DISCUSSION PAPER:

Evaluating forest road networks to protect water quality in NSW

September 2020

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1 Introduction

1.1 Background

The NSW Government has committed to ecologically sustainable forest management across all tenures (national parks, state forests, crown land and private land) under the NSW Forest Management Framework. From this, the government has considered how it should implement this commitment and has asked the Natural Resources Commission (the Commission) to independently oversee and advise on a state-wide monitoring, evaluation, reporting and improvement program (the Program) for NSW forests.

The Program seeks to explicitly link monitoring, evaluation and research to decision-making, both for policy and on-going forest management. The Program is guided by two key documents produced by the Commission - the NSW Forest Monitoring and Improvement Program and the Coastal Integrated Forestry Operations Approval Proposed Monitoring Program.

The effectiveness of forest road network design and management in reducing soil erosion and maintain in-stream water quality is one of the evaluation questions being asked by the Commission. In addressing this question, the Commission is looking to deliver the following outcomes:

- ensure that best practice research, evaluation and monitoring methods are adopted where appropriate and affordable,
- ensure that monitoring, evaluation and research activities are adaptable to new evaluation questions and evolving decision needs,
- enable cost-sharing and increase the cost-effectiveness of monitoring through collaboration between NSW agencies and adoption of new technology,
- build trust in processes and outputs amongst stakeholders and the community.

1.2 Project objectives and success criteria

The overall aim of this project is to develop an evidence-based methodology to assess the effectiveness of forest road network design and management in reducing soil erosion and maintaining in-stream water quality. The project objectives are specifically to:

- apply existing methods to ensure forest road network design and management maintains forest environments as catchments providing high quality surface water,
- draw on peer reviewed literature to establish a field survey method to assess the adequacy of existing road drainage (including stream crossings) to reduce soil erosion and protect water quality,
- select and assess a sample of forest road networks across different forest tenures in NSW,
- present the findings and suggestions for the adaptation of forest road network design and management to improve effectiveness.

To be successful, the method for assessing forest roads and water quality risk should be:

- cost effective and generate key metrics that enable the establishment of baselines and benchmarks that facilitate comparative analysis across different tenures, locations, and times,
- robust and stand up to scrutiny from agencies/groups/users with contrasting views on the use of forest,
- able to be applied broadly across different tenures and fit for purpose in that if the above is not possible it can be adapted so that it is,
- suitable for optimisation of road network/design/practise in relation to water quality, logistical constraints, and best-practice of building roads in forests.

2 Purpose of this discussion paper

The purpose of this discussion paper has been to document our current understanding of forest road networks in NSW and in relation to water quality, including policy and management frameworks, road classification approaches, current management practices and the state of the science.

The discussion paper is structured around the following questions:

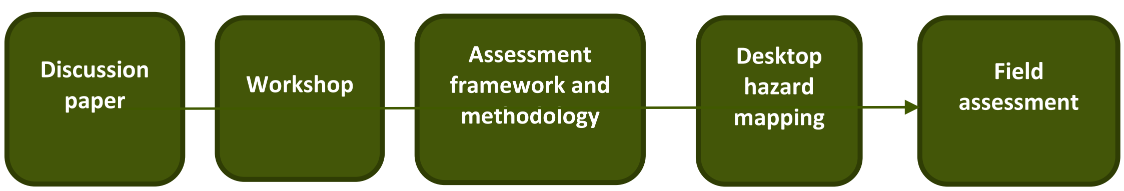
- What are relevant policy and guidelines for design and management of roads and how do these relate to different road types and their classification?
- What are the characteristics of a road network that determine the ability to generate impact on water quality and how is this supported by current scientific literature?
- What tools do we currently have available for evaluating the effectiveness of road designs and management in reducing erosion and impacts on water quality?

In some sections we pose specific discussion questions that have emerged from our review and method development.

In our assessment of forest roads and water quality, we are focusing our discussion on sediment delivery to the stream network. We have assumed, based on the available literature, that this process provides a strong proxy for the possible effects of roads on water quality. There are several complicating factors around sediment grain size distributions, other water quality constituents (e.g. metals and nutrients), and ecological sensitivities that we have not considered.

We have not considered impacts of roads in context of a broader risk framework where impacts are linked to assets and values. The discussion focuses exclusively on the erosion hazard, which we have defined in terms of the sediment delivery to streams.

The discussion paper is the first step towards developing the methodology and forms the starting point for workshop discussion.



3 Forest roads –monitoring, evaluation, and management context

3.1 New South Wales Forest Management Framework

The New South Wales Forest Management Framework (the Framework) is a management system for delivering Ecologically Sustainable Forest Management (ESFM) within the NSW forested estate. The Framework includes overarching policy and legislation, institutional and administrative arrangements, and associated planning and operational systems. It is administered by several State Government agencies and authorities and applies to both public and private land tenures (Figure 1). A completer overview of legislation relevant to forestry, environmental protections and conservation are outlined in Appendix A.

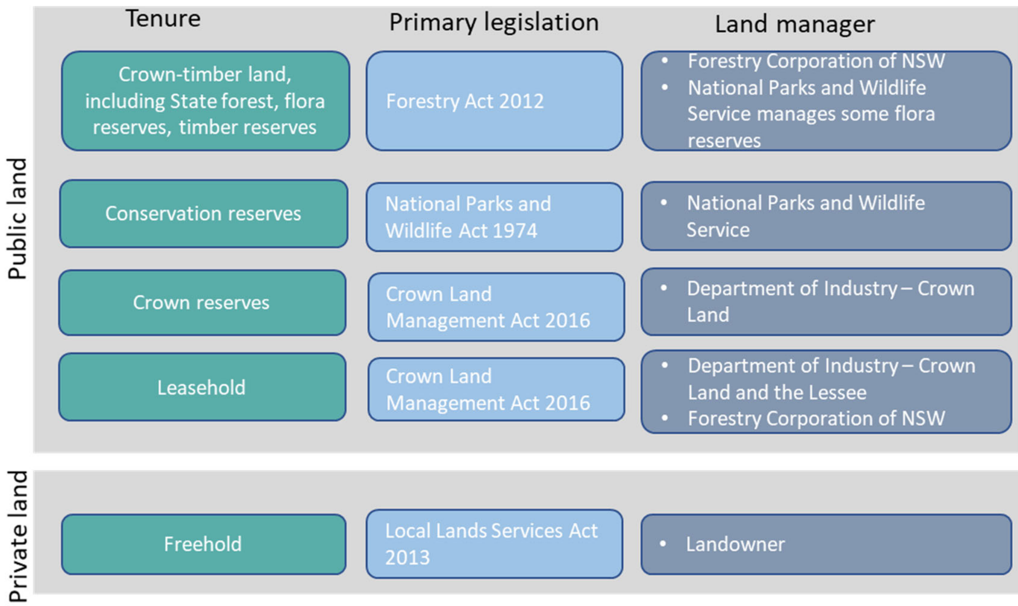


Figure 1. *Primary legislation and land manager across tenures on public and private lands.* ***Note****: land manager may not be responsible for roads.*

The Framework outlines an approach for evidence-based adaptive management and a continual feedback process associated with compliance and enforcement systems, stakeholder engagement, research, monitoring and review. All forests in NSW fall within scope, including national parks, state forests, plantation forests, private native forestry, forests on private and crown land.

