Report for the NRC Forest Baseline & Trend Indicators- Project 3 Task 2

Long-term trends of Water Quality and Quantity of forested catchments within the NSW Regional Forest Agreement (RFA) regions

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Executive Summary

This report summarizes the methodologies, key findings and recommendations for Task 2 of Project 3 of the Forest Monitoring and Improvement Program by the NSW Natural Resources Commission (NRC). This entire project aims to deliver trends and baselines for environmental values related to water quality and quantity, within the three NSW Regional Forest Agreement (RFA) regions. Our study covers the entire NSW RFA regions, therefore includes multiple tenure types which are dominantly national park, state forest and private land (24.7%, 10.5% and 62.1% of the region, respectively).

Task 1 of this project identified the indicators of key water quality and quantity of the health of forested catchments within the NSW RFA regions, and assessed their data availability to perform trend analyses. In the subsequent Task 2, we calculated the long-term trends of each key indicator for all catchments with available data. We summarized the landscape and regional patterns of trends and explored potential drivers of trends with specific focus on forest disturbances from wildfire and harvesting. The key insight of this study are: 1) quantifying of long-term trend that are representative of forested catchments in the entire RFA region; 2) identifying future research priorities to better explain temporal changes in water quality and quantity for forested catchments; 3) making recommendation on key gaps and limitations in existing monitoring for water quality and quantity in the RFA region.

Our key findings on the long-term trends are:

1. Within the NSW RFA regions, over at least the last 35 years, forested catchments (75 catchments with >50% forest coverage) either show statistically significant decreases at a 0.05 level (29 catchments) or insignificant decreases (46 catchments) in annual flow based on hydrological years. No catchment shows increasing annual flow. Most catchments showing significant flow decreases are within the Southern RFA region.
2. For catchments that had significant flow decreases, the magnitude of decline is around 10 to 20% per decade relative to the long-term mean annual flow.
3. Water temperature generally have non-significant trends and electrical conductivity (EC) have a mixture of significant increases and decreases throughout forested catchments within the NSW RFA regions.
4. The monitoring data for Total phosphorus (TP), total nitrogen (TN), pH and turbidity are insufficient to conclude large-scale patterns in long-term trends that are representative of forested catchments for the entire RFA regions.

For identifying the baselines and the drivers of trends, we focused on the trends in annual flow, which have been monitored with the best spatial coverage across the NSW RFA regions. We found that:

1. The magnitudes of annual flow trends at individual catchments (i.e., the decrease in annual flow relative to the catchment mean annual flow) are correlated with catchment characteristics. Specifically, a smaller reduction in flow is correlated individually with i) higher mean annual flow ii) higher proportion of catchment area as national park, iii) higher proportion of catchment area being harvested, and iv) higher proportion of catchment area being burnt. However, defining baseline and explaining spatial differences in flow trends are made challenging by the high cross-correlations between catchment characteristics in climate, hydrology and disturbance history.
2. While the study region experienced a large-scale decreasing trend in flow, the flow data at individual catchments show high interannual variability, which is likely induced by climate and creates a key challenge for finding statistical relationships between trends and forest disturbances.

3. A pseudo-paired catchment analysis shows potential to reduce the noise in flow data arising from climate variability, and thus identifying the impacts of forest disturbance on water quality/quantity.
4. We further assessed the temporal and spatial coverages of flow monitoring in NSW RFA regions, and provided recommendations to facilitate future analyses of disturbance impacts.

The key findings of this project identify a critical research priority for future trend analysis/attribution work. Specifically, we highlight the need to develop novel statistical approaches to identify the flow responses to climate variability and thus to clearly identify any impact of catchment disturbance and forest management. This will be a key focus for the extension phase of the current project, which is expected to commence in Aug 2021 and complete by July 2022.

Contents

1. Background

Project 3 of the Forest Monitoring and Improvement Program by the NSW Natural Resources Commission (‘this project’ hereafter) aims to deliver baselines and trends for environmental values related to water quality and quantity for two distinct monitoring programs (Figure 1):

1. The NSW Forest Monitoring and Improvement Program; and
2. The Coastal IFOA monitoring of landscape-scale trends.

The project aims to generate scientific information to answer the state-wide question of ‘*Are the forest water catchments healthy and what is the predicted trajectory for water availability and quality*?’ The specific objectives of this project are to:

a) Identify the key indicators for water quality and quantity across all tenures in RFA regions;
b) Establish baselines and trends in water quality/quantity indicators and discuss potential influences of forest management.

This project consists of two stages. Task 1 identified the key indicators of water quality and quantity related to the health of forested catchments across all tenures in RFA regions, and also proposed a conceptual framework to analyse baselines/trends in these key indicators. This report addresses Task 2, which aims to understand the trajectory of the key water quantity and quality indicators via estimating their long-term historical trends and explore potential driving factors for these trends.

Statistical trend analysis and time-series analysis were applied to identify the long-term trends in water quality and quantity, as well as their potential drivers. All trend analysis and attribution in Task 2 focused on the key indicators of key water quality and quantity that had previously been identified in Task 1 of the project.

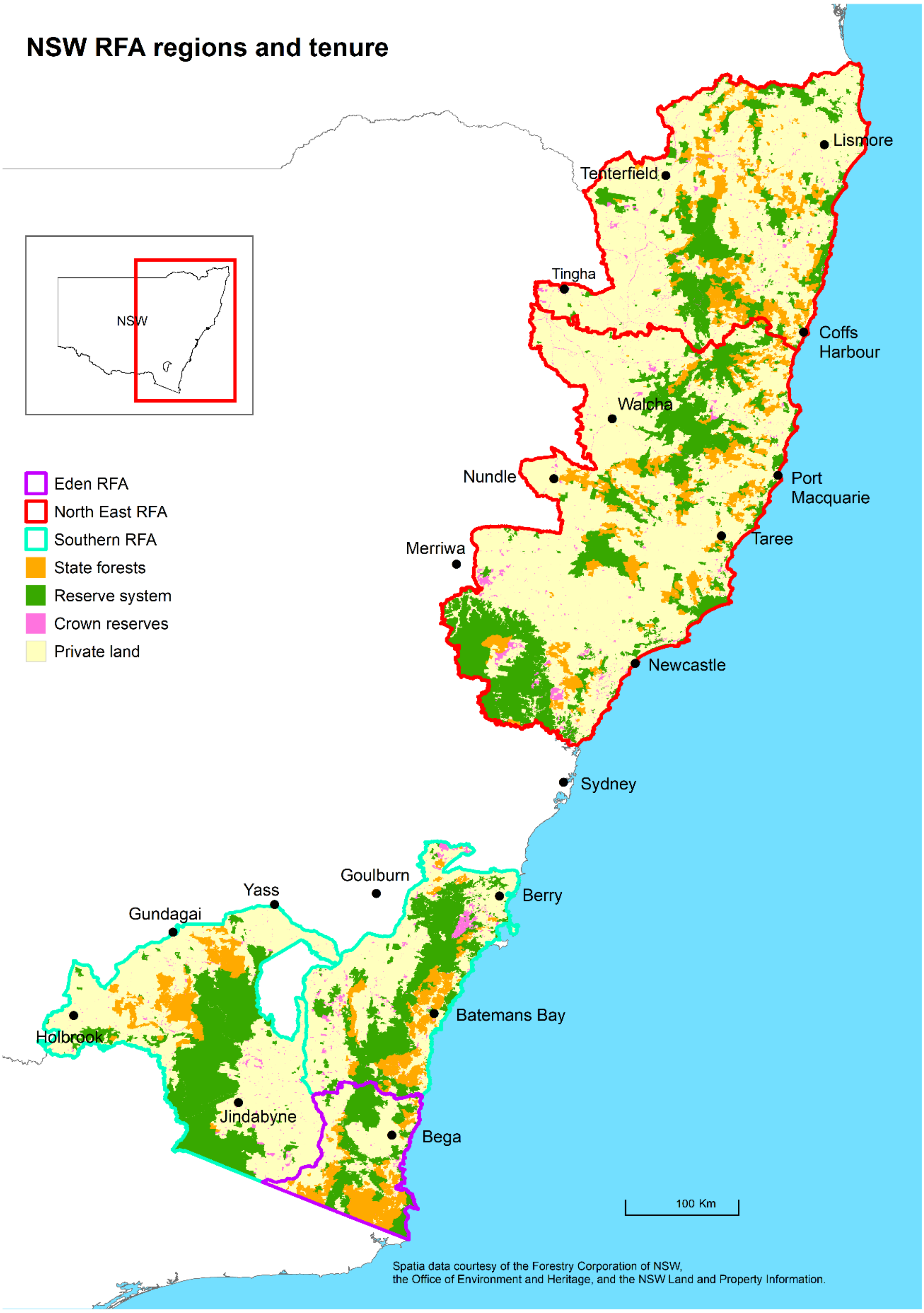


Figure 1. NSW RFA regions and Coastal IFOA (generated from spatial data provided by Forestry Corporation of NSW).

2. Methods

2.1 Review of key water quality and quantity indicators for trend analysis

In Task 1 of the project, a comprehensive literature review was performed to identify the key indicators of water quality and quantity in the designated forest regions, and thus those indicators that should be considered in the trend analyses in Task 2. The review covered areas of sustainable forest management, key drivers of changes in water quantity/quality in forested catchments, and existing national and state-level water quantity/quality guidelines and objectives. This review identified a number of potential water quality/quantity indicators, from which the final set of key indicators (Table 1) was identified using multiple criteria: sensitivity to forest management, suitability and availability of data for landscape-scale assessment, statistical power of data analyses, and effort required for future monitoring. The full detail and justification for choosing these indicators are provided in the Task 1 final report (Guo et al., 2021).

Table 1. Key water quality/quantity indicators recommended for trend analyses (from Task 1)

Water quality	• Nutrients: total phosphorus (TP), total nitrogen (TN), nitrate-nitrite (NOx) • Dissolved oxygen (DO) • pH • Electrical conductivity (EC) • Turbidity • Water Temperature (WTemp) • Macroinvertebrates population and composition: SIGNAL score, Ephemeroptera + Plecoptera + Trichoptera (EPT)
Water quantity	• Signatures of continuous flow data (annual flow) • Indicators of climate-streamflow relationship (rainfall-runoff residual) • indicators of baseflow/drought/high flow (7-day low flow, cease to flow, annual 10^{th} and 90^{th} quantiles of flow) All water quantity indicators are annual summaries aggregated by hydrological years instead of calendar years (see Section 2.3.3 for details on data processing).

*Note: NOx is the sum of the sum of nitrate (NO3) and nitrite (NO2) in mg/L Nitrogen.

We further revised the list of indicators based on data availability within the RFA regions. For water quality, we excluded Macroinvertebrates population and composition (SIGNAL score and EPT) and NOx due to lack of data at a landscape scale. For water quantity, we decided to focus on signatures of daily flow data, the relationship between climate and flow, and indicators of baseflow, drought and high flow – the derivation of each signature indicator is detailed in Section 2.3.3.

2.2 Data acquisition

2.2.1 Water quality and quantity

To estimate trends in water quality and quantity, we collated available monitoring datasets for indicators of water quality and quantity in the NSW Regional Forest Area (RFA) regions (Figure 1). We identified three landscape-scale long-term datasets for water quality and quantity from a previous review of data availability from Task 1:

- *WaterNSW continuous water monitoring network* (WaterNSW, 2020), which monitors the quantity and quality of surface water and groundwater throughout NSW. The monitoring program combines automatic digital sensors, logging devices and manual sampling. All monitoring data are then collated and made publicly available via the WaterNSW's online portal (https://realtimedata.waternsw.com.au/).
- *Water Data Online by Australian Bureau of Meteorology* (BoM WDO) (Bureau of Meteorology, 2020) including the surface water dataset from the abovementioned WaterNSW monitoring,

as well as data owned by organizations such as Snowy Hydro Limited, Hunter Water, Sydney Water Corporation, Dept Planning, Industry and Environment - Water. All data are available from BoM WDO's online portal (http://www.bom.gov.au/waterdata/).

- *Forestry Corporation of NSW* (FCNSW) which maintains monitoring programs in NSW state forests. Datasets are available upon request.

The availability of all water quality and quantity data obtained is summarized in Tables 2 and 3. Note that the last columns of both tables summarize the number of monitoring sites that have sufficient high quality, long-term data for trend analysis – the criteria for this designation will be further discussed in Section 2.3 (Data pre-processing).

Table 2. Summary of data availability for water quality indicators within NSW RFA regions. Data for EC, WTemp, DO, pH and Turbidity are generally continuous with samples collected at a daily or higher frequency; Data for TP, TN and NOx are generally grab sample collected at a monthly or lower frequency.

Data provider	Water quality variable	Total number of sites within NSW RFA regions	Median start year	Median end year	Median data length (years)	Median sampling frequency (per year)	Number of long-term sites with high- quality long-term data[1]	Number of sites analysed (natural forest catchments)[2]
WaterNSW	*EC*	106	2010	2019	8	317.2	35	17
	WTemp	137	2003	2019	8	323.5	48	29
	DO	14	2006	2019	7	291.6	5	5
	pH	28	2014	2019	5	303.3	5	5
	Turbidity	40	2013	2019	6.5	289	5	5
	TP	45	1994	2019	26	10.7	33	18
	TN	45	2002	2019	17	10.4	33	8
	NOx	45	2008	2019	12	9.3	22	0
BoM WDO	*WTemp*	88	2012	2019	5	19282.5	13	7
	pH	13	2017	2019	4	227.8	0	0
	Turbidity	14	2017	2019	4	227.8	0	0
FCNSW	*Turbidity*	45	2001	2010	8	36.1	9	5
	EC	11	1995	1997	2	73	0	0
	pH	11	1995	1997	2	73.25	0	0
	WTemp	2	1996	1999	3.5	190.6	0	0

[1]Sites with >= 10 years of data sampled at a greater frequency than quarterly (4 times a year). [2]Site with that are representative of natural forested catchments. See Section 2.3.1 on the detailed selection criterion considering both aspects.

Table 3. Summary of data availability for streamflow within NSW RFA regions. All summary statistics are based on daily flow data extracted.

Data provider	Total number of sites within RFA regions	Median start year	Median end year	Median data length (years)	Number of sites with high- quality long-term data[1]	Number of sites analysed (natural forest catchments)[2]
WaterNSW	282	1977	2019	42	104	57
BoM WDO	34	1976	2019	43	34	7
FCNSW	43	1995	2014	10	14	11

[1]Sites with > 35 years of records and with >= 350 days of good quality data per year. [2]Site that are representative of natural forested catchments. See Section 2.3.1 on the detailed selection criterion considering both aspects.

2.2.2 Catchment boundaries

We delineated catchment boundaries using ArcMap, based on the locations of the monitoring sites obtained along with the water quality and quantity datasets. The Bureau of Meteorology (BoM)

Geofabric dataset was used to identify upstream contributing areas, thus delineating catchment boundaries. The delineated catchment areas were then compared against an alternative source of catchment area information (only available for WaterNSW monitoring sites) to confirm that errors were no larger than 10%.

2.2.3 Historical climate and forest disturbance data

To represent catchment-average climate, we first extracted the nation-wide daily gridded climate data (5km x 5km) provided by the BoM Australian Water Availability Project (AWAP). We then used the delineated catchment boundaries to clip individual catchment-averaged daily rainfall time-series from the full AWAP dataset, using the R package *AWAPer* [*Peterson et al.*, 2020].

