FINAL REPORT:

Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests

January 2021

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Summary

This document is a review of monitoring and research approaches in peer-reviewed, scientific publications relating to impacts of forest operations on waterway health and water quality in NSW and other relevant jurisdictions. The review has the following specific objectives:

- conduct a desktop study to compile and evaluate peer-reviewed literature concerning forestry impacts on waterway health and water quality in active forestry areas, including the role of headwater stream buffers in maintaining waterway health,
- focus this review and advice primarily on NSW forests but also consider other jurisdictions if there is relevant or transferable information,
- advise on industry-accepted practices and cost-effective approaches to measure waterway impacts associated with forestry operations, to be used as a knowledge base for waterway and wetland health monitoring in Coastal IFOA state forests,
- advise on any other factors the commission should consider in the design and implementation of the Coastal IFOA waterway and wetland health monitoring plan.

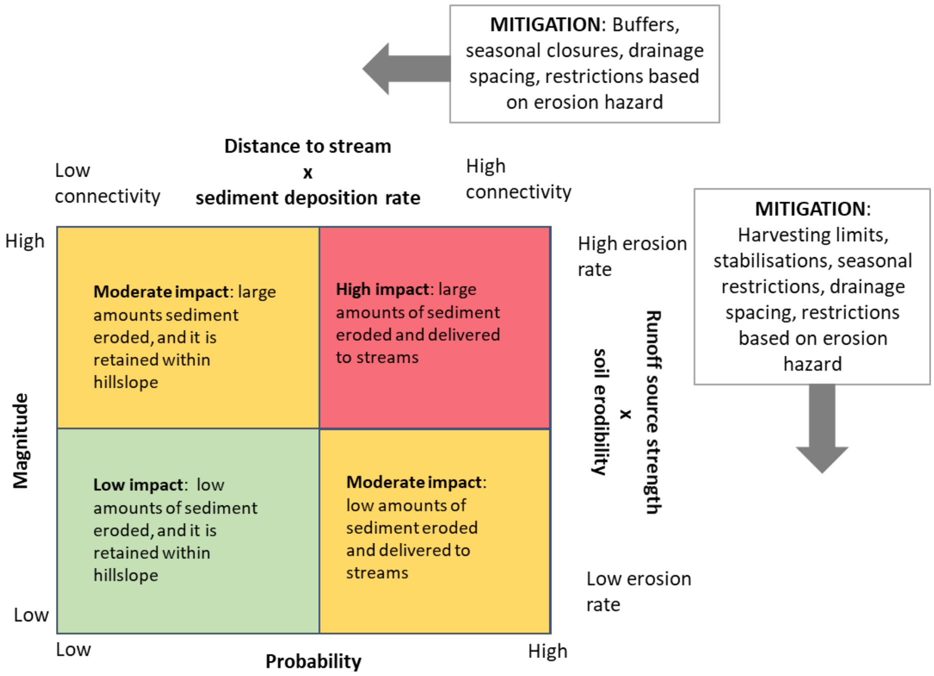
The review is designed to provide a robust and transparent evidence base on which to evaluate and guide monitoring of the impacts of forest harvesting operations on waterway health. The focus is on sediment delivery as the primary threat because that is where mitigation measures are focused and being considered in the monitoring program.

The review considers log dumps, snig tracks, temporary log crossings and the general harvest area as potential pollutant sources. The forest road network more broadly is considered in a separate project, in which a forest road monitoring methodology is being developed as part of the Forest Monitoring Improvement Program (FMIP).

There are two key components to understanding sediment hazard threat from timber harvesting areas:

- Runoff source strength and soil erodibility, which determine how easily soil is detached per unit runoff. Runoff source strength is a function of the surface area that is subject to increased runoff and the drainage structures on those surfaces. Soil erodibility is largely a function of geology.
- The distance that detached sediment needs to travel before reaching a stream and the rate at which that sediment is depositing between eroding surfaces and the stream network. Eroding surfaces and the stream network are either directly linked (road crossing) or indirectly linked (runoff pathways on a vegetated hillslope).

Together, these two components can be conceptualised into a sediment delivery hazard framework:



Process-based research on runoff and erosion processes on roads and forestry compartments have produced important insights into the dominant processes that govern the magnitude of sediment delivery to streams. The key findings from this research in NSW and Victoria (and in the US) point to:

- roads and tracks as the primary source of sediment delivery to streams,
- buffers between source areas and drainage lines as being critical to reducing impacts of forestry related activities on sediment delivery to streams,
- strong evidence that with best management practises the effect of harvesting activities on sediment delivery to streams can be effectively mitigated. However, with the limited number of research studies, and the diversity of geology, soils, vegetation, wildfire regimes, and the non-stationarity in drivers (rainfall), knowledge gaps remain with regard to outcomes in specific geographic settings,
- highly modified soil surfaces (snig tracks, log dumps) being the most dominant sediment sources in forestry compartments and a key focus area for mitigation,
- stream crossings as a challenging pollutant source in terms of mitigation solutions,
- the need to plan for changes in wildfire and rainfall regimes in the design of mitigation efforts

The current regime of forest management practices appears to reduce the impact of forestry operations on water quality, and when major runoff events occur the deterioration of water quality is typically transitory. However, with compounding effects of more extensive and severe wildfire and high-intensity rainfall events, the impacts of timber harvesting on water quality can be more profound and long-lived. The frequency of intense rainfall and bushfires are likely to increase into the future. This has implications for how forestry activities interact with catchment function. Monitoring programs into mitigation effectiveness must consider how these rainfall and wildfire processes, which may be non-stationary, may conflate the signal of harvesting activities. Major events such as those in the 2019/20 wildfire season are important data points that capture some of the regional disturbance processes that are operating alongside timber harvesting as controls on sediment delivery and transport through waterways. Experimental catchments have provided some insights on the combined effects of forest management and wildfire. However, a strategic approach of opportunistically measuring catchment response in areas where harvesting and wildfire intersect is needed to build a better understanding of how current forest management can be adjusted to better address emerging risk associated with new catchment disturbance regimes.

Water quality monitoring studies provide valuable and irreplaceable baseline data to understand the net effects of forest management activities on catchment responses. Because of the large investment needed to commission and maintain these types of studies, it is critical that the monitoring is carried out with clear objectives and strategies for adding value beyond the detection of site-specific responses. Catchment-scale monitoring should therefore be embedded within a broader strategy to develop predictive models and expand understanding past the “black box” outcome resulting from quantifying the catchment exports alone. Opportunities to collect data for improved insights on mitigation effectiveness and model development include sediment tracing and source attribution at multiple scales, hillslope experiments for understanding connectivity and sediment delivery processes, and repeat LiDAR to map changes in channel networks that may arise from channel incision caused by large peak flows from disturbed forest soils.

Recommendations for developing a cost-effective monitoring program are:

1. Refine the objectives of the monitoring program to provide a stronger link between what is being monitored and its relevance for values that are beingmanaged.
2. Develop a risk framework for linking timber harvesting (and the forest road network more broadly) to hydrologic and ecological impacts on waterways and wetlands. This is a starting point for refining the monitoring questions and developing a program for data collection and model development that focuses on the processes that are most problematic in terms of risk to waterway values.
3. Define and justify monitoring parameters based on risk to waterway and wetland values.
4. Embed water quality monitoring programs within a broader set of experimental work, aimed at linking both sediment delivery processes and mitigation measures to catchment-scale responses and waterway impacts.
5. Deliver research projects to address key knowledge gaps:
    - The roles of sediment composition and nutrient bioavailability are poorly quantified in terms of the effectiveness of mitigation measures. Much of the work to date on mitigation effectiveness, both at catchment and hillslopes scales, has examined sediment delivery processes without much regard for grain-size distribution or nutrients.
    - Impacts of temporary log crossings have not yet been addressed by the research in this review. There is a need to evaluate how temporary log crossings compare to conventional crossings in order to evaluate if they are an effective measure to limit sediment delivery into streams.
    - Timber harvesting in context of changing wildfire regimes. There is a need for a monitoring regime that quantifies the past and future frequency and severity of wildfires for harvest areas and combines this with monitoring the recovery from the wildfires in terms of water quality. This may trigger a mining of the historical records to assemble database on which to base summary relationships and related predictions.
    - Impacts of timber harvesting activities on wetlands. Wetlands are often located in low energy settings and the residence times of sediments and other pollutants can be much longer than in streams and rivers. There is a need for more research to understand how timber harvesting interact in the short- and long-term with the ecological, hydrological and biophysical processes in wetlands.
    - Scaling of impacts from steep upland waterways to larger river and estuaries. There is a need to develop a conceptual model to frame timber harvesting impacts on water quality and waterway health in the context of broader hydrological and geomorphic processes that govern the fluxes of sediment, nutrients and other constituents.
6. Frame a model, based on the concept of connectivity, that can be developed over time into a predictive tool for assessing impacts and optimising timber harvesting operations for waterway outcomes.

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Abbreviations

Alluvium	Alluvium Consulting Australia Pty Ltd
BMPs	Best management practices
Coastal IFOA	Coastal Integrated Forestry Operations Approval
the Commission	Natural Resources Commission
FCNSW	Forestry Corporation of NSW
FMA	Forest Management Area
GHA	General Harvest Area
NSW	New South Wales
the Program	Coastal Integrated Forestry Operations Approval Proposed Monitoring Program 2019-2024
the Strategy	Waterway and Wetland Health Monitoring Strategy

1 Introduction and project context

The Coastal Integrated Forestry Operations Approval (Coastal IFOA) sets out rules for native timber harvesting in NSW coastal state forests and establishes environmental outcomes that must be achieved. The overall objective of the Coastal IFOA is to authorise forestry operations:

- in accordance with the principles of ecologically sustainable forest management (ESFM)
- in a manner which integrates the regulatory regimes for:
    - environmental planning and assessment
    - the protection of the environment
    - threatened species conservation and biodiversity
- in accordance with the conditions and protocols of the approval, as applicable.

A condition of the Coastal IFOA (Figure 1) requires that a monitoring program be applied at multiple landscape scales to ensure the ongoing effectiveness of the approval in achieving ESFM. The NSW Natural Resources Commission (the Commission) has led the development of the state-wide monitoring program (the Program)[1] that centres on nine monitoring strategies (Figure 1).

One of these strategies is for waterway and wetland health monitoring (the Strategy). To mitigate against impacts on both waterways and wetlands, the Coastal IFOA establishes exclusion zones that are designed to act as hydrological buffers. The desired outcome is to minimise the transport of sediments (and other pollutants) between areas impacted by forestry operations and waterways/wetlands.

The Program sets the following specific monitoring questions for the Strategy, two of which focus on the effectiveness of the exclusion zones:

1. To what extent are the soil and water conditions effective in minimising the impact of harvesting and roading on waterway condition?
2. Are the exclusion zone conditions for class 1 classified drainage lines effective in minimising the impact on waterway condition?
3. Are the exclusion zone conditions effective in reducing the impact of forestry operations on on areas identified on the State Environmental Planning Policy (Coastal Management) 2018 Coastal Wetlands and Littoral Rainforests Area Map.

In addition to these listed questions, there is a question around temporary log crossings and the effectiveness of their design for mitigating water quality impacts.

To effectively address these monitoring questions there is a need to consolidate the existing body of empirical research on forestry operations, water quality and waterway health in NSW, other jurisdictions in Australia, and internationally. This existing research provides important baseline information on processes, mitigation effectiveness and catchment-scale impacts (e.g. from paired catchment studies) under different forest management regimes. The research is critical for understanding dominant processes, and thereby helps focus efforts to monitor and evaluate impacts.

The aim of this project is to deliver a literature review, including an analysis of monitoring or research approaches in peer-reviewed, scientific publications relating to forestry impacts on waterway health and water quality in active forestry areas in NSW or other relevant jurisdictions.

[1] Natural Resources Commission (2019) Coastal Integrated Forestry Operations Approval Proposed Monitoring Program 2019-2024. prepared by the Natural Resources Commission on behalf of the NSW Forest Monitoring and Improvement Steering Committee.

