Report for NRC Forest Baseline & Trend Project 3 Stage 1

Literature and Data Review: Trends in Water Quality and Quantity in NSW Forests and Links to Forest Management and Disturbances

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Executive summary

This report is for Task 1 of Project 3 of the Forest Monitoring and Improvement Program by the NSW Natural Resources Commission (NRC). This entire project aims to deliver baselines and trends for environmental values related to water quality and quantity, for 1) the NSW Forest Monitoring and Improvement Program; 2) Coastal IFOA monitoring of landscape-scale trends. Task 1 includes two key deliverables, which will both inform the statistical analyses to be performed in Task 2:

1. Identify key indicators of water quantity and quality in Coastal IFOA state forests and across all tenures in RFA regions;
2. Propose a conceptual framework for analysing baselines/trends and preliminary recommendations for future monitoring of proposed key indicators across all tenures.

The outputs from Task 1 will inform Task 2 in terms of available datasets and approaches to analyse baselines and trends. The preliminary plan of analysis and recommendations on future monitoring made in Task 1 will be revised once the statistical results of Task 2 are finalised.

To identify the key water quantity and quality indicators, a comprehensive literature review was performed. The review covered areas of sustainable forest management, key drivers of changes in water quantity/quality in forested catchments, and national and state-level water quantity/quality guidelines and objectives. A number of potential water quality/quantity indicators were first identified, from which a subset of key indicators was identified with multiple criteria, such as: 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 key water quality indicators proposed are:

- Nutrients: total phosphorus (TP), total nitrogen (TN), nitrate-nitrite (NO_x)
- Dissolved oxygen (DO)
- pH
- Electrical conductivity (EC)
- Turbidity
- Water Temperature (WTemp)
- Macroinvertebrates population and composition: SIGNAL score, Ephemeroptera + Plecoptera + Trichoptera (EPT)

The key water quantity indicators proposed are:

- Signatures of continuous flow data
- Indicators of climate-streamflow relationship
- indicators of catchment storage and hydrologic regime

For individual water quality indicators, separate datasets will be acquired and analysed in Task 2. Therefore, preliminary assessment of data availability of individual indicators was considered in prioritizing the indicators in this report. In contrast, data for all water quantity indicators can be extracted from daily streamflow and climate data that have much better spatial and temporal coverage in NSW RFA regions. The specific indicator metrics will be determined as part of the baseline/trend analyses in Task 2.

We propose to analyse the trends of individual indicators with both non-parametric and parametric technique, aiming to obtain the directions and magnitudes of trends along with any uncertainty estimation. A few alternative approaches to define the trends and baselines are introduced and some critical modelling decisions are discussed. The final analytical approach will be informed by further analyses of the water quality/quantity dataset. Based on the review of data availability within NSW RFA regions, we highlight some regions and indicators that future monitoring effort can focus on.

Contents

Acknowledgement ii

Executive summary iii

1. Background 1

2. Methods 3

    2.1 Overview 3

    2.2 Literature review 3

  2.1.1 Key questions to be reviewed 3

  2.1.2 Review and synthesizing literature synthesis 3

    2.3 Dataset review 5

    2.4 Review of key findings based on local and regional datasets 7

3. Results 8

    3.1 Key indicators for water quality/quantity of forest management impacts 8

    3.2 Key forest management and natural disturbances that influence water quality and quantity . 26

  3.2.1 Climate change 26

  3.2.2 Forest wildfires 28

  3.2.3 Forest age/maturity 29

  3.2.4 Forest operations – native forest harvesting, thinning and plantation management 30

  3.2.5 Establishing riparian forest buffers 31

  3.2.6 Plantation establishment 31

  3.2.7 Road construction and increases in impervious areas 31

  3.2.8 Prescribed fires 32

  3.2.9 Land use change 32

  3.2.10 Stream channelization 32

  3.2.11 Summary 33

    3.3 Preliminary assessment of data for the key indicators 33

    3.4 Summary of key findings for local and regional contexts 38

4. Recommendations 40

    4.1 Plan of analyses 40

  4.1.1 Detecting trends 40

  4.1.2 Attributing trends 43

  4.1.3 Establishing baselines 43

    4.2 Future monitoring and research 46

5. Summary 48

References 49

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;
2. The Coastal IFOA monitoring of landscape-scale trends.

The project aims to generate scientific information to answer and report 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) Establish baselines and examine drivers of change over time for water availability and quality, using historical monitoring data;
b) Identify any data gaps and key metrics to track thresholds and support modelling of future outcomes under different scenarios;
c) Design strategic cross-tenure permanent forest plot network to monitor key metrics, which links to remote sensing information. This network will also include fauna monitoring, which is expected to be rolled out initially in RFA regions by end-2022.

This project consists of two tasks. This report addresses Task 1, which aims to:

1. Identify key indicators of water quantity and quality in Coastal IFOA state forests and across all tenures in RFA regions;
2. Propose a conceptual framework for analysing baseline/trends and preliminary recommendations for future monitoring of proposed key indicators across all tenures.

The above outputs from Task 1 will inform the subsequent Task 2 on the selection of datasets and statistical approaches to analyse baseline and trends. The analysis plan will be finalised with further analyses in Task 2. The preliminary recommendations on future monitoring made in this report will be revised once the statistical results of Task 2 are finalised.

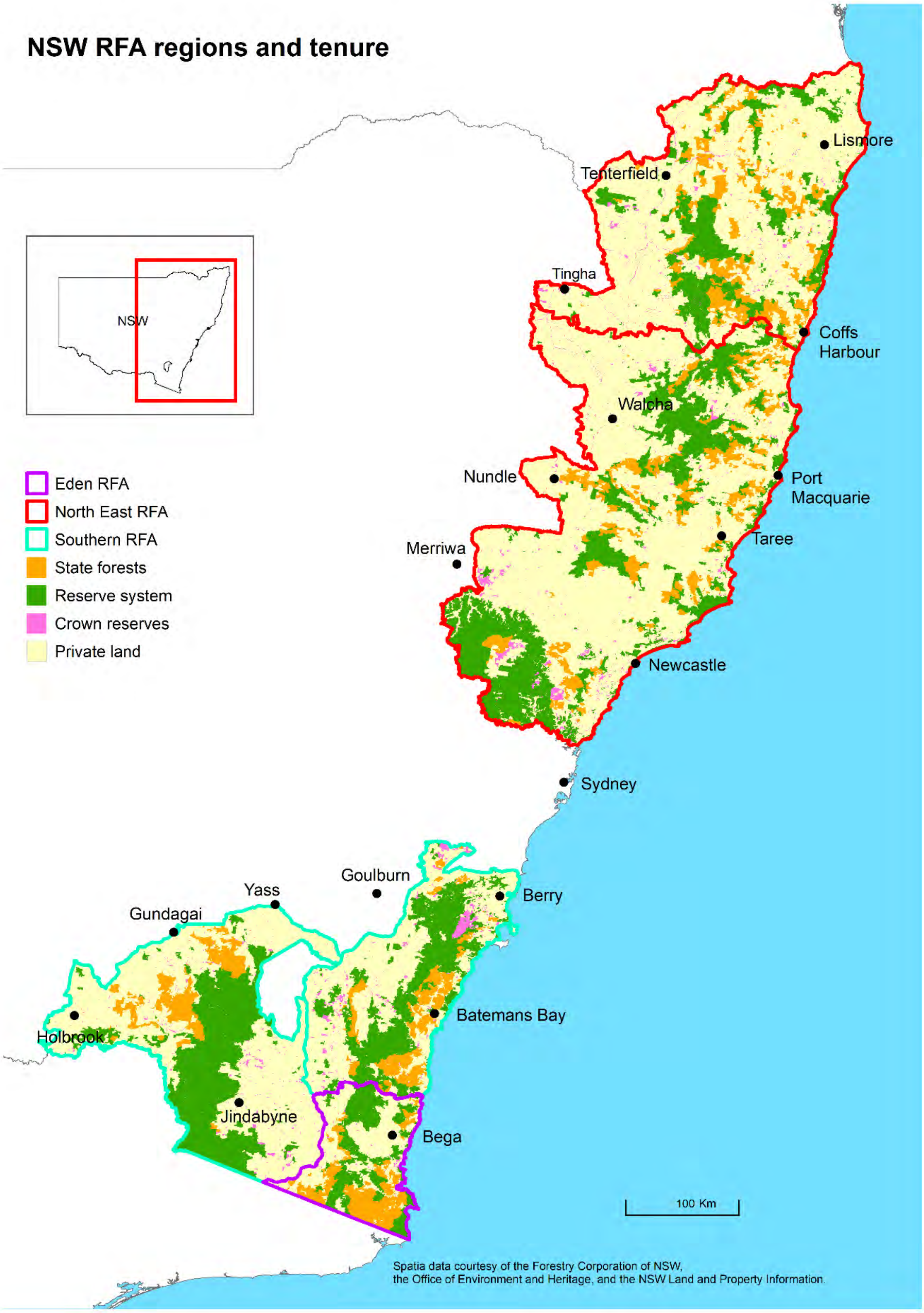

Figure 1. NSW RFA regions and Coastal IFOA regions (generated from spatial data provided by Forestry Corporation NSW).

2. Methods

2.1 Overview

The overall goal of Task 1 is to identify the key water quality and quantity indicators to be analysed for baseline/trends in Task 2, and to provide preliminary recommendations on analyses and future monitoring. Selection of the key indicators was based on comprehensive reviews of literature and existing publicly available datasets, as detailed in Sections 2.2 and 2.3, respectively. A further review is performed on the key findings based fron these datasets, and implications for local and regional forest management contexts (Section 2.4). The review outcomes are presented in Section 3, including the recommended indicators and their corresponding datasets. Section 4 then provides recommendations for future analysis plans and monitoring.

2.2 Literature review

2.1.1 Key questions to be reviewed

A literature review was performed to identify the key indicators of water quality and quantity in the interested forest regions, and thus those indicators that should be considered in the baseline/trend analyses in Task 2 of this project. The relationship between these indicators, forest health, and forest stressors can be summarised as:

- Forest stressors include both natural disturbances (e.g. wildfires, climate change) and forest management (e.g. timber harvesting and other forest operations, prescribed burning), which can affect various soil and hydrological processes in forested catchments;
- These changes in catchment processes will in turn lead to changes in water quality and quantity, which is one aspect of the many that describe forest health conditions of these catchments.

Through consideration of these links, we decided to focus the literature review on two key questions:

1. What are the important water quality/quantity indicators for forest health?
2. What are the key forest management (e.g. timber harvesting and other forest operations, prescribed burning) and natural disturbances (e.g. wildfires, climate) that affect water quality/quantity?

2.1.2 Review and synthesizing literature synthesis

Literature on three topics and their relevance to addressing the abovementioned key questions were reviewed and synthesised (

Table 1).

Table 1. Key topics included for literature review, and their relevance to addressing the key review questions.

Topic reviewed and key literature	Further details on the topic	Relevance to addressing the key questions
1. Montreal Framework on sustainable forest management Review focused on the Montreal framework, adapted for NSW forest management (ANZECC and ARMCANZ, 2000a; NSW EPA, 2016)	• Originally developed in Canada for describing, assessing and evaluating progress towards sustainable forest management in temperate and boreal forests. • Australia is one of the member signatory countries and has adapted the original framework to better suit the country's unique forests. • The framework was then further adapted by NSW Government as the Ecologically Sustainable Forest Management (ESFM) (latest revision in 2016) (NSW EPA, 2016), which has more specific focus on the coastal forest regions of NSW.	Contributing to **Question 1**: to identity the key forest health concerns, and thus the broader aspects that the water quality/quantity indicators should represent. See Table A1 in Appendix for detailed review summary.
2. Australian/NSW water quality guidelines Review focused on government reports and guidelines including: • Australian and New Zealand Environment and Conservation Council (ANZECC) water quality guidelines (ANZECC and ARMCANZ, 2000a; ANZECC and ARMCANZ, 2000b) • NSW water quality objectives (WQO) and river flow objectives (RFO) (NSW Government, 2006)	• The ANZECC guidelines provide authoritative guidance on the water quality management in Australia and New Zealand. The guidance sets water quality and sediment quality objectives designed to sustain current and future community values for water resources. • The NSW WQOs set out the community's values and uses for NSW waterways (e.g. rivers, lakes) and recommend indicators to assess current waterway conditions against those values and uses. The WQOs are consistent with the agreed national framework set out in the ANZECC (2000a,b) Guidelines. • The NSW RFOs are the agreed high-level goals for surface water flow management. They identify the key elements of the flow regime that protect river health and water quality for ecosystems and human uses.	Contributing to **Question 1**: to select the key water indicators that are relevant to individual forest health concerns of interest. See Tables A2-4 in Appendix for detailed review summary.
3. Impacts of forest stressors on water quality and quantity Review focused on scientific studies including journal, conference papers and technical reports both from Australia and across the globe.	• Key information extracted from literature include: 1) The type of forest stressors (anthropogenic or natural); 2) The water quality/quantity indicators that the stressors would affect and the associated processes/pathways; 3) Confidence in the identified impact (monitored, modelled or inferred from conceptual understanding); 4) The relevance of these impacts to NSW forests and the likely timespan to observe such impacts with water quality/quantity monitoring.	Contributing to **Question 2**: to select the key forest stressors for which impacts on water quality and quantity should be understood See Table A5 in Appendix for detailed review summary.

The above review process identified several potential water quality/quantity indicators and multiple forest stressors that are expected to affect individual indicators. A summary of review in each topic is included in Table A1-A5 in the Appendix.

To focus the effort of analyses in Task 2 as well as future monitoring, these potential indicators were further synthesised through a prioritization process, from which a smaller number of indicators were identified as the final set of recommended key indicators, based on a series of criteria (Table 2). For individual potential indicators, assessment of Criterion 4 was based on a review of publicly available datasets (as detailed in Section 2.2); assessment of all other Criteria was based on literature reviewed and expert consultation within the University of Melbourne team and with NSW NRC. The final set of key water quality and quantity indicators is summarised and discussed in Section 3.1, and the key forest stressors that can influence these indicators are summarised in Section 3.2.

Table 2. Criteria considered to prioritise the potential water quality/quantity indicators.

Criteria to prioritise potential water quality and quantity indicators	**Details on criteria**	**Prioritization rationale**
1. Link and sensitivity to forest stressors	• The relationship between water quality/quantity indicators and forest stressors/ management actions • Whether the relationship is assumed, from analyzing historical data or from model runs	An indicator to be prioritised should respond to a number of forest stressors, for which the responses should be widely acknowledged in the literature
2. Impacts on forest health	• Whether an indicator is expected to respond to forest stressors • The definition of 'forest health' here is broader than the traditional one, which covers 'maintaining normal ecosystem functions and sustainably providing productive capacity'	The key indicators should ideally cover different aspects of forest health to minimise duplication
3. Relevance at a landscape scale	• Whether the relevance of any indicator is limited to local/specific processes • Whether there is any existing landscape-scale assessment on the response of each indicator to changes in forest stressors	For an ideal indicator, its response to forest stressors should be observable at a landscape scale
4. Existing monitoring programs, preferably at a landscape scale	• Whether we can take advantage of others' monitoring effort • Whether this indicator has gone through a proof of concept exercise	An ideal indicator should have been widely monitored – which demonstrates high efficiency and value for analyses and future monitoring
5. Known statistical properties of the indicator and implications on how well they represent forest health	• Whether we are confident in understanding the statistical properties of each indicator • Whether we are confident that this indicator reflects a) waterway/forest health, b) management input in the catchment and at a regional scale, c) causal effect	An ideal indicator should be well studied/understood for its statistical properties in reflecting the impacts of forest stressors
6. Consistency of dataset with other indicators	• Whether the data for each indicator can be practically integrated into baseline/trend analyses of other indicators	An ideal indicator would have consistent type and spatial-temporal resolution to others, therefore having high potential to integrate with others into a consistent analytical framework
7. Ease of data collection	• Whether the indicator is expensive/labor-intensive to monitor, or less commonly used/measured • Whether assessment exists on the cost-efficiency to measure at a landscape scale	An ideal indicator should be relatively easy and economical to monitor/analyze for a long term and at a landscape scale. Standard methods for monitoring should already exist that are widely accepted.

2.3 Dataset review

A review was performed to identify publicly available monitoring datasets for indicators of water quality and quantity in the NSW Regional Forest Area (RFA) Regions (Figure 1). The purposes of the review are: 1) to understand data availability as one criterion to assess priority of individual water quality and quantity indicators; 2) to identify gaps in existing monitoring that should be addressed in future works.

This review identified three key datasets for water quality and quantity, which have been monitored over a relatively long period and at a landscape scale:

- *WaterNSW continuous water monitoring network* (WaterNSW, 2020), which has been monitoring the quantity and quality of surface water and groundwater throughout NSW. The monitoring program combines automatic digital sensors, logging devices as well as 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, NSW Department of Industry – Lands and 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 (Figure 2 shows a typical stream and gauge setting in FCNSW's monitoring network).

Figure 2. A typical stream that is monitored by FCNSW (left, Wilson River, northern NSW) and a gauge that measures streamflow (right). Photo courtesy of Ross Peacock (left) and FCNSW (right).

Localised monitoring by regional water supply authorities, normally recording surface storage volumes, was not included in the review unless the data was available through an existing online portal and could be readily converted to a flow estimate.

Table 3 lists the datasets that were extracted and assessed for this review, along with the key sources of information. Key outcomes of this data review are presented in Section 3.3.

Table 3. Summary of preliminary assessment performed to review data availability.

Property of dataset assessed and method of assessment	**Data summary extracted**	**Key sources of data/information**
Spatial extent within NSW RFA Spatial analyses with monitoring site locations and other spatial data	Number of monitoring sites within RFA regions for each water quality and quantity variable	• NSW RFA region spatial map (NSW EPA, 2002) • WaterNSW online portal – surface water stations (WaterNSW, 2020) • FCNSW monitoring data summary (personal communication) • BoM Water Data Online Portal (Bureau of Meteorology, 2020)
Temporal coverage Time-series analyses for extracted data at individual monitoring sites	For each monitoring site and each variable: • Record period • Monitoring frequency • Percentage and duration of missing data and long gaps	• WaterNSW online portal – surface water stations (WaterNSW, 2020) • FCNSW monitoring data summary (personal communication)
Data quality Time-series analyses for extracted data at individual monitoring sites	For each monitoring site and each variable: • Percentage of data with quality issues (by QC flags in the metadata)	WaterNSW online portal – surface water stations (WaterNSW, 2020)
Representativeness of forested catchments* Spatial analyses with monitoring site locations and other spatial maps	For each monitoring site and each variable: • Percentage of drainage catchment area covered by forest • Presence of major dams in drainage catchment	• NSW forest extent map (internal dataset prepared by Spatial Vision under the arrangement of NSW NRC) • WaterNSW online portal – surface water stations and major dams (WaterNSW, 2020)

*In progress – to be considered as a further filtering of the high-quality long-term monitoring sites identified from all data assessments listed above.

2.4 Review of key findings based on local and regional datasets

This review aims to identify from published scientific studies and reports the trends in water quality and quantity, and their relevance to forest management within NSW/NSW RFA regions. The key literature reviewed are:

- *Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests* (Alluvium, 2020), prepared by Alluvium for the NSW NRC on December 2020.

- Archival reports and peer reviewed publications by Forestry Corporation of NSW (FCNSW) and its predecessors based on their water monitoring programs within NSW forests over the last forty years.

3. Results

This section includes our recommendations on the two key questions that our literature review focused on:

1. What are the important water quality/quantity indicators for forest health?
2. What are the key forest management and natural disturbances that affect water quality/quantity?

Section 3.1 discusses the water quality/quantity indicators and the assessment of prioritization for individual indicators to identify the most important ones. Section 3.2 identifies the important forest stressors that are expected to influence these indicators. Section 3.3 then summarises the review of data availability within the RFA regions, related to the key water quantity and quantity indicators. Further, Section 3.4 summarized key findings extracted from these data and implications on local and regional contexts.

3.1 Key indicators for water quality/quantity of forest management impacts

Table 4 lists all water quality/quantity indicators assessed and identified the key indicators to be prioritised for the baseline/trend analyses in Task 2. A detailed assessment of the priority of individual indicators is summarised in Table 5.

Table 4. Summary of recommended indicators to include in baseline/trend analyses.

	To include in analyses (subject to data availability)	**Not to include in analyses**
Water quality	• TP • TN • NO_x • DO • pH • EC • Turbidity • Water Temp	• FRP • NH_4 • Chl-a • Euphotic depth • Residence time • Toxicants
Ecology (as part of water quality)	• SIGNAL score • EPT	• Fish • Algae • Metabolism
Water quantity	• Signatures of continuous flow data • Indicators of climate-streamflow relationship • indicators of baseflow/drought/flood • Other indicators of catchment storage and hydrologic regime (to be identified via further analyses)	• River extraction • Groundwater level • River water level

Table 5. Detailed priority assessment for each water quality/quantity indicator, against the criteria to prioritise the potential water quality/quantity indicators in Table 2. Colour code indicates the priority of each indicator (row) by each criterion (column): red – low; yellow – medium; green – high.

Indicator (category and specific variable)		Link and sensitivity to forest stressors (summarised in Section 3.2)	Impacts on forest health concerns	Relevance at a landscape scale	Existing monitoring programs, preferably at a landscape scale	Known data statistical properties of indicator and implications on how well they represent forest health	Consistency of data type, resolution and analytical method with other indicators	Ease of data collection
Water quality	**TP (mg/L)**	Forest wildfires can increase nutrient losses and soil erosion (Meyer et al., 2001), and pollutants loading (Martin et al., 2016). Also, vegetation mortality due to fires reduces canopy interception, ET, as well as nutrient and water uptake. Forest maturity: mature ecosystems have greater stored biomass and organic matter, higher diversity, increased cycling of detritus and nutrients, improved efficiency, and greater stability (Odum, 2014). Logging/harvest: leaching of nutrients after timber harvesting, especially clearcutting. Timber harvesting can increase soil erosion (Webb and Haywood, 2005), losing the nutrient-rich topsoil and causing degraded soil quality, including losses of plant macronutrients and stored organic carbon (An et al., 2008; Zheng et al., 2005), and decreases in nutrient mineralisation. Moreover, large-scale soil erosion may even cause complete soil loss with only infertile subsoil or denuded	High levels can lead to aquatic system impacts - Nuisance aquatic plants.	Suitable for landscape assessment – as recommended by both ANZECC and NSW WQO.	Within RFA regions: 33 sites have quarterly data over recent 10 years. Only spot-data available, on average 10 samples per year. (WaterNSW)	No notable issues with statistical representativeness. Note the need of removal of seasonal and streamflow effects for trend analyses.	Assessing compliance: Comparing with chemical guideline values Assessing trends: Simple trend analyses/ time-based regression models. Uncertainty on the trend can be quantified to suggest the power to detect trend. Generally requires >10 year data for trend analyses. Data frequency should be at least quarterly to cover contrasting flow regimes/seasonality. Need to account for flow effects and potentially seasonality in trend analyses.	Often monitored with grab sampling and lab analyses – can be labour intensive and challenging to maintain over long term.
	FRP (mg/L)				Within RFA regions: 18 sites have quarterly data over recent 10 years. Only spot-data available, on average 9 samples per year. (WaterNSW)	• Often present in low concentrations in rural/natural catchments in VIC and can frequently be below detection-limit for some cleaner sites (Guo et al., 2020; Guo et al., 2019). • Low SFP (= FRP) concentrations (<20ug/L) were also reported for oligotrophic rivers in the UK (Jarvie et al., 2002). Another issue with low concentrations the samples is that they are most vulnerable to storage and analytical errors since		

		bedrock left, which makes agriculture or reforestation impossible (Montgomery, 2007). Riparian buffers can reduce the influence of agricultural nutrients and chemicals on surface stream waters, protecting and improving water quality and flow regime (Yamada et al., 2007). Vegetation in riparian buffers can deposit or absorb sediments, nutrients and pollutants which are attached to them and in the surface runoff, thus stabilizing riverbanks and regulating the amount of flows into streams, which in further reduce degradation of water quality (Hawes and Smith, 2005; Welsch, 1991). Forest establishment: the leaves of reforested trees can affect the soil nutrient availability and cycling through decomposition processes (Hobbie et al., 2006). Therefore, plantation establishment can affect water quality through the leaf and litter effects on organic carbon and nutrient cycling (Han et al., 2020). Land Use: Irrigation and land-based activities can generate nutrients and pollutants, and change runoff patterns of catchments (Camara et al., 2019).				percentage errors are high.		
	TN (mg/L)				Within RFA regions: 33 sites have quarterly data over recent 10 years. Only spot-data available, on average 10 samples per year. (WaterNSW)	No notable issues with statistical representativeness. Note the need of removal of seasonal and streamflow effects for trend analyses.		
	NOx (mg/L)				Within RFA regions: 24 sites have quarterly data over recent 10 years. Only spot-data available, on average 9 samples per year. (WaterNSW)			
	NH4 (mg/L)				Within RFA regions: 0 site has quarterly data over recent 10 years. Only spot-data available. (WaterNSW)			

