FOREST ROAD SEDIMENT DELIVERY RISK ASSESMENT:

Evaluating forest road networks to protect water quality in NSW

November 2022

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Executive summary

The Forest Monitoring Improvement Program (FMIP) links monitoring, evaluation, and research to decision-making, both for policy and on-going forest management in NSW. Evaluating the effectiveness of forest road network design and management in reducing soil erosion and maintaining in-stream water quality is one of the aims of the FMIP. This report summarises one component of the FMIP: the development and application of a risk assessment tool that can be used by road and land management agencies to plan and then implement mitigation measures to reduce sediment delivery from forest roads to waterways. The risk assessment framework employed by the FMIP ties together earlier outputs of the FMIP (which are summarised in the Attachments to this report), while the risk assessment tool (the focus of this report) is used to evaluate sediment mitigation options at the local scale.

The risk assessment framework described in this report can be used by forest road operators to optimise maintenance of existing road networks, and to identify the most cost-effective measure of reducing sediment delivery to high value waterways in a consistent, transparent and scientifically rigorous manner. The report first outlines the different project stages and how they feed into the overall risk framework. In view of this broader project context, the reports then describes the steps for undertaking a risk assessment, whereby the different components of the risk framework are integrated to focus monitoring efforts, quantify sediment delivery potential and identify effective mitigation options for problematic parts of the road network.

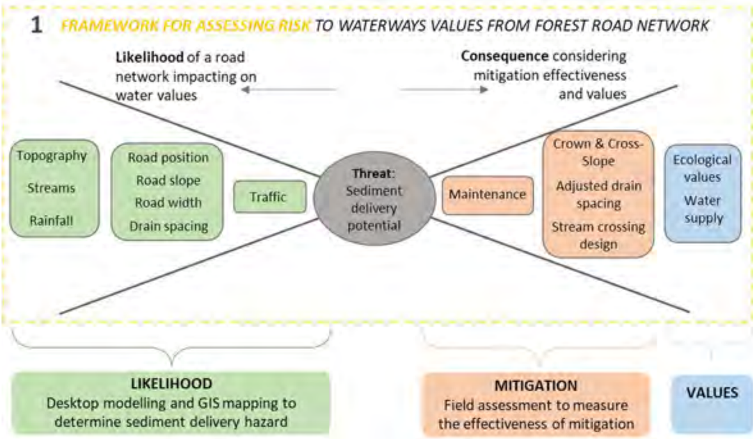
Overall, users of the risk assessment move through a five-step process. The risk assessment uses two key outputs from this project: the statewide sediment delivery potential model (the statewide model), and the local scale sediment delivery potential model (the local model). The statewide and local models use the best available scientific understanding of the processes that the drive erosion of road surfaces, runoff generation and the downslope transport of runoff and sediment to waterways.

Risk framework: Connectivity between road networks and waterways

The risk is conceptualised in terms of:

- The likelihood of impact, considering the location of roads in relation to waterways. This largely about modelling the sediment delivery potential taking into account the hydrological connectivity between roads and drainage networks. The likelihood component is modelled at a state-wide scale, and provides a mechanism for focusing more detailed assessment, and designing cost-effective programmes for monitoring and improvement.
- The consequence. This is about assessing the degree with which the sediment delivery potential translates into a real risk, considering road designs and efforts to mitigate sediment delivery risk. The consequence is assessed using same concepts as what informs the likelihood. However, the modelling is more parameter-intensive and requires field data on location of drains and road topography.

Together, the assessment of likelihood and consequence make up the risk assessment framework and provided a basis for efficient identification and quantitation of risk and associated risk mitigation effectiveness.



Statewide model: Mapping sediment delivery potential

The purpose of the statewide model is to identify the parts of the NSW forest road network that pose a threat to water quality. Using the output of the state model, users select parts of the forest road network in which sediment delivery potential is high, and where application of the local model can provide guidance on the best mitigation measures to reduce sediment delivery to waterways.

The statewide model was applied to all unsealed forest roads across NSW. Spatial data on forest roads that were input to the state model are drawn from National Parks and Wildlife Service (NPWS), NSW Forestry Corporation and private forest tenures. The state model estimates the total mass of sediment delivered to waterways from 100 m long segments of unsealed forest roads during a 30-minute 10 % AEP storm event. By using empirical models for each of the processes that control sediment delivery to waterways, and by employing reasonable assumptions regarding road design and soil properties, all forest road segments are ranked either high, medium, or low sediment delivery potential.

Local model: Assessing sediment delivery mitigation measures

The local model is used to predict the sediment delivery potential of sections of a road network, at the catchment or sub-catchment scale. A desktop GIS process and field assessments are used to obtain network-specific data on road drainage design and the condition of drains and road crossings. The data generated from these, are input into the model to produce a more precise measure of sediment delivery potential, based on information that is not available for application at the statewide scale. The local model estimates sediment delivery from each drain along the road network, and can quantify the reduction in sediment delivery potential with changes to road drainage, and/or if associated mitigation measures are implemented. Outputs are calculated for individual drains surveyed, summarised at the network scale, and then classified as either low, medium or high mitigation effectiveness.

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. On behalf of the NSW Government, the Natural Resource Commission (NRC) seeks to implement this commitment through the implementation of the Forest Monitoring Improvement Program (FMIP).

The FMIP links monitoring, evaluation, and research to decision-making, both for policy and on-going forest management in NSW. Evaluating the effectiveness of forest road network design and management in reducing soil erosion and maintaining in-stream water quality is one of the aims of the FMIP. In addressing this aim, 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.

The methodology for evaluating the forest road network is developed as part of a broader program for monitoring and evaluation of waterway health in relation to forest management and timber harvesting[1].

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.

[1] Alluvium (2020) Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests. Report for the Natural Resources Commission. pp 1-33. December 2020.

1.3 Project framework

The program utilises a risk-based framework, with a sediment delivery hazard model used to quantify the likelihood of sediment delivery to waterways, and a field assessment (combined with information describing catchment specific values being managed for) to define the consequences. The relationship between these components of the program is illustrated in Figure 1.

1.4 Project stages

This project included four stages:

- **Development of a discussion paper and initial stakeholder engagement**. The discussion paper documents current understanding of forest road networks in NSW in relation to water quality, including policy and management frameworks, road classification approaches, current management practices and the state of the science. 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 overall methodology and forms the starting point for workshop discussion. The final discussion paper is included in Attachment A.
- **Risk assessment framework and conceptual model**. The risk assessment framework and the conceptual model of sediment delivery tie each of the major project parts together. The conceptual model combines previous research into a model of sediment delivery that explicitly accounts for both sediment generation and sediment delivery processes. The risk assessment framework relates the physical processes that drive sediment delivery to the modelling and measurement of that threat. The risk assessment framework and conceptual model are summarised in section 1.3 of this report.
- **Statewide mapping of erosion potential to focus monitoring and improvement.** The method development is summarised in a method recommendation report. The method document outlines an approach for assessing the effectiveness of forest road network design and management in reducing soil erosion and maintaining in-stream water quality. The methodology incorporates the issues raised in the discussion paper, has been shaped by the feedback received from the technical panel review, steering committee meeting, the stakeholder workshop, and the reconnaissance field trip. The method recommendation is included in Attachment B.
- **Application of the risk assessment for a sample of forest road network** (this report). The final stage of this project was the development and demonstration of the risk assessment, combining the statewide modelling, and focused modelling of a specific network that was surveyed as part of a field assessment. The key output of this step is a excel based tool that can be used to identify the most effective sediment mitigation measures for a target road network. The risk assessment procedure and the field assessment protocol are summarised in this report.

1.5 Purpose of this report

The purpose of this report is to outline the risk assessment method that can be used to identify the most effective sediment mitigation measures for a surveyed road catchment.

The risk assessment method incorporates a field assessment, basic GIS processing and the use of a local scale implementation of the sediment delivery model. The steps used to undertake this risk assessment are outlined in the main body of this report, while the project discussion paper, method statement and additional supporting detailed that support the risk assessment are provided in Attachments A-D.

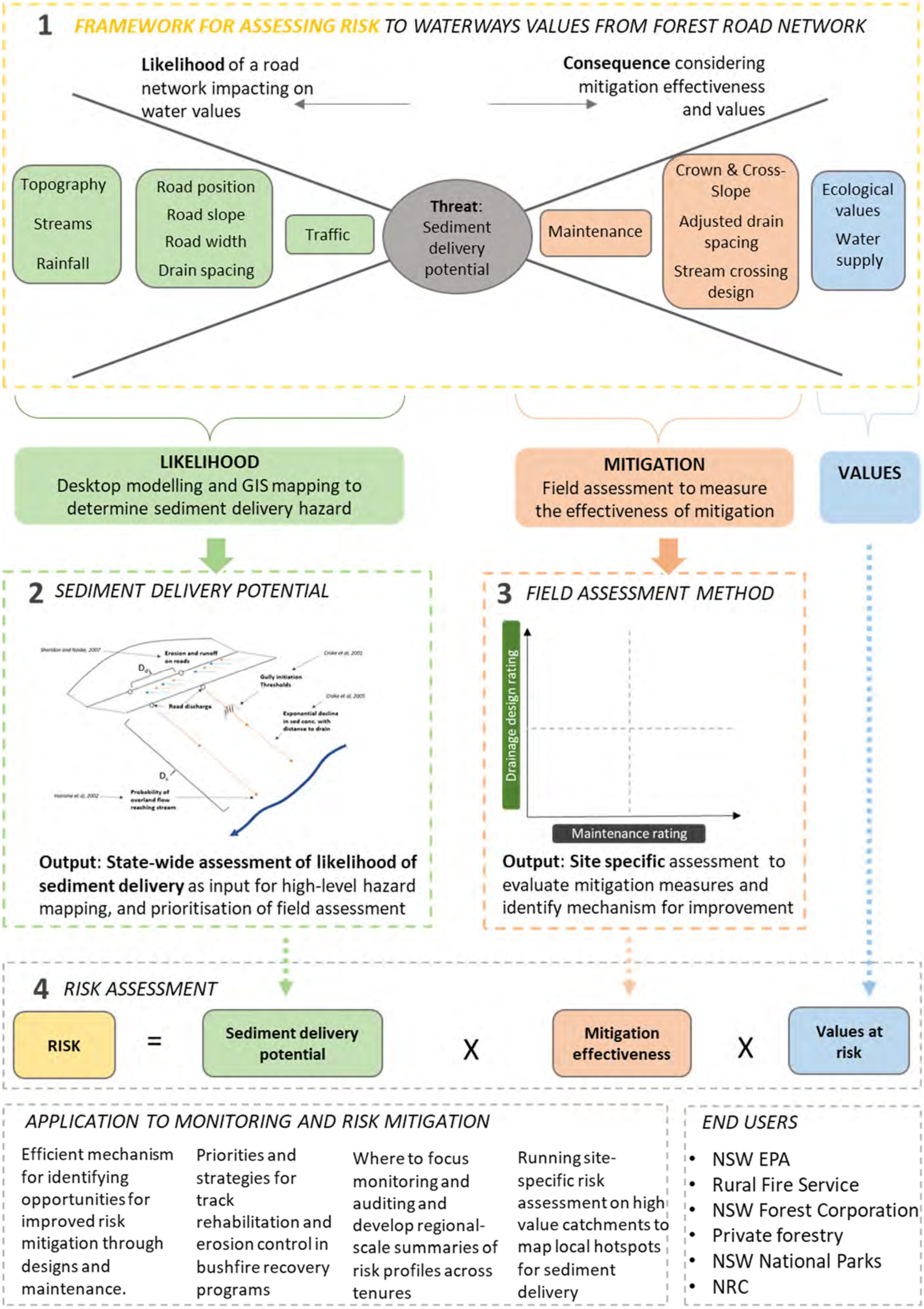


Figure 1. *Diagram relating the modelling (likelihood) and field assessment (mitigation) components of the program used to calculate the risk forest road networks pose to water quality.*

How to access the risk assessment tool

This report summarises the development of a risk assessment tool that can be used to identify sediment delivery hotspots, and the most effective mitigation measures to reduce the delivery of sediment from forest roads to waterways. The local sediment delivery model and risk assessment tool referred to in this document are implemented in excel, and can be freely downloaded, along with the outputs from the statewide model, from the SEED environmental data portal here:

https://www.seed.nsw.gov.au/

All instruction on the use of the excel implementation of the risk assessment tool, and interpretation of the output are included in this document.

2 How the field assessment method was developed

2.1 Risk assessment tool

Links between statewide and local model applications
The risk framework and assessment tool utilise the state and local version of the sediment delivery model to assess the risk sediment delivery from forest roads poses to waterways. The state-wide model is used as a measure of likelihood of impact from forest roads (i.e. sediment delivery potential) and provide information to help focus more detailed monitoring efforts where field assessment are needed to direct and inform the improvement programme. The local model, which is underpinned by the same model components, is implemented using data from field assessment and GIS post processing. When implemented for surveyed road network the model provided a measure of consequence, which is about how the sediment delivery potential translated into risk actual sediment delivery risk, considering road design specification and maintenance,

Field assessments are needed for acquiring the data that is used to define drainage locations, road design parameters and road topography, which are needed for assessing the effective of current mitigation measures. When implemented using field data, the model will identify problematic parts of the road network and determine *how elements of road design and maintenance can be improved to reduce sediment delivery*.

There are three key differences between the state model and the local model:

- **Input parameter values**: the catchment-scale implementation replaces assumptions regarding drain spacing, road slope and width and drain condition with accurate field measurements.
- **Waterway crossings**: Waterway crossings can have a significant impact on sediment delivery hazard and are included in the local model. In terms of runoff generation and sediment delivery to waterways, waterway crossings are a subset of the more generic roads with drains, except the length of a road segment leading to the crossing (the distance between upslope drains and the waterway crossing), and the length of hillslope available to disperse flow between drains and the waterway, are both relatively small. Additionally, the field assessment protocol includes additional measurements and observations at waterway crossings to inform sediment mitigation measures.
- **Unit of analysis**: sediment delivery hazard is modelled for each of the drain surveyed rather than 100m segments of road used in the state-wide implementation of the model.

This report summarises the overall approach to gathering the necessary field data to run the local model, how to transform field data into model inputs, and then steps to run the local model to generate sediment delivery hazard for the catchment. The steps described below assume that users possess, or can access, a basic to moderate level of GIS competency.

Drain assessment
The drainage assessment focuses on mapping the location of road drains and making a small number of measurements at each drain. Those observations are processed and input to the local scale model. In addition to the location of drains, topographic low and high points along the road network are also mapped. The topographic points are used during post-processing to segment the road drainage network, so that the catchment area of each drain can be accurately calculated.

Waterway crossing assessment
The waterway crossing component of the field assessment also relies on mapping the location where the road network crosses waterways and recording a small number of observations at each crossing. Unlike the road drainage component, observations made at waterway crossings are not inputs to the local scale model. Instead, the data obtained from waterway crossings is used to in a more qualitative manner. The intent of the waterway crossings observations is to identify elements of crossing design or maintenance that can be modified to quickly reduce sediment delivery at crossings. For example, the distance to upslope drains, the condition of the approach road surface, and the condition of bridge abutments.

Figure 2. *The two types of features targeted during field surveys: drains and waterway crossings*

2.2 Pilot demonstration

This project undertook a pilot demonstration of the field assessment method, to refine and demonstrate the effectiveness of the field assessment and the overall risk assessment process. Field assessment methods were developed during an initial campaign in the Tallaganda State Forest in May 2021. Key outcomes of the field reconnaissance relevant to the survey method and the demonstration pilot were:

- The need for field assessments accurately geolocate drains and waterway crossings. The absolute location and elevation of sample sites (drains) has a large impact on calculations of road surface area and distance to waterway, which in turn have a large impact on the sediment delivery hazard predicted by the model (see section 3.4). A real time kinematic (RTK) GPS, which captures points with centimetre scale accuracy is the most appropriate tool and is operated most efficiently by an experienced surveyor.
- Road crowning was to be included as an input parameter for the sediment delivery model, due to the impact of crowning on catchment area calculations of each drain.
- A total of 10 km of roads, of varying width, slope and intensity of vehicle use are ideally to be sampled at each of the 3 forest tenure types, to produce a total road sample of 30 km. Surveying a sample of roads across the tenure types provides sufficient road drainage data to serve as a demonstration pilot for the assessment method. The field assessment data can also be used to compare the risk of sediment delivery to streams between the different tenures type, although such a comparison between tenures is beyond the scope of this project. This distance allows a representative sample to be obtained for each tenure while also being feasible for a small (2-3 person) team to accomplish.
- The importance of capturing the contributing catchment area for road crossings, which are a major sediment delivery pathway to forest streams.

The pilot demonstration included:

- 25 km of roads surveyed across State Forest, NPWS and private tenures. Although the target length of road surveys was 30 km, survey speed was substantially reduced in areas where a lack of cell coverage and poor sky visibility due to tree canopy meant an RTK GPS could not be used, and the slower survey method using a laser level total station was used instead.
- Survey areas centred around Tumut, Tumbarumba and Coffs Harbour
- Roads surveyed included haul roads, fire trails, valley floor, ridgeline roads and waterway crossings.

The primary outcome of the pilot demonstration was the risk assessment method outlined in this report, a body of data that included drain and crossing measurements, photos and information on the most efficient method to undertake field surveys and post-processing. The road segments surveyed in each of the tenures are summarised in the following sections.

Wereboldera State Conservation Area
Surveys were conducted along a 2.2 km section of road in the Wereboldera State Conservation Area (NPWS tenure with a small segment that included a waterway crossing within State Forest tenure), in December 2021. The segment of road surveyed spanned a steep ridgeline that enclosed a small subcatchment. The ridgeline road segment was selected to be representative of contemporary road construction concentrated on steep gravel roads/ridgelines not regularly trafficked by large vehicles and with minimal stream crossings. The road is predominantly drained by cross banks and mitre drains. The underlying geology is Quartz-rich shale/slate, siltstone and interbedded fine-grained sandstone[2]. Shallow soils were Chromosols [CH] and are not known to be sodic or dispersive. The extent of the segment surveyed is shown in Figure 3 and example photos are shown in Figure 4.

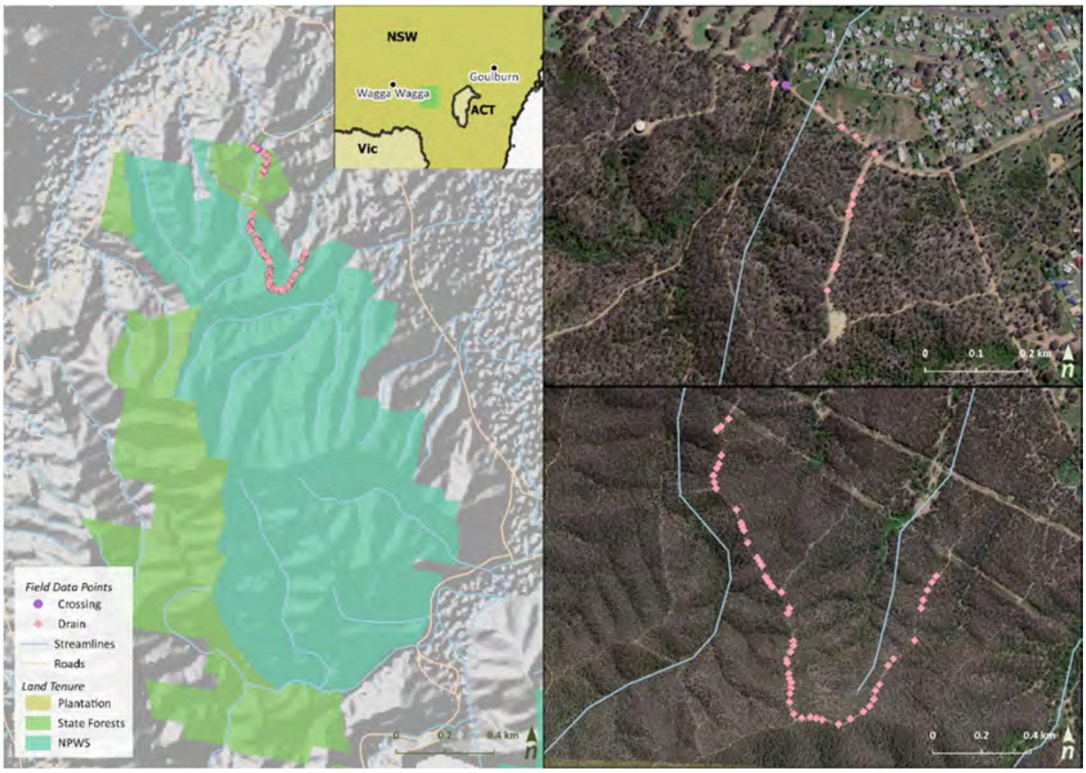


Figure 3. *Road segments surveyed in the Wereboldera State Conservation Area*

[2] https://portal.ga.gov.au/restore/38ed09a9-9e23-45eb-9016-dbe1dc92531d

Figure 4. *Top- Example of cross- bank and mitre drains on ridge crest in the Wereboldera State Conservation Area, bottom- deeply rutted road surface that causes flow to bypass an upslope drain.*

Kosciuszko National Park– Buckeys Trail

A 2.5 km segment of Buckleys trail, on the western margin of Kosciuszko National Park was surveyed in November 2021. The section of trail was chosen to represent a typical fire trail in NPWS tenure land, that ran parallel to contours against a steep hillside. The road is normally closed to vehicle access other than for maintenance so sees little traffic.

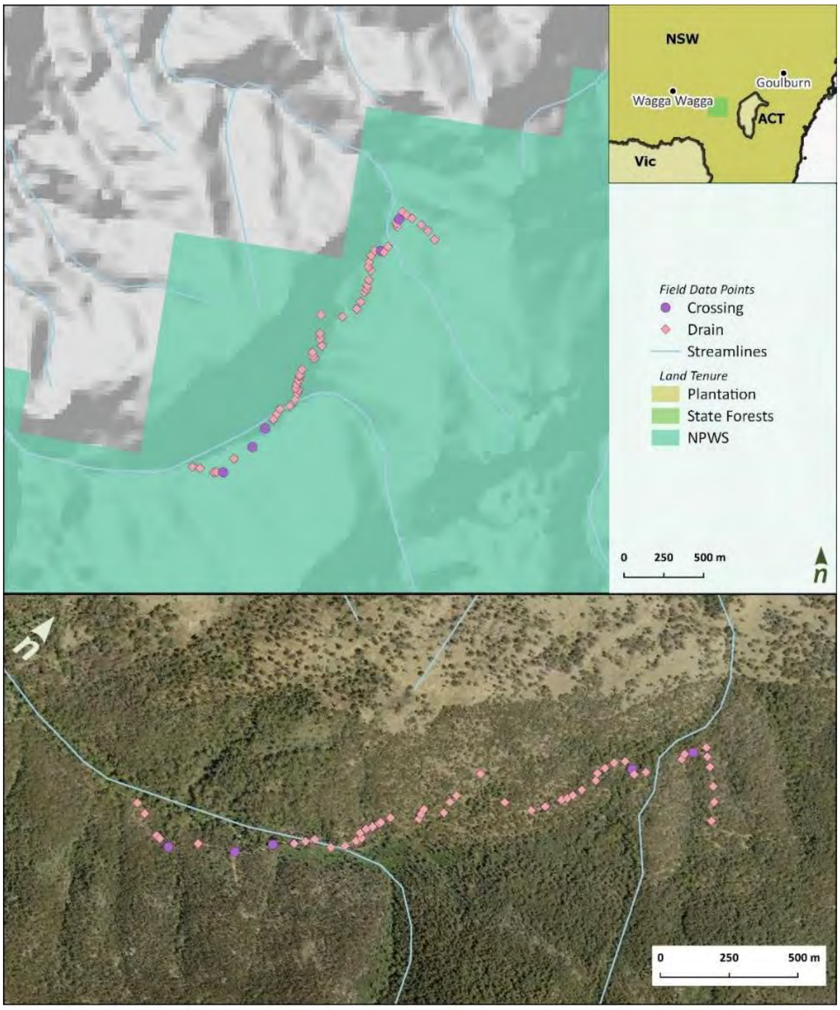


Figure 5. *Road segments surveyed in Kosciuszko National Park– Buckeys Trail*

Figure 6. *Left- A steep approach to a waterway crossing (ford) along Buckleys Trail, and right – example of a mitre drain dispersing flow down slope.*

Bondo State Forest

A 2.5 km segment of road, that includes both a small fire trail and larger haul road, were surveyed in Bondo State Forest in December 2021. The Bondo road segments were chosen to capture smaller fire trails in State forests (which are rarely used and are largely overgrown), and to survey an area with poor cell reception limiting the use of an RTK GPS. The underlying geology is granite and soils are Kurdosols. Poor cell signal and interference from the tree canopy meant that a laser level/total station survey technique was used for most of the road segment. The surveyed segment is shown in Figure 7 and example photos in Figure 8.

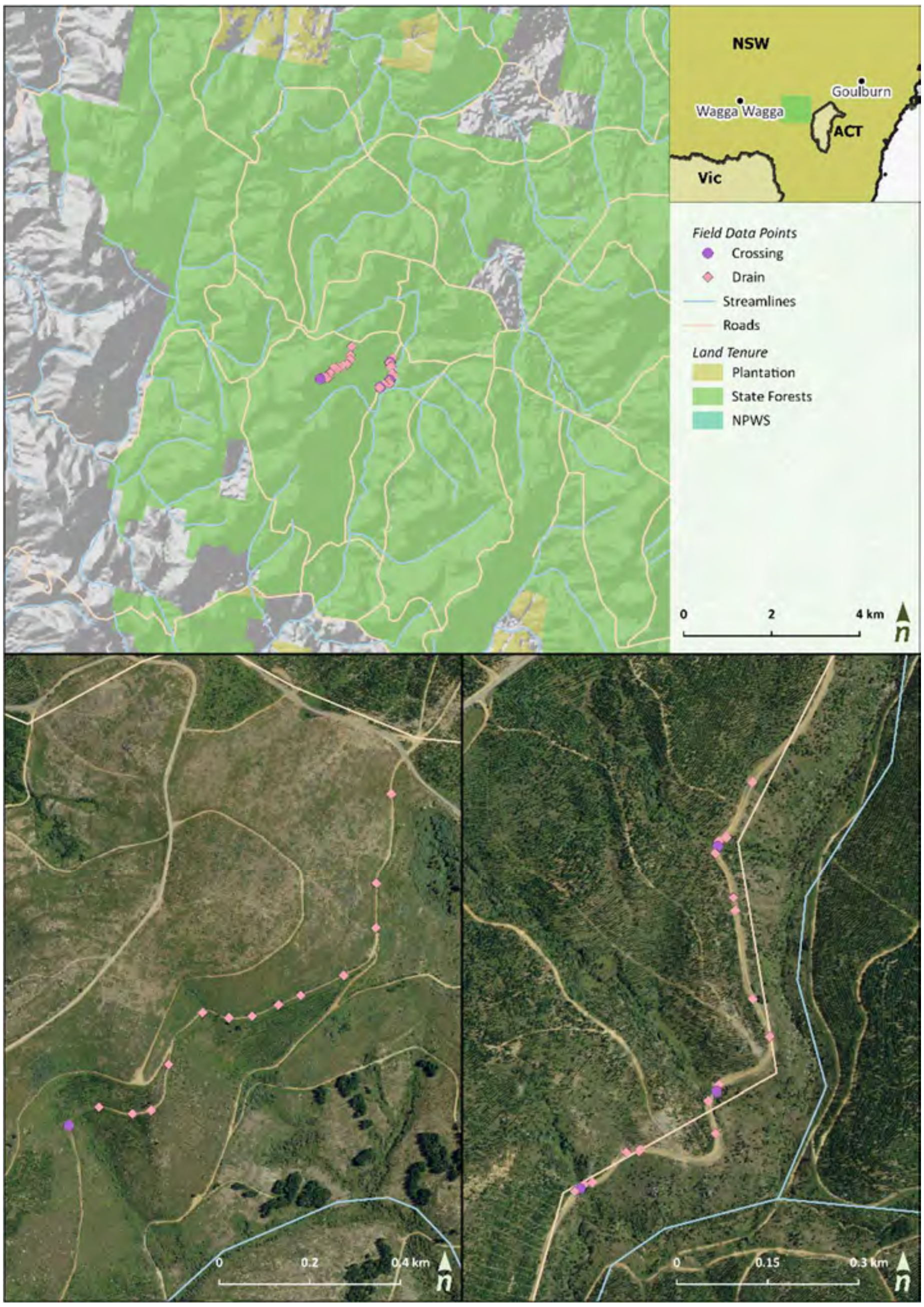


Figure 7. *The segments of road surveyed in Bondo State Forest*


Figure 8. *Left - Example portion of the partially overgrown fire trail in Bondo state forest, right – example portion of the larger haul road in Bondo State Forest.*

Carabost State Forest

A 3.8 km segment of road was surveyed in the Carabost State Forest in December 2021. The Carabost State Forest was selected due to ease of access, strong cell signal that allowed for RTK GPS to be used for much of part of the survey, and as a representative sample of regrowth forest. The underlying geology is sandstone and the soils are Chromosols [CH]. The segment samples is shown in Figure 9 and example photos in Figure 10.

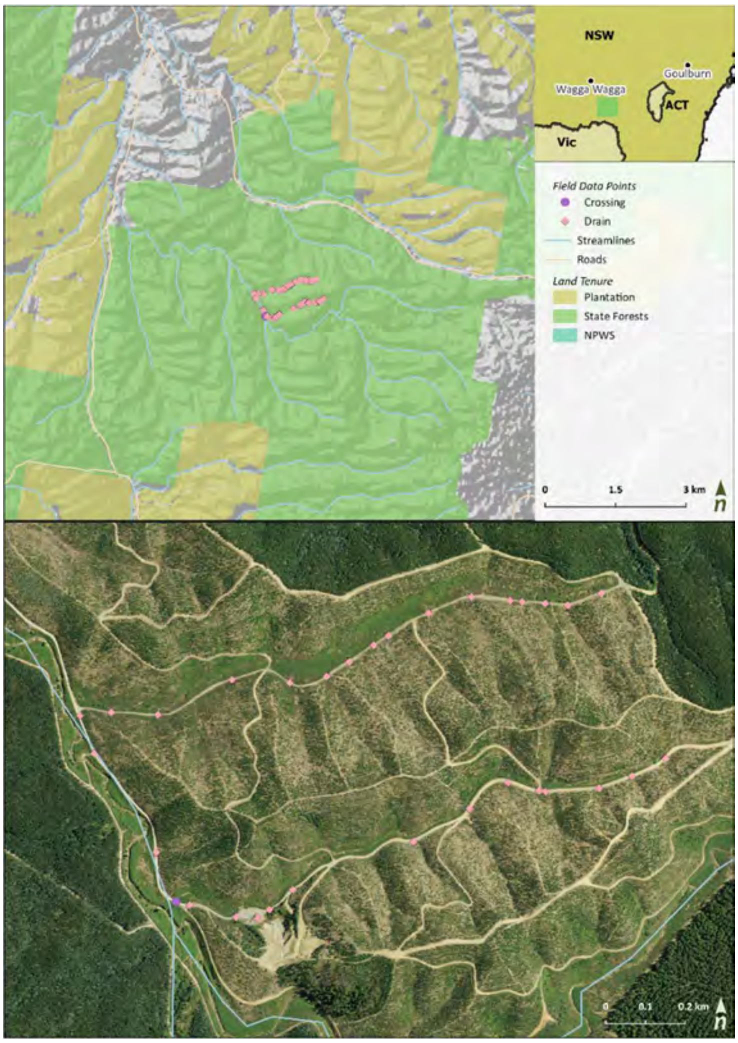


Figure 9. *The segments of road surveyed in Carabost State Forest*

Figure 10. *Left- Example portion of partially overgrown portion of road in Carabost State Forest, right- Example table drain dispersing flow and depositing sediment in a flat area adjacent hillslope the road has been cut into.*

Coppabella Private Plantation

A 5.5 km section of the Coppabella private forestry block was surveyed in May 2022. The Coppabella block was selected to provide a representative privately managed plantation forestry. The underlying geology is sandstone, and the soils are Chromosols [CH]. TH road segment surveyed is shown in Figure 11 and example photos in Figure 12.

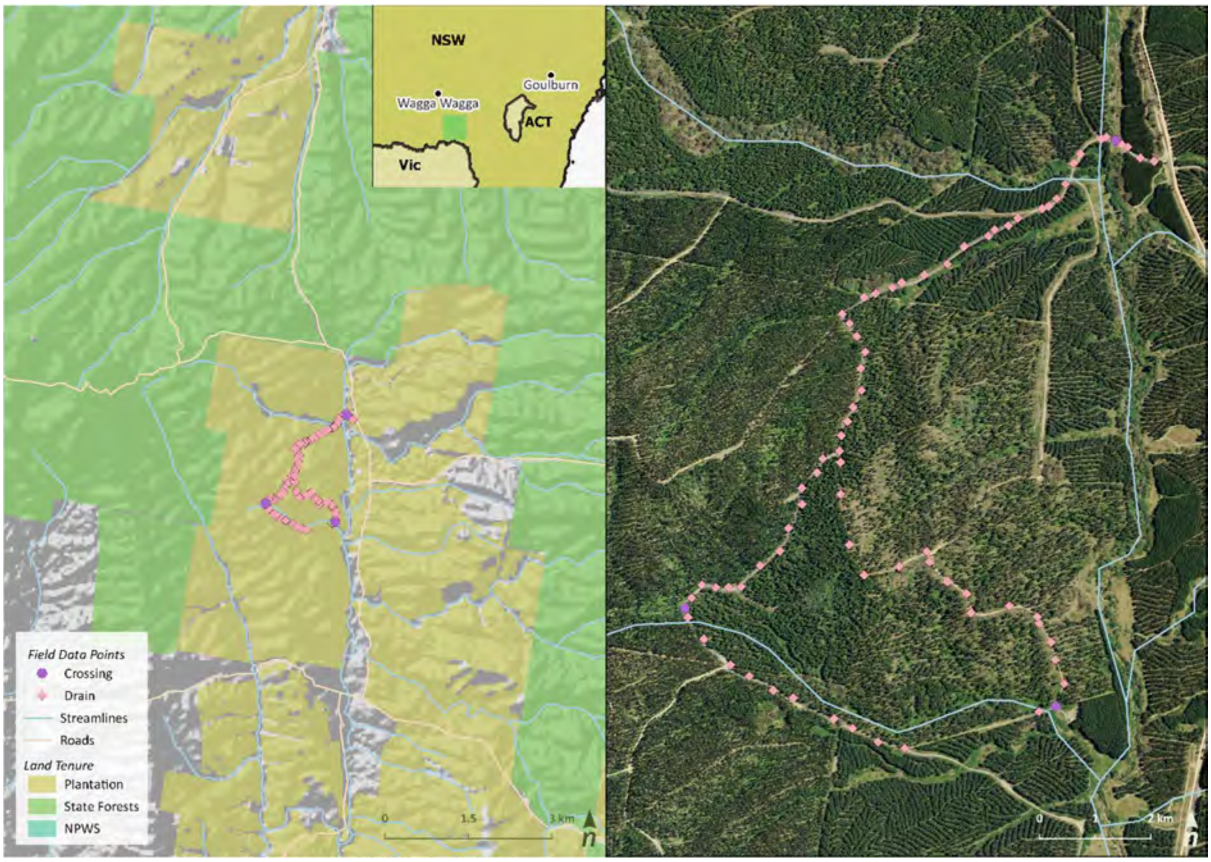


Figure 11. *The segments of road surveyed in Coppabella plantation forestry block*

Figure 12. *Example portion of road segment surveyed in Coppabella private plantation block, right- example waterway crossing, a concrete bridge deck, in a wider valley in the Coppabella private plantation block.*

Orara West State Forest

Two 1.5 km segments of road were surveyed in the Orara West State Forest in December 2021. The sites were chosen to be representitive of state forest roads an alterate climate regime to those surrounding the Tumut region to the south. The underlying geology is muidstone and the soils are soils are Chromosols [CH]. The segments survyed are shown in Figure 13 and example photos in Figure 14.