Catchment-averaged time-series of forest disturbance, specifically for wildfire and harvest were compiled to analyse their potential impacts on water quality and quantity. Wildfire and harvest were selected amongst other types of disturbance (e.g. prescribed fire and forest extent change) since they had the longest available records throughout the study regions (wildfire since 1900, harvest since 1950). For each type of disturbance, the corresponding dynamic spatial data were supplied by the NRC as shapefiles with timestamps. Specifically, these spatial datasets informed the extent of burning and the extent of harvest for individual wildfire and harvesting events, respectively. We then estimated the percentage of catchment area affected by individual disturbance events (either burnt or harvested) using ArcMap spatial analyst. This was done for each catchment, by overlaying the disturbance layer with the corresponding catchment boundary. It is worth noting that the fire extent data might have overestimated the actual area burnt because fire patchiness was not properly considered. As a result, the estimated percentage of burning can be affected by the quality of the fire extent data.

2.2.4 Auxiliary spatial data on catchment modification

Additional spatial data were obtained to assess the extent of modification of each catchment, which enabled us to identify catchments that are predominately covered by forest and have little modification from natural conditions. These datasets are:

- NSW woody area extent representative of the period 2007-2017 (internal data supplied by NRC)
- NSW land tenure (internal data supplied by NRC)
- Australian dams and water storages (Geosciences Australia, publicly available at: https://koordinates.com/layer/739-australian-dams-and-water-storages/data/)
- Location of groundwater bores in NSW (WaterNSW, available at https://realtimedata.waternsw.com.au/)

2.3 Trend analyses for water quantity and quality

Task 1 identified several parametric and non-parametric statistical approaches for trend analysis in Task 2. During this task, we further reviewed the nature of data for individual key indicators of water quality and quantity to finalise the choice of trend approaches.

The water quality indicators directly correspond to the time-series of monitored data (e.g. DO, EC). Thus, we applied a temporal regression model for the full time-series of data for each indicator, observed at each site. The water quantity indicators are based on signatures and indices derived from the monitored time-series of streamflow (e.g. annual flow). Thus, we applied a non-parametric approach including Mann-Kendall (MK) and Sen's Slope to analyse trends for these less temporally explicit data.

All trends were estimated over the full record period for each indicator for individual catchments.

2.3.1 Catchment selection

After obtaining the raw data for water quality and quantity indicators, we first performed a screening of the monitoring sites/catchments to be further analysed. Considering data availability and quality, we focused only on sites with over 35 years of streamflow data and with at least 350 days of high-quality records each year. For each water quality indicator, we focused only on sites with over 10 years of high-quality data, collected at a frequency equal to or higher than seasonally. These recommendations were made in Task 1 of the project. Data quality was assessed with quality codes embedded in the raw data.

A further catchment selection criterion was the representativeness of native forested areas. To address this, we only considered catchments for which forest cover is no less than 50% of total catchment area, as identified from the NSW woody area extent data together with individual catchment boundaries. The catchments should also be free from modification, which is defined as having no large dams within the catchment boundary.

2.3.2 Statistical analyses

As highlighted in the overview of Section 2.3, different statistical approaches were applied to analyse trends in individual indicators for water quality and quantity. For water quality, we used a temporal regression model that explicitly accounts for a linear trend applied across each time step *t* over the whole record, together with effects of flow *f(Q)* and seasonality *f(seasonality)*:

$$\log(C_t) = a + t \times \beta_{tC} + f(\log(Q_t)) \times \beta_Q + f(seasonality) \times \beta_{seasonality} + f(\varepsilon_C) \quad (1)$$

Note that both water quality and flow data were log-transformed due to data non-normality (see details in Section 2.3.3). *a* is the intercept of the regression and $f(\varepsilon_c)$ is the error term, which was a first-order autoregressive (AR1) residual model for water quality indicators sampled at high frequencies (i.e. EC, water temperature, DO, pH and turbidity, sampled roughly at daily frequencies, see Table 2), to account for the potentially high serial autocorrelation. The low-frequency variables (TP and TN) are generally sampled at monthly steps, which we assumed to be sufficiently sparse so that serial autocorrelation is negligible – this was confirmed by checking all model residuals.

The model was calibrated to water quality data at the catchment level, and the values of the calibrated model parameter β_{tC} were extracted to inform the direction, magnitude and significance of temporal trends. We also checked the model residuals to ensure that sites analysed did not experience significant step changes or change in the relationship between water quality and flow, which are beyond the capacity of the trend model.

To identify trends in the water quantity indicators, we applied the non-parametric approaches of Mann-Kendall (MK) and Sen's Slope. Both methods are rank-based and do not require model calibration. The outputs from MK inform the direction and significance of temporal trends. The outputs from Sen's Slope inform the magnitude of the temporal trends.

2.3.3 Data processing

The water quantity indicators were largely based on signatures of daily flow data. Therefore, the daily flow data were first quality controlled based on the quality codes embedded with the raw data. Linear interpolation was performed to infill days with missing data or low-quality data. The daily flow data were then aggregated to derive annual time-series of the following water quantity indicators:

1) Annual flow i.e., the sum of all daily values within each year;
2) Annual rainfall-runoff residual. This was obtained by fitting a linear regression between annual flow and annual rainfall for each catchment and then extracting the residual of this regression. The residuals for each catchment represent the deviations of annual flow from expectation with given rainfall. Therefore, assessing trends in the residuals can help explain whether trends in flow are due to changes in rainfall or other disturbances.

3) Annual 10th and 90th quantiles of daily flow;
4) Annual 7-day low flow, which is the average daily flow during the seven consecutive days with the lowest flow within each year;
5) Annual cease-to-flow (CTF), which is the number of days with zero flow in each year.

It is worth noting that the above annual summaries were aggregated by hydrological years instead of calendar years. The starting month of hydrological years was identified for each catchment as the month with the lowest monthly average flow over the full data period. This approach minimized the chance of significant carry-over flow across years, which can make it more challenging to identify long-term trends.

The annual time-series of each indicator was further processed for the trend analyses (MK test and Sen's Slope, see Section 2.3.2). Since both analyses are non-parametric, they do not require the distribution of data to satisfy any model assumptions; however, both methods require input data to be temporally independent i.e., with no serial correlation. Our preliminary analysis found that the annual flow time-series generally have high correlations. To resolve this, we applied a statistical processing approach, pre-whitening (von Storch, 1995), to the annual time-series of all water quantity indicators across all catchments to remove serial correlation on the data.

The raw data for each water quality indicator were processed to satisfy the data required for the temporal regression (Section 2.3.2). The linear model requires model residuals to be normally distributed. Therefore, we first applied log-10 transformation to the data for all water quality indicators, and then removed outliers that were greater than 3 standard deviations away from the median level of each catchment (Hampel, 1974). Further, some indicators were sampled at high frequencies i.e., roughly daily (EC, water temperature, DO, pH and turbidity). When there was more than one sample recorded in a day, we aggregated these samples to daily averages. Note that the temporal regression model did not require continuous data, so the presence of missing data or gaps had no impact on the water quality model.

2.4 Identifying the baselines and drivers of trends in mean annual flow

2.4.1 Statistical analyses

For identifying the baselines and drivers of trends, we focused on mean annual flow as it has the best spatial coverage of monitoring data across the RFA region. We first explored the spatial variation in the trends of annual flow, specifically by looking at relationships between trend magnitudes and various catchment characteristics, such as long-term average climate, forest cover, land tenure, and summary of historical disturbances.

We then performed catchment scale time-series analyses to assess the impacts of disturbances on temporal variation of annual flow. For this purpose, we tested two statistical approaches to relate time-series of annual flow to disturbance history:

1) Correlation test between annual rainfall-runoff residuals (obtained as in Section 2.3.3) and disturbance history at individual catchments. For this analysis we focused on catchments that have been heavily disturbed. Rainfall-runoff residuals indicate how much the change in annual flow deviates from the expected level with given rainfall. Thus, this analysis can inform *whether disturbances lead to changes in flow responses compared to expectation.*
2) A pseudo-paired catchment analysis, in which we first derived differences in annual flow between paired (a disturbed and a control i.e., never disturbed) catchments, and then performed a correlation test between the flow difference and the difference in disturbance history between the two catchments. This analysis focused specifically on the disturbance

from wildfire and harvest, since they had the longest available record lengths throughout the study regions (since 1900 and 1950, respectively) to facilitate comparison with the long-term patterns in annual flow. Note that the catchment pairs used in this analysis were selected retrospectively by disturbance history, which is different to conventional paired catchment studies in which all catchment pairs were intentionally designed to monitor responses to contrasting levels of disturbances. This analysis can inform *whether catchment wildfire/harvest explain the differences in flow responses between paired catchments of similar climate*.

Two alternative ways to quantify historical disturbance were used for both analyses. Specifically, we considered both the annual time-series of percentage disturbed catchment area (i.e. burnt or harvested), and the 10-year accumulated percentage disturbed catchment area prior to and including the year of flow data. The latter considered potential lag effects due to forest regrowth and recovery.

2.4.2 Data processing

The only data processing required for trend attribution was to compile the annual time-series of catchment-averaged historical records of climate and forest disturbance from the raw time-series obtained in Section 2.2.3. This ensures that the climate and disturbance data are at the same spatial and temporal scales as the mean annual flow to facilitate the trend attribution task. Specifically, the catchment-averaged daily rainfall time-series was aggregated to annual data for the hydrological years identified for each catchment (Section 2.3.3). Similarly, the percentage of catchment area burnt and harvested in individual events were also aggregated to a time-series of annual percentage burnt and annual percentage harvested, by corresponding hydrological years. To enable us to explore any abovementioned lagged effects, a rolling sum of 10-year accumulated disturbance for each of fire and harvest was also derived for each catchment. Note that due to the limited resources in spatial analyses, both the annual sum and 10-year sum of percentage areas were based on sum of percentage areas burnt/harvested by individual events, rather than a spatial union of disturbed areas. This might result in slight over-estimation of the actual cumulative disturbed area if multiple events impacted in the same locations.

3. Results

3.1 Trends in water quantity and quality across RFA regions

Annual flow (Figure 3): There is a wide-spread decreasing trend throughout forested catchments in the RFA regions. Each of the 75 forested catchments has a negative trend, while 29 have significantly decreasing trends. Most catchments that have experienced significant decreases are in the northern part of the North East RFA, and in the western and south-eastern parts of the Southern RFA. For catchments where annual flows are significantly decreasing, the trend magnitudes are mostly 10-20% per decade, relative to the mean annual flow for the full record. Figure 4 presents a time-series summary of annual flow and rainfall over time across all 75 forest catchments, which suggests that the detected trends in flow appear to be related to dry periods of 2002-2006 and 2018-2019 rather than to gradual change over time.

Annual rainfall-runoff residual (Figure 5): There is also a large-scale declining trend in the rainfall-runoff residual, which is, similar to that of annual flow, also more distinct in the Southern RFA region. The similar large-scale declining trends in annual flow and rainfall-runoff residual suggest that the flow decline cannot be attributed solely to changes in rainfall. Considering the large spatial scale of the declining flow, potential drivers other than rainfall are likely climatic. One plausible explanation would be the unexpected longer-term impacts of extended droughts on rainfall-runoff relationship, during which many catchments shifted to a persistent low-runoff state and have not recovered post drought, as found in many Victorian catchments (Peterson et al., 2021; Saft et al., 2015). A potential driving processes include the decline in groundwater store due to lack of recharge during the drought (Peterson et al., 2021).

High and low flows (Figure 6): High and low flows both display large-scale decreasing trends throughout forested catchments in the RFA regions. The spatial distribution of significantly decreasing trends in high flows has a similar spatial pattern to that of the annual flow. This is likely due to the high skewness that is often seen in flow data i.e., mean flow is closer to the higher flow percentiles. The catchments where low flow has decreased significantly are clearly different compared to those that have significant decreases in annual flow. The difference in the spatial pattern of trends in these indicators is particularly evident for the North East RFA region. The Southern RFA shows consistent spatial patterns of significant decrease in high, low and annual flow.

7-day low flow (Figure 7a): 7-day low flow generally decreases throughout forested catchments in the RFA regions, and the spatial distribution of catchments that have significant decreases is highly similar to that of low flow. One catchment (209014) has a large proportion of zero values for which trend is not detectable. Declining trend in 7-day minimum flow indicates likely decline in catchment-wide groundwater levels (Brutsaert, 2008; Zhang, 2014).

Cease-to-flow (CTF, Figure 7b): While the above trends highlight a large-scale decline in water quantity throughout forested catchments in the RFA region, the number of days with no flow each year is generally not changing significantly. This indicates that even where groundwater storage was declining, full disconnection between surface and ground water was not increasing. Trends are not detectable at 19 sites due to a large proportion of zero values.

Water temperature generally shows non-significant trends in RFA forested catchments, while *EC* shows a mixture of increasing and decreasing trends. For both variables there is no clear pattern in the spatial distribution of trend directions. All catchments with long-term *TP* records show significant decreases (Figure 8). For each of *TN, Turbidity (Turb), pH and DO* (Figures 9 and 10), there were fewer than 10 long-term monitoring sites within RFA forested catchments. Apart from the generally limited number of monitoring stations for the water quality variables, the stations also tend to cluster and are thus not representative of the entire RFA regions. These make it difficult to inform large-scale conclusions on water quality trends with existing data. Note that the water quality modelling includes flow among the predictors and the model residuals confirmed that these models have effectively accounted for any impacts from flow. Thus, the significant trends are not due to changes in flow alone.