	Chl-a (ug/L)	(Implied) Wildfires: higher risks of eutrophication and algal blooms with increases of higher N and P export. No studies found that directly suggested this link with data analyses/modelling.	Aquatic system - A surrogate indicator of nutrient pollution/nuisance aquatic plants		Within RFA regions: 0 site has quarterly data over recent 10 years. Only spot-data available. (WaterNSW)	• More relevant to nuisance plant growth than nutrients, but relationship with biomass/cell number can be unclear due to interspecies variation. • Recommended to use together with nutrients to assess phytoplankton concentration.		
	DO (mg/L)	Logging: lower DO possibly due to changes in respiration owing to increases in stream temperature and nutrient export to the stream following clearfelling (Nathan et al., 2000). (Implied) Wildfires: lower DO with higher risks of eutrophication.	Aquatic system – Lack of DO. Affecting habitat and species composition/abundance.		Within RFA regions: 5 sites have data over recent 10 years. Continuous data available, on average 292 samples per year. (WaterNSW)	No notable issues with statistical representativeness. If DO is recorded in % saturation, it will need temperature data to interpret. However, mg/L data seems widely available. Note the need of removal of seasonal streamflow and temperature effects for trend analyses.	Assessing compliance: Comparing with chemical guideline values. Assessing trends: Simple trend analyses/time-based regression models. Uncertainty on the trend can be quantified to suggest the power to detect trend. Generally requires >10 year data for trend analyses. Need to account for flow effects and potentially seasonality in trend analyses. Since data are recorded in short time-steps, autocorrelation should be removed (e.g. data thinning) or appropriately handled in trend analyses	Can be monitored continuously so less labour work involved – more investigation needed on cost of continuous probes that monitor individual constituent.
	pH	Wildfires: significant reduction in pH and ANC, which can be related to areas with naturally base-poor soils and less weatherable rocks (Bayley et al., 1992; Eriksson et al., 2003).	Aquatic system – Unnatural changes in pH. Affecting habitat and species composition/abundance.		Within RFA regions: 5 sites have data over recent 10 years. Continuous data available, on average 303 samples per year. (WaterNSW)			
	Turbidity (NTU)	Forest fires cause changes in the amount of suspended sediment (Martin, 2016; Rust et al., 2018; Smith et al., 2011). Logging/harvest: After logging or clearcutting, the soil surface becomes more susceptible to erosion during rainfall events. Surface runoff and sediment may accordingly increase, which can	Aquatic system – Excess of SPM. Affecting habitat and Species composition/abundance. In very high concentrations, SPM directly impacts biota and can change light		Within RFA regions: WaterNSW: 5 sites have data over recent 10 years. Continuous data available, on average 289 samples per year.			

		affect both water quality and quantity (Rauscher and Johnsen, 2004; Vose and Klepzig, 2013; West and Wali, 2002). Riparian buffers: Riparian forest buffers can help to minimise nutrient loading, control soil erosion and sedimentation, remove soluble nutrients and decrease storm water runoff (Anbumozhi et al., 2005; Yamada et al., 2007). Forest establishment can prevent soil erosion and soil degradation (Clemente et al., 2004; Kou et al., 2016). Road construction: Water turbidity and total suspended solids (TSS) can be changed due to forest road construction, especially downstream of unsealed road stream crossing (Lane and Sheridan, 2002). Sediment yields from road surface erosion can be increased, which may affect water quality (Fahey and Coker, 1992; Fransen et al., 2001). In addition, fine sediment generation rates can be increased by road traffic with the surface materials being detached, abraded and crushed (Sheridan et al., 2006). Land use: Urbanisation and water-resources development can cause greater variability in precipitation and surface runoff, which will affect soil erosion and sedimentation (Zimmerman et al., 2008).	penetration into water bodies.		FCNSW: 14 current sites (mainly 2017-2019) and 17 terminated sites (mainly 1994-2010). Continuous data available, detailed temporal coverage/frequency is to be further assessed.		(e.g. using an autoregression error model).	
	EC (ug/cm)	Land use: Agriculture land use can cause salt mobilization/dryland	Unnatural change		Within RFA regions:			

		salinization. Salinization and waterlogging often degrade water quality in irrigated areas (Scanlon et al., 2007). Natural lands can be converted into rain-fed (non-irrigated) agricultural lands and irrigated agricultural lands, and its impacts on water quality and quantity are often opposite (Scanlon et al., 2007). Changing natural forests which have higher evapotranspiration (ET) rates into non-irrigated agriculture can decrease ET and thereby increase surface runoff that is available for groundwater recharge and streamflow (Zhang et al., 2001). Whereas water quality is degraded due to salt mobilization, salinization, and fertiliser leaching into underlying aquifers (Scanlon et al., 2007). Conversion into irrigated agriculture significantly consumes freshwater and reduces streamflow, and similarly, salt mobilization, salinization in waterlogged areas, and fertiliser leaching degrade the water quality (Scanlon et al., 2007). Extensive clearing or permanent removal of deep-rooted native forest vegetation (mainly eucalypt forest and woodland) for agricultural use can substantially increase the land and stream salinity (Loh and Stokes, 1981; Peck and Williamson, 1987; Schofield et al., 1988). This is because the salt in unsaturated soil profile is mobilised to the land surface and streams by elevated groundwater	in salinity. Species composition/abundance, change of habitat.		35 sites have data over recent 10 years. Continuous data available, on average 317 samples per year. (WaterNSW)			

		recharge and water tables due to land use changes (Peck and Williamson, 1987; Williamson and Bettenay, 1979). <u>Forest establishment:</u> Reforestation of pastured area was found to reduce shallow saline groundwater table in Western Australia, and thus reduce groundwater salinity (Bari and Schofield, 1992; Bell et al., 1990), which can lead to corresponding responses in surface water quality.						
	WaterT (degC)	<u>Logging/harvest:</u> reduced vegetation cover increases light penetration into streams, and water temperature can also be increased due to more exposure to sunlight of stream channels (Nathan et al., 2000). <u>Riparian buffers:</u> The shade created by riparian forest buffers can affect sunlight exposure by reducing incoming diffuse solar radiation, thereby moderating water temperature (Quinn et al., 1997). <u>Climate change:</u> Global mean and river water temperatures are projected to increase by 0.8–1.6 °C on average for the SRES B1–A2 scenario for 2071–2100 relative to 1971–2000. A combination of large increases in river temperature and decreases in low flows are projected for southern Australia (van Vliet et al., 2013).	Unnatural change in temperature. Species composition/abundance, change of habitat.		Within RFA regions: <u>WaterNSW</u> 48 sites have data over recent 10 years. Continuous data available, on average 323 samples per year. <u>Water Data Online</u> 13 sites have data over recent 10 years. Continuous data available, on average 19282 samples per year.		<u>Assessing compliance:</u> Comparing with local variability. i.e. 80% and 20% quantiles <u>Assessing trends:</u> Simple trend analyses/time-based regression models Generally requires >10 year data for trend analyses. Need to account for potentially seasonality in trend analyses. Since data are recorded in short time-steps, autocorrelation should be removed (e.g. data thinning) or appropriately handled in trend analyses (e.g. using an autoregression error model)	
	Euphotic depth (Zeu)	<u>Logging/harvesting:</u> reduced vegetation cover increases light	• Measures indicate how		No large-scale public data for inland water,	No trend analyses found for this indicator-	<u>Assessing compliance:</u>	Monitoring is likely complex and labour

		penetration into streams, and water temperature can also be increased due to more exposure to sunlight of stream channels (Corbett et al., 1978). Any impact of stressors on turbidity is also expected to affect light penetration, but this is an implied impact with no study found.	much an ecosystem is degraded by particulate pollution. • This is likely redundant with turbidity. ANZECC recommends trigger values based on 1) direct measurement and 2) trigger values for turbidity (2000b).		satellite-derived data for ocean/seashore available	questionable whether this is a recommended indicator for any landscape assessment.	Comparing with local variability. Maximum allowable 10-20% depending on water depth <u>Assessing trends:</u> Unlikely to be sufficient data for trend analysis. No previous statistical analysis on trend was found.	intensive – the measurement process involves using an appropriate light sensor such as a PAR sensor and is inversely related to the average diffuse attenuation coefficient (Kav) for downwelling light: Zeu = 4.6/Kav(Kirk, 1994).
	Residence time	No notable links with forest stressors.	• Long residence time leads to nuisance aquatic plants.	• Mainly focused on lakes, storages, reservoirs - less critical for large-scale assessments. • When a waterbody has long residence time (e.g. inadequate mix) may become stratified and vulnerable to cyanobacterial problems (Webster et al., 2000). • Measures of residence time can be used to predict the potential for nuisance growths of cyanobacteria.	No large-scale public dataset found within the RFA regions, but can be inferred from volume and flow rates, but only for lakes/reservoirs.	Questionable whether this is a recommended indicator for landscape assessment (see left column for comments on emphasizing only local processes). No trend analyses found for this indicator.	<u>Assessing compliance:</u> Comparing the average cell doubling time of the species of concern so that cells are flushed out of the system. <u>Assessing trends:</u> Unclear about trend analysis approaches - no previous studies were found. Modelling approaches have been used to assess algal bloom risks with residence time. Persistent and strong thermal stratification were found to affect the growth and dominance of Anabaena circinalis (Mitrovic et al., 2003).	Residence time can be easily estimated with flow data, but analyses/assessment are more complicated (see left column on required analyses).

	Toxicants (collective)	From forest fires, combustion products can increase transboundary chemicals and long-term atmospheric deposition such as mercury (Biswas et al., 2008; Caldwell et al., 2000; Campos et al., 2015), as well as pollutants, such as arsenic, chromium, and lead (Hoefen et al., 2009; Plumlee et al.; Smith et al., 2011), chloride, sulphate and sodium (Smith et al., 2011).	Affecting biota – toxicity depending on chemical and species.	• Implications can be local, source-dependent and species-specific, which have limited values for landscape-scale assessment.	Low availability at a landscape scale. Within RFA regions: Sites with over 10 years' quarterly data: 0, 0, 19, 0 for Cu, Zn, Cl and NO3, respectively (WaterNSW)	Often present in small concentrations (ANZECC and ARMCANZ, 2000b), which may have higher relative variability and therefore higher percentage errors from storage and lab analyses – noise to signal (i.e. unexplained variability) expected to be higher.	Assessing compliance: ANZECC recommended integrated approaches for assessment (instead of comparing to chemical guideline values) (ANZECC and ARMCANZ, 2000b), with 1) chemical-specific guidelines coupled with water quality monitoring; 2) direct toxicity assessment; and 3) biological monitoring. Assessing trends: Simple trend analyses/time-based regression models.	Chemical monitoring requires standard sampling and lab analyses, but analyses/assessment are often complicated (see left column on required analyses).
Ecology	**Fish population and community**	Land use change affects biodiversity, structure and composition of natural communities, and these changes affect ecosystem functioning and services, such as water quality (Martínez et al., 2009; Sliva and Dudley Williams, 2001). Logging: due to logging, the increased light and water temperature can affect multiple physical, chemical, and biological processes within the watershed ecosystem (Corbett et al., 1978). Riparian buffers: due to temperature increase, the photosynthesis and respiration rates of stream metabolism can accordingly be affected, which have direct influence on stream	While fish can be responsive to pollution (general inorganic/organic contaminants) and thus indicate changes to biodiversity and ecosystem processes in forested catchments, they are expected to be immediately responsive only to low DO. Thus, analysing fish may not add significant value/information to that from analysing DO data.	Few fish assessment methods have been used actively to assess water quality, or human impacts due to changes in water quality for management purposes. Standardised bioassessment approaches using fish are not well developed in Australia. Methods have not been sufficiently tested to assess applicability at a broad scale	No large-scale public dataset found within the RFA region.	Current attempts to develop standardised bioassessment approaches using fish are in their infancy in Australia (ANZECC and ARMCANZ, 2000b). Statistical representativeness is limited as: • Abundance: sampling methods have too much measurement uncertainty in abundances. • Species richness – Australia is generally species poor.	Need specific statistical analyses which are inconsistent with analyses for other water quality/quantity indicators.	Fish sampling methods are well established (including trapping, netting, electrofishing, poisoning, recapture after marking, counting of migrating fish etc.) for both running and still waters. but are all labour intensive (ANZECC and ARMCANZ, 2000b).

		habitat and biota (Quinn et al., 1997).		(ANZECC and ARMCANZ, 2000b).		• Biotic integrity – no well-developed index in Australia.		
	SIGNAL (now as SIGNAL2) - Macroinvertebrate population and community		Stream Invertebrate Grade Number — Average Level. Developed specifically for population/community of invertebrates identified to family level in south-eastern Australia.	SIGNAL is widely accepted as a measurement of pollution tolerance and has been adopted as an indicator in State-wide programs such as the State Environmental Protection Policy (SEPP) in Victoria (Victoria DELWP and EPA Victoria, 2018) and recommended by the MDBA Sustainable Rivers Audit (Murray-Darling Basin Commission, 2004). Compared with other indicators such as EPT and O/E, this score shows good ability to differentiate sites with good and bad environmental conditions (Chessman et al., 2006; Growns et al., 1997).	Within RFA regions: 7 sites with macroinvertebrates identified to family level (1994-2003, temporal resolution to be confirmed) – can be used to derive SIGNAL (FCNSW)	Note that for forested areas we are likely to have 'good' values (i.e. low magnitude) for this indicator. Also, this indicator only contains integer values. Both can mean less variability, thus making the trend analyses less informative. In addition, this indicator has a potential bias in that it was developed for fast flowing streams, and its response may be correlated with altitude, and it has since been used in a range of stream types. Further work is required to assess a reference condition for this indicator (Murray-Darling Basin Commission, 2004).	<u>Assessing compliance:</u> Comparing with established standards for healthy rivers. <u>Assessing trends</u>: Event-based sampling method means that its data has different structure to other water quality/quantity indicators (often with rapid bio assessment samples) – meaning that data processing method is different to other indicators, but trend analyses should be similar once data are aggregated over time.	Often done with rapid bio assessment samples (30-min live catch and monitoring at site) – relatively cheap and easy to implement.
	EPT (Ephemeroptera + Plecoptera + Trichoptera**) -**		Diversity / percentage of the community composed of more pollution	EPT is accepted as a useful metric in upland streams, but is not a sensitive indicator in lowland	Within RFA regions: 7 sites with macroinvertebrates identified to family	Similar to SIGNAL, we might not get much data variability for this indicator when looking at forested catchments		Often done with rapid bio assessment samples (30-min live catch and monitoring at site) –

	Macroinvertebrate population and community		sensitive groups. An internationally widely used indicator.	Australian streams, where very few of those taxa occur (Murray-Darling Basin Commission, 2004). The use of an indicator in one part of the catchment but not in another was considered as a potential but cannot be justified for whole-catchment assessment (i.e. being biased by the extra information in the uplands). Ideally, a sensitive taxa index should be developed for the lowlands (Murray-Darling Basin Commission, 2004).	level (1994-2003, temporal resolution to be confirmed) – can be used to derive EPT (FCNSW)	where environmental conditions are generally good.		relatively cheap and easy to implement.
	Algae	<u>Wildfire</u> is expected to lead to higher risks of eutrophication and algal blooms with the subsequent increases of higher N and P export – this is an implied effect instead of being explicitly reported in any study with data analyses/modelling.	Investigating organic and inorganic nutrient issues and expected to change far more readily and at an earlier stage of contamination than more popular invertebrate indicators. May not add much value/information	Standard indicators/analytical methods are less adapted to Australia so not widely used (ANZECC and ARMCANZ, 2000b). A few commonly used international indicators include: 1) Phytoplankton biomass: necessary	No large-scale public dataset found	Not well understood due to limited applications.	Unclear due to less developed standards in Australia	One of the major difficulties which arises when algae communities are used for biological assessment is that taxonomic keys are not readily available for local environments. This necessitates that monitoring outside of simple biomass measures will require skilled operators — at

			to analysing nutrient data.	ecological research required to underpin development of monitoring programs in Australia has not been conducted or is not readily available, especially for seasonal and temporary running waters. 2) Biotic indices: A common problem with many of these indices is that they have little physiological base to them, being derived instead on the basis of distribution (and hence correlation).				least for situations in which species or generic-level of identification is required (ANZECC and ARMCANZ, 2000b).
	Stream metabolism	<u>Riparian buffers:</u> due to temperature increase, the photosynthesis and respiration rates of stream metabolism can accordingly be affected (Quinn et al., 1997).	Measure production (via photosynthesis) and respiration. Sensitive to small changes in water quality (particularly input of labile organic pollution and sedimentation) and riparian conditions, including light	The Australian Commonwealth Environmental Water Office (CEWO) Long Term Intervention Monitoring Project is the largest scale monitoring program in the world (MDB whole-basin, over 5 years).	No large-scale public dataset found.	Data interpretation methods and standards are generally immature for Australia (ANZECC and ARMCANZ, 2000b).	<u>Assessing compliance:</u> Comparing with established standards for healthy rivers (P/R, GPP, R24). <u>Assessing trends</u>: Event-based sampling method means that its data has different structure to other water quality/quantity	Difficult to monitor and process raw data.

			inputs (ANZECC and ARMCANZ, 2000b). May not add much value/information to analysing nutrient, turbidity and DO data.	This project found that even small increases in discharge can result in the production of more organic carbon to sustain aquatic food webs. The project is a good demonstration for large-scale applicability of metabolism, but key finding suggests that metabolism will likely respond more to flow regime changes instead of water quality (Grace, 2020; Hale J et al., 2020).			indicators – meaning that data processing method is different to other indicators, but trend analyses should be similar once data are aggregated over time.	
Water quantity	**Signatures of continuous flow data** including: • Flow quantiles • Mean, SD and CoV of daily flow • Extreme flow conditions e.g. annual 7-day minimum flow	Forest establishment: less surface runoff – a meta-analysis with 43 studies suggest that reduction in annual flow is about 23% after 5 years and 38% after 25 years. Flow reduction is likely to persist for up to five decades; partial flow recovery is seen for some catchments after an initial decrease (~15 years on average), but this cannot be commonly expected (Bentley and Coomes, 2020; Zhang et al., 2001). Climate change: changing the type (rain or snow), amount, intensity and drop size, duration and timing of precipitation, and number of events (Crockford and Richardson,	Important indicators for: • Protect pools in dry time • Protect natural low flows • Maintain natural flow variability • Minimise effects of weirs and other structures • Protect important rises in water levels • Mimic natural drying in intermittent waterways	Relevant to landscape scale – implied from NSW RFO	Within RFA regions: WaterNSW: • 116, 104 and 75 sites have high-quality continuous data over recent 30, 35 and 40 years Water Data Online: • 34, 34 and 23 sites have high-quality continuous data over recent 30, 35 and 40 years FCNSW:	Widely adopted statistics and proven representativeness to establish baseline/trends at landscape scales. All statistics can be calculated with continuous flow data while individual indicators may have different requirement e.g. analysing long-term effects or more extreme events such as drought/flood needs longer records generally for >30 years. A	No standard values available for assessing compliance. Assessing trends: Simple trend analyses/time-based regression models/rainfall-runoff relationships. Need to account for climatic variability.	Can be monitored continuously.

	• % and duration of cease-to-flow • Recession constant • Flashiness index[55]	2000) – affecting baseflow, stormflow, groundwater recharge, and flooding (Karl et al., 2009). Plant water use will be increasing in warmer condition through ET, thereby decreasing the amount of precipitation available for streamflow (i.e. change the rainfall-runoff ratio) or groundwater recharge. In addition, increases in atmospheric CO2 concentrations can reduce the transpiration in many species, leading to increased streamflow (Ainsworth and Rodgers, 2007). <u>Forest wildfires</u> can lead to increases in runoff at the plot scale but not always the corresponding runoff in catchment-scale (Kutiel and Inbar, 1993; Prosser and Williams, 1998). <u>Forest management:</u> harvesting and thinning both reduces canopy cover, and thus can lead to increased streamflow due to reduced interception and evapotranspiration (Sanders and McBroom, 2013; Webb et al., 2007; Jayasuriya et al., 1993; Ruprecht et al., 1993). The impacts of forest harvesting on water quality is mainly related to changes in energy balance which leads to increased stream water temperature (Corbett et al., 1978); leaching of nutrients after timber harvesting, especially clearcutting (Nathan et al., 2000; Sanders and McBroom, 2013; Webb et al., 2007); and soil erosion and	• Minimise effects of dams on water quality • Maintain natural rate of change in water levels		12 current sites (mainly 1979-2019) and 20 terminated sites (mainly 1994-2010). Continuous data available, detailed temporal coverage/frequency is to be further assessed.	preliminary data analysis will be performed to inform the final section of statistics to analyse for trend.		

		sediment (Rauscher and Johnsen, 2004; Vose and Klepzig, 2013; West and Wali, 2002). Road: Impacts of road construction on forest can be long lasting (Ford et al., 2011b). Forest road construction can also increase impervious areas, which affect the infiltration rate of water and surface runoff, therefore affecting water quantity (Rauscher and Johnsen, 2004; Swank et al., 2001). Land use: converting forest lands to urban uses can cause greater variability in precipitation and surface runoff (Zimmerman et al., 2008). The increase of impervious surface areas with urbanization can increase stormflow rates and volumes, and change baseflow dynamics, which in turn degrade water quality (Sun and Lockaby, 2012).						
	Indicators of climate-streamflow relationship including: • annual/seasonal runoff/rainfall ratio • trend in rainfall-runoff residuals • moving-window rainfall-	Climate change: In the long term, the composition and distribution of forest trees might be changing (Iverson et al., 2008) because of changes in annual and seasonal ET and interception (Sun and Lockaby, 2012; Vose and Klepzig, 2013). Forest age: Water yield from regrowth forests (10-100 years old) is lower than that from mature and old-growth forests for some forest species (>100 years old) (Watson et al., 1999). "Kuczera curve" was developed to quantify such relationship between forest age and water yield (Figure 4) (Andreassian and Trinquet, 2009; Brown et al., 2005; Kuczera, 1987).	Not mentioned in RFO but considered as key responses to forest stressors.	Relevant to landscape scale – implied from experience/literature of catchment changes.	See above for availability of continuous flow data.			

	runoff elasticity	However, Brown et al. (2005) suggested that Kuczera curve is only specific to Mountain Ash forest. Forest wildfires: vegetation mortality due to forest fires reduces canopy interception and evapotranspiration, as well as nutrient and water uptake. Fires can change soil structure, decrease soil porosity and increase hydrophobicity, thereby affecting infiltration rates and compacting the soil. This, in turn, can increase surface runoff during rainfall or storm events (Elliott and Vose, 2006).						
	River extraction, particularly during dry, low-flow and high-flow periods	Climate change: increases in water use and thus more water extraction but likely less relevant to forested area.	• Protect pools in dry times • Protect natural low flows • Protect natural high flows	Relevant but likely only for few regions (e.g. Hunter) within RFA regions.	No public water extraction data found within RFA regions.	Doubtful whether extraction is accurately captured with many water sharing plans in place.		Difficult to measure with good accuracy.
	• **% or period inundated** • **Area inundated as spatial maps**	See above for the impacts on streamflow.	Maintain wetland and floodplain inundation	Relevant but only to floodplain forest	Can be assessed by the top end of flow duration curve derived from continuous flow data (see above)	Statistical power is currently unclear, because assessing changes of large flood needs long records (at least >30 years). Preliminary analyses are needed to understand availability/quality of the flood data (derived from continuous flow) to assess this indicator.	Assessing compliance: Site-specific assessment need to be based on specific flood studies, getting threshold for inundation and then estimating flood frequency at gauge. We can provide some general recommendations in this project, but site-specific ones are not practical. Assessing trends: Standard trend analyses/time-based	Derived from monitoring continuous flow data.

							regression models as other water quality indicators. But note that limited information can be extracted for trend analyses if flow data is limited in record length.	
	• **Groundwater level** • **Baseflow and proportion of baseflow**	<u>Forest establishment:</u> reforestation of pastured area was found to reduce shallow saline groundwater table in Western Australia (Bari and Schofield, 1992; Bell et al., 1990). The magnitude of this reduction was shown to increase with the proportion of cleared area reforested and with the crown cover of the reforestation (Bell et al., 1990). <u>Climate change:</u> groundwater responses to climate change were explored in several modelling studies for forested catchments in Europe, which reached consistent conclusion that groundwater recharge would decrease under climate change scenarios (Eckhardt and Ulbrich, 2003; Neukum and Azzam, 2012; Woldeamlak et al., 2007).	Manage groundwater for ecosystems. Protect natural low flows.	Relevant to landscape assessment as recommended in RFOs.	Within RFA regions, 7 groundwater bores are continuously and currently monitored for GW level by WaterNSW. The data lengths are generally limited (<10 years) and are unlikely sufficient for analysing groundwater trends. Further, the data representativeness needs further investigation with consideration of disturbances e.g. water extraction. In Australia, most bores are in agriculture lands instead of in natural catchments – thus suspecting that the	Statistical power is likely low considering the limited duration and spatial representativeness of available time-series data. There is often significant divergence between individual bores. Water extraction can add big noise to data.	<u>No standard values available for assessing compliance.</u> <u>Assessing trends</u>: Simple trend analyses/time-based regression models. Require accounting for climate variability.	Difficult/expensive to measure and maintain long records. Use of baseflow as an indicator of groundwater is likely to be the most efficient approach.