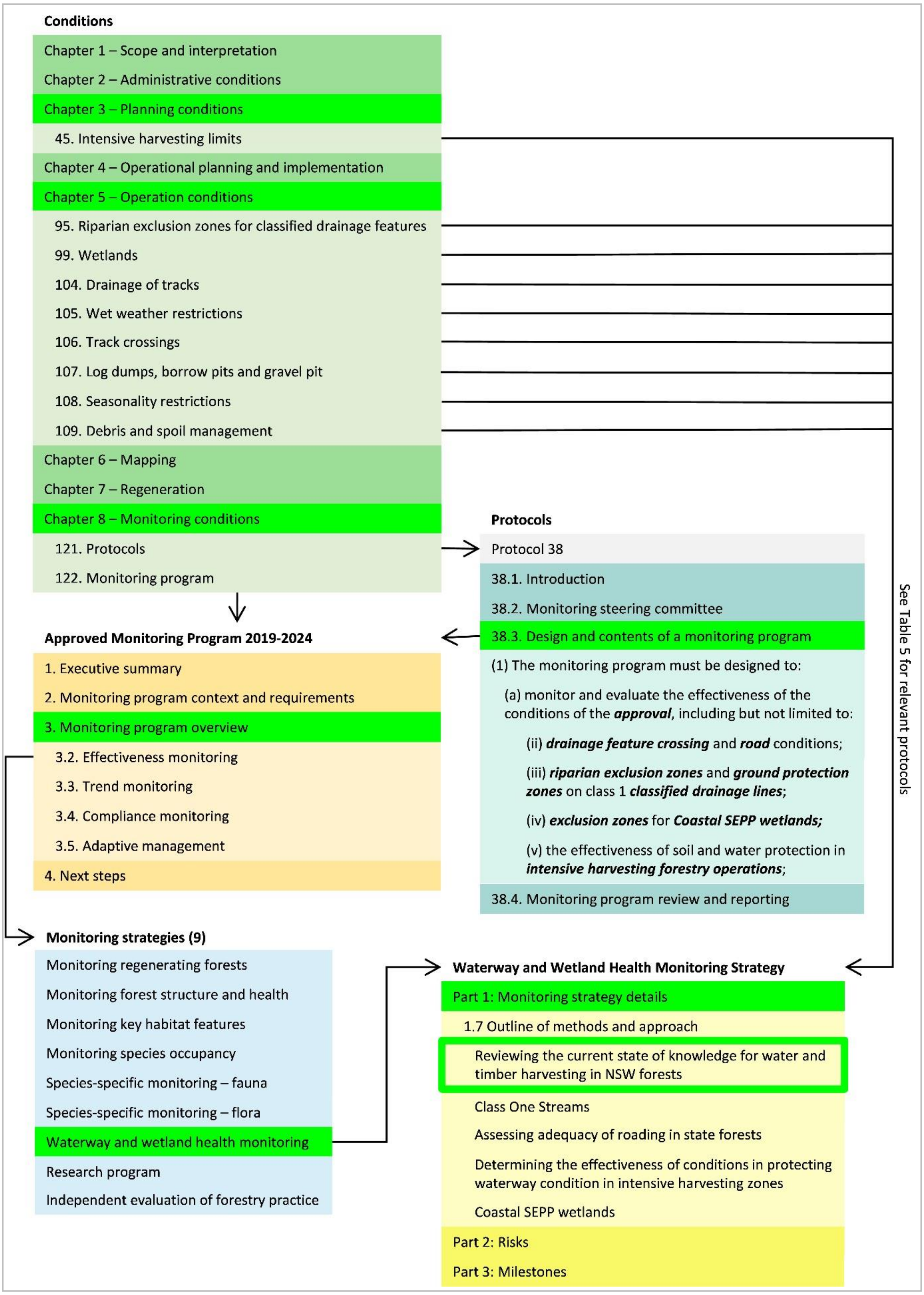

Figure 1. *Project context in relation to the conditions, protocols, monitoring program, and monitoring strategies of the Coastal IFOA.*

2 Literature review: objectives and questions

The review will provide a robust and transparent evidence base on which to evaluate and guide monitoring of the impacts of forestry operations on waterway health. The review has the following specific objectives:

- conduct a desktop study to compile and evaluate peer-reviewed literature concerning forestry impacts on waterway health and water quality in active forestry areas, including the role of headwater stream buffers in maintaining waterway health
- focus this review and advice primarily on NSW forests but also consider other jurisdictions if there is relevant or transferable information
- advise on industry-accepted practices and cost-effective approaches to measure waterway impacts associated with forestry operations, to be used as a knowledge base for waterway and wetland health monitoring in Coastal IFOA state forests
- advise on any other factors the commission should consider in the design and implementation of the Coastal IFOA waterway and wetland health monitoring plan.

The review is focused on forestry operations related to the general harvesting area, log dumps, and snig tracks in the Coastal IFOA regions (Figure 2), and is guided by six review questions specified in the Strategy (Table 1).

Roads are often identified to be the most significant sediment source in logged catchments (Lacey, 1993; Motha et al., 2003; Croke, 2004; Croke and Hairsine, 2006). In this review, we only consider part of the road network that is used for accessing the timber during harvesting operations (i.e. snig tracks and temporary roads for accessing the log landing) and not those that are part of the broader forest road network, and that are used for timber haulage and other purposes such as recreation, fire-fighting, fuel management.

The forest road network more broadly is considered in a separate project led by the Commission and delivered by Alluvium[2].

Table 1. Review questions.

Subject	Review question
Dominant processes contributing to impacts on water quality	1. What are the major sources of pollutants, including sediments, to streams draining from NSW coastal state forests?
Hydroclimatic and biophysical factors that interact with operations	2. What is the significance of major catchment events for the control or mitigation of these pollutant sources? 2.1. What is the significance of wildfires for the control or mitigation of pollutant sources? 2.2. What is the significance of thunderstorms and east coast lows for the control or mitigation of pollutant sources?
Effectiveness of mitigation measures	3. How do existing pollution mitigation measures (i.e. Coastal IFOA conditions and associated protocols) address each of these pollution sources? 4. Given the relative sources of pollution within NSW state forests and the other forms of pollution mitigation measures, are the use of buffers of class one streams effective for pollution control purposes? (Noting these buffers also provide ecological functions in a harvested landscape) 5. Where wetlands exist within NSW forests, what pollution mitigation measures are warranted?
Benefits and design of water quality monitoring projects	6. Given the responses to the above questions, what is the relative merit to continue or reinstate the Middle Brother, Yambulla, Kangaroo River and Karuah water quality monitoring projects?

[2] Alluvium (in progress) Evaluation of Forest Road Network Design and Management to Protect Water Quality. Project with the Natural Resources Commission,

Our review focuses primarily on sediment as a threat to waterway health because that is the primary focus of the mitigation measures being considered in the monitoring program. Sediment delivery to streams impacts waterways directly through increasing turbidity, smothering coarse stream bed gravels, and changing aquatic habitats (Kaller and Hartman, 2004; Kemp et al., 2011; Jones et al., 2012). Research also indicates that much of the water quality impacts associated with forest disturbance, including total phosphorus and total nitrogen solutes, are strongly linked to surface runoff and sediment transport (Croke et al., 2000; Lane et al., 2006a; Kreutzweiser et al., 2008; Smith et al., 2012). Soil erosion and sediment delivery into streams therefore represent the dominant processes leading to forestry-related impacts on water quality. Importantly, we note here that sediment (and nutrient) fluxes in forested landscapes is part of a natural process, and it is only when the rate is elevated above background levels that sediment can be considered a "pollutant" associated with detrimental impacts.

There are additional waterway health parameters that may be impacted by forestry but which we have not considered in this review, largely due to the paucity of data on these processes and their relation to mitigation measures. These additional parameters include changes to coarse woody debris in waterways (Tinker and Knight, 2000), benthic coarse particulate organic matter (CPOM) in streams (Smolders et al., 2018), stream temperatures (Kibler et al., 2013), and long-term water yield (Lane et al., 2010).

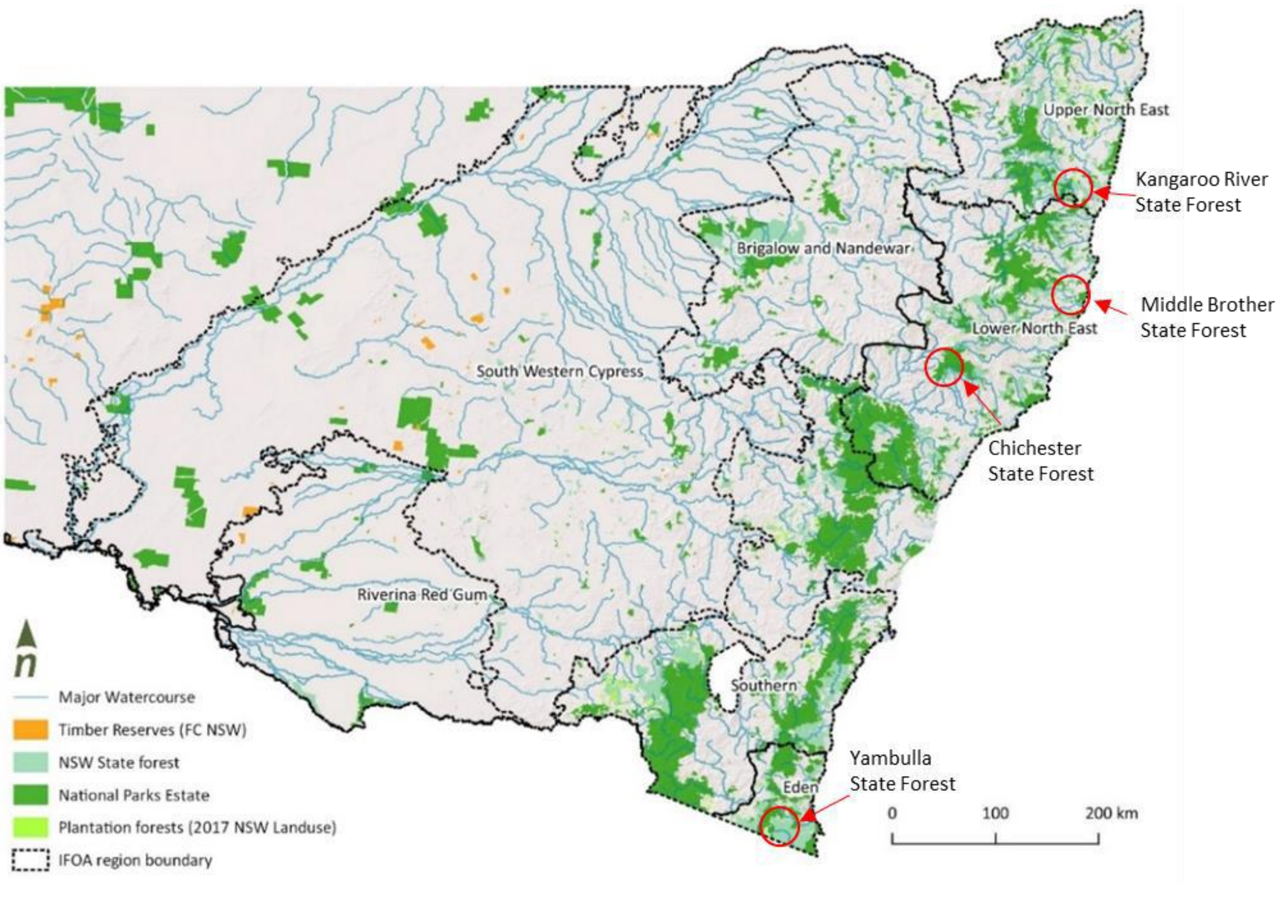

Figure 2. *Map showing locations of state forests within the Coastal IFOA regions of NSW and the sites of four water quality monitoring projects that are assessed in Question 6 of the review.*

3 Key processes and concepts

3.1 Forests and water

Forested catchments support healthy waterways by delivering high-quality water that contains low sediment and nutrient concentrations (see review by Neary et al., 2009). There are several forest attributes that help support healthy waterways:

- Dense vegetation cover in forests means that soils are protected from the erosive forces of rainfall and surface runoff (Robichaud et al., 2010).
- High soil organic matter, bioturbation and root networks promote high infiltration rates, which means that surface runoff (from overland flow) in forests is relatively rare when compared to cleared catchments (Luxmoore et al., 1990).
- Tree roots stabilise soils, reducing the frequency of mass failures, when compared to landscapes that have been cleared (Schwarz et al., 2010).
- Deep and stable soil profiles mean that hillslopes on forests often have high water holding capacity, which is important in regulating flow regimes (Davis et al., 1999).
- Nutrient cycling by forests means that nutrient losses to waterways are lower when compared to non-forested land (Attiwill, 1980; Lintern et al., 2018).

As a result of these attributes, most rainfall in forests moves relatively slowly to streams by subsurface flow pathways where nutrient uptake, cycling, and contaminant sorption processes are rapid. Disturbance of forested catchments (e.g. wildfires, forestry operations, roads, disease) can result in changes to these processes, resulting in changes in peak flows, sediment loads, and nutrient loads being delivered to streams (Smith et al., 2012; Webb et al., 2012a; Walsh et al., 2020). This can in turn can have impacts on water quality and waterway health. The pollutants most often associated with forestry operations are shown in Table 2.

Table 2. Pollutants most commonly associated with forestry operations and some key impacts on water quality and waterway health.

Pollutant	References	Physiochemical effects	Associated ecological impacts
Fine sediment	(Kaller and Hartman, 2004) (Jones et al., 2012)(Kemp et al., 2011)	Increases suspended sediment load, and therefore turbidity and light attenuation.	Reduced photosynthesis, leading to reduced productivity at all trophic levels. Invertebrates in particular are also susceptible to direct impacts of suspended sediment, such as abrasion and clogging.
		Increases sedimentation (deposition) which smothers and alters the substrate, including altered bed stability, reduced oxygen supply and other physiochemical changes.	Alters benthic habitat and reduces the abundance and diversity of animals and plants. Some invertebrates are also susceptible to direct burial.
Coarse sediment	(Kemp et al., 2011)	Inputs of coarse sediment in high flow events can modify local hydraulic patterns, resulting in greater scour and fill.	Greater scour and fill can affect, for example, spawning sites; deeply burying or scouring eggs during the incubation period, resulting in increased mortality.
Nutrients	(Dodds, 2007)	Excessive nutrient enrichment can result in eutrophication, which can be a concern when excessive algal biomass develops.	Eutrophication can have detrimental effects on the food web and ecosystem function.