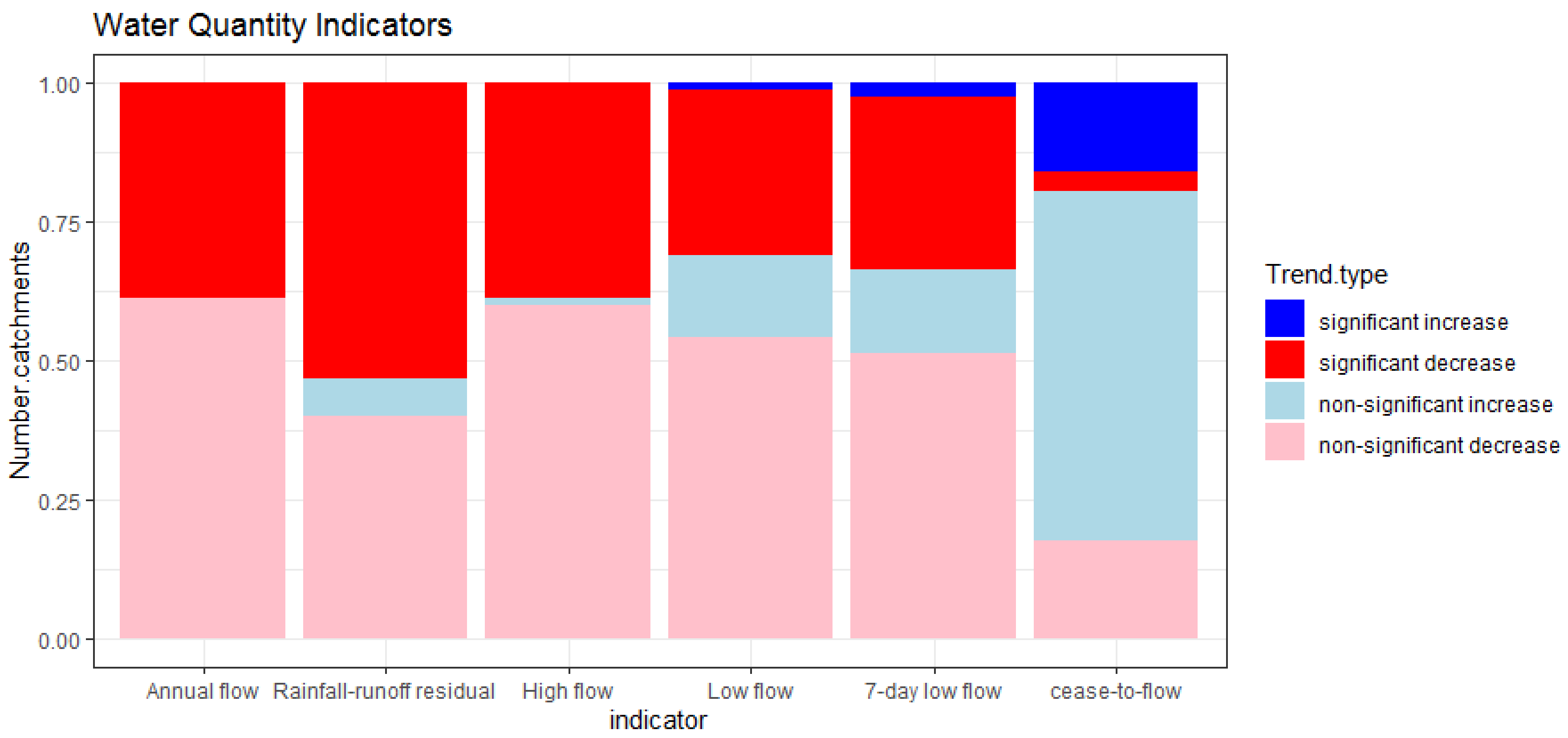
Table 4 presents a summary of trend directions for individual indicators, with the corresponding proportion of catchments with each type of trend further summarized in Figure 2. The detailed maps of trends for individual catchments for each indicator are shown in Figure 3, and Figures 5 to 10.

Table 4. Summary of trends for individual water quality/quality indicators

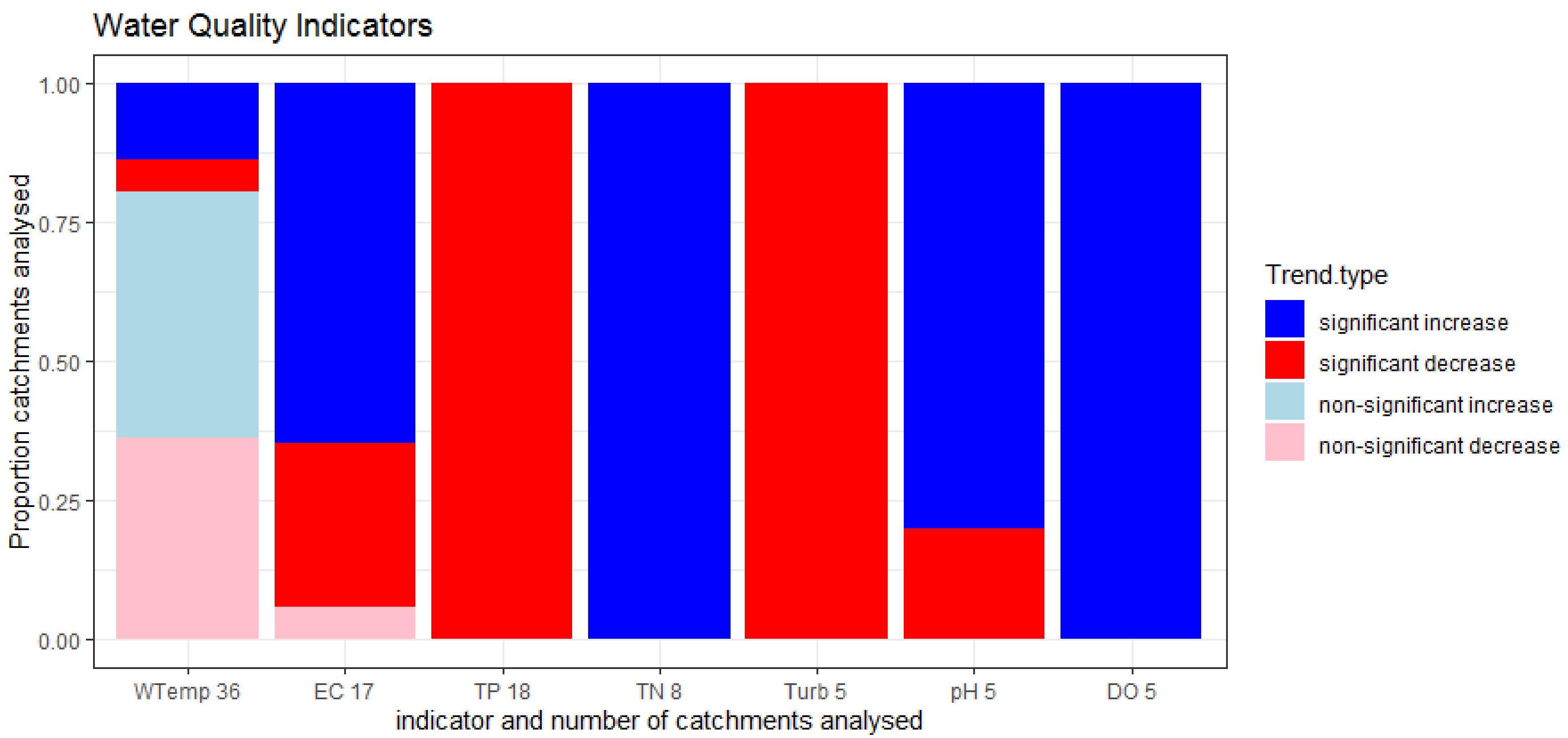
Water quality of quantity indicator	**Number of forested catchments analysed**	**Number of catchments with sig. increases (at a 0.05 level)**	**Number of catchments with sig. decreases (at a 0.05 level)**	**Number of catchments with non-significant increases**	**Number of catchments with non-significant decreases**
Annual flow	75	0	29	0	46
Rainfall-runoff residual	75	0	40	5	30
High flow	75	0	29	1	45
Low flow	75	1	22	11	40
7-day low flow[1]	75	2	23	11	38
CTF (cease-to-flow)[2]	75	9	2	35	10

WTemp (water temperature)	36	5	2	16	13
EC (electrical conductivity)	17	11	5	0	1
TP (total phosphorus)	18	0	18	0	0
TN (total nitrogen)	8	8	0	0	0
Turbidity	5	0	5	0	0
pH	5	4	1	0	0
DO (dissolved oxygen)	5	5	0	0	0

*Note: [1]Trends are not detectable at 1 site due to a large proportion of zero values.; [2]Trends are not detectable at 19 sites due to a large proportion of zero values.

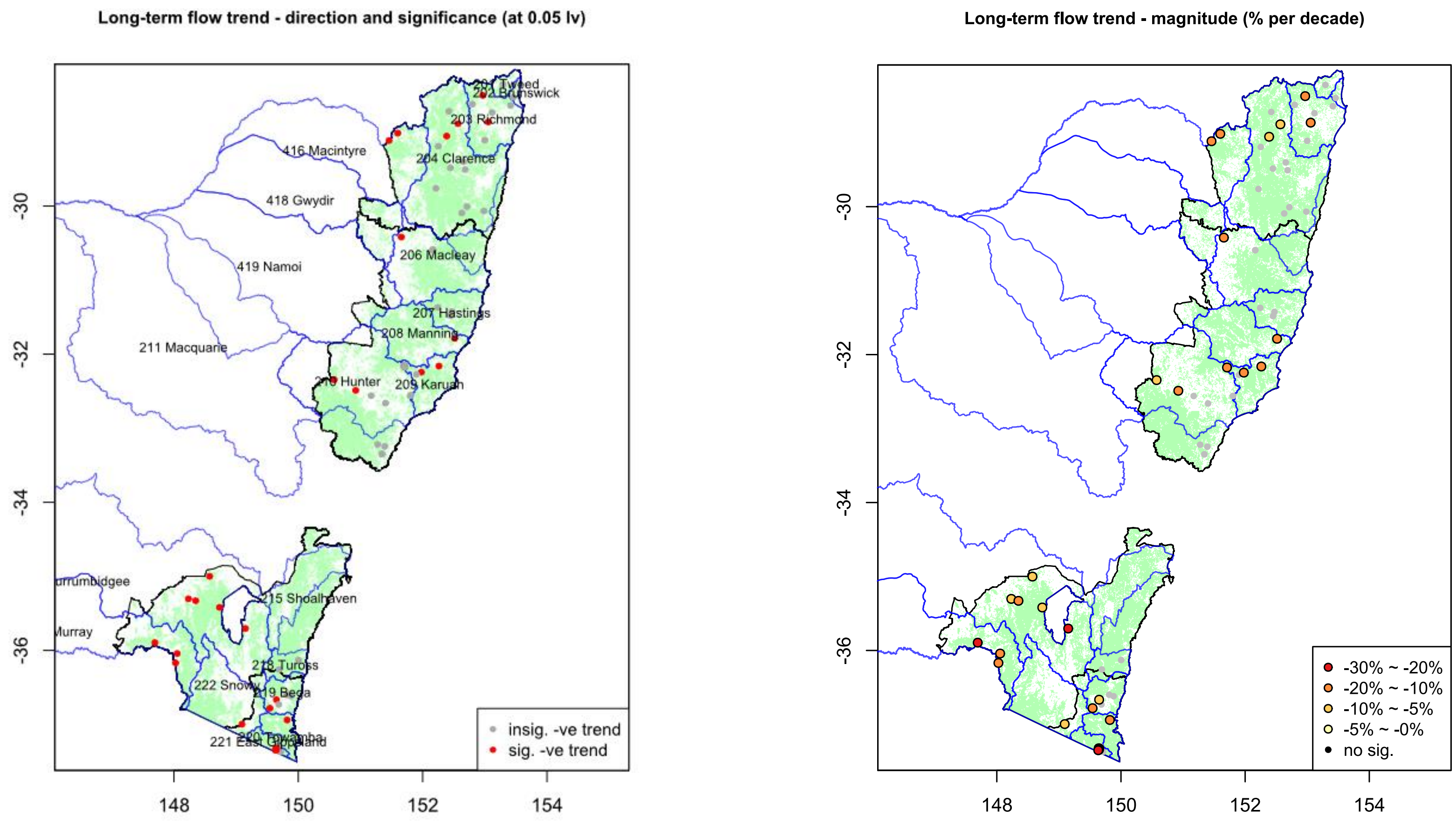

Water Quantity Indicators
1.00
0.75
0.50
0.25
0.00
Number.catchments
Annual flow
Rainfall-runoff residual
High flow
Low flow
7-day low flow
cease-to-flow
indicator
Trend.type
significant increase
significant decrease
non-significant increase
non-significant decrease

a)



b)

Figure 2. Proportion of forested catchments analysed that has shown each type of long-term trend: significant increase, significant decrease, non-significant increase or non-significant decrease, for a) water quantity indicators; b) water quality indicators, along with the number of catchments analysed on the x-axis; abbreviations for water quality variables are: WTemp = water temperature, EC = electrical conductivity, TP = total phosphorus, TN = total nitrogen, Turb = turbidity, DO = dissolved oxygen. Note that the availability of water quality data is generally limited to conclude large-scale trend patterns. All corresponding locations of the catchments analysed for each indicator are shown in Figure 3 and Figures 5-10.



a)

b)

Figure 3. The a) direction and significance; and b) magnitude of long-term trends in mean annual flow across forested catchments within the RFA regions. All trend magnitudes are in percentage change per decade, relative to the long-term averages of individual sites.

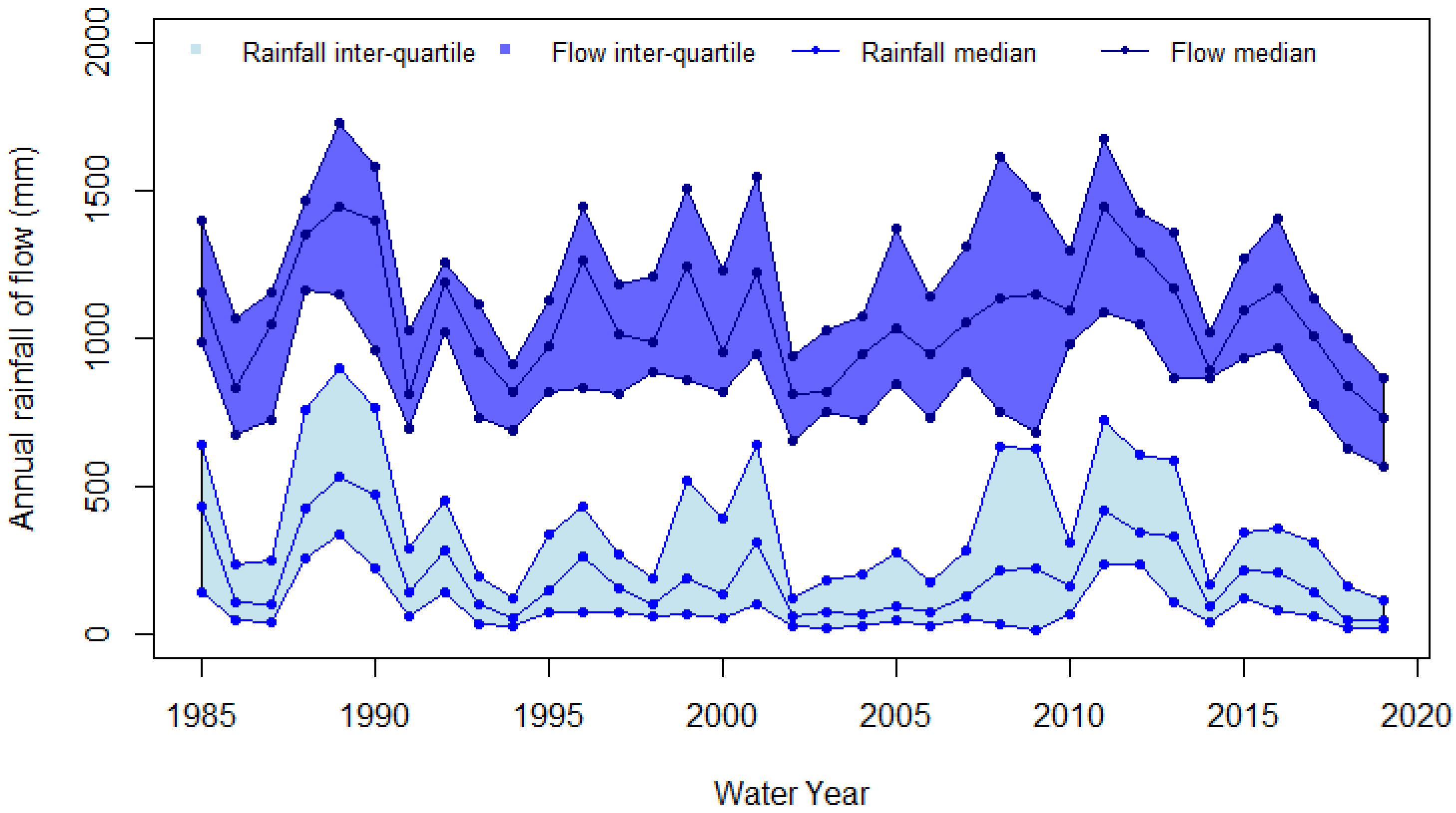


Figure 4. Annual rainfall and runoff for the period 1985-2020 across 75 forested catchments in NSW RFA regions. Solid lines indicate the median across the catchments with 25th and 75th percentile range shown in shades. The inter-quartile ranges indicate the variability in annual rainfall and flow each year across all forest catchments studied.