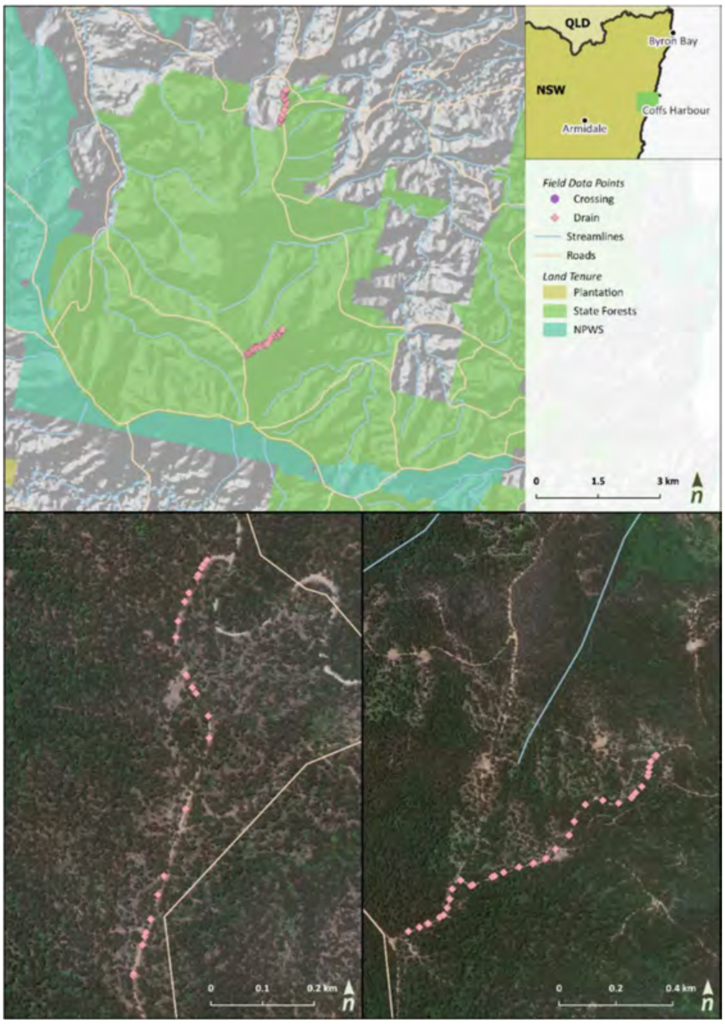


Figure 13. *The segments of road surveyed in the Orara West State Forest, Coffs Harbour area.*

Figure 14. *Left -Example segments of road surveyed in the Orara West State Forest and, right – A drain directly connected to a waterway at a crossing, discharging sediment laden runoiff a waterway in Orara West State Forest.*

Bindarri National Park
A 1.5 km segment of Bindarri National Park was surveyed in December 2022, usng the laser level and total station approach. The area was chosen to capture national park in a climate regime other than those surveyed in the Tumut area and to include a high density of waterway crossings. Rain events during the surveyed meant that drainage patterns and sediment delivery to waterways could be directly observed. The surveyed segment are shown in Figure 15 and example photos in Figure 16.

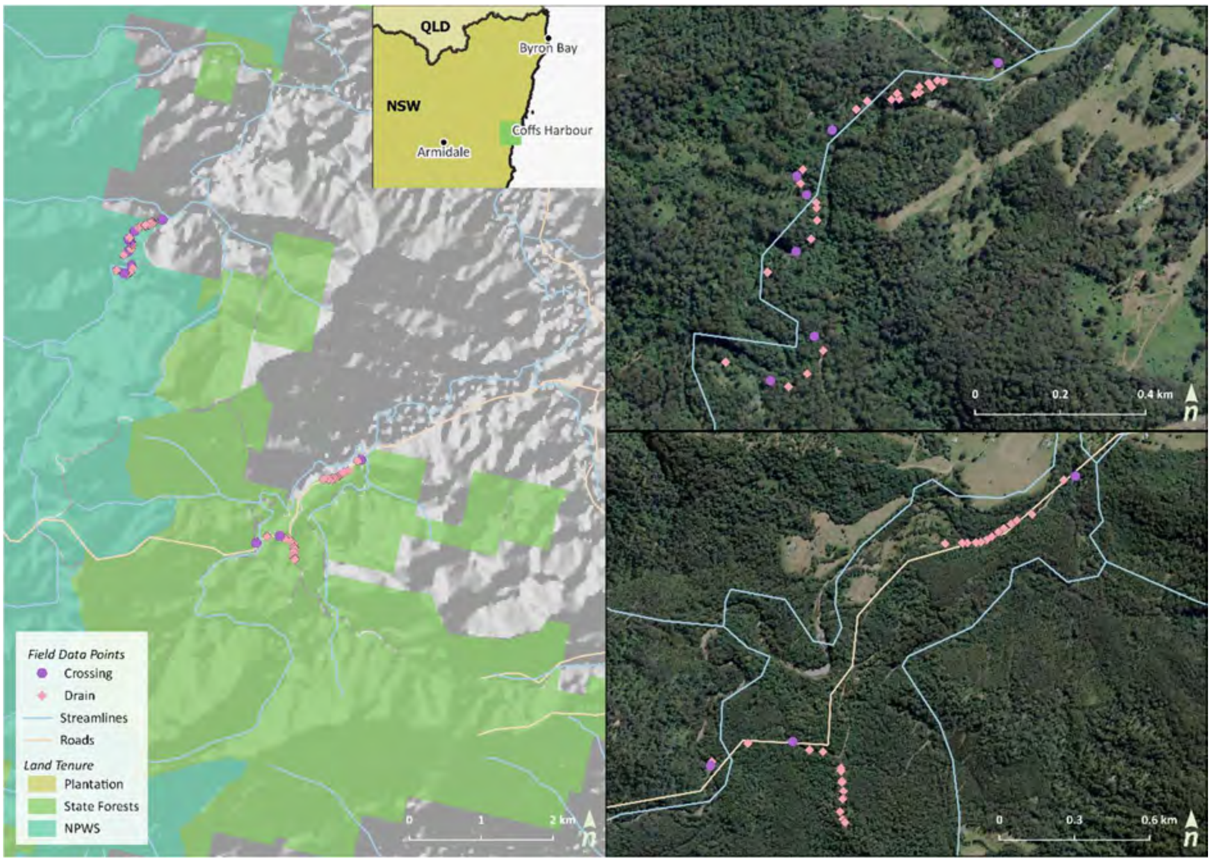


Figure 15. *The segments of road surveyed in Bindarri National Park, Coffs Harbour area.*

Figure 16. *Left- Example of sediment-laden runoff flowing into a ford type waterway crossing in Bindarri National Park, right- steep section of road upslope from the waterway crossing at left.*

Yarriabini National Park

A 2 km segment of road in Yarriabini National Park was surveyed in December 2021. This final segment of road was chosen to compliment NPWS roads surveyed in the Coffs Harbour area and included several waterway crossings.

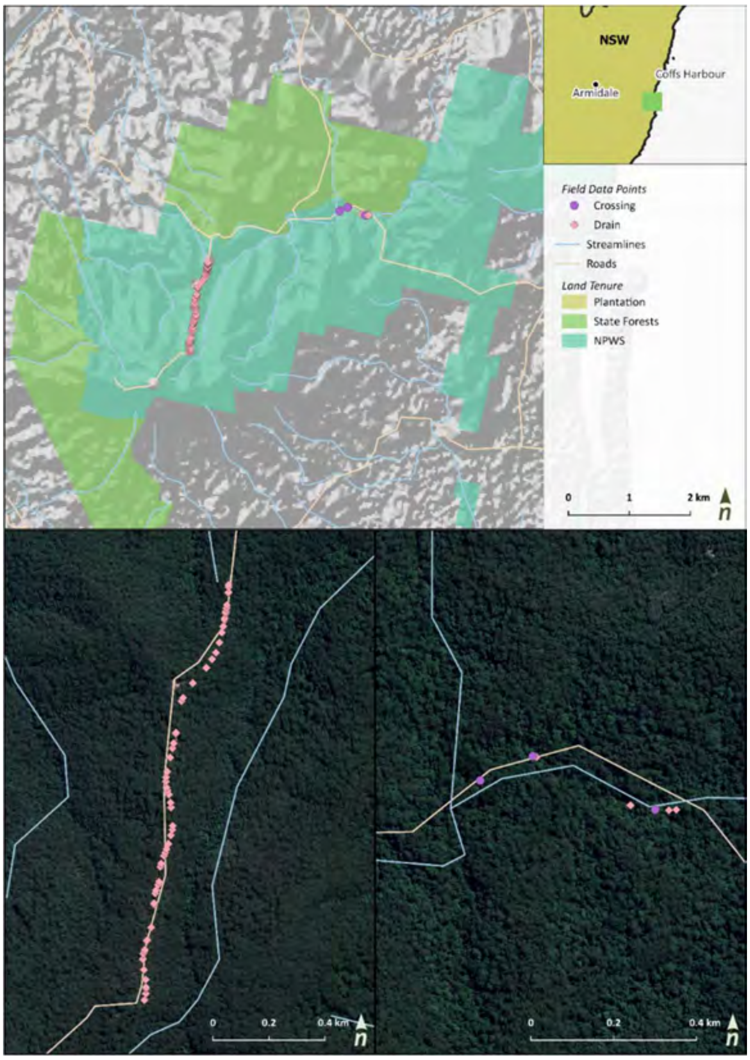


Figure 17 *The segments of road surveyed in Yarriabini National Park, Coffs Harbour area.*

Figure 18. *Left – example of a silt fence installed to intercept flow from a drain that directly connects with a waterway, Yarriabini National Park, right- example crossing.*

3 Risk assessment method

The risk assessment method developed for this project integrates the theoretical framework, the statewide sediment delivery potential mapping, field assessments and consideration of sediment mitigation measures. The risk assessment is a six-step process, with each step using the outputs form the previous step. Overall, the risk assessment moves from the state/regional scale and generalised assessment of sediment delivery potential to the local scale and a more explicit quantification of sediment delivery potential grounded in field measurements. The six-step process is outlined in Figure 19.

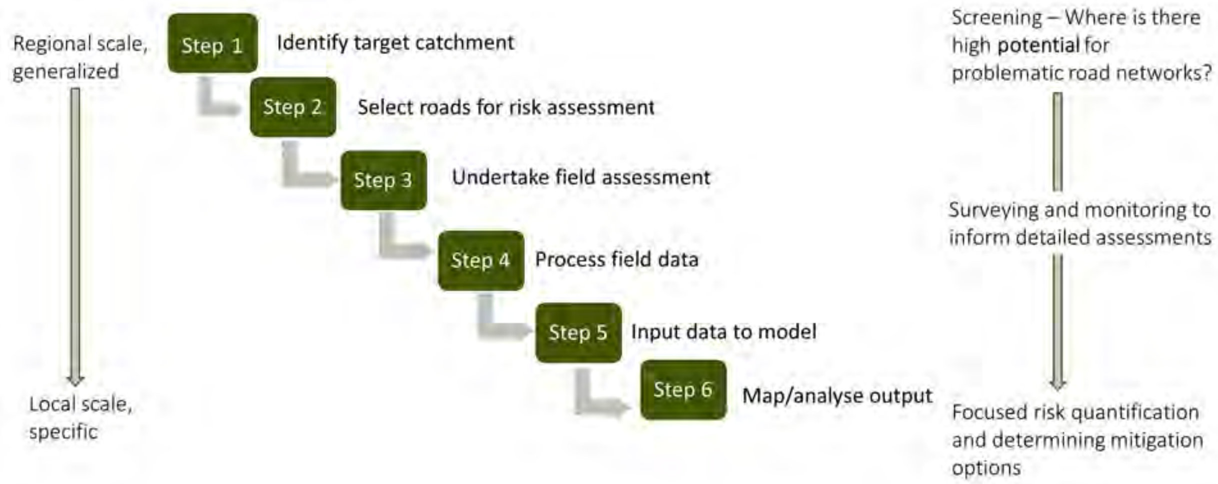


Figure 19. *The six steps in the risk assessment method developed for this project*

3.1 Expertise and key data inputs

Organizations or users of the risk assessment method require access to the following expertise to run the local model and undertake the risk assessment:

- Sufficient expertise in a GIS software to post-process field data and derive model inputs using readily available processing tools with well documented instructions.
- Basic skills in excel, to input data into and into the local sediment model and extract outputs.
- Experience working in forest roads and confidence in identifying road drains, including whether those drains are by-passed/outflanked by erosion or due to blockage.

- Surveying expertise commensurate with the survey method chosen. The use of RTK GPs or laser level total station require a high level of skill and experience, similar to that provided by a qualified surveyor. Other methods, such as mapping of drains using remote sensing data or a hand-held GPS require less experience, and users can be trained in the task relatively quickly.

The risk assessment uses two spatial data inputs to compute sediment delivery potential for each drain in a target road network: The location of individual drains in the road network, the location of waterways that may receive sediment inputs from those drains. The distance between a drain and a waterway is a key control on the sediment delivery potential of a drain. The more accurately drains and waterways are located, the more reliable the model output. The risk assessment method is flexible in that a range of field surveying and desktop processing techniques can be used to geolocate drains and waterways.

Drain and crossing geolocation

Accurate geolocation of drains is used to calculate the distance between drains and nearby waterways. The distance between drains and waterways is one input to the local sediment model, and this parameter has a significant impact on the sediment delivery potential calculated for each drain. Reliable model outputs therefore rely on both accurate geolocation of drains and waterways.[3] The greater the uncertainty in the true location of drains and waterways, the greater the uncertainty in the final model outputs. This uncertainty is most pronounced where road segments are close (less than ~ 10 m) to waterways and is less pronounced when road segments and waterways are further apart. There are four broad methods that can be used to geolocate drains and waterway crossings. Those methods, ordered from most to least accurate (and time consuming) are summarised in Table 4.

Handheld GPS devices are widely available and by far the fastest means of geolocating drains and waterway crossings. The large vertical errors can be mitigated to some extent using other field measurements (road slope, labelling of point types), but the horizontal errors will remain.

A combination of manual laser (total station) and RTK GPS survey methods were used to develop and undertake field survey during this project. These more accurate methods were selected because they minimise one important (and potentially large) source of uncertainty within the local sediment model. It should be noted that this method is optimal but by no mean's essential, and the use of advanced surveying techniques should not be barrier to the adoption of this method. **Users should select the survey method, or combination of survey methods, that best suits the available data, resources and desired accuracy of the model outputs in their target catchment.**

Waterways

An important step in the post-processing workflow is the definition of a stream network. There are multiple means of defining a stream network, and users should select the most accurate method based on available data and resources.

The stream network is defined in GIS software. An important aspect is the definition and mapping of headwater streams, not just the larger, higher order streams that are often included in published topographic maps or statewide spatial datasets. The methods that can be used to derive streamlines, in order from most to least accurate are:

- Appling flow direction and accumulation algorithms to a high-resolution (~1m, preferably derived from LiDAR), hydrologically conditioned[4], digital elevation model (DEM). A GIS software is required for this step but there are numerous existing processing tools that make this procedure straightforward once the underlying DEM has been obtained. The use such GIS algorithms is described in Attachment C. The state model uses a 30 m DEM, which is coarse but appropriate at this large scale. The local model requires higher resolution elevation data of at least 5 m resolution, but preferably less. In order of increasing resolution, publicly available elevation data sources for NSW include:

[3] Approaches to mapping waterways are summarised in step 4 of this risk assessment.

[4] A hydrologically conditioned DEM is a DEM whose flow direction defined the expected flow of water over the terrain, not the actual elevation recorded in the DEM. Hydrologically conditioning an existing DEM usually requires field work and local knowledge.

- 30 m DEMs across the entire state (used in the state model).
- 5 m DEMs across the entire state
- 1 m and 2 m LiDAR-derived DEMs available for selected areas

Publicly available spatial data can be accessed via the ELVIS[5] online spatial data platform, maintained by Geoscience Australia. The Australian Hydrological Geospatial Fabric spatial data (the Geofabric)[6], also hosted by Geosciences Australia and the Bureau of Meteorology, may be a useful means of defining waterways in some parts of NSW where waterways have been mapped at a smaller scale (in the order of 1:25,000). However, the current version of the geofabric is based a relatively coarse 30 m DEM. The lower resolution of the DEM used to define streamlines means that across much of NSW the Geofabric is unlikely to be suitable for defining waterways at the small scale at which the field assessment are applied.

- Applying the flow direction and accumulation algorithms to DEMs which are not hydrologically enforced and accepting the computed streamlines as is – this may be required when very large areas are being surveyed.
- Manual mapping/digitizing streamlines in a GIS software, with the aid of:
  - The highest resolution DEM available
  - Aerial or satellite photography
  - Local knowledge or site inspections to identify waterway (especially smaller headwater streams)
  - Extension of existing streamlines from publicly available data.

3.2 Step 1 - Identify target catchment

The first step in the risk assessment is to identify a target catchment, where the field assessments and local sediment delivery model will be applied. Target catchments can be identified using a number of criteria, including:

- Catchments mapped as having a high sediment delivery potential in the statewide model.
- Catchments with high waterway values, such as water supply catchments, specific habitat requirements or rare or threatened species are present
- Catchments with a known history of sediment delivery issues, or catchments where high sediment delivery has recently been observed
- Catchments where the road network is expected to see an increase in traffic, for example plantation or state forestry coupes that are entering the harvesting phase.
- Catchments within which Private Native Forestry is proposed.
- Catchments in which roads are to be decommissioned.

Key assumptions about two of the factors that contribute to sediment delivery from roads to waterways were made in order to produce best- and worst-case scenarios for each road segment, where a best case assumes crowning combined with BMP drain spacing while a worst case does not (Table 1). The model was rerun to produce best- and worst-case sediment delivery hazard outputs for each road segment across NSW.

[5] https://elevation.fsdf.org.au/
[6] http://www.bom.gov.au/water/geofabric/

Table 1. Contributing factors used to define best- and worst-case sediment delivery potential scenarios

Best case	Worst Case
Crowning for entire length (0.5*road width)	No crowning (road width left as is)
Drain spacing is set to at Best Management Practice (BMP) spacing guidelines with a maximum of 100m.	Drain spacing set to 100m for all instances, thus assuming full drain bypass per segment when road is significantly sloped.

Given the sensitivity of sediment delivery to drain spacing and road width (See Sensitivity analysis - Section 6.2 of Attachment B), the difference between worst and best-case scenarios is noticeable. Summary statistics of the difference in sediment delivery potential between the best case and worst-case scenario are provided in (Table 13 of Attachment B).

The Integrated Forestry Operations Approvals (IFOA) region with the greatest range of values for average sediment delivered per m in the worst-case scenario was used to establish 5 categories of sediment delivery hazard (very low, low, moderate, high, and very high) applicable for all IFOA regions (Table 2). The Lower NE IFOA had the greatest range of sediment delivery values, with a range of 0 to 28.37 kg per metre of road

Table 2. Sediment delivery hazard categories

Avg. Sed. del. per m. (kg)	Sediment delivery hazard
0 - 0.2	Very Low
0.2 - 2	Low
2 - 5	Moderate
5 - 10	High
> 10	Very High

The worst-case sediment delivery hazard, categorised according to Table 2, is shown in Figure 20.

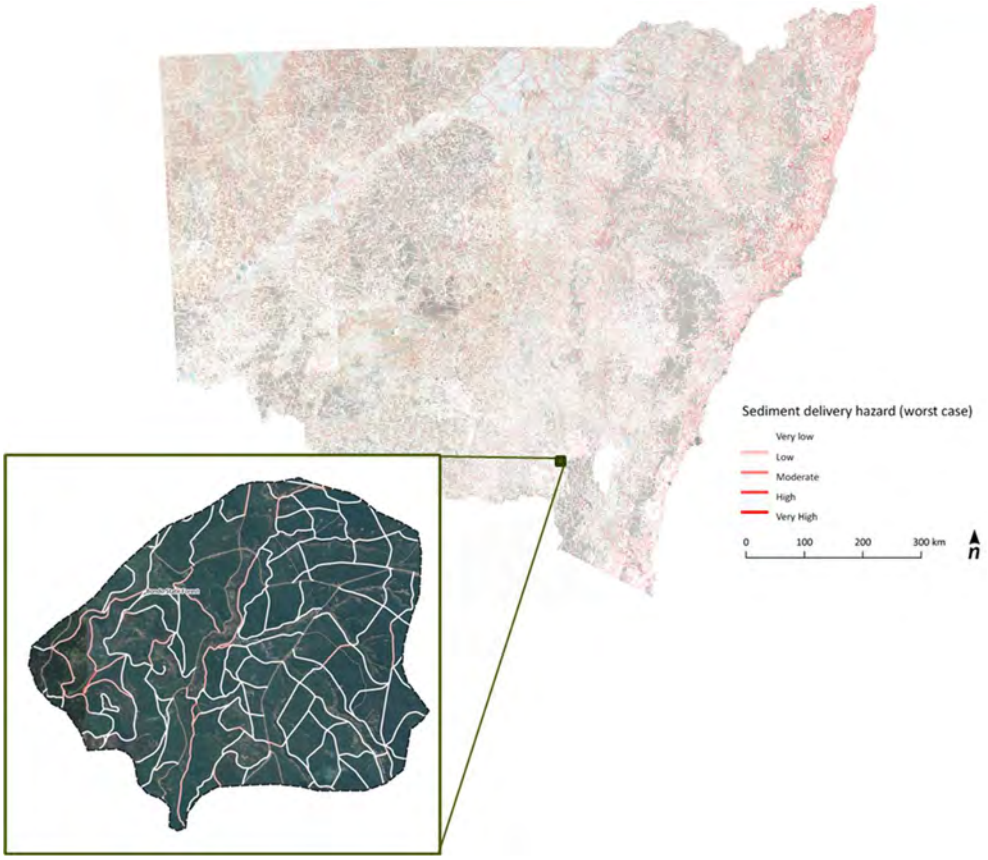


Figure 20. *Selecting catchments with high sediment delivery potential from the statewide model outputs*

Accuracy of statewide data

The statewide sediment delivery dataset includes assumptions regarding average drain spacing, traffic intensity and has been built using data captured at a resolution of 30 m. These assumptions and approaches enable calculations to be applied consistently across the entire state but mean that the statewide dataset does not accurately capture local-sale, onground road conditions. Users should be aware of the limitations of the statewide model when using this dataset to select catchments for catchment scale assessments, and supplement this data with other, local scale information wherever possible. Information that can be used to supplement the statewide dataset when selecting catchment for more detailed analyses include:

- Local knowledge of onground conditions within IFOA regions
- Records of road age, road width and drainage design
- Known impacts of fire history and soil type/erodibility

3.3 Step 2 - Select roads for risk assessment

Once a target catchment has been identified, a portion of the road network within the catchment must be sampled for field assessments. The length of road segment that can be sampled will depend on the time and resources available to the users of this method, and the technique used to geolocate drains and waterway crossings. Typical lengths of road that can be surveyed by a two-person team in a single day for three different survey methods are provided in Table 3.

Table 3. Typical length of road covered by field assessment in a single day for three survey methods

Drain survey method	Limiting factor	Typical length of road surveyed per day
Hand-held GPS or RTK GPS, with vehicle	Time taken to make measurements at each drain	~ 25 km/day
Hand-held GPS or RTK GPS, walking	Time taken to make measurements at each drain + walking speed	~ 6 km/day
Manual laser (total station) surveying	Time taken to make measurements at each drain + walking + back-sighting point for elevation	~2.5 km/day

Many catchments will include vastly greater lengths of road than the resources for field surveys may allow. Therefore, representative segments of the network are sampled instead, and the insights from the field assessment and local scale model are applied to the wider network of roads in the catchment. Selecting a representative sample of roads from a catchment network is also a means to reduce the cost per-survey, which may allow the frequency of repeat surveys to increase.

The criteria used to select road segments that are representative of the wider network will depend on the motivation for the assessment. For example, if the purpose is to assess sediment delivery potential in roads prior to harvesting a coupe (when road traffic intensity will increase), then the segments subject to a field survey will be limited to those in coupes scheduled for harvesting. If the purpose of the risk assessment is to obtain a more generalised, catchment-wide understanding of sediment delivery potential or to identify specific roads of concern, then a broader range of roads will need to be surveyed.

Surveyed segments should include the full range of types found in the wider catchment. The number (or length) of each road ‘type’ sampled should be roughly proportionate to the total number (or length) of roads of that type in the wider catchment. Characteristics which can be used to define road type and select segments for field assessment include:

- Road class
- Road slope
- Road width
- Road age
- Average annual (or expected) traffic intensity
- Slope position (ridgeline, mid-slope or valley floor)

In addition to the road characteristics above, field surveys are most efficient when these road segments are joined in a near-continuous path, rather than as short segments spread across a wide area. For this reason, it may be simplest to select sub catchments (such as a headwater stream) and sample all road segments in that sub catchment.

3.4 Step 3 - Undertake field assessment

The purpose of the field assessments is to generate data inputs that are fed into the local sediment model. Once field data has been collected, some GIS processing (step four in this risk assessment) is required to finalise and format data for the local sediment model. Field assessments consist of two tasks:

- Accurately surveying the location of road drains ad waterway crossings
- Making simple measurements or observations at each drain and waterway crossing

Field assessments are most efficient when:

- Done in teams of two.
- Multiple vehicles are used, to minimise the total distance travelled by foot.
- Drain locations are marked with survey paint, so that accurate surveying of the drains can be done at any time, by manual or remote sensing methods.

Field measurements

The final use of the field data should be kept in mind when collating observations for each drain. Data that can be easily aligned with survey points, using point IDs, is much faster to process in step four of this risk assessment. Any method of recoding observations at each drain can be used, whether that be a simple table with pen and paper, or form-based applications/software on a tablet.

A more detailed description of each of the measurements made at each drain and waterway crossing is provided in Attachment D. In summary, the field measurements are:

- Four types of point being either: drain, crossing, topographic low, or topographic high
- Drain measurements:
    - Drain location (RTK GPS)
    - Drain type (mitre, culvert, pushout)
    - Drain slope
    - Drain outlet (gully/dispersed)
    - Drain status (functioning/blocked/bypassed)
- Road measurements (taken adjacent each drain):
    - Road width
    - Road slope
    - Road crowning
- Waterway crossing measurements:
    - Distance between crossing and upslope drains (can also be determined in step 4)
    - Road crowning upslope of crossing
    - Road condition upslope of crossing (eroded, smooth, compact)
    - Crossing abutment condition

Table 4. Survey methods to geolocate drains and waterway crossings

Survey method	Vertical and horizontal accuracy	Pros	Cons
Manual laser (total station) surveying	Typically has vertical and horizontal accuracy of ± 0.01 m	• High absolute accuracy • Works in all areas	• Very slow
Real-time kinematic (RTK) GPS surveys	Typical vertical and horizontal accuracy of ± 0.05 m	• High absolute accuracy • Fast	• Cell coverage or established base station required • Adequate sky view and satellite coverage required-challenging in mature forests
Combined desktop and field survey: Georeferencing of drain locations using aerial imagery and Light Detection and Ranging (LiDAR) Field surveys for remaining road, drain and waterway crossing measurements	Desktop based drain and waterway crossing geolocation accuracy depends on the accuracy of the underlying data, and the method used to identify and map the drains or crossings. Typical vertical and horizontal accuracies are in the order of ± 0.5 m (aerial imagery) and ± 0.015 m (LiDAR).	• Desktop based component reduces but does not eliminate, field survey time • Still requires field survey to obtain some road, drain measurements and waterway crossing measurements • Qualified surveyor not required	• Requires Light Detection and Ranging (LiDAR) data for entire catchment (covering roads and waterways), and for drains and waterway crossings to be clearly visible in aerial imagery. • Does not eliminate need or field surveys entirely
Hand-held GPS devices	Typically have an absolute horizontal accuracy of ± 3m[7], and an absolute vertical accuracy of ± 120 m, depending on the satellite configuration at the time of survey.	• Relatively fast and simple • Surveyor not required	• Poor absolute accuracy of ± 3m (horizontal) and ± 120 m (vertical). • GPS errors are random and the magnitude (m) of error will depend on satellite configuration, weather at the time of the surveys, the amount of sky visible to the receiver (which can be limited by buildings, hillslopes and tree canopy)

[7] The GPS location accuracy of Garmin handhelds is around 3 meters, 95% of the time - https://support.garmin.com/en-AU/?faq=ZYN0dmiaBM3acpi5JceDA9#:~:text=The%20GPS%20location%20accuracy%20of,meters%20of%20your%20actual%20location.

Instruments required to undertake the field assessment are:

- Survey paint to mark drain and waterway crossing locations.
- A suitable GPS device, selected from the options outlined in Table 4.
- All necessary PPE, which will vary by tenure, site operations and season.
- A means of recording field measurements. Options include:
    - Pen and paper.
    - A tablet or smartphone using form-based or data collection software.
- A means of measuring road and drain slope. Options include:
    - A smartphone or tablet with slope measurement application.
    - A hand-held laser level that can record both distances and angles
    - Marking of additional survey points that can be either surveyed and post-processed with a total station or RTK GPS.
    - A high resolution DEM from which road and drain slopes can be extracted from.

At the same time the specific measurement outlined above are being made, users should pause, and take note of the road and drain condition. While the model removes the need for most subjective assessments of drains, additional pictures and notes taken during the field assessment are useful for:

- Diagnosing whether ruts in the road surface cause flow to outflank drains, leading to the partial or complete bypass of the drain.
- Diagnosing whether sediment is blocking the drain, which prevents runoff from draining down the slope and may also result in the partial or complete bypass of the drain.
- Identifying obvious sources of sediment delivery at waterway crossings *where possible.*
- Capture photos that can be used for visual comparison during repeat surveys.

Identifying sediment sources at waterway crossings is challenging, even for practitioners experienced in the design and maintenance of forest roads. Measurements at waterway crossings should focus on identifying obvious sources of sediment, such as rutting and gullying in the road surface or section of road batter or crossing abutments that are actively collapsing. For crossings at particularly high-value waterways, more experienced practitioners, such as those who have undergone specific training in the identification and management of erosion, may be necessary.[8]

3.5 Step 4 - Process field data

Field data must be post-processed before it is ready to be input into the sediment delivery model. Post-processing steps performed in a GIS system and moderate skills in a GIS software are required (the methods used in this assessment can be implemented in any GIS software but are most straightforward using the ArcGIS software). Detailed instruction for GIS post-processing steps is provided in Attachment D. Overall, desktop processing has two parts: defining a stream network and flow distances (Attachment D) and segmenting the road drainage network.

Segmenting the road drainage network

Each road segment, which includes all drains and waterway crossing surveyed in the field, must be further broken into smaller drain segments, so that the catchment area of each drain can be accurately measured.

[8] For example a Certified Professional in Erosion and Sediment Control, administered by the Australian branch of the International Agency of Erosion Control - https://www.austieca.com.au/cpesc

This step is required so that small-scale variation in topography, which control how runoff is partitioned between drains, are reflect in the model output. The approach to further segmenting surveyed roads and defining the catchment area of each drain is shown in Figure 21.

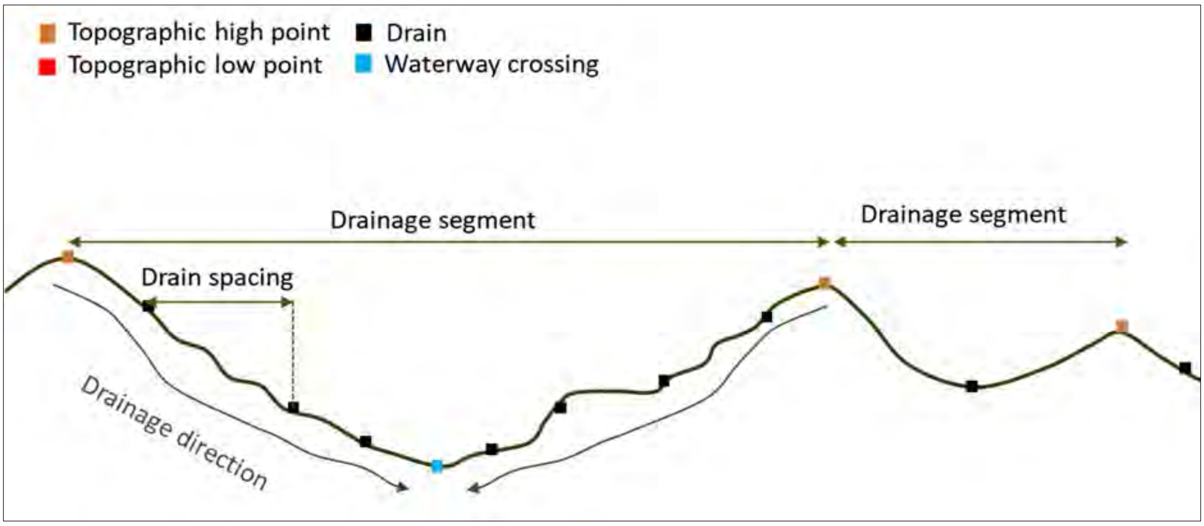


Figure 21. *A simplified representation of segmenting the drainage network of a road.*

During road segmenting, the following values are calculated for each drain:

- Drain location, by joining surveyed drain points and drain measurements by a common ID (e.g., point name).
- Rainfall intensity and total annual rainfall values to each point (extracted from BOM web portal)
- Road use measure (axles per week)
- Distance to nearest waterway
- Drain catchment area (Figure 22), by calculating:
    - Distance between successive, operating drains. If the drain immediately upslope is bypassed (not draining the road), then the distance is extended to meet the next functioning drain upslope.
    - Distance to next drain upslope, whether or not that upslope drain is functioning.
    - Modifying catchment area by accounting for any road crowning, that shed flow to the road margin before it can accumulate in the downslope drain

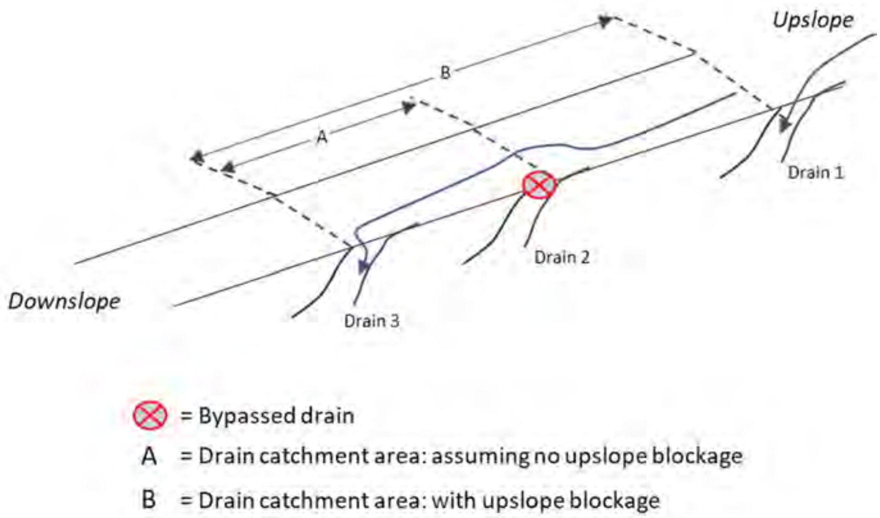


Figure 22. *Segmenting drain catchment area with and without bypassed drains*

Ultimately, the drain field measurements and the outputs of the post-processing will need to be formatted so that it can be input to the local model. This requires that each row of data represents a single drain. The ordering of columns/field data should match those in the model so input data can be simply copy and pasted into each of the model tabs described in step 5. The format of input data for each drain in the local model are described in detail in Attachment D.

Processing crossing data
Field observations made at waterway crossings require little to no post-processing, since the measurements are not used as inputs to the local model. One exception is the distance between waterway crossings and the two upslope drains. Calculating the distance between a waterway crossing and nearest, functioning upslope drains is straightforward, and can be done:

- Using the same approach used to calculate the distance between successive drains.
- By manually measuring the distance between the waterway crossing and the next functioning upslope drain in GIS software.
- Measuring the distance in the field using a measurement wheel or laser level total station.

3.6 Step 5 - Input data to model

Once filed measurements and post-processing have been finalised and formatted, the data can be input to the local model (Figure 23). The local model is provided as an excel workbook, and input data is simply pasted into each of the four tables, which are marked as management variables in Figure 24. The columns are identical for all tabs and are shaded green. Each management 'variable' is an implementation of the local model, with one or more variables held modified. The management variables correspond to a road design or maintenance activity that has can be used to reduce sediment delivery potential of road drains, and which can be measured in the field. For example, by reducing the catchment area of each drain (by crowning the road or decreasing drain spacing), or by clearing and re-establishing drains that are blocked and bypassed. Those management variables are:

- **Base case.** Base case model runs are the point of reference for other model tabs. The input values for each parameter are those measured in the field. The model output is sediment delivery potential as it currently stands, assuming no intervention.
- **Drain catchment area.** Drain catchment area model runs are used to quantify the change in sediment delivery potential that can be achieved by reducing the catchment area of a drain. Drain catchment area can be reduced in two ways:
    - By crowning the road so a proportion of total runoff is shed to the road buffer, rather than accumulating at the drain.
    - By reducing the spacing between drains.

  The impact of reducing drain catchment areas is modelled by varying the road crowning factor by increments of 25, between 25 and 100. The road crowning factor just reduces catchment area, so can be used to represent crowning and drain spacing. The output is a value of sediment delivery potential for each road crowning factor.

- **Blocked and bypassed**. Blocked and bypassed model runs calculate the impact that blocked drains, which effectively double the catchment area of downslope drains, have on sediment delivery potential for those downslope drains that continue to function, and receive the additional flows. The drain bypass factor is set to bypassed (value=1) for all drains. The output is of this model run is used to compute the change in sediment delivery potential possible with a comprehensive maintenance program (or conversely the lack thereof).
- **Gullying**. Gullying model runs calculate the impact that gullying at the drain has on the length of runoff plumes emanating from drains, and the total mass of sediment delivered to waterways from each drain. The gullying factor is set to gullied (If gullied then value =1) for each drain. The output from the model run is used to compute the change in sediment delivery potential possible were

measures to prevent gully development (such as armouring of the hillslope), or works to restore gullies to a hillslope profile that disperses flow.