With regards to roads and ecologically sustainable management outcomes for water quality, there are two key questions:

- *Coastal Integrated Forestry Operations Approval Proposed Monitoring Program*: Are **drainage feature crossings and road features effectively designed and maintained** to reduce the impact of forestry operations on waterway condition?
- *NSW Forest Monitoring and Improvement Program:* What is the health and stability of soil in forests, and what is their predicted trajectory? Under this state-wide evaluation question, one of the focus areas is to evaluate the effectiveness of forest management practices, including the **road network** to minimise soil erosion and health in high risk areas.

3.2 Management agencies and responsibilities in relation to forest roads

***Discussion question # 1**: Do we have a sufficient understanding and data to map out what is guiding design and who should be enacting an appropriate level of management to minimise impact of roads on water?*

***Discussion question # 2**: Is it useful to define boundaries/categories in relation to forest road network? If so, by tenure? By activity? By management agency? By the guidelines used to manage water and soil values? By hydroclimatic zones?*

***Discussion question # 3**: As water flows through all tenures- where it gets initially polluted may not be where it eventually appears. Who is responsible for the monitoring of water quality with respect to roads?*

Overview

Several government agencies share responsibility for management of forest roads in NSW (Table 1). Codes, approvals and guidelines for management of roads vary depending on land tenure, forest management activity or management agency responsible for the road network outside their tenure (e.g. state road in national park). Thus, the responsibility for design and maintenance of a road network within a small geographic region (e.g. a catchment) can reside with multiple agencies.

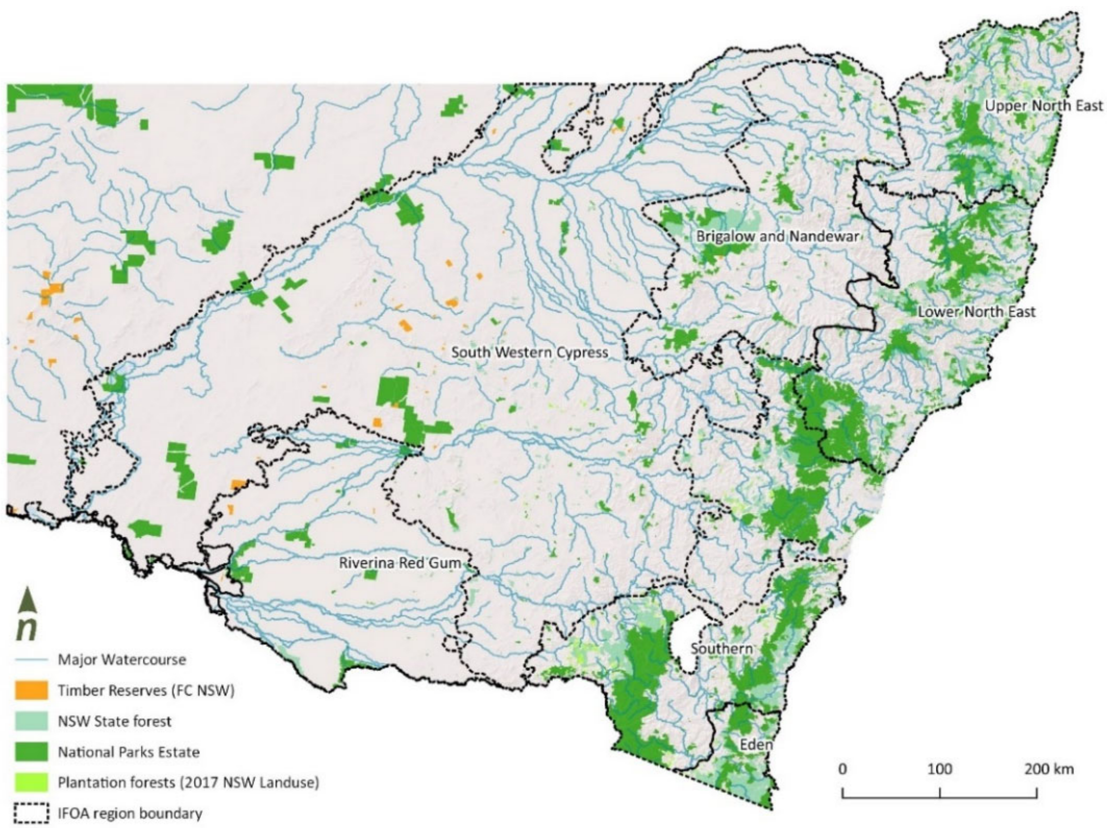


Figure 2. *New South Wales forest estate showing the extent of timber reserves, state forest, plantation and national park.*

Table 1. Roles and responsibilities of council, management agencies, relevant Acts, and their relation to management of roads

Agency	Legislation	Responsibility for forest management	Relating to management of forest roads
NSW Department of Primary Industries and Environment (DPIE)	Forestry Act 2012 Plantations and Reafforestation Act 1999 Fisheries Management Act 1994	Regulation of plantations Compliance of Crown forestry with licence under Forestry Act Forest industry policy and forest science	Lead research and policy development on forest management, including roads and impacts on water quality. DPIE Fisheries approve in stream works for road crossings
Forestry Corporation of NSW	Forestry Act 2012 Forestry Regulation 2012	Land manager of Crown-timber land, including State forest, timber reserves and flora reserves Forestry operations on Crown-timber land in compliance with IFOAs Selling wood Establishing and maintaining plantations	Responsible for the design and management of roads related to forestry operations in Crown-timber land and plantations
Local Land Service	Local Land Services Act 2013	Approvals and advice for private native forestry Advice to private landholders on land management options	Responsible for the design and management of roads related to private native forestry operations
NSW Rural Fire Service	Rural Fires Act 1997 (NSW).	The responsibilities of the NSW RFS are set out under the Rural Fires Act 1997	Not a land manager but does establish the Fire Access and Fire Trails Plan and sets standards for construction and maintenance through the *Fire Trail Standards*
National Parks and Wildlife Service	National Parks and Wildlife Act 1974	Manages national parks and reserves, covering over 7 million hectares of land Plant and animal conservation, fire management, sustainable tourism and visitation, research, education, volunteering programs and more.	Responsible for roads within parks, that are park roads, management trails and Ministerial Roads. Not Public road, which are the responsibility of Roads and Maritime Services or councils.
Councils and Roads and Maritime Services	Road Act 1993	Water quality management for state and regional road construction and the operation of the state road network is an environmental responsibility for Roads and Maritime Services Local roads are managed by Councils	Responsible for the design and management of public roads (state, regional and local)
Environment Protection Authority	Protection of the Environment Operations Act (POEO) 1997	The primary environmental regulator for New South Wales	Responsible for the regulation of native forestry operations (including roads) on private and public land in NSW.
Natural Resources Commission		Independent, evidence-based advice and thought leadership to Government to secure triple bottom line outcomes in natural resource management.	Oversee and advise on a state-wide monitoring, evaluation, reporting and improvement program