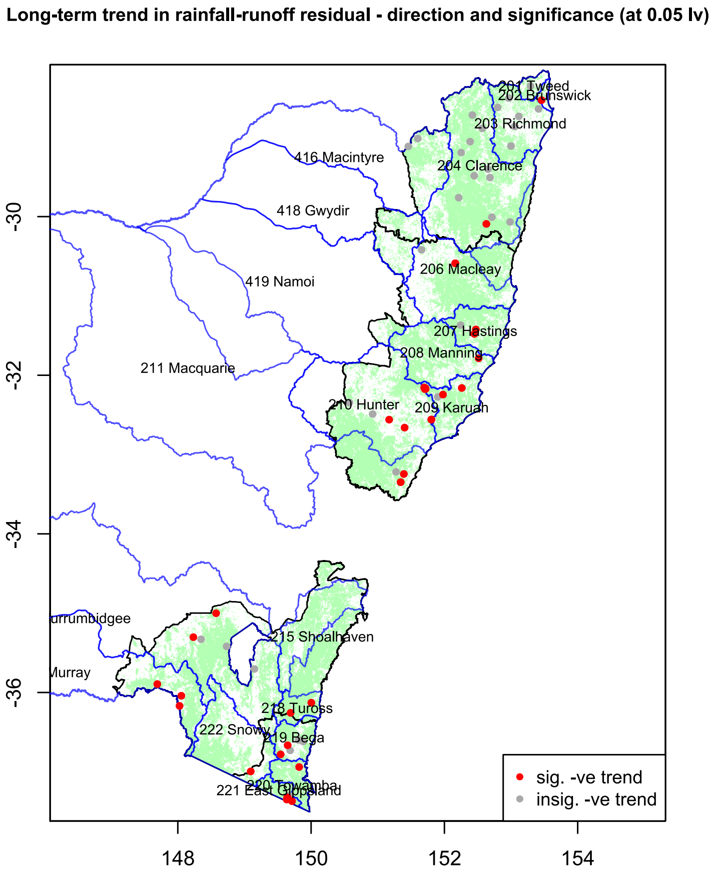
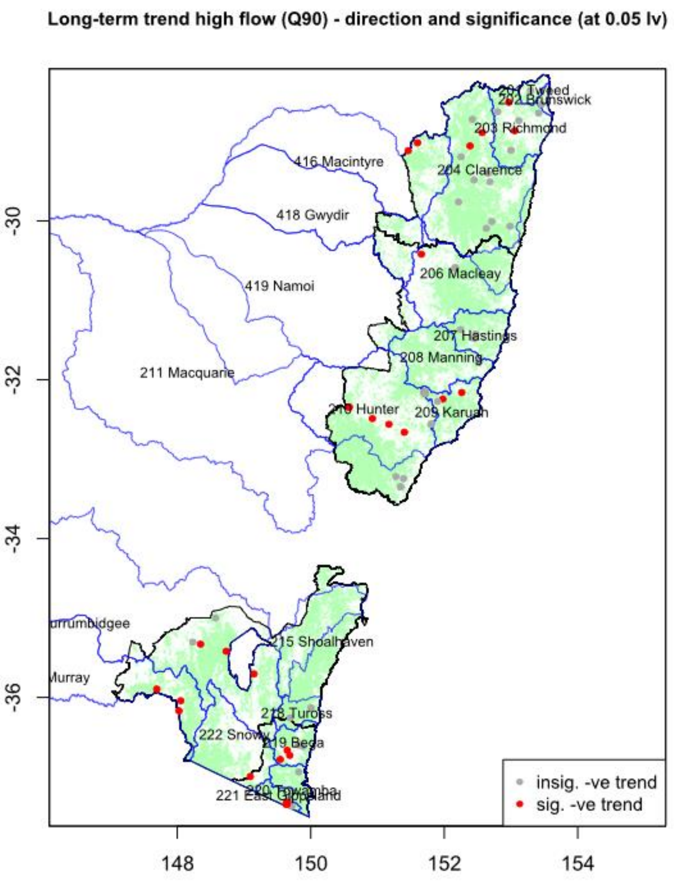
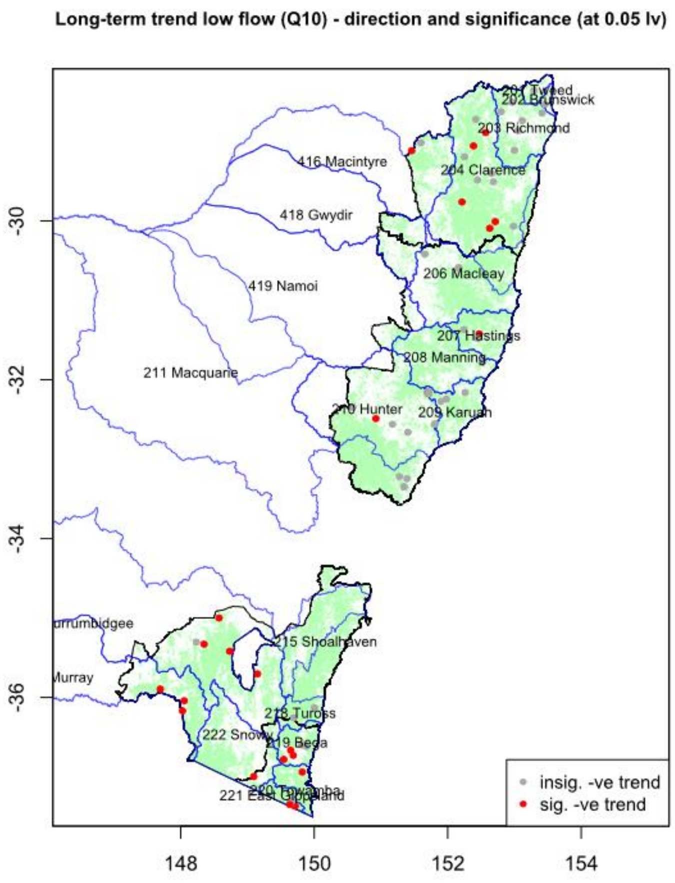


Figure 5. The direction and significance of long-term trends in annual rainfall-runoff residuals across forested catchments within the RFA regions, estimated for individual catchments.

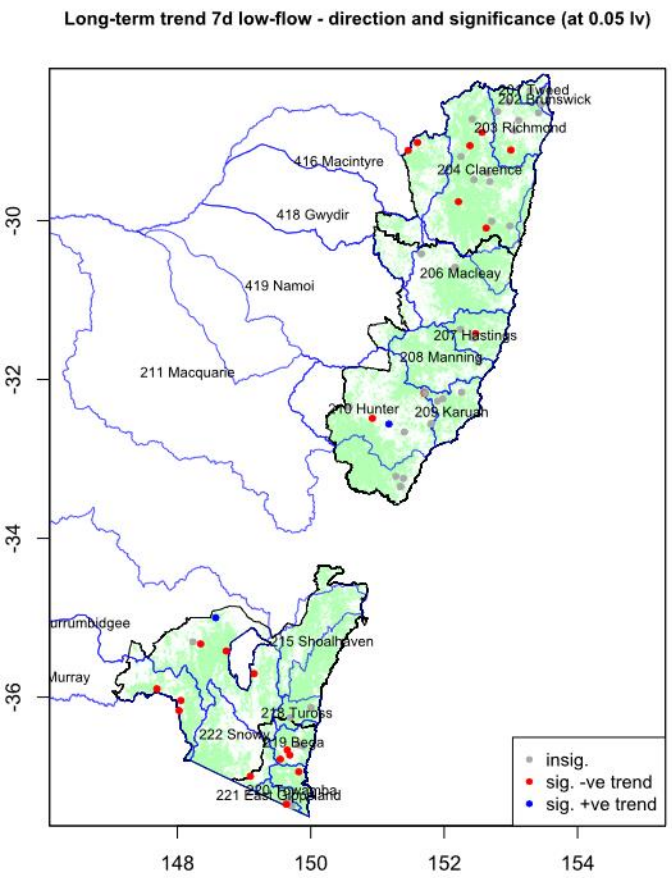


a)

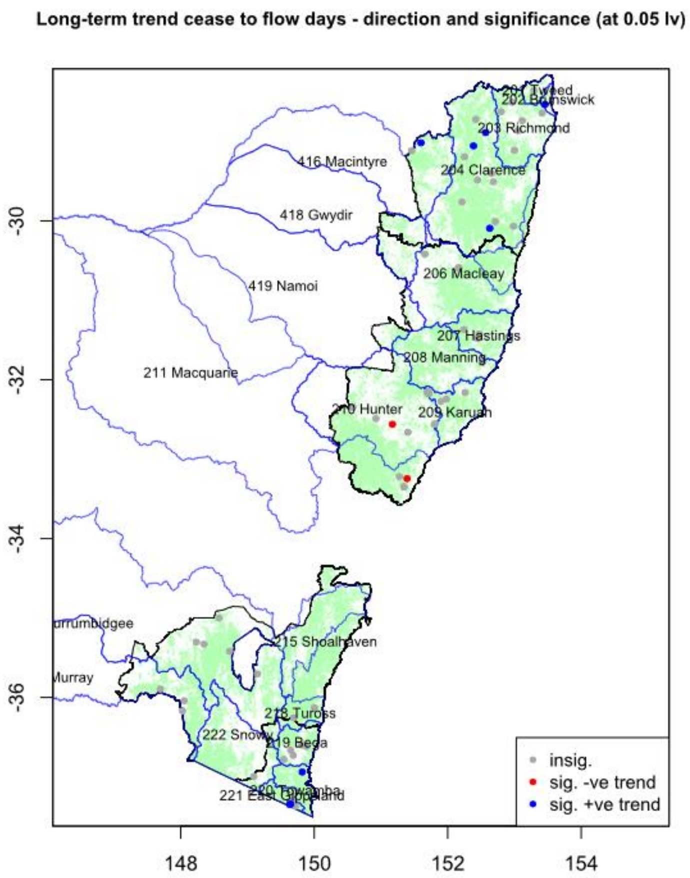


b)

Figure 6. The direction of long-term trends in a) high flow and b) low flow, across forested catchments within the RFA regions. High flow Q90 is the annual 90th percentile of all daily flow and low flow Q10 is the annual 10th percentile of all daily flow, both estimated for individual catchments.

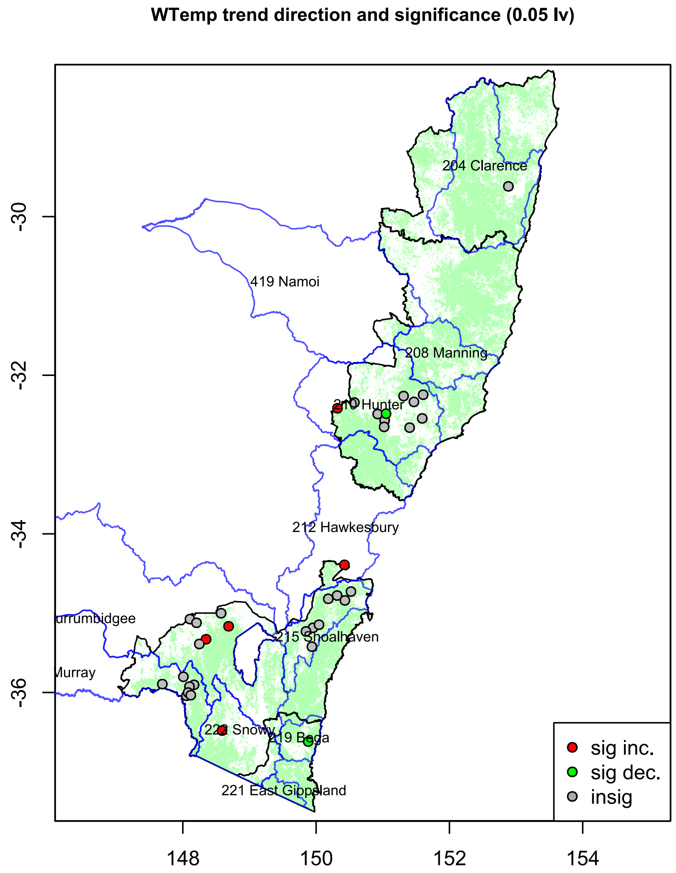


a)



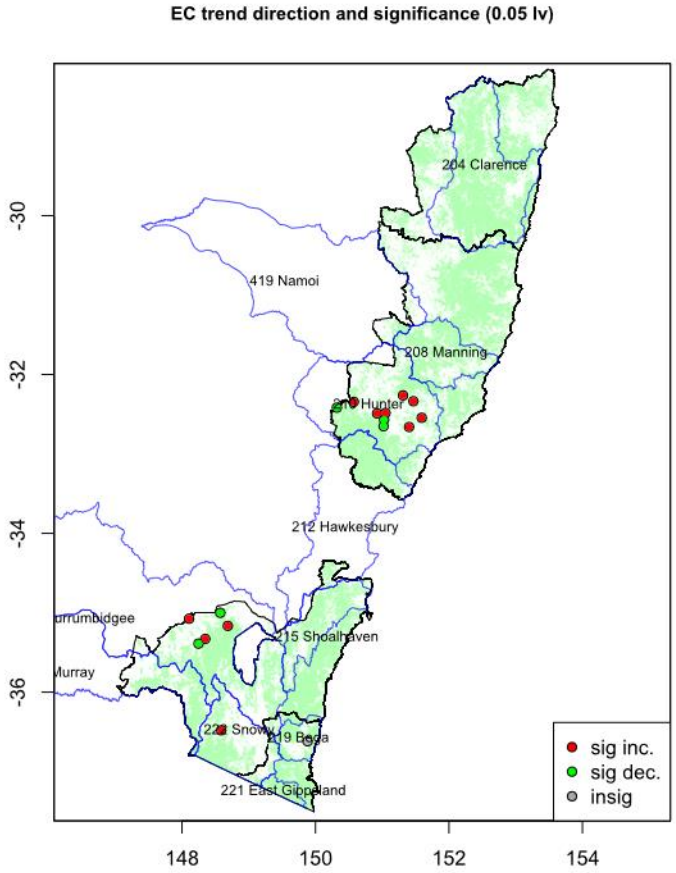
b)

Figure 7. The direction of long-term trends in a) 7-day low flow and b) cease-to-flow, across forested catchments within the RFA regions. 7-day low flow is the average flow over the 7 days in each year for which have the lowest flows, cease-to-flow is the number of days with no flow in each year, both estimated for individual catchments.