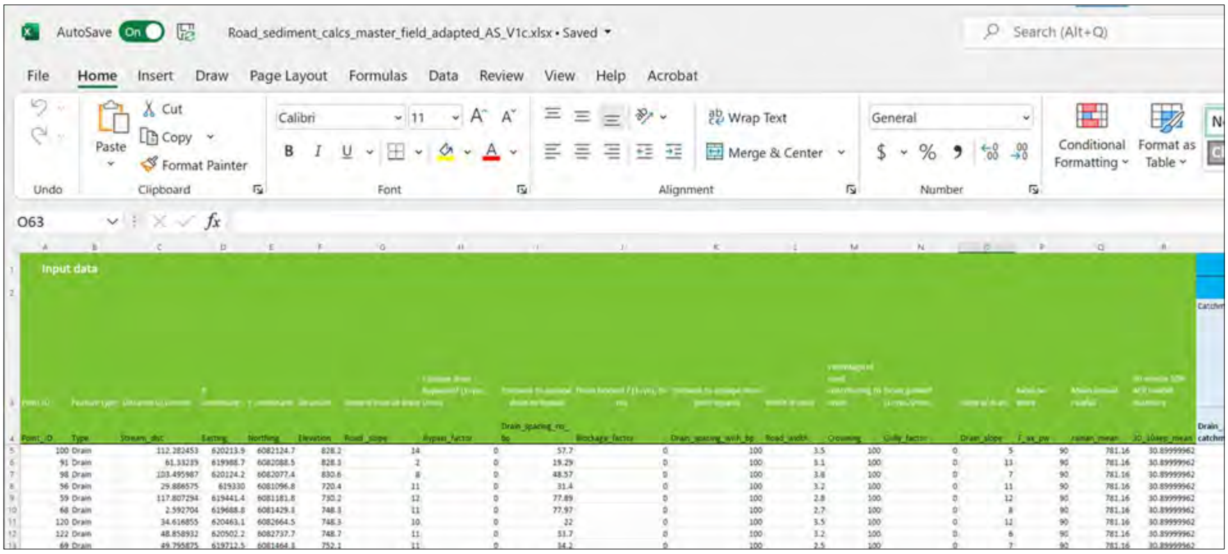


Figure 23. *Format of data input to the local model, which is implemented in excel.*

Figure 24. *Tabs in the local model*

3.7 Step 6 – Map and analyse model output

The final step in the risk assessment is to map and analyse model outputs. There are three tabs used to analyse the model output (each of which is automatically populated):

- **Base case.** The base case includes the model sediment delivery using the inputs form the field measurements. The based case represents sediment delivery potential of drains as they currently stand, without any interventions applied. The base case serves as the basis to which each of the management interventions outlined in step 5 are compared. The outputs from the Base Case model run are automatically copied to the GIS output tab, so the base case results can be easily imported to a GIS software.
- **Segment summary**: The reduction (%) in total sediment delivery potential of the local road network achieved by each management intervention. This output is provided a high-level, network-scale overview of the relative change in sediment delivery potential possible with each management interventions.
- **GIS output**: Includes the predicted sediment delivery potential (kg) for each drain and the change in sediment delivery potential for each drain.

Segment summary

The segment summary is a table, which the model automatically populates, assigning an intervention score to each intervention type. The intervention scores are intended to provide an overview of the effectiveness of interventions at the network scale. The scores are based on the average percentage reduction in the total sediment delivery to waterways sediment from the entire network of drains surveyed. The scores can be used to compare between the reduction in sediment delivery when an intervention is applied to an entire network of drains. There are three scores are using the percentage reductio in total sediment delivery relative to the base case. The scores are:

- **Low:** The possible reduction in sediment delivery from roads to waterways is less than 33 %.
- **Medium:** The possible reduction in sediment delivery from roads to waterways is between 33 and 66 %.
- **High:** The possible reduction in sediment delivery from roads to waterways is greater than 66 %.

An example of the segment summary table is provided in Figure 25 and an example of sediment delivery potential (base case) mapped in a GIS is shown inf Figure 26.

Score	Description
HIGH	The possible reduction in sediment delivery from roads to waterways, relative to the base case, is less than 33 %
MEDIUM	The possible reduction in sediment delivery from roads to waterways, relative to the base case, is between 33 and 66 %
LOW	The possible reduction in sediment delivery from roads to waterways, relative to the base case, is greater than 66 %

Road design	Sediment reduction relative to base case	Intervention score
25 % reduction in drain catchment area	46%	MEDIUM
50 % reduction in drain catchment area	71%	HIGH
75 % reduction in drain catchment area	90%	HIGH
Maintenance		
Clear drains of accumulated sediment to prevent blockage and drain bypass	0%	LOW
Increase erosion resistance at drain outlet to prevent gully development	37%	MEDIUM

Figure 25. *Example segment summary table*

The segment summary averages the results from all drains. Although the segment summary provides a useful overview, it obscures the potentially large differences in sediment delivery reduction between different drains. To identify which drains have high sediment delivery potential (and therefore to prioritise interventions within a surveyed road network), users can instead use the GIS output tab.

GIS output

The GIS output is a table, with each row corresponding to a drain and the corresponding model output. The output table includes drain coordinates and can easily be imported into a GIS software for mapping and further analysis. The model output stored for each drain (each of which can be used to symbolise results) are:

- Observed drain catchment area
- **Absolute** sediment delivery potential (in kg) for:
    - The base case
    - Each of the four, drain catchment/road crowning scenarios
- The **reduction** in sediment delivery potential (in kg, and as percent change) relative to base case achieved by:
    - Each of the four drain catchment area/road crowning scenarios
    - Elimination of gullying at the drain outlet.
    - Reinstatement of upslope drains which were bypassed.

Of the management interventions above, elimination of gullying at the drain outlet is most challenging. Often, major engineering works may be required, and smaller scale works (for example as log piles to disperse flow) may be met with limited success. Road managers may therefore choose to focus on measures that reduce drain catchment area or reinstatement of blocked/bypassed drains instead.

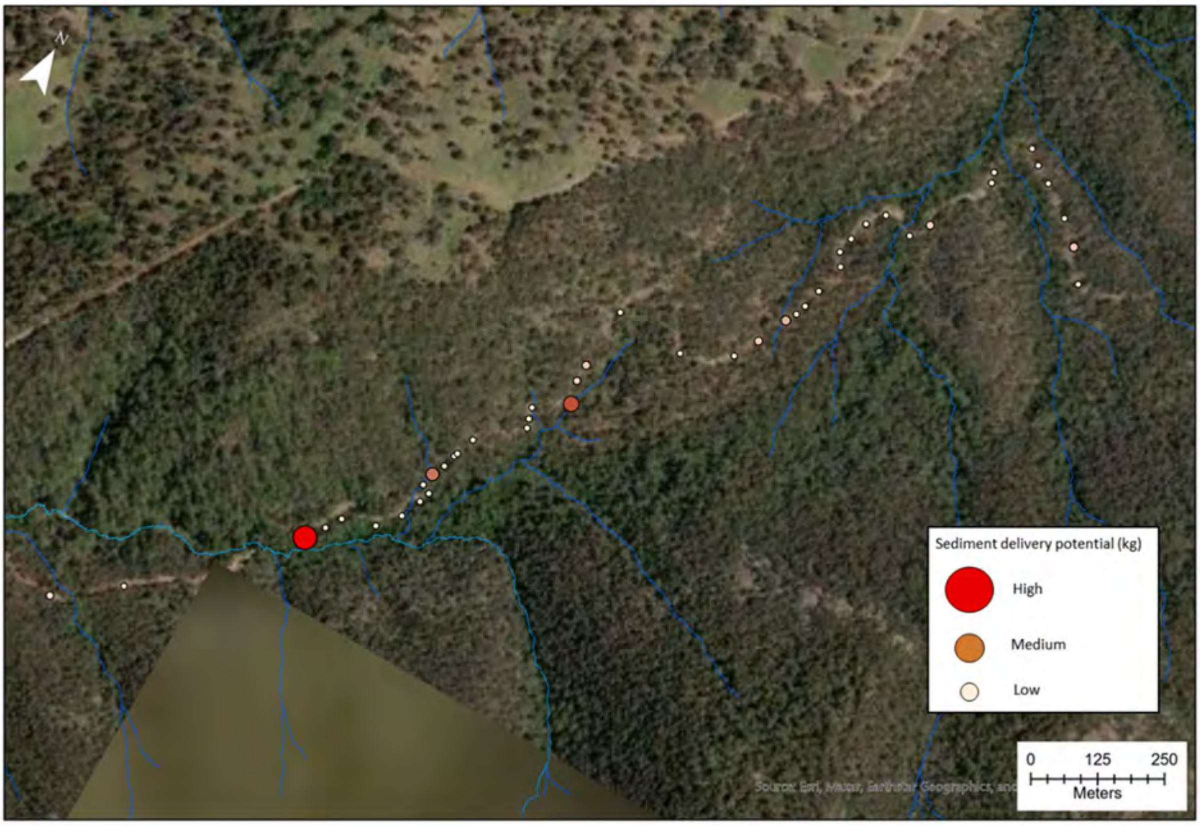


Figure 26. *Example of the GIS model output, imported to a GIS and symbolised by the base case seidment dleivery potential (kg).*

The segment summary, or the output for individual drains, can be used to compare interventions aimed at reducing sediment delivery to waterways. The modelled reduction in sediment delivery potential can be used in conjunction with information on the feasibility, costs of each intervention to prioritise if, where and by what means interventions to reduce sediment delivery potential will be used in a road network. Whether an intervention is feasible and cost effective will depend on the waterway values in the target catchment.

Analysing the waterway crossing data

The risk assessment assumes that all waterway crossings are sediment delivery hotspots and represent a high threat to waterway values. This risk assessment focuses on the treatment of sediment delivery from roads to waterways, not the equally as important threat of instream erosion caused by the presence of the crossing. Design and maintenance of waterway crossings to reduce instream erosion is covered in appropriate road design guidelines.

The waterway crossing assessment and identification of interventions to reduce sediment delivery potential has four principles. Each of the principles and resulting intervention should be considered together. The most effective, and most feasible, intervention measure will depend on local context. The four principles are:

1. **Minimise the road catchment area of each crossing.** Upslope drains should be approximately 10 m from the waterway crossing.[9] Drain-crossing spacing is a trade-off between minimums the catchment area of the crossing and providing adequate hillslope length to buffer flow and sediment inputs form the drain before the plumes reach the waterway. As with all drains, crowning the road upslope of the crossing will also decrease the catchment area of the crossing.
2. **Minimise erosion in a crossing's road catchment area.** Rutted, eroding roads in poor condition generate substantially more sediment. Re-grading and the addition of suitably sized and compacted rock on the road surface can be used to reduce the concentration of fine sediment within road runoff. Thus, reducing sediment delivery at waterway crossings.
3. **Minimise or eliminate erosion of crossing abutments.** Exposed and eroding crossing abutments, and the earth mounds that enclose culvert pipes, deliver sediment directly to waterways due to road runoff and when submerged by high flows. Armouring abutments with concrete, vegetation or geotextiles to increase erosion resistance will reduce sediment inputs to waterways.
4. **Disconnect drains from waterways.** Crossings that connect directly to waterways can be disconnected re-orienting their outlets, so flow is instead dispersed across available hillslope. Where drain outlets cannot be re-oriented, flow dispersion structures and/or vegetation can be used to attenuate flow as much as possible (where setting allows).

The crossing assessment and associated interventions to reduce sediment delivery at waterway crossings are summarised in Figure 27.

[9] Sheridan and Noske, 2005. Quantifying the water quality benefits of erosion and sediment control practices on unsealed forest roads. Final Report 2005: Research Report for the Gippsland Lakes Future Directions Action Plan and the Victorian Forest Service, Department of Sustainability and Environment.

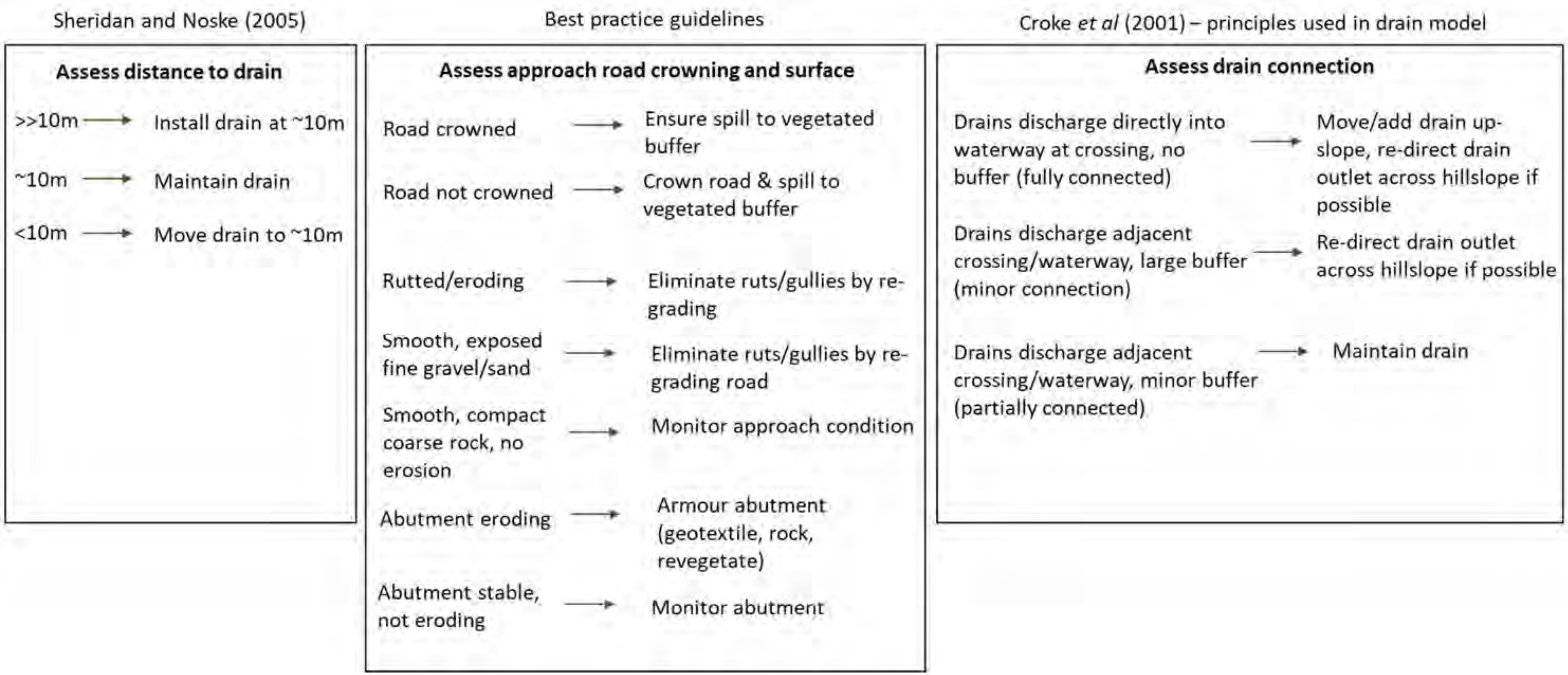


Figure 27. *Waterway crossing assessment criteria and associated intervention options*.

4 Conclusion

This report summarises the fourth and final stage of the Forest Monitoring Improvement Program (FMIP) project: *Evaluating forest road networks to protect water quality* project. The overarching aim of the project was 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.

This project has four stages, with each stage using the insights and outputs form previous stages to develop tools and methods to quantify sediment delivery potential and identify mitigation measures to reduce sediment delivery to waterways. The four stages were:

1. Development of a discussion paper and initial stakeholder engagement (Attachment A).
2. Risk assessment framework and conceptual model (section 1.3 of this report and Attachment B).
3. Statewide mapping of erosion potential to focus monitoring and improvement (Attachment C)
4. Development of a field assessment protocol using samples of the forest road network across tenures (this report).

The risk assessment outlined in this report is used to identify target catchments, select road segments for field survey, and to then apply the local sediment model to calculate sediment delivery potential. The risk assessment process has both a desktop and field component. The desktop component uses statewide modelling of sediment delivery potential undertaken during earlier stages of this project, and the field assessment method is used to collect measurements that are input to a local scale implementation of the statewide model. Surveying or mapping the location of drains, waterway crossings and waterways underpins application of the risk assessment to a target section of the forest road network. This report provides guidance on survey method selection and outlines the trade-offs between accuracy and feasibility associated with each of the possible survey methods. Outputs from the local sediment delivery model, which is implemented in excel, are:

- Sediment delivery potential (in kg) for existing conditions (the base case to which other intervention scenarios are compared) for each drain surveyed during field assessments.
- The absolute reduction in sediment delivery potential (in kg), relative to the base case, for four interventions aimed at reducing sediment delivery to waterways. Sediment reductions are calculated for each drain surveyed during field assessment and for the network as a whole.
- A simple classification of the sediment delivery reductions associated with each intervention option as either high, medium or low.

This risk assessment process, and the local scale model in particular, can be used to:

- Evaluate the sediment delivery potential of existing forest roads of any size or age, quantitatively and consistently.
- Identify and compare options to mitigate sediment delivery in a forest road network
  - Prioritise network scale maintenance and/or mitigation
  - Identify and map hotspots/problem drains or segments in a network
- To evaluate a proposed road drainage design
  - By inputting proposed drainage layout into the model
  - Varying drain spacing, crowning assumptions to compare sediment delivery potential with build and maintenance costs

4.1 Future priority needs

During the course of this project, several future priority needs were identified. These priority needs were beyond the scope of this project, but would contribute to ongoing efforts to improve water quality by reducing sediment delivery to waterways from the forest road network:

- A full comparison between forest roads of differing forest tenures. Comparing the sediment delivery potential, road design and management practices between tenures can be used to identify gaps between existing and best practice management approaches, and for responsible agencies to modify relevant policies and guidelines so that forest road management to reduce sediment deliver to waterways can be better standardised across the industry.
- Further development of the field assessment method to explicitly quantify the impact of using less accurate handheld GPS devices to geolocate drains on the accuracy and interpretation of local scale model outputs
- Engagement with industry and practitioners to drive uptake of the risk assessment framework and the field assessment tool, to refine the method and ensure that future iterations of the method are well suited to the needs of forest road managers.

Attachment A Discussion paper

alluvium

DISCUSSION PAPER:

Evaluating forest road networks to protect water quality in NSW

September 2020

Document history

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Author/s	Petter Nyman Alex Sen Tony Weber
Checked	Tony Weber
Approved	Neal Albert

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Introduction

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.

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.

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:

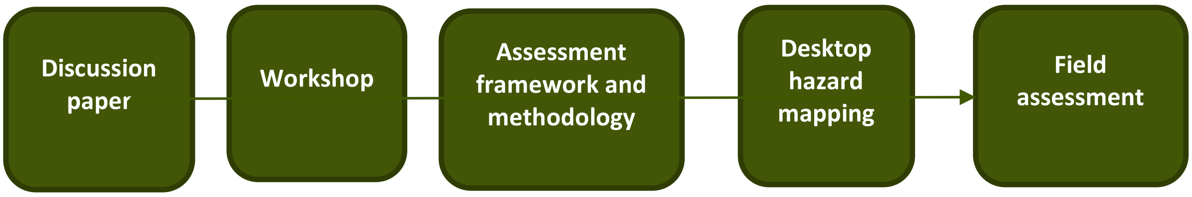
- What are relevant policy and guidelines for design and management of roads and how do these relate to different road types and their classification?
- What are the characteristics of a road network that determine the ability to generate impact on water quality and how is this supported by current scientific 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.



Forest roads –monitoring, evaluation, and management context

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 28). A completer overview of legislation relevant to forestry, environmental protections and conservation are outlined in Appendix A.

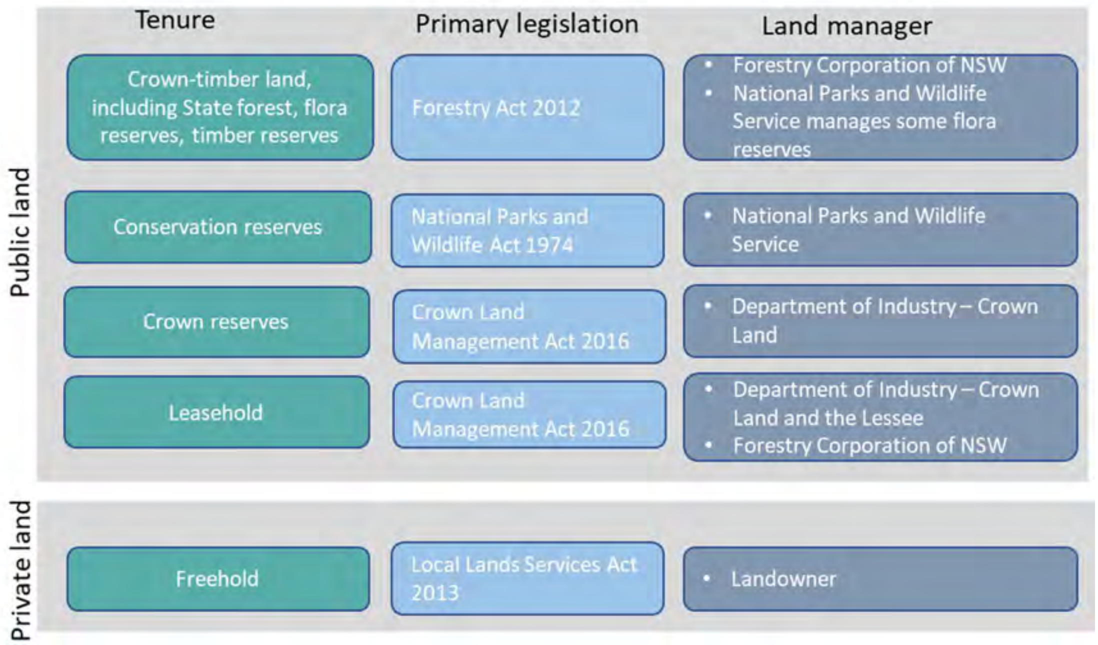


Figure 28. *Primary legislation and land manager across tenures on public and private lands.* ***Note****: land manager may not be responsible for roads.*

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.

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 5). 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.

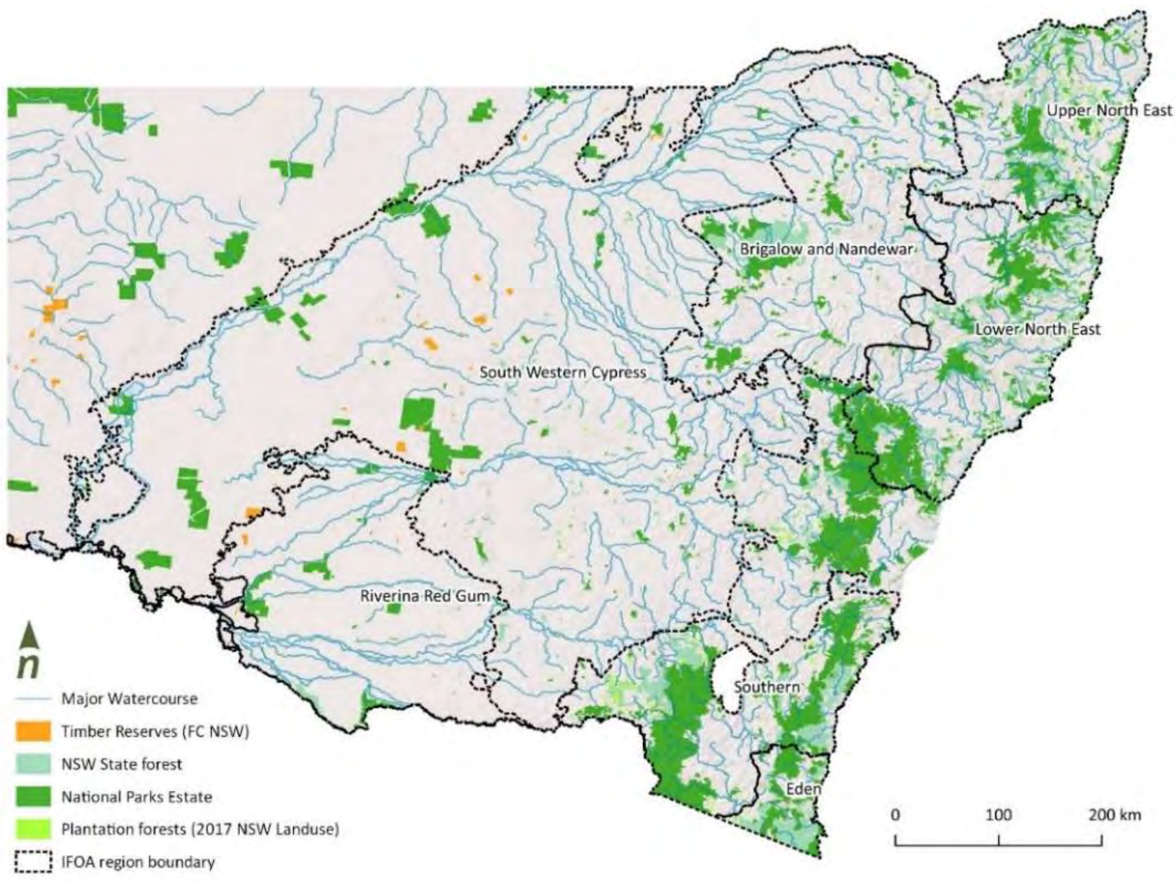


Figure 29. *New South Wales forest estate showing the extent of timber reserves, state forest, plantation and national park.*

Table 5. 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 29). 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)

Forest roads, erosion and key management issues arising

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 30 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.

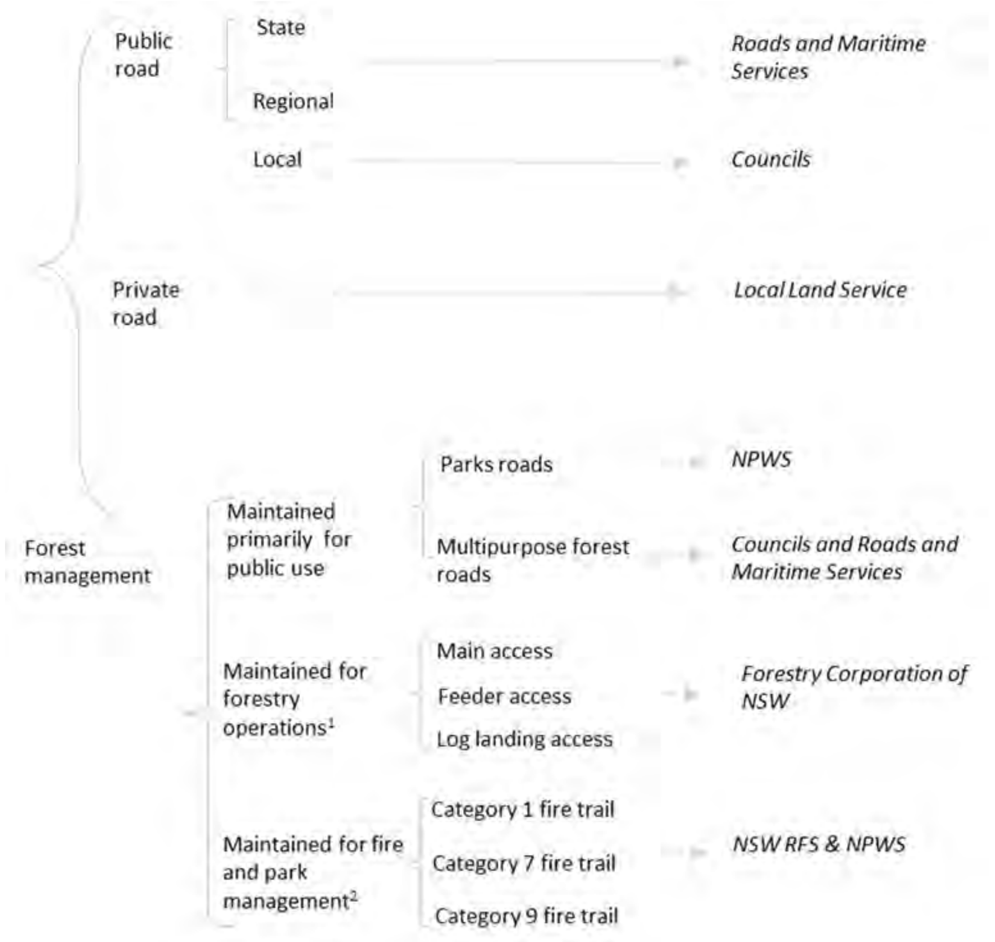


Figure 30. *Forest road classification for NSW (adapted from Gucinski (2001)). [1]Forestry Roads classification based on Croke and Mockler (2001). [2]Fire trails classification based on Fire Trail Standards* (NSW_RFS, 2019).

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 31. *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 32. *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 33. (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)*

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).

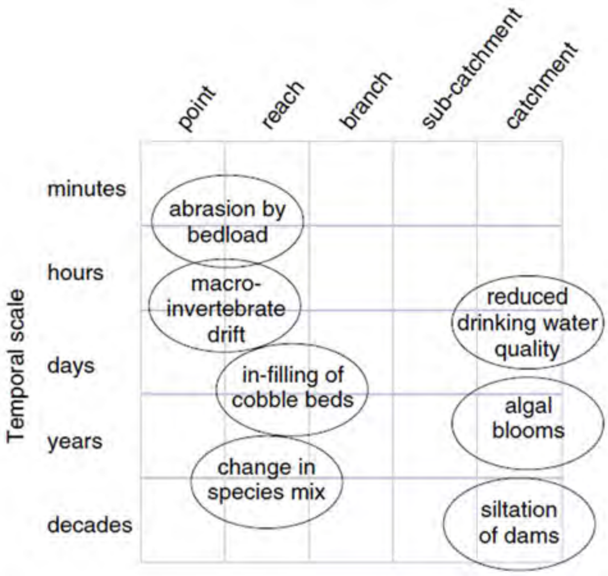


Figure 34. *The spatial and temporal scale of waterway impacts due to sediment delivery. From Sheridan and Noske (2007)*

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.

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.

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

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.

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 35). 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.

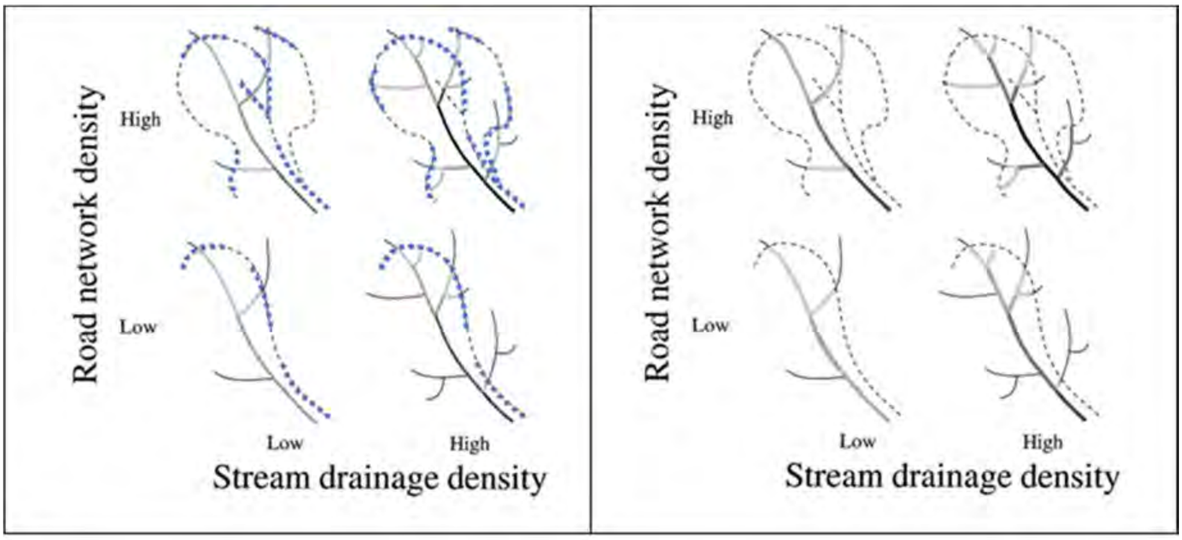


Figure 35. *Spatial association between drainage network and road networks provide a high-level indicator of potential road impacts on sediment delivery to streams. (left) Effect of increasing draining densities of the road network (dashed lined) and the stream network (solid line) on the number of road-segment 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).

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).

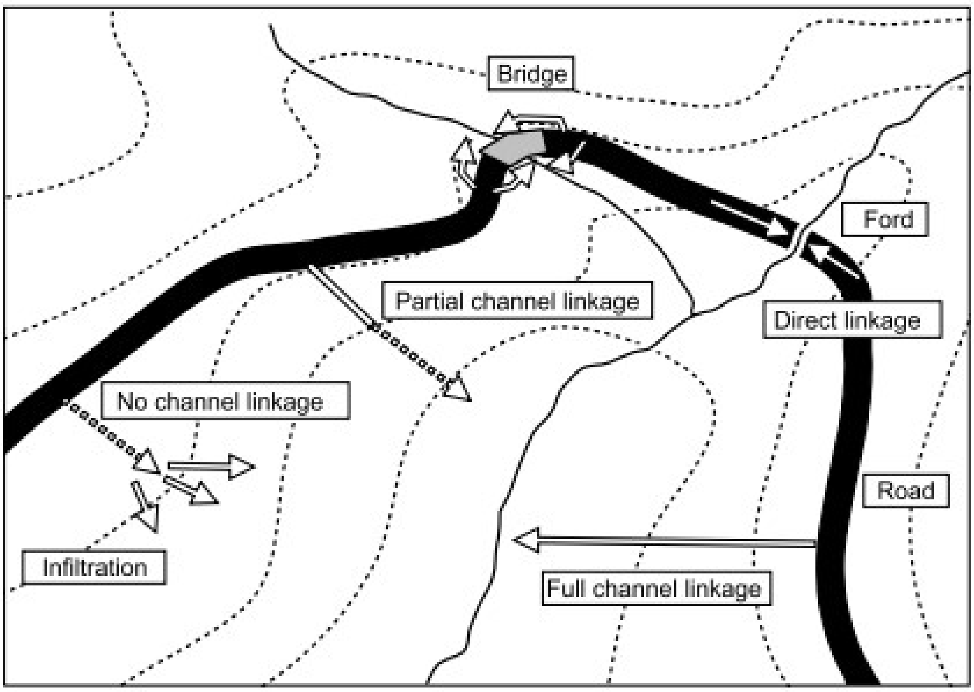


Figure 36. *The range of potential linkage categories within a forested catchment - from full channel, partial channel, and no channel linkage, to the direct linkage that occurs at a ford or bridge crossing. These categories can be used to determine the degree to which major sources like roads and tracks, are linked to stream (Croke et al, 1999).*

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.

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).

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

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 37). 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.

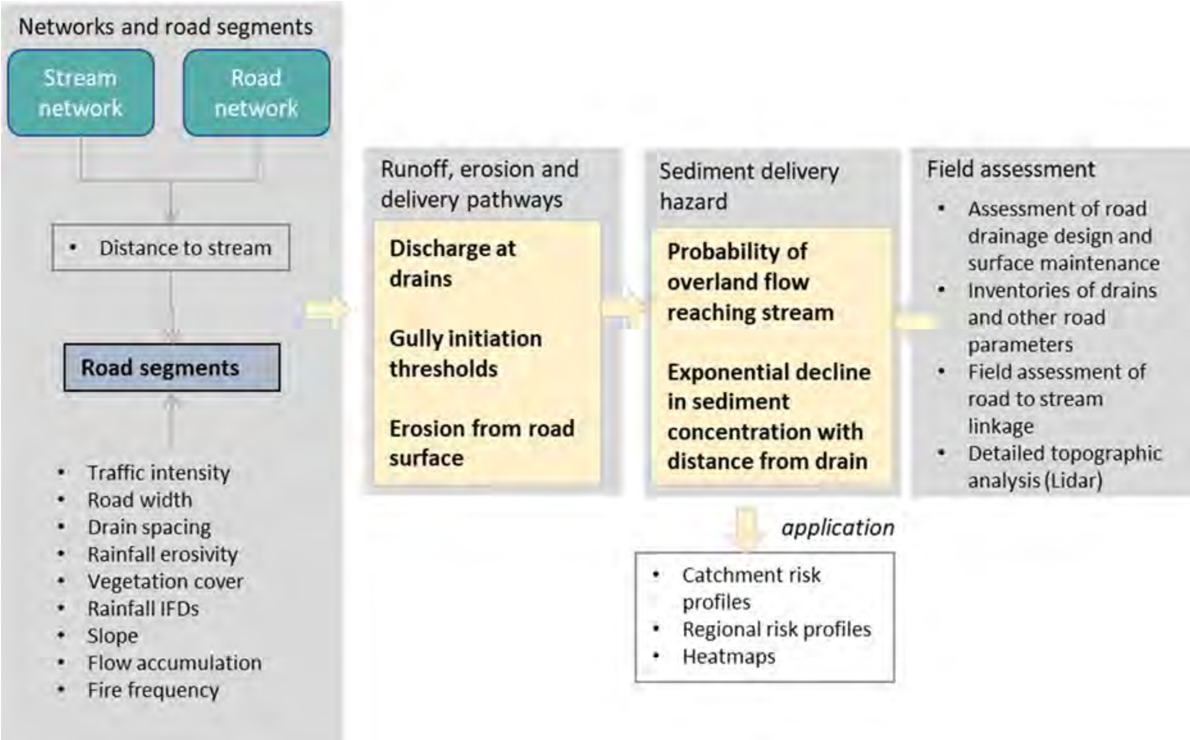


Figure 37. *Processing step in implementing the sediment delivery hazard assessment.*

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 6. 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)

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.