					WaterNSW bores are unlikely monitored for natural catchment conditions.			
	River water levels, particularly the rate of change	See previous discussion on the impacts on streamflow.	Maintain natural rate of change in water levels (a less important RFO for the whole NSW RFA regions).	Less relevant to landscape scale – considered as a more local issue related to regulated rivers in NSW RFO.	Can be estimated from continuous flow data.	Containing similar information with Q data – unlikely adds value to analyse.	No standard values available for assessing compliance. Assessing trends: Simple trend analyses/time-based regression models.	Derived from monitoring continuous flow data.

3.2 Key forest management and natural disturbances that influence water quality and quantity

The review identified several forest stressors, including both natural disturbances and forest management activities, that are expected to affect water quality and quantity in forests (Figure 3). The major pathways and processes via which these impacts take place are also presented. The detailed impacts of individual stressors are discussed in the remainder of this section.

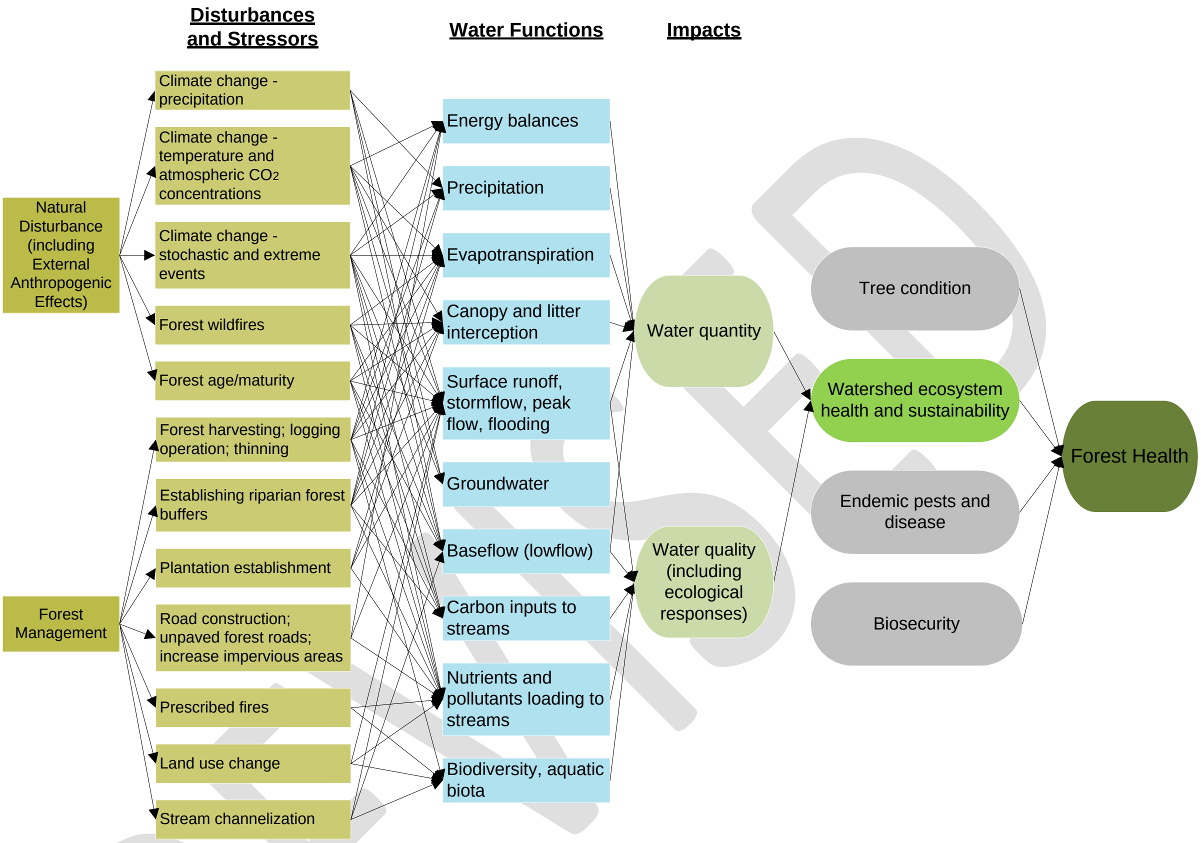

Figure 3. Natural disturbances and forest management, and their impacts on watershed ecosystem in forest, adapted from Sun and Lockaby (2012) based on this literature review.

3.2.1 Climate change

Precipitation

Climate change may change the hydroclimatic regimes in many areas of the world (Dai, 2013) and significantly affect water availability (Milly et al., 2005). Since climate change has the potential for both biological and physical impacts on hydrologic processes, it can have both direct and indirect impacts on water quality/quantity in forested watersheds (Sun et al., 2007).

Climate change directly affects water resources by changing the type (rain or snow), amount, magnitude, duration, the timing of precipitation, and the number of events (Crockford and Richardson, 2000), which thereafter influences baseflow, groundwater recharge, and runoff events (Karl et al., 2009).

According to the Intergovernmental Panel on Climate Change, the increases in global surface air temperature is mainly due to elevated anthropogenic greenhouse gas emissions since the mid-20th century (IPCC, 2014). Global warming may alter precipitation and other climate variables. Rainfall and runoff for the east coast of Australia (the study regions), winter and spring rainfall are projected to reduce, while temperatures and potential evapotranspiration will increase (CSIRO and Bureau of Meteorology, 2015).

One method for estimating the influence of climate change on surface runoff is directly using historical seasonal or annual climate and runoff time series. Another method is using hydrological models, which are used in most studies (Chiew et al., 2009). Chiew et al. (2009) developed a conceptual rainfall-runoff model SIMHYD to estimate the impacts of climate change on runoff. Based on 15 global climate models (GCMs), a daily scaling method is adopted to simulate the future climate series based on historical series, which considers the future changes in daily rainfall distribution, mean seasonal rainfall and potential evapotranspiration. Less runoff is projected in southeast Australia in the future. Recent evidence (Saft et al., 2015; Fowler et al., 2020) suggest such models may under-estimate the reduction in runoff under changing climate, and thus future runoff reduction may be greater than projected by modelling studies.

Temperature and atmospheric CO_2 concentrations

Changes in temperature and atmospheric CO_2 are important indirect influences of climate change, which may cause both short-term and long-term ecosystem responses (Ford et al., 2011b). In the short term, higher temperature may increase plant water use through evapotranspiration, thereby decreasing the rainfall amount available for streamflow (i.e. change the rainfall-runoff ratio) or groundwater recharge. Elevated CO_2 levels are expected to increasing forest water use efficiency via increasing photosynthesis and net carbon uptake, and decreasing evapotranspiration (Keenan et al., 2013). Since changes of other variables can also affect evapotranspiration, such as vapour pressure, wind patterns, elevated CO_2 concentrations and net solar radiation, the impacts of temperature may be exacerbated or mitigated by these other factors (Ford et al., 2011b).

In the long term, global warming is likely to change the composition and distribution of forest communities (Iverson et al., 2008), because the water and other climatic requirements are considerably different for different species (Sun et al., 2011; Vose & Klepzig, 2013). In addition, laboratory and field studies indicate that elevated atmospheric CO_2 concentrations can reduce transpiration in many species, leading to increased streamflow (Ainsworth and Rodgers, 2007). This has been reinforced in later studies that explicitly considered the CO_2 effect in projecting future changes in streamflow (Butcher et al., 2014; Fowler et al., 2019).

Stochastic and extreme events

Stochastic and extreme events, including extreme precipitation, east coast low events, flooding events, and droughts, are projected to increase worldwide (Kelly et al., 2016). This poses greater challenges for water resources than average conditions (Ford et al., 2011b).

<u>Extreme precipitation</u>

Considering future precipitation regimes, studies using general climate models (GCMs) predict that the frequency of extreme precipitation will globally increase (Sun et al., 2007; O'Gorman & Schneider, 2009). There is high confidence in the prediction of these increases from both historical trends and projections of future rainfall (Bao et al., 2017; Guerreiro et al., 2018; Wasko et al., 2018).

Although the increases in extreme precipitation are expected to lead to increased frequency of floods (Thober et al., 2018), and potentially deteriorated water quality, recent studies suggest that at a global scale, flood magnitude decreases with increasing extreme rainfall (Do et al., 2017; Wasko and Sharma, 2017). This is likely due to decreases in moisture conditions prior to storm event, which can modulate the flood response (Sharma et al., 2018). The importance of precipitation event size relative to antecedent soil water conditions increases as precipitation events become larger i.e. for rarer precipitation events (Do et al., 2017; Wasko and Sharma, 2017).

Droughts

The frequency and severity of droughts are predicted to increase in the future because global warming causes a decrease in regional precipitation and an increase in evapotranspiration (Sheffield et al., 2012; Solomon et al., 2007). Drought can decrease net primary production and stand water use in forests through reducing stomatal conductance in response to low soil water availability (Hanson and Weltzin, 2000). Drought can also affect the energy balance of the land surface and many ecohydrological processes. The hydrologic and biogeochemical responses to drought, such as changes in stream chemistry, are determined by vegetation water use and forest population dynamics, as well as local hydrogeology. The impacts may vary from stand to watershed scales, due to changing species assemblages in forest, because different species in different landscape positions vary in the eco-physiological characteristics that affect water use patterns (Vose et al., 2016). Some species and classes are more tolerant to drought than others, leading to the potential for drought-induced shifts in both species composition and community structure. Apart from causing mortality of seedlings and saplings, more severe, prolonged and frequent droughts may render even mature trees more susceptible to insects or disease (Hanson and Weltzin, 2000; Vose et al., 2016).

Drought may decrease the rates of litterfall and decomposition of organic material on the forest floor, leading to ramifications for fire regimes and nutrient cycling (Brando et al., 2008; Hanson and Weltzin, 2000). Moreover, drought history is more important than soil moisture status in determining hydrophobicity and infiltration rates of soil. This can affect runoff and groundwater recharge, thereby affecting water quantity (Gimbel et al., 2016).

Although droughts are unpredictable and difficult to prepare for, some forest management options can be adopted to minimise the influence of droughts on water quality and quantity. These include reducing leaf area by thinning, or regenerating cut forests with species that consume less water (Vose et al., 2016).

3.2.2 Forest wildfires

The impacts of forest wildfires are mainly related to reduced canopy interception and evapotranspiration, changes in infiltration rate of water and overland flow (Elliott and Vose, 2006), nutrient losses, soil erosion (Meyer et al., 2001), and pollutant loading (Martin, 2016). On the one hand, vegetation mortality due to forest fires reduces canopy interception and evapotranspiration, as well as nutrient and water uptake. Fires can change soil structure, decrease soil porosity and increase hydrophobicity, thereby affecting infiltration rates and compacting the soil. This, in turn, can increase surface runoff during rainfall or storm events (Elliott and Vose, 2006). These changes can impact water quantity. In addition, from a longer-term perspective, vegetation regrowth after wildfires will have impacts on evapotranspiration, canopy interception. The regenerated forests often require more water than the mature forests than they replaced and thus leading to reduced water availability (Kuczera et al., 1987; Vertessy et al., 2001) – further details will be discussed in the subsequent '*Forest age/maturity*' section (3.2.3).

On the other hand, biomass components such as trees, grasses, organic matter in soil can be changed by the combustion process (Martin, 2016). Moreover, combustion produces various pollutants that can be deposited in forest soils. These include: ash and charcoal from burned vegetation (Bodí et al., 2014), atmospheric deposition such as mercury (Biswas et al., 2008; Caldwell et al., 2000; Campos et al., 2015); and pollutants such as arsenic, chromium, and lead (Hoefen et al., 2009; Plumlee et al.;

Smith et al., 2011), chloride, sulphate and sodium (Smith et al., 2011). Apart from this, forest fires cause substantial changes in the amount of suspended sediment, and nutrients such as nitrogen, phosphorus, and organic carbon, particularly within several years (mainly < 10) of fire (Martin, 2016; Rust et al., 2018; Smith et al., 2011). These changes can affect water quality.

3.2.3 Forest age/maturity

Forest age, canopy height, structural complexity of forest, species composition, litter depth, amount of soil organic matter, and microtopography, are all important factors affecting ecosystem functions (Weber and Boss, 2009). The biomass and complexity of forests will increase as they mature. In such mature forests, nutrients cycling is also at higher efficiency (Ma et al., 2007), which can potentially benefit water quality.

Relationship between forest age and water yield have been explored in many studies in Australia, mainly focusing on mountain ash (*Eucalyptus regnans*) forests. Water yield from regrowth forests (10-100 years old) is lower than that from more mature forests for mountain ash forest (>100 years old) (Watson et al., 1999; Jayasuriya et al., 1993), largely caused by differences in transpiration. The "Kuczera curve" was developed through work in Mountain Ash forests in Melbourne's water supply catchments to quantify relationships between the amount of water yield and forest maturity (Kuczera, 1987) (Figure 4). The mean annual water yield during the first few years of forest growth is relatively lower in these forests, shown by a rapid decline on the water yield curve to age 27. The water yield then gradually rises back to "equilibrium" levels by about age 200 (Haydon et al., 1997; Jordan et al., 2006; Vertessy et al., 2001; Watson et al., 1999).

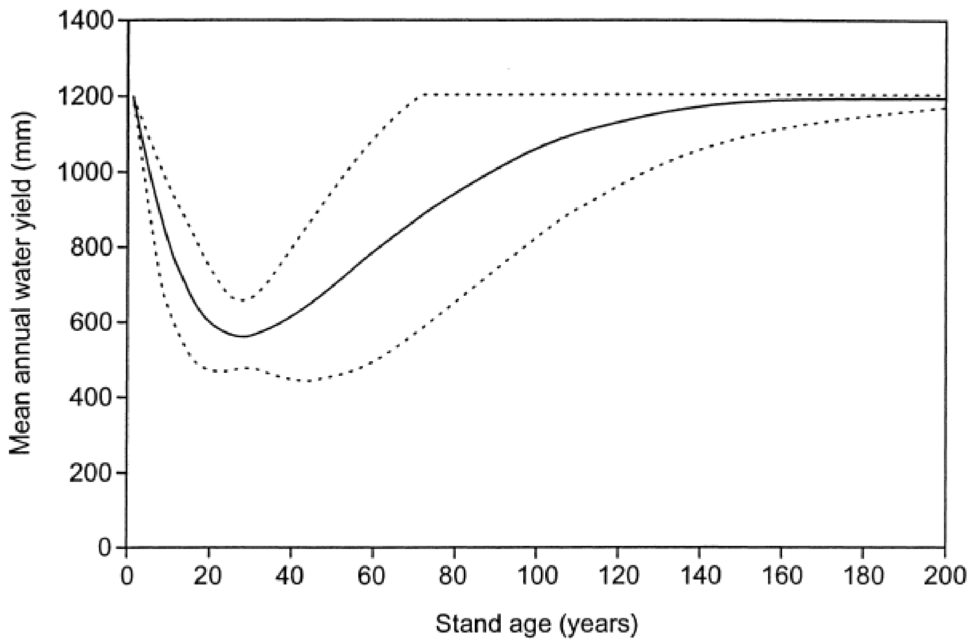

Figure 4. Relationship between mean annual water yield and stand age from mountain ash forest catchments, after Kuczera (1987). The dashed lines denote the 95% confidence limits on the relationship.

To evaluate the within-year impacts on streamflow due to changes in forest age, Jordan et al. (2006) developed separate seasonal curves for the variation in runoff with forest age, based on simulation experiments with the Macaque model (Watson et al., 1999), which is a physically based distributed process model for assessing the water balance of forested catchments.

By measuring leaf area index (LAI), sapwood area index (SAI), and different watershed components, Vertessy et al. (2001) state that there are no significant differences in sap velocity among stands of different ages, but decreased stand transpiration and overstory LAI are associated with a systematic decline in SAI during aging processes. Overall, there is an obvious declining trend in total stand transpiration as the forest becomes more mature. Rainfall interception per unit leaf area is also shown to decline, which is related to less turbulent mixing as well as increased humidity in mature forests.

However, there are two major limitations in Kuczera's analysis (Marcar et al., 2006):

1) When this curve was derived for Melbourne's catchments in 1985, no data on stream flow from forested catchments was available for an age range from 50 to 150 years, causing large errors in the stream flow recovery phase.
2) This curve was empirically developed from observed data of Melbourne's catchments in *Eucalyptus regnans* dominated forests, so it is difficult to be applied in other locations that have different forest types and climate regimes from Melbourne. For example, Webb et al. (2012b) analysed observations from six small NSW catchments with mixed species eucalypt forests, and found that Kuczera-type yield reductions does not generalize across catchments of different forest types. Webb et al. (2012b) thus does not recommend applying the water yield models derived from Mountain ash to other eucalypt forests.

3.2.4 Forest operations – native forest harvesting, thinning and plantation management

In general, forest management can have either transient or long-term impacts on forest watersheds as it can significantly change the structure and functions of forests (Vose et al., 2011), depending on the intensity of management and extent of influence on biological and physical watershed properties (Ford et al., 2011b). Biologically, forest management can change evapotranspiration by altering albedo, canopy roughness, and canopy interception. Specifically, species have very different rates of leaf area, transpiration, and overall whole-tree water use properties. This is due to their variation in root depth, maturity, tree height, leaf boundary layer resistance, leaf chemistry, leaf duration, and stomatal conductivity (Bond et al., 2008; Ford et al., 2011a; Stoy et al., 2006). In addition, stand density and leaf area duration (i.e. evergreen vs. deciduous) also have different impacts on evaporation, transpiration and interception (Ford et al., 2011a). Physically, forest management activities may change hydrology by causing soil disturbances or changing flow paths. Disturbances such as forest harvesting have more short-term impacts, with little impact on long-term streamflow (Ford et al., 2011b).

The impact of forest harvesting on water quantity is mainly related to decreased evapotranspiration and canopy interception due to vegetation loss (Sanders and McBroom, 2013; Webb et al., 2007; Zhang et al., 2001). Its impacts on water quality is mainly related to changes in energy balance, which leads to increased stream water temperature (Corbett et al., 1978), leaching of nutrients after timber harvesting, especially clearcutting (Nathan et al., 2000; Sanders and McBroom, 2013; Webb et al., 2007), and soil and sediment erosion (Rauscher and Johnsen, 2004; Vose and Klepzig, 2013; West and Wali, 2002). Specifically, reduced vegetation cover increases light penetration into streams, and water temperature can also be increased due to more exposure to sunlight of stream channels. The increased light and water temperature can affect multiple physical, chemical, and biological processes within the watershed ecosystem (Corbett et al., 1978). After timber harvesting, the soil surface becomes more susceptible to erosion during rainfall events. Surface runoff and sediment may increase accordingly, affecting both water quality and quantity (Rauscher and Johnsen, 2004; Vose and Klepzig, 2013; West and Wali, 2002).

Forest thinning has been proposed to be a potential forest management strategy to reduce evapotranspiration and thereby alleviate water shortages caused by climate change (Komatsu, 2020;

Sun and Vose, 2016). Several studies showed that thinning in Australian forests reduces interception and evaporation, increases the available water and thus the saturated source area, which can in turn produce higher streamflow (Jayasuriya et al., 1993; Ruprecht et al., 1993).

3.2.5 Establishing riparian forest buffers

Establishing riparian buffer strips is one of the best management practices (BMPs) adopted by forest managers to protect streams, thereby achieving sustainable forest and aquatic ecosystem management (Webb et al., 2007). The shade created by riparian forest buffers can affect stream sunlight exposure by reducing incoming diffuse solar radiation, moderating water temperature (Quinn et al., 1997). The amount of suspended sediment, water turbidity and clarity, nitrogen, phosphorus, and dissolved organic carbon (DOC) concentrations, can also be affected by riparian forest buffers. Rates of photosynthesis and respiration can be affected, thus having direct influence on stream habitat and biota (Quinn et al., 1997).

Riparian forest buffers can help to minimise nutrient loading to streams, control soil erosion and sedimentation, decrease sediment and nutrient delivery, decrease storm runoff, decrease groundwater recharge, and moderate water temperature (Anbumozhi et al., 2005; Yamada et al., 2007). In addition, they can reduce the impacts caused by agricultural chemicals on surface waters by reducing their delivery to streams, thereby protecting and improving water quality and flow regime in urbanizing watersheds (Broadmeadow and Nisbet, 2004; Matteo et al., 2006). This can also reduce the impacts of landuse activities have on the effect of disturbance events, such as strong winds, severe storms, and flooding (Matteo et al., 2006).

3.2.6 Plantation establishment

Plantation establishment (afforestation and/or reforestation) can reduce water availability (Brown et al., 2005). However, it is one of the most effective strategies for combating the negative impacts of climate change on forest watersheds (Bastin et al., 2019), for preventing soil erosion and soil degradation (Clemente et al., 2004; Kou et al., 2016), and for improving water conservation capacity and promoting restoration of ecosystems with degradation (Zhang et al., 2011). Large-scale reforestation can change the physical and chemical characteristics of soil (Han et al., 2020) because the physicochemical properties and microbial communities of soil can be affected by different forest species (Prescott and Grayston, 2013). In addition, nutrient availability and cycling in soil can be influenced by the leaves of reforested trees through decomposition processes (Hobbie et al., 2006). Therefore, plantation establishment can affect water quality through the leaf and litter effects on organic carbon and nutrient cycling (Han et al., 2020). In general, the impacts of forest plantation to the watershed include vegetation water use, soil properties and quality, nutrient loss, pest and disease, and hydrology (Zaiton et al., 2020).

3.2.7 Road construction and increases in impervious areas

Impacts of road construction in forest water quality and quantity can be long lasting (Ford et al., 2011b). Water turbidity and total suspended solids (TSS) can be changed due to forest road construction, especially downstream of unsealed road stream crossings (Lane and Sheridan, 2002). Sediment yields from road surface erosion can be increased, which may affect water quality (Fahey and Coker, 1992; Fransen et al., 2001). In addition, fine sediment generation rates can be increased by road traffic with the surface materials being detached, abraded and crushed (Sheridan et al., 2006).

Forest road construction can also increase impervious areas, which reduces the infiltration rate of water and increase surface runoff, thereby affecting water quantity (Rauscher and Johnsen, 2004).

3.2.8 Prescribed fires

Prescribed fires can affect water resources in forest by changing the soil type and chemical properties of soil. Their influences depend on the fire regime (i.e. fire frequency, season of burn, fuels, climate) and fire weather (i.e. specific burning days) (Coates et al., 2020). Some studies show that long-term prescribed fire use has insignificant impact on total nitrogen (N) (Boyer and Miller, 1994; Godwin et al., 2017; McKee and William, 1982). Godwin et al. (2017) found that increases in phosphorus (P), calcium (Ca), potassium (K), and pH of soil are insignificant, with significant increases only found in carbon (C) and magnesium (Mg). Considerably elevated P and Ca concentrations were found by McKee and William (1982) at the 0–5 cm and 0–8 cm depths of soils. Ca immobilization in the O horizon (i.e. soil layers that have high organic matter contents) may be caused by lack of fires, thereby influencing early successional vegetation, biological richness, and species diversity (McKee and William, 1982). Compared to the significant impacts of forest wildfires on water quality and quantity, the effects of prescribed fires are marginal.

3.2.9 Land use change

Urbanisation of forested regions can cause greater variability in surface runoff, which will affect soil erosion, leading to more sedimentation (Zimmerman et al., 2008), as well as elevated levels of nutrients (Brett et al., 2005) and salinity (Brown et al., 2005). Urbanisation can also change landscape and associated vegetation (Peters & Meybeck, 2000). Agricultural activities can generate nutrients and other pollutants, and change runoff patterns of catchments (Ngah and Othman, 2012). Land use changes such as conversion between agriculture and forestry can affect stream habitat, water quality, periphyton, and benthic invertebrates through changes to the following aspects: channel morphology, stream width, water velocity, suspended inorganic solids (SIS) content, and coarse woody debris (CWD) (Quinn et al., 1997). Salt mobilisation, salinization and fertiliser leaching are important problems in some regions with agricultural land use, which can degrade the water quality in irrigated areas (Scanlon et al., 2007). Agrochemical application also releases human-made pollutants into the water, influencing water quality and stream biodiversity (Sun and Lockaby, 2012).

Increased pollutant sources and decreased retention capacity are two major factors affecting water quality and quantity through changes in land use. Specifically, urbanisation of forest increases impervious surface areas, thereby increasing stormflow rates and volumes, changes baseflow dynamics, and degrades water quality (Bonneau et al., 2017; Burns et al., 2012). Converting rural areas into urban lands can change the structure of landscape, impose stresses on ecosystems and thus having negative impacts on water quality (Sun and Lockaby, 2012). Nitrogen loading during land development can lead to loss of wetlands within an urban watershed (Murphy and Stallard, 2008; Rauscher and Johnsen, 2004).

Land use changes may locally reduce forest species and degrade natural habitats and ecosystem functions, resulting in declining biodiversity and the loss of some ecosystem services. Such effects are gradually accumulating, especially for pollination services and carbon storage (Martínez et al., 2009; Sliva and Dudley Williams, 2001).

3.2.10 Stream channelization

Channelization can cause stream habitat loss and degradation, which threatens biodiversity, both in terms of abundance and species richness (Johansson, 2013). This occurs because channelization can reduce structural complexity, alter flow patterns, and reduce availability of microhabitats for many different organisms (Karr and Chu, 2000). Additionally, it may also result in soil erosion and channel incision, as well as loss of floodplain connectivity and wetlands. In addition, the overall density and diversity of stream biota may decrease through channelization, causing an influx of arthropods from the stream to adjacent land (Kennedy and Turner, 2011), thereby reducing the abundance of terrestrial predators (Laeser et al., 2005; Paetzold et al., 2008).