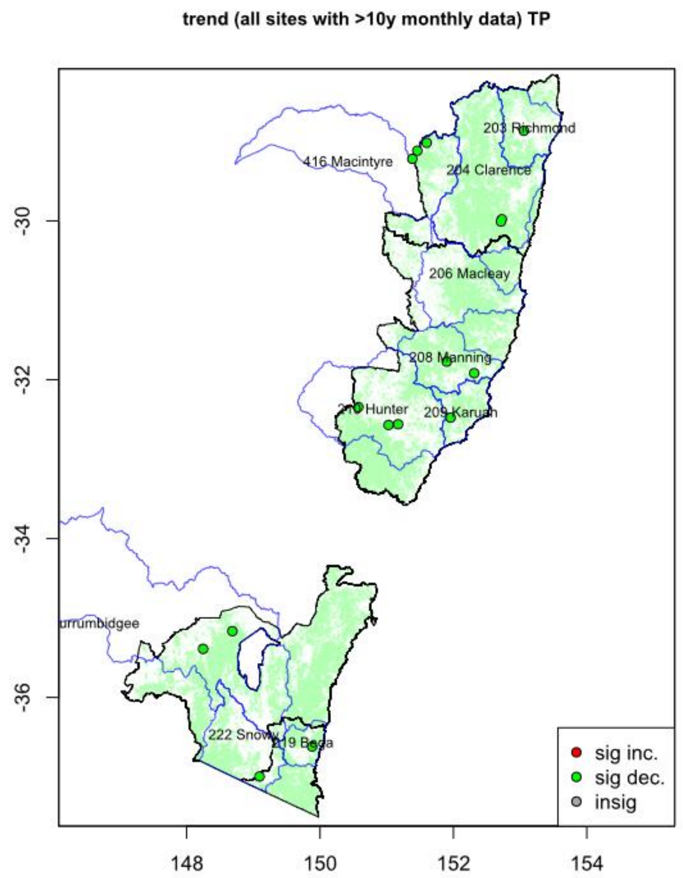
WTemp trend direction and significance (0.05 lv)
204 Clarence
419 Namoi
208 Manning
210 Hunter
212 Hawkesbury
215 Shoalhaven
222 Snowy
219 Bega
221 East Gippsland
urrumbidgee
Murray
sig inc.
sig dec.
insig
-30
-32
-34
-36
148
150
152
154

a)



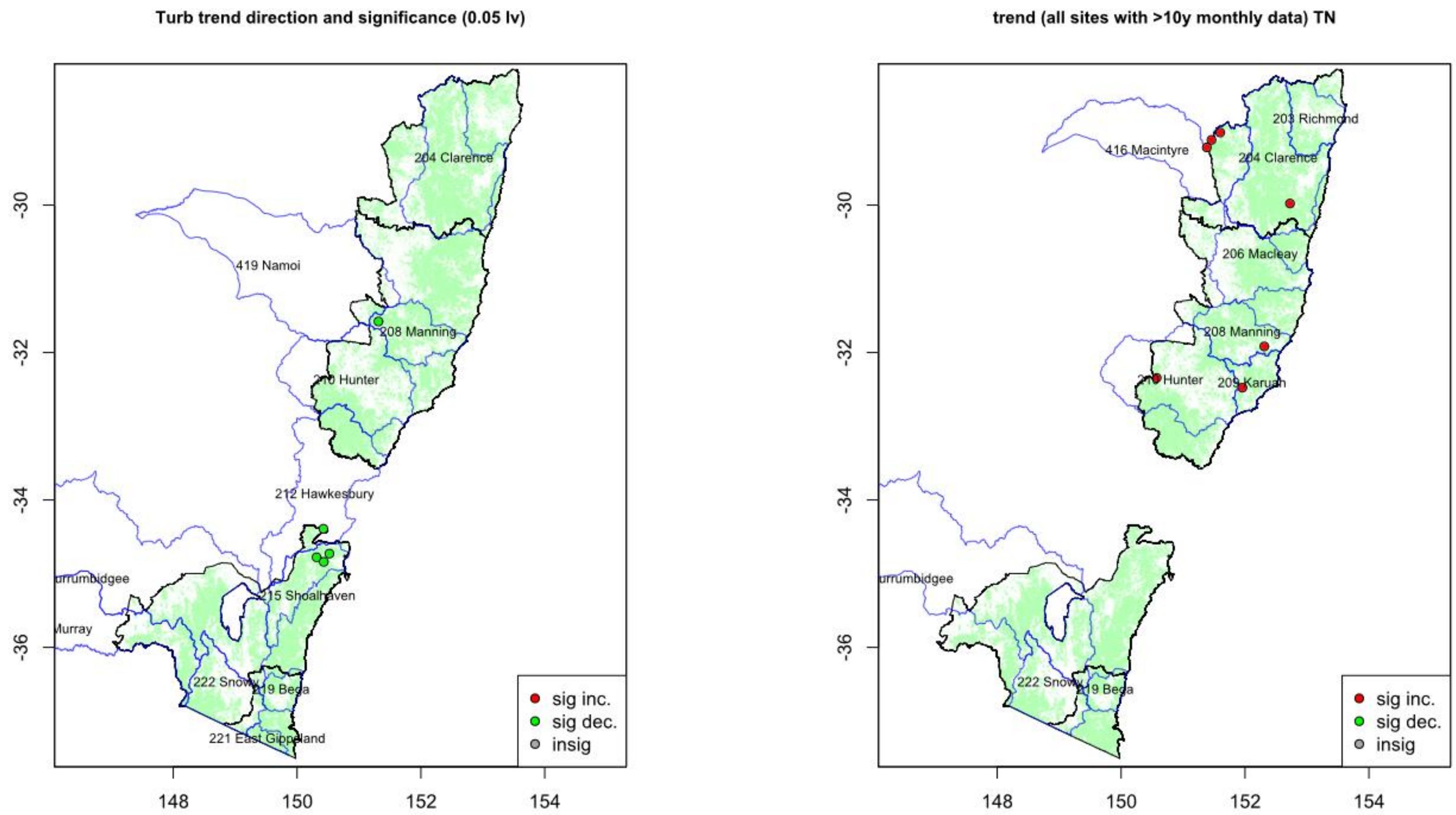
EC trend direction and significance (0.05 lv)
204 Clarence
419 Namoi
208 Manning
210 Hunter
212 Hawkesbury
215 Shoalhaven
222 Snowy
219 Bega
221 East Gippsland
urrumbidgee
Murray
sig inc.
sig dec.
insig
-30
-32
-34
-36
148
150
152
154

b)



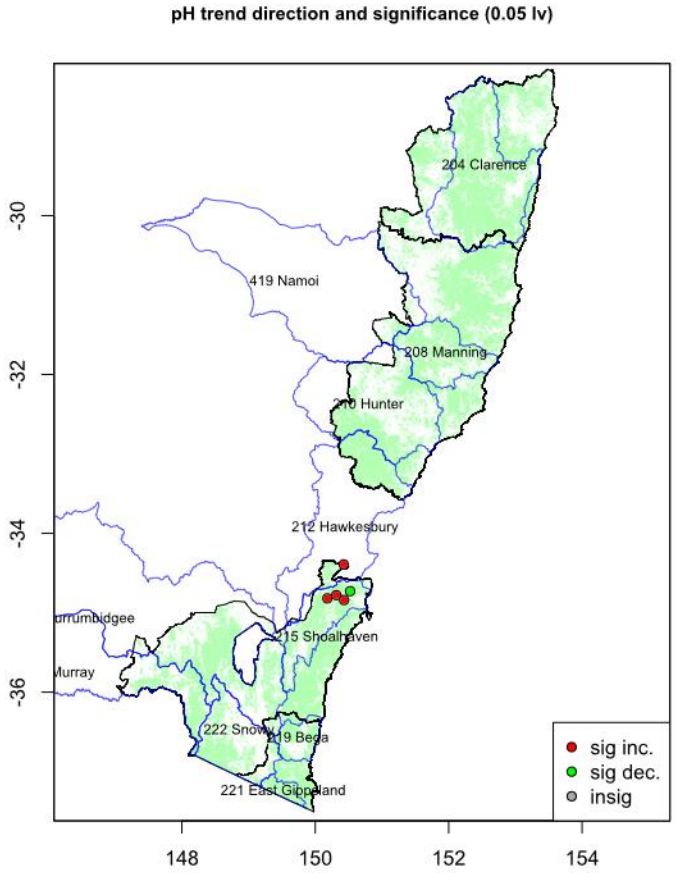
c)

Figure 8. The direction of long-term trends in a) water temperature (WTemp) b) electrical conductivity (EC) and c) total phosphorus (TP), across forested catchments within the RFA regions, all estimated for individual catchments.

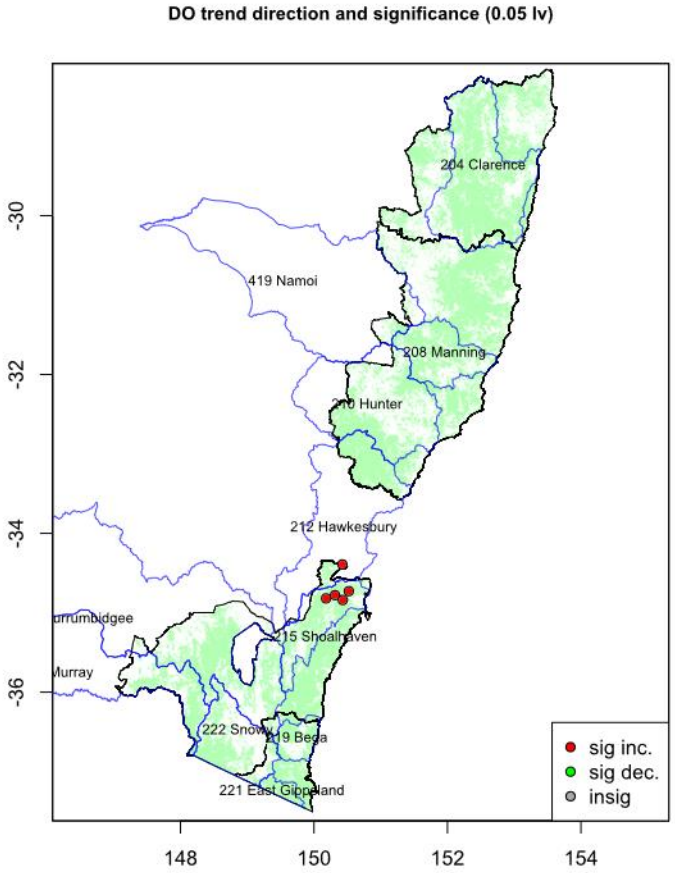


a) *b)*

Figure 9. The direction of long-term trends in a) turbidity (Turb) and b) total nitrogen (TN), across forested catchments within the RFA regions, both estimated for individual catchments. Note that data availability (number of catchments and their spatial representativeness) is highly limited to inform large-scale conclusions on water quality trends.



a)



b)

Figure 10. The direction of long-term trends in a) pH and b) dissolved oxygen (DO), across forested catchments within the RFA regions, both estimated for individual catchments. Note that data availability (number of catchments and their spatial representativeness) is highly limited to inform large-scale conclusions on water quality trends.

3.2 Baselines and drivers of annual flow trends

3.2.1 How are flow trends changing over space with catchment features?

We first discuss how the identified long-term trend in flow varies across catchments with their characteristics. Figure 11 shows the relationship between the percentage of decadal flow decrease (trend magnitudes) in annual flow and catchment characteristics across RFA forested catchments, and only includes catchments that show significant decreasing trends (29 catchments, see Table 4). The four catchment characteristics shown (mean annual flow (in mm), percentage catchment area as national park, total percentage catchment area harvested, and total percentage area burnt) were selected from a greater set of variables that represent the climate, land use and disturbance of catchments because they show the strongest correlation with the trend magnitudes. The catchment characteristics not presented are: mean annual rainfall (mm), percentage catchment area as forest, percentage catchment area natural land use, and percentage catchment area as state forest – all having a Spearman's rank correlation of less than 0.1, which is also non statistically significant (at a 0.05 level).

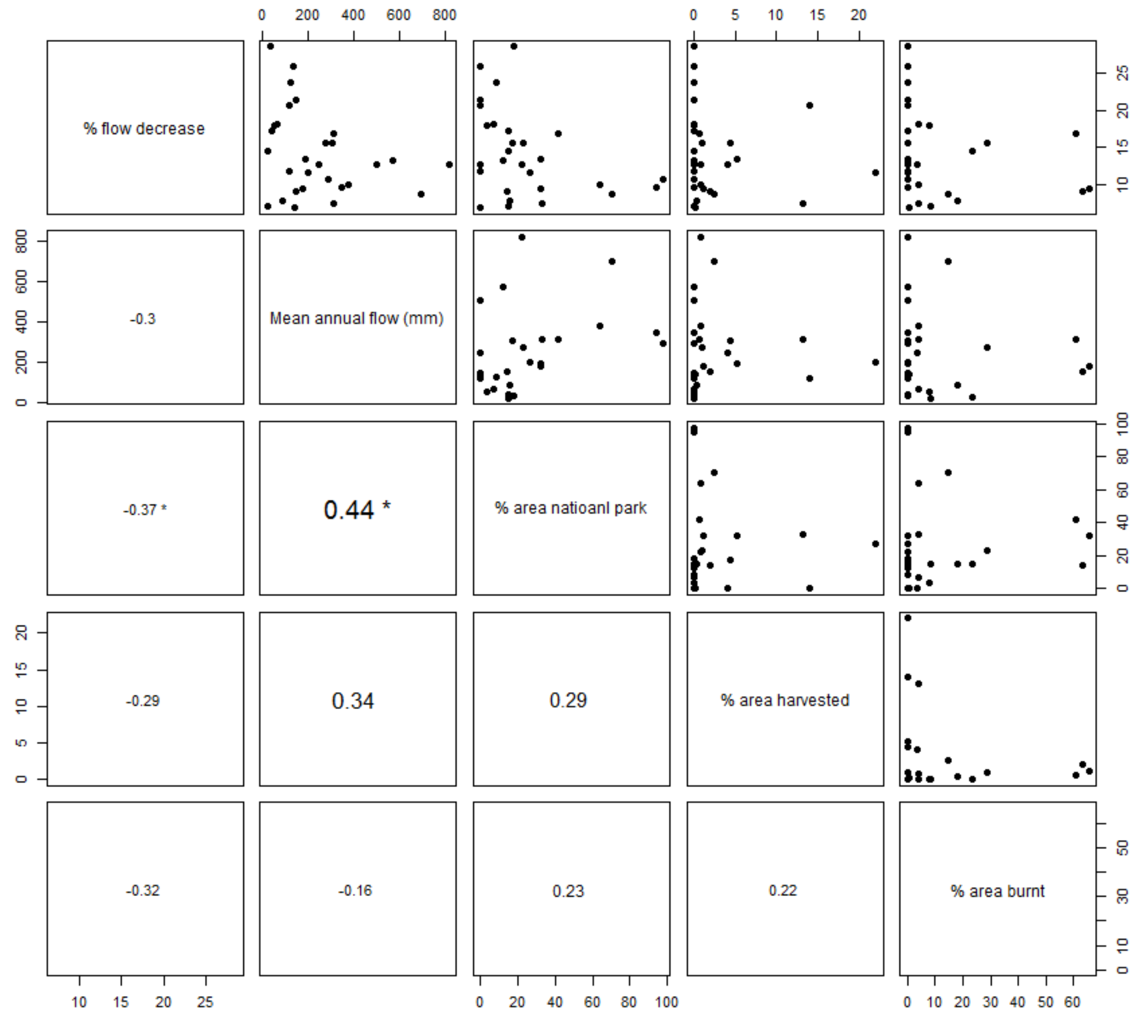


Figure 11. Relationship between the percentage decadal decrease in annual flow and four catchment characteristics across RFA forested catchments that have significant decreasing trends. The top right triangle panels show the scatter plots between each pair of variables: the y-axis of the top row shows the magnitude of percentage decline per decade relative to the long-term average annual flow. The y-axes of the four bottom rows show the values of individual catchment characteristics: mean annual flow (in mm), percentage catchment area as national park, total percentage catchment area harvested, and total

*percentage area burnt. The bottom triangle panels show the pair-wise Spearman's rank correlation between each pair of variables, with * indicating a statistically significant correlation at 0.05 level.*

Figure 11 explores how the magnitude of flow reduction change across RFA forested catchments with varying characteristics, and how the catchment characteristics correlated with each other. When assessing the first row, we can see how the magnitude of flow reduction (i.e., smaller reduction in annual flow relative to the catchment mean annual flow) correlates with individual catchment characteristics. Specifically, a smaller flow reduction is seen for catchments that have either a higher mean annual flow, a greater percentage catchment area as national park, a greater percentage catchment area harvested, or a greater percentage catchment area burnt. However, only the percentage catchment area as national park shows a statistically significant correlation with trend magnitudes in annual flow and visually it shows a strong similarity to the trends against mean annual flow.