Public road network - state, region and local roads
These are designated as public roads under the Roads Act 1993. Assessment and management of water quality is incorporated in the planning, design, construction and maintenance of the public road network that fall under the responsibility of Roads and Maritime Services in Transport for NSW. Management of water quality impacts is guided by the Erosion and Sediment Management Procedure (RTA, 2008). The procedure assists with commitments to identify and mitigate risks associated with erosion from roads.

Roads in Native Forestry on Crown Land - The Integrated Forestry Operations Approvals (IFOA)
The Integrated Forestry Operations Approvals (IFOA) establish Protocols for each forestry region (across State Forests and Crown Timber Lands): South Western Cypress, Riverina Red Gum, Brigalow Nandewar and Central, and Coastal (Figure 2). These apply to the provision of roads *and* fire trials within these regions and contain the terms of the environmental protection licences needed in construction and maintenance of ancillary roads, which are designed to enable or assist in the forestry and fire management operations (NSW_EPA, 2010). For each region, Forest NSW utilises a Road and Fire Trail management plan, which aims to assist efficient forestry operations while limiting adverse environmental impacts relating to roads and fire trails. It is reviewed every five years considering the results of the monitoring and assessment carried out under the plan (Clause 59(5) of the IFOA). Concerns over the sensitivity of coastal areas and the higher rate of development has led to amendments of the Coastal IFOA so they contain increased protections for stream headwaters as well as allowances for track construction within ground protection zones. These allowances are subject to review if evidence suggests functional impact (NSW_EPA, 2018).

Roads in Private Native Forestry - Private Native Forestry Code of Practice
The Private Native Forestry Code of Practice guides native forestry operations in NSW and is the key document against which the EPA assess compliance of native forestry operations on private and Crown land (other than Crown timber Land). The Code is divided into 4 regions: Northern NSW, Southern NSW, River Redgum forests and Cypress and western hardwood forests. For each region, the Code (in sections 4 and 5) stipulates how roads are to be constructed and maintained to protect landscape and drainage features (e.g. NSW_Environment_Protection_Authority, 2016).

National Parks roads
National park and Wildlife Service (NPWS) adhere to a vehicle access policy which is focussed on supplying opportunities for visitors to understand, enjoy and appreciate parks whilst minimizing impacts on nature and cultural heritage. Overall, National park road networks aim to be fit for purpose, and any road that does not have a clear purpose should be deemed surplus to needs and be permanently closed. There are three road categories:

- Ministerial roads are roads, vested with the Minister for the Environment under Part 11 of the NPW Act, which traverse a park but are not reserved as part of the park. However, Ministerial roads are treated as part of the park under the NPW Regulation and this policy
- Park roads are roads reserved as part of a park that are open to the public, although they can be closed for park-management reasons. They are maintained by NPWS according to the Field Guide for Erosion and Sediment Control Maintenance Practices published by NSW Office of Environment and Heritage (NSW_Office_of_Environment_And_Heritage, 2012).
- Management trails are vehicle trails on lands reserved or acquired under the NPW Act and which are maintained by NPWS for the purpose of park-management activities. If these trails are open to public vehicle use, then they are roads under the road legislation.

Fire trails
Amendments to the Rural Fires Act 1997, through the Rural Fires Amendment (Fire Trails) Act 2016, provides a legislative basis for the establishment and maintenance of an enhanced fire trail network. The Fire Trail Standards made by the NSW RFS Commissioner (pursuant to section 62K of the Rural Fires Act 1997) establish the requirements to achieve an integrated and strategic fire access and fire trail network. The Standards set out design and construction requirements for identified fire trails in NSW and is used in conjunction with the NSW Rural Fire Service Fire Trail Design, Construction and Maintenance manual (Soil_Conservation_Service, 2017)

4 Forest roads, erosion and key management issues arising

4.1 What is the forest road network?

Discussion questions # 4*: How should we define forest roads for the purpose of this project? Do we consider both sealed and unsealed roads?*

Discussion questions # 5*: What is the most useful approach for classification? Base on type of use or type of impacts on erosion processes*? *What makes most sense in term of management?* is classification below in Figure 3 from US Forest Service useful in this context (https://www.fs.fed.us/t-d//pubs/pdf/11771811.pdf)?

As a working definition in this discussion paper, we consider forest roads to be those that support forest recreation, forestry, and fire management across all tenures. Forest roads are therefore broadly defined as any route (sealed or unsealed) used for vehicular access that supports forestry, fire management and tourism/recreation.

In context of forestry, the road network provides access to logs from the point of loading (log landing) within the forest area (NSW EPA 2016). Snig tracks, whilst a potential source of sediment (Croke et al., 1999), are not considered part of the road network. Instead, we consider these tracks part of the temporary disturbance associated with the general harvest areas. The impacts of the general harvesting areas and forestry operations, including snig tracks, are considered as a separate forest activity with its own set of monitoring and evaluation questions. Similarly, not all trails which may be accessed for fire-fighting purposes are fire trails. A fire trail is one that is designated as such, based on design standards for classes of fire-fighting vehicles. Fire trails are defined as those which are actively maintained and provide ongoing support for fire management. Temporary bulldozer tracks cleared during firefighting are not considered as part of the road network. They are considered during the management of post-fire response and rehabilitation efforts.

No road type exists in isolation but is part of a hierarchical network serving a variety of purposes over time. For example, a remote forest, without timber harvesting activity, will have a road network designed and managed primarily for the purpose of fire management. These roads are likely to experience little use when compared to those in other contexts, such as a National Park, where the main purpose of the road network may be to provide public access to sites of interest. In road networks built as part of forestry operations, the roads will typically range in permanence and activity and may experience low or high volumes of traffic depending on timber harvesting activity.