References

Anderson, C.J., and Lockaby, B.G., 2011, Research gaps related to forest management and stream sediment in the United States: Environmental Management, v. 47, p. 303–313.

Bracken, L.J., and Croke, J., 2007, The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems: Hydrological Processes, v. 21, p. 1749–1763, http://dx.doi.org/10.1002/hyp.6313.

Cornish, P.M., 2001, The effects of roading, harvesting and forest regeneration on streamwater turbidity levels in a moist eucalypt forest: Forest Ecology and Management, v. 152, p. 293–312, doi:https://doi.org/10.1016/S0378-1127(00)00611-3.

Croke, J., and Croke, J., 1999, Managing sediment sources and movement in forests: The forest industry and water quality: Cooperative Research Centre for Catchment Hydrology.

Croke, J.C., and Hairsine, P.B., 2006, Sediment delivery in managed forests: a review: Environmental Reviews, v. 14, p. 59–87, doi:doi:10.1139/a05-016.

Croke, J., Hairsine, P., and Fogarty, P., 1999, Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia: Hydrological Processes, v. 13, p. 2705–2720, doi:10.1002/(SICI)1099-1085(19991215)13:17<2705::AID-HYP843>3.0.CO;2-Y.

Croke, J., and Mockler, S., 2001, Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia: Earth Surface Processes and Landforms, v. 26, p. 205–217, doi:10.1002/1096-9837(200102)26:2<205::AID-ESP168>3.0.CO;2-G.

Croke, J., Mockler, S., Fogarty, P., and Takken, I., 2005, Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity: Geomorphology, v. 68, p. 257–268, http://www.sciencedirect.com/science/article/B6V93-4FD79RJ-1/2/2d1c588b44264ab0a31c5e2cbad46c97.

Erskine|Erskine, W., 2013, Soil colour as a tracer of sediment dispersion from erosion of forest roads in Chichester State Forest, NSW, Australia: Hydrological Processes, v. 27, p. 933–942, http://unimelb.hosted.exlibrisgroup.com/sfxlcl41?sid=google&auinit=WD&aulast=Erskine&atitle=Soil colour as a tracer of sediment dispersion from erosion of forest roads in Chichester State Forest%2C NSW%2C Australia&id=doi%3A10.1002%2Fhyp.9412&title=Hydrol.

Gucinski, H., 2001, Forest roads: a synthesis of scientific information: DIANE Publishing, v. 509.

Hairsine, P.B., Croke, J.C., Mathews, H., Fogarty, P., and Mockler, S.P., 2002, Modelling plumes of overland flow from logging tracks: Hydrological Processes, v. 16, p. 2311–2327, doi:10.1002/hyp.1002.

Hancock, G.R., Hugo, J., Webb, A.A., and Turner, L., 2017, Sediment transport in steep forested catchments – An assessment of scale and disturbance: Journal of Hydrology, v. 547, p. 613–622, doi:https://doi.org/10.1016/j.jhydrol.2017.02.022.

Jones, J.I., Murphy, J.F., Collins, A.L., Sear, D.A., Naden, P.S., and Armitage, P.D., 2012, THE IMPACT OF FINE SEDIMENT ON MACRO-INVERTEBRATES: River Research and Applications, v. 28, p. 1055–1071, doi:10.1002/rra.1516.

Jones, J.A., Swanson, F.J., Wemple, B.C., and Snyder, K.U., 2000, Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks: Conservation Biology, v. 14, p. 76–85.

Kaller, M.D., and Hartman, K.J., 2004, Evidence of a threshold level of fine sediment accumulation for altering benthic macroinvertebrate communities: Hydrobiologia, v. 518, p. 95–104.

Kemp, P., Sear, D., Collins, A., Naden, P., and Jones, I., 2011, The impacts of fine sediment on riverine fish: Hydrological Processes, v. 25, p. 1800–1821, doi:10.1002/hyp.7940.

Landcom, 2004, Managing Urban Stormwater: Soils and Construction:, https://www.landcom.com.au/assets/Uploads/managing-urban-stormwater-soils-construction-volume-1-fourth-edition-compressed.pdf.

Lane, P.N.J., Hairsine, P.B., Croke, J.C., and Takken, I., 2006, Quantifying diffuse pathways for overland flow between the roads and streams of the Mountain Ash forests of central Victoria Australia: Hydrological Processes, v. 20, p. 1875–1884, doi:10.1002/hyp.5940.

Lane, P.N.J., and Sheridan, G.J., 2002, Impact of an unsealed forest road stream crossing: water quality and sediment sources: Hydrological processes, v. 16, p. 2599–2612.

Luce, C.H., 2002, Hydrological processes and pathways affected by forest roads: what do we still need to learn? Hydrological processes. 16 (1): 2901-2904,.

Luce, C.H., and Black, T.A., 1999, Sediment production from forest roads in western Oregon: Water Resources Research, v. 35, p. 2561–2570, doi:10.1029/1999WR900135.

MacDonald, L.H., and Coe, D.B.R., 2008, Road sediment production and delivery: processes and management, *in* Proceedings of the First World Landslide Forum, Tokyo, Japan, v. 381384.

Morris, B.C., Bolding, M.C., and Aust, W.M., 2015, Effectiveness of forestry BMPS for stream crossing sediment reduction using rainfall simulation, *in* In Proceedings of the 17th biennial southern silvicultural research conference. e–Gen. Tech. Rep. SRS–203. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station. 7 p., v. 2015, p. 84–90.

Motha, J.A., Wallbrink, P.J., Hairsine, P.B., and Grayson, R.B., 2003, Determining the sources of suspended sediment in a forested catchment in southeastern Australia: Water resources research, v. 39.

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.

NSW_Environment_Protection_Authority, 2016, Private Native Forestry Code of Practice for Northern NSW:, https://www.lls.nsw.gov.au/__data/assets/pdf_file/0006/807423/Private-Native-Forestry-Code-of-Practice-for-Northern-NSW.pdf.

NSW_EPA, 2010, Integrated Forestry Operations Approval for Brigalow-Nandewar Region (Amended 2013):, https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/forestagreements/integrated-forestry-operations-approval-brigalow-nandewar-region-including-amends1-3.pdf?la=en&hash=716C6FE7FF520A68DA9CE0CEB4C81CD04F66C19D.

NSW_EPA, 2018, Summary of the NSW Government’s response to public feedback on the draft Coastal IFOA. NSW Environmental Protection Authority:, https://www.epa.nsw.gov.au/your-environment/native-forestry/native-forestry-nsw-overview/regulating-native-forestry/native-forestry-regulatory-framework.

NSW_Office_of_Environment_And_Heritage, 2012, Erosion and sediment control on unsealed roads: A field guide for erosion and sediment control maintenance practices:, https://www.environment.nsw.gov.au/research-and-publications/publications-search/erosion-and-sediment-control-on-unsealed-roads.

NSW_RFS, 2019, NSW Fire Trails Standards:, https://www.rfs.nsw.gov.au/__data/assets/pdf_file/0009/69552/Fire-Trail-Standards-V1.1.pdf.

Nyman, P., Sheridan, G., and Lane, P.N.J., 2010, Synergistic effects of water repellency and macropore flow on the hydraulic conductivity of a burned forest soil, south-east Australia: Hydrological Processes, v. 24, p. 2871–2887, doi:10.1002/hyp.7701.

Parsons, A.J., Bracken, L., Poeppl, R.E., Wainwright, J., and Keesstra, S.D., 2015, Introduction to special issue on connectivity in water and sediment dynamics: Earth Surface Processes and Landforms, v. 40, p. 1275–1277.

Reid, L.M., and Dunne, T., 1984, Sediment production from forest road surfaces: Water Resources Research, v. 20, p. 1753–1761.

Riley, S.J., 1988, Soil loss from road batters in the Karuah state forest, Eastern Australia: Soil Technology, v. 1, p. 313–332, doi:https://doi.org/10.1016/0933-3630(88)90012-8.

RTA, 2008, Erosion and sedimentation management procedure:, https://www.rms.nsw.gov.au/documents/about/environment/erosion-sedimentation-management-pn143p.pdf.

Sheridan, G.J., Lane, P.N.J., and Noske, P.J., 2007, Quantification of hillslope runoff and erosion processes before and after wildfire in a wet Eucalyptus forest: Journal of Hydrology, v. 343, p. 12–28, doi:10.1016/j.jhydrol.2007.06.005 DOI: 10.1016/j.jhydrol.2007.06.005.

Sheridan, G.J., and Noske, P.J., 2007, Catchment-scale contribution of forest roads to stream exports of sediment, phosphorus and nitrogen: Hydrological Processes, v. 21, p. 3107–3122, doi:10.1002/hyp.6531.

Sheridan, G.J., Noske, P.J., Whipp, R.K., and Wijesinghe, N., 2006, The effect of truck traffic and road water content on sediment delivery from unpaved forest roads: Hydrological Processes, v. 20, p. 1683–1699, doi:10.1002/hyp.5966.

Sidle Colin L.|Pearce,Andrew J., R.C. |O'Loughli., 1985, Effects of Land Management on Soil Mass Movement: v. 11, http://unimelb.hosted.exlibrisgroup.com/sfxlcl41?id=doi%3A10.1029%2FWM011&sid=wiley&genre=book&date=1985&btitle=Hillslope Stability and Land Use&title=Hillslope Stability and Land Use&tpages=-1&series=Water Resources Monograph&isbn=0-87590-315-0&atitle=Ef.

Sidle, R.C., Sasaki, S., Otsuki, M., Noguchi, S., and Rahim Nik, A., 2004, Sediment pathways in a tropical forest: effects of logging roads and skid trails: Hydrological Processes, v. 18, p. 703–720.

Smith, H.G., Sheridan, G.J., Lane, P.N.J., and Bren, L.J., 2011, Wildfire and salvage harvesting effects on runoff generation and sediment exports from radiata pine and eucalypt forest catchments, south-eastern Australia: Forest Ecology and Management, v. 261, p. 570–581, doi:10.1016/j.foreco.2010.11.009.

Soil_Conservation_Service, 2017, NSW Rural Fire Service Fire Trail Design, Construction and Maintenance This manual has been developed by the Soil Conservation Service for the NSW Rural Fire Service Manual.:

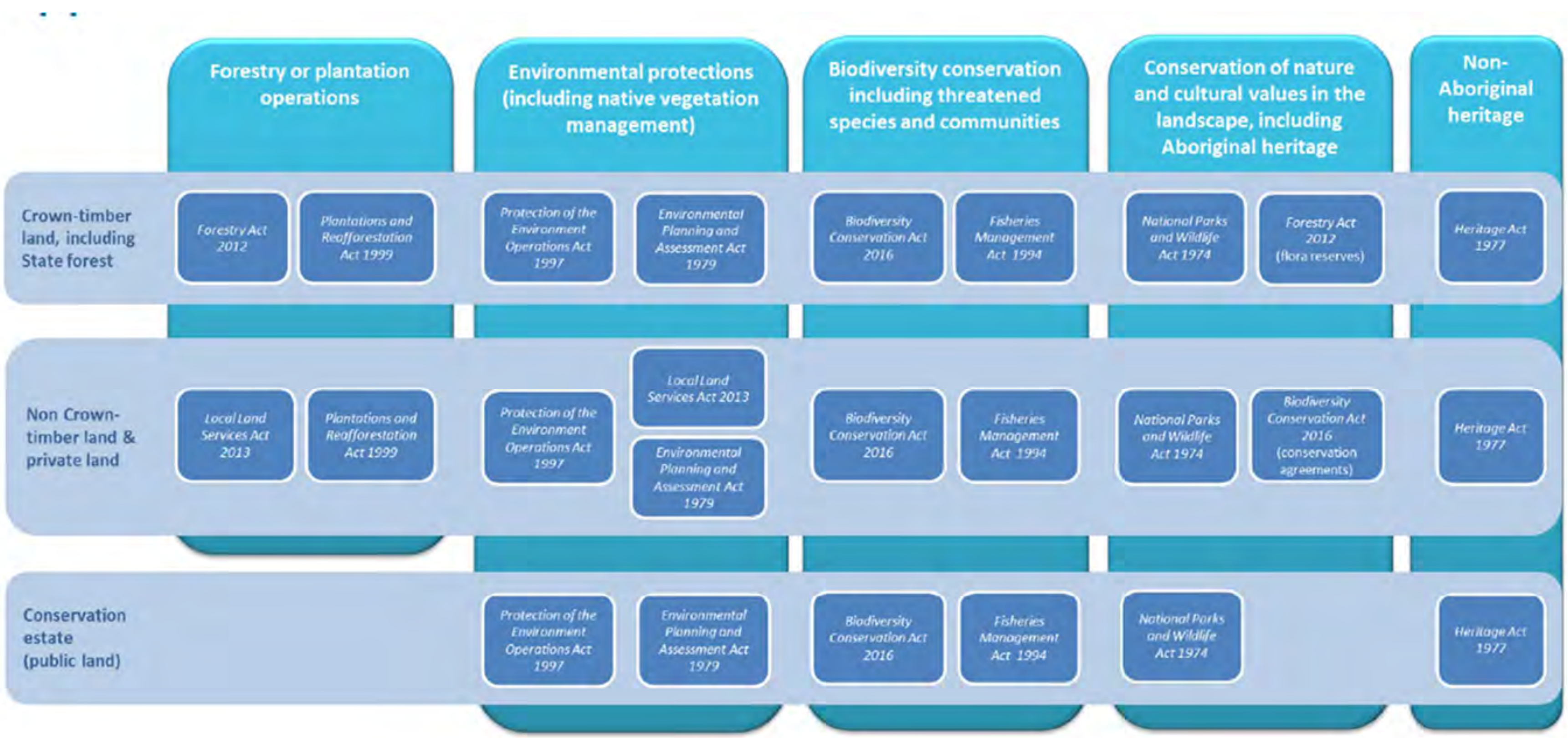
Takken, I., Croke, J., and Lane, P., 2008, A methodology to assess the delivery of road runoff in forestry environments: Hydrological Processes, v. 22, p. 254–264, %3CGo.

Tomkins, K.M., Humphreys, G.S., Gero, A.F., Shakesby, R.A., Doerr, S.H., Wallbrink, P.J., and Blake, W.H., 2008, Postwildfire hydrological response in an El Nino-Southern Oscillation-dominated environment: Journal of Geophysical Research-Earth Surface, v. 113, doi:F02023 10.1029/2007jf000853.

Yang, X., Zhu, Q., Tulau, M., McInnes-Clarke, S., Sun, L., and Zhang, X., 2018, Near real-time monitoring of post-fire erosion after storm events: a case study in Warrumbungle National Park, Australia: International Journal of Wildland Fire, v. 27, p. 413–424, doi:https://doi.org/10.1071/WF18011.

Overview of legislation in the NSW Forest Management Framework

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



Attachment B Method recommendation

DRAFT METHODOLOGY RECOMMENDATION:

Evaluating forest road networks to protect water quality in NSW

November 2020

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General Introduction

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. On behalf of the NSW Government, the Natural Resource Commission (NRC) seeks to implement this commitment through the implementation of the Forest Monitoring Improvement Program (FMIP).

The FMIP links monitoring, evaluation, and research to decision-making, both for policy and on-going forest management in NSW. Evaluating the effectiveness of forest road network design and management in reducing soil erosion and maintaining in-stream water quality is one of the aims of the FMIP. In addressing this aim, 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.

The methodology for evaluating the forest road network is developed as part of a broader program for monitoring and evaluation of waterway health in relation to forest management and timber harvesting[10].

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.

[10] Alluvium (2020) Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests. Report for the Natural Resources Commission. pp 1-33. December 2020.

Methodology recommendation

Overview of modelling approach

This document outlines an approach for assessing the effectiveness of forest road network design and management in reducing soil erosion and maintaining in-stream water quality. The methodology incorporates the issues raised in the discussion paper[11], has been shaped by the feedback received from the technical panel review, steering committee meeting, the stakeholder workshop, and the reconnaissance field trip.

The methodology is 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. The key assumption with the proposed methodology is that a sediment delivery hazard can be effectively captured by considering two processes: erosion on roads and associated drainage infrastructure and the probability that eroded sediment reaches the streams.

The intent is to provide a modelling framework that can be implemented to achieve the following outcomes:

- To map sediment delivery hazard across different tenures in NSW using available data on terrain, road networks, rainfall regime, drainage networks and road design guidelines. The regional-scale mapping provides sediment delivery hazard maps for benchmarking and to focus and guide the field assessments, not to produce quantitative estimates of sediment delivery.
- To provide detailed assessment of sediment delivery hazard in priority catchments using field observations that provide more accurate input parameters with regards to delivery pathways, road surfaces, traffic and drainage structures.
- To deliver quantitative understanding of priority areas for addressing sediment delivery hazard with improved design and maintenance. The conceptual model and field assessment will guide improvement to road network designs and maintenance through both operational and strategic management interventions.

By outlining a robust modelling framework, we ensure that there is consistency in the overall approach to assessing a road network, including field assessment, monitoring and mitigation. The concepts that underpin the modelling are carried through to the design of field assessment and provide a mechanism for adaptive management whereby new site-specific data on parameters and erosion responses are used to refine our models over time. This helps ensure field assessments and monitoring activities provide value beyond the local setting where the data is collected.

The framework currently considers sediment delivery processes from roads to operate independently of some processes that are known to be important. For example, it does not consider disturbance from bushfire, spatial variability in infiltration rates or differences in erodibility as result of geology. We have excluded these factors from the modelling to arrive at parsimonious approach that is aligned with the data availability and best available science. However, the model is developed by explicitly considering the dominant processes that govern sediment delivery and is driven by physically meaningful parameters that can be adapted for different road and catchment conditions. The proposed model is therefore flexible and can accommodate additional complexity, should data on parameters and link to processes come available.

We note that linking erosion processes related to the road network to in-stream water quality parameters is challenging to implement as part of a monitoring program. In-stream monitoring is costly and often ineffective in identifying the dominant processes leading to impacts. However, where appropriate, our recommendation for monitoring and evaluation program identify opportunities to gain insights by analysing historical records in catchment that are instrumented to measure discharge, turbidity and suspended sediment.

[11] Alluvium (2020) Discussion Paper: Evaluating forest road networks to protect water quality in NSW. Produced by Alluvium consulting for the NRC.

Linking model implementation, field assessment and monitoring in terms of risk

The program outlines two main components for the assessment of risk to waterway values from a forest road network:

GIS-based mapping of sediment delivery hazard

The goal of the mapping is to provide a *means for identifying hotpots* where the likelihood of road and stream linkage is high and where monitoring and evaluation of the road network should be prioritised. The mapping uses data on road networks, stream networks, slope and rainfall regimes. Specifically:

- The mapping is based on published model components which utilises available datasets to estimate sediment delivery to streams from road segments.
- The model is implemented using an approach that is aligned with the data that we can obtain without field assessments.
- The model provides a reasonable approximation of sediment delivery hazard from road networks given mean drainage conditions or when a specified road drainage regime is in place.
- The intention is not to provide quantitative prediction of sediment delivery. Instead, the output from this mapping provides an indication of relative sediment delivery hazards as governed by rainfall, terrain, distance to streams and basic road parameters which there is available data.

*Essentially, the mapping indicates the **likelihood** of a road network impacting on water values (Figure 38)*

Field assessments to measure the effectiveness of mitigation

Field assessments to collect data (model parameters and sediment delivery hazards) for identifying problematic parts of the road network and d*etermine how effective elements of road design and maintenance are in mitigating* sediment delivery in relation to water quality values. Specifically:

- The field assessments collect field data to assess the degree of erosion and coupling between roads and streams (gullied vs non-gullied, full vs partial linkage) using tested methods deployed in previous work.
- Field assessments will measure drain location, layout of drainage ditches (single or double) and the location of topographic maximums and minimums of the road. The field survey serves to get the hard surface catchment area of each drain.
- The data from field assessment will be combined into a model of sediment delivery hazard for individual road segments and scored to ascertain the relative contribution of road design and/or maintenance to sediment delivery.
    - For example, a road may be well maintained, but because of its placement, the sediment delivery hazard remains high.
    - Conversely, a road me be designed to effectively mitigate against water quality impacts but presents a sediment delivery hazard due to poor maintenance.
- Field assessments will consider catchment specific values, capturing data which relates to their sensitivity to the hazard.

*By capturing this information, the field assessments evaluate how effective maintenance and design are in mitigating the **consequence** of sediment delivery upon downstream water quality values (Figure 38).*

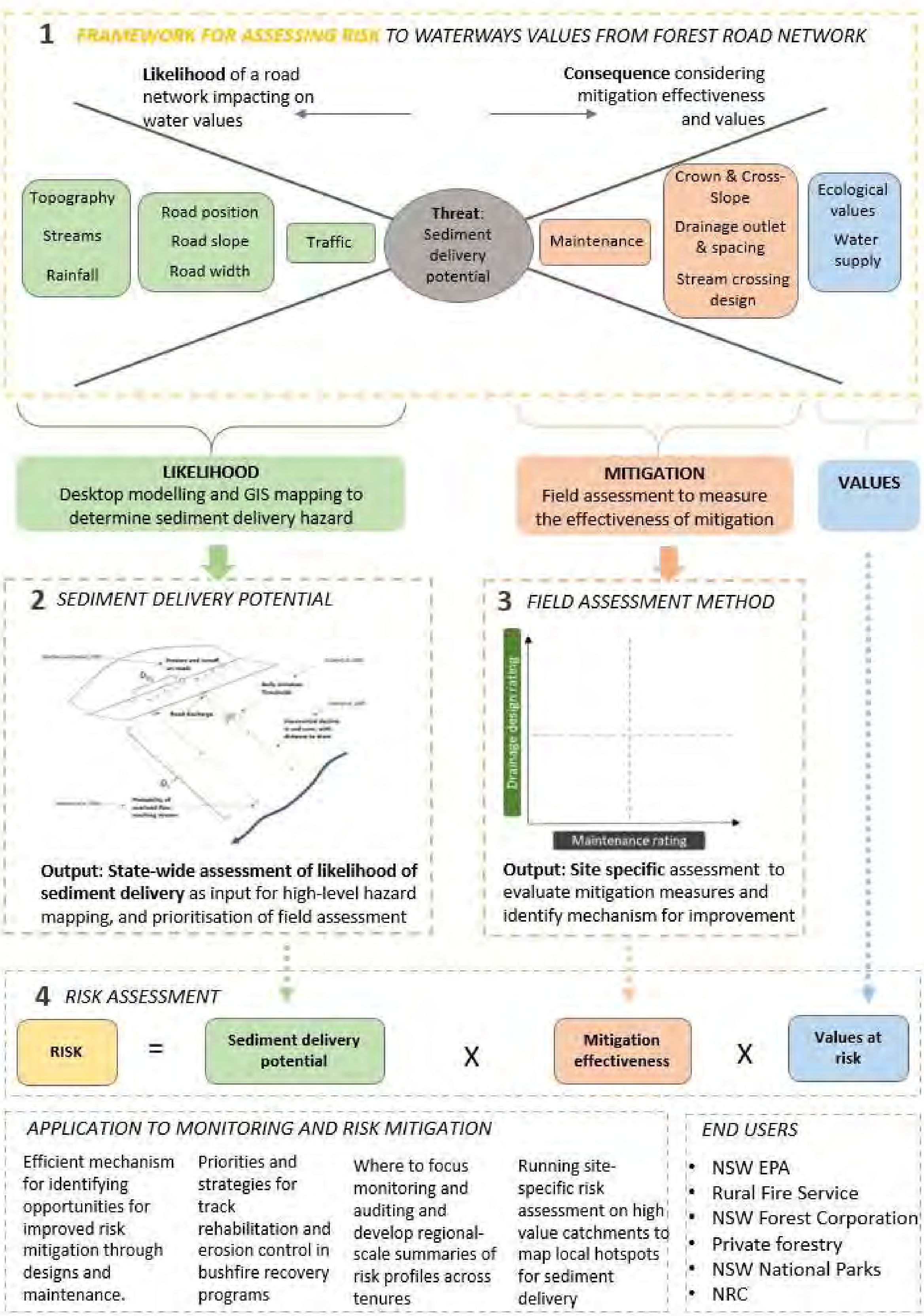


Figure 38. *Linking model implementation and field assessments in terms of risk.*

Task outline for field assessments

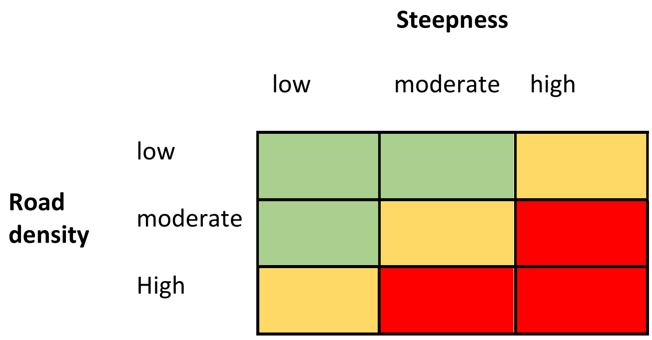
State-wide mapping of sediment delivery hazard from forest road network

Translate conceptual model into a set of GIS geoprocessing steps that can be applied using existing spatial data and guidelines on road design. Implement the model for the NSW forest road network. The outputs from this will be a series of hazard maps that can be used to help guide the selection of sites for detailed field assessment. NOTE: model development, GIS workflow and state-wide implementation have been completed (see sections 4, 5, 6)

Catchment selection for field reconnaissance

The state-wide sediment delivery hazard mapping will inform the selection of catchments that will be used to test the field assessment methodology. Catchments with contrasting sediment delivery hazard and land tenure will be selected. The selection will be governed in part by road density and overall steepness of the terrain in which the road network is situated, as these two factors are high-level control on the degree of influence of roads on sediment delivery to streams (e.g. Table 7). For the field reconnaissance, 2-3 contrasting catchments will be selected.

Table 7. Matrix illustrating the link between topography, road density and sediment delivery hazard.



Field reconnaissance

The purpose of the field reconnaissance is to develop an understanding of the practical aspects of surveying erosion and sediment delivery hazard and ensure that the field methodology is aligned with what is achievable in the field. Two catchments will be visited, and we propose participation by Peter Hairsine, Jefferey Bell, Petter Nyman and Kurt Laboyrie. The two catchments will be identified in accordance with Table 1 to provide contrasting cases. The field recognisance will answer the following questions:

1. Does the conceptual model match with what we see in the field?
2. What can be achieved in a day in terms of surveying road drains and road to channel coupling according to the tested methods (e.g. Table 8)?
3. What are some opportunities and constraints in terms of efficiency in carrying out field assessments?
4. Are there aspects of the GIS implementation that we should revisit?
5. Do the GIS mapping match with field observations?

Table 8. An example of the field checklist to be populated key parameters and coupling indicators

Site	Lat/long of road segments[1]	Road class	Road material	Hard surface width	Drain spacing	Drain type	Delivery pathway[2]	Drain blocked (Y/N)	Drain bypassed (Y/N)	Road crowned (Y/N)
1		Feeder access	Gravel	10	100m	Culvert	Gullied or dispersive			

[1] all road topographic maximums and minimums will need to be mapped as rows to permit contributing hard surface length/area to be calculated.[2]*Gullied* road discharge points: Discharge points where incision deeper than 30cm occurs. Measured in terms of length (after Croke et al., 2005). *Dispersive* road discharge points: discharge points where there is no incision, or it is less than 30cm in depth.

Draft field survey template and hazard mapping
The results from the preliminary assessment will guide the development of a final field survey template.. The GIS approach will then be applied across 9 catchments selected according to the criteria in Table 7 and with the criteria that they are accessible for field assessment. A subset of the 9 catchments may need to be shortlisted for field assessment if the field reconnaissance indicated that 9 catchments is too much given the available resources.

In finalising the assessment method, we are guided by the criteria that the approach:

- Provides data that is aligned with conceptual model of sediment delivery hazard
- Is practical and provides data inform road network improvement
- Is cost effective, balancing detail/robustness and the need to cover large areas.
- Scalable, delivering local scale information (e.g. for road segments) that can be aggregated to composite measures that describe the overall sediment delivery hazard at the catchment scale
- Applicable to all tenures

The overall aim of the field assessment method is to evaluate the effectiveness of this methodology in its broader application. Given our conceptual model of sediment delivery, which has been implemented in earlier work, the field methods will be largely guided by existing methods described that literature (e.g.Takken et al., 2008).

With regards to identifying opportunities for improvement there are two key sources of sediment that the survey will focus on:

- The remediation of existing gullies by relocating drains and future gullies by adding more drains. Gullies below road drainage outlets are major contributors to water quality problems (often hundreds or thousands of tonnes of fine sediment) compared with sediment delivery via ungullied pathways as described by Hairsine et al. (2012). Also, gullies are effectively permanent. This may lead to different design criteria for the two distinct processes whereby drain spacing must ensure, for example that:
    - that gullies must not occur in a 1: 100 year rainfall event
    - non-gullied pathways should not connect in a 1:5 year event
- Priority list of stream crossings to remediate. Stream and drainage line crossings are treated the same as other road drainage outlets. However, they are likely to be many (typically 4 to 20) drainage outlets in the vicinity of the crossing (often including outlets on bridges), and these are often highly connected to the stream network.

Meeting with Steering Committee
We will present the outcomes of the risk assessment and mapping, our recommended pilot locations and method to the steering committee prior to commencing the field survey.

Field Survey and Demonstration Pilot
The field assessment will be led by Soil Conservation Service (Kurt Laboyrie).

Pilot documentation
The outcomes of the field surveys will be documented, including any recommendations for improving the field survey approach.

Key considerations in development of methodology

Data constraints

A key constraint in monitoring and evaluation is the difficulty of collecting data to ascertain the effectiveness of 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 mechanisms 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 limitation in 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.

Connectivity and its implications for sediment delivery to streams

In the 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 in 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.

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 segments 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 35). 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.

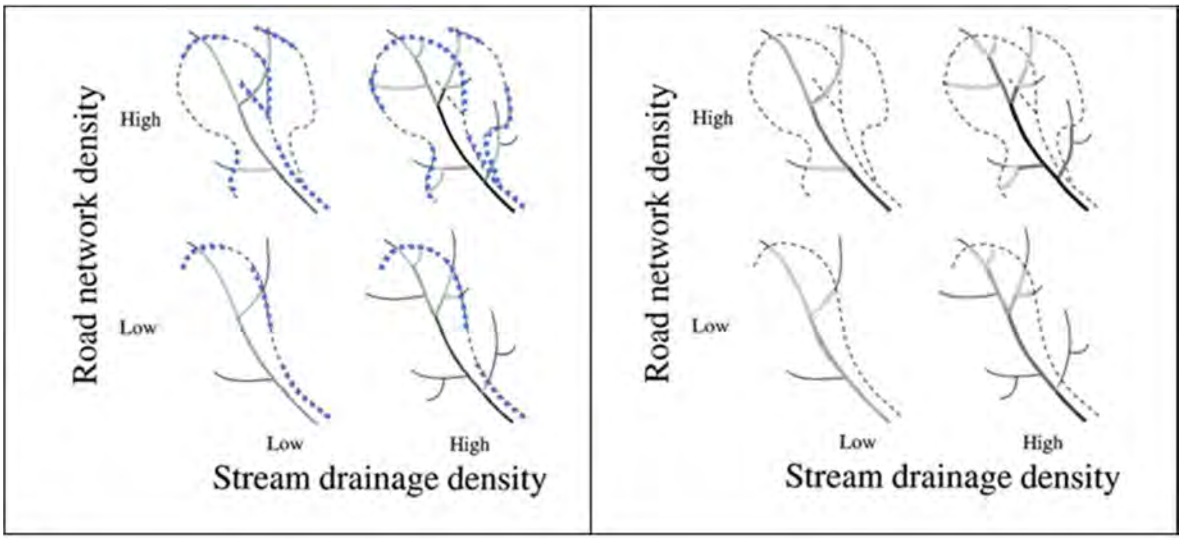


Figure 39. *Spatial association between drainage network and road networks provide a high-level indicator of potential road impacts on sediment delivery to streams. (left) Effect of increasing draining densities of the road network (dashed lined) and the stream network (solid line) on the number of road-segment 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).

Connectivity between road segments and streams

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 purposes, 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).

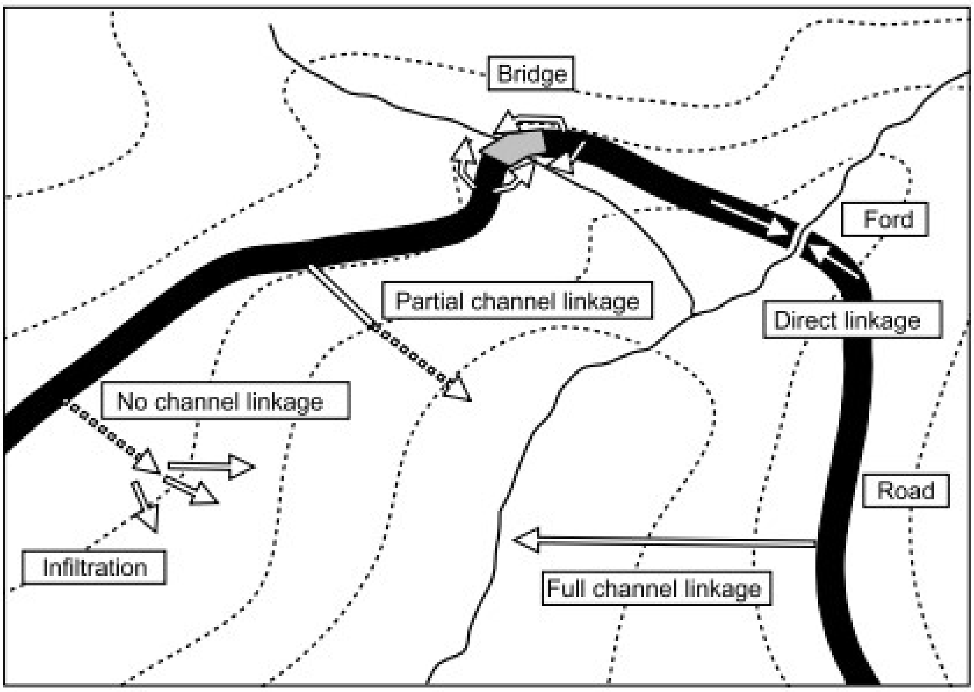


Figure 40. *The range of potential linkage categories within a forested catchment - from full channel, partial channel, and no channel linkage, to the direct linkage that occurs at a ford or bridge crossing. These categories can be used to determine the degree to which major sources like roads and tracks, are linked to stream (Croke et al, 1999).*

Sediment delivery model

Model overview

The conceptual model in (Figure 41) illustrates how the proposed framework captures the key processes which lead to sediment delivery from forest roads. The method considers four key processes and draws on published relationship and analytical tools to quantify how those process vary across the road network.

1. Erosion and runoff on roads (Sheridan and Noske, 2007)
2. Gully initiation thresholds (Croke and Mockler, 2001)
3. Probability of overland flow reaching stream (Hairsine et al, 2002)
4. Exponential decline in sediment concentration with distance to drain (Croke et al, 2005)

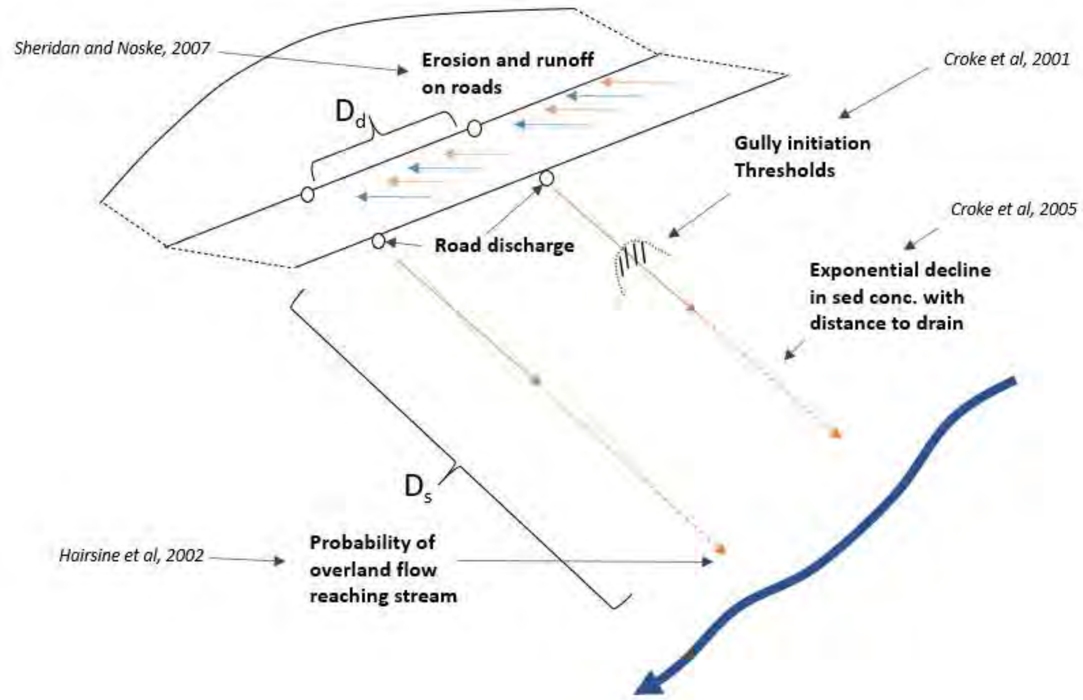


Figure 41. *How each key process relates to one another in the conceptual model*

When implanted using design storms, the outputs provide a measure of sediment load (in kg) reaching the stream from each road segment on the network. While this is a quantitative model, the results are associated with large uncertainties that stem from data inputs, assumptions and parameters estimates.