3.2 Forestry operations and their impacts on erosion and sediment delivery

This review considers four operational units within the forestry compartment that can impact on catchment processes (Table 3). These units (snig tracks and the road into the log landing, log landings, general harvest areas and temporary log crossings) are defined based on their role in supporting timber harvesting. However, because of their distinctiveness in both spatial arrangement and hydrological impacts, they also provide a meaningful basis for discriminating sources of water quality impacts and for understanding where and how mitigation measures might be best implemented and designed. The different components of timber harvesting operations are also commonly treated as distinct sources in research on timber harvesting and sediment transport.

Table 3. Sources focused on in this review defend according to forestry operational units. The forest road network beyond the forestry compartment, and its role in sediment delivery to streams, is considered separately as part of the development of a state-wide forest road network monitoring program[3].

Source	Alternative terms	Definition
General harvest area (GHA)	General logging area	Areas of land subject to active harvesting operations or forest products operations.
Snig track and road into the log landing	Skid track/ trail Log access/ extraction trail	A track along which 'snigging' occurs; snigging is the practice of hauling or dragging a log to a log dump, landing or stockpile using a skidder (or similar machine).
Log landings	Log dumps	Areas where timber and other forest products are collected for processing and sorting prior to loading onto a truck.
Temporary log crossings	-	A type of temporary track crossing (i.e. a crossing structure that is removed at the completion of harvesting operations), located in 1st or 2nd order drainage lines, where logs are temporarily placed in a drainage feature to enable the short-term passage of machines or vehicles.

By removing vegetation and by compacting the soil surface, forestry operations inevitably result in increased hillslope erosion rates in some areas when compared to undisturbed forests. When compared to forestry operations in tectonically active regions such as Japan and the Western USA (Swanson and Dyrness, 1975; Imaizumi et al., 2008), the incidence of management-induced mass failure as a sediment delivery mechanism is relatively rare in eastern Australia (Sidle and Ochiai, 2006). Higher erosion rates stemming from forestry are instead typically linked to two key factors:

- An increase in the erosive forces (surface runoff) that cause soil detachment and sediment transport across source areas on the hillslopes. Runoff rates on disturbed forests soil (e.g. snig racks and log landings) are typically higher than on undistributed forest soils and therefore the shear stress acting on the soil is higher, causing more detachment of soil particles. Higher runoff rates stem from the following impacts on vegetation and soil:
    - Soil compaction on log landing and snig tracks, which reduces soil porosity and infiltration capacity (Lacey, 1994; Rab, 1994; Croke et al., 1999a)
    - Reduced vegetation and surface cover, which means less interception, depression storage and surface roughness (Wilson, 1999; Croke et al., 1999b)
    - Increased flow concentration due to the development of rills and gullies where roads discharge onto hillslopes (Croke and Mockler, 2001).
- An increase in the soil detachment in source areas, which stems from these impacts:
    - When vegetation is removed and surface cover is low, the soils tend to erode faster for any given amount of flow or shear stress that it is being exposed to (Wilson, 1999; Wagenbrenner et al., 2010)
    - Soils that are disturbed and shifted as part of timber harvesting operations and track establishment lack cohesion and can be unstable and easily eroded (Lacey, 1993; Lane and Sheridan, 2002; Sheridan et al., 2008).
    - Post-harvesting vegetation can recover into a state that provides less stability than the original vegetation cover (Williamson and Neilsen, 2003).

An increase in erosion rate does not translate directly to increased delivery of sediment to streams (Croke and Hairsine, 2006). For example, erosion from a snig track can divert sediment onto the general harvest areas

[3] Alluvium (2020) Evaluating forest road networks to protect water quality in NSW. Report for the Natural Resources Commission. pp. 1-45. November 2020.

where all of it might deposit and become entrained into the soil profile. In this case the sediment is redistributed entirely on the hillslope with limited or minimal impacts on sediment delivery to streams. In another contrasting case where a snig track crosses a drainage line (e.g. temporary log crossing), the erosion occurring on the track may be transported directly to the stream resulting in sediment delivery that is directly attributed to timber harvesting operations. The different outcomes in these two examples can be described in terms of connectivity (Croke and Hairsine, 2006). If there is low connectivity between eroding source areas and the stream network, the change in sediment delivery to streams that can be attributed to timber harvesting is also low.

3.3 The rationale underlying the Coastal IFOA conditions

To understand sediment delivery hazard that can be attributed to timber harvesting activities, and the opportunities for mitigation, it is useful to consider sediment delivery processes in the context of potential sources and the connectivity of those sources with the stream network. We need to understand:

- Runoff source strength and soil erodibility, which determine how easily soil is detached per unit runoff. Runoff source strength is a function of the surface area that is subject to increased runoff and the drainage structures on those surfaces. Soil erodibility is largely a function of geology. Sand-dominated soils tend to be more erodible than clay-dominated soils (Murphy et al., 1998).
- The distance that detached sediment needs to travel before reaching a stream and the rate at which that sediment is depositing between eroding surfaces and the stream network. Eroding surfaces and the stream network are either directly linked (road crossing) or indirectly linked (runoff pathways on a vegetated hillslope). For a given flow event coarse grained sediment eroded from sand-dominated soils deposit at a faster rate than fine sediment originating from clay-dominated soils (Murphy et al., 1998).

Together, these two components can be conceptualised into a framework for evaluating the impact of timber harvesting on sediment delivery (Figure 3). Erosion on disturbed source areas describes the magnitude of potential impact from timber harvesting, and the connectivity between source areas and the waterways describes the probability that potential impacts are realised through sediment delivery events. The way the impact translates into risk for waterway health depends on the ecological values that are being considered, and the sediment size fraction that is likely to be most problematic for that specific ecological value. It has been shown that sediment delivery to streams can be mitigated with carefully designed protocols, designed to reduce the intensity with which erosion processes are operating in source areas and the probability that those processes are coupled with the stream network (see review by Anderson and Lockaby, 2011).

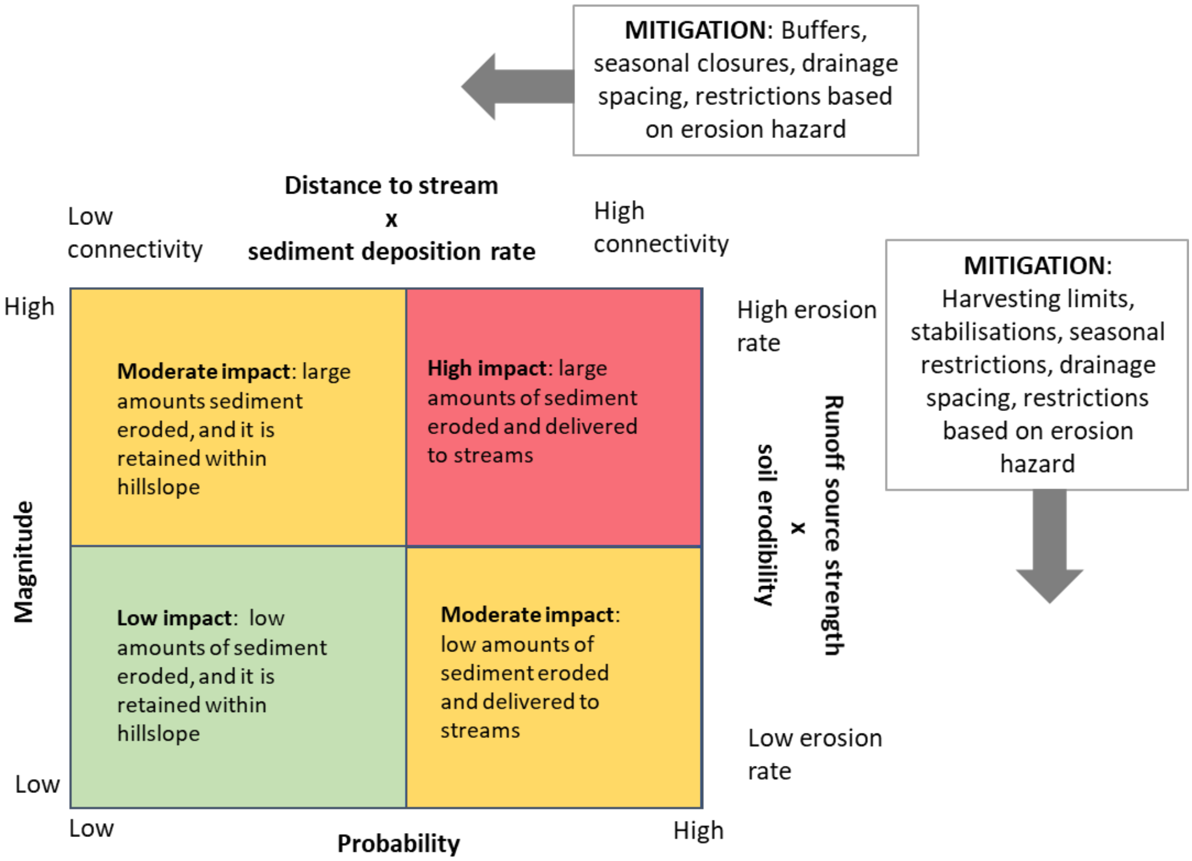

Figure 3. *Hazard framework for sediment delivery illustrating how mitigation measures contribute to reduced likelihood and consequence of sediment delivery events from timber harvesting. Adapted from Croke and Hairsine, (2006).*

3.4 Review question 1: What are the major sources of pollutants, including sediments, to streams draining from NSW coastal state forests?

A number of studies have identified and assessed general harvest areas, snig tracks and log landings as pollutant sources (Table 4). These studies have employed a range of methods including rainfall simulation, tracer budgets, and water, sediment and soil sampling. The road network more generally, outside of the forestry compartment itself, can be an important source of sediment (Grayson et al., 1993; Motha et al., 2003; Croke and Hairsine, 2006). This pollutant source is considered specifically in a separate project in the Forest Monitoring Improvement Program (FMIP).

In terms of the overall contribution of pollutants to streams from forestry compartments, there are three key aspects to consider:

- The area occupied by the defined pollutant source (general harvest areas, skid trails, log landings, and temporary log crossings)
- The runoff and erosion rates per unit area in those sources
- The degree of connectivity between the source and the stream network.

Hydrological studies that examine these sediment sources typically investigate the runoff and erosion processes occurring within and between each source and, together with estimates of connectivity, determine the contribution of different sources to the sediment delivered to streams (e.g. Figure 4). Studies that use sediment tracing to understand source contribution apply strategic sampling across space and time to map losses and gains in sediment and thereby provide the data needed to develop sediment budgets. In the following sub-sections, we summarise some of the findings on major pollutant sources from such hydrological and geomorphic studies. We focus primarily on work that has been carried out in temperate forests of eastern Australia.

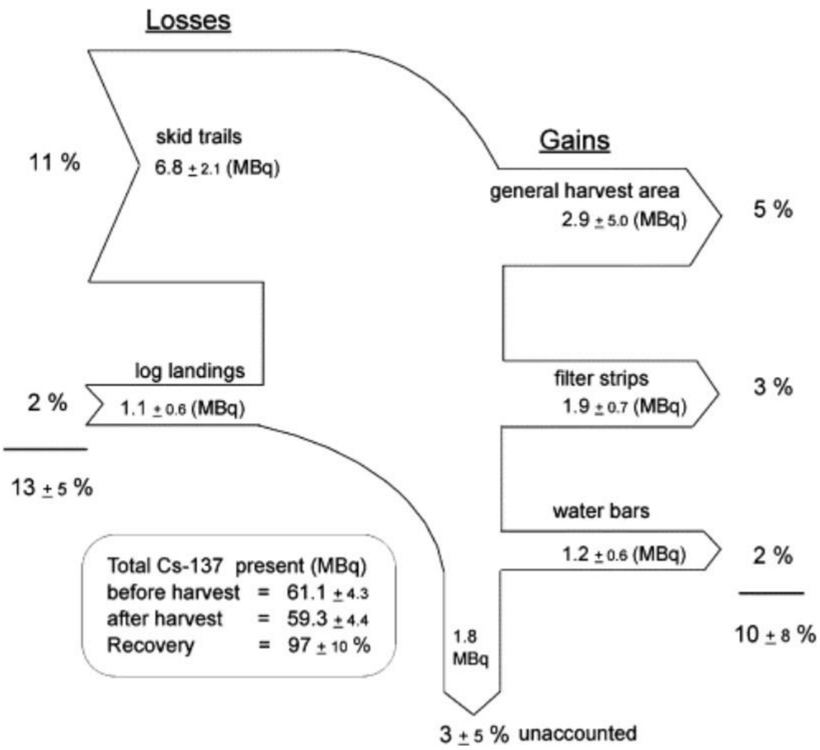

Figure 4. *One example of a sediment budget that considers different sediment source areas within a forestry compartment. This budget was constructed based on fallout radionuclides and not direct measurement. Taken from Wallbrink and Croke (2002)*

Snig tracks

Studies undertaken in southern forests of the Coastal IFOA region indicate that snig tracks, as compacted surfaces, are a major and often the predominant sediment source from forestry operations (Croke et al., 1999a, 2000; Wallbrink and Croke, 2002; Wallbrink et al., 2002). The importance of snig tracks as a pollutant source stems from the highly altered soil and runoff conditions (Lacey, 1994; Croke et al., 1999a). Studies consistently show that high bulk densities of surface soil on snig tracks result in low infiltration rates (low saturated hydraulic conductivity) that persist for several years after the initial disturbance. This in turn leads to higher runoff rates, high stream power, and high rates of soil detachment and sediment transport. Sediment flux from snig tracks has been found to be proportional to stream power (Croke et al., 1999b). Wallbrink and Croke (2002) found that the most dramatic increases in soil transport occur in the first year or two following initial disturbance.