It is also worth noting that there are more undisturbed catchments (i.e., having near-zero percentage area harvested or burnt), for which the percentage of flow reduction spreads over a much wider range compared with disturbed catchments. These results illustrate that although we saw a correlation between a larger proportion of undisturbed catchment and a greater flow reduction, the flow reduction is also highly variable for catchments that are rarely disturbed by fire and harvesting. This suggests no clear link between the spatial differences in long-term flow trends and the history of fire and harvest. These high variabilities may be explained by additional landscape characteristics not considered here. These low disturbance catchments have a very wide range of mean annual flow; they therefore have a wide variability in mean annual rainfall and potentially in other physiographic characteristics). The other limitation with the current analysis is the high cross-correlation between the catchment characteristics, which increases the challenge of separating their individual effects on the flow trends and thus estimating the baseline trends for different catchments. This is an area that requires further work with improved statistical approaches as well as a larger number of study catchments with a wider spread of catchment land use and disturbance conditions.

There are (non-significant) negative correlations between percentage flow decrease and disturbance (harvest and burning). These patterns are similar to the relationships between mean annual flow and disturbance, for which there is clearly not a direct causal link. This underlines the challenge of separating the effects of multiple factors. The subsequent Section 3.2.2 presents preliminary findings with a more detailed time-series analysis on individual catchments, to help understand these potentially non-linear responses of flow to forest disturbances.

3.2.2 Are there significant impacts of historical disturbances (harvest and wildfire) on flow over time for induvial catchments?

Following the above exploration on the spatial variation of long-term flow trend, we then focus on how the flow changes over time at individual catchments and how these changes link to the unique catchment disturbance history due to fire and harvesting. The first catchment-level trend attribution analysis focuses on the heavily disturbed catchments, which were identified as ones with either: a) over 10% catchment area burnt by wildfire in any single year; or b) over 2% area harvested in any single year. This enables us to focus on catchments with the largest disturbances from fire and harvest, where we expect greater flow responses to these disturbances. Figures 12 and 13 compare the time-series of annual rainfall-runoff residuals with the wildfire burning history and harvest history, respectively, for each heavily disturbed catchment. Each type of disturbance is summarized by both the annual and 10-year cumulative area affected, with the latter considering accumulated disturbance impact. Since the rainfall-runoff residuals (top rows of both figures) represent the deviation of annual flow from the expected level with given rainfall, comparing these time-series could help identify any relationships between changes in flow responses and disturbance.

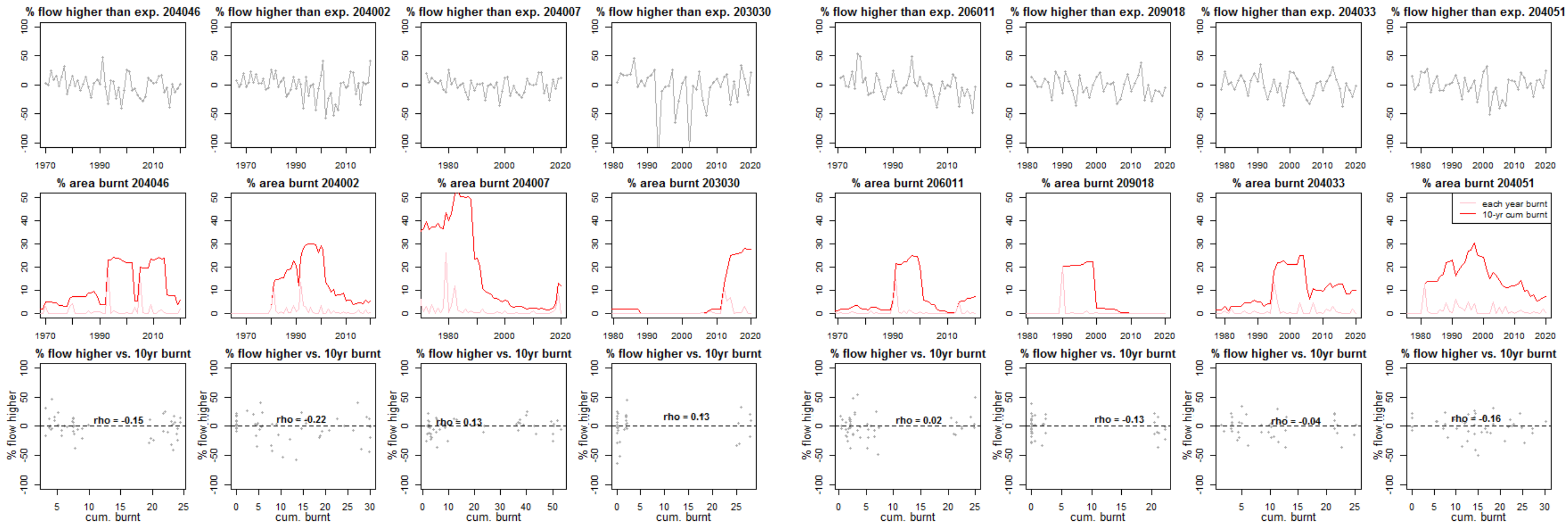


*Figure 12. The annual rainfall-runoff residuals (top row), along with the corresponding disturbance history as both the annual and 10-year cumulative area burnt (middle row). Each column shows one catchment that has been heavily burnt, identified with over 10% area burnt in any single year. The bottom row shows the scatter plot of rainfall-runoff residual and 10-year cumulative area burnt along with the Spearman's rank correlation between the two variables; * indicates a statistically significant correlation at 0.05 level.*

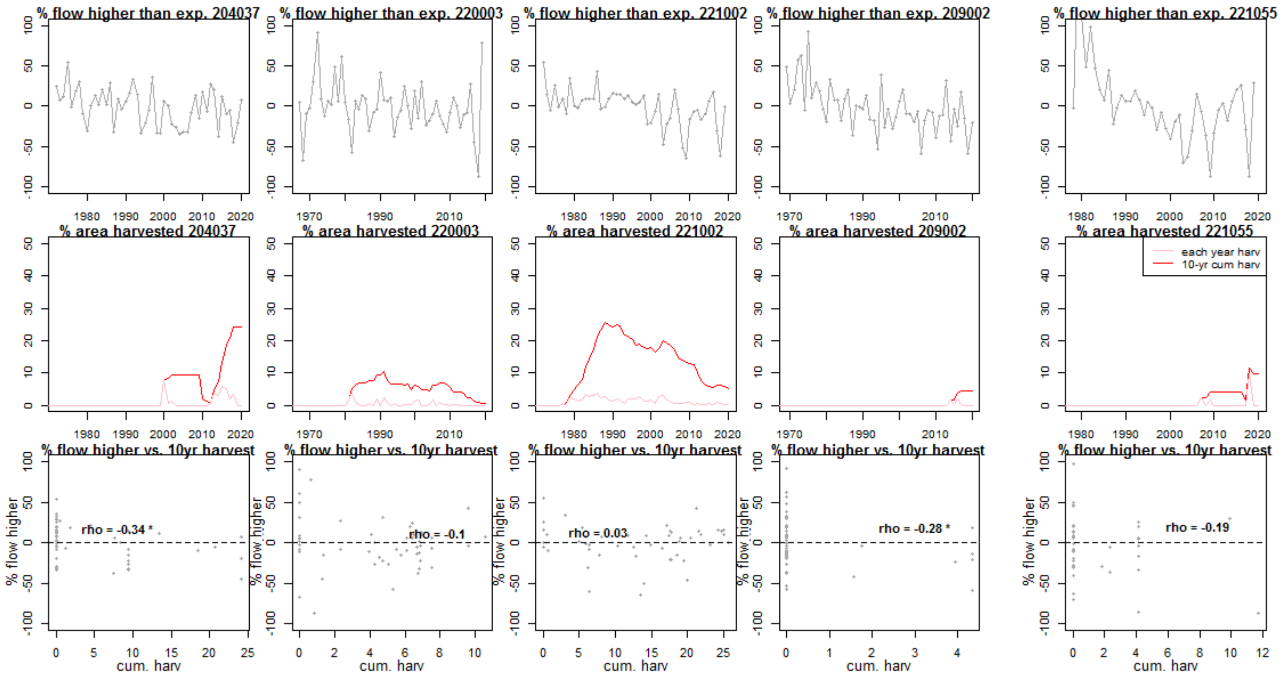


*Figure 13. The annual rainfall-runoff residuals (top row), along with the corresponding disturbance history as both the annual and 10-year cumulative area harvested (middle row). Each column shows one catchment that has been heavily harvested, identified with over 2% area harvested in any single year. The bottom row shows the scatter plot of rainfall-runoff residual and 10-year cumulative area harvested, along with the Spearman's rank correlation between the two variables; * indicates a statistically significant correlation at 0.05 level.*

Figures 12 and 13 show mostly no statistically significant correlations between the rainfall-runoff residuals and the disturbance records for either fire or harvest, with generally weak correlations (<0.3). The lack of correlation may be a result of the highly noisy rainfall-runoff residuals relative to the disturbances, which is likely due to climate variability, both interannual and intraannual (e.g., size of rainfall events, changes in seasonality). In addition, within the catchment pairs identified, there also seems to be a long-term decreasing trend in the rainfall-runoff residuals before 2000. This means that the flow is gradually decreasing for a given rainfall, suggesting a change in the rainfall-runoff relationship possibly due to regional changes in climate patterns other than annual rainfall or forest age (to be further investigated). Such regional climate-driven changes in flow make it difficult to detect any disturbance impacts for individual catchments.

We then performed a pseudo-paired catchment analysis focusing on catchment pairs including one disturbed and one control catchment that are close to each other (<50km). This is different to conventional paired catchment analyses as all catchment pairs were selected retrospectively by disturbance history. For each pair, a disturbed catchment was identified with over 5% catchment area affected by either wildfire or harvest, accumulated over any 10 years; while a corresponding control catchment was identified as one that has not been affected by either wildfire or harvest in the data record period. The rationale for the 5% threshold to identify a disturbed catchment is to focus on the largest fire/harvest disturbances as we expect any impact of these disturbances on flow would be more identifiable. Figures 14 and 15 show the annual flow differences (standardised) between each pair of catchments, along with the corresponding wildfire or harvest history for the disturbed catchment, respectively. In considering the accumulated disturbance impacts, different periods of accumulation were explored to identify the period that led to the highest correlation between flow differences and disturbance (bottom row of Figures 14 and 15).

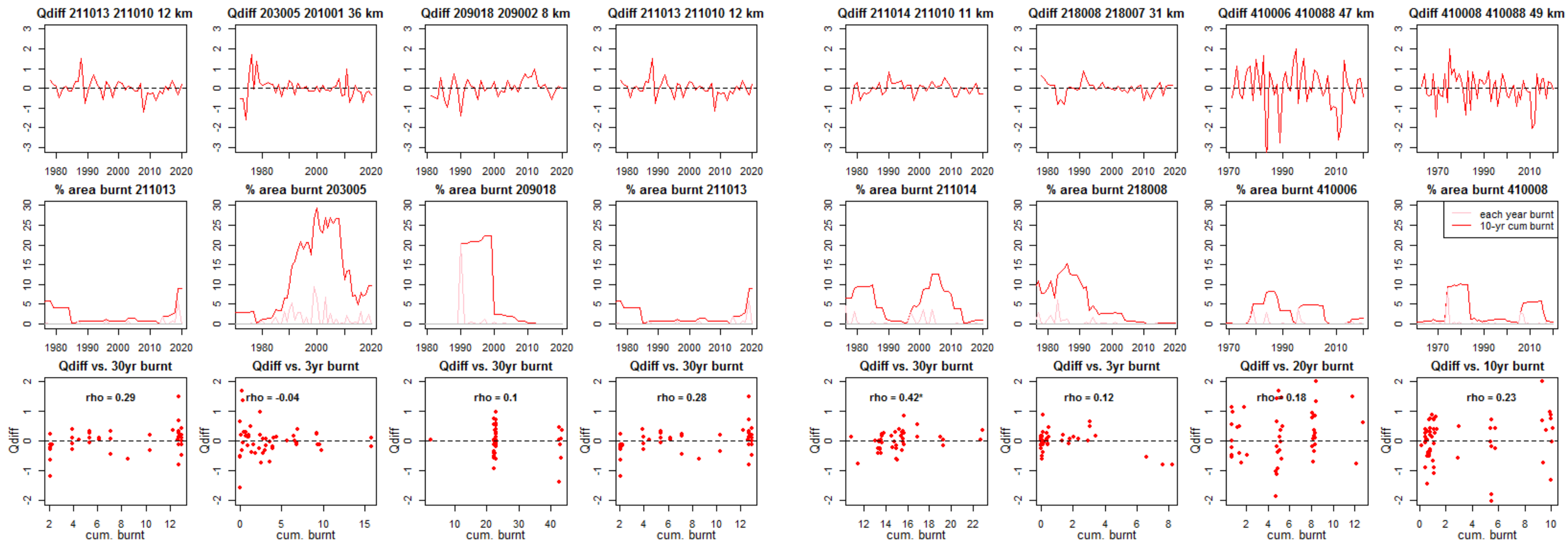


*Figure 14. The annual flow differences (standardised, flow at the disturbed catchment minus flow at the undisturbed catchment) between each pair of catchments (top row), along with the corresponding disturbance history as both the annual and 10-year cumulative area burnt (middle row). Each column shows one catchment pair consisting of: a) one 'disturbed' catchment with >5% cumulative area burnt over any 10 years; and b) another 'control' catchment that has never been burnt; c) the two catchments are less than 50km apart. The bottom row shows the scatter plot of flow differences against cumulative area burnt, over either 3, 5, 10, 15, 20 or 30 years – only the cumulative period that led to the highest correlation was presented; * indicates a statistically significant Spearman's rank correlation at 0.05 level.*