NOTE: In the absence of model calibration and testing, the results should be interpreted in a qualitative sense and used to assigns hazard scores to road segment from 1 (very low) to 5 (very high).

Erosion and runoff on roads (Sheridan and Noske, 2007a)

This component is developed from Sheridan and Noske (2007 who measured sediment generation from roads by capturing runoff and sediment at drainage outlets. 20% of the experimental sites comprised of a catchment area of the road surface only, while 80% incorporated not just the road itself, but also the adjacent features such as the table drain, cut slope and culvert. Overall, the study resulted in equations which can be used to approximate sediment delivery rates for gravel surfaced forest roads when the rainfall, road slope, road area and truck traffic are known (Figure 42).

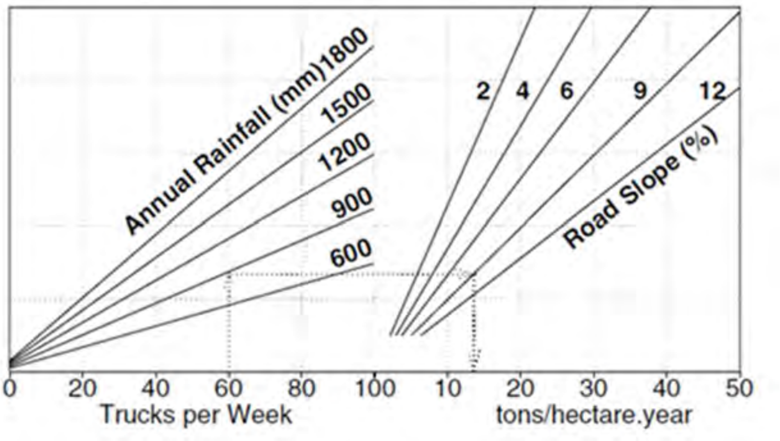


Figure 42. Nomogram for estimating the annual sediment load from gravel surfaced forest roads.

Outputs:	The output from this model is the mean annual sediment produced (in kg) by a road surface. We consider this annual mass of sediment to be what is available for transport into streams for a given design storm.	
Inputs	Traffic	This determined how much sediment is available for erosion -more traffic – more erosion Poor data on this. Invoke to assumption about road type and traffic.
	Annual Rainfall.	More rainfall means more erosion Data from BoM
	Road slope	Steeper roads generate more sediment Data obtained by extracting elevation at both ends of 100m road segments and using 30m SRTM DEM
Assumptions:	The model is applied to all forest road surface types, including natural and gravel. Developed for a rainfall energy in the range 1500–2000 MJ mm/ha/hr/year. The model is developed for gravel roads so this model may over and underpredict erosion rates for roads with natural surfaces. Implementing a state-wide model of road erosion that takes into account the road surface type is not feasible given data constraints. However, the structure of the model lends itself to being updated with this information. Assumes all sediment generated from the road in a given year is available for redistribution by the 10-year event when it occurs Coarse and fine sediment are not separated and soil type in the areas between the road and stream are not considered. This means that differences in connectivity as dictated by geology/soils are not considered in the model. The peer-reviewed literature does not currently support a methodology that explicitly considered soil type in assessing sediment delivery hazard. However, an overlay of readability can be used a qualitative indicator of where, for a given hazard, the risk of impact to waterway is high.	

Gully initiation thresholds (Croke and Mockler, 2001)

The extent of road to stream linkage can be measured in terms of channelled and non-channelled flow paths. When these flow paths are analysed in terms of their contributing road area and the discharge gradient, a threshold value for channel (or gully) initiation can be derived (Figure 43).

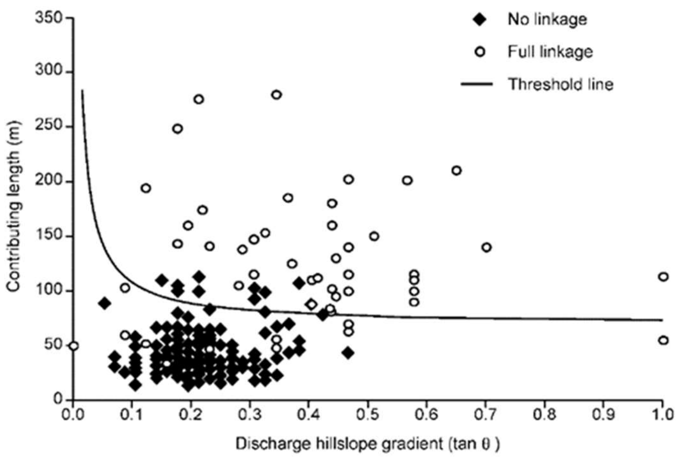


Figure 43. *Fitted threshold curve separating channelled and non-channelled road drains for the study area (Croke and Mockler 2001).*

Outputs:	This model provides a binary indicator of gully initiation threshold exceedance. We consider the yes or no value to determine the type of overland flow (gullied or dispersive) downstream of the drain.	
Inputs:	Road Slope.	Based on the difference in elevation of the endpoints (Derived from the SRTM DEM) divided by the length of each road segment (100m).
	Drain spacing.	Drain spacing a determining factor of runoff volume at drain outlet. Drain spacing is assumed for each road type based on relevant tenure guidelines. Some guidelines inform minimum spacing of road drains based on slope *and* soil erosion classes, however only slope is considered in this model.
	Road width	Road width is a determining factor of runoff volume at drain outlet. Data sources unclear, but we have enquired with NRC.
	Slope below road	The slope is required to determine if the conditions at the drain outlet means that the gully initiation threshold is exceeded. The downstream slope is derived from a slope determination algorithm (TauDEM D8 Slope) applied to the conditioned DEM. The mean slope within 10m of the road segment, one either side, is assumed as the slope downstream of the road.
Assumptions:	This threshold has been shown to vary between studies. The threshold curve utilised does not consider other variables, such as hillslope curvature and fire regime. Coincidence between timing of rainfall and road construction would also have an impact on gully development. Based on the measurement of the length of D8 drainage pathways as determined through the TauDEM GIS processing tools. We assume that the drain spacing modifiers, which are based on soil erodibility and stability class as outlined in the Soil Conservation Service Fire trail design manual, do not apply We assume that road width is a function of road type	

Probability of overland flow reaching stream (Hairsine et al, 2002)

This study uses the concept of volume to breakthrough to develop a simple statistical representation of the spatial extent of plumes from road drain outlets. With knowledge on the likely runoff and spatial distribution of roads and streams the equations support the prediction of which outlets are most likely to contribute overland flow and associated sediment delivery to streams. The equations emphasize the trade-off between intercross-bank and available hillslope length for flow dispersal (Figure 44).

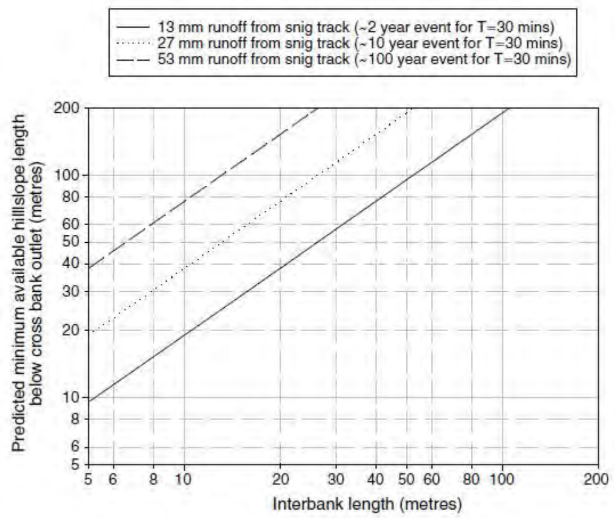


Figure 44. *An example of how interbank length performs under three different runoff rates. The greater the interbank or outlet spacing, the greater the length of drainage pathway required to avoid delivery to stream.*

Outputs:	A prediction of mean plume lengths and the mean volume of overland flow reaching the stream.	
Inputs:	Rainfall intensity	30-minute design storm from BOM (10 year event)
	Road infiltration rate	Assumed to be fixed at ~12 mm/hr as per Takken et al 2008.
	Mean volume to breakthrough (vbt5 Mean)	A constant used to determine the plume length for a given discharge at drain outlet Measured in wide range of forest types and considered random variable that is widely representative of infiltration in undisturbed forests
	Distance between drain outlet and stream	This is the slope length along the flow D-8 direction measured using a 30m DEM. We use 30m DEM as this is available for all of NSW.

Assumptions:

The overland flow leaving the cross-bank is non-eroding. This requires that the resistance of the GHA surface be such that incision does not occur (Hairsine et al., 2002).

The behaviour of the 5-m segments of hillslope containing the plume is representative of the hillslopes within the compartments. This implies that the concentration of flow resulting from the cross-bank and that occurring 5 m downslope are identical in terms of their effect on the spatial distribution of vbt5. It also implies that the distribution of soil hydraulic properties in the plume area as influencing the calculated values of vbt5 are representative of those of the compartment (from Hairsine et al., 2002).

The values of vbt5 for adjacent plume areas are spatially independent, although drawn from the same population (Hairsine et al., 2002).

vbt5 describes all losses of overland flow. This assumption neglects any losses occurring after the time of breakthrough (Hairsine et al., 2002).

All hillslope lengths are greater than interbank lengths, so it is assumed that overland flow plumes from a sequence of cross banks do not connect with one another (Hairsine et al., 2002).

Exponential decline in sediment concentration with distance to drain (Croke et al, 2005)

This study describes the nature of sediment concentration changes with distance downslope to reveal the importance of runoff infiltration in reducing sediment fluxes to streams. A relationship from initial average sediment concentration for both dispersive and gullied pathways was determined from a sample set (Figure 45). These relationships can be utilised to estimate the sediment concentration of plumes as they reach and or breakthrough to the stream.

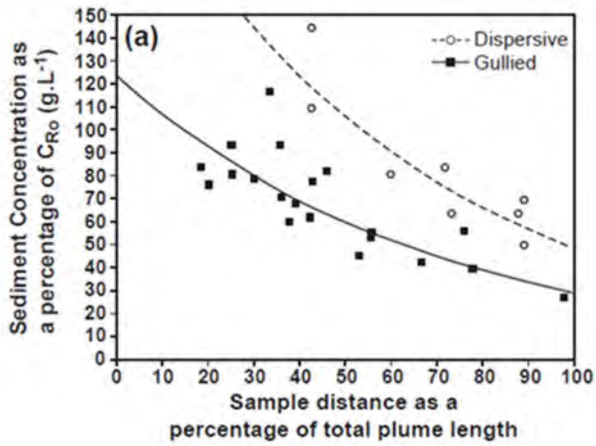


Figure 45. *The exponential relationship between initial sediment concentration for both dispersive and gullied pathways (Croke et al, 2005).*

Outputs:	Sediment concentrations of overland flows which reach or breakthrough to stream	
Inputs:	Initial sediment concentration	Determined as the combination of road runoff from 10-year storm and mean annual sediment generation from road surface
	Distance to stream	This is the slope length along the flow D-8 direction measured using a 30m DEM
	Percentage of plume lengths which reach the stream	Calculated from the predicted plume lengths (gullied and dispersive) from the Hairsine et al., (2002) model and the distance to stream.
	Parameter describing the exponential decline in sediment concentration with plume length	Obtained for gullied and dispersive flows from field experiments in Croke et al 2005 We use the exponent for all sediments (not just fines)
Assumptions:	Some of the assumptions listed in Hairsine could result in the overprediction of plume length, therefore representing a conservative estimation of sediment delivery (Croke et al., 2005). Assumes road runoff volume from 10-year rainfall event and the annual road erosion rate from Sheridan and Noske, (2007) combine to give initial suspended sediment concentration	

GIS implementation

Overview

Utilising the conceptual model as outlined above, a numerical model estimating sediment delivery of a forest road network is possible through a six-stage combination of GIS and spreadsheet-based data processing (Figure 66):

1. Stage 1 conditions the Digital Elevation Model (.TIFF) to allow for distance to streams calculation.
2. Stage 2 involves the harmonisation of the various roads vector files (.shp) into one cross-tenure roads file which is then converted into equal length segments and buffered zones for subsequent processing stages.
3. Stage 3 utilises the zonal statistics tool to gather the mean values of available raster datasets (such as annual rainfall and rainfall intensity) for each buffered road segment.
4. Stage 4 takes the segmented road lines and populates their attribute table with key parameters, including those from the buffered road segments which were previously sampled in Stage 3.
5. Stage 5 takes the attribute data from the parameterised road segments shapefile into Excel to feed the model equations sourced from the literature mentioned.
6. Stage 6 joins the processed model outputs and reintegrates them with their corresponding road segments in GIS to produce a heatmap of modelled values.

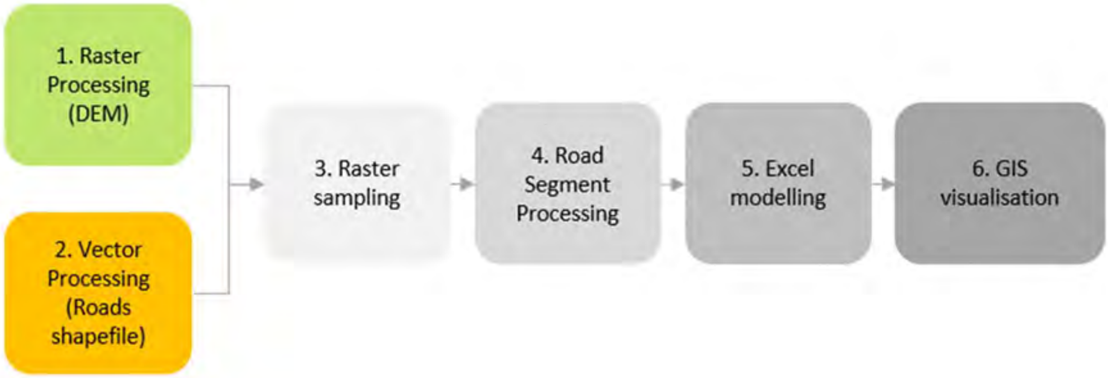


Figure 46. *An overview of the stages of data processing*

The parameters which comprise the proposed model are listed below as inputs and outputs in “Attachment A: Inputs and outputs”. As already mentioned, the assumptions associated with each input and processing equation lend to a cumulation of uncertainty which render the output as a qualitative risk indicator.

GIS implementation: example outputs

To demonstrate the model applications, the GIS workflow was implemented to produce heat maps of sediment delivery hazard across the Southern IFOA region, utilising the FC Roads dataset as provided by NRC. The model was implemented using a 1 in 10-year storm event.

Initial heat mapping displayed raw model estimates of sediment delivery in **kg per road segment**. Given that these segments are not all of equal length, estimates were then aggregated and averaged over total road length to produce the metric of average sediment delivery in **kg per m of road length**.

This aggregation serves to facilitate landscape scale identification of generally hazardous road networks, as opposed to specific road segments, which are beyond the resolution of the model to evaluate accurately. Heat maps of model outputs for both metrics at both the regional and local scale are provided for comparison below (Figure 47, Figure 48, Figure 49 and Figure 50).

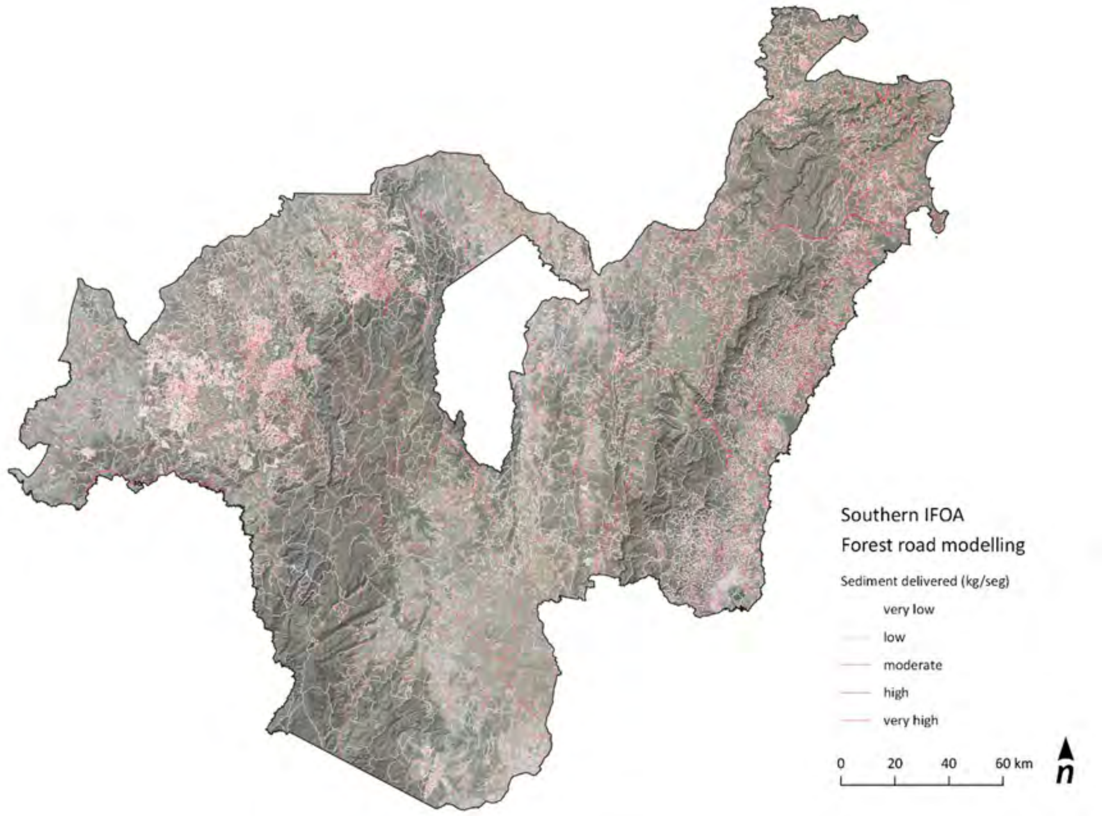


Figure 47. *Model estimates of sediment delivery hazard by road segment*

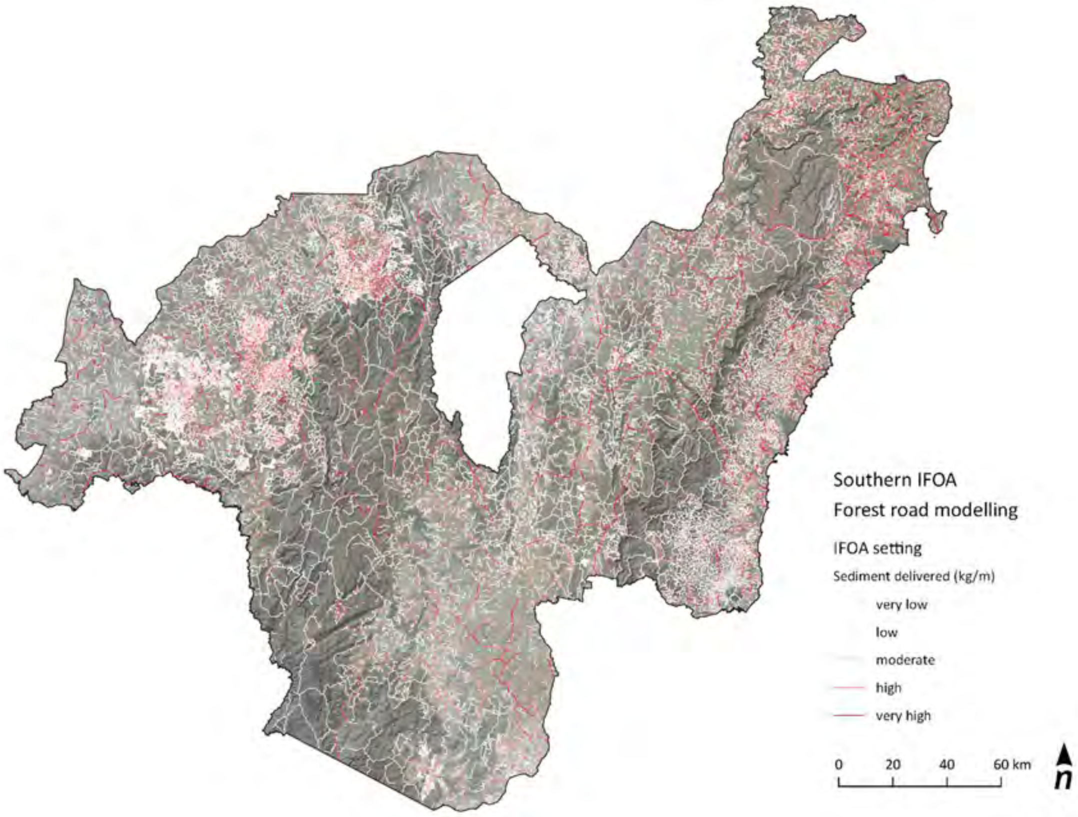


Figure 48. *Model estimates of sediment delivery hazard in kg per metre of road.*

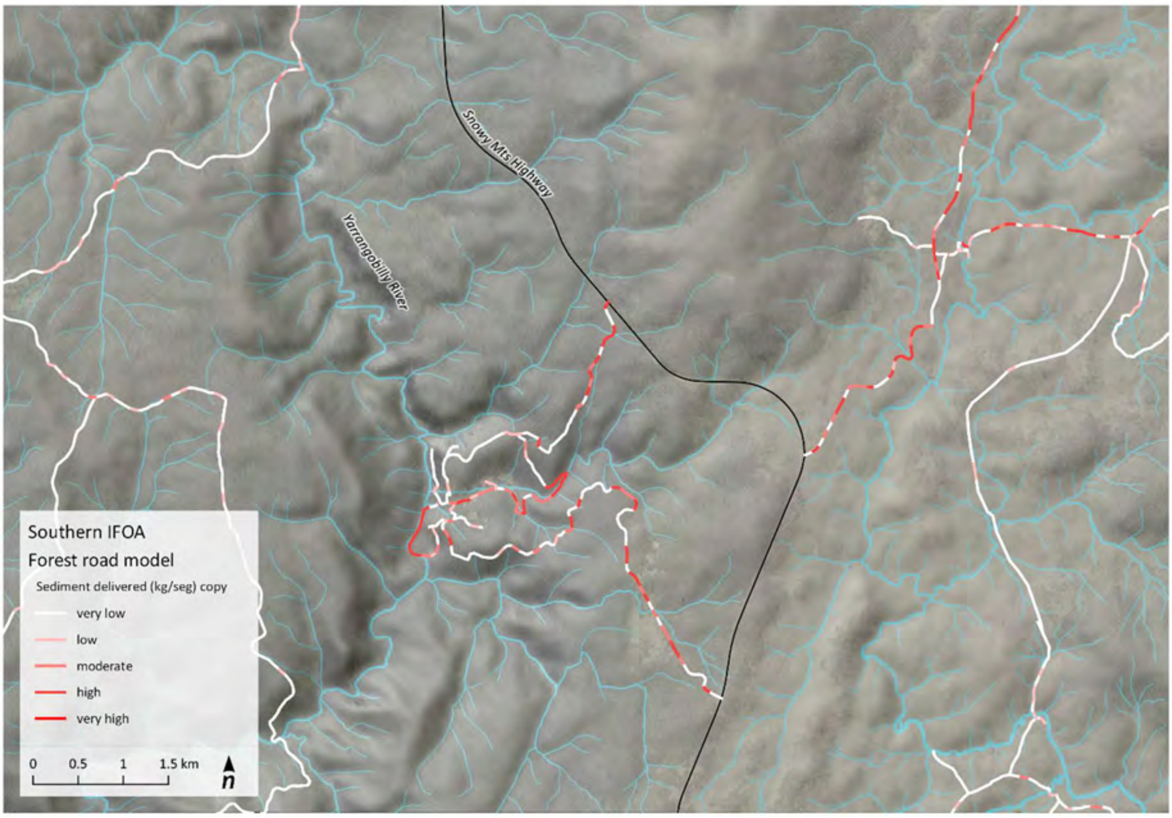


Figure 49. *Sediment delivery hazard by road segment*

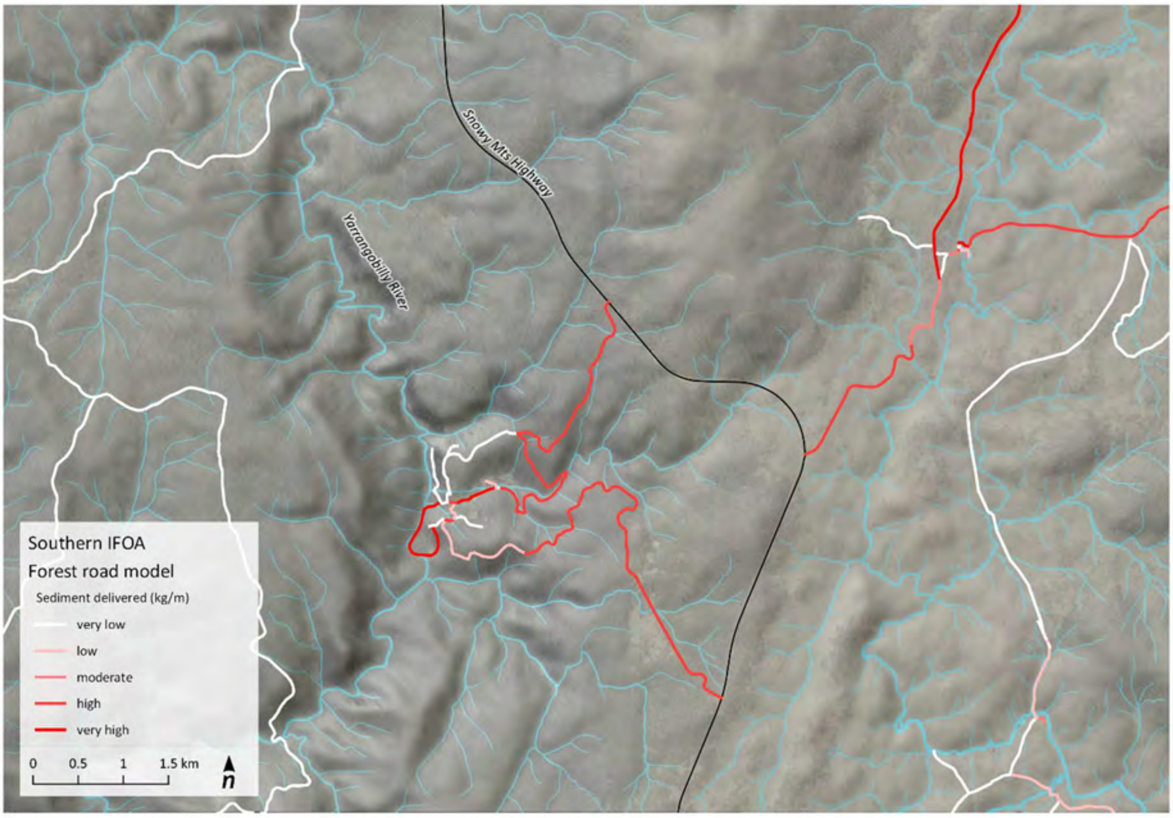


Figure 50. *Overall sediment delivery hazard in terms of the average sediment delivered by metre of road.*

Model Evaluation

The Southern IFOA region was chosen to evaluate the model for its variability in tenure, topography, rainfall, and recent burn severity. As shown above, the model was implemented across the entire Southern IFAO region to produce a series of sediment delivery hazard heat maps. These maps were subsequently used to guide site selection for field reconnaissance and desktop evaluation.

Reconnaissance

Field reconnaissance spanned two days, sampling a variety of unsealed roads across State, Private and NPWS tenure. The objectives were to understand how desktop modelling represents ground conditions, refine the field method for the Pilot Study and discuss broader project objectives and how best to package the work to make it useful for end users.

Specifically, the reconnaissance aimed to address 5 key questions, each of which are addressed below:

1. Does the conceptual model match with what we see in the field?
2. What can be achieved in a day in terms of surveying road drains and road to channel coupling according to the tested methods?
3. What are some opportunities and constraints in terms of efficiency in carrying out field assessments?
4. Are there aspects of the GIS implementation that we should revisit?
5. Do the GIS mapping match with field observations?

Does the conceptual model match with what we see in the field?

While the conceptual model broadly captures the key processes of sediment delivery, it does not represent the complexity of all ground conditions.

For example, the conceptual model assumes that all runoff flows through a designated drain outlet, however this is not always the case. At site 1 it was observed that a road segment can exhibit high variability in diffuse or concentrated flow paths, particularly in gently sloping or flat conditions. Delivery of these flows may be significantly influenced by the buffering capacity of the adjacent landscape, even when there is only a short distance to a stream.

Q2: *What can be achieved in a day in terms of surveying road drains and road to channel coupling according to the tested methods and (Q3) What are some opportunities and constraints in terms of efficiency in carrying out field assessments?*

P. Hairsine recalled a maximum road coverage rate of **25km per day** when collecting data for Croke and Mockler in their gully initiation threshold study. The most time intensive process for them involved the measurement of drain outlets to determine whether they were gullied or not, which involved getting out of the car and using and a measuring pole and inclinometer.

Monitoring technology has improved since the Croke and Mockler study. Handheld GIS tablets linked with car mounted LiDAR/GPS technology will likely streamline data collection. Forestry Corp NSW utilise a custom-built map app which may provide a suitable template for the FMIP to emulate and build upon. Such a tool would be indispensable in the Pilot Study.

Pre-processing of a survey area with higher resolution DEM and satellite imagery can allow for the identification and characterisation of topographic highs and lows. This processing can likely be automated, therefore streamlining some field data collection by reducing it to road-based GPS verification.

Tying the field survey in with a broader effort to represent key model parameters at a state-wide level. Carefully structured field surveys designed around explanatory variables (e.g., tenure, terrain, geology, road position). This may provide input to machine learning algorithms or statistical learning aimed at mapping model parameters.

Q4: *Are there aspects of the GIS implementation that we should revisit?*

The GIS implementation represents the first of what will be a series of iterations throughout the course of the FMIP. As discussed in the field, implementation may be improved through:

- Refinement of the method determining which roads in the FCROADS dataset are sealed or unsealed. The reconnaissance revealed that some roads which were thought to be sealed were in fact unsealed or vice versa.
- Investigation of how mining Google maps road/traffic data (if available) may improve estimates of traffic intensity. Discussions with agency reps revealed that traffic intensities will vary and may not necessarily correlate with FCROADS dataset road categorisation.
- Investigating how mining Google maps data (if available) may also improve estimates of road width.
- Liaising with agency reps to validate the accuracy and quality of the FCROADS dataset. There may be inherent biases within the dataset which vary across tenure or region.
- There may be an additional calculation which can factor for the higher potential for diffuse flow paths along flat road segments as well as the effect of vegetated or non-vegetated buffers.
- As already mentioned, pre-processing of a survey area with higher resolution DEM and satellite imagery may allow for the identification and characterisation of topographic highs and lows. Such identification will enable more accurate road segment slope estimation and therefore a better understanding of potential runoff volumes.

More generally, the modelling approach could be reframed to deliver an envelope of sediment delivery hazard by setting road parameters to worst- or best-case scenarios. The gap between best and worst case describes the benefit in ensuring adequate drainage maintenance and design at a particular site.

Overall, a comparison of the outputs of both a high and low-resolution DEM implementation of the GIS model along with field data will guide how to best optimise state-wide implementation.

5.Do the GIS mapping match with field observations?

The GIS mapping produced mixed results when compared to field observations. This is to be expected, given that the model is designed to capture sediment delivery hazard at the broader landscape scale.

While the reasons for the discrepancies are multiple, many are likely to stem from the model's wholesale application of OEH/NPWS guidelines for drain spacing by road slope. Steep road segments assume a shorter drain spacing and thus a smaller catchment area, whereas gentle road segments inherit a significantly larger one. This difference leads to relative differences in modelled runoff volumes which are sufficient to present sediment delivery hazard ratings counter intuitive to what ground conditions suggest.

The fact of the matter is that drain spacing does not strictly adhere to guidelines. As discussed in the field, road maintenance and design operators make drainage decisions which take local variables into consideration, most of which cannot be captured by the model. These variables include things such as:

- the relative elevation of the road,
- road material,
- its operational value,
- the condition of the vegetative buffer, and
- whether the road was crowned or not

A summary of the reconnaissance sites visited (Figure 51 and Figure 52) is outlined in Table 9 below. The table outlines each site's modelled hazard level, observed ground conditions and commentary on the underlying reasons why or why not the modelled and perceived hazards align.