The higher runoff rates from snig tracks, relative to the general harvest area, can persist for at least 5 years following disturbance (Croke et al., 1999a). Sediment detachment, however, decreases as vegetation establishes on the track (Croke et al., 1999b), resulting in an exponential decline in soil loss with time since disturbance. Establishment of cross-banks can be highly effective at trapping coarse sediment, but largely ineffective in limiting transport of fines to adjacent areas (Croke et al., 1999b; Wallbrink and Croke, 2002).

Snig tracks can occupy a relatively large area of the forestry compartment (10-20%) and, because they traverse the hillslope, they can often be in proximity of drainage lines. In the case of temporary log crossings, they produce a direct pathway between sediment generate at the snig track and the stream network. Log dumps in NSW are usually located on ridges wherever possible, hence upslope patterns of snigging are the norm. This prevents converging dendritic patterns in the track network. When downhill snigging is unavoidable the FCNSW harvesting standard operating procedure recommends that tracks enter the dump from the side and a vegetative buffer strip is retained above the dump to reduce the potential to concentrate runoff onto the dump.

Log landings

Log landings, which experience some soil impacts (compaction, vegetation removal) that are similar to those of snig tracks (Lacey, 1994), are another source which can be a major contributor to sediment transport. In contrast to snig tracks, the log landings experience more traffic, and the topsoil is highly modified. On log landings there is also more intensive work towards rehabilitation following the harvesting operations. Erosion rates can very high on log dumps (101 t/ha/yr) compared to snig tracks (25 t/ha/yr) (Wallbrink et al., 2002). These rates are very high and the authors note that much of this estimated erosion may have been caused by mechanical displacement during the harvesting operation (Wallbrink et al., 2002). In general, because log dumps occupy a relatively small area (3%) compared to snig tracks (18%), Wallbrink et al. (2002) found that the overall contribution to soil loss within a timber harvesting compartment was an order of magnitude lower. Impacts of log landings on sediment delivery to streams can be readily mitigated by drainage management, rehabilitation, and strategically locating the landings to minimise connectivity to streams.

General harvest areas

In the absence of cable harvesting and wildfire, the general harvest areas (GHAs) can be a sediment sink (Croke et al., 1999a; Wallbrink and Croke, 2002; Wallbrink et al., 2002). While the soil and runoff condition may be altered compared to undisturbed forests (Lacey, 1994; Rab, 1994), the infiltration rates on GHAs remain relatively high on average, and large volumes of litter and timber harvesting slash is retained in patches, resulting in high surface roughness and cover (Croke et al., 1999a; Walsh and Lacey, 2003; Lane et al., 2004). Together, the patches of high infiltration capacity and high surface roughness means the runoff generated from GHAs is relatively low. This finding is consistent across different forest types, both in Australia and elsewhere (Croke et al., 1999a; Wilson, 1999; Lane et al., 2004; Puntenney-Desmond et al., 2020; Rachels et al., 2020).

On the occasions when surface runoff was observed on GHAs, Croke et al., (1999a) noted that this was occurring on disturbed surfaces and tended to be discontinuous with limited sediment transport capacity. Sediment detachment and transport on general harvest areas was therefore relatively low. However, the grain-size of the eroded sediment has a large impact on transport (Croke et al., 1999a), with sediments sourced from Ordovician metasediment (high fine fraction) being much more mobile than those sourced from granites and tertiary sands (small fine fraction). In addition to grain-size, other factors related to runoff and erosion processes, such as local geomorphic setting (slope and geology), soil hydraulic conductivity, the degree of soil disturbance from timber harvesting (Croke et al., 1999a; Walsh and Lacey, 2003), and the location of the GHA in relation to the stream network, are all important in determining the degree to which the GHA acts as a sediment source or sink.

In timber harvesting operations that lead to highly disturbed harvest areas (e.g. through cable harvesting), large volumes of runoff and high erosion rates can be generated. Studies in northeast Victoria for example show that log drag lines associated with cable harvesting on steep slopes can have significant impacts on hydrology and sediment transport (Smith et al., 2011a). After high intensity burning the GHAs can also become a major source of runoff and sediment (Wilson, 1999), but the magnitude of this impact is dependent on underlying soil properties. Lane et al. (2004) for example found that the combination of harvesting and slash-burning did not trigger changes in soil hydraulic properties that were sufficient for runoff to occur even under extreme rainfall conditions. Timber harvesting followed by wildfire may cause more significant impacts on the hydrology due to higher fire severity and more homogenous fire footprints.

Temporary log crossings

Temporary log crossings are built within the timber harvesting compartments and allow snig tracks to cross small headwater drainage lines (1st or 2nd order drainage lines), which are ephemeral, typically flowing only when there is significant rainfall. There is no data on the contribution of these temporary structures to sediment delivery. Also, it is unclear the impacts of these compare with standard snig track crossing, which involves logging machinery snigging logs through the stream bed, sometimes requiring the cutting down of the banks to allow trafficability. By inference from research on roads and sediment delivery in forests, it is likely that crossings in general are a potentially important source of sediment input, because of the direct linkage between the sediment source (snig track) and the drainage line (Hairsine et al., 2002; Lane and Sheridan, 2002; Croke, 2004; Takken and Croke, 2004).

Given the current Coastal IFOA conditions, the crossings are temporary, and they are rehabilitated immediately after use. However, during construction the soil around the drainage line is disturbed, causing a big spike in sediment availability at that location. This spike, however, may be lower than a conventional natural surface snig track crossing. The degree to which this sediment is being delivered into the waterways depends on rainfall. If rainfall is occurring regularly while the crossings are being installed, then these structures could comprise am important source of sediment. More work is needed to understand the differences between the two types of crossings.

Moreover, the snig tracks leading towards the crossing are likely to have highly compacted soils and can remain a source of sediment for several years following the timber harvesting operations (as discussed above). The contribution of the snig tracks to sediment delivery may represent a persistent source of increase in sediment delivery. The magnitude depends largely on the drainage structures on either side of the crossing, which determines the size of the contributing area. In general, it has been observed that the more road crossings are present in forestry operations, the more sediment is delivered to streams (Cornish, 2001). The same could be inferred from snig tracks, i.e. the magnitude of the sediment delivery hazard is proportional to the number of crossings.

Table 4. Key studies identifying sources of pollutants from managed forests in coastal NSW

Source	Study	Study location (NSW in bold)	Main study methods	Pollutants identified/assessed	Importance as a source and/or other relevant impacts
Snig tracks	(Croke et al., 1999b)	**Eden FMA (NSW)** East Gippsland FMA (VIC)	Rainfall simulation	Sediment – particularly fine-grained Possibly 'sorbed' pollutants	Major source – sediment generation on snig tracks is an order of magnitude higher than adjacent GHAs (but an order of magnitude less than roads)
	(Croke et al., 1999b)	**Eden FMA (NSW)**	Rainfall simulation	Nutrients (sediment-bound nitrogen and phosphorous)	Dominant source
	(Lacey, 1994)	**Native forest near Eden (NSW)** **Plantation near Oberon (NSW)**	Soil sampling	Sediment	High levels of exposed mineral soil and soil displacement Increased potential for runoff High bulk density (major tracks only)
	(Wallbrink and Croke, 2002)	**Eden FMA (NSW)**	Rainfall simulation Tracer (^{137}Cs) budget	Sediment	Primary source – account for majority of production and redistribution
	(Wallbrink et al., 2002)	**Bondi State Forest (NSW)**	Tracer (^{137}Cs) budget	Sediment	Primary source – the greatest net transport occurred from snig tracks
	(Walsh and Lacey, 2003)	**State forests (51) (NSW)**	Field measurements (erosion)	Sediment	Sites of erosion and sediment movement, particularly in integrated timber harvesting operations
General harvest area (GHA)	(Croke et al., 1999b)	**Eden FMA (NSW)** East Gippsland FMA (VIC)	Rainfall simulation	Sediment – particularly loose organic material, ash and fine particles	Secondary – sediment generation on GHAs is an order of magnitude less than snig tracks
	(Croke et al., 1999b)	**Eden FMA (NSW)**	Rainfall simulation	Nutrients (sediment-bound nitrogen and phosphorous)	Secondary relative to snig tracks. GHAs can be a net sediment sink.
	(Wallbrink et al., 2002)	**Bondi State Forest (NSW)**	Tracer (^{137}Cs) budget	Sediment	Significant sediment trap
Log landings	(Lacey, 1994)	**Native forest near Eden (NSW)** **Plantation near Oberon (NSW)**	Soil sampling	Sediment	Increased potential for runoff High bulk density
	(Wallbrink and Croke, 2002)	**Eden FMA (NSW)**	Rainfall simulation Tracer (^{137}Cs) budget	Sediment	On a per unit area basis, a significant source of erosion
	(Wallbrink et al., 2002)	**Bondi State Forest (NSW)**	Tracer (^{137}Cs) budget	Sediment	Erosion rate per unit area was highest in the log landings
	(Walsh and Lacey, 2003)	**State forests (51) (NSW)**	Field measurements (erosion)	Sediment	Sites of erosion and sediment movement, particularly in integrated timber harvesting operations

4 Hydroclimatic and biophysical factors that interact with operations

4.1 Review question 2.1: What is the significance of wildfires for the control or mitigation of pollutant sources?

Wildfires occur regularly in eastern Australia. Temperate forests in this region are highly productive with high fuel loads and wildfires activity therefore controlled by moisture conditions rather than fuel loads. Wildfires are also controlled by other factors, such as fire weather and ignition sources. However, as evident from the recent 2019/20 wildfire season, when the landscape is dry, the ignition sources tend not to be a limitation on wildfire activity (Nolan et al., 2020). Future climate condition is likely to favour increased intensity in drying cycles that pre-condition catchments for major wildfire events (Cai et al., 2009, 2014). There is evidence of intensification in regional climate drivers (Indian Ocean Dipole and El Niño/Southern Oscillation), which promote cycles of intense growth of biomass, followed by drought. This pattern would make fire conditions more likely to be widespread across coastal NSW.

Wildfires can trigger widespread increases in erosion rates with major implications for water quality and waterway health (Smith et al., 2011c). With the likely increase in frequency of large wildfires or 'mega-fires' (Adams, 2013; Di Virgilio et al., 2019) in the Coastal IFOA region, it is therefore important to consider mitigation measures in forestry operations in the context of fire regimes and their impacts on hydrology, in particular the connectivity between the dominant sources and the stream network.

Wildfires cause changes to soil hydraulic properties due to ash deposition on the soil surface and water repellency (Tulau, 2016). Typically, after a fire the infiltration capacity of forest soil is reduced (Wilson, 1999; Sheridan et al., 2007; Nyman et al., 2010, 2014). Reduced infiltration capacity means more surface runoff is generated during rainfall events, which means the soil is subject to higher shear stresses (Wilson, 1999; Noske et al., 2016). The effects of wildfires on hydrology, erosion and sediment delivery to streams is highly variable. However, the sediment transport into streams after high severity wildfire is in the order of 1-2 orders of magnitude higher than background rates, which are typically 0.01-0.1 t/ha/yr in the temperate forests of eastern Australia (Lane et al., 2006b; Sheridan et al., 2016; Hancock et al., 2017).

The largest impacts on water quality have been documented in severely burned catchments with steep terrain and relatively dry forest types, where soils are prone to generating high runoff rates when disturbed (Noske et al., 2016; der Sant et al., 2018). The impact of fire on hydrology and erosion is most pronounced after fire that has resulted in crown scorch or crown burn, and which lacks patchiness in the severity footprint (Cawson et al., 2013; Moody et al., 2015; Nyman et al., 2015). In these settings, the post-fire rainfall events can trigger very large erosion events including debris flows, which cause widespread stripping of topsoil on hillslopes and scour of sediment that is stored in ephemeral drainage lines (Nyman et al., 2015). Although these types of processes are well documented in parts of Victoria and the ACT (White et al., 2006; Wade et al., 2013), they have not been widely reported or researched in NSW forests (with the exception of the Warrumbungle post fire debris flows (Tulau et al., 2019)).