Often, such as in the case of some National Parks, road positioning can be the result of historic purposes which are no longer relevant (such as historic logging trails) yet continue to be repurposed and/or modified despite their poor design/placement, as the construction of a new road may not be worth the perceived social, ecological or economic impact. Many of the forest roads constructed for timber harvesting had their placement optimised for accessing log dumps and followed ridges or mid-slope positions. A vast number in NSW are left to passively regeneration where the land is no longer managed for timber harvesting and is only contemplated for re-opening during emergency fire-fighting operations. The NSW RFS fire trail register often identifies these as 'dormant' trails.

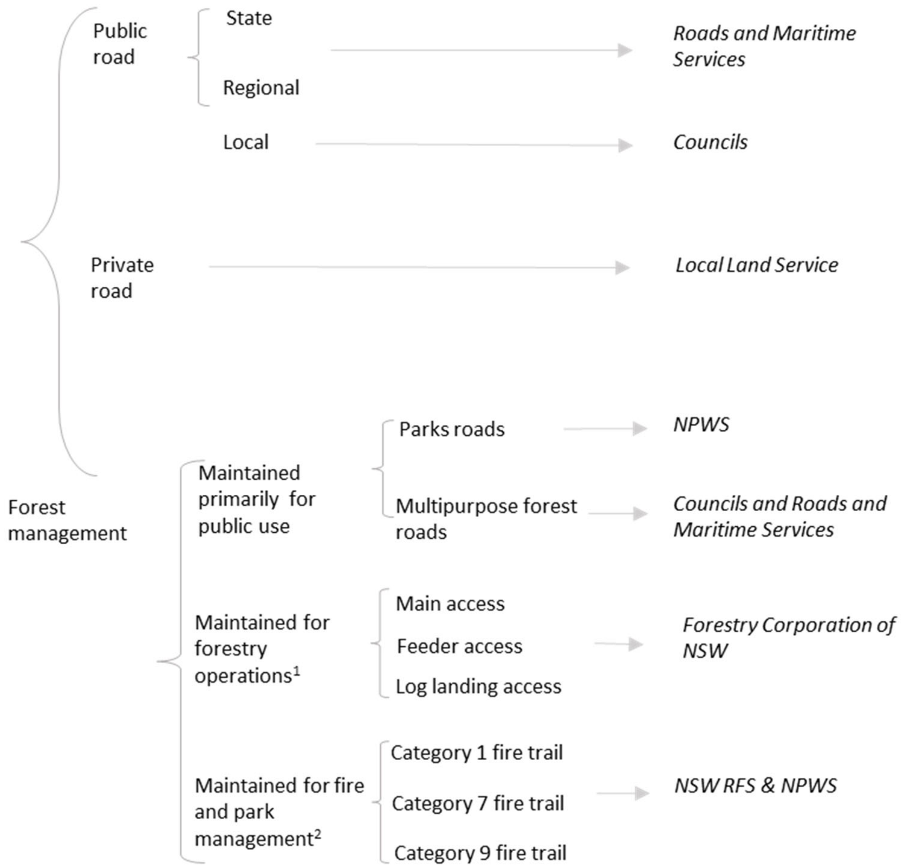


Figure 3. *Forest road classification for NSW (adapted from Gucinski (2001)).* [1]*Forestry Roads classification based on Croke and Mockler (2001).* [2]*Fire trails classification based on Fire Trail Standards* (NSW_RFS, 2019).

4.2 How do forest roads impact on erosion and water quality?

There are three key mechanisms (tied to erosion, runoff generation, and sediment transport) by which roads can impact on sediment delivery to streams:

- slope instability and more frequent mass failure (Sidle et al, 1985; Erskine, 2013). Roads constructed using side-casting techniques (where excavated material is simply pushed over the edge of the roadway), are vulnerable to landslides. This fill material is not compacted or stabilized in any way and often rests in unconsolidated piles on steep slopes. When this material becomes saturated, its strength is reduced until the material fails; often this occurs during large precipitation events (Reid and Dunne, 1984; MacDonald and Coe, 2008). Whilst this process results in high erosion rates, the delivery to streams is highly dependent on the degree of coupling between the sediment source areas and the stream network.
- increased erosion through sediment detachment from road surfaces and cut/fill batters (Reid and Dunne, 1984; Riley, 1988; Sheridan et al., 2006). Road surfaces and batters are directly exposed to erosive forces from raindrop impact and overland flow, and have erodibilities that are higher than surrounding hillslopes (Luce and Black, 1999). Depending on traffic intensity and moisture conditions, the road surface can have very high availability of fine sediment that is easily eroded (Sheridan et al., 2006). The impact of road erosion on sediment delivery to stream is highly dependent on the degree of coupling between the road drains and the stream network.
- increased surface runoff, which cause higher peak flows and more erodible flows during rainfall events (Jones et al., 2000). The impervious nature of road surface means that runoff generation occurs even in mild rainfall events (Luce, 2002). Road runoff, delivered to streams via table drains,

culverts and stream crossings, is one of the main mechanisms buy which sediment is delivered from roads to streams (Croke and Hairsine, 2006). When runoff is discharged from roads onto hillslopes, the erosion of hillslope soils can lead to increased coupling between road runoff and streams (Croke and Mockler, 2001).

The way in which these erosion and sediment delivery mechanisms impact on sediment loads in streams depends on a wide range of factors related to the generation of sediment from roads and the delivery of that sediment to the stream network. Generation of sediment from roads is largely a function of road surface, traffic, slope and the drainage areas contributing with runoff to the road. The delivery to stream network in largely a function of drain spacing (which governs discharge), the distance between road drains and stream network and the hydraulic properties for the hillslope. In addition to road-related parameters and catchment properties, the hydroclimatic setting is also important. For example, steep catchments in areas with frequent rainstorms are likely to be more vulnerable to road-related water quality issues than roads a low relief (i.e. flat) catchment that rarely receives high-intensity rainfall.

Figure 4. *Examples of road-related erosion. (left: Photo Gary Sheridan) Road runoff and detachment of sediment from the road surface. (right) Hillslope erosion caused by discharge from the road surface after a bushfire.*

Figure 5. *Examples of road-related erosion. (left: Photo Ross Peacock) Road runoff overwhelms culverts (left) and transports sediment and debris downslope (right: Photo Ross Peacock)*

Figure 6. (left) *Example of a road constructed in the 1950s using side-casting techniques (where excavated material is simply pushed over the edge of the roadway), and has collapsed a during large precipitation event in 2013 (Photo FCNSW). (right) Failure in road batter located in a very steep hillslope in response to east coast low heavy precipitation event (441 mm in 3 days)*

4.3 Management issues arising and mitigation

Discussion questions # 6*: Is there a tension between cost – safety – environmental impacts?*

When roads are eroding and generating sediment, there is the potential for increase sediment delivery into stream networks (Motha et al., 2003). This can have adverse consequences for catchment values, including waterway health and drinking water supply (Luce, 2002; Anderson and Lockaby, 2011). Several studies have shown that fine-grained material is a concern to water quality and the survival of aquatic organisms (Kaller and Hartman, 2004; Kemp et al., 2011; Jones et al., 2012).