3.2.11 Summary

This review identified a number of key stressors that affect forest water quality and quantity. These stressors can be categorised as either natural disturbance or forest management.

1. The key *natural disturbances* include *climate change (including changes in precipitation, temperature, CO_2 and stochastic and extreme events), wildfires, forest maturity*;
2. The key *forest management stressors* include *Logging/harvesting, plantation establishment, road construction, prescribed fires, land use change, stream channelization*.

The impacts of all stressors were considered when assessing the priorities of water quality/quantity indicators (Section 3.1).

3.3 Preliminary assessment of data for the key indicators

The data review identified a total of 483 water monitoring sites within the NSW RFA region. This includes sites that measure all variables covered in the recommended key water quality/quantity indicators (see Table 4), and is composed of:

- 316 WaterNSW sites;
- 23 sites owned by Snowy Hydro Limited and 11 sites owned by NSW Department of Industry – Lands and Water (both via BoM WDO);
- 43 sites owned by FCNSW.

For individual water quality indicators (e.g. TP and TN), the availability of monitoring data was summarised (Table 6). In contrast, data for all water quantity indicators can be extracted from daily streamflow data; therefore, data availability for the water quantity indicators is summarised by the availability of streamflow data (Table 7). For each variable within both the water quality and quantity datasets, we also highlight the number of monitoring stations where long-term records have been maintained – which will be used for identifying suitable monitoring sites to be considered for the next stage of analyses (see Section 4.1). Detailed site-specific summaries of data availability are included in Tables A6-A9 in the Appendix.

Table 6. 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 (year)	Median sampling frequency (per year)	Number of long-term with high-quality long-term data*			
							Last 10y quarterly	Last 20y quarterly	Last 10y monthly	Last 20y monthly
WaterNSW	EC	106	2010	2019	8	317.2	35	29	35	29
	WTemp	137	2003	2019	8	323.5	48	38	48	38
	DO	14	2006	2019	7	291.6	5	5	5	5
	pH	28	2014	2019	5	303.3	5	5	5	5
	Turbidity	40	2013	2019	6.5	289	5	1	5	1
	TP	45	1994	2019	26	10.7	33	26	33	26
	TN	45	2002	2019	17	10.4	33	14	33	14
	NOx	45	2008	2019	12	9.3	24	13	22	12
BoM WDO	WTemp	88	2012	2019	5	19282.5	13	5	13	5
	pH	13	2017	2019	4	227.8	0	0	0	0
	Turbidity	14	2017	2019	4	227.8	0	0	0	0
FCNSW	Turbidity	45	2001	2010	8	36.1	9	0	9	0
	TSS	41	2003	2011	7	32.9	8	0	8	0
	EC	11	1995	1997	2	73	0	0	0	0
	pH	11	1995	1997	2	73.25	0	0	0	0
	WTemp	2	1996	1999	3.5	190.6	0	0	0	0
	Macro	7	2015	2018	4	2 (Spring and Autumn)	0	0	0	0

*Only quality-controlled data are considered for all WaterNSW, BoM WDO and FCNSW datasets.

Table 7. 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	Number of sites with high-quality long-term data*		
					last 30y	last 35y	last 40y
WaterNSW	282	1977	2019	42	116	104	75
BoM WDO	34	1976	2019	43	34	34	23
FCNSW	43	1995	2014	10	17	14	14

*Only accounts for site with >= 350 days of good quality data per year.

Within the abovementioned monitoring sites, the spatial coverage of high-quality long-term sites for water quality and quantity are also shown in Figures 5 and 6. Figure 5 shows the locations of water quality monitoring sites that have at least 10 years of quarterly data. Figure 6 shows the locations of streamflow monitoring sites that have at least 35 years of continuous data. Note that the map also shows the approximate locations of unmapped monitoring sites within the FCNSW dataset, which have been excluded from in this project (Section 4.1) until station metadata has been compiled and accurate forest management and catchment disturbances information included to interpret changes in water quality and quantity. Once accurate locations are being identified in the future, these sites could potentially contribute to compliment the current analyses. Higher resolution maps focusing on data availability for individual RFA regions are presented in Figures A1-4 in the Appendix. A list of unmapped FCNSW sites is in Table A10 in the Appendix.

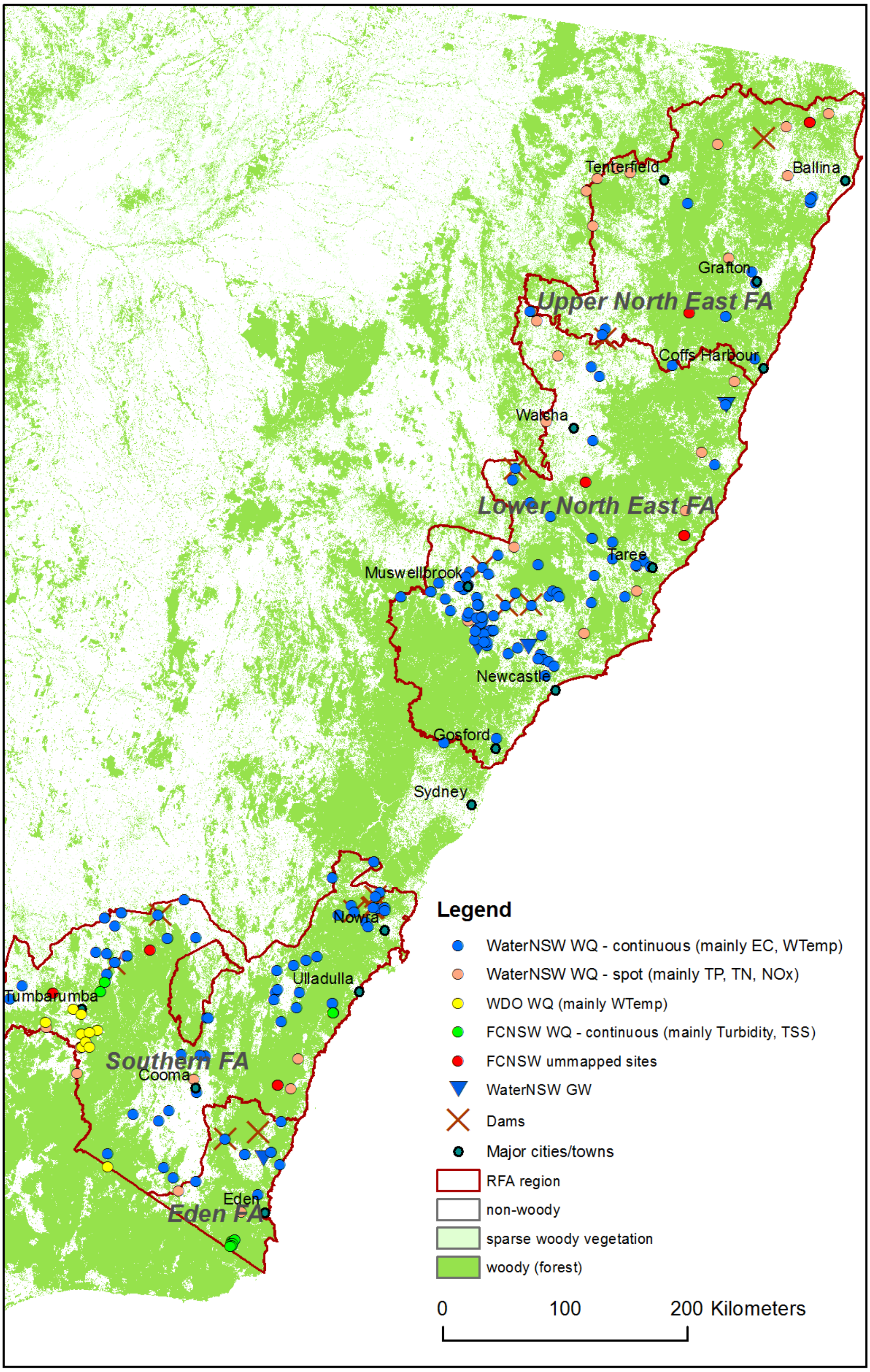

Figure 5. Long-term water quality monitoring sites within NSW RFA regions. Only sites with 10 years of quarterly data are shown. The approximate locations of the unmapped FCNSW sites are also shown – identifying the accurate locations of these sites are in progress.

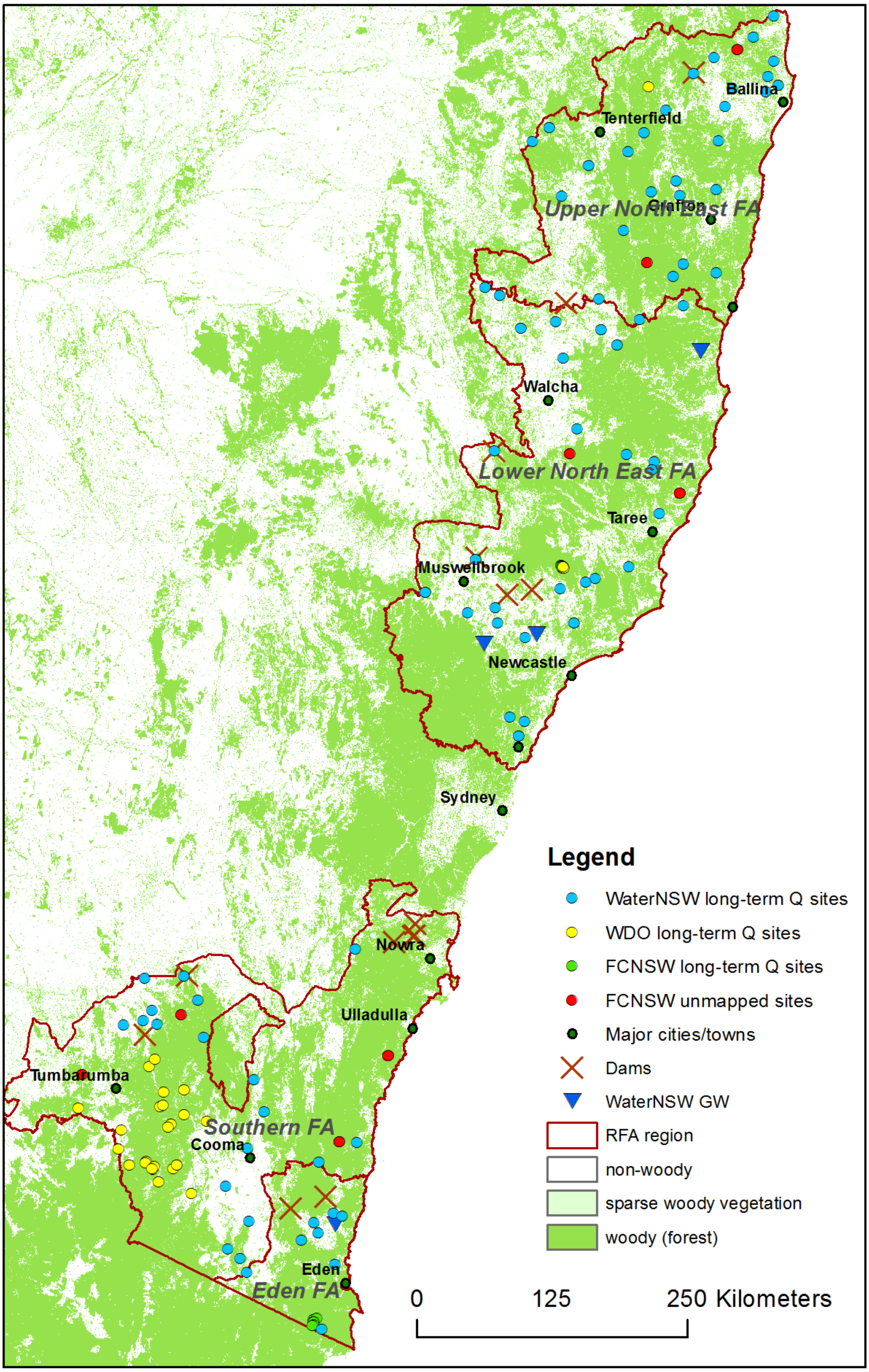

Figure 6. Long-term water quantity (flow) monitoring sites within NSW RFA regions. Only sites with greater than 35 years of high-quality data are shown. The approximate locations of the unmapped FCNSW sites are also shown – identifying the accurate locations of these sites are in progress. All sites have continuous data at daily frequency.

3.4 Summary of key findings for local and regional contexts

The report by Alluvium (2020) reviewed studies on the impacts of forest harvesting operations on waterway health – the waterway health is specifically focused on sediment delivery, while the forest harvesting operations considered include log dumps, snig tracks, temporary log crossings and the general harvest area as potential pollutant sources. Most studies reviewed were conducted in NSW or eastern Victoria. The review has identified process-based research on runoff and erosion processes via which roads and forestry compartments can influence sediment delivery to streams. The review confirms that roads and tracks as the primary source of sediment delivery to streams. Regarding mitigation interventions, the review suggests:

- Buffers between source areas and drainage lines is critical to reduce the impacts of forestry activities on sediment delivery.
- Strong evidence that the effect of harvesting activities on sediment delivery to streams can be effectively mitigated with best management practises (BMPs). Understanding on specific geographic is however limited due to the limited number of study sites explored – and thus limited inclusion of contrasting geology, soils, vegetation, bushfire regimes, and the non-stationarity in drivers (e.g. rainfall).
- Highly modified soil surfaces (snig tracks, log dumps) are the most dominant sediment sources in forestry compartments and thus should be a key focus area for mitigation.
- Stream crossings is a challenging pollutant source for mitigation, which is further complicated by the potential impacts of bushfire and changes in rainfall.

The report also reviewed catchment-scale water quality monitoring studies which support the above findings. These monitoring studies generally suggest that when occurring, the impacts on sediment transport, turbidity and nutrient loads are relatively short-lived and are smaller than the expected background variability.

Forestry Corporation of NSW (FCNSW) has produced a body of work based on their established long-term monitoring network of water quality and quantity within NSW forests (detailed data availability is reviewed in Section 3.3). In these studies, forest harvesting is the key disturbance of interest. Consistent with the report by Alluvium (2020), these studies generally identified impacts of harvesting on both water quality and quantity (i.e. streamflow and stream sediments). However, harvesting following the best management practises (BMPs) is found to have minimal impacts on water quality and quantity. The individual FCNSW monitoring studies and their main findings are summarized in Table 8.

Table 8. key FCNSW studies that explored the impacts of forest management and disturbances on water quality and quantity in NSW forests

Reference	**Study region**	**Study period**	**Water quality/quantity indicator interested**	**Management activities/disturbances interested**	**Key finding**
Cornish (1986)	13 catchments in the Wallagaraugh, Towamba and Bega River catchments in south-eastern NSW	1974-1984	Streamflow, turbidity, specific conductivity, sodium and calcium	logging	Streamflow is the major factor that explains variations in water quality. Logging and roading effects are more difficult to measure but are considered small.

Walsh and Lacey (2003)	94 compartments across eight regions, incorporating 51 separate State forests	1997-1999	Erosion severity estimated from surveys	Integrated logging and selective logging	In general, for selective operations erosion and sediment movement was relatively minor. More Erosion and sediment movement are seen following integrated operations but had since stabilised. Unexplained variation in erosion severity was large for all of the operational units – these can be explained by factors such as erosivity, slope class and time since logging in selective operations, and slope class in integrated operations.
Webb and Jarrett (2013)	6 catchments in Yambulla, SE NSW	1977-2011	Streamflow, baseflow and stormflow	Wildfire, logging operations, mixed species eucalypt forest regeneration	Overall speaking, there was a cumulative increase in streamflow following disturbances. These catchment-scale hydrological responses to disturbance of mixed species eucalypt forests do not follow the unusual response often reported in wet Mountain Ash forests.
Webb et al. (2012a)	5 small catchments in Kangaroo River State forest in northern NSW	2001-2009	Streamflow, suspended sediment	Forest harvesting	Streamflow increases following harvesting. Minor increases in suspended sediments were observed following harvesting, and was contributed by best management practices (BMPs) utilised during the harvesting operations.
Webb and Kathuria (2012)	2 small catchments in Red Hill NSW	1989-2009	Streamflow	Afforestation, forest age, thinning	For the study catchments, thinning at Year 14 after afforestation had a significant positive effect on streamflow that lasted for at least 6 years. Droughts coupled with a catchment soils recharging contributed to a delayed response to thinning.
Smolders et al. (2018)	5 catchments in Kangaroo River State Forest in northern NSW	Before and after the harvest following BMPs in 2007	Benthic coarse particulate organic matter (CPOM) and invertebrate detritivores	Forest harvesting using BMPs	Harvesting following BMPs do not alter CPOM and invertebrate detritivores for the study catchments.
Lacey (2000)	12 runoff plots of 5m wide and 20-30m long with different buffer treatments.	Dec 1995 – Mar 1997	Streamflow, sediments	Forest buffers	Undisturbed buffers greatly reduced overland flow and decreased sediment yields. Disturbed buffers achieved similarly large reductions in runoff and sediment yield.
Webb et al. (2012b)	6 catchments in Karuah, NSW	1975-2009	Streamflow	Wildfire, logging operations, mixed species eucalypt forest regeneration	Overall, catchments see a significant initial increase in streamflow following logging and burning, which can last for 2 years or over 5 years. Long-term changes in streamflow are highly uncertain across catchments. Forests other than Mountain Ash seem to not follow the same water yield responses following disturbances.
Hancock et al. (2017)	8 headwater catchments in Chichester State Forest, NSW	2004-2012 and 2013-2016	Sediment loads (both suspended and bedload)	Forest harvesting	No difference in sediment loads from the harvested and Control catchments, suggesting that management practices employed in each catchment were effective in the long term, although land disturbance has previously occurred.
Webb (2008)	5 headwater catchments in mid-north coast of NSW	2002-2006	Turbidity and suspended sediment, streamflow	Forest harvesting using BMPs	Sediment yields and streamflow peaks increased in all channels following harvesting. However, harvesting using BMPs in selected catchments did not significantly alter the magnitude of the sediment response to harvesting.

4. Recommendations

4.1 Plan of analyses

4.1.1 Detecting trends

This analysis aims to identify the temporal trend of each key water quality/quantity indicator using available historical data. Trends will be estimated with both non-parametric and parametric approaches – both are capable to estimate the magnitudes, directions and significance of trends.

Non-parametric approaches do not require model calibration, and are applicable to analyse trends in the key water quality and quantity indicators identified. These approaches are powerful for analysing highly skewed data (which is likely the case for both water quality and quantity variables) without the need for data transformation. Key analytical approaches include:

The *Mann-Kendall (MK) trend test,* which is recommended by the World Meteorological Organization (WMO) and is widely applied to assess the direction and significance of trends in hydro-climatic data (Kendall, 1955; Mann, 1945). The MK test requires input data to be temporally independent i.e., with no serial correlation. This will be checked prior to running the MK test; if data display strong serial correlation, statistical approaches will be applied to remove the correlation (e.g., pre-whitening). For any time series of n values $x_i = x_1, x_2, \ldots x_n$, trend direction can be estimated with their corresponding ranks in ascending order $R_1, R_2, \ldots, R_n$. Each pair of neighbouring ranks R_i and R_j (where $j=i+1$) are compared and the results for the full time-series are aggregated to derive the test statistic S (Eqn. 1).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij} \qquad [1]$$

$$a_{ij} = \operatorname{sign}(R_j - R_i) = \begin{cases} 1, & x_i < x_j \\ 0, & x_i = x_j \\ -1, & x_i > x_j \end{cases} \qquad [2]$$

Sen's slope is a non-parametric approach to estimate the magnitude of trend (Sen, 1968; Theil, 1992]. This test computes a set of linear slopes, d_k for $1 \leqslant i < j \leqslant n$, as:

$$d_k = \frac{X_j - X_i}{j - i} \qquad [3]$$

Sen's slope is then estimated as the median of all d_k.

The parametric approaches, such as temporal regression models, are widely-used to detect trends in water quality (Halliday et al., 2012; Yang and Moyer, 2020). These models are effective in quantifying the influences of key driving factors other than the trend effects and serial correlation. The key drawback is that when data are highly skewed, these regression models often requires data transformation to satisfy the statistical assumptions, which could lead to potential modelling bias. In addition, model conceptualization is less straight forward for the water quantity indicators, as discussed below.

A temporal regression model of one water quality indicator at a monitoring site can be expressed as Eqn. 4. The model explicitly accounts for a linear trend applied across the whole record, together with effects of runoff and seasonality. This model structure is informed by our understanding of the key factors driving temporal variation in river water quality (Guo et al., 2019).

$$C_t = C_0 + f(t) \times \beta_{tC} + f(Q_t) \times \beta_Q + f(seasonality) \times \beta_{seasonality} + f(\varepsilon_C) \qquad [4]$$

In Eqn. 4, C_t is level of the water quantity indicator (often as concentrations in mg/L) at any time step t (often separated by 15 minutes or one day for continuous data, and by one month for the spot sampled data). C_0 the level of that indicator at the starting point of the trend analysis. The individual predictors and their coefficients are defined as:

- $f(t)$ is a function of the sampling time t, and β_{tc} is its coefficient that quantifies the trend.
- $f(Q_t)$ is a function of the streamflow at the corresponding time t, Q_t, while its impact on water quality is described with parameter β_Q.
- *f(seasonality)* is a function of seasonality, which often uses day of the year (DoY) as the key predictor. For analysing water quality trend, this often takes the form of sinusoidal functions with a period of 1 year, which represent a seasonal cycle.
- $f(\varepsilon_c)$ is the error term, which can be defined by a first-order autoregressive (AR1) residual model to account for the potentially high temporal (serial) autocorrelation in the modelling of water quality data, especially when the monitoring frequency is high (e.g. daily). The specific error function for each water quality indicator will be determined after a preliminary analysis of the data autocorrelation structure.

Setting up temporal regression models for the water quality indicators is straight forward, because each key water quality indicator identified are directly corresponding to the time-series of monitored data (e.g., total phosphorus (TP) and total nitrogen (TN)). Impacts of streamflow can be separated from trend estimation with $f(Q_t)$, with the streamflow at the same time step of each water quality sample. In contrast, the water quantity indicators are largely based on signatures and indices derived from the monitoring time-series data of streamflow; this makes it less explicit to link to the impacts of the key driver, rainfall.

The final selection of modelling approach for trend analyses will be informed by further analyses of the datasets as well as consultation between the UoM team and the NSW NRC. During this process a set of specific modelling decisions will also be made, as discussed subsequently.

Temporal period of interest

Our preliminary analysis shows that, for each key water quality/quantity indicator, record lengths vary across monitoring sites (Section 3.2). For each water quality indicator, analysis of trends requires time-series data of individual monitoring datasets (e.g., total phosphorus (TP) and total nitrogen (TN) rely on two separate datasets). As a general recommendation of data availability, each monitoring site should have a minimum of 4 samples per year, if not continuously monitored; the data length should span at least three years (Oelsner et al., 2017). However, these minimal requirements will result in low power to detect trends. This is illustrated by a recent analytical study which shows that, regardless of having continuous or monthly spot-sampled data, the monitoring data at a site should span at least 10 years to confidently detect an annual trend of 10% (Liu et al., 2020). Using data of limited record period may be a pragmatic response where data availability is low. The estimated trends in this analysis will require careful interpretation and the confidence to statistically detect each trend will be described using the model fitting statistics.

In contrast to water quality, data for all recommended water quantity indicators can be extracted from the continuous (typically daily) streamflow monitoring data that are more widely available. Australian streamflow generally has high temporal variability, so the length of the data set should be at least 30 years when used for trend detection (Chiew and McMahon, 1993). Given the occurrence of Millennium drought, a prolonged and highly unusual event in term of streamflow response (Saft et al., 2015), we suggest including gauges with at least 35 or 40 years of record to better capture pre-drought conditions.

While considering these previous recommendations on data requirements, for analysing the entire study region, we propose two alternative ways of using data from individual sites. These approaches have different data requirements, while providing different aspects of trend information, as discussed and illustrated in Table 9 and Figure 7:

Table 9. Summary of three alternative decisions on the temporal period of trend analysis, which are illustrated in Figure 6.

	Option 1	**Option 1b**	**Option 2**
Selection of sites	All sites that satisfy minimum record period requirement (e.g. recent 35 years for streamflow and recent 10 years for water quality).	All sites that satisfy minimum record period requirement.	All sites available regardless of record period.
Period of analyses	Common period as the minimum record period.	Full record period at each site that satisfies minimum record period requirement.	Full record periods at all sites.
Pros	Trends at individual sites are estimated for a consistent period, making them easy to compare and interpret.	Better reveal site-specific trend patterns with use of all available data – especially at sites with long records.	Better reveal site-specific trend patterns with use of all available data – especially at sites with long records. Improved spatial representativeness across study regions.
Cons	Inevitable loss of information when omitting data at sites with long records, while some sites may be eliminated completely from analyses.	Sites with shorter records may be eliminated completely from analyses. Between-site comparison can be difficult to interpret.	Between-site comparison can be difficult to interpret. Uncertainty can be high in estimates at sites with shorter records. Bayesian hierarchical models is an alternative to make better use of shorter records (Webb and King, 2009; Clark et al., 2005; Guo et al., 2020), but requires substantial effort in preliminary analyses and model setup.

