. We thank Mr Peter Walsh and Mr Martin Krogh for their constructive feedback on the analysis approaches and interpretation of key results in this study. We also acknowledge the Traditional Owners, who were the first custodians of Australian waterways.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.129979.

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