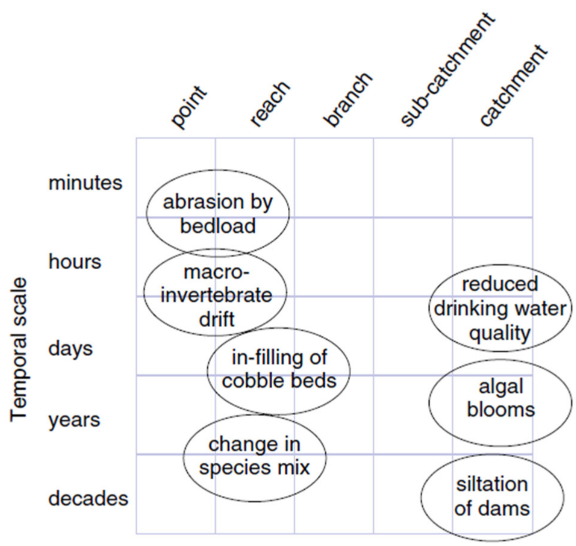


Figure 7. *The spatial and temporal scale of waterway impacts due to sediment delivery. From Sheridan and Noske (2007)*

In many cases, the potential impacts outlined above can be addressed with careful management of road drainage and road positioning across landscapes (Croke et al, 1999). Research shows that with careful design the sediment delivery from roads to can be minimised, resulting in low impact on catchment scale sediment transport (Cornish, 2001; Croke and Hairsine, 2006; Sheridan and Noske, 2007; Morris et al., 2015; Hancock et al., 2017).

Recognising the both the importance and opportunity to mitigate impacts, various agencies have developed best management practise (BMP) guidelines, recommendation and prescriptions on road designs and maintenance. These provide defined methods and design-guidelines that minimize erosion from road surfaces and the connection between roads and the stream network. They are written to facilitate BMP in road design and ultimately meet the objective of Ecologically Sustainable Forest Management (ESFM) in NSW.

With regards to erosion and water quality, there are two key principles, based on the available science, that underpin BMP in road design across all tenures:

- Drainage structures, stabilisation, maintenance, and road positioning all can assist to minimise the amount of runoff and erosion occurring as part of the road infrastructure. Drain spacing is a key design parameter, and can be optimised to limit the development of gullies at road-discharge outlets and reduce probability of linkage between a sediment source and stream (Croke and Mockler, 2001; Croke et al., 2005). Road drains, such as mitres, can slow runoff and induce sediment deposition within the drain structure.
- Minimising the road-stream interaction by positioning roads network away from the stream network. Proximity of the runoff source areas (road) to a stream determines the dispersal area below a road drain that is available for runoff to infiltrate before it reaches a wet-area or stream channel. By increasing in the distance between roads and stream network the probability of sediment delivery is reduced (Hairsine et al., 2002; Lane et al., 2006)

Key manuals and guidelines include:

- Fire Trail Design and Construction and Maintenance Manual (SCS, 2017). This manual has been written for the government authorities responsible for planning, constructing, or maintaining of fire trails. To effectively serve their purpose, fire trails must be, designed, constructed, and maintained to a standard that allows traffic by standard firefighting vehicles. They must also be built in such a way as to minimise the environmental impacts caused by soil erosion and sediment runoff.
- The 'Blue Book': Managing urban stormwater – Soils and Construction (Landcom, 2004). The purpose of this document is to provide guidelines, principles, and recommended design standards for good management practice in erosion and sediment control for unsealed roads. The target audience for this document includes those within local government, State government, utility providers, consulting firms, landholders and contractors who have a role in the planning, design, construction, or maintenance of unsealed roads in New South Wales.
- Erosion and sediment control on unsealed roads: A field guide for erosion and sediment control maintenance practices (NSW_Office_of_Environment_And_Heritage, 2012). Provides practical guidance on soil erosion and sediment control practices that improve assets management and minimise sediment entering waterways. The information and advice provided is based on best management practices.

Codes and legislative documents include:

- Coastal IFOA Protocol (2020) details the protocols that support requirement in the approval (NSW_Environment_Protection_Authority, 2020). This includes elements of road design, soil assessment, mass movement assessment, drainage design, riparian protection. The protocol also sets out a procedure of inherent soil erosion and water pollution hazard assessment, however it does not apply to roading. The Protocol also defines the methods and parameters of the drainage network.
- Private Native Forestry Codes (e.g. NSW_Environment_Protection_Authority, 2016). There are four of these, one for each region. The purpose of the Codes are to ensure timber harvesting is carried out whilst *maintaining non-wood values at or above target levels considered necessary by society for the prevention of environmental harm and the provision of environmental services for the common good* Codes for the Protection of the Environment and Codes for Construction and Maintenance of Forest Infrastructure, including roads, are given in Sections 4 and 5 of the Code.

- Plantations and Reafforestation (Code) Regulation 2001 which codifies best practice environmental standards, and provides a streamlined and integrated scheme, for the establishment, management and harvesting of timber and other forest plantations.

4.4 The case for monitoring, evaluation, and adaptive management

Given the large investments in management and mitigation to reduce sediment delivery, there is a strong case for using evidence to evaluate effectiveness of mitigation measures. There is a demand for information to answer questions such as:

- What is the return on effort in terms of reduced sediment delivery from different aspects of road design, construction standards and maintenance?
- Where should efforts to reduce sediment delivery be prioritised?
- When/where is the demand for road access justifiable when considering the potential impact on sediment delivery?
- How are road design, construction standards and management improving (or not) over time?
- What are the legacy effects for erosion and water quality of not maintaining surfaces and drainage structures on dormant forest roads?
- What are useful ways to measure baselines and benchmarks for comparative over time and across tenure?

A key constraint in monitoring and evaluation is the difficulty of collecting data to ascertain the effectiveness road design in mitigating sediment delivery rates to stream networks. Collecting catchment scale data on water quality parameters is extremely resource intensive and often not feasible for routine-based assessments of road impacts and mitigation effectiveness at large scales. Moreover, information in sediment transport from catchment-scale experiments fall into the black-box category and without efforts to quantify sediment provenance, they are typically inconclusive with regards to the exact mechanism that drive changes in water quality parameters (Croke and Hairsine, 2006).

In the concepts presented below, we approach the question of water quality impacts and monitoring in view of this limitations of catchment-scale measurements. We use the concept of hydrological connectivity (Bracken and Croke, 2007) as a means for understanding (and mapping) the intensity with which processes are likely to cause increased sediment delivery to streams.