Given reduced infiltration rates after wildfire, mitigation measures in forestry operations may become less effective than in unburned conditions. When the infiltration capacity decreases, the performance of riparian exclusion zones in limiting the delivery of sediment can become diminished. In a study of hydraulic conductivity and surface runoff in wet eucalypt forests in northeast Victoria, Sheridan et al. (2007) found that runoff ratios from hillslopes after wildfire were 1.5 to 2 times higher than unburned hillslopes. In overland flow experiments, this difference resulted in overland flow plumes that were 2 times longer immediately flowing the wildfire, when compared to hillslope conditions after 1 year of recovery. The results therefore indicate that there is a large initial effect in these wet eucalypt forests, but recovery is quick, and the infiltration capacity returns to background conditions within a year or so.

The study by Sheridan et al. (2007) represented the response from tall wet forests, which are systems that shows the least post fire hydrologic response. The highly organic and microporous soils in these forests means that infiltration rates remain high despite fire-induced water repellency. Water typically bypasses the water repellent layer by infiltrating through macropores (Nyman et al., 2010). In drier and less productive forests, the soils have less macropores and are therefore more strongly impacts by water repellency and more prone to produce post-fire runoff (Noske et al., 2016; der Sant et al., 2018). In drier systems the runoff on recently burned hillslopes can be 1-2 order of magnitude higher than unburned hillslopes. Thus, there is a lot of spatial variation in how fire impacts erosion and sediment delivery. This in turn means that the magnitude of the measures to mitigate against impacts of erosion in the post-fire period may need to be scaled according to the landscape parameters that determine the sensitivity of soils to fire impacts.

There are two important implications of wildfires in designing and evaluating mitigation measures:

- Under the initial post-fire conditions, the riparian zone itself becomes a sediment source (Smith et al., 2011b) and because of the lower infiltration rates it provides reduced capacity for buffering runoff and sediment delivery from upslope source areas. Based on the results in (Sheridan et al., 2007) and those in (Nyman, 2009), the post-fire setting would require buffers that are twice the width of unburned buffers in order to achieve similar effectiveness to the unburnt setting. Their work, however, was focused on soil types that are known to have high infiltration rates even after fire, and where post-fire hydrologic response is relatively muted. In other soil types, the specific measures needed to address fire-related changes in hydrology are likely to differ from the case studies noted above. During salvage harvesting, these fire impacts should be considered as special conditions that are applicable for timber harvesting operations in burned areas (e.g. DEPI, 2014). For timber harvesting activities in unburned conditions, the extent to which the potential for fire disturbance should be considered in the design of mitigation options is less clear.
- In the first 1-2 years after wildfire, erosion and sediment delivery to streams can be large (1-2 order of magnitude above background conditions) (Noske et al., 2016), in which case the effects of timber harvesting operations may be small in comparison, and masked for some time due to the increase in sediment availability in rivers as a result of wildfire. In the event of a wildfire, the attribution of water quality impacts to different sources is challenging. The large areas typically affected by wildfires means that pulses of sediment are likely to be generated somewhere in a catchment during intense rainfall irrespective of road networks and forestry operations (White et al., 2006; Atkinson, 2012; Yang et al., 2018). These events can have a legacy on sediment availability in streams that lasts beyond the initial 1-2-year period when hillslope erosion rates are elevated above background levels (Prosser et al., 2001; Moody, 2017; Nyman et al., 2019a). Such wildfire-related changes in water quality and sediment transport must be carefully considered when designing monitoring programs, and when evaluating the effectiveness of mitigation measures in maintaining water quality in downstream river systems.

4.2 Review question 2.2: What is the significance of thunderstorms and east coast lows for the control or mitigation of pollutant sources?

Intense rainfall events are a key driver of erosion in forests (Kirchner et al., 2001; Miller et al., 2003; Smith et al., 2011a; Nyman et al., 2019b). This is because many of the processes that govern runoff generation, sediment detachment and transport are threshold-driven. There are therefore step changes in erosion rates and sediment delivery with increased intensity and duration of rainfall events. Both the intensity and duration of rainfall are important in determining erosion rates and sediment delivery.

There are two main types of rainfall events that drive erosion processes in eastern Australia:

- Short bursts of rainfall associated with convection and thunderstorms. These types of rainfall event typically occur during the warmer months and are typically of relatively short duration (a few hours or less), producing totals that are generally < 50 mm. The high intensity of these rainfall events means that runoff is generated even if the catchment is relatively dry. Runoff is produced because rainfall intensity exceeds the infiltration capacity of the soil. This means that runoff can be generated anywhere on the hillslope, depending on the distribution of hydraulic conductivities (Langhans et al., 2016).
- Prolonged rainfall associated with east coast lows, which are intense low-pressure systems that produce large volumes of rainfall (> 100 mm, occasionally > 500 mm) over several days. They are more common in the cooler autumn and winter months. On the north coast of NSW they are more common toward the end of summer and early autumn. These events tend to cause saturated

conditions and runoff occurs because rainfall volumes and intensities exceed the drainage capacity of the soils.

The intensity of both types of rainfall events are likely to increase with global warming (Westra et al., 2014; Cai et al., 2015; Guerreiro et al., 2018). Hourly rainfall intensities are predicted to increase by ~20% for every degree of warming (Guerreiro et al., 2018). East coast lows are likely to increase in frequency as ENSO cycles intensify (Cai et al., 2015).

The strong link between sediment delivery and rainfall intensity and duration is an important consideration for the design of an effective monitoring program:

- First, it is these infrequent but geomorphologically significant events that should be considered in designing and evaluating mitigation measures. For example, Takken et al. (2008) modelled the impact of forest roads assuming a 10-year rainfall event. Hairsine et al. (2002) and Croke et al. (1999a) modelled plumes of overland flow and sediment redistribution from timber harvesting tracks and harvest areas using 2-, 10- and 100-year rainfall events. These event magnitudes corresponded with the range of flood frequency and magnitude conditions used by timber harvesting operations in their design of drainage measures. The need to consider rainfall events of different magnitudes extends to evaluation of mitigation effectiveness, through rainfall simulations or measurement of runoff and erosion response from natural rainfall. As noted by Walsh and Lacey (2003), the effectiveness of different mitigation measures is best evaluated by examining the response to rainfall events that do most of the geomorphic work over time.

- Second, in experiments that use gauged catchment to measure water quality response to timber harvesting, long-term monitoring records are needed to capture the events that are most important for erosion and sediment delivery. Records that are short relative to the frequency of significant events are unlikely to yield insights into the dominant processes that underlie impacts on water quality and waterways. Even in cases where large events are captured in the records, and even if an experiment is set up as a paired catchment study, the low sample number (in terms of events) can often lead to inconclusive results with regards to the effect of timber harvesting. Furthermore, the large events that has most impact on sediment delivery and water quality can be difficult to sample in high energy streams because of equipment failure, such as when weirs fill with bedload and when flow rates exceed the range of conditions for which the weirs and gauges have been designed (Smith et al., 2011a; Noske et al., 2016). These issues with catchment-scale experiments present challenges in the evaluation of mitigation effectiveness.

5 Mitigation measures to reduce sediment delivery to streams

By the 1960s, numerous North American studies were demonstrating that control over forest practices could significantly reduce soil erosion and stream sediment levels, and the implementation of guidelines for mitigation practices became widespread (see Cornish, 1989 and references therein). Guidelines were subsequently developed specifically for Australian forestry practices and were enforced in NSW by 1977 as conditions attached to timber harvesting licences in native forests, with subsequent application in pine plantations (Cornish, 1989).

In the years since, local studies from NSW have found that mitigation measures for reducing sediment delivery from timber harvesting operations can be effective in managing impacts on waterways. The effectiveness of mitigation measures have been evaluated explicitly at the hillslope scale (Croke et al., 1999b; Wallbrink and Croke, 2002) and implicitly by measuring hydrological and water quality responses at the catchment scale (Cornish, 2001; Webb and Haywood, 2005; Hancock et al., 2017; Walsh et al., 2020). The effectiveness of such practices also continues to be demonstrated in North America (Rachels et al., 2020) and there is little doubt that their effective implementation can significantly reduce sediment delivery to streams in managed forests (Croke and Hairsine, 2006).

The following three review questions explore the effectiveness of current conditions and protocols in greater detail.

5.1 Review question 3: How do existing pollution mitigation measures address each of the pollution sources?

In this section we consider the mitigation measures that are targeting forest harvesting activities within the harvesting compartment, including snig tracks. Mitigation measures related to the forest road network, more generally beyond the forestry compartments, is considered separately as part of the development of a state-wide forest road network monitoring program[4].

In general, the mitigation measures for harvesting activities in the Coastal IFOA[5,6] (Table 5) are consistent with best management practice (BMP) for management soil and water resources (Neary et al., 2009).

The mitigation measures are designed around the following strategies:

- *Intensive harvesting limits*, which limit the area within a catchment that is in a state of recovery from soil and vegetation disturbance caused by timber harvesting.
    - Setting intensive harvesting limits, the IFOA protocols ensures that there is a maximum proportion of a catchment (1/3) and total area (45 ha) at any point in time where potential harvesting-related pollutant sources are active.
    - Based on 5-year recovery trajectories in Croke et al. (2001), harvesting rotation of 10 years would be adequately spaced such that disturbed soils and surface cover are likely to have recovered prior to the establishment of a new harvesting area within a catchment.
- *Riparian protection*, which inhibits connectivity between pollutant sources and the stream network and ensures streambank stability is maintained.
    - The riparian protection is achieved through ground protection zones (harvesting permitted but no earthworks) and riparian exclusion zones (no harvesting or earthworks).

[4] Alluvium (2020) Discussion paper - Evaluating forest road networks to protect water quality in NSW. Report for the Natural Resources Commission. pp 1 -23. September 2020.
[5] NSW_Environment_Protection_Authority, 2020, Coastal Integrated Forestry Operations Approval – Protocols:, https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/forestagreements/coastal-ifoa-protocols.pdf.
[6] NSW_Environment_Protection_Authority, 2020, Coastal Integrated Forestry Operations Approval – Conditions:, https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/forestagreements/18p1177-coastal-ifoa-conditions.pdf

- The Coastal IFOA protocols for riparian protection are designed so that the width of the hydrological buffers scale with both the magnitude of the runoff and erosion processes operating upslope (i.e. soil erosion hazard), and the likelihood that the source is linked to surface water (i.e. drainage area). For example, class 1 drainage lines (defined in the Coastal IFOA protocol as a mapped drainage line with area < 20 ha), where water flows are intermittent, has a narrower exclusion zone (5-10 m) than a drainage line with a contributing area of >400 ha, where the exclusion zone is 50 m.
- For wetlands, the same principles apply and exclusion zones range in width from 10 m-40 m depending on wetland surface area. For SEPP wetlands the exclusion zone is always 40 m.
- The literature shows that undisturbed riparian zones can be highly effective in limiting transport of pollutants between source areas and the stream network (Hairsine et al., 2002; Lane et al., 2006a). Riparian buffers can also give rise to very complex spatial arrangement of buffer/non-buffer areas and may result in the formation of 'islands', which cannot be accessed except by passing through a buffer zone (Bren, 1995).

- *Track (snig tracks) design conditions and protocols*, which ensure that water and sediment from snig tracks are not diverted into drainage features, and that discharges are low such that channelised flow is not initiated.
  - The conditions state that drainage structures must be sized and spaced to accommodate the runoff generated from a 2-year event.
  - By diverting sing-track runoff into buffer zones (e.g. GHAs and riparian exclusions zones), and ensuring it remains non-gullied overland flow plume (not incising) (Croke and Mockler, 2001), the probability of pollutants reaching streams is low (Hairsine et al., 2002; Lane et al., 2006a; Takken et al., 2008). This principle applies to snig tracks and forest roads more generally.
- *Temporary road crossing conditions,* which are designed to limit the duration that the crossing provides direct linkage between the track and drainage networks and to keep the machines and logs out of the drainage feature.
  - The conditions state there can only be one active temporary log crossing in a forestry compartment at any one time, and it can only be active for 5 days.
  - Linkages between tracks and streams are minimised by locating the nearest drain within 5 – 20 m of the crossing and by stabilising and rehabilitating the disturbed surfaces within 20 m on either side.
- *General soil and water conditions*, which include measures that:
  - exclude timber harvesting activities in areas with high inherent erosion hazard including susceptibility to mass movement – these measures, which vary with slope, soil regolith and rainfall erosivity, are aligned with the broad erosion hazard survey conducted by (Walsh and Lacey, 2003).
  - In assigning a hazard-rating based on soil regolith, the effect of both erodibility and sediment delivery potential are considered (Murphy et al., 1998). Soils that are easily eroded (low cohesion) and easily transported (fine grained) are assigned a high hazard level (rating 4) in the soil regolith classification. Soils that are resistant to erosion (high cohesion) and that are not readily transported (coarse grained) are assigned a low hazard rating (rating 1) in the soil regolith classification.
  - separate exposed bare ground from surface waters – by creating separation between disturbed areas and drainage lines, the likelihood of sediment delivery is minimised.
  - limit harvesting activities when conditions are more likely to be wet (e.g. through seasonal restrictions), thereby reducing the likelihood of erosion occurring and sediment being delivered to streams.