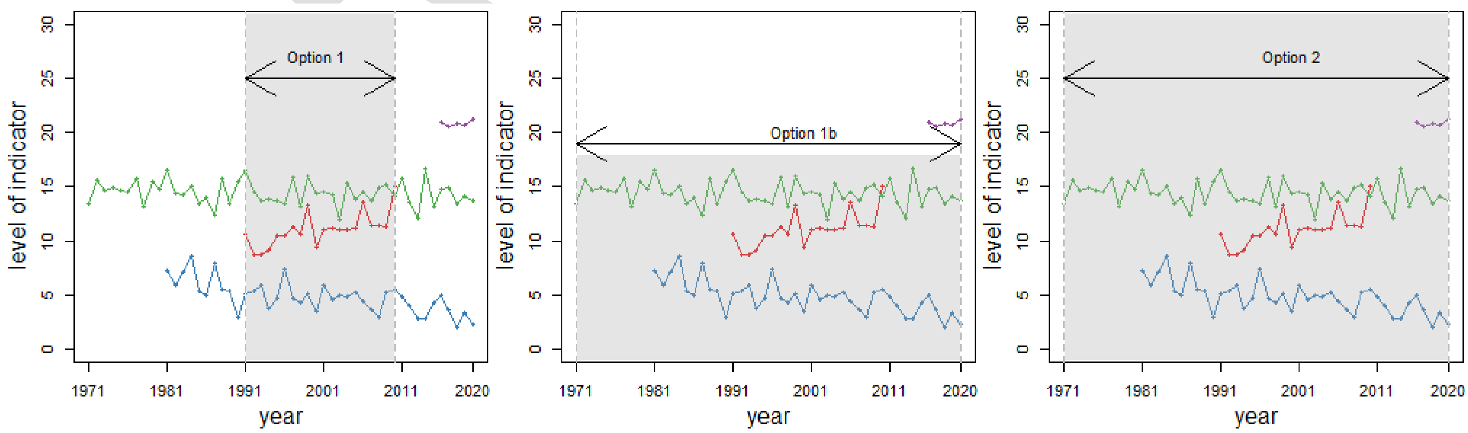

Figure 7. Comparison of the three alternative options for the temporal period of trend analysis (shaded). Hypothetical data from four individual monitoring sites are shown for illustration in different colours.

Option 1 is appropriate if the management interest is in regional trend patterns over a consistent period. The trends estimated at individual sites are easy to compare and interpret; however, trimming all sites to a common period means that there is an inevitable loss of information when omitting data at sites with long records, while some sites may be eliminated completely from analyses. Option 2 is appropriate if site-specific trend patterns are of interest. This approach effectively makes use of the full data period at individual sites, which can potentially extract valuable information for sites with long records. However, shorter records will have larger uncertainty in trend estimates. The abovementioned Bayesian hierarchical models may improve trend estimation for the short-record sites by pooling information from sites with longer records, however, it also requires substantially preliminary analyses on the data suitability, as well as substantial effort in model conceptualization and run time. For practical consideration on managing uncertainty and computational efficiency, we propose to start the trend analyses with Option 1b that focuses on the full records of sites with long records. Following this analysis, it is possible to apply Bayesian hierarchical models to explore sites with shorter records.

Characterising non-linear trends and change points

Trends in water quality/quantity indicators are likely non-linear and involve step changes. In non-parametric trend analyses. For example, the Pettit's test (Pettit, 1979) is widely applied to detect a single change-point in hydrological series or climate series with continuous data. At any time-step *t*, the key test statistics K_T, can be obtained directly from the *S* statistic from the MK test, as:

$$K_T = max|S| \tag{5}$$

The significance of K_T can then be estimated to suggest whether a change point exists at time *t*. These non-linear and step changes features can also be incorporated in the parameter temporal regressions (Eqn. 4), by specifying the forms of functions used for each predictor as either:

- A spline function, which can incorporate higher degrees of freedom and represent non-linear time trends and step changes.
- A linear function, which characterises only linear trend.

A further step of analysing the model residuals ($f(\varepsilon_c)$ and $f(\varepsilon_Q)$) can help to identify any non-linearity and step changes.

4.1.2 Attributing trends

To explain the estimated trends for each water quality/quantity indicator, an analysis will be performed on the trends of the key forest stressors that are expected to affect these indicators (e.g. climate, land use, fire). This analysis will focus on the statistically significant trends for individual water quality/quantity indicators, to seek possible explanations from comparing these trends to those in the forest stressors. To enable temporal trends in the forest stressors to be identified, stressor data needs to be considered as either time-series or multiple snapshots within the analysis period for water quality/quantity trends. Developing stressor time-series requires spatial data of individual forest stressors, which will then be averaged at a catchment scale to establish links with individual water quality/quantity monitoring stations. The specific forest stressors to include in this analysis will depend on the availability of spatial datasets in the RFA regions, which are to be determined in consultation with NSW NRC.

4.1.3 Establishing baselines

This analysis aims to establish baseline levels of each water quality/quantity indicator. These baselines will serve two key purposes:

1) To set up *historical reference conditions* to enable analyses of disturbances (e.g. climate, fire, management);
2) To set up *current reference conditions* to enable modelling of future values under various scenarios and using monitored values to test hypothesis.

These baselines to be established are highly relevant to the concept of 'guideline values' in the ANZECC guideline (ANZECC and ARMCANZ, 2000; ANZG., 2018), which are defined as:

> *"Water/sediment quality guideline values are used as a general tool to help ensure that certain physical and chemical stressors in waterways do not exceed harmful levels.*
>
> *We can define a guideline value as a measurable quantity (threshold) or condition of an indicator for a specific community value below or, for some stressors, above which we consider to be a low risk of unacceptable effects occurring."*

Considering the conceptual similarly between the 'guideline values' in ANZECC and 'baselines' in our project, our plan for establishing the baselines can thus be informed by the recommended approaches to derive the guideline values in ANZECC. Considering the scope of water quality and quantity indicators covered in this project, the 'reference-site' approach recommended in ANZECC is seen as the most relevant approach to derive the baseline of individual indicators. We summarise this approach and our proposed plan of adaptation subsequently. We note that the original approach recommended in the ANZECC targets for water quality; we propose to extend this to water quantity as well in this project.

Recommended approached in ANZECC

At a regional scale, water quality baselines can be defined with established levels from regional/large-scale datasets and models. These regional baseline values enable a quick, high-level assessment of the large-scale water quality status. examples include:

- Regional baselines derived for 12 inland water drainage divisions in Australia, using data from regional reference sites (Hale et al., 2012).
- Regional baselines derived for 54 mesoscale bioregions in Australia, based on the Integrated Marine and Coastal Regionalisation of Australia (IMCRA 4.0) (Commonwealth of Australia, 2006).

Water quality baselines can also be defined at individual reference sites, often defined as either the 80th percentile of the site-specific monitoring data, or the 20th percentile for indicators that cause problems at low concentrations, such as oxygen. Several specific considerations are required in deriving site-specific baselines:

- Data availability: At least two years of monthly sampling are required to sufficiently capture ecosystem variability and thus to derive a relatively stable baseline.
- Site selection: An appropriate reference site should be in upstream of impacted areas, or from appropriate local reference systems that are representative of unimpacted water bodies. Using sets of reference sites will provide a better characterisation of the local regional characteristics than a single site.
- Dynamic values: Water quality in some regions are influenced by strong seasonal and/or flow event effects e.g., wet and dry seasons for tropical catchments. Therefore, the definition of baseline values should capture these variabilities. Defining flexible and dynamic baseline value, such as via a flow-based model (e.g. van Dam et al., 2014).

Proposed plan of adaptation to this project

The regional and site-specific derivation of baselines both can help extract useful information and thus should be both explored in the analyses. Potential approaches to derive baselines are summarised in Figure 8. Assessing the regional baselines for the water quality indicators will involve a review of existing baselines established for the geographical/bioregions that are relevant to NSW RFA regions (e.g., Hale et al., 2012; Commonwealth of Australia, 2006). The site-level baselines can be established via statistical analysis of available data of individual water quality indicators.

Considering the emphasise of temporal trend in this project, there are two potential ways to estimate the site-level baselines, at either a group of sites or individual sites, respectively. The two approaches enable identification of disturbances from the spatial and temporal aspects, respectively. The final set of baseline analyses to be performed will be informed by the availability and representativeness of data of each indicator that is collected in the project.

To adapt the baseline approaches to water quantity indicators, a review will be performed on available regional guidelines and reference levels for runoff and its signatures (e.g., Australian Rainfall and Runoff (ARR); Ball et al., 2019). The runoff data collected in this project will be further assessed to determine the approaches to define site-level baselines.

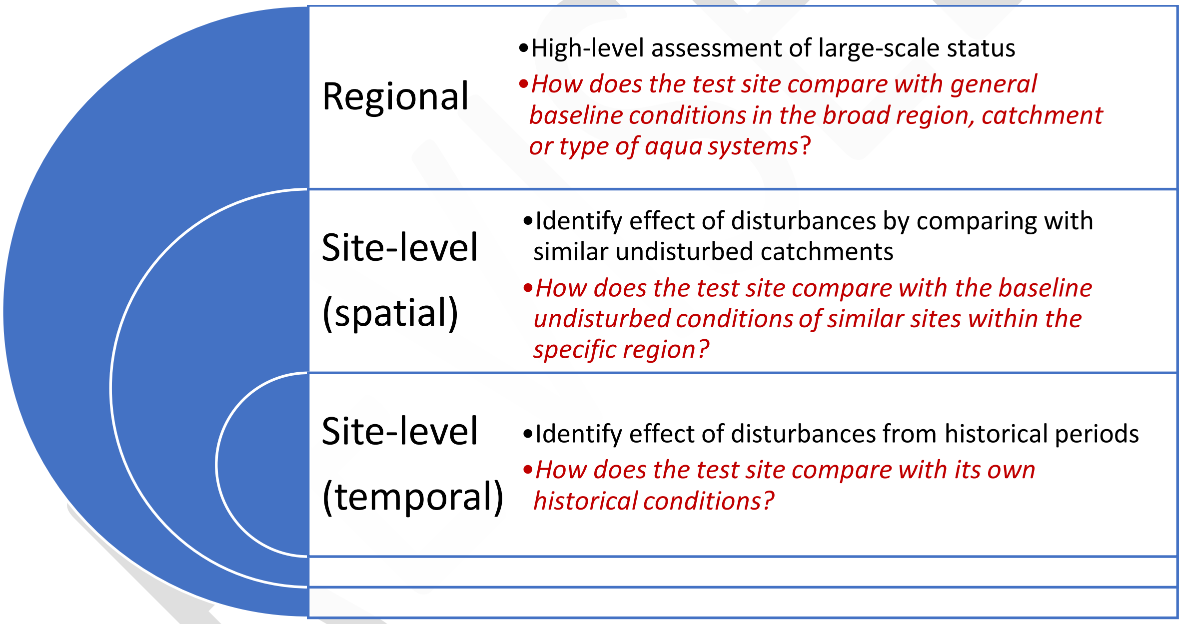

Figure 8. Potential approaches to be used to establishing site-level baselines and the key question that each one addresses.

The site-level baselines for individual indicators can be established with potential statistics include:

- Percentiles of empirical distributions, e.g., flow duration curves, percentiles of water quality parameter concentrations;
- Relationships with key driving variables, e.g., flow-based estimates of water quality parameter concentrations, rainfall-runoff relationships.

Depending on the disturbance level and spatial representativeness of the water monitoring sites, and the presence of temporal trend in individual water quality and quantity indicators, the two potential site-level baseline approaches (spatial and temporal) can address the two key objectives in different ways. For example, if no significant trend is detected for an indicator for an undisturbed site, then all historical data from that site can potentially be used to set both the *historical* and *current baselines*.

The final selection of baseline approach will be identified with further data analyses and to be consulted with NSW NRC.

4.2 Future monitoring and research

The data availability assessment (Section 3.2) suggests that the temporal coverage of water quantity monitoring is generally high within NSW RFA regions, with over 100 monitoring sites maintaining high-quality flow data over the recent 35 years. The relatively good availability of long-term streamflow monitoring sites enables various questions on forest management impacts to be explored. In contrast, water quality monitoring within RFA regions is quite limited within the monitoring period. In general, the median monitoring period for each water quality indicator is around 10 years. This could potentially limit the statistical power for identifying trends as and impacts of forest stressors on water quality, as some effects are only observable at longer timescales.

Within the recommended key water quality indicators, long-term monitoring is lacking for DO, pH and macroinvertebrate within NSW RFA regions. Turbidity, although monitored at a number of sites, has relatively short record lengths across all sites. Long-term monitoring for EC, WTemp, TP, TN and NO_x is better established with a reasonable number of sites (20-50) with over 10 years of record throughout RFA regions.

Based on the maps of monitoring stations in Figures 5 and 6, we provide some general comments on the spatial coverage and gaps of water monitoring within each NSW RFA region (Table 10). Across the four regions, the Upper North East FA receives the least monitoring attention for both water quality and quantity. Lower North East FA also has a relative limited monitoring network for water quantity. Based on Figures 5 and 6, the key regions requiring improved monitoring effort for both water quality and quantity are the north-east part of the Lower North East FA region, the north-west part of the Southern FA.

Table 10. Summary of the coverage of long-term monitoring networks in individual NSW RFA regions, based on the spatial distribution of long-term monitoring stations in the regions (Figures 5 and 6).

NSW RFA region	Water quality Number of long-term sites	Water quantity Number of long-term sites
Upper North East	21 (0.5 per 1000 km^2)	29 (0.7 per 1000 km^2)
Lower North East	91 (1.6 per 1000 km^2)	36 (0.6 per 1000 km^2)
Southern	71 (1.6 per 1000 km^2)	42 (0.9 per 1000 km^2)
Eden	16 (2.0 per 1000 km^2)	13 (1.5 per 1000 km^2)

To benchmark the status of water quality/quantity monitoring in NSW forests, a high-level review of current large-scale monitoring programs in other Australian states was performed, as summarised in Table 11. Note that this table does not include NSW, for which the availability of water quality/quantity data for forested regions has been reviewed comprehensively in Section 3.2 and discussed at the start of Section 4.2. Apart from NSW, there is no searchable water monitoring program that explicitly focuses on forest regions and/or understanding the impacts of forest management. All water monitoring programs identified are conducted by relevant state agencies on water, environment or natural resources. In some states, agencies (e.g. VIC DELWP Monitoring Partnership, TAS DPIPWE) either work in partnership with, or collate water quality/quantity data from, local/regional monitoring programs such as those by councils, local governments and water corporations. In general, the coverage of water quality and quantity data is the greatest for VIC, TAS and QLD; a further reduction of site number for each state is expected if restricted to forested area and sites with long-term records only. The fact that there are 483 water monitoring sites (regardless of whether long-term data is maintained) within only the NSW RFA regions (approx. 3.15 per 1000 km^2) suggest that the water monitoring in forest in NSW is well established and compares favourably to other Australian states.

Table 11. Summary of large-scale water quality/quantity monitoring programs in states other than NSW. State areas are based on inland areas provided by Geoscience Australia (2020).

State	**Other large-scale monitoring programs**	**Common vars measured**	**Number of sites (total inc. both water quality/quantity)**
VIC	VIC DELWP Regional Water Monitoring Partnerships (BoM, MDBA, water corporations, catchment management authorities and local governments) https://www.water.vic.gov.au/water-reporting/surface-water-monitoring	Continuous: Flow, DO, EC, pH, water temperature, Turbidity Spot: TSS, NO_x, NH4, TN, P, FRP	780 (3.4 per 1000 km^2)
SA	SA DEW State Water Monitoring Network https://www.environment.sa.gov.au/topics/water/monitoring/about/state-water-monitoring-network SA EPA aquatic ecosystem condition reports https://www.epa.sa.gov.au/environmental_info/water_quality/water_quality_monitoring	Continuous (DEW): Flow, DO, EC, pH, Turbidity Nitrogen, phosphorus and organic carbon Spot (EPA): Nutrients, salinity, DO, water temperature, macroinvertebrate and vegetation coverage	245 (0.3 per 1000 km^2)
NT	NT DENR https://denr.nt.gov.au/water/water-resources/water-monitoring	Flow and water quality (little information but seems highly localised)	>150 (0.1 per 1000 km^2)
TAS	TAS DPIPWE, along with local councils, natural resource management groups, WaterWatch and private organizations https://dpipwe.tas.gov.au/water/water-monitoring-and-assessment/water-monitoring/surface-water-quality/water-quality-monitoring	Continuous: Flow, DO, EC, water temperature, turbidity, pH Spot: NH4, TP, NO_2, NO_3	631 (9.8 per 1000 km^2)
QLD	QLD DNRME https://www.qld.gov.au/environment/water/quality/monitoring	Continuous: Flow, water temperature, EC, DO Spot: Nutrients, major ions, dissolved metals, suspended solids	400 (0.2 per 1000 km^2)
WA	WA DWER https://www.water.wa.gov.au/water-topics/water-quality/monitoring-and-assessing-water-quality	Continuous: flow, pH, DO Spot: TN, TP, TDS, DOC, turbidity colour	>200 (0.08 per 1000 km^2)

5. Summary

This report covers Task 1 of Project 3 of the Forest Monitoring and Improvement Program by the NSW Natural Resources Commission. The specific objectives of Task 1 are to: 1) identify key indicators of water quantity and quality in Coastal IFOA state forests and across all tenures in RFA regions; 2) propose a conceptual framework for analysing baseline/trends and preliminary recommendations for future monitoring of proposed key indicators across all tenures.

A comprehensive review of literature and publicly available datasets was performed to identify the key indicators of water quality and quantity. These indicators have good potential to be analysed and focused on for future monitoring, to understand trends and how these can be linked to forest health natural disturbances and management changes in forests. For water quality, a number of key indicators were recommended including concentrations of nutrients and dissolved oxygen, pH, electrical conductivity (salinity), water temperature, along with the population and composition of macroinvertebrates; for water quantity, the key indicators identified include the short-term variability and long-term signatures of flow and indicators of catchment storage and hydrologic regime.

The report provides recommendations on: 1) the statistical analyses to be performed for understanding the baselines and trends in each water quality/quantity indicator, and the key considerations within this; 2) the data availability of the key indicators within the NSW RFA regions and regions to focus effort for future monitoring. The next stage of the project (Task 2) will focus on delivering the baseline/trend analyses, including exploring feasible modelling decisions and finalise the methodology. The current recommendations for future monitoring will be updated based on the results of the statistical analyses.

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Appendix A

Detailed summary of each topic of literature review

Table A1. The full list of forest health concerns under the Montreal framework (NSW adaptation; NSW EPA (2016)). To identify key water quality/quantity indicators, this review focuses only on the concerns that are expected to be influenced by water quality and quantity (highlighted in red). Concerns that are expected to drive changes in water quality and quantity are highlighted in blue and covered in a separate review of key drivers/disturbances (Table A5). Other forest concerns that are less relevant to water quality/quantity are shown in grey.

1. Conservation of biological diversity - *forest dwelling species*
1.1a Ecosystem diversity
1.1b Area of forest by growth stage
1.1c Area of forest in protected area categories
1.1d Fragmentation of forest cover
1.2a Forest-dwelling species for which ecological information is available
1.2b The status of forest-dwelling species at risk of not maintaining viable breeding populations, as determined by legislation or scientific assessment
1.2c Representative species from a range of habitats monitored at scales relevant to regional forest management • This indicator provides information on population levels for representative species (both flora and fauna) across habitats. • Using 'representative' species identified at the State level, data may be interpreted to show changes in population levels across the species' range relevant to regional forest management.
1.3b Native forest and plantations of indigenous timber species that have genetic resource conservation mechanisms in place
2. Maintenance of productive capacity of forest ecosystems
2.1a Native forest available for wood production, area harvested and growing stock of merchantable and non-merchantable tree species
2.1b Age class and growing stock of plantations
2.1c Annual removal of wood products compared to the volume determined to be sustainable for native forests, and the future yields for plantations
2.1d Annual removal of non-wood forest products compared to the level determined to be sustainable
2.1e The proportion of the total area of native forest harvested that has been effectively regenerated, and the area of plantation clearfell harvested and the proportion of that effectively re-established
3. Maintenance of ecosystem health and vitality
3.1a Scale and impact of agents and processes affecting forest health and vitality

3.1b Area of forest burnt by planned and unplanned fire
4. Conservation and maintenance of soil and water resources
4.1a Area of forest land managed primarily for protective functions
4.1b Management of the risk of soil erosion in forests
4.1c Management of the risks to soil physical properties in forests
4.1d Management of the risks to water quantity in forests • This indicator aims to measure the extent to which the risk to water quantity has been identified and addressed in forest management. Water quantity is important for forest ecosystem heath and for maintaining sustainable water supply to downstream users. • Information collected should be interpreted by considering: · the significance of measures in place and · how they might minimise risk to water flows and variation in flow. Note: this indicator applies to all forests including plantations.
4.1e Management of the risks to water quality in forests • This indicator aims to measure the extent to which the risk to water quality has been identified and addressed in forest management. Water quality is important for ecosystem health and for maintaining sustainable water supply. • Information collected should be interpreted by considering: · the extent of management controls in place for assessing risks to water quality, · risk-reduction strategies and significance of water quality problems. · water quality guidelines and policy management objectives. Note: this indicator applies to all forests including plantations
5. Maintenance of forest contribution to global carbon cycles
5.1a Contribution of forest ecosystems and forest industries to the global greenhouse gas balance
6. Maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of society
6.1a Value and volume of wood and wood products
6.1b Values, quantities and use of non-wood forest products

	6.1c Value of forest-based services
	6.2a Investment and expenditure in forest management
	6.2b Investment in research, development, extension and use of new and improved technologies
	6.3a Area of forest available for public recreation/tourism and the use and type of facilities and activities on offer
	6.4a Area of forest to which Indigenous people have use and rights that protect their special values and are recognised through formal and informal management regimes
	6.4b Registered places of non-Indigenous cultural value in forests that are formally managed to protect those values
	6.4c The extent to which Indigenous values are protected, maintained and enhanced through Indigenous participation in forest management
	6.5a Direct and indirect employment in the forest sector
7.	Legal, institutional and economic framework for forest conservation and sustainable management
	7.1a Extent to which the legal framework supports the conservation and sustainable management of forests
	7.1b Extent to which the institutional framework supports the conservation and sustainable management of forests
	7.1c Extent to which the economic framework supports the conservation and sustainable management of forests
	7.1d Capacity to measure and monitor changes in the conservation and sustainable management of forests
	7.1e Capacity to conduct and apply research and development aimed at improving forest management and delivery of forest goods and services

Table A2.a. Key water quality indicators that are expected to affect aquatic ecosystems, based on ANZECC 2000 and NSW WQO. Each indicator generally has 4 trigger values (corresponding to slightly disturbed ecosystems in SE Australia), specifically for: upland rivers, lowland river (which may be divided to coast-inflow rivers or rivers within MDB), lakes & reservoirs, and estuaries. The recommended trigger values of indicator variables are also shown – where bold text highlights the values recommended by both ANZECC and NSW WQO, plain text indicates trigger values that only appear in ANZECC.