5 Connectivity and road-to-stream linkage: concepts for assessing road impacts on sediment delivery to streams

5.1 Connectivity and its implications for sediment delivery to streams

In context of forest roads, hydrological connectivity is a concept for linking road-related erosion and runoff processes to the net sediment outputs across multiple scales within catchments (Bracken and Croke, 2007; Parsons et al., 2015). If a road network is decoupled or dis-connected from the stream network, the potential impact of local road-related erosion and runoff processes on catchment scale response is minimal. Minimising connectivity between road and stream networks is the therefore the main principle that underlie the water quality mitigation strategies in BMP.

In terms of intrinsic attributes of the road network, the level of road-stream connectivity is a function of road drainage spacing, road positioning in the landscape, and the hydraulic characteristics of the hillslope (Croke and Mockler, 2001; Sidle et al., 2004). These are all important in determining the degree of road-to-stream linkage:

- The road design (road width and drain spacing in particular) determines the volume of surface runoff produced at drainage structures such as culvert and mitre drains. Longer and steeper distances between road drains can mean more water discharge from roads onto the hillslope. More discharge means higher probability of runoff travelling further downslope, and therefore potentially connecting with the stream network. In steep slopes the concentrated discharge from roads can trigger an expansion the hydrological drainage network creating gullies between road and the stream network.

- The road positioning determines how much distance there is between the road drainage and the stream network. Given similar drainage spacing, a road traversing a hillslope 100m upslope from a drainage line is less likely to deliver discharge and sediments into the stream network compared to a road located 10m from the drainage line. Also, a road draining into converging topography is more likely to produce gullies and concentrated flow travel a long distance downstream than a road draining into diverging topography, where flows tend to be more dispersive.

The effectiveness with which road connectivity is minimised through careful design is contingent on maintenance. Connectivity can increase if the decoupling mechanisms (drainage structures, batter stability, hillslope buffering capacity) fail or are not maintained.

5.2 Spatial association between drainage network and road networks

When developing concepts for evaluating road impacts on sediment delivery across all forest tenures in NSW, an analysis of spatial association between roads and stream network provide a high-level insight into *potential* impacts. Overall, across a catchment, a road network that has many segment that fall into close proximity of stream networks is more likely to impact on sediment delivery than a network with fewer segment in close proximity to streams (Figure 8). In dissected uplands, for example, with high drainage density, the association between roads and streams would be stronger than it would in a low relief landscape with fewer drainage lines. The degree with which potential impacts translate to actual sediment delivery can be conceptualised at a much finer scale, for individual road segments.

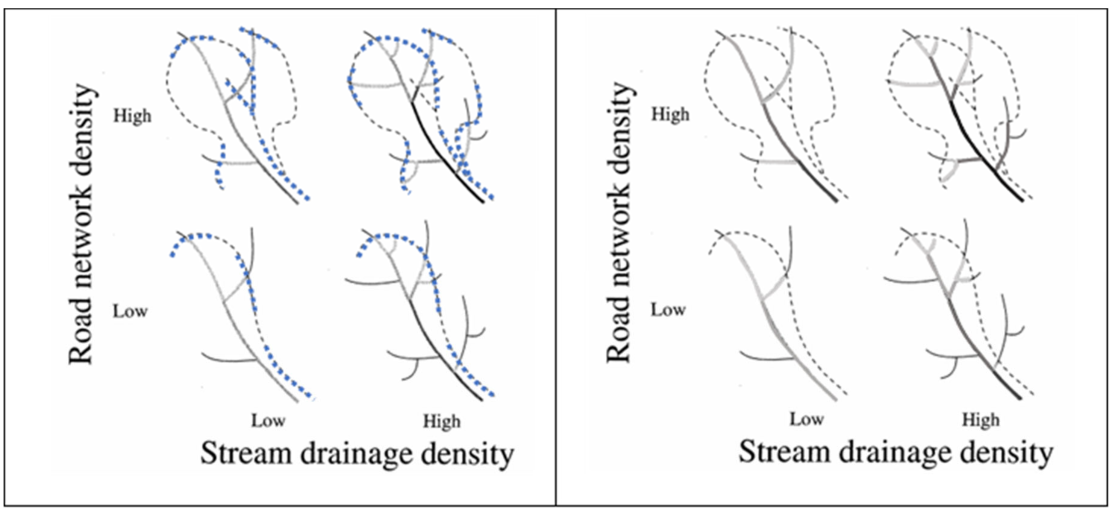


Figure 8. *Spatial association between drainage network and road networks provide a high-level indicator of potential road impacts on sediment delivery to streams. (left) Effect of increasing draining densities of the road network (dashed lined) and the stream network (solid line) on the number of road-segment crossing in a landscape. Blue dashed line indicates where on the road network there is a potential for road-stream coupling. (right) Spatial patterns of peak-flow disturbance patches (greater effect in shaded tones) created by road network (dashed lined) and the stream network (solid line). From* Jones et al (2000)*.*

5.3 Connectivity between road segments and streams

Discussion questions # 7*: How can we strike the right balance between cost and effectiveness (repeatable, representative and high- quality monitoring data)?*

For a given road segment where there is potential for impact, the connectivity between the road and the stream can be described in terms of road-to-channel linkages, which characterise the degree to which roads are hydrologically linked to the receiving waters. As per Croke et al (1999) these linkages can be:

- Full channel linkage, where a gully extends the entire distance from a discharge point, like a drain or culvert, to a stream.
- Partial channel linkage, where the incised pathway terminates some distance down the hillslope, often coinciding with a change in slope towards the valley bottom, or with the presence of an obstruction such as a fallen tree or debris mound.
- No channel linkage, where the discharge disperses as it leaves the source area and there is no morphological evidence of any concentrated flow.
- Direct linkage, where runoff and sediment reach the stream directly at stream crossings (fords or bridges). Road stream crossings increase the potential for sediment delivery as it is where sediment sources are often combined with the shortest delivery pathways, which inherently reduces the opportunity for infiltration, trapping or diversion of sediment laden runoff (Lane and Sheridan, 2002).

For modelling purposed the two types of sediment delivery pathways that need to be considered separately are:

- incised channels or gullies, where flow is concentrated, resulting in high sediment-transport capacity and runoff delivery downslope
- non-channelized (or diffuse) pathways, where water disperses or spreads across the hillslope, reducing flow depth, velocity and, consequently, the ability of the flow to transport sediment

Dispersed delivery extends typically up to 30m while direct channel has been found to extend up to three to four times as much (Croke et al., 2005; MacDonald and Coe, 2008).