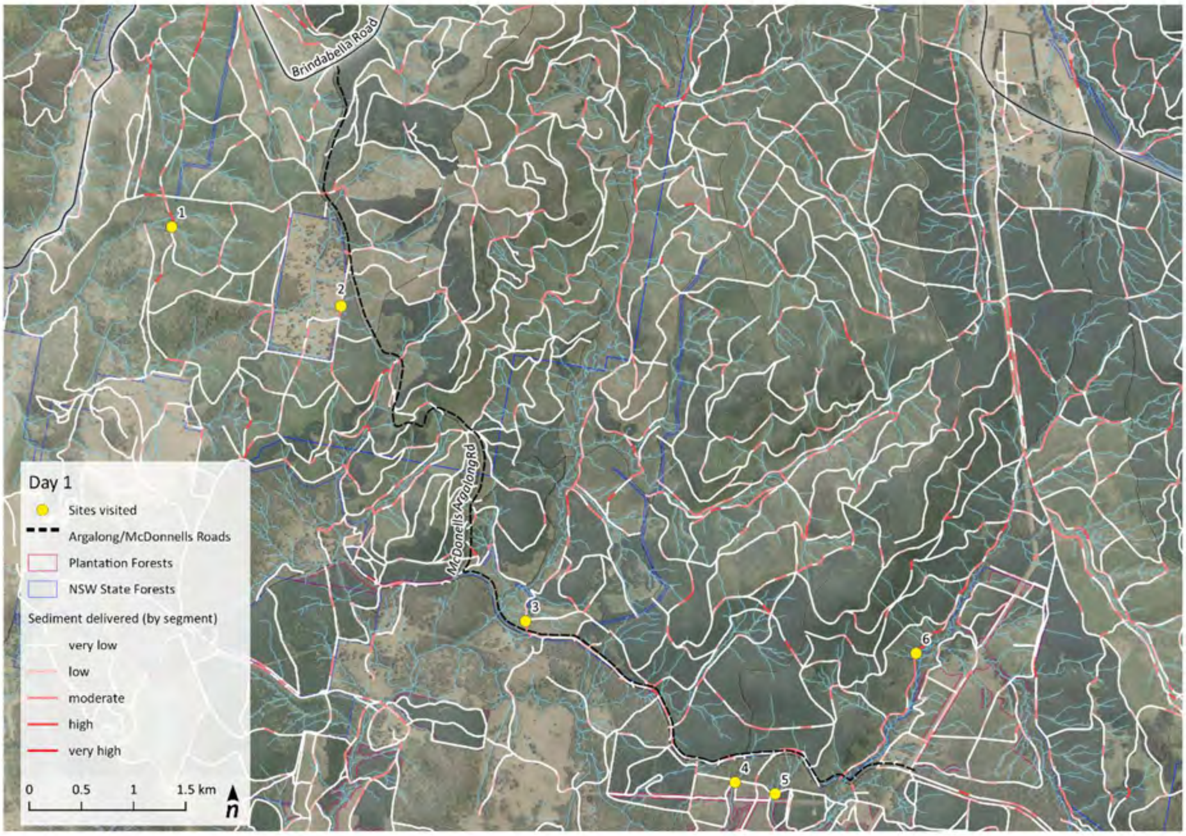


Figure 51. *Overview of sites visited on Day 1*

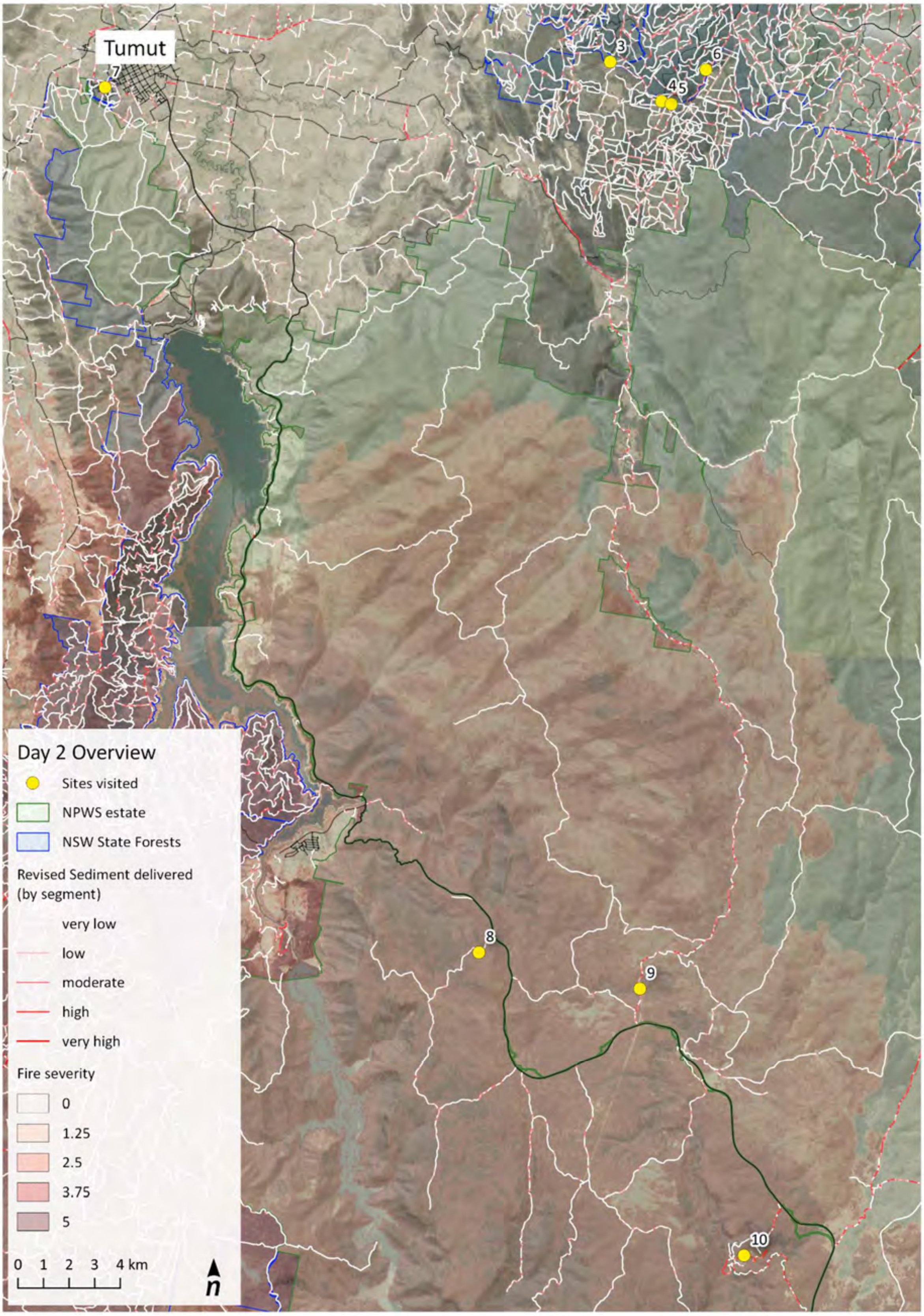
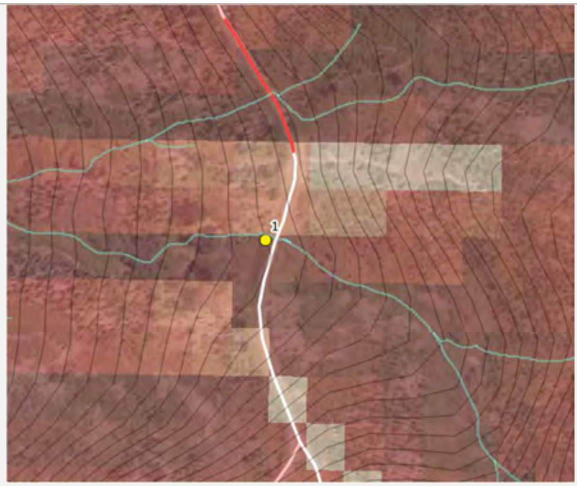
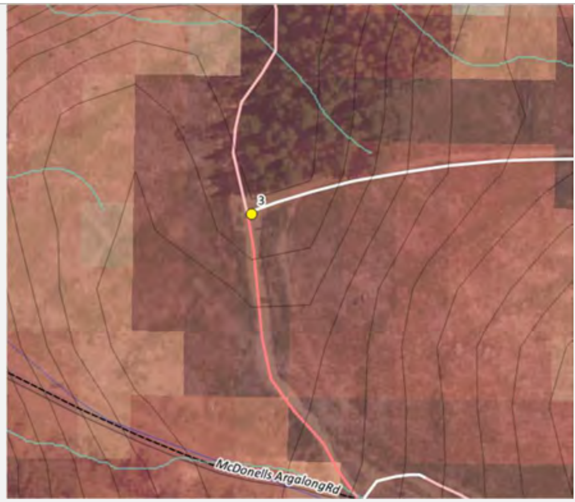
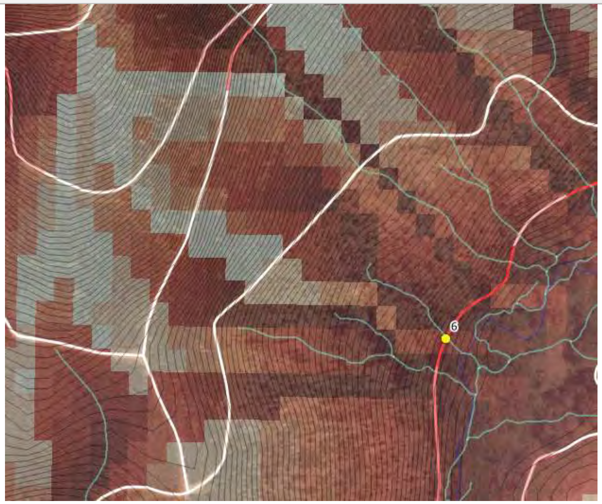


Figure 52. *Overview of sites visited on Day 2*

Table 9. Summary table of reconnaissance sites visited, modelled conditions, ground conditions, and commentary on both.

Site number	Parameters	Modelled hazard conditions (with distance to stream raster and 2m contour overlay)	Ground conditions	Commentary
1	*<u>Inputs (SEG ID: 304098)</u>* Road width: 5.5m Seg Slope: 1.7deg D-spacing: 200 Axpw: 360 Terrain slope: 0.1 Dist to stream: 275m Mean Rainfall: 1054mm I30_10aep: 22.7mm *<u>Outputs</u>* Gully initiation: Y Length g plume: 269m Volume at stream: 0m^3 Road erosion: 635kg Sed delivery: 0		Gently sloping to flat road segment at stream crossing with a range of diffuse and concentrated flow paths. Vegetation buffers these flow paths (Figure 53). The track continues upslope to the south, where rill erosion and incision degrade the road, leading to delivery flow paths which are likely to be less buffered than those seen off the flat road section.	The high hazard rating for the gently sloping stream crossing to the north did not correlate with ground observations. This discrepancy can be attributed to gentle slopes attracting broader drain spacing and thus a greater catchment area than steeply sloping roads, which assume frequent drainage. In this instance, issues surrounding drain design and placement on the sloping segment contributed to the observed sediment delivery hazard. Inaccuracies in the model parameters led to nil sediment delivery at the road crossing
2	*<u>Inputs (SEG_ID: 303636)</u>* Road width: 4m Seg Slope: 1.7deg D-spacing: 200m Axpw: 360 Terrain slope: 0.12 Dist to stream: 50m Mean Rainfall: 1039mm I30_10aep: 22.6mm *<u>Outputs</u>* Gully initiation: Y Length g plume: 193 Volume at stream: 1.6m^3 Road erosion: 455kg Sed delivery: 226kg		A stream crossing along the boundary between private and state forest. Drain placement approaching the stream may be improved by ensuring outlet is placed on surface which promotes dispersive rather than concentrated flow.	The moderate sediment delivery hazard can be largely attributed to the gentle slope assuming a larger catchment area coinciding with a stream. The presence of vegetation in drains, crowning and dispersive flow paths would suggest that sediment delivery hazard may be lower than qualitative estimates.

3	*<u>Inputs (SEG_ID:296876)</u>* Road width: 4m Seg Slope (deg): 3.4 D-spacing: 125m Axpw: 360 Terrain slope: 0.06 Dist to stream: 10m Mean Rainfall: 1068mm I30_10aep: 22.7mm *<u>Outputs</u>* Gully initiation: N Length d plume: 41m Volume at stream: 1.7m^3 Road erosion: 475kg Sed delivery: 244kg		Day 1 Lunch stop. Rill erosion and incision across the road at road junction.	In this instance the distance to stream calculations do not match exactly with the FCROADS stream network. Higher resolution DEMs will enable greater precision of this factor Road maintenance likely to occur when plot scheduled for logging. Another consideration in the development of the model.
4	*<u>Inputs (SEG_ID:288806)</u>* Road width: 3m Seg Slope (deg): 1.3 D-spacing: 200m Axpw: 90 Terrain slope: 0.2 Dist to stream: 80m Mean Rainfall: 1069mm I30_10aep: 22.7mm *<u>Outputs</u>* Gully initiation: Y Length g plume: 146 Volume at stream: 0.7m^3 Road erosion: 102kg Sed delivery: 20kg		Private forestry trail log crossing and T junction. Broad exposure of unsealed road surface, rilling with flow pathways leading direct into stream.	Despite this road segment crossing a stream, the average distance to stream for the crossing was 70m. This is because the average for a segment is calculated over a 200m^2 area. The distance to stream resolution at 30m leaves the potential for a relatively low delivery rating, especially when the road segment is low gradient, classified as 3m in width and has the lowest traffic intensity categorisation (Figure 54).

5	*Inputs (SED_ID:314025)* Road width: 3m Seg Slope (deg): 2.8 D-spacing: 150m Axpw: 90 Terrain slope: 0.1 Dist to stream: 37.5m Mean Rainfall: 1069mm I30_10aep: 22.7mm *Outputs* Gully initiation: 0 Length d plume: 37m Volume at stream: 0m^3 Road erosion: 123kg Sed delivery: 0kg		Private forestry trail stream crossing with cement culvert. Drains upslope of the crossing appear to have been bypassed, with a significant gravel/sand sediment slug directly downstream of crossing. Trail appears to have followed old fence line and has incised into the landscape over time (Figure 55).	This track ranks low on all the parameters which contribute to sediment delivery except distance to stream. The low volume of flow predicted, combined with the inaccuracy regarding slope, mean that the gully threshold was not exceeded. The dispersive flow estimate was subsequently less than the mean distance to stream, meaning that the model assumed no flow reaches the stream.
6	*Inputs* Road width: 4.2m Seg Slope (deg): 0.57 D-spacing: 250m Axpw: 360 Terrain slope: 0.2 Dist to stream: 47m Mean Rainfall: 1069mm I30_10aep: 22.7mm *Outputs* Gully initiation: Y Length g plume: 256m Volume at stream: 1.8m^3 Road erosion: 487kg Sed delivery: 300kg		State Forest, final stop. A crowned, flat seemingly well-maintained road at the foot slope of a hill adjacent to yet just elevated above a meandering valley fill. The presence of a considerable vegetative buffer and good drainage would suggest that the sediment delivery hazard would be low.	The mean distance to stream for this segment was reduced by the concentration of flow pathways intersecting the 100m road segment. With a higher traffic intensity and width than the previous two sites, as well as a high enough terrain slope, the gully initiation threshold was exceeded, allowing for a relatively high sediment delivery rating despite the observed ground conditions.

7	*Inputs (SEG_ID:295430)* Road width: 4m Seg Slope: 1.1deg D-spacing: 200m Axpw: 360 Terrain slope: 0.01 Dist to stream: 10m Mean Rainfall: 823mm I30_10aep: 24.3 *Outputs* Gully initiation: N Length d plume: 75m Volume at stream: 2.2m^3 Road erosion: 359kg Sed delivery: 252kg		State forest trail near Tumut with ad hoc mountain bike trail modifications. An undulating trail cut into bedrock as well as alluvium and colluvium along creek line. Ad hoc drains to manage pools along undulations reduce overall efficacy of the vegetative buffer, which would appear adequately wide otherwise. Discussion at creek crossing expressed the need for minimising the unbuffered length of stream crossing (Figure 56).	A moderate sediment delivery hazard is understandable at this stretch given its proximity to the stream and the assumptions around drain spacing for a relatively level segment of road. The undulating nature of the road however is not captured, and such undulations make for smaller road catchments and therefore the decreased likelihood of sediment delivery.
8	*Inputs (SEG_ID:191031)* Road width: 3m Seg Slope: 1.7deg D-spacing: 200m Axpw: 360m Terrain slope: 0.08 Dist to stream: 22.5m Mean Rainfall: 1159mm I30_10aep: 22.2mm *Outputs* Gully initiation: N Length d plume: 47m Volume at stream: 0.8m^3 Road erosion: 380kg Sed delivery: 93kg		Cumberland Trail: A National Parks trail with a variety of uses and therefore an increased budget for maintenance. A seemingly well-designed trail, in a severely burned landscape (Figure 57).	The model in this instance may be relatively accurate but possibly not for all the right reasons. Low sediment delivery can be attributed the model assuming a narrow width 3m, moderate traffic intensity and nil exceedance of the gully initiation threshold. These assumptions however are incorrect, as the road is a little wider (4.5) (which may lead to gully initiation given the terrain) and is subject to a much greater traffic intensity. In this instance, it is the design and maintenance of the road, with multiple drains and the import of extra road base, which contribute to its seemingly good performance.

9	*Inputs (SEG_ID:175123)* Road width: 5.5m Seg Slope: 3.4deg D-spacing: 125m Axpw: 360 Terrain slope: 0.1 Dist to stream: 35 Mean Rainfall: 1186mm I30_10aep: 22.9mm *Outputs* Gully initiation: Y Length G plume: 162 Volume at stream: 2.3m^3 Road erosion: 724kg Sed delivery: 405kg		Goobragandra Powerline Trail: Well graded, high utility road adjacent to a quarry (Figure 58). At the confluence of two streams, the crossing bears evidence of gravel entering the stream, which has since become obscured by vegetation at drain outlets.	High sediment delivery by the model can be attributed to its width estimate (5.5m), its moderate traffic intensity, and its proximity to stream.
10	*Inputs (SEG_ID:144016)* Road width: 5.5mm Seg Slope: 0 deg D-spacing: 250mm Axpw: 360 Terrain slope: 0.16 Dist to stream: 110mm Mean Rainfall: 1192mm I30_10aep: 22.4 *Outputs* Gully initiation: 1 Length G plume: 322m Volume at stream: 1.9m^3 Road erosion: 708kg Sed delivery: 274		Yarrangobilly Caves Circuit: Final stop in Kosciuszko National Park. A steep, incised valley, severely burnt terrain which intuitively lends itself to high sediment delivery. Pipeline works within the valley reveal the high hazard. Road has been largely sealed and culverts especially designed to deal with high traffic volumes and delivery hazard.	The model provides a good indication of the hazard, as it incorporates a broader formation width (6.5) with a moderate traffic intensity on steep slopes.

Figure 53. *Site 1. Largely flat road segment with variably diffuse and concentrated flow paths with strong vegetative buffer despite being relatively close to a stream.*

Figure 54. *Site 4. Broad exposure of road surface, much greater than the assumed 3m width used in the model.*

Figure 55. *Site 5. Rill development as flows bypass upslope drains, further incising the landscape.*

Figure 56. *Stream crossing upstream of site 7.*

Figure 57. *Cumberland trail displayed drainage spacing at higher intervals than modelled.*

Figure 58. *A road of high operational value, facilitating access to powerlines, adjacent private land, and a quarry.*

Sensitivity Analysis

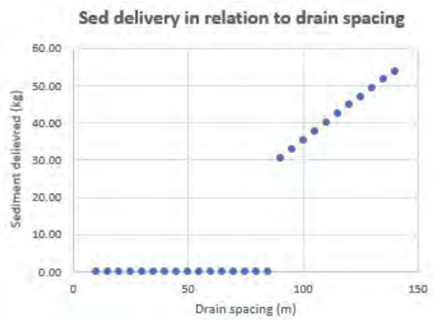
The sensitivity analysis involved running the model for incremental values of one variable while keeping all other key variables set at a mean, high or low hazard setting. Hazard conditions are set as the 5th and 95th percentile values derived from the Southern IFOA dataset, which constitutes a data pool of over half a million road segments (Table 10).

Table 10. Control values applied for the sensitivity analysis

Parameter	Low Hazard	Mean	High hazard
Seg length (m)	27.7	91.1	100.1
Seg slope (deg)	0.0	3.5	7.1
Drain spacing (m)	55.0	154	250.0
Road width (m)	3.0	3.6	5.5
Traffic intensity (axles per week)	90.0	297.3	360.0
Distance to stream (m)	366.7	156.8	21
Terrain slope (D8 slope (ratio))	0.020	0.1	0.3
Mean annual rainfall (mm)	552.4	880.6	1217.7
I30 10aep (mm)	21.8	26.1	35.4

As described in Table 11 below the sensitivity analysis reveals the nature of the sediment delivery response to all key model parameters.

Table 11. Sediment delivery estimates are graphed against all model parameters across their applicable range by three representative settings: low, mean, and high hazard conditions.

Low Hazard Conditions	Mean Conditions	High Hazard Conditions	Description
			Under high hazard conditions the sediment delivery displays a linear relationship to segment length. This makes intuitive sense, as segment length increases, so does the assumed road catchment area and therefore the contributing volume discharged towards the stream.
			Under high hazard conditions sediment delivery exhibits an initially linear relationship to road segment slope which is then limited to a maximum as slope approaches unrealistic values, i.e., slopes beyond 40 degrees.
			Sediment delivery is activated under mean and high hazard conditions when considering drain spacing. Mean conditions see sediment delivery begin when spacing is greater than or equal to 90m. Under high hazard conditions, delivery begins earlier at 25 metres, proceeds linearly until the gully threshold is reached, which elevates values before they reach a limiting value of approximately 700kg.

<table>
<tr><th>Low Hazard Conditions</th><th>Mean Conditions</th><th>High Hazard Conditions</th><th>Description</th></tr>
<tr>
<td>
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</td>
<td>Sed delivery is initiated earlier under high hazard conditions as opposed to mean conditions when considering road width. Sediment delivery and road width follow what is by in large a linear relationship. A linear relationship is to be expected, given that the same occurs when considering segment length. The small jump at the beginning is due to gully threshold exceedance</td>
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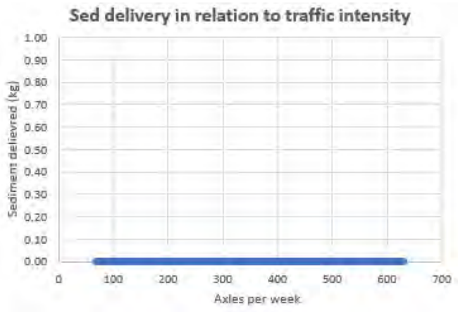
<tr>
<td>
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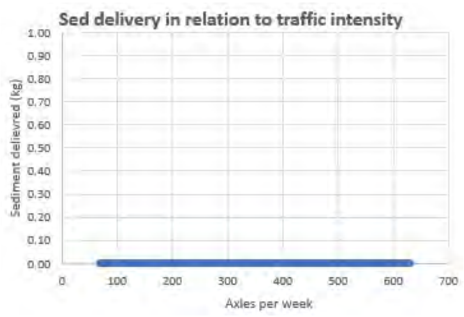
<td>
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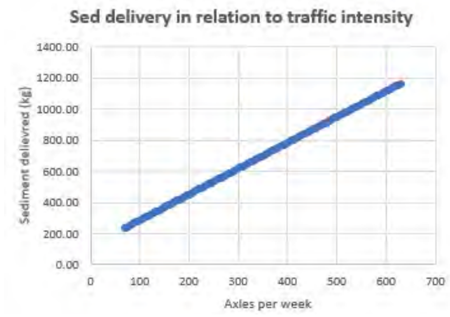
<td>
</td>
<td>As per the Sheridan and Noske formula, sediment generation is modelled as a linear function of traffic intensity, which is only activated under high hazard conditions.</td>
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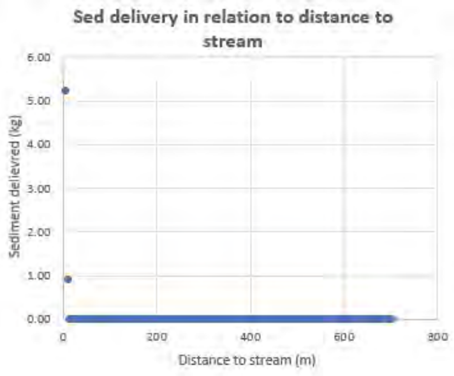
<tr>
<td>
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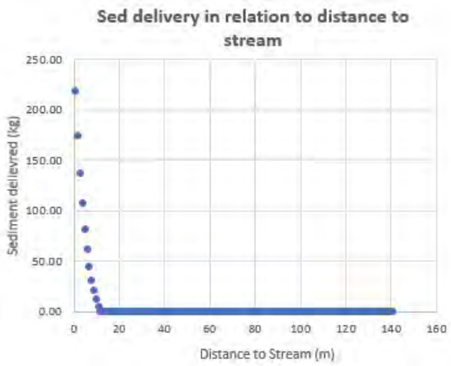
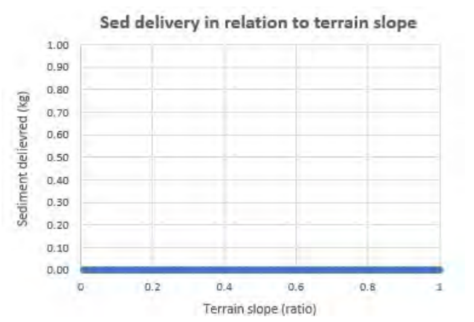
<td>
</td>
<td>
</td>
<td>Under all three conditions sediment delivery is activated in one way or another. Low hazard conditions lend to delivery from road segments within 20m of a stream, mean conditions within 50m of a stream and high hazard conditions to within 700m of a stream</td>
</tr>
</table>

<table>
<tr><th>Low Hazard Conditions</th><th>Mean Conditions</th><th>High Hazard Conditions</th><th>Description</th></tr>
<tr>
<td>
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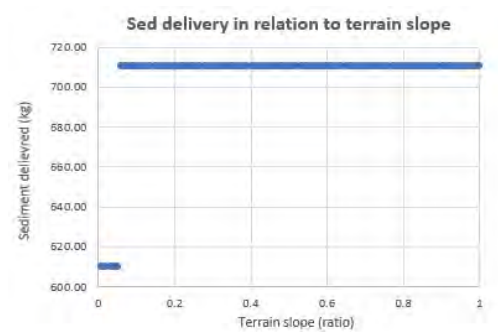
<td>
</td>
<td>Terrain slope is a key factor in the gully initiation calculation. Under mean conditions, gully-based sediment delivery is activated at slopes greater than 0.13. Under high hazard conditions, gully-based delivery is activated more readily, in this case along slopes greater than 0.06.</td>
</tr>
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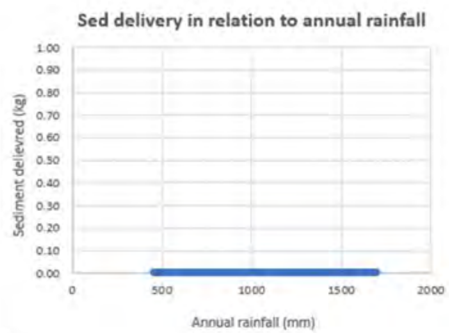
<td>
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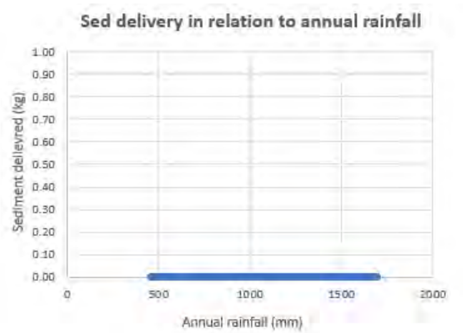
<td>
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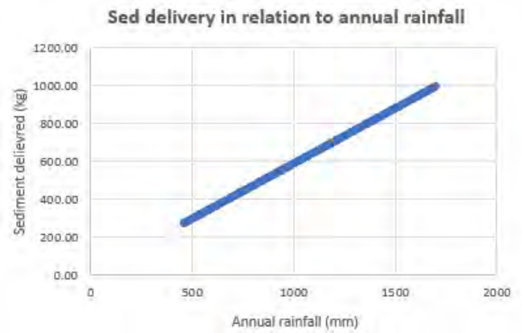
<td>
</td>
<td>Sediment delivery exhibits a linear relationship to annual rainfall under high hazard conditions. We assume that once water leaves the road, all landscapes behave the same.</td>
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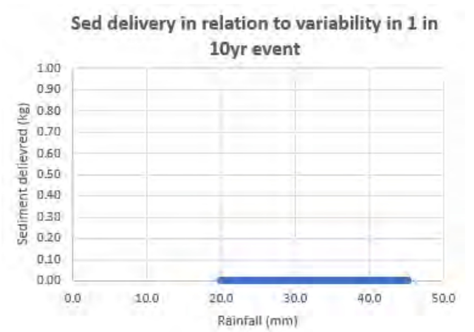
<td>
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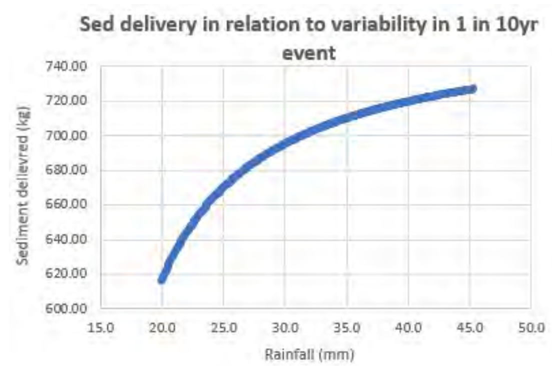
<td>
</td>
<td>Under high hazard conditions sediment delivery exhibits logarithmic growth which decreases as rainfall reaches its upper limit.</td>
</tr>
</table>

Discussion of model refinement

The reconnaissance proved extremely useful in addressing its initial objectives. It provided the first opportunity to understand how desktop modelling represents ground conditions, showing all attendees that at the segment scale there are a complexity of local factors which are not adequately represented in the model.

While these factors do lead to discrepancies between modelled and observed conditions, their identification allowed for discussions around the refinement of the field method as well as the modelling approach. Three key ideas to come out of the discussions were:

1. **Reframing the project in terms of risk**, where risk is a calculated in terms of sediment delivery potential (modelled outputs), mitigation through design and maintenance and downstream values (assessed through the field method).
2. Producing not one but **two estimates of sediment delivery as best- and worst-case scenarios.** By estimating the upper and lower limits of sediment delivery hazard, the result would be a map of where there are large gains to be made by going from poor drainage to good drainage.
3. Improvement of the field method for characterising stream crossings, **by including the measurement of the distance from the drain outlet to the stream, whether outlet positions facilitated dispersive or concentrated and the length of unbuffered/buffered crossing**.

Method Refinement

Reframing in terms of Risk

Following the sensitivity analyses and after discussion with stakeholders, the decision was made to re-frame the project, and the use of the statewide model, in terms of risk, rather than in terms of absolute sediment delivery predicted by the model. These changes are to be reflected in the final methodology recommendation and the development of the local scale implementation of the sediment delivery model.

Best- and worst-case scenarios

Two key assumptions were made to produce best- and worst-case scenarios for each road segment, where a best case assumes crowning combined with BMP drain spacing while a worst case does not (Table 12). The model was rerun to produce best and worst case sediment delivery hazard outputs for each road segment across NSW.

Table 12. Assumptions shaping best and worst-case scenarios

Best case	Worst Case
Crowning for entire length (0.5*road width)	No crowning (road width left as is)
Drain spacing is set to at BMP spacing guidelines with a maximum of 100m.	Drain spacing set to 100m for all instances, thus assuming full drain bypass per segment when road is significantly sloped.

Given the sensitivity of sediment delivery to drain spacing and road width (See Sensitivity analysis - Section 6.2), the difference between worst and best-case scenarios is noticeable. Summary statistics of the difference provides an indication of the potential reductions in sediment delivery hazard across a region (Table 19).

Proposed Field Method

The field method is yet to be refined completely. Essentially the method will need to consider how to collect the explanatory variables underpinning sediment delivery hazard and then classify them in terms of road maintenance and design.

The refinement will need to determine what exactly constitutes design parameters as well as those regarding maintenance, as it is the measure of maintenance and design that will ultimately yield the mitigation score.

As a first pass, design and maintenance parameters are listed in the field tables below (Table 13 and Table 14).

Table 13. Example field checklist for topographic highs, lows and drains

					Road attributes				Drain attributes			
#	**Easting**	**Northing**	**Elevation**	**Feature**	**Road class**	**Road material**	**Hard surface width**	**Road crowned**	**Drain type**	**Delivery pathway**	**Drain blocked**	**Drain bypassed**
1	xxxx	yyyyy	zzz	(Topo high, Topo low or Drain)	Feeder access	Gravel	10	(Y/N)	Culvert/Mitre/Crossbank/Pushout	Gullied or dispersive	(Y/N)	(Y/N)

Table 14. Example field checklist for stream crossings

Site	**Easting**	**Northing**	**Elevation**	**Crossing type**	**Buffered length**	**Unbuffered length**	**Outlet to stream distance**	**Delivery pathway** (is the outlet positioned so that it facilitates dispersive flow, as opposed to concentrated flow?)

Essentially, the data collected will allow for the derivation of four key qualitative measures of maintenance and design:

- Culvert operating ratio (blocked/unblocked culverts).
- Discrepancy between BMP drain spacing and actual drain spacing.
- Ratio of gullied outlets to non-gullied outlets.

Discretisation

Sediment delivery hazard

The IFOA region with the greatest range of values for average sediment delivered per m in the worst-case scenario was used to establish 5 categories of sediment delivery hazard (very low, low, moderate, high, and very high) applicable for all IFOA regions. This was the Lower NE IFOA, with a range of 0 to 28.37 kg per m of road (Table 15). Best- and worst-case scenario statistics are provided for comparison (

Table 17 and Table 16).

Table 15. Sediment delivery hazard categories

Avg. Sed. del. per m. (kg)	Sediment delivery hazard
0 - 0.2	1. Very Low
0.2 - 2	2. Low
2 - 5	3. Moderate
5 - 10	4. High
> 10	5. Very High

Table 16. Summary Statistics for best case calculations of average sediment delivery hazard in kg per m across each IFOA.

BEST CASE SCENARIO									
	Upper North East	**Riverina Red Gum**	**Non IFOA Sydney**	**Lower North East**	**Eden**	**Brigalow and Nandewar**	**Southern**	**Non IFOA NW**	**South Western Cypress**
Count	381483	420540	456250	610900	145880	519559	523411	724802	1951136
Unique values	368	67	233	394	198	191	220	115	191
NULL values	0	0	0	0	0	0	0	0	0
Min. value	0	0	0	0	0	0	0	0	0
Max. value	8.69	1.45	3.93	11.74	4.92	3.49	6.17	2.64	2.98
Range	8.69	1.45	3.93	11.74	4.92	3.49	6.17	2.64	2.98
Sum	30982	2848	7627	38884	4325	24545	7840	11108	45326
Mean	0.08	0.01	0.02	0.06	0.03	0.05	0.01	0.02	0.02
Median	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
SD	0.24	0.02	0.08	0.22	0.14	0.12	0.09	0.06	0.08
Coefficient of Var.	3.00	3.45	4.80	3.49	4.65	2.47	5.93	3.96	3.30

BEST CASE SCENARIO									
	Upper North East	**Riverina Red Gum**	**Non IFOA Sydney**	**Lower North East**	**Eden**	**Brigalow and Nandewar**	**Southern**	**Non IFOA NW**	**South Western Cypress**
Minority (rarest value)	2.33	0.3	1.06	2.16	0.99	1.36	1.07	0.91	1.06
Majority (most frequent value)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1st quartile	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3rd quartile	0.05	0.00	0.00	0.03	0.00	0.04	0.00	0.01	0.01
IQR	0.05	0.00	0.00	0.03	0.00	0.04	0.00	0.01	0.01

Table 17. Summary Statistics for worst case calculations of average sediment delivery hazard in kg per m across each IFOA.

WORST CASE SCENARIO									
	Upper North East	**Riverina Red Gum**	**Non IFOA Sydney**	**Lower North East**	**Eden**	**Brigalow and Nandewar**	**Southern**	**Non IFOA NW**	**South Western Cypress**
Count	381483	420540	456250	610900	145880	519559	523411	724802	1951136
Unique values	1016	199	679	1221	730	613	736	291	522
NULL values	0	0	0	0	0	0	0	0	0
Min. value	0	0	0	0	0	0	0	0	0
Max. value	20.36	4.18	13.28	28.37	13.94	10.56	16.53	6.25	7.46
Range	20.36	4.18	13.28	28.37	13.94	10.56	16.53	6.25	7.46
Sum	243583	28100	83940	336944	46940	179670	89872	67406	323558
Mean	0.64	0.07	0.18	0.55	0.32	0.35	0.17	0.09	0.17
Median	0.16	0.01	0.01	0.11	0.02	0.11	0.01	0.02	0.04
SD	1.28	0.14	0.52	1.26	0.94	0.65	0.59	0.26	0.39
Coefficient of Var.	2.01	2.14	2.82	2.29	2.93	1.88	3.42	2.79	2.36
Minority (rarest value)	5.70	1.33	3.22	6.38	2.73	3.71	3.07	1.85	3.65

WORST CASE SCENARIO									
	Upper North East	**Riverina Red Gum**	**Non IFOA Sydney**	**Lower North East**	**Eden**	**Brigalow and Nandewar**	**Southern**	**Non IFOA NW**	**South Western Cypress**
Majority (most frequent value)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1st quartile	0.02	0.00	0.00	0.01	0.00	0.04	0.00	0.01	0.01
3rd quartile	0.60	0.06	0.12	0.44	0.16	0.32	0.08	0.05	0.12
IQR	0.58	0.06	0.12	0.43	0.16	0.28	0.08	0.04	0.11

As shown below, discretisation considers to the broadest range of values Lower NE IFOA (worst case), which like all other results is positively skewed (Figure 59). Not surprisingly, the skew means that flat and low hazard terrains, such as the Riverina Red Gum IFOA, yield relatively low hazard scores (Figure 60).