Table 5. Pollution mitigation measures set out in the coastal IFOA conditions.

Existing pollution mitigation measures	Relevant conditions	Protocol	Key points in relation to mitigating impact on waterways and water quality
Intensive harvesting limits Distribution of harvesting across the landscape	45	-	Harvesting operations are distributed across the landscape and over time, to support a mosaic of forest age classes and maintenance of forest structure in the operational area or local landscape area. • The maximum area that can be subject to intensive harvesting in a local landscape area in any single intensive harvesting cycle is no more than 1/3 of the net harvest areas of that local landscape area. • The minimum time until completion of all three intensive harvesting cycles of a local landscape area using intensive harvesting is 21 years from the commencement of the first intensive harvesting cycle. • The maximum size of each coupe in an intensive harvesting zone is 45 hectares.
Riparian protection Operating conditions	95, 99	15, 16, 19	Vegetation adjacent to drainage features and wetlands is protected, and groundcover is retained, to maintain water quality, stream stability, riparian habitat and contribute to habitat connectivity. • A riparian exclusion zone must be retained on each side, and for the entire length, of drainage lines. • The widths of exclusion zones range from 5 to 50 m depending on stream order, the applicable harvesting type, ground slope, soil type, and whether the exclusion zone is for a drainage line or a wetland/water storage. • Width of exclusion zones consider inherent soil erosion and water pollution hazard assessment.
Tracks and temporary log crossings Operating conditions	104-106	18,14, 17,32	Water quality, aquatic habitat and native fish movement are maintained through the implementation of best management practices for tracks and stream crossings. • Track drainage structure must be located, designed, installed and maintained in such a way that water is not diverted into drainage lines but onto a stable surface that will trap sediment, dissipate energy from the flow, while not incising due to concentrated flow. • A track must not be used where the use of that track causes or contributes to runoff that causes water pollution. • A temporary log crossing must only be constructed (when water is not flowing) on a drainage depression, first order ordered drainage feature, or second order ordered drainage that is no more than one metre deep. • A crossing is not to be used when that crossing is saturated or if water is running over the surface of the crossing. • A track must be drained between 5 and 20 metres on each side of a drainage line crossing, measured from the bank full level. • A temporary log crossing must be removed within five days of the completion of operations in that area and must be stabilised and rehabilitated prior to opening another crossing in that area.
General soil and water operating requirements Operating conditions	107-109	12, 15,	Water quality and aquatic habitat are protected and maintained through the implementation of best management practices. • Runoff from a borrow pit, gravel pit or log dump must not discharge directly into a drainage feature and be located at least 10 metres from the outer edge of the any riparian exclusion zone or ground protection zone • Harvesting is prohibited or restricted on any land that is inherent erosion and water pollution hazard level 4 • Seasonality restrictions are applied based on rainfall erosivity.

5.2 Review question 4: Are the use of buffers of class one streams effective for pollution control purposes?

Riparian zones can serve important ecological functions in harvested catchments and are recognised worldwide as having a key role in moderating the impact of land use on stream water quantity and quality (Norris, 1993; Croke and Hairsine, 2006; Neary et al., 2009). In the Coastal IFOAs, buffers around class one streams are achieved through two mechanisms: a "riparian exclusion zone" combined with a "ground protection zone". The riparian exclusion zone is where harvesting is not permitted. The ground protection zone is where disturbance to the soil surface and understory vegetation is not permitted. For steep catchment with dispersible soils, the exclusion and protection zones are both 10m wide (see Chapter 5, Division 3 in the IFOA Conditions[7]). For other areas, the exclusion zone is 5m and the protection zone is 10m.

The literature review generally indicates that the use of riparian buffers is one of the most effective management practices for controlling pollution, particularly in native forest harvesting. Research suggests all drainage lines, where concentrated flow occurs, should be protected, irrespective of size. Key examples from NSW are summarised in Table 6. Similar results have been reported in other studies. For example, in the Oregon Coast Range (USA), Rachels et al. (2020) found that while harvesting activity resulted in mobilisation of hillslope sediments, the riparian buffer was effective at reducing sediment transport to the stream. Riparian buffers can also be effective in removing nutrients such as nitrate (Norris, 1993).

The effectiveness of any riparian buffer in protecting waterway health depends on factors such as width, structure, species composition, vegetation management, and the level of harvesting or disturbance. While buffer widths can vary greatly, widths of as little as 10 m have been found to be effective at trapping sediment (Lacey, 1993). In their review of riparian forest management, (Broadmeadow and Nisbet, 2004) note that buffers of 5-30 m have been found to provide at least 50% (and often 75% or greater) effectiveness at protecting stream functions from harvesting activities. The mechanism by which buffers work is often (in many of the studies described here) via infiltration of runoff, rather than directly by trapping of sediment. Therefore, the effectiveness of buffers is highly dependent on the hydraulic properties of the soils within the buffer. When soils are poorly structured, are burned or have low porosity, the runoff may not infiltrate, in which case the buffer is less effective, with silt and clays transported by runoff through to the drainage network.

It can be possible to selectively harvest within buffers without causing significant impacts on waterways. In Brooman State Forest on the south coast of NSW, (Walsh et al., 2020) found that selective harvesting in the riparian buffers, using best management practices, did not alter the magnitude of the runoff and sediment response. Similar findings have also been reported in other locations (Neary et al., 2010). However, it is also widely recognized that disturbance of the riparian zone inhibits its functions (Croke and Hairsine, 2006). Sheridan et al. (2007) demonstrated that, following fire, buffers not only fail to trap sediment from upslope but themselves become a primary source of sediment and pollutants to streams.

The effectiveness of buffers in plantations may also be limited, relative to native forest. Cornish (1989) note numerous problems can arise with the use of buffers in *Pinus radiata* plantations, so that buffers may be ineffective at times depending on their management and composition.

[7] NSW_Environment_Protection_Authority, 2020, Coastal Integrated Forestry Operations Approval – Conditions:, https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/forestagreements/18p1177-coastal-ifoa-conditions.pdf

Table 6. Effectiveness of buffers in previous studies NSW and Victoria.

Study	Location	Summary of effectiveness
Cornish (2001)	Karuah Hydrology Research Area, NSW	A 20 m buffer on either side of the stream, together with the exclusion of fire from riparian areas and the drainage of snig tracks, was effective in preventing additional sediment from entering the stream.
Wallbrink and Croke (2002)	Eden Forest Management Area, NSW	On a per unit area basis, the buffer retained 8 times the sediment of the GHA, although the greatest overall trapping of fine sediment occurred in the latter.
Wallbrink et al. (2002)	Bondi State Forest, NSW	The buffer played a fundamental role in trapping and storing inflowing sediment (particularly from snig tracks), confirming the utility and necessity of buffers as part of erosion mitigation strategies.
Hairsine et al. (2002)	Eden Forest Management Area, NSW	Buffer effectiveness, modelled analytically using volume to breakthrough (vbt5), was shown to vary strongly with the intensity of rainfall on the snig track. For a 2-year event, only 0.5% of plumes from snig tracks were likely to connect with streams, while for 10- and 100- year events, 2% and 16% of plume lengths were greater than the available hillslopes buffers.
Lane et al. (2006a)	Upper Tyres, VIC	Results indicate that sites in Victoria (Mountain ash forests) where soils are very permeable are similar to those in Hairsine et al (2002) in the capacity of buffers and accommodate surface runoff from roads.

Limitations of applying buffers in class 1 streams according to the Coastal IFOA conditions

Historically there have been limitations in mapping and classifying streams, and therefore in applying suitable buffer widths to different stream classes (see (Webb, 2008) and references therein). In the coastal IFOA class 1 streams is a *mapped drainage line that is less than 20 hectares in catchment size. The headwater or point of origin of a class 1 classified drainage line may extend beyond or fall short of the mapped drainage line and must be verified in the field*[8]. According to the coastal IFOA conditions, class 1 streams begin at the channel head which is the upstream limit of where there is a defined drainage depression. The drainage depression is a *feature that is a level to gently inclined shallow, open depression with a smoothly concave cross-section, rising to moderately inclined hillslopes*.

With this definition within the Coastal IFOA approvals and conditions, the channel head is ultimately determined using field data. Using field data to determine channel heads helps ensure that the location of channel heads and buffers reflect the flow conditions that are operating in the field at any point in time.

However, there remains some ambiguity in what constitutes a class 1 drainage line because the definition of the channel head based on drainage depression (Protocol 16[8]) is open to interpretation that leads to misclassification of drainage lines. In headwater systems, where catchment areas are in the order of 10s of hectares, these features are subtle, and slight differences in assumptions, interpretation or experience of the field surveyor can have major implications for how the class 1 drainage network is mapped. For example, in colluvial hollow, there is likely to be concentrated flow (i.e. there is flow convergence) when there is sufficient runoff, but under most (undisturbed) conditions the flows are not incising into the soil, because of dense vegetation and low surface runoff rates under undisturbed conditions. There may not be a distinct drainage depression. In such cases, a field surveyor may classify the landscape position as not being a drainage line, despite the overall topography (the curvature) clearly indicating that the area is subject to concentrated flow.

If high quality LiDAR is available, more robust and cost-effective methods for defining the channel head are available (Clubb et al., 2014). Objective methods for defining channel heads and drainage lines from LiDAR should be used to help ensure buffers are applied consistently and non-subjectively across different forest compartments and landscapes. LiDAR-based methods are quantitative and based on the curvature of the terrain. They provide a consistent and transparent approach that is guided by metrics that describe expected changes in morphometry as dominant processes shift from diffusive flow to concentrated flow. Lidar-based classification of drainage lines, using landscape morphometry, should complement (not replace) field surveys.

[8] NSW_Environment_Protection_Authority, 2020, Coastal Integrated Forestry Operations Approval – Protocols:, https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/forestagreements/coastal-ifoa-protocols.pdf.

5.3 Review question 5: Where wetlands exist within NSW forests, what pollution mitigation measures are warranted?

There is a paucity of research on this topic in NSW and our evaluation below is mainly based on a review by Shepard (1994), which draws on research from forest in North Carolina and Michigan in the US.

In contrast to upland forests in dissected uplands with confined valleys, surface water flow rates are lower in wetlands, which typically have less topographic relief and wider valleys, and therefore have less energy available to export sediment. In a review of literature on water quality in forested wetlands, Shepard (1994) found that silvicultural activities generally resulted in small and short-lived water quality impacts. Impacts were greater in upland wetlands, where relief is greater and soils are shallower, than in lowland wetland forests. Shepard (1994) concludes that silvicultural activities "do not constitute a permanent threat to the ability of wetlands to maintain or improve water quality."

As discussed above for riparian buffers, buffer width is one of the most critical factors in wetland buffer effectiveness, including for effective nutrient retention (Fennessy and Cronk, 1997). For example, at Goshen Swamp in North Carolina, the use of a 10 m buffer was insufficient to prevent increased nutrient levels, higher suspended solids, and other water quality impacts following clearcutting (Ensign and Mallin, 2001). The widths of existing riparian and wetland buffers range from 10 to 500 m, depending on the needs and hydrological, biological, and physical characteristics of the site (Klemas, 2014). In general, the principles of connectivity of forestry compartments and the waterbody apply to mitigation of water quality impacts on wetlands.

Buffers around wetlands also serve other important functions, beyond just water quality. For example, Lemckert (2011) assessed approaches to protect anurans (frogs) from the impacts of forestry operations in coastal NSW. Buffers applied around wetlands and other water bodies provided significant protection for breeding, and it was concluded that current forestry practices are unlikely to have significant long-term negative effects if current protective measures (which also include habitat trees and corridors) are retained to protect identified sensitive habitats.Benefits and design of monitoring programs

5.4 Review question 6: What is the relative merit to continue or reinstate the Middle Brother, Yambulla, Kangaroo River and Karuah water quality monitoring projects?

Background and key papers

A forest hydrology research program was initiated in the mid-1970s to investigate the potential impacts of native forest harvesting. Catchment-scale water quality monitoring has since been conducted in a number of native forests and pine plantations throughout NSW (Figure 2). The objective has been to support the NSW Forestry Corporation in their effort to design mitigation measures that ensure streams, drainage lines, and waterways are protected from run-off during roading and timber harvesting. These catchment-scale water quality monitoring projects, with data records dating back more than 40 years across diverse forest systems along the east coast Table 7), provide invaluable information on hydrological and water quality responses in streams given contrasting forest management activities, rainfall variability, and any additional disturbance such as wildfires, which occur regularly in these catchments.

Table 7. Summary of the water quality monitoring projects in State Forests of NSW.