<table>
<tr><th rowspan="2">Water quality indicators</th><th rowspan="2">Guideline trigger values (ANZECC/NSW WQO)</th><th colspan="5">Impacts on aquatic ecosystem (relevant to NSW Montreal criteria 1.2c, 4.1e)</th></tr>
<tr><th>Growth of nuisance plant and cyanobacteria</th><th>Affecting biota including fish</th><th>Change of habitat</th><th>Affecting ecological and geomorphological processes</th><th>Oxidation of organic matter</th></tr>
<tr><td rowspan="2">Phosphorus (P) as TP, FRP (mg/L as N)</td><td>TP:
0.02,
0.025 (coast),
0.05 (MDB),
0.01,
0.03</td><td rowspan="5">High nutrient can stimulate the growth of cyanobacteria and nuisance plants which can dominate and change the dynamics of an aquatic ecosystem</td><td rowspan="5">• changes in biotic community structure[1]
• ammonia is toxic to aquatic biota at high concentrations, with increasing toxicity at decreasing dissolved oxygen concentrations</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>FRP:
0.015,
0.02,
0.005,
0.005.</td></tr>
<tr><td rowspan="3">Nitrogen (N) as TN, NOx and NH4+ (mg/L as P)</td><td>TN:
0.25,
0.35 (coast),
0.5 (MDB),
0.35,
0.3</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>NOx:
0.015,
0.04,
0.01,
0.015</td></tr>
<tr><td>NH4:
0.013,
0.02,
0.01,
0.015</td></tr>
</table>

Chlorophyll-a as Chl-a (mg/L)	**Chl-a: NA, 0.005, 0.005, 0.004**	Chl a concentration is often used as a general indicator of plant biomass because all plants, algae and cyanobacteria contain about 1–2% (dry wt) chlorophyll a.		• diminish light availability to other species below • mats of periphyton can cover the stream bed and reduce habitat quality for fish and invertebrates • cause excessive diurnal fluctuations in pH and dissolved oxygen which can stress or eliminate sensitive species, and which in turn affect P solubility and P sorption by suspended sediments[3]	• displace endemic species e.g. flagellates displacing centric diatoms (algae)[2] • obstruct waterways and impede fish migration • clog water filtration systems	when large amounts of biomass are degraded by bacteria, the biological oxygen demand (BOD) of the bacteria can deplete the oxygen concentration in the water leading to severe events like fish kills
Dissolved oxygen as DO (%)	**DO: 90-110, 85-110, 90-110, 80-110**		• Low DO concentrations can result in adverse effects on many aquatic organisms (e.g. fish, invertebrates and microorganisms) which depend upon oxygen for their efficient functioning.	At reduced DO concentrations it is known that many toxic compounds become increasingly Toxic – including lead, copper and ammonia[45].		
pH	**pH: 6.5-8,0, 6.5-8.5, 6.5-8.0, 7.0-8.5**		• Changes to pH may affect the physiological functioning (e.g. enzymes, membrane processes) of biota. • Chronic effects have been reported below pH 5, with			

			harmful effects on eggs and fry[6]. • Loss of fish populations have been attributed to spawning failure and diminished hatching success at moderate (less than 6.0) pH levels[7]. • Low pH can also adversely affect stream macroinvertebrate communities. • Changing the toxicity of several contaminants, e.g. low pHs can increase the toxicity of cyanide and aluminium; increased pH increases the toxicity of ammonia[6].			
Turbidity or suspended particulate matter, as the SPM (suspended particulate matter) (mg/L) or as light measurement (NTU)	**Turbidity:** **2-25,** **6-50,** **1-20,** **0.5-10**		• Reduction in light penetration can have adverse effects on the photosynthetic capability of phytoplankton, aquatic macrophytes and seagrasses[8]. • Scour algae from stream beds, and hence reduce the biomass • Adverse effects can also occur on fish due to mechanical and abrasive impairment of gills and impaired respiration and development[8]. • Adversely affect endemic flora and fauna	When it settles, SPM can cause adverse effects by smothering on benthic organisms and their habitats.	In suspension, the main impact of SPM is to reduce light penetration and thus affect primary production.	

Salinity as TDS, total dissolved substances (mg/L) or EC, electrical conductivity (us/cm)	**EC:** **30-350 (upland),** **125-2200 (lowland),** 20-30 (lakes, reservoirs)		• Toxicity to organisms through physiological changes (particularly osmoregulation) — both increases and decreases can have adverse effects • modifying the species composition of the ecosystem and affecting species that provide food or refuge			
Temperature (°C)	**Whether changes in temperature is unnatural, as: >80%ile or <20%ile of the data from reference ecosystem (not specified)**		• Altering organism's growth, metabolism, reproduction, mobility and migration patterns. • Fish such as trout prefer colder waters but in eutrophic stratified lakes, the fish cannot tolerate the low oxygen concentration at the bottom (hypolimnion).			
Optical properties: Light penetration Visual clarity and Colour, as euphotic depth (Zeu)	Euphotic depth: Rivers and lakes: In fresh waters that are deeper than 0.5 Zeu the natural euphotic depth Zeu should not be permitted to change by more than 10%. In waters shallower than 0.5 Zeu the maximum reduction in light at the sediment bed should not exceed		• Light requirements of submersed plants are tightly coupled to the plants' ability to harvest light, and hence to the growth form. • Change of light regime affects macrophyte populations which provide food and shelter for a range of other species9. • The colour of water may also affect aquatic ecosystems by influencing the spectral distribution of underwater			

	20% to protect the light regime of benthic plants. Estuaries: The natural Zeu should not be permitted to change by more than 10%.		light available for photosynthesis.			
Hydrodynamics: Residence time Mixing (stratification)	Residence times should be reduced to less than the average cell doubling time of the species of concern so that cells are flushed out of the system (not specified).	when a waterbody has long residence time and is inadequately mixed, it may become stratified and extremely vulnerable cyanobacterial problems[10]. (particularly in summer)	The hydrodynamics of upstream rivers largely dictates the characteristics of the ecosystem (e.g. macroinvertebrate and algal community structure).		In the stratified system without mixing, the benthic (bottom) layer can be an anoxic environment leading to chemical changes that release elements like iron, manganese, nitrogen and phosphorus into water column e.g. denitrification	In the stratified system without mixing, the epilimnion (surface) loses more and more of its phytoplankton as they die and fall to the hypolimnion (underlayer), together with nutrients – which are are not replaced and therefore the epilimnion becomes increasingly more nutrient deficient, clear, warm and oxygenated.
Chemical contaminants/toxicants	**Chemical-specific guidelines based on level of protection (% species) – see ANZECC 2000 Table 3.4.1**	Broad effects depending on species and specific chemicals				
Biological assessment indicators	Directly evaluates whether management goals for ecosystem protection are being achieved (e.g. maintenance of a certain level of species diversity, control of nuisance algae below a certain level, protection of key species, etc) – thus can reflect broad ecosystem health.					

Table A2.b. Summary of trigger values of water quality indicators, for slightly disturbed ecosystems in SE Australia. Values for generic ecosystem types are based on ANZECC 2000 and NSW WQO. Values for a few specific catchments are based on Healthy River Commission inquiry for individual catchments in NSW, focusing only on forested areas. Bolded text indicates trigger values that are recommended by both ANZECC and NSW WQO, plain text indicates trigger values that appear only in ANZECC or the HRC individual inquiries.

Water quality indicators and guideline trigger values		Ecosystem type				Specific catchment as required by HRC			
		Upland river	Lowland river	Lakes and reservoirs	Estuaries	Hawkesbury Nepean	Bega	Georges River - Botany Bay	Shoalhaven
Phosphorus (P) as TP, FRP (mg/L as N)	**TP**	**0.02**	**0.025 (river to coast)** **0.04 (MDB)**	**0.01**	**0.03**	0.05	0.03 (freshwater) 0.02 (estuary)	As per ANZECC 2000	Upper, middle: 0.04; 0.06 Kangaroo valley: 0.03; 0.06 Estuary: 0.05 (dry weather; wet weather)
	FRP	0.015	0.02	0.005	0.005	-	-		-
Nitrogen (N) as TN, NOx and NH4+ (mg/L as P)	**TN**	**0.25**	**0.35 (river to coast)** **0.5 (MDB)**	**0.35**	**0.3**	0.7	0.45 (freshwater) 0.3 (estuary)		Upper, middle: 0.5 Kangaroo valley: 0.5 Estuary: 0.4
	NOx	0.015	0.04	0.01	0.015	-	-		-
	NH4	0.013	0.02	0.01	0.015	-	-		-
Chlorophyll-a as Chl-a (mg/L)	**Chl-a**	**-**	**0.005**	**0.005**	**0.004**	0.007	-		**-**
Dissolved oxygen as DO (%)	**DO**	**90-110**	**85-110**	**90-110**	**80-110**	-	-		-
pH	**pH**	**6.5-8.0**	**6.5-8.5**	**6.5-8.0**	**7.0-8.5**	-	-		-
Turbidity or suspended particulate matter, as the SPM (suspended particulate matter) (mg/L) or as light measurement (NTU)	**Turbidity**	**2-25**	**6-50**	**1-20**	**0.5-10**	-	-		-
Salinity as	**EC**	**30-350**	**125-2200**	20-30	-	-	-		-

TDS, total dissolved substances (mg/L) or EC, electrical conductivity (us/cm)									
Temperature (°C)	**Whether changes in temperature is unnatural, as: >80%ile or <20%ile of the data from reference ecosystem (not specified)**					-	-	-	-
Optical properties: Light penetration Visual clarity and Colour, as euphotic depth (Zeu)	Euphotic depth: Rivers and lakes: In fresh waters that are deeper than 0.5 Zeu the natural euphotic depth Zeu should not be permitted to change by more than 10%. In waters shallower than 0.5 Zeu the maximum reduction in light at the sediment bed should not exceed 20% to protect the light regime of benthic plants. Estuaries: The natural Zeu should not be permitted to change by more than 10%.					-	-	-	-
Hydrodynamics: Residence time Mixing (stratification)	Residence times should be reduced to less than the average cell doubling time of the species of concern so that cells are flushed out of the system (not specified).					-	-	-	-
Chemical contaminants/toxicants	**Chemical-specific guidelines based on level of protection (% species) – see ANZECC 2000 Table 3.4.1**					-	-	-	-
Biological assessment indicators	**Many potential indicators exist which may relate to single species, multiple species or whole communities. Recognised protocols using diatoms and algae, macrophytes, macroinvertebrates, and fish populations and/or communities may be used in NSW and interstate (e.g. AusRivAS - a prediction system used to assess the biological health of Australian rivers $99 to access).**					-	-	-	-

Table A3. Key water quality indicators that are expected to have socio-economic impacts, based on ANZECC 2000 and NSW WQO/RFO (note: 1. drinking water and aquatic food for consumption are not included as they are not key concerns under Montreal framework; 2. Trigger values are based on NSW WQO while ANZECC generally has more strict requirements)

		Impacts on socio-economy (relevant to NSW Montreal criteria 6.3a)		
Water quality/quantity indicators and guideline trigger values		Visual amenity (no contact)	Secondary contact recreation (less frequent contact with water e.g. boating)	Primary contact recreation (frequent direct contact with water e.g. swimming)
Visual clarity and colour	• Natural visual clarity should not be reduced by more than 20%. • Natural hue of the water should not be changed by more than 10 points on the Munsell Scale. • The natural reflectance of the water should not be changed by more than 50%.	✓	✓	✓
Surface films and debris	• Oils and petrochemicals should not be noticeable as a visible film on the water, nor should they be detectable by odour. • Waters should be free from floating debris and litter.	✓	✓	✓
Nuisance organisms inc. algae & blue-green algae	• Macrophytes, phytoplankton scums, filamentous algal mats, blue-green algae, sewage fungus and leeches should not be present in unsightly amounts. • < 15 000 cells/mL	✓	✓	✓
Toxic chemicals	• Waters containing chemicals that are either toxic or irritating to the skin or mucous membranes are unsuitable for recreation. • Toxic substances should not exceed values in tables 5.2.3 and 5.2.4 of the ANZECC 2000 Guidelines.		✓	✓
pH	5.0-9.0			✓

Temperature	15°-35°C for prolonged exposure.			✓
Turbidity	A 200 mm diameter black disc should be able to be sighted horizontally from a distance of more than 1.6 m (approximately 6 NTU).			✓
Protozoans	Pathogenic free-living protozoans should be absent from bodies of fresh water. (Note, it is not necessary to analyse water for these pathogens unless temperature is greater than 24 degrees Celsius).		✓	✓
Faecal coliforms	Median bacterial content in fresh and marine waters of < 1000 faecal coliforms per 100 mL, with 4 out of 5 samples < 4000/100 mL (minimum of 5 samples taken at regular intervals not exceeding one month).		✓	✓
Enterococci	Median bacterial content in fresh and marine waters of < 230 enterococci per 100 mL (maximum number in any one sample: 450-700 organisms/100 mL).		✓	✓

Table A4. Key water quantity indicators that are expected to impact natural flow regime in aquatic systems, based on ANZECC 2000 and NSW RFO. The last four aspects of impact are less important as they are only of interest for a small number of catchments.

Water quantity indicators that are relevant to each RFO	Impacts on natural flow regime (relevant to NSW Montreal criteria 4.1d)									
	Protect pools in dry times	Protect natural low flows	Maintain natural flow variability	Minimise effects of weirs and other structures	Maintain wetland and floodplain inundation	Manage groundwater for ecosystems	Protect important rises in water levels **only for Illawarra, Murrumbidge e, Murray and Castlereagh*	Mimic natural drying in temporary waterways **only for Illawarra, Murrumbidg ee, Murray and Castlereagh*	Minimize effects of dams on water quality **only for George and Castlereag h*	Maintain natural rate of change in water levels **only for Illawarra and Castlereagh*
Statistics of daily flow including: • Daily flow quantiles: · 95% and 80% exceedance of non-zero daily flows defines period of 'very low' and 'low' flows for which extractions should be assessed · Other percentiles e.g. 10%, 25%, 50%, 75% and 90% can help characterising the	• During dry times, some streams stop flowing and form pools. Pools and wetlands are refuges for aquatic plants and animals. • Pumping water from these areas can make it more difficult for many species to recover after a drought.	Water extraction and storage are high in dry times and impose long artificial droughts that increase the stress on aquatic plants and animals.	River diversion, hydro-electric release and urban development often create problems with streambank stability, biodiversity and signals for breeding and migration.	Most instream structures (e.g. weirs) convert flowing water to still water, thus altering habitat and increasing the risk of algal blooms or other water quality problems. Barriers restrict the passage of plant propagules (e.g. seeds) and animals.			'Pulsing' of river flows, including their duration, may trigger migration of animals and reproduction of plants and animals; provide over-bank flows to wetlands and floodplains; shape the river channel; and control water quality and nutrients. Water storage	In streams and wetlands that naturally dry out, artificial wetting (e.g. releases) can create problems in maintaining habitat, vegetation, nutrient cycling and signals for breeding. It can also lead to a high water table	See temperatur e and DO WQOs	

natural variability of flow · 80% quantile of all non-zero daily flows defines the ‘high-flow’ · Duration of high and low flows • Mean, SD and CoV of daily flow • Extreme flow conditions e.g. annual 7-day maximum/minimum flow • % and duration of cease-to-flow • Recession constant • Flashiness index[1]							and extraction can alter or remove freshes, inhibiting these vital processes. The height, duration, season and frequency of higher flows are all important.	and associated salinity problems.			
River extraction, particularly during dry, low-flow and high-flow periods											
Long-term flow metrics (can be derived from daily flow) including: • annual/seasonal runoff/rainfall ratio • trend in rainfall-runoff residuals	* Additional indicators proposed to understand long-term changes in water balance (not a focus in NSW RFO but seems relevant to forest management).										

• moving-window rainfall-runoff elasticity										
• % or period inundated • Area inundated as spatial maps					• Floodplain works can change the flooding patterns, which will then lead to changes in habitat and vegetation. • These changes can be expected to reduce or change the diversity and abundance (or both) of species in the ecosystem. • In particular, they can lead to reduced numbers of native fish and to water quality problems.					
• Groundwater level						• GW systems may provide base flows in rivers during dry periods				

• Baseflow and proportion of baseflow						and be primary sources of water for wetland, floodplain and riparian vegetation. • Also, serious depletion of groundwater in dry times may lead to unnatural recharge of groundwater from surface waters during the next flow event.				
River water levels, particularly the rate of change										If water levels fall too fast (e.g. shutting dams), water does not drain properly from riverbanks and they may collapse. Migration of aquatic animals may also be restricted by such sudden

										falls in river height.

Table A5. Impacts of forest disturbances and stressors on water quality and quantity

Water Functions / Disturbances and Stressors	Energy balances	Precipitation	Evapotranspiration	Canopy and litter interception	Surface runoff, stormflow, peak flow, flooding	Ground-water	Baseflow (lowflow)	Carbon inputs to streams	Nutrients and pollutants loading to streams	Biodiversity, aquatic biota
Climate change - precipitation		√			√	√	√			
Climate change - temperature and atmospheric CO_2 concentrations	√		√	√	√	√	√			
Stochastic and extreme events	√	√	√		√	√	√	√	√	
Forest wildfires			√	√	√		√	√	√	
Forest age/ maturity			√	√	√			√	√	
Forest harvesting; logging operation; thinning	√	√	√	√	√			√	√	√
Establishing riparian forest buffers	√	√	√	√	√			√	√	
Plantation establishment			√	√	√				√	
Road construction; unpaved forest roads; increase impervious areas	√				√				√	
Prescribed fires									√	√
Land use change					√				√	√
Stream channelization					√		√			√

Data availability for water quality/quantity indicators – site-level summaries

Table A6. Summary of data availability for streamflow within NSW RFA. Summary statistics are for individua water quality variables at individual monitoring sites owned by WaterNSW and NSW Department of Industry.

Site	Start year	End year	Average number of samples per year	Variable Name
WaterNSW				
203403	2013	2019	330	EC
203450	2013	2019	302	EC
203470	2013	2019	330	EC
204001	1999	2003	331	EC
204008	1994	1997	247	EC
204025	1997	2005	319	EC
204400	2013	2019	330	EC
204413	2013	2019	345	EC
205015	2008	2009	107	EC
206008	1998	1998	54	EC
206402	2013	2019	330	EC
208028	2013	2019	292	EC
208400	2013	2019	330	EC
208420	2013	2019	330	EC
209002	2010	2010	201	EC
209006	2010	2011	123	EC
210002	1992	2019	348	EC
210004	1992	2019	324	EC
210015	1996	2019	342	EC
210016	2002	2019	333	EC
210021	1997	2019	345	EC
210028	2000	2019	339	EC
210031	1992	2019	322	EC
210039	1999	2019	347	EC
210040	1993	2019	319	EC
210044	1993	2019	354	EC
210055	1993	2019	348	EC
210056	1998	2019	350	EC
210064	1992	2019	347	EC
210076	1993	2016	342	EC
210079	2002	2019	343	EC
210083	1991	2019	358	EC
210084	1997	2019	350	EC
210089	1996	2009	309	EC
210110	1994	2019	317	EC
210114	1999	2017	316	EC
210126	1993	2019	312	EC
210127	1993	2019	345	EC
210128	1993	2000	312	EC
210129	1993	2019	357	EC
210130	1993	2019	309	EC
210134	1993	2019	337	EC
210144	2014	2019	325	EC
210151	2015	2019	300	EC
210409	2013	2019	330	EC
210410	2013	2019	330	EC
210432	2013	2019	330	EC
210448	2013	2019	330	EC
210452	2013	2019	330	EC
210455	2013	2019	330	EC
212271	2019	2019	149	EC
2122801	2019	2019	248	EC
212407	2013	2014	149	EC
215007	2003	2005	229	EC
215207	2019	2019	46	EC
215208	2019	2019	187	EC
215209	2019	2019	82	EC
2152131	2019	2019	219	EC
215216	2019	2019	219	EC
215220	2019	2019	149	EC

2152201	2019	2019	248	EC
215223	2019	2019	248	EC
215233	2019	2019	154	EC
215237	2019	2019	248	EC
215242	2019	2019	76	EC
215430	2013	2019	330	EC
217006	1997	2010	312	EC
219003	1996	2011	296	EC
219016	1998	2010	274	EC
219025	1996	2019	326	EC
220003	1996	2002	211	EC
222008	2009	2019	294	EC
222013	2009	2019	251	EC
222026	1998	2019	346	EC
222027	2002	2019	346	EC
41000270	2012	2019	306	EC
41000271	2012	2019	287	EC
41000272	2013	2019	277	EC
410004	1993	2019	346	EC
410008	2001	2019	313	EC
410024	1999	2019	337	EC
410050	2012	2019	323	EC
410057	1999	2019	341	EC
410061	2004	2019	339	EC
410073	1993	2019	353	EC
410081	2012	2019	301	EC
410097	2000	2019	330	EC
410106	2003	2012	335	EC
410141	2012	2019	311	EC
410176	1999	2019	337	EC
410187	2001	2011	336	EC
419081	1991	1998	224	EC
D21019001	2017	2019	303	EC
D21019006	2017	2019	315	EC
D21019009	2017	2019	317	EC
D21019010	2016	2019	261	EC
D21019013	2016	2019	291	EC
D21019081	2017	2019	304	EC
D21019111	2017	2019	313	EC
D21019990	2017	2019	307	EC
D21019991	2017	2019	287	EC
D21019992	2018	2019	284	EC
D21019993	2017	2019	324	EC
D21019996	2017	2019	267	EC
D21019998	2017	2019	326	EC
D21019999	2017	2019	317	EC
203403	2013	2019	343	Wtemp
203450	2013	2019	315	Wtemp
203470	2013	2019	343	Wtemp
204001	1999	2003	331	Wtemp
204008	1994	1997	247	Wtemp
204025	1997	2005	323	Wtemp
204033	1996	1997	255	Wtemp
204400	2013	2019	343	Wtemp
204413	2009	2019	328	Wtemp
205015	2008	2009	107	Wtemp
206008	1998	1998	54	Wtemp
206018	2000	2001	256	Wtemp
206032	1994	1997	218	Wtemp
206035	1998	2004	354	Wtemp
206038	1998	2000	136	Wtemp
206402	2013	2019	343	Wtemp
208001	2016	2018	154	Wtemp
208028	2013	2019	292	Wtemp
208400	2013	2019	343	Wtemp
208420	2013	2019	343	Wtemp
209002	2010	2010	201	Wtemp

209006	2010	2011	123	Wtemp
210001	2014	2019	324	Wtemp
210002	1996	2019	341	Wtemp
210004	1996	2019	315	Wtemp
210014	2010	2011	235	Wtemp
210015	1996	2019	342	Wtemp
210016	2002	2019	323	Wtemp
210021	1997	2019	352	Wtemp
210028	2000	2019	335	Wtemp
210031	1999	2019	334	Wtemp
210039	1999	2019	344	Wtemp
210040	1999	2019	342	Wtemp
210044	1994	2019	342	Wtemp
210055	1994	2019	337	Wtemp
210056	1998	2019	343	Wtemp
210064	1994	2019	336	Wtemp
210076	1994	2016	344	Wtemp
210079	2002	2019	344	Wtemp
210083	1992	2019	339	Wtemp
210084	1999	2019	353	Wtemp
210089	1996	2009	324	Wtemp
210110	1994	2019	327	Wtemp
210114	1989	2019	315	Wtemp
210126	1993	2019	310	Wtemp
210127	1994	2019	321	Wtemp
210128	1994	2000	251	Wtemp
210129	1994	2019	346	Wtemp
210130	1993	2019	301	Wtemp
210134	1993	2019	338	Wtemp
210136	2014	2019	344	Wtemp
210137	2014	2019	345	Wtemp
210144	2009	2019	330	Wtemp
210150	2015	2019	332	Wtemp
210151	2015	2019	300	Wtemp
210409	2013	2019	343	Wtemp
210410	2013	2019	343	Wtemp
210432	2013	2019	343	Wtemp
210448	2013	2019	343	Wtemp
210452	2013	2019	343	Wtemp
210455	2013	2019	343	Wtemp
211013	2009	2010	27	Wtemp
212271	2017	2019	223	Wtemp
2122801	1990	2019	333	Wtemp
212407	2013	2014	201	Wtemp
215007	2003	2005	229	Wtemp
215207	1995	2019	325	Wtemp
215208	1994	2019	334	Wtemp
215209	1994	2016	338	Wtemp
215210	1994	2017	326	Wtemp
2152131	2014	2019	279	Wtemp
215215	1991	2019	324	Wtemp
215216	1991	2019	325	Wtemp
215217	2019	2019	187	Wtemp
215220	1995	2019	324	Wtemp
2152201	2014	2019	309	Wtemp
215223	2014	2019	293	Wtemp
215233	2013	2019	323	Wtemp
215235	2019	2019	187	Wtemp
215237	1994	2019	321	Wtemp
215238	1994	2016	354	Wtemp
215239	1994	2017	326	Wtemp
215241	1994	2017	323	Wtemp
215242	1994	2017	311	Wtemp
215430	2013	2019	343	Wtemp
216002	2009	2011	147	Wtemp
217006	1997	2015	318	Wtemp
219003	1996	2013	314	Wtemp

219016	1998	2015	301	Wtemp
219025	1996	2019	331	Wtemp
219033	1994	1999	337	Wtemp
219410	2013	2013	73	Wtemp
220003	1995	2002	223	Wtemp
222007	2010	2011	210	Wtemp
222008	2009	2019	295	Wtemp
222013	2009	2019	260	Wtemp
222016	2010	2011	235	Wtemp
222019	2008	2010	283	Wtemp
222026	1998	2019	358	Wtemp
222027	2002	2019	350	Wtemp
41000270	2012	2019	306	Wtemp
41000271	2012	2019	295	Wtemp
41000272	2013	2019	286	Wtemp
410004	1993	2019	352	Wtemp
410008	2001	2019	314	Wtemp
410024	1999	2019	343	Wtemp
410038	2002	2007	280	Wtemp
410039	2002	2019	307	Wtemp
410050	2012	2019	323	Wtemp
410057	1999	2019	344	Wtemp
410059	2003	2005	336	Wtemp
410061	2004	2019	340	Wtemp
410073	1993	2019	353	Wtemp
410081	2012	2019	329	Wtemp
410097	2000	2019	334	Wtemp
410106	2003	2012	333	Wtemp
410141	2012	2019	311	Wtemp
410176	1999	2019	339	Wtemp
410187	2001	2011	326	Wtemp
410777	2003	2019	352	Wtemp
418008	2015	2019	226	Wtemp
419045	1992	2019	342	Wtemp
419081	1991	1998	277	Wtemp
D21019001	2017	2019	303	Wtemp
D21019006	2017	2019	290	Wtemp
D21019009	2017	2019	317	Wtemp
D21019010	2016	2019	297	Wtemp
D21019013	2016	2019	291	Wtemp
D21019081	2017	2019	301	Wtemp
D21019111	2017	2019	313	Wtemp
D21019990	2017	2019	307	Wtemp
D21019991	2017	2019	284	Wtemp
D21019992	2018	2019	284	Wtemp
D21019993	2017	2019	324	Wtemp
D21019996	2017	2019	267	Wtemp
D21019998	2017	2019	326	Wtemp
D21019999	2017	2019	317	Wtemp
204001	1999	2003	331	DO
204025	1997	2003	266	DO
210150	2015	2019	332	DO
212271	2017	2019	233	DO
2122801	1994	2019	315	DO
215207	1996	2019	288	DO
2152131	2014	2019	278	DO
215215	1991	2019	288	DO
215216	1991	2019	292	DO
215217	2019	2019	187	DO
215220	1996	2019	291	DO
2152201	2014	2019	307	DO
215223	2014	2019	294	DO
215233	2013	2019	323	DO
204001	1999	2003	331	pH
204025	1997	2003	252	pH
210126	1993	1994	161	pH
212271	2017	2019	232	pH