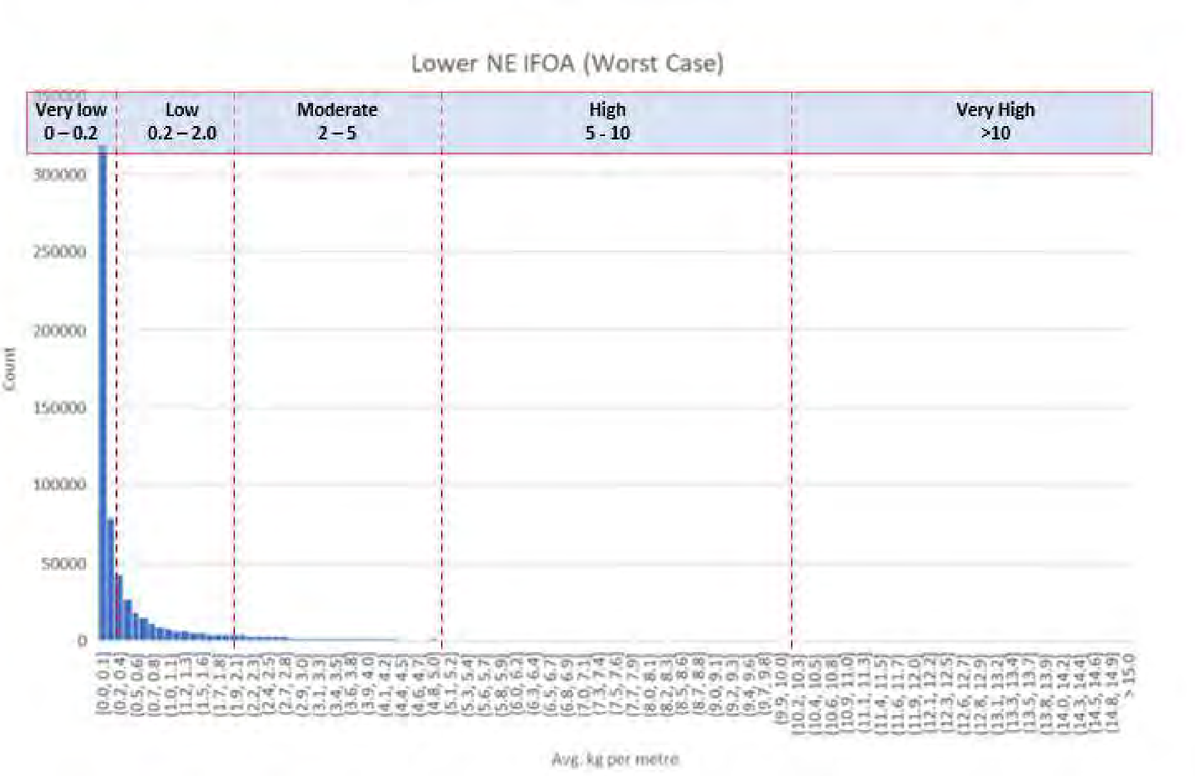


Figure 59. *The Lower North East IFOA yielded the greatest range of sed delivery hazard values, which like all other results, are positively skewed.*

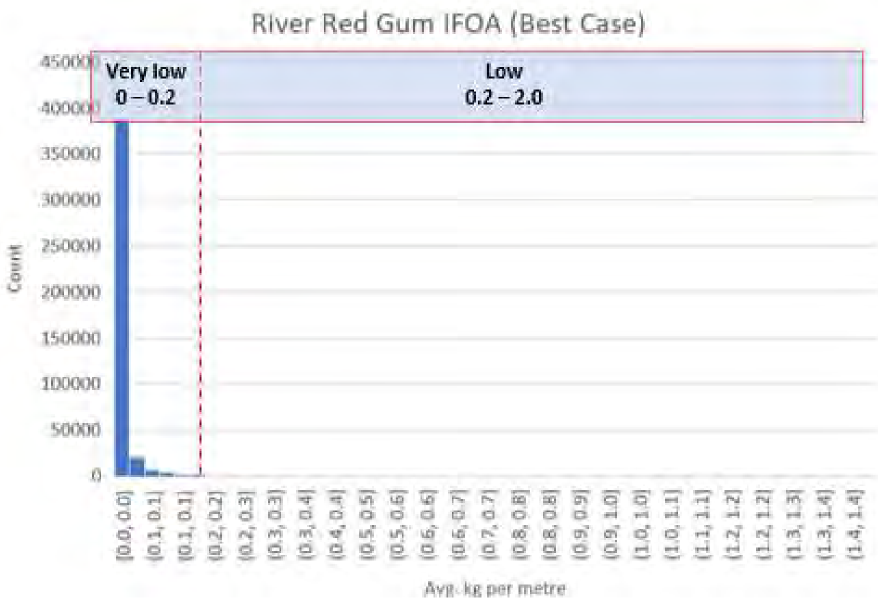


Figure 60. *The Riverina Red Gum IFOA (Best Case) yielded the smallest range of sed delivery hazard values.*

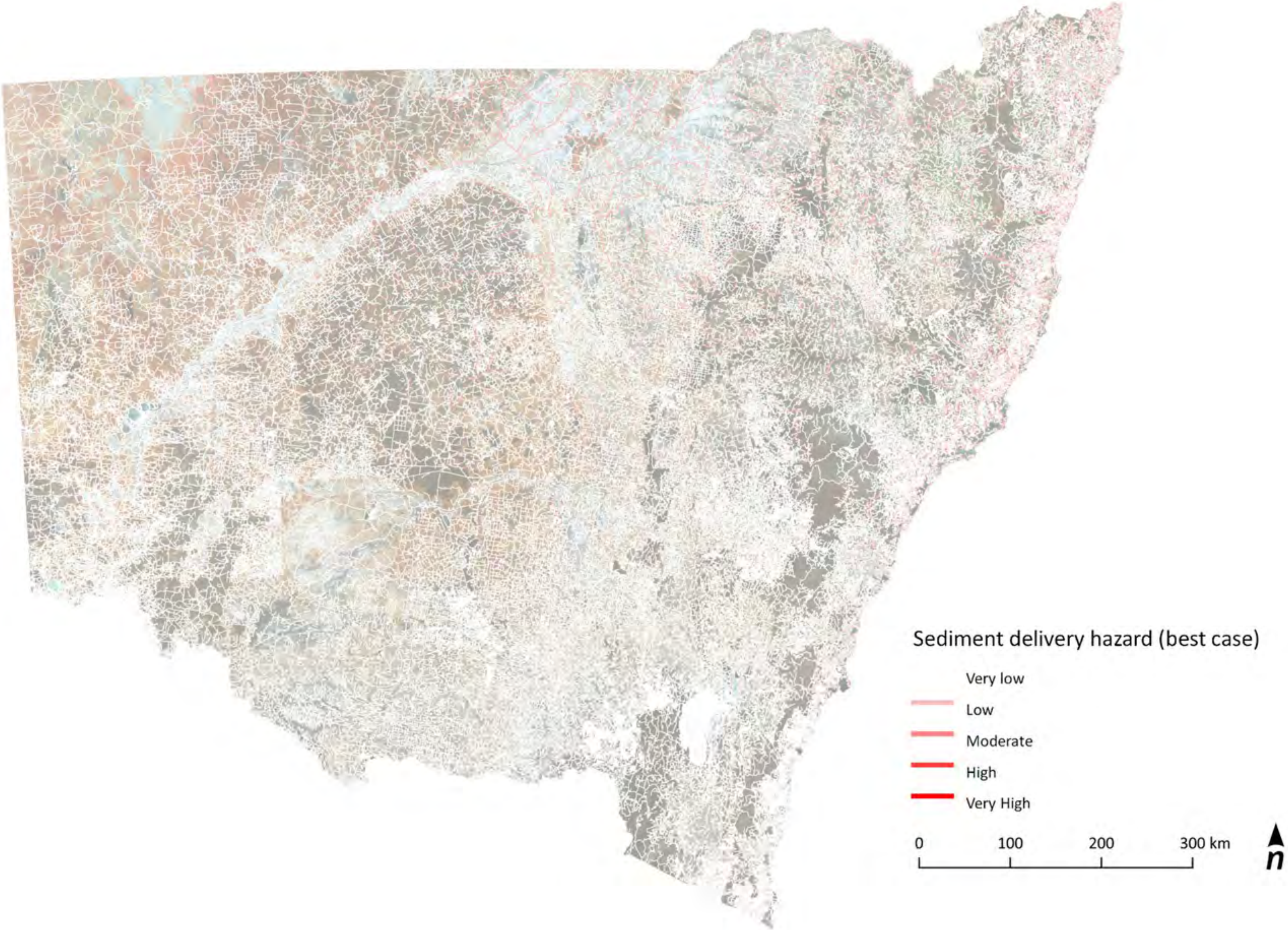


Figure 61. *Best case estimated sediment delivery hazard ratings for unsealed roads across NSW*

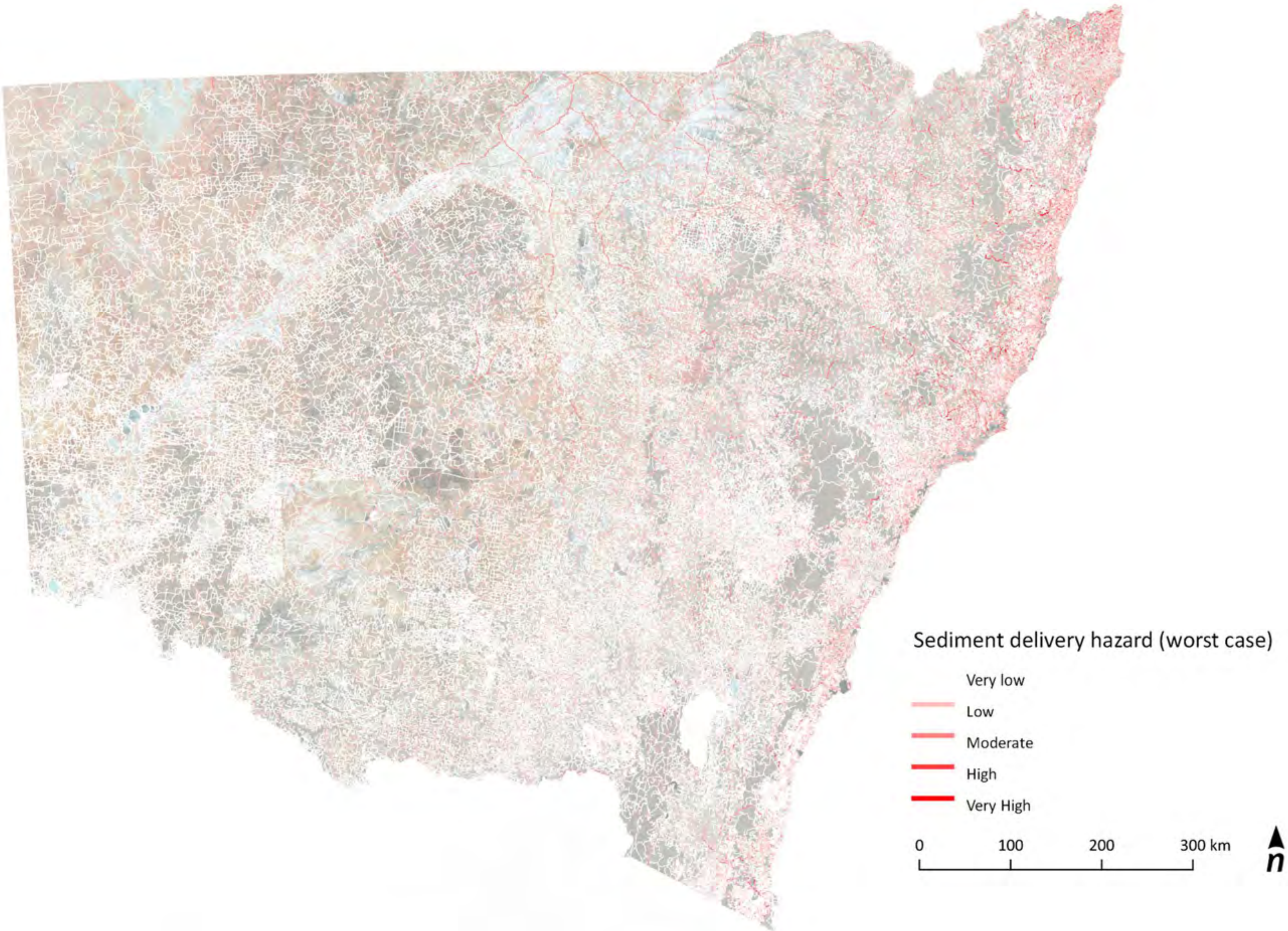


Figure 62. *Worst case estimated sediment delivery hazard ratings for unsealed roads across NSW*

Mitigation Potential

As mentioned in Section 7, the difference between the best- and worst-case scenarios provides an efficient mechanism for identifying where the greatest opportunities lie for improved risk mitigation through design and maintenance. The difference, in the kg per m of road, can therefore be conceptualised as the mitigation potential available to road management agencies (Table 19).

This potential was discretised by means of the same approach utilised for best and wort case average sediment delivery, taking the IFOA with the greatest range in mitigation potential (Lower NE IFOA 0-18.17kg), and then breaking it into 5 categories (very low, low, moderate, high and very high) (Table 18).

Table 18. Mitigation potential categories

Avg. Sed. del. per m. (kg)	Mitigation Potential
0 - 0.2	1. Very Low
0.2 - 1	2. Low
1 - 4	3. Moderate
4 - 8	4. High
> 8	5. Very High

Table 19. Summary Statistics of the difference between best- and worst-case calculations of average sediment delivery hazard in kg per m across each IFOA.

DIFFERENCE									
	Upper North East	Riverina Red Gum	Non IFOA Sydney	Lower North East	Eden	Brigalow and Nandewar	Southern	Non IFOA NW	South Western Cypress
Count	381483	420540	456250	610900	145880	519559	523411	724802	1951136
Unique values	889	171	601	1073	687	510	676	236	414
NULL values	0	0	0	0	0	0	0	0	0
Min. value	0	0	0	0	0	0	0	0	0
Max. value	16.85	2.73	10.11	18.17	10.80	9.77	13.52	3.61	6.94
Range	16.85	2.73	10.11	18.17	10.80	9.77	13.52	3.61	6.94
Sum	212557	25120	76284	298011	42605	155040	81982	55923	277716
Mean	0.56	0.06	0.17	0.49	0.29	0.30	0.16	0.08	0.14
Median	0.15	0.01	0.01	0.11	0.02	0.10	0.01	0.02	0.04
SD	1.09	0.12	0.46	1.09	0.84	0.55	0.52	0.20	0.32
Coefficient of Var.	1.96	2.05	2.76	2.23	2.88	1.84	3.33	2.65	2.26
Minority (rarest value)	5.76	1.06	3.26	4.75	2.50	3.49	2.45	1.76	2.97

DIFFERENCE									
	Upper North East	**Riverina Red Gum**	**Non IFOA Sydney**	**Lower North East**	**Eden**	**Brigalow and Nandewar**	**Southern**	**Non IFOA NW**	**South Western Cypress**
Majority (most frequent value)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1st quartile	0.02	0.00	0.00	0.01	0.00	0.04	0.00	0.01	0.01
3rd quartile	0.53	0.05	0.12	0.40	0.15	0.28	0.08	0.05	0.10
IQR	0.51	0.05	0.12	0.39	0.15	0.24	0.08	0.04	0.09

As shown below, discretisation considers to the broadest range of mitigation potential, which occurs in the Lower NE IFOA (Figure 63). In flat and low hazard terrains, such as the Riverina Red Gum IFOA, the range in potential is much lower (Figure 64).

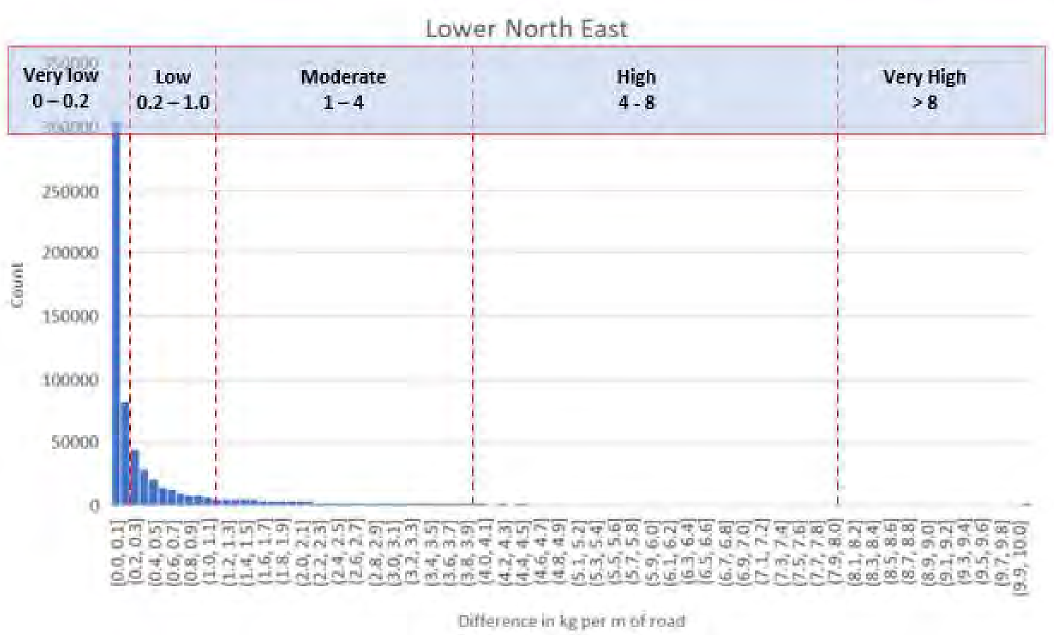


Figure 63. *The Lower North East IFOA yielded the greatest range in terms of the potential to mitigate sediment delivery.*

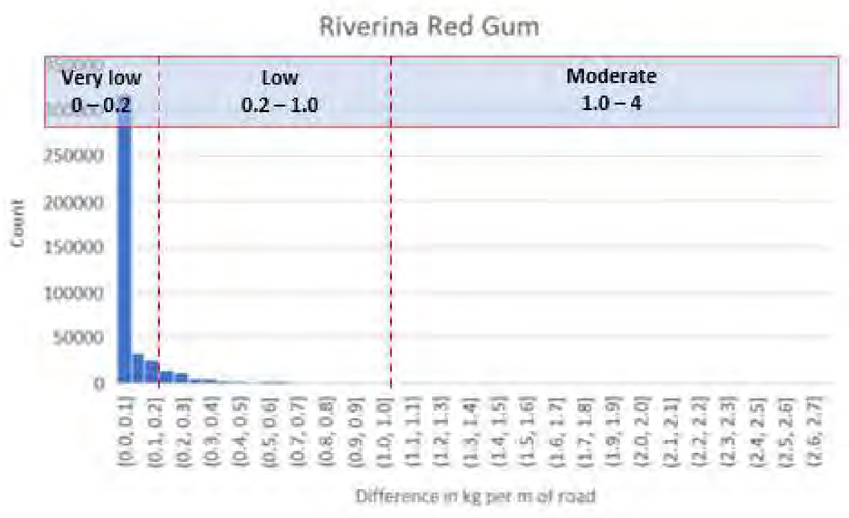


Figure 64. *The Riverina Red Gum IFOA (Best Case) yielded the smallest range of sed delivery hazard values, lending to very low to low mitigation potential across the board.*

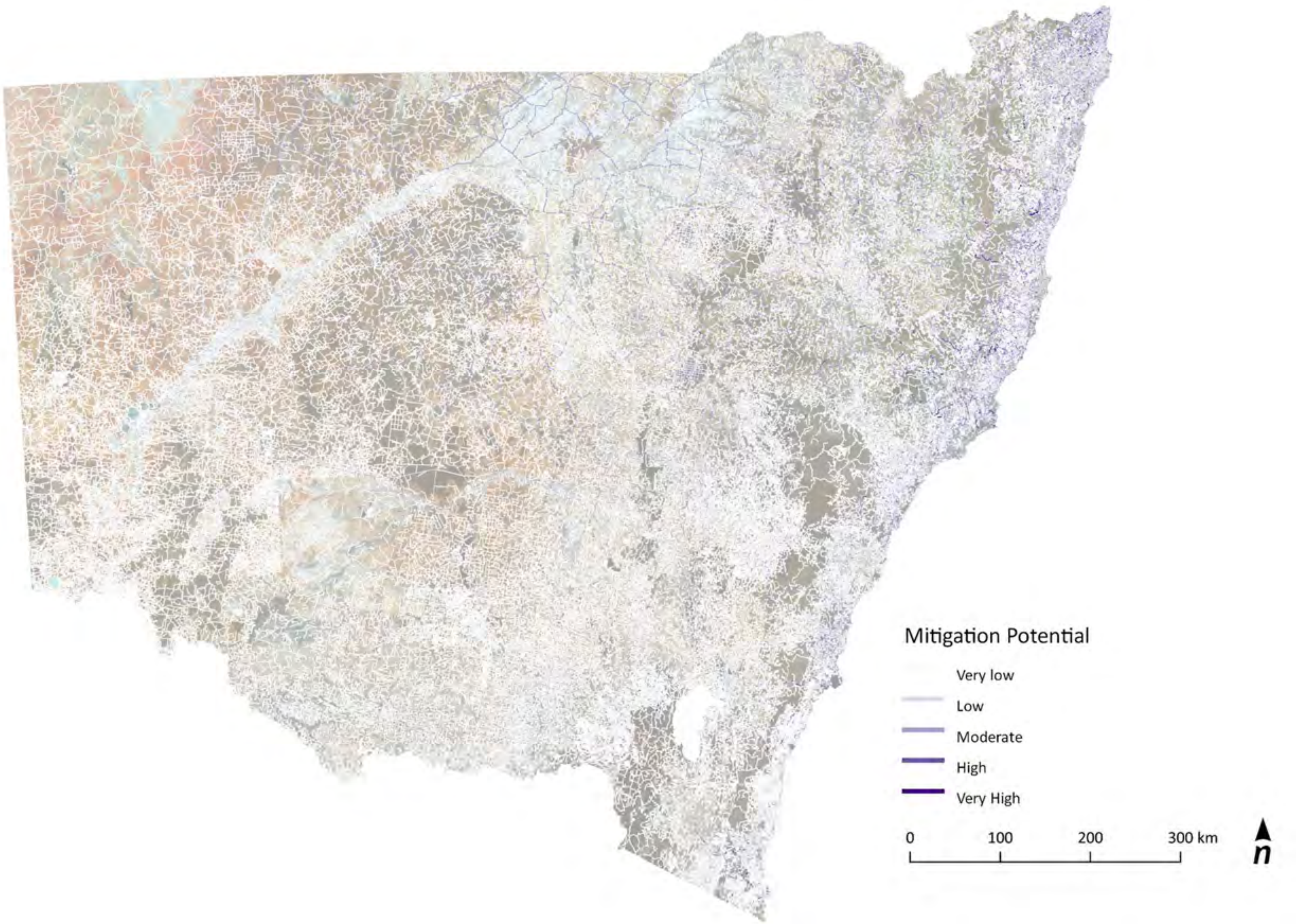


Figure 65. *Mitigation potential as a function of the difference between worst- and best-case estimates of sediment delivery hazard across NSW*

References

Bracken, L.J., and Croke, J., 2007, The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems: Hydrological Processes, v. 21, p. 1749–1763, http://dx.doi.org/10.1002/hyp.6313.

Croke, J.C., and Hairsine, P.B., 2006, Sediment delivery in managed forests: a review: Environmental Reviews, v. 14, p. 59–87, doi:doi:10.1139/a05-016.

Croke, J., and Mockler, S., 2001, Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia: Earth Surface Processes and Landforms, v. 26, p. 205–217, doi:10.1002/1096-9837(200102)26:2<205::AID-ESP168>3.0.CO;2-G.

Croke, J., Mockler, S., Fogarty, P., and Takken, I., 2005, Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity: Geomorphology, v. 68, p. 257–268, http://www.sciencedirect.com/science/article/B6V93-4FD79RJ-1/2/2d1c588b44264ab0a31c5e2cbad46c97.

Hairsine, P.B., Croke, J.C., Mathews, H., Fogarty, P., and Mockler, S.P., 2002, Modelling plumes of overland flow from logging tracks: Hydrological Processes, v. 16, p. 2311–2327, doi:10.1002/hyp.1002.

Jones, J.A., Swanson, F.J., Wemple, B.C., and Snyder, K.U., 2000, Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks: Conservation Biology, v. 14, p. 76–85.

Lane, P.N.J., and Sheridan, G.J., 2002, Impact of an unsealed forest road stream crossing: water quality and sediment sources: Hydrological processes, v. 16, p. 2599–2612.

MacDonald, L.H., and Coe, D.B.R., 2008, Road sediment production and delivery: processes and management, *in* Proceedings of the First World Landslide Forum, Tokyo, Japan, v. 381384.

Parsons, A.J., Bracken, L., Poeppl, R.E., Wainwright, J., and Keesstra, S.D., 2015, Introduction to special issue on connectivity in water and sediment dynamics: Earth Surface Processes and Landforms, v. 40, p. 1275–1277.

Sheridan, G.J., and Noske, P.J., 2007, A quantitative study of sediment delivery and stream pollution from different forest road types: Hydrological Processes, v. 21, p. 387–398, doi:10.1002/hyp.6244.

Sidle, R.C., Sasaki, S., Otsuki, M., Noguchi, S., and Rahim Nik, A., 2004, Sediment pathways in a tropical forest: effects of logging roads and skid trails: Hydrological Processes, v. 18, p. 703–720.

Takken, I., Croke, J., and Lane, P., 2008, A methodology to assess the delivery of road runoff in forestry environments: Hydrological Processes, v. 22, p. 254–264, %3CGo.

Attachment C: GIS implementation of the statewide sediment delivery potential model

Attachment C: GIS implementation of the statewide sediment delivery potential model

The model outline din Attachment B (the methodology recommendation) is implemented using a series of GIS processing steps, before final sediment delivery calculations are undertaken in excel. This section summarises those GIS processing steps used to generate model inputs.

Input and output parameters

Table C- 1. Statewide sediment delivery Input parameters

Input parameter	Category	Unit	Source/Derivation	Assumption(s)
SRTM 1 Arc Second Global	Terrain	Degrees (WGS84)	Statewide 30 m resolution Digital Elevation Model used as an input to derive elevation values for road segments, and slope values for adjacent hillslope segments. Data acquired via the Shuttle Radar Topography Mission (2001) accessed vi creative commons license from: https://earthexplorer.usgs.gov/	
National Parks Roads Dataset	Road attribute	Vector shapefile	https://data.gov.au/dataset/ds-nsw-57c5e7c7-c8fc-4eb7-9b36-19e315056c01/details?q=	
Annual Rainfall	Climate	Mm	Used as an input parameter to the sediment generation calculations of Sheridan and Noske (2007a). Extracted from gridded (Ascii grid) data compiled by the BoM using interpolated mean annual rainfall between 1961 and 2015. Accessed via: http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp	
Rainfall intensity	Climate	mm/0.5 hours	Used as an input parameter to the sediment generation calculations of Sheridan and Noske (2007a). Extracted from gridded (Ascii grid) data compiled by the BoM using Intensity Frequency Duration rainfall curves derived for Australia using AR&R (2016) techniques. Accessed via: http://www.bom.gov.au/water/designRainfalls/ifd/ (one in 10-year event)	The 10 year AEP 30 minute duration storm event was selected as the nominated storm event for the purposes of the statewide model. Other events can be used. The magnitude and intensity of the vent is commensurate with those uses by Sheridan and Noske (2007a) and is suitable given the conditions under which other components and assumptions in the statewide model were originally derived.
Terrain Slope	Terrain	degrees	Average slope of the hillslope adjacent each 100 m road segment. Calculated using the TauDEM processing of SRTM DEM using the D8 Flow Directions tool. It is as evaluated in the direction of steepest descent and is reported as drop/distance.	It is assumed that the mean slope across the 100m road width (plus ten metres either side) is representative of the hillslope angle on the downslope (streamside) section adjacent the road.
Road width	Road attribute	m	Based on road type, natural - 5m, gravel - 8m, sealed - 10m.	These values are arbitrary and not based on any road classification criteria that NPWS may utilise
Drain spacing	Road attribute	metres	The maximum drainage spacing guidelines varies between tenures (see below). The drainage spacing for the statewide model was set according to the spacing policy within the NPWS guidelines, which were considered conservative. For National Parks, drain spacing is subject to variation according to soil class/erosion risk. Given that classification of erosion risk is undertaken at the local scale, drainage spacing in the statewide model does not take soil class into account and instead uses the default values without soil-related modifiers applied. Drainage spacing used in the statewide model are presented in the **drainage spacing** section of this Attachment	In allocating drain spacing to road segments, we did not consider the soil type to inform the spacing distances as recommended in the OEH guidelines.
Traffic intensity	Road attribute	Axles per week	Traffic intensity has been applied in a generic fashion across the State, despite it being likely that traffic will greatly vary in accordance with tenure management and proximity to population centres. Sheridan and Noske (2007) quantify traffic intensity in terms of truck axles per week. The axles per week metric is also employed in the statewide model. The estimate is a function of 'Lanecount', 'Trafficability' and 'RoadType', all of which are assumed to be directly related to the number of trucks that use a road. The number of axles per week has been assigned based on the calculations in section 4.4 of Attachment D, traffic intensity is either low (90) medium (360) or high (630) axles per week.	We assume there are 9 axles per truck.
Road Slope	Road attribute	rise/run	Calculated by taking the difference in elevation between the endpoint of each 100 m road segment, divided by segment length to calculate segment slope. All elevation values drawn from the 30 m SRTM DEM.	100m segment length used to define slope endpoints for slope calculations mean that ab average of three elevation points will be intersected by each 100 m line segment Finer scale slope measurements would be limited by the resolution of the underlying DEM, and coarser scale measurements have the

Input parameter	Category	Unit	Source/Derivation	Assumption(s)
				potential to 'smooth-out', smaller-scale changes in slope that have an important impact on road erosion.
Distance to stream	Road attribute	metres	Flow distance between drain outlet and nearest waterway. Calculated using TauDEM processing of SRTM DEM using the Distance to Streams tool. The tool requires both a stream raster (Strahler order) and D8 flow directions	
Infiltration rate	Hydrology	millimetres/hour	From Croke *et al* 2006. The constant rate at which rainfall is able to infiltrate the road surface during the nominated rainfall event. All rainfall delivered to the road surface at an rainfall intensity (mm/hr) above the infiltration rate is converted to runoff.	Infiltration rate is held constant throughout the duration of the nominated storm event (30 min 10aep event) and is insensitive to other local scale factors such as road slope, soil type and road condition.
Volume to breakthrough vbt5	Hydrology	m^3	From Hairsine *et al* 2002 Volume to breakthrough is the volume of runoff that may enter an area before a discharge is observed at the downslope boundary of that area. The volume is a combination of water lost to overland flow through infiltration, water stored above ground in depressional storage and water in transit between the upper and lower boundary of the area. A constant vbt5 is used in the statewide model to calculate the plume length for a given discharge at each drain outlet for the nominated storm event.	Key assumptions (Hairsine *et al*, 2002): The overland flow leaving the cross-bank is non-eroding. The behaviour of the 5-m segments of hillslope containing the plume is representative of the hillslopes within the compartments. The values of vbt5 for adjacent plume areas are spatially independent, although drawn from the same population All hillslope lengths are greater than interbank lengths, so it is assumed that overland flow plumes from a sequence of cross banks do not connect with one another
Area threshold	Hydrology	m^2	Croke and Mockler, 2001 A threshold value of contributing road drain catchment area calculated using a constant value of 70 m^2 and the relevant hillslope angle. Used to distinguish between gullied and dispersive flow paths.	Ignores hillslope curvature and uses a statistical approach to discriminate between gullies and dispersive flow paths. Does not explicitly account for local factors such as hillslope curvature, soil type, road age and hillslope disturbance history.

Table C- 2. Statewide sediment delivery model output parameters

Parameter	Unit	Source/Derivation	Assumption(s)
Slope adjustment factor	constant	Sheridan and Noske 2007 The erosion results from each of the different road segments were normalized for slope effects using a slope adjustment factor. For a range of soils and surfaces, the response to slope is about three times greater when flow-driven processes are active than when rainfall-driven (interill) processes are active. Suspended load is assumed to be mostly generated and transported via interill processes; therefore, this component of the load is adjusted using the slope adjustment factor.	The analysis described above considers sediment loads from roads at an annual scale
Sediment delivery	tonnes/Ha/year	Sheridan and Noske 2007 Annual suspended sediment delivery from each road segment to the drain outlet, adjusted for slope, area, and rainfall	
Volume	m^3	Total volume of runoff generated by the nominated storm event and delivered to the drain outlet. Calculated using the rainfall intensity, infiltration rate and the area of road segment.	Using constant infiltration rate from (Croke et al 2006)
Predicted mean volume of overland flow reaching stream - dispersive	m^3	Compares the calculated plume length (Hairsine *et al*, 2002) for the given runoff volume to the distance between the drain outlet and the nearest waterway.	Assumes a constant rate of volume loss (via infiltration to hillslope) per m of hillslope traversed by plume: dV/dL = 0.065
Predicted mean volume of overland flow reaching stream -gullied	m^3	Compares the calculated plume length (Hairsine *et al*, 2002)adjusted for the presence of a gully at the drain outlet that extends plume length, for the given runoff volume to the distance between the drain outlet and the nearest waterway.	Based on dV/dL = 0.065 and a 3X increase in plume length with gullies (Croke et al, 2005)
Mean plume length dispersive	m	Calculated using Hairsine *et al.,* 2002 assuming no gully forms at the drain outlet	
Mean plume length gullied	m	Calculated using Hairsine *et al.,* 2002 assuming a gully forms at the drain outlet	
Gully (y=1 & n=0)	constant	If the contributing area for the given drain (and given hillslope angle) exceeds the threshold defined by Croke and Mockler (2001) then a gully (1) is attributed, if not then (0), no gully.	Croke and Mockler
Road contributing area	m2	Length of the road segment (100m) and road width (as above)	It is assumed that the contributing area is only the road itself, not any of the adjacent hillslopes.
Road surface area	Ha	The above road contributing area value converted to Hectares	As for Road Contributing Area
Sediment generation	tonnes/year	The product of the calculated sediment delivery values from the Sheridan and Noske (2007a) calculations multiplied by the Road surface area.	
Sediment generation	grams/year	Conversion of sediment generation in tonnes/year to grams per year	
Initial sediment concentration	grams/litre	The concentration of suspended sediment as predicted by the Sheridan and Noske (2007a) divided by the width of the road and a constant derived in Hairsine et al., 2002.	
Sediment concentration at stream - gullied	Kilograms/ m^3	The concentration of suspended sediment in the plume that reaches the stream assuming dispersive flow, based on an assumed exponential decline in sediment concentration with distance downslope from the drain outlet, as derived by Croke *et al*., 2005.	
Sediment concentration at stream - dispersive	Kilograms/ m^3	The concentration of suspended sediment in the plume that reaches the stream assuming gullied flow, based on an assumed exponential decline in sediment concentration with distance downslope from the drain outlet, as derived by Croke *et al*., 2005.	
Sediment delivered	kg	The total mass of sediment delivered to the stream from the drain during the nominated storm event. The product of the sediment concentration at the stream for the relevant plume type (gullied or dispersive) multiplied by the total volume of flow that reaches the stream.	

GIS process overview

Utilising the conceptual model as outlined above, a numerical model estimating sediment delivery of a forest road network is possible through a six-stage combination of GIS and spreadsheet-based data processing (Figure 66):

7. Stage 1 conditions the Digital Elevation Model (.TIFF) to allow for distance to streams calculation.
8. Stage 2 involves the harmonisation of the various roads vector files (.shp) into one cross-tenure roads file which is then converted into equal length segments and buffered zones for subsequent processing stages.
9. Stage 3 utilises the zonal statistics tool to gather the mean values of available raster datasets (such as annual rainfall and rainfall intensity) for each buffered road segment.
10. Stage 4 takes the segmented road lines and populates their attribute table with key parameters, including those from the buffered road segments which were previously sampled in Stage 3.
11. Stage 5 takes the attribute data from the parameterised road segments shapefile into Excel to feed the model equations sourced from the literature mentioned.
12. Stage 6 joins the processed model outputs and reintegrates them with their corresponding road segments in GIS to produce a heatmap of modelled values.

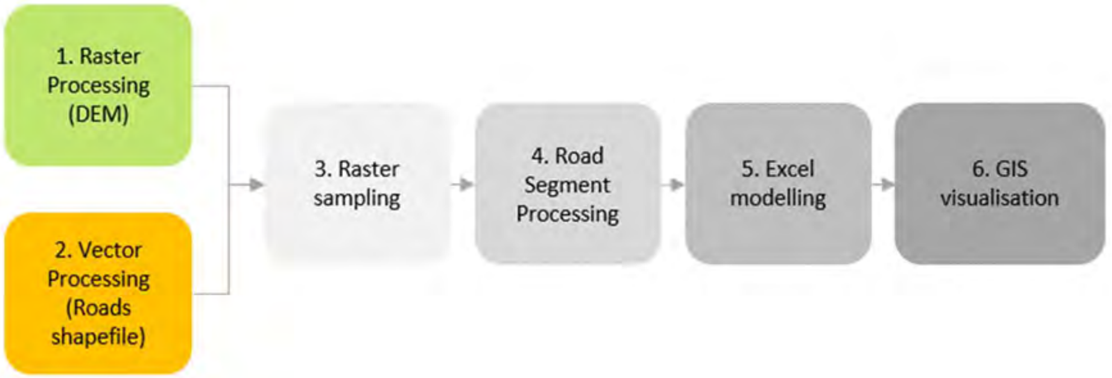


Figure 66. *An overview of the stages of data processing*

The parameters which comprise the proposed model are listed below as inputs and outputs **Error! Reference source not found.**. As already mentioned, the assumptions associated with each input and processing equation lend to a cumulation of uncertainty which render the output as a qualitative risk indicator.

The following document presents details of the GIS workflow for the estimation of sediment delivery for any given road network, assuming all necessary data are available. The workflow consists of the following 6 stages as outlined below (Figure 67) and described in the main document.