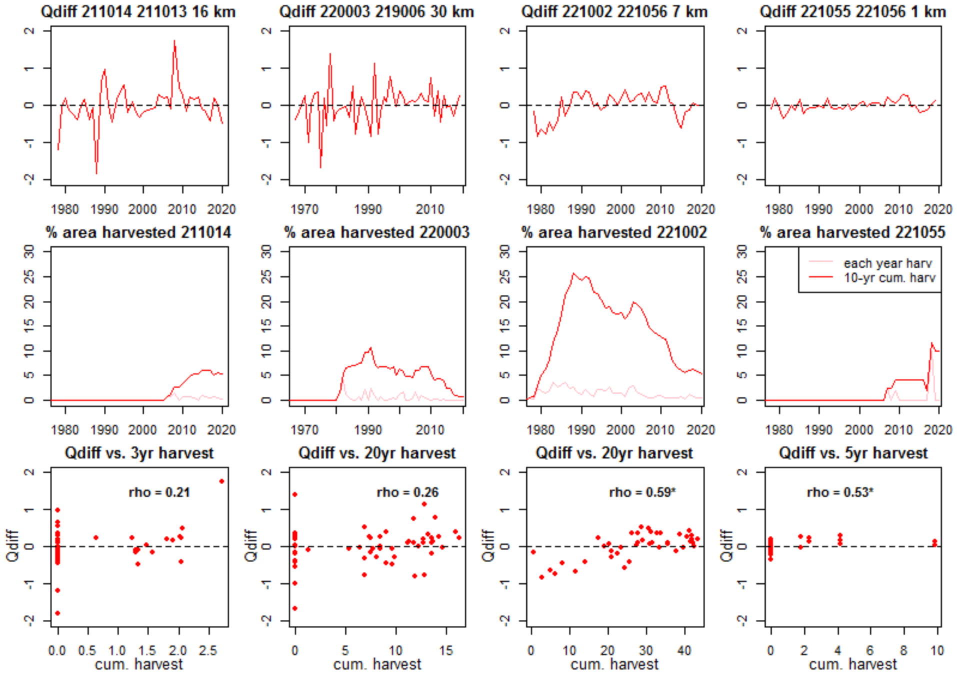


*Figure 15. The annual flow differences (standardised, flow at the disturbed catchment minus flow at the undisturbed catchment) between each pair of catchments (top row), along with the corresponding disturbance history as both the annual and 10-year cumulative area harvested (middle row). Each column shows one catchment pair consisting of: a) one 'disturbed' catchment with >5% cumulative area harvested over any 10 years; and b) another 'control' catchment that has never been harvested; c) the two catchments are less than 50km apart. The bottom row shows the scatter plot of flow differences against cumulative area harvested, over either 3, 5, 10, 15, 20 or 30 years – only the cumulative period that led to the highest correlation was presented; * indicates a statistically significant Spearman's rank correlation at 0.05 level.*

In Figure 14, we generally see weak positive correlations (<0.3) between cumulative burnt areas and flow differences. One pair of catchments suggests significant impact of fire, in which cumulative burnt area shows significant positive correlation the flow differences between the disturbed catchment (211014) and the control catchment (211010).

Figure 15 highlights the stronger impacts of harvest on flow in two catchment pairs. Specifically, the flow differences between 221002 and 221056, and between 221055 and 220156, both have significant positive correlations with the cumulative harvested area at the corresponding disturbed catchments (221002 and 221055). In other words, in both catchment pairs, harvests at the disturbed catchments are associated with higher flows. The consistent flow response to fire and harvest is likely a result of reduction in forest water use due to these disturbances.

Compared to the previous single-catchment analysis (Figures 11 and 12), this pseudo-paired catchment analysis identifies stronger effects of disturbances. By focusing on flow differences between catchments with similar climate but contrasting disturbance history, this approach can effectively reduce the impact of climate variability on flow, allowing us to better focus on the impacts of disturbances. However, there are still substantial scatters of the relationships between flow and disturbance across catchments, which might be due to different recovery periods i.e., from the time of disturbance to when water yield reaches equilibrium (Brown et al., 2005). Further, it also seems that some catchment pairs show more scattered flow differences than others (e.g., second column in Figure 15, 220003 and 219006), suggesting potential for further impacts from spatially variable climate, differences in catchment properties, or other disturbances that have not been considered. This analysis is limited by the number of available catchment pairs (neighbouring disturbed and non-disturbed catchments) that can be identified from existing data, and the limited variation in catchment characteristics. We expect to gain higher statistical power to explain the flow responses from extending this analysis to a larger number of catchments with a wider range of climate and disturbance conditions and contrasting levels of disturbances.

4. Discussions and Recommendations

4.1 Recommendations on defining baselines and drivers of trends in flow

The trend analysis demonstrates a large-scale decline in flow across the RFA regions. Results in Section 3.2.1 identify catchment features that differentiate larger and smaller magnitudes of flow decline. Specifically, individual catchment attributes associated with smaller flow declines include: i) higher mean annual flow, ii) greater percentage catchment area as national park; iii) greater percentage catchment area harvested, and iv) greater percentage catchment area burnt. However, due to the high cross-correlations between the catchment characteristics, we concluded that these spatial patterns in trends are insufficient to establish baselines or identify drivers of spatial differences in flow trends.

Our results in Section 3.2.2 highlight the need for catchment-scale time-series analysis to identify the impacts of disturbances on flow. Specifically, a pseudo-paired catchment analysis shows good potential to tackle this problem. It can effectively remove some noise in the flow data due to interannual climate variability at individual catchments, making it easier to identify disturbance impacts.

Combining all findings on the baselines and drivers of trends (Section 3.2), we identify the need for further studies to explicitly focus on separating the impacts of climate from catchment disturbances, taking into account: 1) catchment specific lags in disturbance effects; 2) impacts of interannual variability and long-term changes in climate; and 3) potential interactions amongst catchment climate, changes in catchment internal functioning, and disturbance.

In the subsequent Section 4.2, we review existing paired catchment analyses in NSW and their key findings on the impacts of wildfire and harvest, and discuss our results in the context. In Section 4.3, we further assess the availability and representativeness of existing monitoring data in NSW RFA regions, to make recommendations on future monitoring for better facilitating paired catchment analyses.

4.2 Impacts of wildfire and harvest identified by existing paired catchment studies in NSW

A number of paired catchment analyses have previously been undertaken to identify the impacts of disturbance on water quantity and quality in NSW forests (Table 5). These studies largely focused on identifying the effects of fires and forest harvesting. For harvests, the longest running study was conducted from 1976 to 1991 in the eight catchments within the Karuah Hydrology Research Area in Chichester State forest to the north of Sydney (Cornish, 1993; Cornish, 2001; Cornish & Vertessy, 2001). From 1997 to 2011, Webb et al. (2012b) studied the same eight catchments in the Karuah area to evaluate the longer-term changes in streamflow after harvesting in forest. Webb (2008) studied five unmapped headwater catchments (i.e. with no harvesting exclusion zones or buffer strips applied near river channels) in the Kendall State forest on the Mid-North coast of NSW from 2002 to 2006.

In south-eastern NSW, there have been two long-term studies mainly evaluating the impacts of harvesting on streamflow and water yield, including six catchments in the Yambulla State forest from 1977 to 1987 (MacKay & Cornish, 1982; Moore et al., 1986; Crapper et al., 1989; Roberts, 2001; Roberts et al., 2001; Webb & Jarrett, 2013), and three catchments in the Tantawangalo Creek from 1986 to 1997 (Lane & Mackay, 2001). Paired studies in five catchments in Kangaroo River State forest from 2001 to 2009 (Webb et al., 2012a) and in another five catchments in the Brooman State Forest from 2007 to 2014 (Walsh et al., 2020) have studied the effects of harvesting on water quality indicators (turbidity and suspended sediment yields). In the Central West of NSW, Webb et al. (2007) conducted a paired study from 1999 to 2006 in three small catchments in the Canobolas State forest and found increases in harvest (represented by percentage catchment area harvested) led to an increase in water yields, due to an increase in the baseflow component of total streamflow.

Past paired catchment studies on the effects of harvests have generally found increasing flow/water yield after harvests, consistent with our preliminary findings (Section 3.2.2). In the Karuah study, following harvesting, initial water yield increased markedly – by about 150-250 mm/year – in five of the six treated catchments, with the magnitude affected by the percentage of harvesting (Cornish, 1993). Webb et al. (2012b) also found that there was a significant increase in streamflow after harvesting, equivalent to annual water yield changes ranging from 120 mm to 319.6 mm. This is because there is a reduction in evapotranspiration after harvesting, resulting in an initial increase in water yield, which can persist for 4 to 7 years (Watson et al., 1999; Webb, 2012). Both baseflows and stormflows increased after harvesting (Cornish & Vertessy, 2001; Lane & Mackay, 2001; Roberts 2001; Roberts et al., 2001; Webb & Jarrett, 2013). Some studies reported a subsequent decrease in flow with regrowth of the forest, falling below pre-harvest levels after seven years (Cornish & Vertessy, 2001). These results suggest that reforestation should be considered in analysing flow responses in harvested/burnt catchments.

Existing paired catchment studies on water quality largely focus on sediments. Following harvesting, suspended sediment yields increased in the short-term (Webb, 2008; Webb et al., 2012a); however, Best Management Practices (BMPs) were effective in reducing the magnitude and persistence of impacts from harvesting, thereby maintaining water quality and protecting the integrity of aquatic ecosystems in forests (Webb et al., 2012a; Walsh et al., 2020). Turbidity levels after harvesting can probably be reduced by applying effective BMPs and by rapid and extensive revegetation after harvest

(Cornish, 1993; Cornish, 2001; Cornish & Vertessy, 2001). The rate of sediment transfer after wildfires usually increases (Prosser & Williams, 1998), depending on fire severity (Dragovich & Morris, 2002). BMPs are applied on publicly managed forests in NSW through the Integrated Forestry Operations Approvals (IFOAs), which set environmental rules for how forestry operations can be carried out in State Forests and Crown Timber Lands in NSW. Likewise, BMPs are applied on privately managed forests through the Private Native Forestry Codes of Practice, which are statutory documents that guide private native forestry operations in NSW.

Paired studies on the impacts of wildfires or prescribed fires on water yield or water quality are very limited in NSW. Four adjacent sub-catchments (two sets of paired sub-catchments) in Kangaroo River State Forest in south-eastern NSW were studied to evaluate the impact of wildfires on suspended sediment yields (Dragovich et al., 2012). This study observed sediment pulses as response to high-intensity rainfall events post wildfire, but also reported minimal impacts on post-fire sediment yield for low rainfall conditions. Thus, the study highlighted the importance of timing and magnitude of post-fire rainfall events on sediment transport after wildfires.

Table 5. Summary of existing paired catchment studies in NSW forests on the impacts of disturbance on water quantity and quality.

Ref.	Study region	Study catchments	Study period	Type of disturbance	Response indicator	Statistical approach	Key findings
Cornish (1993; 2001); Cornish & Vertessy (2001)	Eight catchments in the Karuah Hydrology Research Area, which is near Dungog, NSW	Six treated catchments: Barratta Cornish (1993), Cornish (2001), and Cornish & Vertessy (2001) (36.4 ha), Bollygum (15.1 ha), Corkwood (41.1 ha), Jackwood (12.5 ha), Kokata (97.4 ha), and Coachwood (37.5 ha). Two control catchments: Crabapple (14.7 ha), and Sassafras (25.3 ha).	1976-1991	Harvesting	Turbidity and water yield	Analysis of variance on log-transformed turbidity values obtained weekly before and after treatment; double mass plots and regression residuals on paired data	Turbidity: harvesting in the absence of roads generally reduced turbidity levels, which is probably because of effective Best Management Practices (BMPs), and extensive revegetation after treatment. Water yield: there were significant initial water yield increases by about 150-250 mm/year in five of the six treated catchments. Both baseflows and stormflows increased after harvesting, then decreased with regeneration.
Webb et al. (2012b)	Eight catchments in the Karuah Hydrology Research Area in Chichester State forest	Six treated catchments: Corkwood (41.1 ha), Jackwood (12.5 ha), Barratta (36.4 ha), Bollygum (15.1 ha), Kokata (97.4 ha), and Coachwood (37.5 ha). Two control catchments: Crabapple (14.7 ha), Sassafras (25.3 ha).	1997-2011	Harvesting	Streamflow	The regression model was fitted with the treated catchment flow values as response variables and the control catchments as the independent variables.	There is a significant increase in streamflow after harvesting, equivalent to annual water yield changes ranging from 120 mm to 319.6 mm.
Webb (2008)	Five unmapped headwater catchments in the Kendall State forest on the Mid-North coast of NSW, Australia (31°38'S, 152°41'E)	Three treated catchments: 1.78 ha, 0.87 ha, and 4.23 ha. Two control catchments: 2.13 ha, and 2.41 ha.	2002-2006	Harvesting	Sediment yield	1-tailed *t*-test and F-tests using Event Mean Concentrations (EMC) of suspended sediment and Event Mean Turbidity (EMT) values for each flood event	The peaks of both sediment and streamflow increased in all channels following harvesting. However, harvesting with BMP did not pose significant change in the sediment responses. This suggests the potential of BMPs to mitigate for additional sediment delivery to the drainage network.
MacKay & Cornish (1982); Moore et al. (1986); Crapper et al. (1989); Roberts (2001);	Six small catchments in the Yambulla State forest (37°20'S, 149°35'E), located 50 km southwest of the township of Eden in southeastern NSW	Five treated catchments: Geebung (79.6 ha), Peppermint (127.5 ha), Grevillea (92.5 ha), Stringybark (140.0 ha), and Germans (225.1 ha). One control catchment: Pomaderris (75.9 ha).	1977-1987	Wildfires & integrated logging	Total streamflow, baseflow and storm flow	Regression models were fitted with the treated catchment values as response variables and the control catchment as the independent variables.	Increases in total streamflow, baseflow and stormflow were detected.

Roberts et al. (2001); Webb & Jarrett (2013)							
Lane & Mackay (2001)	Three catchments in the Tantawangalo Creek, southeastern NSW, Australia	Two treated catchments: Willbob (85.6 ha), and Wicksend (68.2 ha). One control catchment: Ceb (21.7 ha).	1986-1997	Harvesting	Water yield	Standard regression techniques; Analysis of variance (ANOVA) to test significance of longer-term (3-4 years) monthly flow deviations using a multiple pairwise t-statistic (Fischer's Protected Least Significance Difference test)	There are both monthly and annually increase in total streamflow and baseflow after treatment.
Webb et al. (2012a)	Five catchments in Kangaroo River State forest in southeastern NSW, Australia	The catchments are between 302 and 770 ha in area.	2001-2009	Harvesting & Best Management Practices (BMPs)	Stream flows; suspended sediment yields	For the analyses of flow Q, SSY (suspended sediment yields) and/or MMC (monthly mean concentrations), regression models were fitted with the treated catchment values as response variables and the control catchments as the independent variables.	Stream flows increased in 2 of 3 impact catchments after selective harvesting. Suspended sediment yields increased for 12 months in one catchment. BMPs were effective in reducing impacts of harvesting.
Walsh et al. (2020)	Five catchments (4 impact & 1 control) in the Brooman State Forest, 25 km north of Batemans Bay on the south coast of NSW, Australia	Burroman creek catchment: 165 ha. Five catchments: 1.3 ha, 2.1 ha, 1.6 ha, 4.8 ha and 3.3 ha.	2007-2014	Selective timber harvesting using Best Management Practices (BMPs)	Runoff, turbidity and suspended sediment yield	Generalised Least Squares (GLS) model was used to account for the different variability for the time periods and treatments; maximum likelihood was used for comparing nested models	Implementation of BMPs in the buffer strips were effective in maintaining water quality in an intensively harvested eucalypt forest.
Webb et al. (2007)	Three small catchments in the Canobolas State forest, located near the township of Orange in the Central West of NSW	Two treated catchments: Catchment CNBL05 (55.3 ha), Catchment CNBL07 (55.4 ha). Control catchment: Catchment CNBL01 (170 ha).	1999-2006	Harvesting using Best Management Practices (BMPs)	Water quality and quantity	Analysis of turbidity and total suspended sediment (TSS) concentration per the appropriate methods (APHA, 1998)	Post-harvest water yields increased and was attributable to an increase in the baseflow component of total streamflow. No significant differences were observed in event mean concentrations of suspended sediment, mean turbidity, or low-flow turbidity or TSS.