2122801	1994	2019	333	pH
215207	1995	2019	332	pH
2152131	2014	2019	275	pH
215215	1991	2019	304	pH
215216	1991	2019	316	pH
215217	2019	2019	187	pH
215220	1995	2019	316	pH
2152201	2014	2019	309	pH
215223	2014	2019	291	pH
215233	2013	2019	316	pH
219003	1996	2000	200	pH
219025	1996	2000	215	pH
220003	1998	2000	254	pH
41000272	2013	2017	187	pH
D21019001	2017	2019	303	pH
D21019006	2017	2019	315	pH
D21019009	2017	2019	317	pH
D21019010	2016	2019	297	pH
D21019013	2016	2019	291	pH
D21019081	2017	2019	304	pH
D21019990	2017	2019	307	pH
D21019991	2017	2019	284	pH
D21019993	2017	2019	324	pH
D21019998	2017	2019	326	pH
204001	1999	2003	261	Turbidity
204025	1999	2003	262	Turbidity
208003	2012	2019	294	Turbidity
208004	2014	2019	307	Turbidity
208005	2013	2019	300	Turbidity
208009	2011	2019	325	Turbidity
208011	2015	2019	234	Turbidity
208027	2011	2015	238	Turbidity
212271	2017	2019	234	Turbidity
2122801	1995	2019	307	Turbidity
215207	2011	2019	284	Turbidity
2152131	2014	2019	278	Turbidity
215215	2011	2019	286	Turbidity
215216	2008	2019	262	Turbidity
215217	2019	2019	187	Turbidity
215220	2007	2019	253	Turbidity
2152201	2014	2019	304	Turbidity
215223	2014	2019	300	Turbidity
215233	2013	2019	311	Turbidity
219025	1997	1997	4	Turbidity
220003	1996	1997	78	Turbidity
41000270	2012	2019	266	Turbidity
41000271	2012	2019	287	Turbidity
41000272	2013	2019	300	Turbidity
410004	1993	2012	270	Turbidity
410008	2001	2012	236	Turbidity
410050	2012	2017	291	Turbidity
410081	2012	2018	209	Turbidity
410141	2012	2019	299	Turbidity
419081	1995	1998	228	Turbidity
D21019001	2017	2019	303	Turbidity
D21019006	2017	2019	315	Turbidity
D21019009	2017	2019	317	Turbidity
D21019010	2016	2019	297	Turbidity
D21019013	2017	2019	306	Turbidity
D21019081	2017	2019	304	Turbidity
D21019990	2017	2019	307	Turbidity
D21019991	2017	2019	284	Turbidity
D21019993	2017	2019	324	Turbidity
D21019998	2017	2019	326	Turbidity
203004	1983	2018	7	TP
203005	2018	2018	4	TP
204001	1982	2018	12	TP

204051	2009	2018	9	TP
206011	1986	2018	10	TP
208004	1982	2018	11	TP
208011	1992	2018	9	TP
209003	1984	2018	10	TP
210001	1979	2018	11	TP
210002	1979	2018	22	TP
210004	1979	2018	12	TP
210005	1991	2018	10	TP
210009	1997	2018	14	TP
210031	1979	2017	15	TP
216002	1993	2018	11	TP
217007	2015	2018	10	TP
219025	1993	2018	11	TP
222004	1993	2018	11	TP
401003	1999	2018	10	TP
401201	2008	2018	11	TP
401556	2000	2018	16	TP
410004	1985	2018	12	TP
410024	2001	2018	15	TP
410033	1985	2018	10	TP
410038	2001	2018	15	TP
410073	1989	2018	14	TP
416003	1992	2018	10	TP
416008	1982	2018	10	TP
416011	1982	2017	11	TP
416032	1992	2017	11	TP
418008	1992	2018	13	TP
418014	2002	2017	11	TP
419010	2009	2017	9	TP
20110017	1994	2018	12	TP
20410043	1994	2018	12	TP
20510051	2009	2018	9	TP
20710002	2009	2018	10	TP
20910017	1999	2018	9	TP
21010092	1998	2018	12	TP
21810018	2012	2018	10	TP
21910054	2016	2018	11	TP
22010241	2015	2018	9	TP
41010924	1995	2018	14	TP
41610079	2002	2017	10	TP
41810006	2002	2017	11	TP
203004	2009	2018	8	TN
203005	2018	2018	4	TN
204001	1994	2018	10	TN
204051	2009	2018	9	TN
206011	2008	2018	9	TN
208004	1991	2018	10	TN
208011	2001	2018	10	TN
209003	1991	2018	10	TN
210001	2004	2018	9	TN
210002	1991	2018	13	TN
210004	2000	2018	10	TN
210005	1991	2018	9	TN
210009	1998	2018	14	TN
210031	1991	2017	12	TN
216002	2008	2018	10	TN
217007	2015	2018	10	TN
219025	2008	2018	11	TN
222004	2008	2018	10	TN
401003	1999	2018	10	TN
401201	2008	2018	11	TN
401556	2000	2018	16	TN
410004	1990	2018	11	TN
410024	2007	2018	11	TN
410033	2007	2018	10	TN
410038	2007	2018	11	TN

410073	2007	2018	11	TN
416003	1992	2018	10	TN
416008	1992	2018	10	TN
416011	2002	2017	10	TN
416032	1992	2017	11	TN
418008	2003	2018	13	TN
418014	2002	2017	11	TN
419010	2009	2017	9	TN
20110017	1994	2018	12	TN
20410043	1994	2018	12	TN
20510051	2009	2018	9	TN
20710002	2009	2018	10	TN
20910017	1999	2018	9	TN
21010092	1999	2018	10	TN
21810018	2012	2018	10	TN
21910054	2016	2018	11	TN
22010241	2015	2018	9	TN
41010924	2007	2018	11	TN
41610079	2002	2017	10	TN
41810006	2002	2017	11	TN
203004	2009	2018	8	NOx
203005	2018	2018	4	NOx
204001	1994	2018	9	NOx
204051	2009	2018	8	NOx
206011	2008	2018	9	NOx
208004	2000	2018	10	NOx
208011	1999	2018	9	NOx
209003	2000	2018	10	NOx
210001	2004	2018	10	NOx
210002	1999	2018	19	NOx
210004	2000	2018	10	NOx
210005	1999	2018	10	NOx
210009	1999	2018	13	NOx
210031	1999	2017	14	NOx
216002	2011	2018	9	NOx
217007	2015	2018	10	NOx
219025	2011	2018	9	NOx
222004	2011	2018	9	NOx
401003	1999	2018	9	NOx
401201	2016	2018	9	NOx
401556	2000	2018	11	NOx
410004	1990	2018	9	NOx
410024	2016	2018	9	NOx
410033	2016	2018	9	NOx
410038	2016	2018	9	NOx
410073	2016	2018	9	NOx
416003	1990	2018	6	NOx
416008	1990	2018	8	NOx
416011	2016	2017	8	NOx
416032	1990	2017	9	NOx
418008	2016	2018	8	NOx
418014	2002	2017	9	NOx
419010	2016	2017	7	NOx
20110017	1994	2018	10	NOx
20410043	1994	2018	11	NOx
20510051	2009	2018	9	NOx
20710002	2009	2018	10	NOx
20910017	1999	2018	9	NOx
21010092	1999	2018	14	NOx
21810018	2012	2018	10	NOx
21910054	2016	2018	11	NOx
22010241	2015	2018	9	NOx
41010924	2000	2018	8	NOx
41610079	2016	2017	7	NOx
41810006	2016	2017	9	NOx
NSW Department of Industry – Lands and Water				
410198	2003	2005	10188	Wtemp

208033	2013	2016	21132	Wtemp
210133	1994	1998	11337	Wtemp
219026	1996	1999	2669	Wtemp
219410	2013	2013	7103	Wtemp
210131	1994	2003	3855	Wtemp
41000270	2012	2019	29356	Wtemp
215017	2005	2005	5768	Wtemp
215015	2002	2006	227	Wtemp
203450	2013	2019	33773	Wtemp
215217	2019	2019	18049	Wtemp
204460	2013	2013	8530	Wtemp
212407	2013	2014	19283	Wtemp
210088	2002	2007	2690	Wtemp
222028	2009	2019	28544	Wtemp
214007	2003	2005	81	Wtemp
210123	1989	2004	11130	Wtemp
210149	2013	2016	25215	Wtemp
215237B	2013	2016	19956	Wtemp
210132	1994	1994	302	Wtemp
204400	2013	2019	32299	Wtemp
210432	2013	2019	31499	Wtemp
20601027	2010	2019	20075	Wtemp
20601026	2010	2019	18014	Wtemp
20601025	2010	2019	7075	Wtemp
210448	2013	2019	32356	Wtemp
D21019013	2016	2019	78140	Wtemp
D21019996	2017	2019	77834	Wtemp
D21019999	2017	2019	75599	Wtemp
D21019111	2017	2019	88079	Wtemp
D21019990	2017	2019	82962	Wtemp
D21019081	2017	2019	31958	Wtemp
D21019009	2017	2019	83057	Wtemp
D21019006	2017	2019	24	Wtemp
D21019992	2018	2019	74832	Wtemp
D21019998	2017	2019	87352	Wtemp
D21019993	2016	2019	70886	Wtemp
D21019991	2017	2019	86774	Wtemp
D21019001	2017	2019	86045	Wtemp
D21010000	2015	2015	6655	Wtemp
21010057	1999	2000	6366	Wtemp
221010	2010	2010	5939	Wtemp
401013	2003	2019	19561	Wtemp
206460	2013	2013	20558	Wtemp
206402	2013	2019	32201	Wtemp
20801001	2010	2012	7112	Wtemp
208420	2013	2019	32457	Wtemp
401008	2000	2019	18918	Wtemp
401017	2000	2019	19803	Wtemp
401026	2004	2019	21433	Wtemp
401009	2000	2019	16879	Wtemp
220006	2010	2010	4173	Wtemp
214009	2003	2004	32	Wtemp
416004	2012	2016	8180	Wtemp
401549	2019	2019	12700	Wtemp
210455	2013	2019	32493	Wtemp
21101002	2008	2012	14781	Wtemp
416075	2012	2017	12702	Wtemp
416076	2012	2016	7913	Wtemp
416077	2012	2016	11106	Wtemp
416078	2012	2016	14127	Wtemp
416074	2015	2016	10312	Wtemp
416073	2012	2017	13808	Wtemp
21010061	1999	2000	5055	Wtemp
216003	1999	1999	5	Wtemp
210409	2013	2019	32335	Wtemp
210410	2013	2019	32529	Wtemp
210452	2013	2019	31835	Wtemp

203403	2013	2019	32128	Wtemp
203470	2013	2019	31518	Wtemp
204413	2009	2019	31746	Wtemp
21010063	1999	2000	6877	Wtemp
215430	2013	2019	32065	Wtemp
222021	2009	2019	28062	Wtemp
222501	1962	1966	4153	Wtemp
222023	1999	2019	14605	Wtemp
21101001	2008	2009	1638	Wtemp
208410	2013	2015	32560	Wtemp
416053	1995	2000	1029	Wtemp
21010055	1999	2000	6954	Wtemp
401014	2002	2019	21829	Wtemp
401014B	2013	2016	19415	Wtemp
401024	2004	2019	25748	Wtemp
401007	2000	2019	18226	Wtemp
41010891	2002	2018	16729	Wtemp
210125	1994	2016	12692	Wtemp
401016	2005	2019	21907	Wtemp
208400	2013	2019	31664	Wtemp
219026	1996	1999	2403	pH
215217	2019	2019	18049	pH
D21019013	2016	2019	83151	pH
D21019990	2017	2019	84529	pH
D21019081	2017	2019	81691	pH
D21019009	2017	2019	85996	pH
D21019006	2017	2019	90327	pH
D21019998	2017	2019	90997	pH
D21019993	2016	2019	70886	pH
D21019991	2017	2019	86774	pH
D21019001	2017	2019	86172	pH
401549	2019	2019	12700	pH
21010061	1999	2000	4720	pH
219026	1996	1999	1972	Turbidity
41000270	2012	2019	26331	Turbidity
215217	2019	2019	18049	Turbidity
D21019013	2017	2019	86167	Turbidity
D21019990	2017	2019	84531	Turbidity
D21019081	2017	2019	81693	Turbidity
D21019009	2017	2019	85974	Turbidity
D21019006	2017	2019	90329	Turbidity
D21019998	2017	2019	90997	Turbidity
D21019993	2016	2019	70886	Turbidity
D21019991	2017	2019	86776	Turbidity
D21019001	2017	2019	86170	Turbidity
401549	2019	2019	12578	Turbidity
21010061	1999	2000	2426	Turbidity

Table A7. Summary of data availability for streamflow within NSW RFA. All summary statistics are based on daily flow data extracted for individual monitoring sites owned by WaterNSW, NSW Department of Industry – Lands and Water and Snowy Hydro Limited.

Site	Number of years with >=350 days of records	Min. number of days monitored per year	Start year	End year
WaterNSW				
201001	58	177	1900	2019
201005	35	0	1900	2019
201012	36	205	1900	2019
201015	10	248	1900	2019
201900	35	0	1900	2019
201901	46	74	1900	2019
201902	9	59	1900	2019
203002	41	57	1900	2019
203004	47	252	1900	2019
203005	45	184	1900	2019
203010	50	197	1900	2019
203012	38	92	1900	2019
203014	58	131	1900	2019
203023	42	83	1900	2019
203024	18	0	1900	2019
203030	40	95	1900	2019
203034	17	123	1900	2019
203041	24	0	1900	2019
203056	8	65	1900	2019
203057	8	58	1900	2019
203059	0	75	1900	2019
203060	8	151	1900	2019
203061	7	151	1900	2019
203062	3	252	1900	2019
203900	24	0	1900	2019
204001	48	0	1900	2019
204002	49	167	1900	2019
204004	43	55	1900	2019
204006	8	0	1900	2018
204007	45	140	1900	2019
204008	39	0	1900	2019
204014	40	235	1900	2019
204015	42	219	1900	2019
204017	46	135	1900	2019
204025	43	61	1900	2019
204030	40	124	1900	2019
204031	33	252	1900	2019
204033	41	252	1900	2019
204034	46	137	1900	2019
204036	59	98	1900	2019
204037	46	252	1900	2019
204039	32	152	1900	2019
204041	49	166	1900	2019
204043	52	252	1900	2019
204046	46	177	1900	2019
204051	38	252	1900	2018
204055	35	0	1900	2019
204056	42	222	1900	2019
204067	36	252	1900	2019
204068	24	139	1900	2019
204069	21	105	1900	2019
204071	15	224	1900	2019
204072	19	135	1900	2019
204073	20	135	1900	2019
204900	36	0	1900	2019
204906	43	46	1900	2019
205002	34	234	1900	2019
205015	12	213	1900	2019
205016	12	153	1900	2019
205017	8	106	1900	2019
205018	7	169	1900	2018

205019	8	170	1900	2019
206001	38	212	1900	2019
206008	30	0	1900	2019
206009	62	217	1900	2019
206011	46	252	1900	2019
206014	60	191	1900	2019
206018	58	0	1900	2019
206024	42	187	1900	2018
206025	45	2	1900	2019
206026	42	103	1900	2019
206027	39	0	1900	2019
206032	23	59	1900	2019
206033	35	14	1900	2018
206034	34	252	1900	2019
206035	22	251	1900	2019
206037	21	44	1900	2019
206038	20	29	1900	2019
206039	21	252	1900	2019
207004	41	124	1900	2019
207006	38	0	1900	2019
207008	12	252	1900	2019
207009	17	0	1900	2019
207010	22	0	1900	2019
207013	41	131	1900	2019
207014	33	234	1900	2019
207015	35	214	1900	2019
207017	9	16	1900	2019
207018	8	169	1900	2019
208001	52	28	1900	2019
208003	64	198	1900	2019
208004	61	121	1900	2019
208005	61	184	1900	2019
208006	65	0	1900	2019
208007	64	169	1900	2019
208008	47	0	1900	2019
208009	56	160	1900	2019
208011	47	61	1900	2019
208015	47	190	1900	2019
208019	30	0	1900	2010
208020	16	252	1900	2019
208024	34	161	1900	2019
208026	33	241	1900	2019
208027	27	91	1900	2019
208028	15	115	1900	2019
208029	13	220	1900	2019
208031	9	119	1900	2019
208032	9	119	1900	2019
209002	47	13	1900	2019
209003	45	66	1900	2019
209006	48	252	1900	2019
209018	37	13	1900	2019
210001	107	252	1900	2019
210002	73	0	1900	2019
210004	85	0	1900	2019
210010	83	30	1900	2019
210011	80	252	1900	2019
210014	65	0	1900	2019
210015	74	34	1900	2019
210016	64	0	1900	2019
210017	63	43	1900	2019
210018	65	151	1900	2019
210021	59	0	1900	2019
210022	69	20	1900	2019
210028	43	0	1900	2019
210031	60	38	1900	2019
210039	19	86	1900	2019
210040	57	23	1900	2019

210044	63	252	1900	2019
210052	52	21	1900	2019
210055	43	0	1900	2019
210056	35	0	1900	2019
210064	51	27	1900	2019
210076	45	137	1900	2019
210079	59	0	1900	2019
210080	40	199	1900	2019
210083	50	107	1900	2019
210084	44	56	1900	2019
210089	20	0	1900	2019
210093	39	0	1900	2019
210110	15	213	1900	2019
210114	27	0	1900	2019
210118	15	245	1900	2019
210124	23	252	1900	2019
210126	15	30	1900	2017
210127	24	190	1900	2019
210128	24	158	1900	2019
210129	19	0	1900	2019
210130	16	65	1900	2019
210134	22	30	1900	2019
210135	21	45	1900	2019
210136	22	153	1900	2019
210137	22	107	1900	2019
210142	13	192	1900	2019
210143	13	214	1900	2019
210144	11	232	1900	2019
210147	9	147	1900	2019
210150	4	252	1900	2019
210151	4	85	1900	2019
210152	0	222	1900	2019
210153	0	222	1900	2019
210154	0	222	1900	2019
210903	22	248	1900	2019
211008	37	13	1900	2019
211009	40	6	1900	2019
211010	45	11	1900	2019
211013	39	49	1900	2019
211014	39	51	1900	2019
211015	16	70	1900	2019
211017	8	100	1900	2019
212009	21	67	1900	2018
212021	16	0	1900	2019
212271	28	0	1900	2018
212290	34	176	1900	2018
214010	17	229	1900	2019
215002	74	0	1900	2019
215004	75	115	1900	2019
215007	12	17	1900	2019
215008	41	0	1900	2019
215014	38	252	1900	2019
215016	14	181	1900	2017
215018	10	226	1900	2018
215019	4	213	1900	2017
215207	39	109	1900	2018
215208	41	55	1900	2019
215209	27	0	1900	2018
215210	28	0	1900	2017
215215	21	89	1900	2018
215216	25	22	1900	2019
215220	37	55	1900	2019
215223	2	212	1900	2016
215233	39	47	1900	2018
215234	31	228	1900	2018
215237	8	0	1900	2008
215238	20	112	1900	2018

215239	19	220	1900	2018
215241	16	101	1900	2017
215242	18	29	1900	2018
216002	49	176	1900	2019
216004	30	203	1900	2018
216009	33	252	1900	2019
217006	22	71	1900	2019
217007	8	252	1900	2019
218001	59	0	1900	2019
218005	54	188	1900	2018
218007	45	202	1900	2019
218008	41	252	1900	2019
219001	77	0	1900	2019
219003	76	252	1900	2019
219006	68	252	1900	2019
219013	43	0	1900	2019
219016	42	0	1900	2019
219017	53	177	1900	2019
219018	32	0	1900	2019
219022	47	31	1900	2019
219025	43	58	1900	2019
219032	22	252	1900	2019
219034	17	211	1900	2019
220003	53	122	1900	2019
220004	47	232	1900	2018
221002	46	31	1900	2019
222004	78	252	1900	2019
222007	70	239	1900	2019
222008	68	252	1900	2019
222013	43	202	1900	2019
222016	39	252	1900	2019
222017	38	122	1900	2019
222019	24	88	1900	2019
222026	22	210	1900	2019
410004	117	139	1890	2019
410006	47	252	1900	2019
410008	55	72	1900	2019
410024	100	103	1900	2019
410033	93	252	1900	2019
410038	49	153	1900	2019
410039	57	0	1900	2019
410050	65	0	1900	2019
410057	62	221	1900	2019
410058	23	0	1900	2019
410059	19	0	1900	2019
410061	72	111	1900	2019
410062	62	0	1900	2019
410073	56	0	1900	2019
410076	41	105	1900	2019
410081	46	0	1900	2019
410088	56	0	1900	2019
410097	32	104	1900	2019
410106	20	0	1900	2019
410107	35	47	1900	2018
410114	42	217	1900	2019
410141	37	225	1900	2019
410152	33	252	1900	2019
410176	20	190	1900	2019
410187	13	124	1900	2019
410199	7	252	1900	2019
410851	20	142	1900	2019
411003	33	159	1900	2017
416003	43	0	1900	2019
416008	43	105	1900	2019
416011	44	91	1900	2019
416022	39	252	1900	2019
416023	40	252	1900	2019

416032	47	174	1900	2019
418008	44	0	1900	2019
418014	45	0	1900	2019
418021	40	0	1900	2019
419045	47	223	1900	2019
419081	27	179	1900	2019
2122791	9	0	1900	2018
2122801	23	173	1900	2019
2152131	1	81	1900	2018
2152201	2	77	1900	2016
41000200	7	252	1900	2019
41000208	11	194	1900	2019
41000260	8	235	1900	2019
41000261	7	201	1900	2019
41000269	7	236	1900	2019
41000271	6	129	1900	2019
41000272	6	247	1900	2019
NSW Department of Industry – Lands and Water				
209014	44	98	1976	2019
209017	44	98	1976	2019
222522	63	245	1957	2019
222527	54	211	1966	2019
401008	48	129	1972	2019
401009	72	30	1948	2019
401013	47	54	1973	2019
401017	36	178	1984	2019
401501	64	92	1956	2019
401501	64	92	1956	2019
401549	36	92	1984	2019
Snowy Hydro Limited				
222522	63	245	1957	2019
222527	54	211	1966	2019
401560	56	70	1964	2019
410094	41	245	1979	2019
410514	42	245	1978	2019
410534	59	211	1961	2019
410535	59	243	1961	2019
410575	45	245	1975	2019
410576	36	153	1984	2019
600161	36	92	1984	2019
600162	36	92	1984	2019
600165	54	134	1966	2019
600166	54	134	1966	2019
600167	36	153	1984	2019
600168	53	211	1967	2019
600175	36	153	1984	2019
600176	36	153	1984	2019
600177	36	153	1984	2019
600178	36	153	1984	2019
600179	51	114	1969	2019
600577	35	31	1985	2019

Table A8. Summary of availability of water quality data owned by FCNSW.