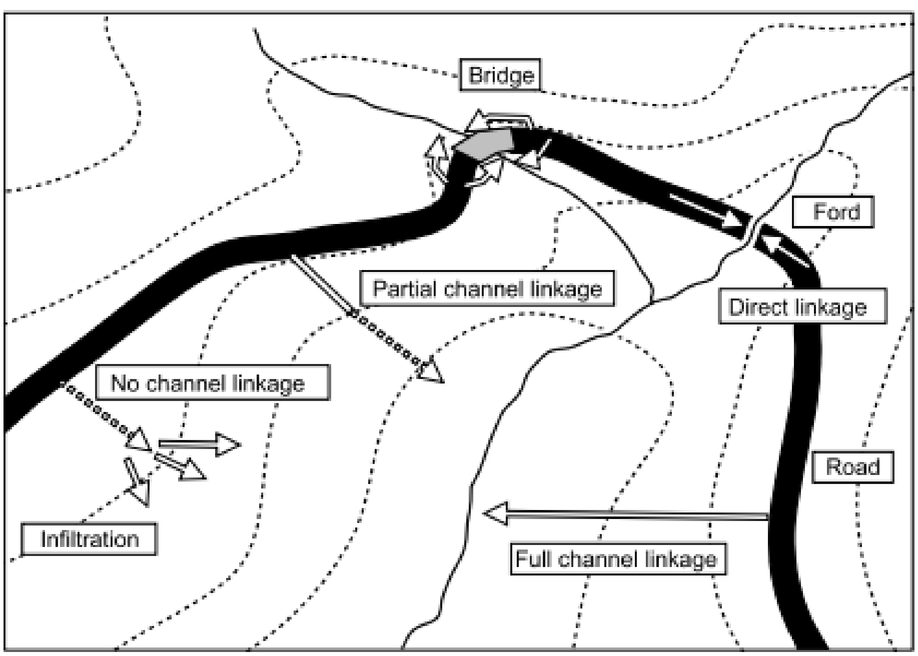


Figure 9. *The range of potential linkage categories within a forested catchment - from full channel, partial channel, and no channel linkage, to the direct linkage that occurs at a ford or bridge crossing. These categories can be used to determine the degree to which major sources like roads and tracks, are linked to stream (Croke et al, 1999).*

5.4 Catchment attributes contributing to connectivity

There are several catchment attributes that are important for determining the degree of connectivity between road and stream networks.

- Hillslope gradient is important. Discharge from roads on steep slope is more likely incise and travel long distance downstream when compared to a low-gradient hillslope.
- The hydraulic properties of the hillslope (vegetation cover and soil hydraulic conductivity) are also particularly important because they determine the length of hillslope needed to accommodate a given volume of runoff (Hairsine et al., 2002; Lane et al., 2006). Properties can be highly variable across forested landscapes. After bushfire, for example, the length of buffer required to accommodate a given an amount of runoff is about double that of a unburned hillslope because burned soils have lower infiltration rate and less surface roughness (Smith et al., 2011).
- Erodibility and dispersiveness of hillslope soils is important. More erodible and dispersive soils are likely to generate more efficient linkages between roads and streams because channelized flows form more readily at the points where road discharge is released onto the hillslope.
- Susceptibility to mass movement (related to slope and soil cohesion) is important. If a hillslope is prone to mass movement, there is an increased likelihood of road-related runoff and erosion leading to increased sediment generation and channel incision, which increase connectivity to streams.

5.5 Hydroclimatic attributes and bushfire regimes

There are two key hydroclimatic factors that are important in regulating connectivity and road-to-stream linkage:

- The rainfall regime is important in regulating connectivity and road-to-stream linkage. Theoretically, if all else were equal, a road network in a catchment with high chance of receiving intense rainfall is more connected to streams than a road network in a catchment with less intense rainfall (Hairsine et al., 2002). In terms of precipitation, it is type, amount, intensity and duration all affect surface runoff generation and subsequently water discharge. Much of surface-dominated erosion occurs in response to short and intense burst of rainfall. The 30-minute rainfall intensity, often used a metric to represent these erosive rainfall bursts, is captured in rainfall erosivity. However, the events that trigger mass failure are caused by longer duration rainfall and may be more strongly related to daily totals. Both rainfall types should be considered in evaluating risk to water quality from road networks.
- Wildfire regimes are also important. Discharge from road networks in burned landscape may be more connected to streams than in unburnt landscapes, driven in large part by reduced infiltration rates and less vegetation cover (Sheridan et al., 2007; Nyman et al., 2010). Discharge from roads is higher due to higher surface runoff rates from upslope, and there is less infiltration occurring on the hillslope (buffer) between roads and streams. The frequency and intensity of bushfire may therefore an important consideration when evaluating connectivity and the effectiveness of road design in mitigating impacts on sediment delivery. Impacts of bushfires on runoff and erosion is highly contingent on post-fire rainfall. In some cases, a large wildfire is followed by intense rainfall (Yang et al., 2018) whilst at other times wildfires occur within droughts when post-fire rainfall is less than average (Tomkins et al., 2008).

6 A framework for assessing the effectiveness of forest road network design and management in reducing soil erosion and maintain in-stream water quality

6.1 Overview

Discussion questions # 8*: Does the framework strike the right balance between capturing key processes whilst providing a pragmatic approach to monitoring and evaluation? Does it seem feasible? What is missing?*

Discussion questions # 9*: Is there value in using state-wide (desktop-based) mapping of road segments as a baseline for understanding catchment- to regional-scale differences in the potential for roads to impact on water quality?*

Discussion questions # 10*: How quantitative do we want to be in developing a desktop assessment to guide and focus the field assessment?*

We propose a framework based on earlier work (Croke and Mockler, 2001; Hairsine et al., 2002; Takken et al., 2008) to assess forest road impacts on sediment delivery across different tenures and road types in NSW (Figure 10). In this framework, the information at each road segment (e.g. Figure 8) provides the input needed for implementing a probabilistic model of sediment delivery to streams. The intent of the model framework is to produce sediment delivery hazard maps for benchmarking and to focus and guide the field assessments, not to produce quantitative estimates of sediment delivery.

There are three steps in the analysis:

- Extracted road segments based on distance to streams. Road segment locations occur ?where stream networks come within some specified distance (e.g. < 100m) of the stream network, where road to stream linkage may occur. These road segments will be populated with attributes as far as possible given data constrains. Key attributes include traffic, drain spacing, road width, storm IFDs, distance to stream, mean annual rainfall, and other supporting information that is relevant for context, but not necessarily a model input.
- Modelling sediment generation, runoff and pathways. Using assumed drain spacings (according to codes and guidelines) and assumed traffic, the modelling will first yield a measure of erosion rates on roads (e.g. Sheridan et al., 2006) and discharge at drains for a rainstorm event with a given return interval (Takken et al., 2008). The degree with which road segments impacts on sediment delivery depends on the type of sediment delivery pathways (gullied or dispersive) linking roads and streams. In the absence of field data, the gullied and dispersive pathways will be discriminated using the threshold approach described in Croke and Mockler (2001).
- Implementation of the model to assesses sediment delivery hazard using approach outlined in (Croke et al.(2005) where both the discharge plume from drains and exponential decline in sediment concentration are considered in producing an estimate of likely sediment delivery from roads to steams. The output will be linked to each road segment and used to provide a mapping tool for assessing hazard, sensitivities and prioritising field assessments.