Table 5 (cont.). Summary of existing paired catchment studies in NSW forests on the impacts of disturbance on water quantity and quality.

Ref.	**Study region**	**Study catchments**	**Study period**	**Type of disturbance**	**Response indicator**	**Statistical approach**	**Key findings**
Dragovich et al. (2012)	Four adjacent sub-catchments (two sets of paired sub-catchments) in Kangaroo River State Forest, southeastern NSW	/	2001-2004	Wildfires	Suspended sediment yields	Analysis of turbidity and suspended sediment concentration according to standard methods (APHA, 1998)	Timing and magnitude of post-fire rainfall events significantly affect the sediment transport after wildfires.

4.3 Recommendations on monitoring to identify impacts of wildfire and harvest

We illustrated the value of paired catchment analysis for trend attribution especially identifying non-climatic disturbances such as fire and harvest on flow (Section 3.2.2). In this analysis we noted the limited number of catchment pairs that can be included, due to the lack of long-term monitoring sites that are representative of different disturbance conditions across space. In this section we provide an overview of the spatial and temporal coverage of monitoring stations within NSW RFA regions along with future recommendations. We focus this assessment on flow, because the monitoring for water quality indicators is generally broadly lacking across the regions (as previously illustrated in Figures 8-10).

Figure 16 summarizes the temporal coverage of records from of all flow monitoring stations within the NSW RFA regions. Combining our three data sources (WaterNSW, WDO and FCNSW), there are a total of 452 monitoring stations with 42 beginning before 1950. There seems to be a decline in monitoring with a distinct proportion of stations being decommissioned/discontinued since about 2000. This large-scale decommissioning of stations is generally seen for the more recently established stations i.e., the more recently established stations generally maintained for shorter records. In contrast, stations that have been maintained over longer periods (e.g., established prior to 1990) have generally been maintained. Continuous records are critical to analysing trends and changes; so this assessment highlights the significant value of maintaining the long-term monitoring stations within the RFA regions, especially given their increasing importance in an environment where we expect significant climate change and we have seen unexpected longer-term impacts of extended droughts on catchment flows across south-eastern Australia (Peterson et al., 2021; Saft et al., 2015).

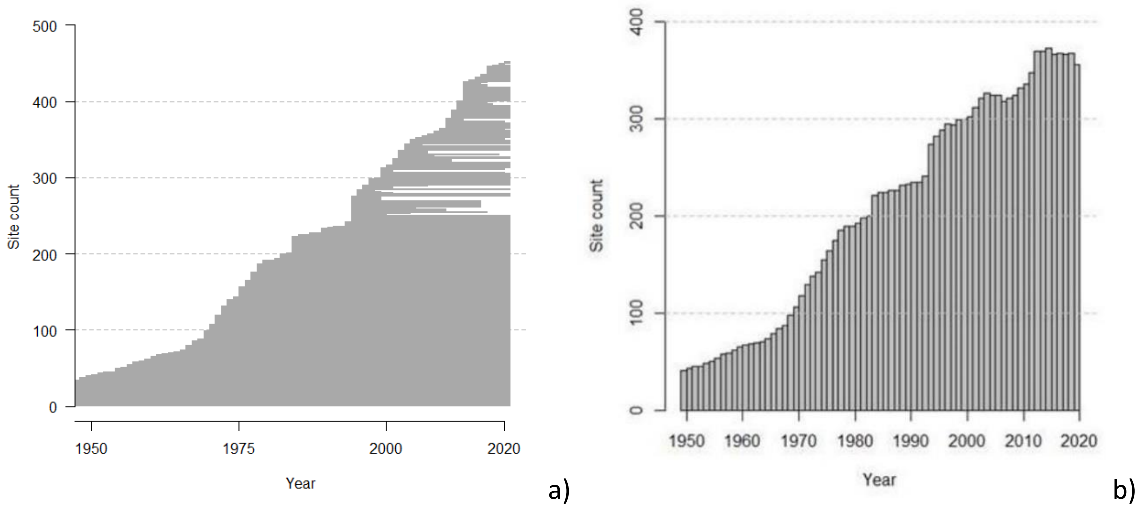


Figure 16. a) Periods of flow records monitored at all individual stations within the NSW RFA regions; b) number of active flow monitoring stations each year. Both plots used combined data from WaterNSW, BoM WDO and FCNSW. Record periods started before 1950 were not shown for better visibility of the key data gaps in recent decades.

A further assessment was performed on the representativeness of the long-term monitoring stations (>35 years) for various forest cover and disturbance conditions. Figure 17 summarizes the spatial distribution of these long-term sites and their level of forest cover, and Figure 18 shows the spatial distribution of catchments that experienced different levels of disturbance from wildfire and harvest.

Figure 17 shows that the current flow monitoring network has a good coverage of forested catchments, especially for the eastern part of the RFA regions. Figure 18 highlights some monitoring gaps on representing contrasting disturbance levels by wildfires and harvests. Regarding wildfire (Figure 18a), monitored catchments within the northern part of the North East RFA region are often extensively disturbed; this seems to be a region that frequently experiences fire events, which makes it challenging for monitoring to represent catchments that are not disturbed by wildfires. The southern part of the North East RFA region is well covered by monitoring sites that represent both minimal and severe impacts of wildfire and harvest. During the historical period wildfire extent records are available (since 1900, see Section 2.2.3), the monitored catchments within the Southern RFA region are generally undisturbed by wildfire, which may underrepresent disturbed conditions. Disturbance from harvest (Figure 18b) is generally minor for monitored catchments throughout the RFA regions, with limited representation of catchments that have been severely disturbed by harvest. It is worth noting that this assessment only focuses on the long-term flow monitoring network and how this monitoring represents different levels of historical disturbances from wildfire and harvest, but not other types of disturbances such as prescribed fire, land use, grazing and water extraction.

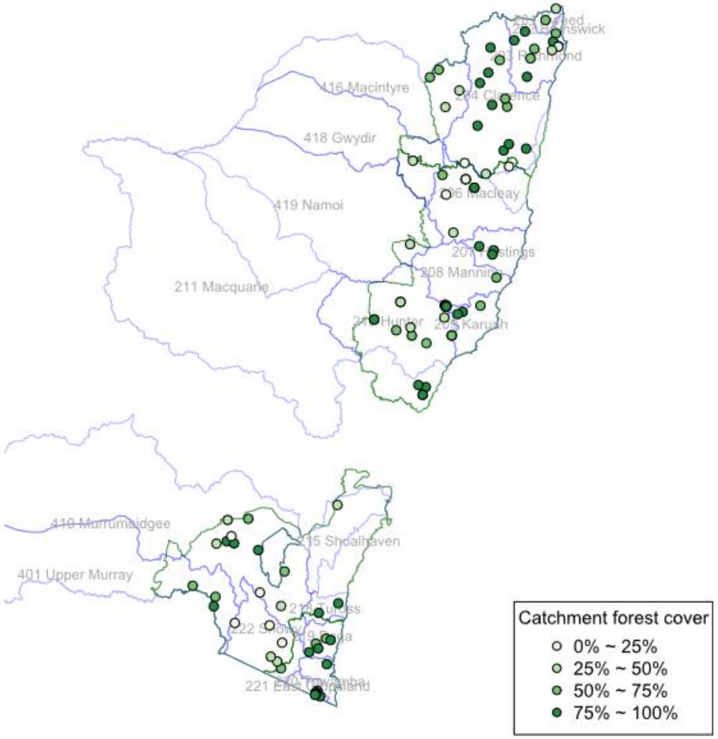
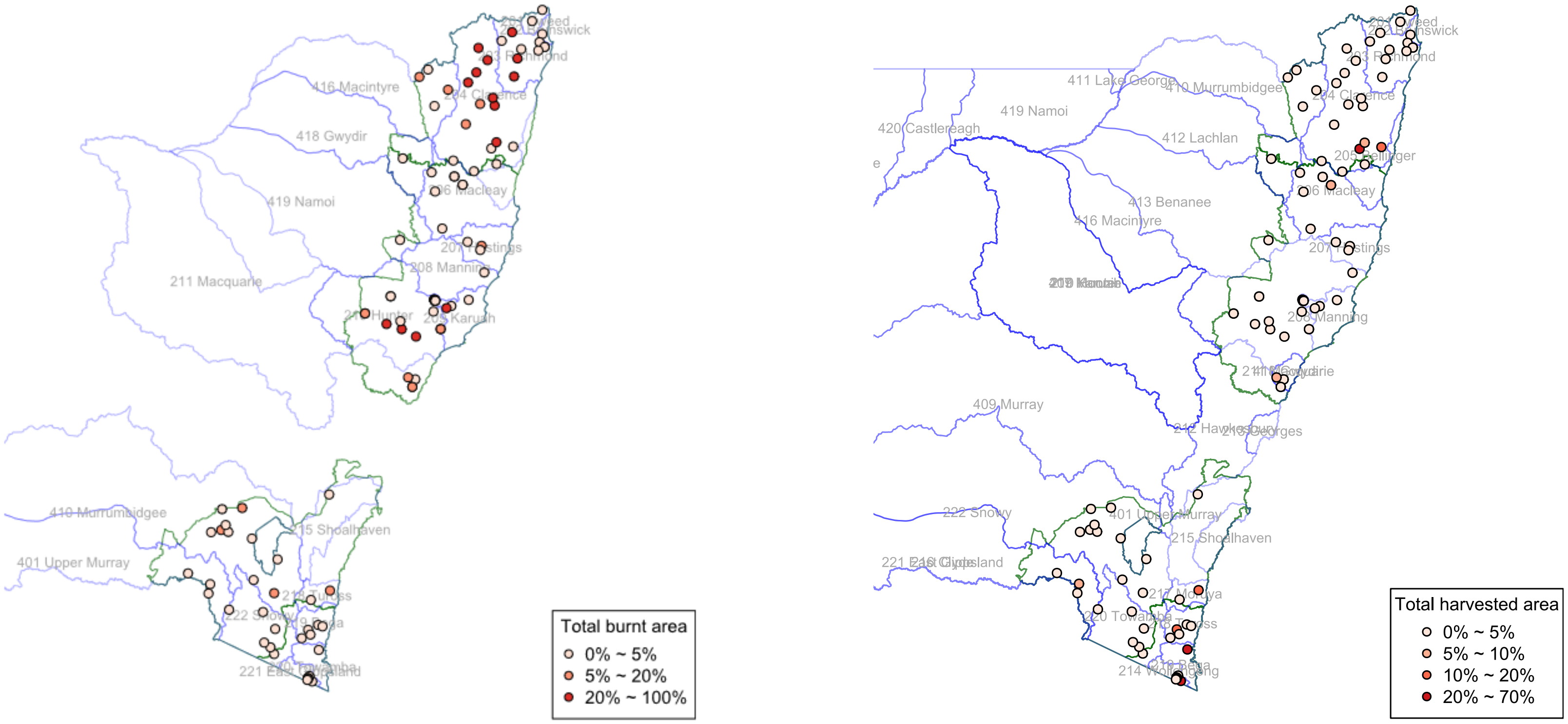


Figure 17. The percentage of forest cover (based on an NRC-provided internal forest extent dataset representative of 2007-2017, see Section 2.2.4) for the catchment corresponding to each monitoring station. This assessment focuses only on the long-term flow monitoring stations that are suitable for trend analyses (over 35 years, see Section 2.3.1).



a) *b)*

Figure 18. a) Total burnt area; b) total harvested area, both cumulated over the entire period of historical disturbance record (fire: since 1900; harvest: since 1950), and expressed as percentages of individual catchments corresponding to each of the monitoring stations. This assessment focuses only on the long-term flow monitoring stations that are suitable for trend analyses (over 35 years, see Section 2.3.1).

5. Summary and Future Works

This report presents the key findings and recommendations of Task 2 of Project 3 of the Forest Monitoring and Improvement Program by the NSW NRC. We have identified the long-term trends in water quality and quantity throughout three NSW RFA regions, the key findings are:

- Within the NSW RFA regions, forested catchments (75 catchments with >50% forest coverage) either show significant decreases (29 catchments) or non-significant decreases (46 catchments) in mean annual flow. Most catchments showing significant flow decreases are within the Southern RFA region.
- For catchments that had significant flow decreases, the magnitude of decline is around 10 to 20% per decade relative to the long-term mean annual flow.
- Water temperature is generally not changing, with 29 out of 36 forested catchments analysed showing non-significant trends. Stream salinity (EC) shows statistically significant trends at 16 out of 17 forested catchment sites studied, with 11 showing a significant increase and 5 showing significant decrease. For both variables there is no clear pattern in the spatial distribution of trend directions.
- The monitoring data for Total phosphorus (TP), total nitrogen (TN), pH and turbidity are insufficient to establish landscape-scale long-term trends that are representative forested catchments in the RFA regions.
- There is insufficient spatial coverage of water quality data in general to report conclusively on the impacts of forest management on water quality from monitoring data.
- The magnitude of flow reduction (i.e., reduction in annual flow relative to the catchment mean annual flow) correlates with several individual catchment characteristics. A smaller decline in flow is generally seen in catchment with i) higher mean annual flow, ii) higher percentage of catchment area as national park, iii) greater percentage catchment area being harvested, or iv) greater percentage catchment area being burnt. However, this finding is likely inconclusive due to the high cross-correlations between catchment characteristics in climate, hydrology and disturbance history.
- To identify any impact of catchment disturbances (from wildfire and harvesting) on flow, we ran a pseudo-paired catchment analysis. We see statistically significant correlations between wildfire and flow responses in 1 of the 8 cases where inter-catchment comparisons can be made; 2 of the 4 cases we analysed show significant correlations between harvest and flow responses. We acknowledge that these results are limited in by the number of catchments analysed, but considering the great challenge to identify impacts of wildfire and harvest due to climate variability, our analysis shows good potential to eliminate some effects of climate variability to focus on impacts of catchment disturbances.

In explaining the flow trends, we have noted substantial impacts of interannual climate variability on flow, which limits the capacity to identify disturbance impacts. Further analysis is required to separate the flow responses to climate variability from other disturbances, and thus improving our ability to identify any impact of catchment disturbance and forest management. In our analysis, we highlighted the promising potential of the pseudo-paired catchment analyses to separate the impacts from climate from disturbance. In our next study, we will expand the study scope to all forested areas in NSW. This will potentially lead to a greater number of paired catchments with a wider range of climate and disturbance conditions, and thus providing stronger statistical power to identify disturbance impacts. We plan to compare multiple approaches to explore both the spatial variation in long-term trends, and also the impacts of interannual climate variability and disturbances. These should improve our ability to explain trends and variability in both water quality and quantity.

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