Project	State forest	Years active	Summary	References	Key learnings
Kangaroo River	Kangaroo River State Forest (subtropical)	2001 to 2009	Three 'impact' catchments (selectively harvested in 2007 using BMPs) to assess effects of forestry activities on runoff and suspended sediment yields.	(Smolders et al., 2018) (Webb et al., 2012a)	Management practices are effective in mitigating effects of harvesting. They should continue to be employed in NSW for the benefit of the aquatic environment and water users downstream.
Karuah	Chichester State Forest (Hunter region)	Established 1974-75, Data collection ongoing	Eight small experimental catchments, originally established to examine the hydrological effects of eucalypt-to-eucalypt forest succession.	(Cornish, 2001) (Hancock et al., 2017a, b) (Webb et al., 2012b)	Road-stream connectivity is the most important factor in sediment delivery to streams in roaded catchments. Significant increases in streamflow following forest disturbance. Use of water yield models derived from Mountain Ash results in other eucalypt forests is inappropriate. Management practices are effective in the long term.
Middle Brother	Middle Brother State Forest	1993 to circa 2004	A paired catchment (impacted and control) monitoring site, assessing impacts of selective native eucalypt forest harvesting.	(Webb and Haywood, 2005)	Potential for forestry activities to impact upon the erosion and transport of hillslope sediment resulting in effects on in-stream turbidity levels. Soil conservation measures, particularly for roads, tracks and stream crossings, are essential to reduce the magnitude of possible non-point-source pollution.
Yambulla	Yambulla State Forest (South East region)	Established 1977, last known data collection 2019 (then damaged by fire)	Six catchments (including one added in 1979) to determine the effects of timber harvesting on soil physical properties and runoff.	(Harper and Lacey, 1997) (Lacey, 1994) (Webb and Jarrett, 2013)	Increases in total streamflow, baseflow and stormflow following the 1979 wildfire and/or integrated timber harvesting activities that occurred at various intervals. Catchment-scale hydrological responses to disturbance of mixed-species eucalypt forests do not follow the unusual response often reported in wet Mountain Ash forests.

Long-term monitoring in a changing climate

Long-term catchment scale monitoring studies play an increasingly important role in assessing the impacts of climate change and addressing the recovery following wildfires, which appear to be increasing in frequency and extent in SE Australia (Boer et al., 2020). When forests are subject to multiple stressors (not just harvesting), the long-term data provided by experimental catchments provide critical information to understand and predict trajectories of change in catchment function and the ecosystem services they provide. Some of the studies listed in Table 7 have investigated the impacts of wildfire (Webb and Jarrett, 2013). However, large gaps remain with regard to possible compounding effects of repeated wildfire, climate change and harvesting. The unprecedented wildfires during the 2019/20 wildfire season, caused by drought and extremely dry fuels (Deb et al., 2020), underscores this issue and demonstrates that there is a demand for long-term monitoring to understand catchment recovery and resilience during periods of non-stationary conditions with increasing extremes.

Evaluation of water quality monitoring projects

The framework below is used to evaluate the relative merit to continue or reinstate catchment-scale water monitoring programs. The projects are evaluated against the overall objective to design mitigation measures that ensure waterways are protected from erosion caused by timber harvesting operations.

Table 8 Achievement, lessons learnt and opportunities for improvement.

Project achievements to date against what it set out to do	Impact	*1. To what extent have the studies resulted in positive outcomes?* The data and publications that have been produced from the catchment-scale studies have provided critical information on the downstream impact of forest harvesting on peak flows, water quality parameters and longer-term water yield. The results have validated many of the inferences that have been made from process-based studies on runoff and erosion within harvest areas. Together, the catchment-scale studies and hillslope-scale experiments provide the necessary insights to evaluate the impacts of harvesting and the effectiveness of mitigation measures. On their own, neither approach would provide the evidence-based needed to guide the design of best management practises.
	Effectiveness	*2. To what extent have the studies been successfully delivered?* The studies have delivered high-quality data, which have underpinned several peer-reviewed publications in some of the leading international journals on catchment hydrology and forest management. The study designs have been effective in targeting research and monitoring questions directly applicable to our understanding of forest harvesting impacts and mitigation effectiveness.
	Efficiency	*3. To what extent have the studies represented good value relative to its costs?* Catchment-scale monitoring studies are expensive. • First, infrastructure, maintenance, and data management all require resources including technical support staff and upgrades and replacement of sensors and monitoring systems. • Second, using the data to generate insights that are published in reports and peer-reviewed journals is a large undertaking requiring high level input from forest hydrologist and engineers. The program appears not to have capitalised sufficiently on the opportunity to improve efficiency with complementary experiment such as sediment tracing and model development, which often help reveal the internal processes that govern the large-scale response.
Lessons learnt and opportunities for improvement	Appropriateness	*4. Might there have been a better way to achieve the project's intended outcomes?* Hillslope scale experiments and surveys of erosion achieve similar outcomes in terms of understanding mitigation effectiveness, albeit at different scales. Hillslope-scale experiment cannot replace catchment-scale studies. Both approaches are needed to link measured water quality impacts back to management practises and hillslope processes. No other type of study could deliver the insights that these catchment-scale experiment have. They are highly appropriate and provide insights that other techniques are unable to provide. The peer-reviewed publications are a testament to the scientific rigour that these studies provide.
	Legacy	*5. What can give us confidence that the project would be successful into the future?* Continuing to monitor catchment-scale hydrology and water quality without clear links to management objectives and mitigation measures is unlikely to provide value for money. To be successful into the future, the monitoring program should reassess the objectives of monitoring, the questions being asked, and develop strategies for funding with support from both industry, government, and research institutions. Complementary monitoring and research activities, such as model development, carefully designed hillslope experiments, and tracing can contribute towards cost-efficiency and adding value and new insights beyond what has already been achieved.

6 Water quality monitoring projects for evaluating effectiveness of mitigation: recommendations

We recommend catchment-scale monitoring studies, such as those listed in Table 7, continue to form an important component towards achieving monitoring objectives because they provide the only direct measurement of in-stream responses and how they change in catchments over time. Maintaining funding for long-term catchment hydrology studies is key to being able to detect temporal change in catchment function, particularly in the context of processes that are driven not just by changes in timber harvesting operations, but also climate change and wildfire (Neary et al., 2009; Bren, 2014).

However, for catchment-scale monitoring to deliver value beyond what has been achieved to date there are several aspects of a monitoring program that need to be addressed:

1. The **objectives of the monitoring program must be refined** to provide a stronger link between what is being monitored and its relevance for values that are being protected. Currently the monitoring questions are framed in terms of the *condition of waterways and SEPP wetlands*. There is insufficient nuance to the exact meaning of the *condition*, and how they relate to waterway health and water quality in these systems. In this review we have worked with sediment delivery to streams as a proxy for impacts on waterway health and water quality from timber harvesting. But what is our benchmark for evaluate effectiveness? Sediment transport through waterways is a natural process and sediment only becomes a pollutant once its characteristics and concentration reach or exceed some threshold. To be cost-effective, the monitoring of timber harvesting impacts on waterways and wetlands must provide more specific definition of the values that are at risk of being impacted and the parameters that are likely to cause those impacts. With clear objectives and defined values, the suitable investment in research and monitoring programs can be evaluated objectively, considering potential ecological costs alongside the economic and social value of the timber industry.
2. A **risk framework** for linking timber harvesting to ecological impact on waterways and wetlands should be developed as a starting point for refining the monitoring questions and developing a program for data collection that focuses on the processes that are most problematic in terms of risk to waterway values. For example, are there threatened or endangered aquatic species that would be at risk if the water quality protection measures did not work? Waterway and wetland values can be defined and mapped spatially to provide the catchment context that is critical for focusing efforts. The risk framework should draw on fundamental knowledge related to the movement of sediments and associated pollutants through catchments (e.g. Hairsine, 2017), including scale-effects and residence times of pollutants. With this as a starting point, the consequence for values can be mapped and used as a tool for designing a cost-effective monitoring program where parameters, processes and study areas are aligned with where the consequence of impact may be high (see Waterhouse et al., 2017 for good examples). The likelihood of consequences can also be mapped at landscape scales, from erosion hazards assessment based on topography, soil properties and rainfall erosivity. Together, spatial products showing likelihood and consequence of impacts will help ensure monitoring is targeting those areas where it is most needed. The framework should specifically consider resilience such that the ability of systems to bounce back from disturbance forms part of the risk quantification.
3. Key **monitoring parameters** should be defined and justified based on risk to waterway and wetland values. These parameters may vary depending on the values that are at risk from changes in catchment processes because of timber harvesting. The risk framework provides information for prioritising the parameters that are most important. For example, it may be that turbidity alone is not a good indicator of the dominant sources of risk. For high-energy upland streams for example, the delivery of coarse-grained bedload sediment causing changes to in-stream bedform could be a more important risk factor than fine sediment, which has a short residence time and impacts the stream only during short periods when the erosion is occurring. In lower-energy downstream systems, including SEPP wetlands, the cumulative effect of increases in the delivery of fine sediment by multiple sub-catchments may be the main risk factor, causing poor water quality and changes to waterway health. And within the suspended sediment fraction, it may be that a specific grain-size fraction is what causes most damage to a particular value (Garzon-Garcia et al., 2018b). Research on

fine sediment transport and risk to the Great Barrier Reef is a useful reference that includes important concepts for developing effective monitoring parameters (e.g. Bainbridge et al., 2018)

4. Water quality monitoring programs should be **embedded within a broader set of experimental work** aimed at linking both sediment delivery processes and mitigation measures to catchment-scale responses and waterway impacts. Plot- and hillslope-scale erosion and sediment transport studies (many of which have informed this review) provide critical insights on processes and pathways by which pollutants reach the stream network. Further work is needed to link these types of hillslope-scale studies to catchment-scale monitoring of water quality parameters, and unpack in more detail the processes that underlie the catchment-scale responses, and expanding understanding past the "black box" outcome resulting from quantifying the catchment exports alone (Croke and Hairsine, 2006; Lane et al., 2012). As noted by Croke and Hairsine (2006), there are three key components that should be addressed in any monitoring program aimed at understanding and predicting how changes in surface runoff and erosion processes due to harvesting and land clearing impact on stream water quality:

    - identify the major sources of runoff and sediment and their spatial distribution with respect to streams,
    - describe the delivery pathway of each of these sources and its effects on sediment fluxes as runoff moves through the landscape from source to stream,
    - assess the effectiveness of best management practices with respect to sediment production and delivery.

The selection of measurement techniques for achieving these outcomes are varied and depend on expertise, budgets, timeframes, the emphasis on research vs monitoring, and the opportunities that emerge as result of synergies with other programs. *Hillslope experiment measuring erosion and sediment delivery* under simulated or natural rainfall are extremely valuable in that they are direct measurements of sediment transport processes, and they provide water and sediment samples than can be analysed to determine pollution implications. But such experiments require large investment in fieldwork and capacity to deliver research. Repeat t*opographic surveys* (using airborne and terrestrial LiDAR) can be useful to track the evolution of channel and rill networks, in disturbed and undisturbed settings. However, the vertical precision of LiDAR in forested catchments is typically > 20cm and the usefulness of these data is therefore limited if the dominant sediment sources are linked erosion processes that are operating within the top 20 cm of soil. Carefully designed *sediment tracing* experiments can provide useful insights on dominant sources and processes (Wallbrink et al., 2002; Motha et al., 2003) at hillslope and catchment scales. However, they are unlikely to resolve where from within timber harvesting areas sediment is being sourced and delivered to streams.

5. There is a need to **address knowledge gaps with additional research**. With regard to erosion processes from timber harvesting and the impacts on waterways we identify three key knowledge gaps:

    - The roles of sediment composition and nutrient bioavailability are poorly quantified in terms of the effectiveness of mitigation measures. Much of the work to date on mitigation effectiveness, both at catchment and hillslopes scales, has examined sediment delivery processes without much regard for grain-size distribution or nutrients. Yet, there is strong evidence that sediment characteristics has large implications for water quality and algal blooms in response to changing land use practices (Garzon-Garcia et al., 2018a, 2018b). Earlier work by Croke et al. (2005) and Croke et al. (1999b) points towards important signals in their data in terms of a grain-size dependency in the effectiveness of mitigation measures. In future studies, for both catchment- and hillslope-scale monitoring, it is recommended that details on sediment characteristics are measured (e.g. using different dispersion techniques and laser particle diffraction) with the goal to understand the pollution implications of sediment delivery. Refer to the report by Garzon-Garcia et al. (2018a) for more detail in these considerations.

- Impacts of temporary log crossings have not yet been addressed by the research in this review. Temporary log crossings directly impact on sediment availability in channels and therefore have the potential to generate a direct spike in sediment transport through drainage networks. Experiments and measurements (e.g. using simulated or natural flow events in affected channels) are needed to determine how these structures impact on sediment delivery, and how this compares to other sources currently addressed in the literature. In particular, there is a need to evaluate how log crossings compare to conventional crossings in order to evaluate if they are an effective measure to limit sediment delivery into streams.