The key assumption with this framework is that sediment delivery hazard can be effectively captured by considering two processes: erosion on roads and the probability that eroded sediment reaches the streams. In this model, these processes are considered independently of catchment attributes (e.g. soil properties, and vegetation), bushfire regimes and mass movement. However, road segments can be populated with variables such as flow accumulation, rainfall probabilities, soil properties to help inform other aspects of sediment delivery hazards that are not considered the framework presented above.

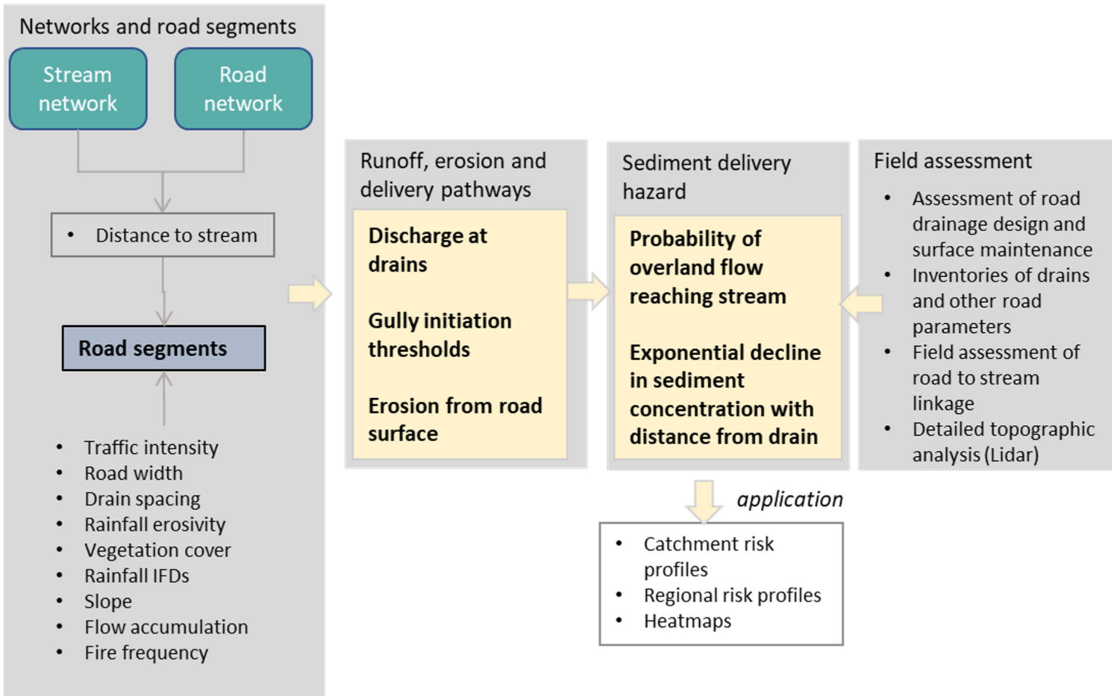


Figure 10. *Processing step in implementing the sediment delivery hazard assessment.*

6.2 Data sources

Data requirement and possible sources for desktop assessment are listed in Table 2. This list is not exhaustive, and it also includes data that may not be used in the assessment. For field assessments, there are likely to be additional data requirements and opportunities.

Table 2. Relevant attributes for mapping sediment delivery hazard and possible data sources.

Attribute	Description	Data sources for consideration
Road network	Reliable information on road network and types is needed to inform the hazard assessment	• Geoscience Australia (TOPO250K_Roads) • Other road data (PSMA) • NPWS road network • RFS Fire Trails Register spatial layer (trail by capacity, classification, dormant versus active, etc)
Distance to stream	Distance to stream determines how much hillslope is available to accommodate discharge from road drainage structures	• Spatial analysis using DEMs to construct drainage network
Drain type and spacing	Drain types determine how water is delivered to the hillslope	• Road inventories • Field assessments
Traffic and road surface	Traffic and road surface are important for erosion rates on road surface	• Road inventories and data on truck movement from FCNSW • Historical records? • Measurements (field assessment) • Maintenance program • Age and type of crossing (bridge) structures – risk of collapse of earth rammed timber bridges into stream

Slope downstream from road segments	Local slope at the hillslope link is important for how much energy is available to detach and transport sediment	• From DEMs and extracted for relevant hillslope segments • Lidar where available
Geology/soil in area surrounding road segments	Soil/geology at the segments provide catchment indicators of how slope stability and the capacity of surrounding terrain to accommodating runoff and	• NSW Soil erodibility (RUSLE layer) • Monthly hillslope erosion (Yang model) • Seasonal hillslope erosion (Yang model) • Mean annual hillslope erosion (Yang model)
Ground Cover in area surrounding road segments	Ground cover (vegetation) at the segment assesses risk of runoff not infiltrating	• NSW C-factor (RUSLE layer) (Yang model) • Any other vegetation cover indices?
Flow accumulation	These are important in determining how much energy is available for runoff and detachment. A segment in flat terrain represent less risk than a segment in a steep catchment.	• Digital elevation models • NSW Slope Steepness (RUSLE layer)
Rainfall regimes	The rainfall regime partially determines how much runoff is likely to be generated at the from road surfaces	• Intensity-frequency-duration curves (BoM) • Daily rainfall erosivity (Yang model) • Monthly rainfall erosivity (Yang model) • Seasonal rainfall erosivity (Yang model) • Annual mean rainfall erosivity (Yang model) • Daily rainfall data grid (BoM) • NSW Rainfall erosivity (RUSLE layer) (current and future) from NARCliM
Fire regime	Frequency and intensity for bushfire will impact on how often the landscape experiences a temporary increase in runoff and erodibility.	• Fire history (wildfire and prescribed fire) data from NSW (Seed). This is only reliable for NPWS lands. Use RFS layer which is cross-tenure • FESM – fire severity layer (SSED)

7 Review process and next steps

The discussion paper will be presented to NRC in preparation for stakeholder workshop. Outcomes from workshop will be used to guide the final recommendation on methodology.

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Attachment A
Overview of legislation in the NSW Forest Management Framework

Taken from page 81 in Overview of the New South Wales Forest Management Framework.