Site	Syear	Eyear	Variables	Sampling program
BAGOG1	1995	2009	Turbidity	Bago - Tumut
BAGOG3	1995	2008	Turbidity	Bago - Tumut
BAGOG4	1999	2007	Turbidity	Bago - Tumut
BAGOG5	1999	2007	Turbidity	Bago - Tumut
BRMN01	1995	2014	Turbidity	Brooman
BRMN02	1995	2014	Turbidity	Brooman
BRMN03	1995	2014	Turbidity	Brooman
BRMN11	2008	2014	Turbidity	Brooman
BRMN12	2007	2014	Turbidity	Brooman
BRMN13	2007	2014	Turbidity	Brooman
BRMN14	2012	2014	Turbidity	Brooman
BRMN15	2007	2014	Turbidity	Brooman
CARB02	1996	1996	Turbidity	Carabost
CARBC1	1997	1998	Turbidity	Carabost
DMPR01	1995	1999	Turbidity	Dampier
DMPR02	1995	1999	Turbidity	Dampier
KNGRC1	2001	2009	Turbidity	Kangaroo River - Coffs Harbour
KNGRC2	2001	2009	Turbidity	Kangaroo River - Coffs Harbour
KNGRT1	2001	2009	Turbidity	Kangaroo River - Coffs Harbour
KNGRT2	2001	2009	Turbidity	Kangaroo River - Coffs Harbour
KNGRT3	2001	2008	Turbidity	Kangaroo River - Coffs Harbour
209010	2004	2010	Turbidity	Karuah hydrology research area - Dungog
209011	2004	2012	Turbidity	Karuah hydrology research area - Dungog
209012	2004	2010	Turbidity	Karuah hydrology research area - Dungog
209013	2004	2010	Turbidity	Karuah hydrology research area - Dungog
209014	2004	2011	Turbidity	Karuah hydrology research area - Dungog
209015	2004	2012	Turbidity	Karuah hydrology research area - Dungog
209016	2004	2010	Turbidity	Karuah hydrology research area - Dungog
209017	2004	2012	Turbidity	Karuah hydrology research area - Dungog
KNDL01	2003	2005	Turbidity	Kendall
KNDL02	2003	2004	Turbidity	Kendall
KNDL03	2003	2006	Turbidity	Kendall
KNDL04	2003	2005	Turbidity	Kendall
KNDL05	2003	2005	Turbidity	Kendall
MBRO01	1995	2003	Turbidity	Middle Brother
MBRO02	1995	2003	Turbidity	Middle Brother
410997	2010	2019	Turbidity	Red Hill hydrology research area - Tumut
410998	2010	2019	Turbidity	Red Hill hydrology research area - Tumut
410999	2010	2019	Turbidity	Red Hill hydrology research area - Tumut
221051	1999	2017	Turbidity	Yambulla hydrology research area – Eden
221052	1999	2012	Turbidity	Yambulla hydrology research area – Eden
221053	1999	2018	Turbidity	Yambulla hydrology research area – Eden
221054	1999	2017	Turbidity	Yambulla hydrology research area – Eden
221055	1999	2018	Turbidity	Yambulla hydrology research area – Eden
221056	1999	2017	Turbidity	Yambulla hydrology research area - Eden
BAGOG1	1998	2009	TSS	Bago - Tumut
BAGOG3	1998	2008	TSS	Bago - Tumut
BAGOG4	1999	2007	TSS	Bago - Tumut
BAGOG5	1999	2007	TSS	Bago - Tumut
BRMN01	2007	2014	TSS	Brooman
BRMN02	2007	2014	TSS	Brooman
BRMN03	2008	2014	TSS	Brooman
BRMN11	2008	2014	TSS	Brooman
BRMN12	2007	2014	TSS	Brooman
BRMN13	2007	2014	TSS	Brooman
BRMN14	2012	2014	TSS	Brooman
BRMN15	2007	2014	TSS	Brooman
KNGRC1	2001	2009	TSS	Kangaroo River - Coffs Harbour
KNGRC2	2001	2009	TSS	Kangaroo River - Coffs Harbour
KNGRT1	2001	2009	TSS	Kangaroo River - Coffs Harbour
KNGRT2	2001	2009	TSS	Kangaroo River - Coffs Harbour
KNGRT3	2001	2008	TSS	Kangaroo River - Coffs Harbour
209010	2004	2010	TSS	Karuah hydrology research area - Dungog
209011	2004	2012	TSS	Karuah hydrology research area - Dungog

209012	2004	2010	TSS	Karuah hydrology research area - Dungog
209013	2004	2010	TSS	Karuah hydrology research area - Dungog
209014	2004	2011	TSS	Karuah hydrology research area - Dungog
209015	2004	2012	TSS	Karuah hydrology research area - Dungog
209016	2004	2010	TSS	Karuah hydrology research area - Dungog
209017	2004	2012	TSS	Karuah hydrology research area - Dungog
KNDL01	2003	2005	TSS	Kendall
KNDL02	2003	2004	TSS	Kendall
KNDL03	2003	2006	TSS	Kendall
KNDL04	2003	2005	TSS	Kendall
KNDL05	2003	2005	TSS	Kendall
MBRO01	1998	2003	TSS	Middle Brother
MBRO02	1998	2003	TSS	Middle Brother
410997	2010	2019	TSS	Red Hill hydrology research area - Tumut
410998	2010	2019	TSS	Red Hill hydrology research area - Tumut
410999	2010	2019	TSS	Red Hill hydrology research area - Tumut
221051	1999	2017	TSS	Yambulla hydrology research area – Eden
221052	1999	2012	TSS	Yambulla hydrology research area – Eden
221053	1999	2018	TSS	Yambulla hydrology research area – Eden
221054	1999	2017	TSS	Yambulla hydrology research area – Eden
221055	1999	2018	TSS	Yambulla hydrology research area – Eden
221056	1999	2017	TSS	Yambulla hydrology research area - Eden
BAGOG1	1995	1997	EC	Bago – Tumut
BAGOG3	1995	1997	EC	Bago – Tumut
BRMN01	1995	1997	EC	Brooman
BRMN02	1995	1997	EC	Brooman
BRMN03	1995	1997	EC	Brooman
CARB02	1996	1996	EC	Carabost
CARBC1	1997	1998	EC	Carabost
DMPR01	1995	1999	EC	Dampier
DMPR02	1995	1999	EC	Dampier
MBRO01	1995	1998	EC	Middle Brother
MBRO02	1995	1998	EC	Middle Brother
BAGOG1	1995	1997	pH	Bago – Tumut
BAGOG3	1995	1997	pH	Bago – Tumut
BRMN01	1995	1997	pH	Brooman
BRMN02	1995	1997	pH	Brooman
BRMN03	1995	1997	pH	Brooman
CARB02	1996	1996	pH	Carabost
CARBC1	1997	1998	pH	Carabost
DMPR01	1995	1999	pH	Dampier
DMPR02	1995	1999	pH	Dampier
MBRO01	1995	1998	pH	Middle Brother
MBRO02	1995	1998	pH	Middle Brother
CARBC1	1995	1998	Temp	Carabost
DMPR02	1996	2000	Temp	Dampier

Table A9. Summary of availability of streamflow data owned by FCNSW.

Site	Syear	Eyear	Monitoring program
KNGRC1	2001	2010	Kangaroo River - Coffs Harbour
KNGRC2	2001	2010	Kangaroo River - Coffs Harbour
KNGRT1	2001	2010	Kangaroo River - Coffs Harbour
KNGRT2	2001	2010	Kangaroo River - Coffs Harbour
KNGRT3	2001	2010	Kangaroo River - Coffs Harbour
BAGOG1	1994	2009	Bago - Tumut
BAGOG3	1994	2009	Bago - Tumut
BAGOG4	1994	2009	Bago - Tumut
BAGOG5	1994	2009	Bago - Tumut
MBRO01	1994	2003	Middle Brother - Wauchope
MBRO02	1994	2003	Middle Brother - Wauchope
410997	1989	2019	Red Hill hydrology research area - Tumut
410998	1989	2019	Red Hill hydrology research area - Tumut
410999	1989	2019	Red Hill hydrology research area - Tumut
221051	1977	2010	Yambulla hydrology research area - Eden
221052	1977	2010	Yambulla hydrology research area - Eden
221053	1977	2010	Yambulla hydrology research area - Eden
221054	1977	2010	Yambulla hydrology research area - Eden
221055	1977	2010	Yambulla hydrology research area - Eden
221056	1977	2010	Yambulla hydrology research area - Eden
209010	1977	2019	Karuah hydrology research area - Dungog
209011	1975	2019	Karuah hydrology research area - Dungog
209012	1975	2019	Karuah hydrology research area - Dungog
209013	1975	2019	Karuah hydrology research area - Dungog
209014	1975	2019	Karuah hydrology research area - Dungog
209015	1975	2019	Karuah hydrology research area - Dungog
209016	1975	2019	Karuah hydrology research area - Dungog
209017	1975	2019	Karuah hydrology research area - Dungog

Table A10. FCNSW historical sites for which locations are only known as approximate. Identifying the accurate locations of these sites are in progress.

Site	Site
BRMN01	Old paired catchment studies @ Brooman
BRMN02	Old paired catchment studies @ Brooman
BRMN03	Old paired catchment studies @ Brooman
BRMN11	Unmapped drainage study @ Brooman
BRMN12	Unmapped drainage study @ Brooman
BRMN13	Unmapped drainage study @ Brooman
BRMN14	Unmapped drainage study @ Brooman
BRMN15	Unmapped drainage study @ Brooman
BRMN26	Unmapped drainage study @ Brooman
BRMN27	Unmapped drainage study @ Brooman
CARB02	Old paired catchment studies @ Carabost
CARBC1	Old paired catchment studies @ Carabost
CHLD01	Old paired catchment studies @ Chaelundi
CHLD02	Old paired catchment studies @ Chaelundi
DMPR01	Old paired catchment studies @ Dampier
DMPR02	Old paired catchment studies @ Dampier
KNDL01	Unmapped drainage study @ Kendall
KNDL02	Unmapped drainage study @ Kendall
KNDL03	Unmapped drainage study @ Kendall
KNDL04	Unmapped drainage study @ Kendall
KNDL05	Unmapped drainage study @ Kendall
KNDL06	Unmapped drainage study @ Kendall
KNDL07	Unmapped drainage study @ Kendall
KNDL08	Unmapped drainage study @ Kendall
KNDL09	Unmapped drainage study @ Kendall
KNDL10	Unmapped drainage study @ Kendall
KNDL11	Unmapped drainage study @ Kendall
KNDL12	Unmapped drainage study @ Kendall
MEBN01	Old paired catchment studies @ Mebbin
MEBN02	Old paired catchment studies @ Mebbin
OLDMB01	Data that Theiss had when they managed Hydstra database @ Middle Brother
OLDMB02	Data that Theiss had when they managed Hydstra database @ Middle Brother
ORAR01	Old paired catchment studies @ Orara East
ORAR02	Old paired catchment studies @ Orara East
RMUK01	Old paired catchment studies @ Riamukka
RMUK02	Old paired catchment studies @ Riamukka

Spatial coverage of water monitoring sites in each NSW RFA region

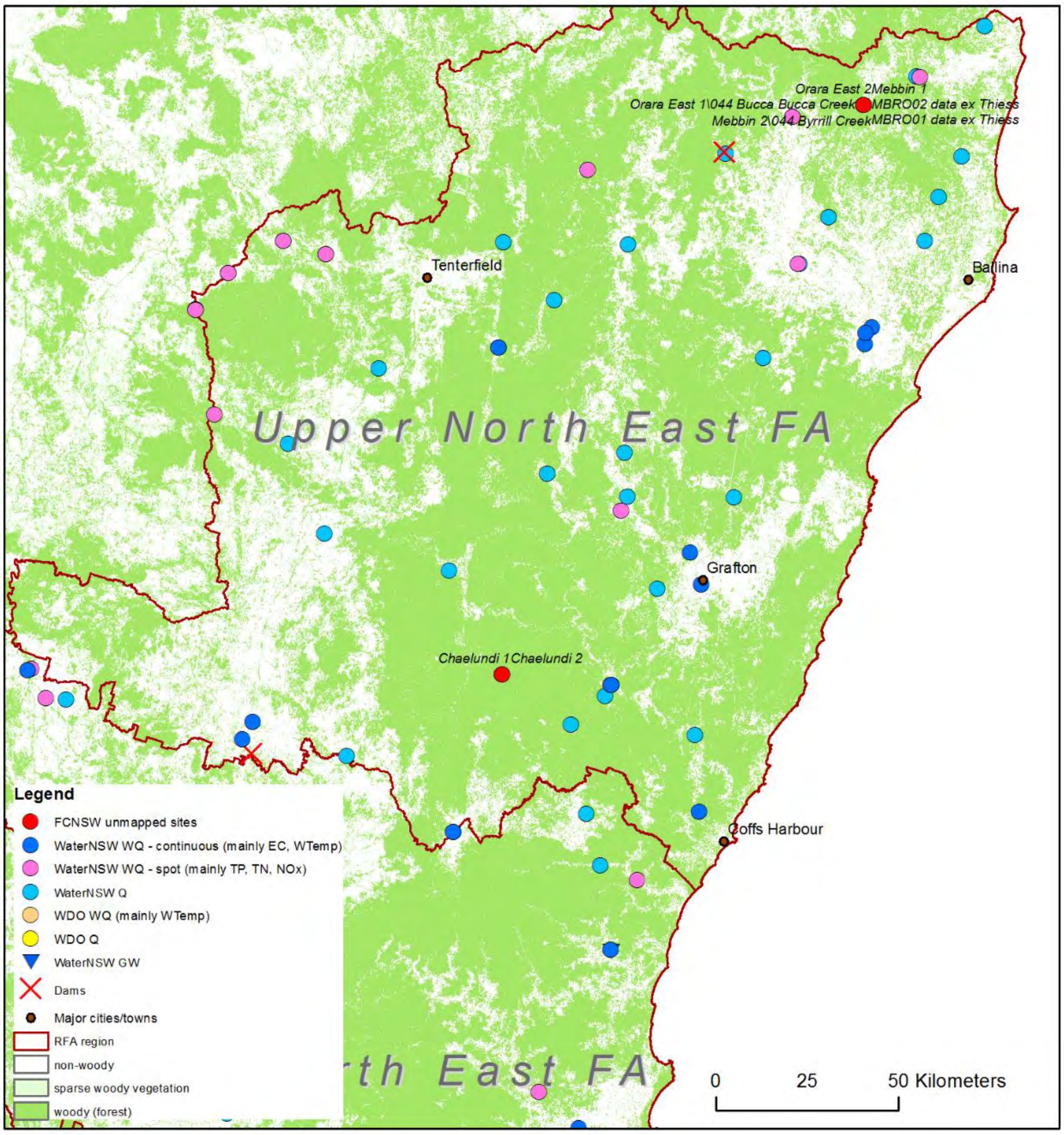

Figure A1. Water quality and quantity monitoring network the Upper North East FA. For water quality, only sites with 10 years of quarterly data are shown; for streamflow, only sites with 35 years of continuous data are shown. The approximate locations of the unmapped FCNSW sites are also shown – identifying the accurate locations of these sites are in progress.

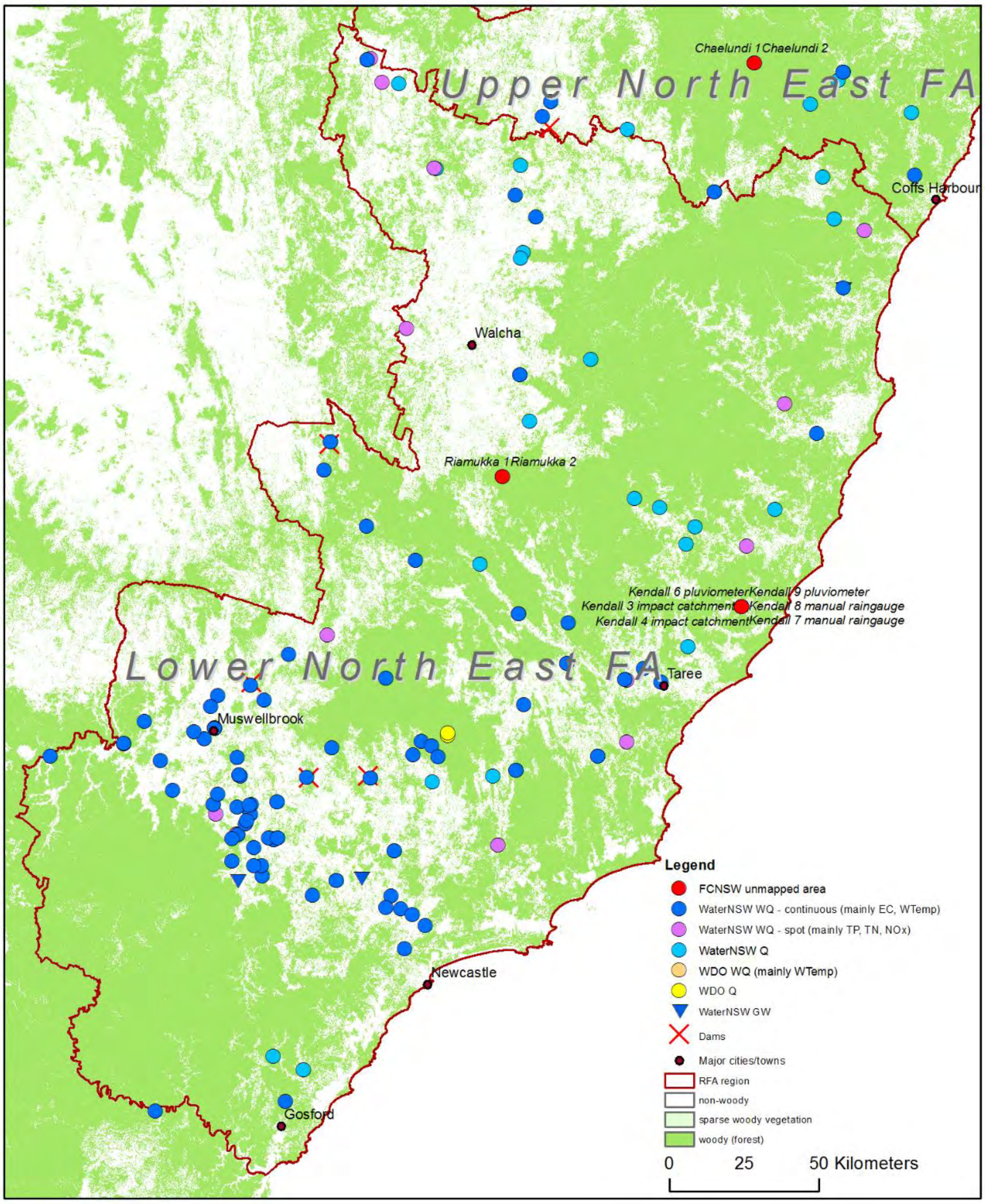

Figure A2. Water quality and quantity monitoring network the Lower North East FA. For water quality, only sites with 10 years of quarterly data are shown; for streamflow, only sites with 35 years of continuous data are shown. The approximate locations of the unmapped FCNSW sites are also shown – identifying the accurate locations of these sites are in progress.

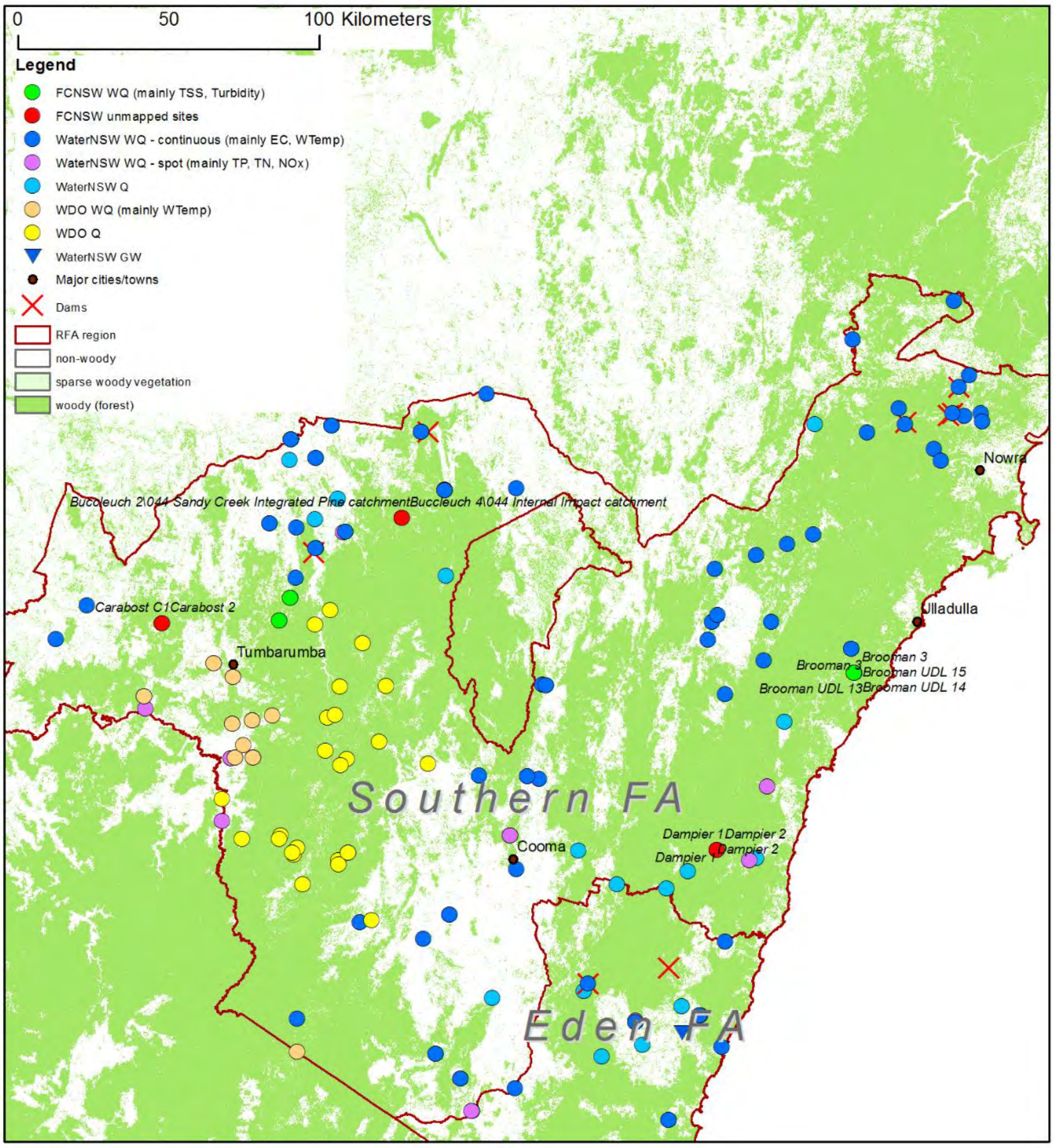

Figure A3. Water quality and quantity monitoring network the Southern FA. For water quality, only sites with 10 years of quarterly data are shown; for streamflow, only sites with 35 years of continuous data are shown. The approximate locations of the unmapped FCNSW sites are also shown – identifying the accurate locations of these sites are in progress.

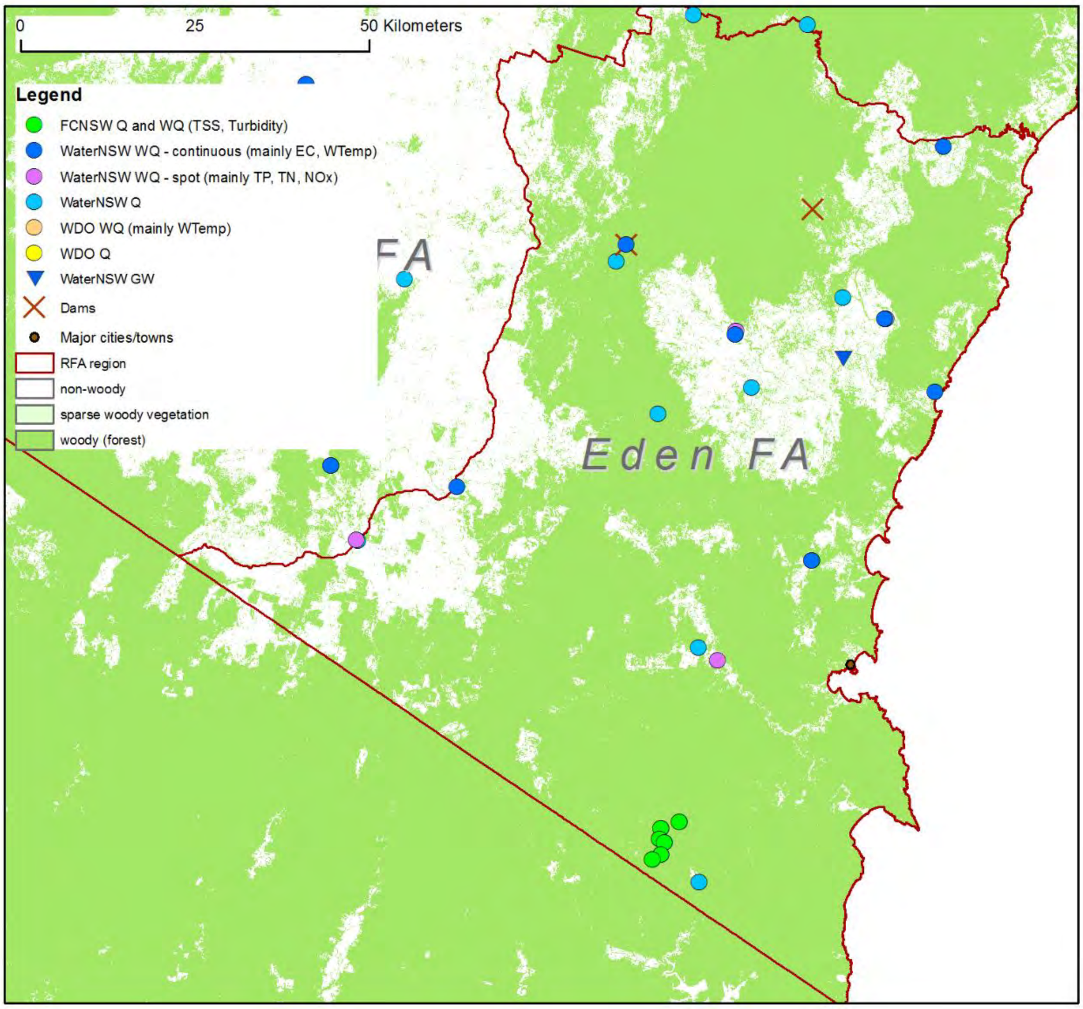

Figure A4. Water quality and quantity monitoring network the Eden FA. For water quality, only sites with 10 years of quarterly data are shown; for streamflow, only sites with 35 years of continuous data are shown.