- Impacts of timber harvesting activities on wetlands. Wetlands are often located in low energy settings and the residence times of sediments and other pollutants can be much longer than in streams and rivers. There is a need for more research to understand how timber harvesting interact in the short- and long-term with the ecological and biophysical processes in wetlands.

- Timber harvesting in context of changing wildfire regimes. There is a need for a monitoring regime that quantifies the past and future frequency and severity of burns for harvest areas and combines this with monitoring the recovery from the burns in terms of water quality. This may trigger a mining of the historical records to assemble database on which to base summary relationships and related predictions.

- Scaling of impacts from steep upland waterways to larger river and estuaries. There is a need to develop a conceptual model to frame timber harvesting impacts on water quality and waterway health in the context of broader hydrological and geomorphic processes that govern the fluxes of sediment, nutrients and other constituents. Across a large landscape, the spatial scaling of timber harvesting areas and overlapping rainstorms means that some nature of disturbance is generally pretty common within a large area (e.g. within a large watershed), but that disturbances among areas tend to be somewhat asynchronous. Timber harvesting typically involves a large disturbance to a relatively small area in any one year. Local impacts can (potentially) be large, while larger scale impacts may be small because area harvested is small. As the spatial scale increases, the signal to noise ratio in water quality parameters decreases, limiting detection of impacts. This landscape-scale context is important for understanding how timber harvesting contributes to waterway impacts when considered alongside other land use practices (agriculture, urbanisation) and other disturbance events leading to large sediment delivery events (e.g. wildfire, east coast lows). There are opportunities to develop and test this type of conceptual model around current and historic monitoring across NSW's RFA forests, data which is being compiled as part of a concurrent project with the NRC[9].

6. **Frame a model, based on the concept of connectivity**, that can be developed over time into a predictive tool for assessing impacts and optimising timber harvesting operations for water quality outcomes. As highlighted by Croke and Nethery (2006), existing approaches to modelling erosion and sediment delivery in forests (e.g. RUSLE, WEPP, TOPOG) are not suited to widespread use as decision making tools for assessing erosion hazards in forestry environments. However, the insights from multi-scale investigations and observations of catchment-scale responses, as advocated above, can provide a basis for developing and testing models that are aligned with the connectivity concept. There are examples of connectivity being used in implementing sediment delivery models for forest roads (Takken and Croke, 2004). There is an opportunity to expand such efforts to include different sediment sources in timber harvesting areas and use catchment-scale measurement of sediment transport for model validation. Model development should form a central part of a broader strategic approach to forest and water management, which involves not just the forestry sector, but also tertiary research and government agencies working in the forest and water sectors.

   The development of predictive models is critical in terms of being able to simulate how forest management will impact on soil and water resources into the future (Neary et al., 2009; Smith et al.,

9 Guo et al (2020) Report for NRC Forest Baseline & Trend Project 3. Stage 1 Draft Report – Literature and Data Review

2011a). When developed for forest managers as the end-users, models can become tools for examining scenarios and optimising management practices to achieve water quality outcomes. Such tools provide critical input to the design and evaluation of best management practices as we move into conditions where wildfires and rainfall regimes are changing. For model development, it can be argued that there is more to be gained by focusing efforts and investment in one or two locations, instead of supporting monitoring activities across many sites. A risk framework from (1) above will help guide which location provide most return on effort.

7 Review outcomes and concluding remarks

The review of the literature on impacts of timber harvesting on waterways has presented the current state of knowledge about the effectiveness of mitigation and strategies for monitoring and improvement. Some of the key papers that have informed the review and their relevance to the different thematic areas are summarised in Table 9.

Overall, the knowledge base on forestry activities and sediment delivery in NSW catchments is strong relative to most forestry environments in the developed world. Much work has been done to understand sources of sediment, dominant processes, and the effectiveness of mitigation measures such as buffers and road drainage. The majority of the questions addressed in the review have been responded to using research from NSW or eastern Victoria, which is comparable to southern NSW in terms of climate, landform, and vegetation. We have drawn on research outside these regions to expand on some key points or add more weight to some of the broader findings that emerged in the research.

7.1 Summary of outcomes from the review

- Process-based research on runoff and erosion processes on roads and forestry compartments has produced important insights on the dominant processes that govern the magnitude of sediment delivery to streams. The key findings from this research in NSW and Victoria (and in the US) point to:
    - roads and tracks as the primary source of sediment delivery to streams,
    - buffers between source areas and drainage lines as being critical to reducing impacts of forestry related activities on sediment delivery to streams,
    - strong evidence that with best management practises the effect of harvesting activities on sediment delivery to streams can be effectively mitigated. However, with the limited number of research studies, and the diversity of geology, soils, vegetation, wildfire regimes, and the non-stationarity in drivers (rainfall), knowledge gaps remain with regard to outcomes in specific geographic settings.
- Catchment-scale studies corroborate findings from process-based research and show that impacts on sediment transport, turbidity and nutrient loads are relatively short-lived when they occur. Often, the impacts do not exceed expected background variability:
    - Peak flows and streamflow tend to increase for 1-2 years following harvesting,
    - When compared to Mountain and Alpine Ash forests, the long-term declines in streamflow appear less pronounced in the mixed species forests typical of those managed for silviculture in NSW. However, given conflicting results on this topic (see for example Cornish and Vertessy, 2001; Brown et al., 2005), more experimental work is needed to understand water yield implication of harvesting in SE Australian mixed-species forests.
- The frequency of intense rainfall and wildfires are likely to increase into the future. This has implications for how forestry activities interact with catchment function. Monitoring programs into mitigation effectiveness must consider how these rainfall and wildfires processes, which may be non-stationary, may conflate the signal of harvesting activities. Major events such as those in the 2019/20 wildfire season are important data points that capture some of regional disturbance processes that are operating alongside timber harvesting as controls on sediment delivery and transport through waterways. By not capturing these major events in the monitoring records, we miss the opportunity to position the effects of timber harvesting on waterways in a broader landscape context.
- Current IFOA conditions[10], including the buffers, are consistent with best management practise in mitigating for water quality impacts in forests managed for timber harvesting. The definition of channel heads, however, appear to be somewhat ambiguous both in the derivation of the channel

[10] NSW_Environment_Protection_Authority, 2020, Coastal Integrated Forestry Operations Approval – Conditions:, https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/forestagreements/18p1177-coastal-ifoa-conditions.pdf

network from DEMs and in the field assessment that is required under the IFOA conditions. A more objective approach to define channel heads would be beneficial. This approach should be consistent with the intent of the buffers, which is to minimise sediment delivered to drainage lines with concentrated flow. There are methods available for using LiDAR to identify where the dominant flow process shifts from diffusive to channelised.

- Temporary log crossings are likely to reduce sediment delivery hazard compared to conventional crossings. However, the benefit of log crossings needs to be evaluated based on field assessments.
- Water quality monitoring studies provide valuable and irreplaceable data to understand the net effects of forest management activities on catchment responses. Because of the large investment needed to commission and maintain these types of studies, it is critical that the monitoring is carried out with clear objectives and strategies for adding value beyond the detection of site-specific responses.
- The value of the long-term monitoring extends beyond the forestry sector, and there is strong argument for collaboration and co-funding amongst researchers, land and water management sectors and research funding bodies.
- Catchment-scale monitoring should be embedded withing a broader strategy to develop predictive models. This can be achieved by building on current research to frame conceptual models, then using catchment scale measurements to test and build confidence around model performance. The models should be targeting end-users in the land management sector, and be simple and pragmatic, but also aligned with the dominant processes that are known to lead to impacts. Opportunities to collect data for model development in gauged catchments include sediment tracing and source attribution at multiple scales, hillslope experiment for understanding connectivity and sediment delivery processes, and repeat lidar to map changes in channel network that may arise from channel incision caused by large peak flows from disturbed forest soils.

7.2 Recommendations for development of a monitoring program

We make the following recommendations for the development of a monitoring program:

1. Refine the objectives of the monitoring program to provide a stronger link between what is being monitored and its relevance for values that are being protected.
2. Develop a risk framework for linking timber harvesting to ecological impact on waterways and wetland. This is a starting point for refining the monitoring questions and developing a program for data collection and model development that focuses on the processes that are most problematic in terms of risk to waterway values.
3. Define and justify monitoring parameters based on risk to waterway and wetland values.
4. Embed water quality monitoring programs within a broader set of experimental work, aimed at linking both sediment delivery processes and mitigation measures to catchment-scale responses and waterway impacts.
5. Deliver research projects to address key knowledge gaps including both water quality and water yield implications of forest harvesting activities.
6. Frame a model, based on the concept of connectivity, that can be developed over time into a predictive tool for assessing impacts and optimising timber harvesting operations.

Table 9. Relevance of key publications to the six review questions (does not include all of the publications cited in this review).

Publication	Site / geographic scope	What are the major sources of pollutants, including sediments, to streams draining from NSW coastal state forests?	What is the significance of wildfires for the control or mitigation of these pollutant sources?	How do existing pollution mitigation measures (i.e. Coastal IFOA conditions and associated protocols) address each of these pollution sources?	Are the use of buffers of class one streams effective for pollution control purposes?	Where wetlands exist within NSW forests, what pollution mitigation measures are warranted?	What is the relative merit to continue or reinstate the Middle Brother, Yambulla, Kangaroo River and Karuah water quality monitoring projects?
(Atkinson, 2012)	Royal National Park, NSW	● yellow	● green	● red	● red	● red	● red
(Cornish, 1988)	Adelong Creek Catchment, NSW	● yellow	● red	● green	● red	● red	● red
(Cornish, 1989)	[General review]	● yellow	● green	● yellow	● green	● red	● red
(Cornish, 2001)	Karuah Hydrology Research Area, NSW	● green	● red	● green	● yellow	● red	● green
(Croke, 2004)	[General review]	● green	● green	● red	● red	● red	● red
Croke & Hairsine (2006)	[General review]	● green	● red	● green	● green	● red	● red
(Croke and Mockler, 2001)	Eden Forest Management Area, NSW	● green	● red	● yellow	● yellow	● red	● red
(Croke et al., 1999a)	Eden Forest Management Area, NSW East Gippsland FMA, Victoria	● green	● red	● yellow	● red	● red	● red
(Hancock et al., 2017)	Chichester State Forest, NSW	● red	● red	● yellow	● red	● red	● green
(Lacey, 1994)	Native forest near Eden, NSW Plantation near Oberon, NSW	● yellow	● red	● red	● red	● red	● yellow
Lacey (1993)	[General review]	● yellow	● red	● yellow	● yellow	● red	● red
(Major et al., 1998)	Red Hill, NSW	● red	● red	● red	● red	● red	● red
Office of Environment and Heritage (2012)	NSW	● red	● red	● yellow	● red	● red	● red
(Prosser et al., 2001)	[General review]	● yellow	● red	● red	● red	● red	● red
(Sheridan et al., 2007)	East Kiewa, northeast Victoria	● yellow	● green	● red	● yellow	● red	● red
(Smith et al., 2011a)	Cropper Creek, northeast Victoria	● yellow	● red	● red	● red	● red	● red
(Smith et al., 2011b)	East Kiewa, northeast Victoria	● yellow	● green	● red	● yellow	● red	● red
(Smith et al., 2011c)	[General review]	● yellow	● yellow	● red	● red	● red	● red
(Smolders et al., 2018)	Kangaroo River State Forest, NSW	● red	● red	● green	● red	● red	● green
(Turner et al., 1996a)	Towamba, NSW	● red	● red	● red	● red	● red	● red
(Turner et al., 1996b)	Bago State Forest, NSW	● red	● red	● red	● red	● red	● red
(Wallbrink and Croke, 2002)	Eden Forest Management Area, NSW	● green	● red	● green	● green	● red	● red
(Wallbrink et al., 2002)	Bondi State Forest, NSW	● green	● red	● yellow	● green	● red	● red
(Walsh and Lacey, 2003)	51 separate state forests in NSW	● green	● red	● green	● yellow	● red	● red
(Walsh et al., 2020)	Brooman State Forest, NSW	● yellow	● red	● green	● green	● red	● red
(Webb, 2008)	Kendall State forest, NSW	● red	● red	● yellow	● yellow	● red	● red
(Webb and Jarrett, 2013)	Yambulla State Forest, NSW	● red	● red	● red	● red	● red	● green
(Webb and Haywood, 2005)	Middle Brother State Forest, NSW Pjurrigan National Park, NSW	● yellow	● red	● green	● red	● red	● green
(Webb and Kathuria, 2012)	Red Hill, NSW	● red	● red	● red	● red	● red	● red
(Webb et al., 2012a)	Kangaroo River State forest, NSW	● yellow	● yellow	● green	● yellow	● red	● green
(Webb et al., 2012b)	Chichester State Forest, NSW	● red	● red	● red	● red	● red	● green
(Wasson et al., 2003)	ACT	● yellow	● green	● red	● red	● red	● red

● (red) = no or limited relevance ● (yellow) = useful ● (green) = directly relevant

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