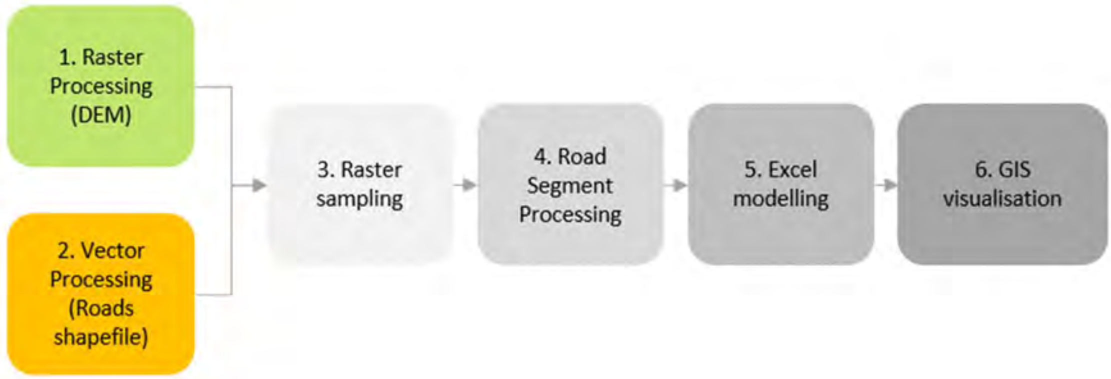


Figure 67. *Processing stages*

GIS steps overview

The processes contained within the six-stage approach as outlined in Figure 66 are detailed in the following flow diagrams (Figure 68 to Figure 72). QGIS v3.14 is used for Geospatial processing of raster and vector files while Microsoft Excel is used for spreadsheet-based processing. Attachment A provides greater detail on the GIS tools used in the following processing workflow.

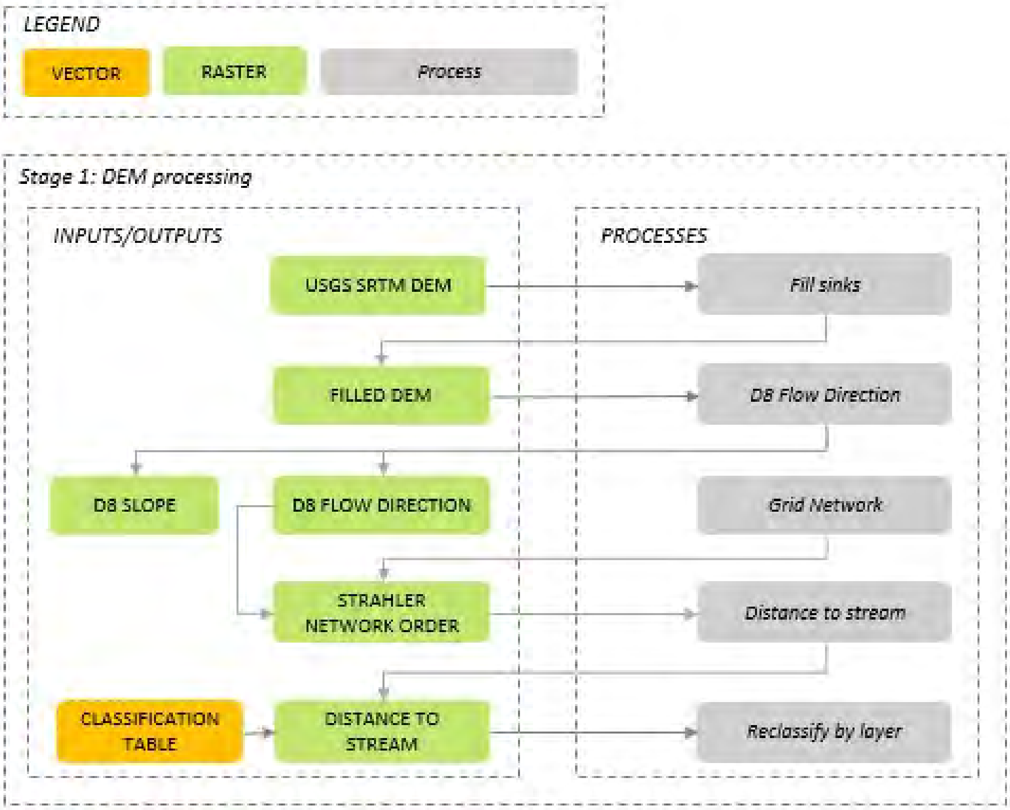


Figure 68. *Stage 1 outlines the process of condtioning the Digital Elevation Model to calculate distance to streams.*

It should be noted that the road shapefile standardisation as a process in Stage 2 below has *not* been established. At this stage it is assumed that a pan-agency road shapefile will be standardised in a manner suitable for the needs of NRC and the agencies combined and will be provided to Alluvium prior to any further advancement of the proposed methodology.

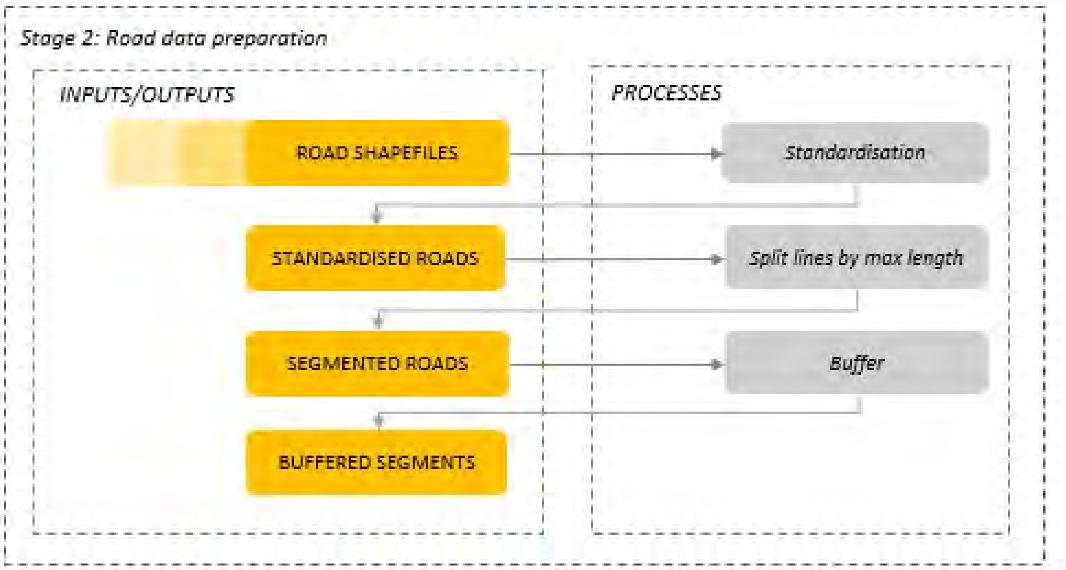


Figure 69. *Stage 2 prepares the road vector file into segments and buffer zones for subsequent stages.*

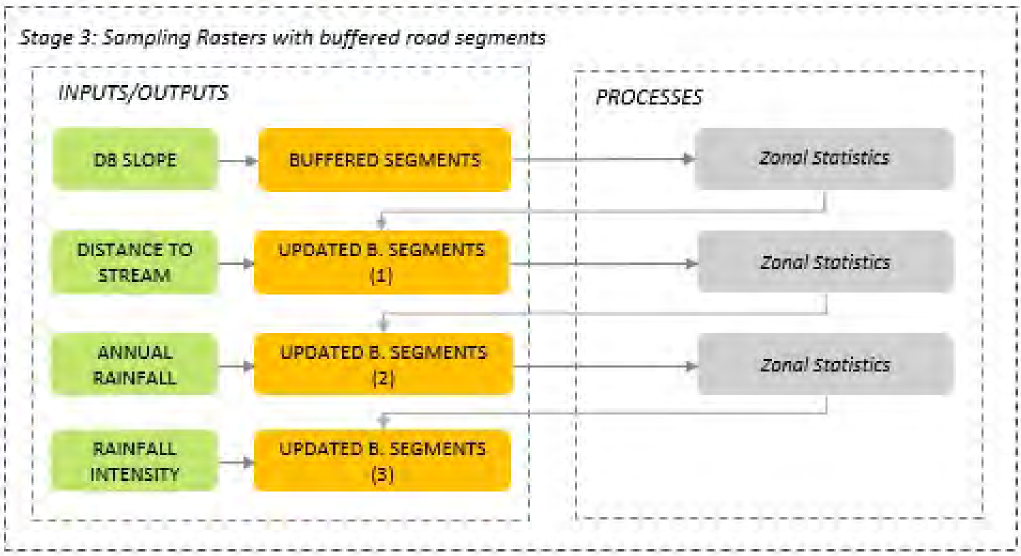


Figure 70. *Stage 3 utilises the zonal statistics tool to gather the mean values of raster datasets for each buffered road segment.*

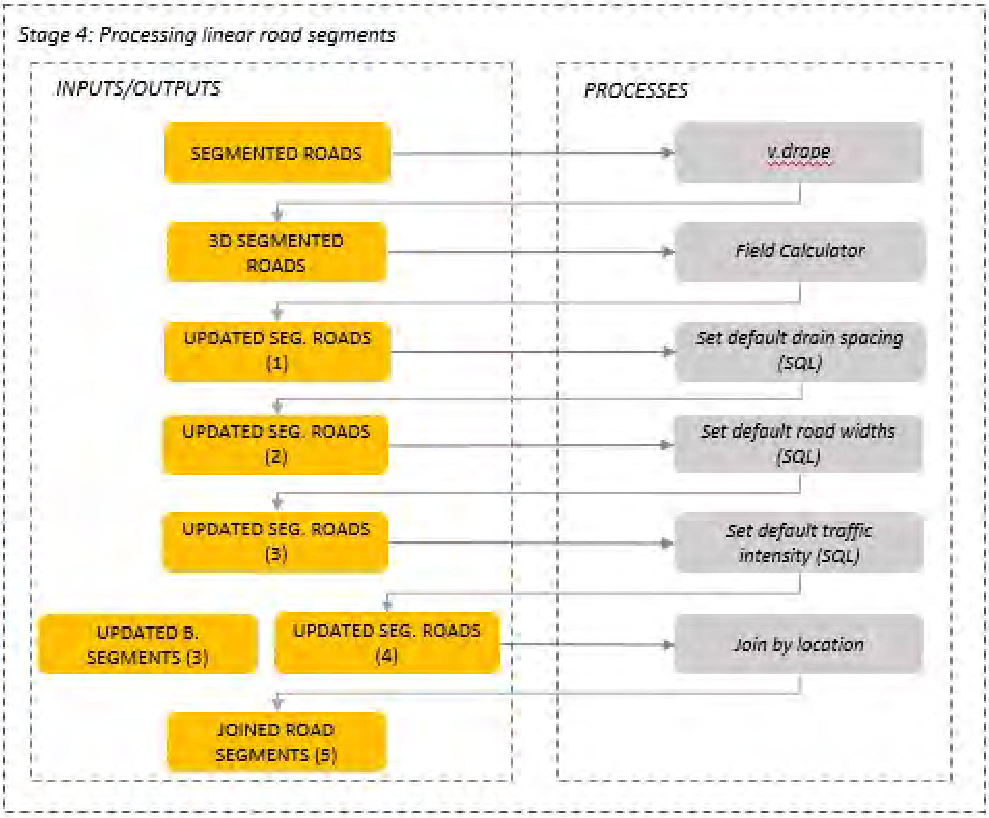


Figure 71. *Stage 4 takes the segmented road lines and poplulates their attribute table with key parameters, including those from the buffered road segments, which sampled the raster datasets.*

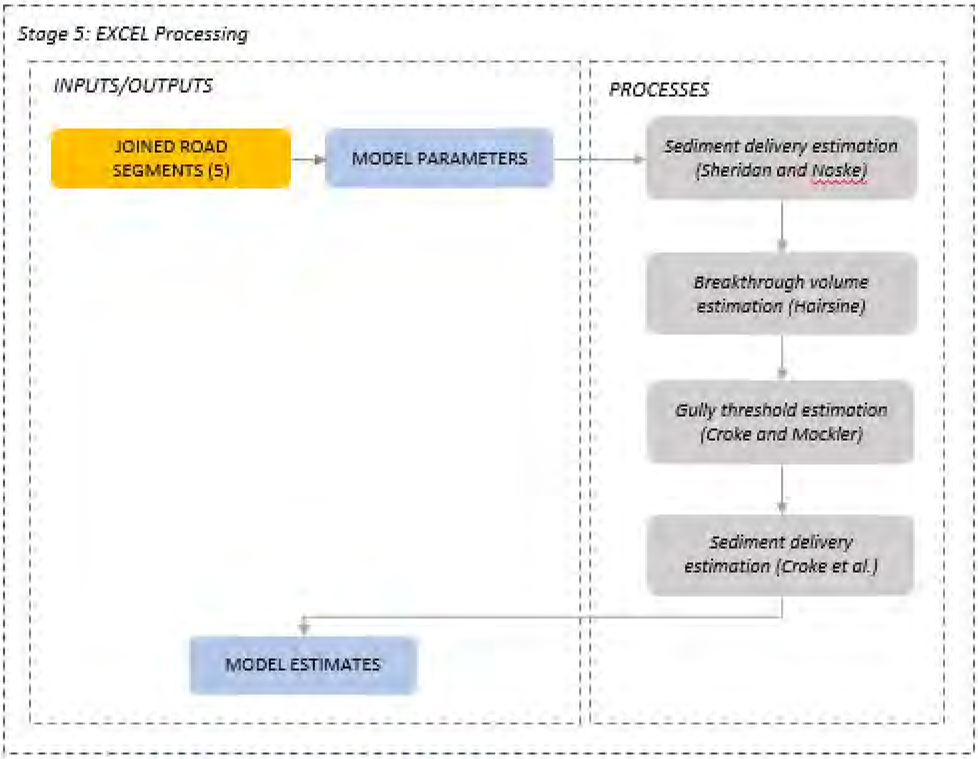


Figure 72. *Stage 5 takes the attribute data from the parameterised road segments shapefile into Excel to feed the model equations sourced from the literature mentioned.*

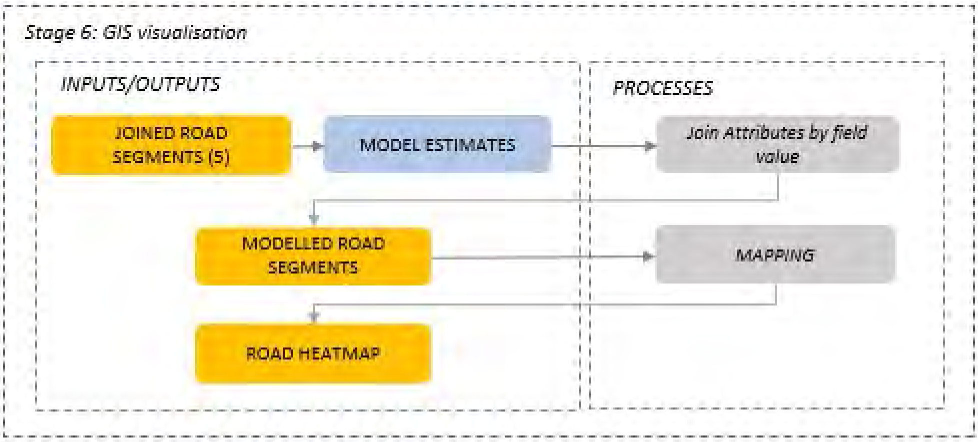
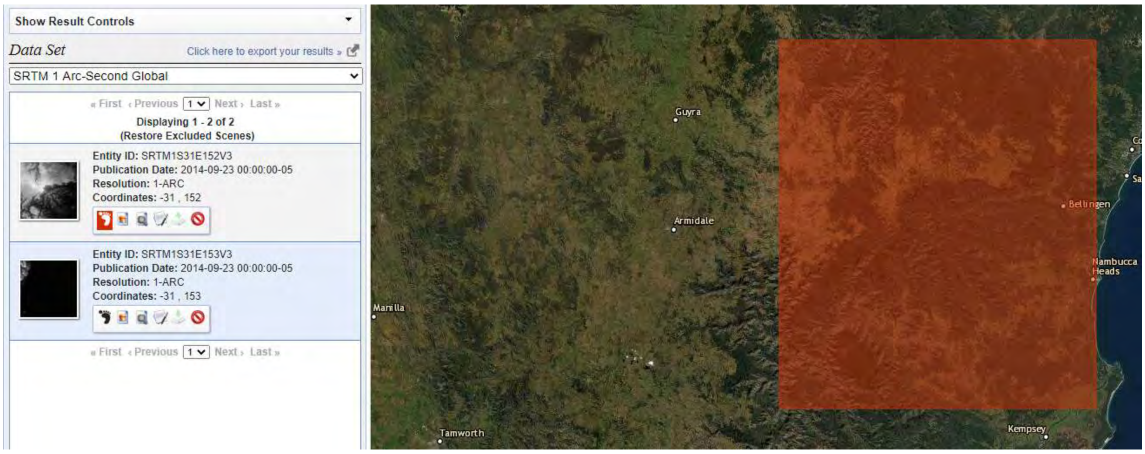


Figure 73. *Stage 6 joins the processed model outputs and reintegrates them with their corresponding road segments in GIS to produce a heatmap of moadelled values.*

Raster Processing

Intro

Note: A hydraulically conditioned (pit filled) DEM with equal/square x/y cell dimensions is required for this analysis. To avoid errors, leave the DEM in its original co-ordinate reference system until the final layer is calculated. The DEM used in this example is sourced from https://earthexplorer.usgs.gov/



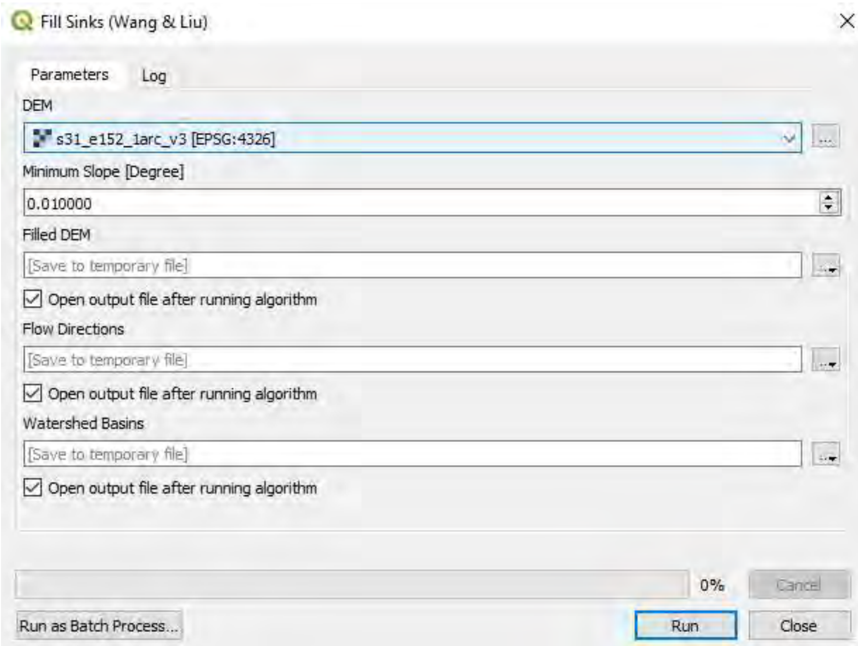
The drainage distance from any road segment to the nearest stream can be calculated by the **TauDEM D8 Distance to Streams tool.**

NOTE: TauDEM requires a partly manual installation to work on QGIS. Installation details provided in the following link: https://gis.stackexchange.com/questions/272797/adding-taudem-provider-to-qgis-3

To run the Distance to Stream tool, two inputs are required, which are produced through two TauDEM tools:

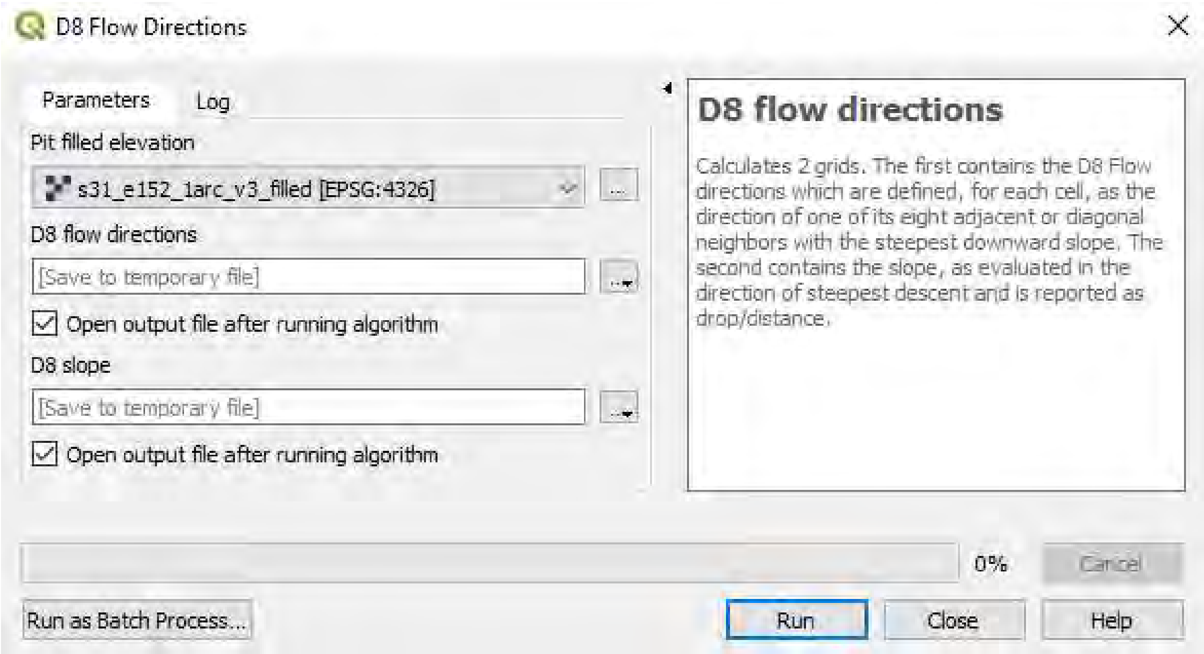
- D8 Flow Directions
- Grid Network (which produces the Strahler stream raster)

Fill Sinks



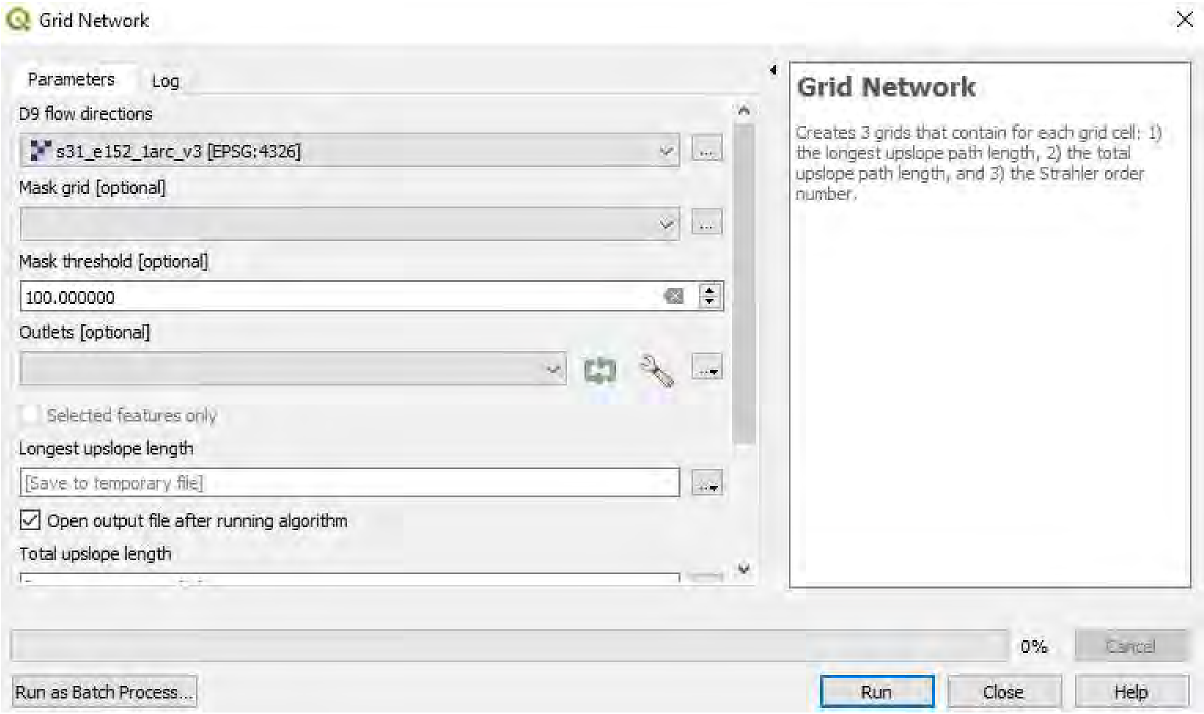
D8 Flow Direction

The pit filled raster is fed into the *D8 Flow Direction* tool. The tool produces two outputs, D8 flow directions and D8 Slope, both of which are saved to be utilised at a subsequent stage in the method.

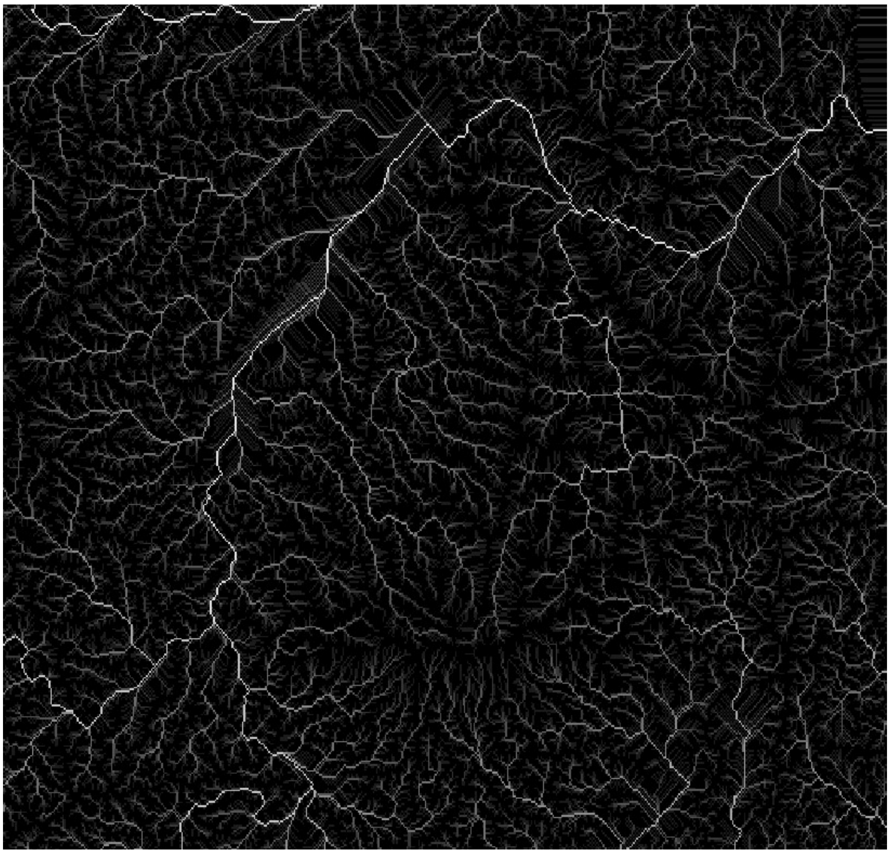


Grid Network

The *D8 flow directions* output is fed into the *Grid Network tool*. *Note that this tool does not provide an area threshold by which stream ordering initiates*, instead it assigns drainage pathways with no contributing cells as with the Strahler order 1 and then carries on as per the ordering approach detailed in the link below:
https://hydrology.usu.edu/taudem/taudem5/help53/GridNetwork.html

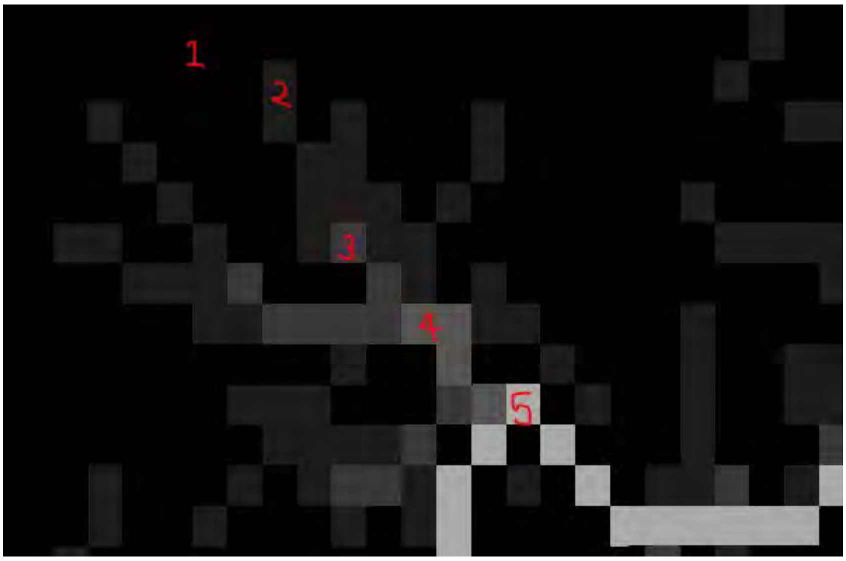


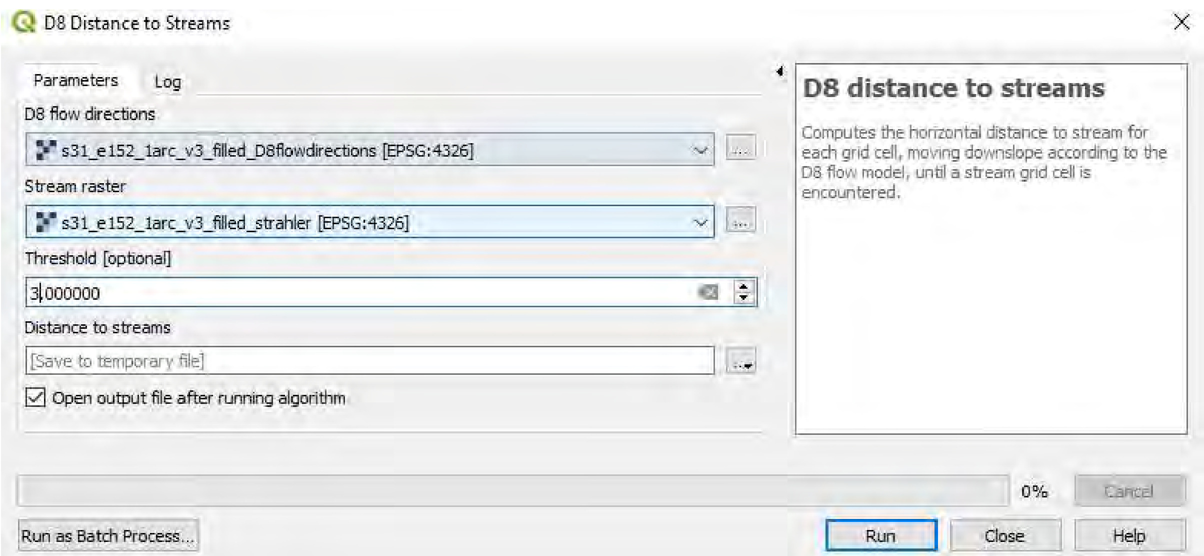
OUTPUT: A fully connected stream network grid is the desired result, as shown below. If the stream network appears to be disconnected, then there is likely to an issue with the previous processing stages.



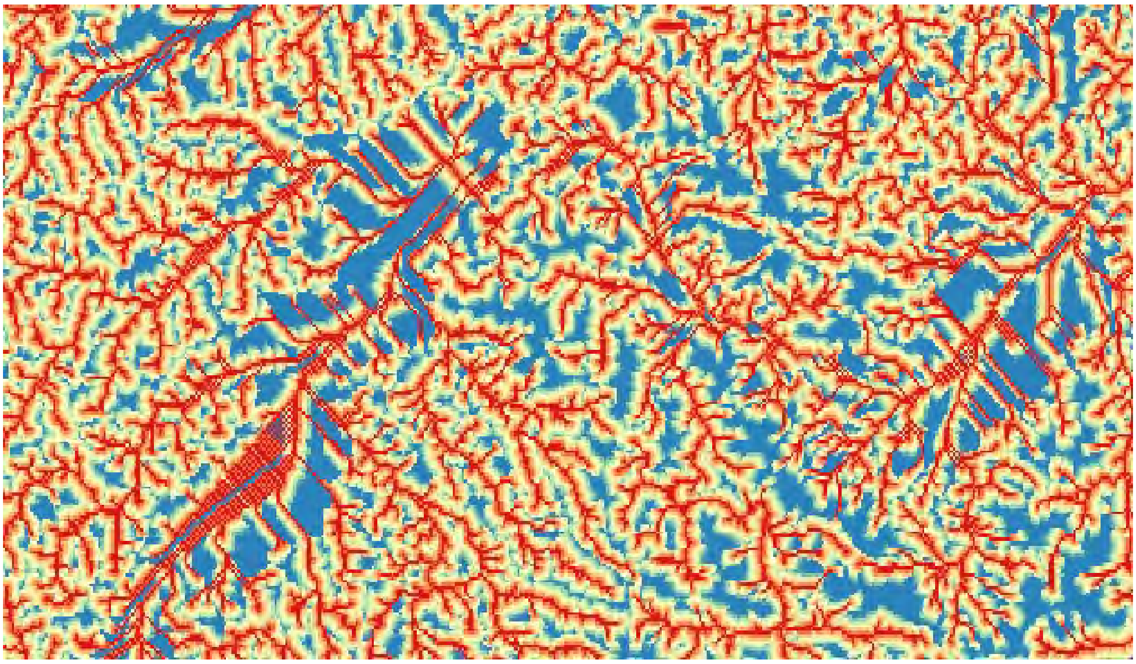
Distance to stream

Both preceding outputs (i.e., the D8 flow directions grid and the stream network grid) can be utilised in the *D8 Distance to Stream tool*. The optional threshold in the tool dialog box responds to the stream order values. The number entered as the threshold value determines what the tool considers to be a stream to which it can calculate the drainage pathway distance. In this case we set the distance to stream threshold at 3 (as shown below). Comparison of these calculated 3rd order streams with existing waterways and road network data suggested that this 3rd order suitably represented a what would otherwise be considered a 1st order stream in other government datasets.



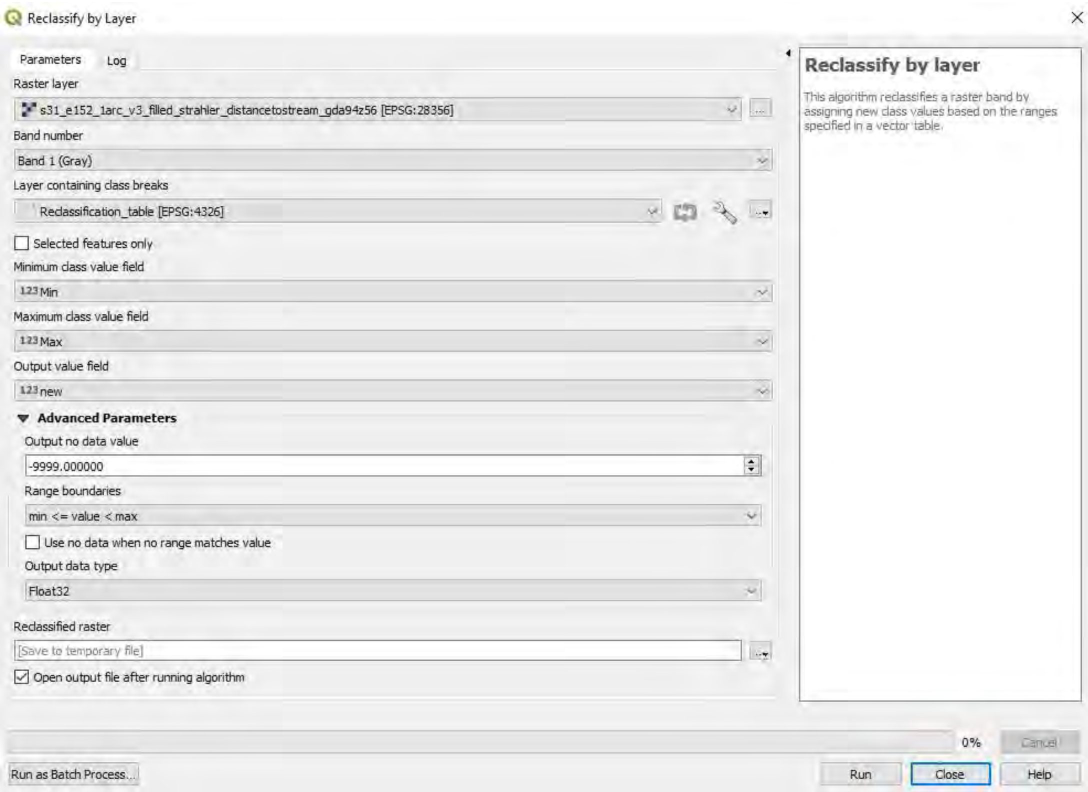


OUTPUT:



Reclassify by layer

The ‘Reclassify by layer’ tool allows for the binning of distance values according to an appropriate range as defined by a vector layer with min/max/new value fields. The tool is applied to the distance to streams raster to simplify the dataset. Once the distance to streams layer is reclassified all raster processing should be complete and ready for sampling as per Section 3.



Reclassification_table — Features Total: 30, Filtered: 30, Selected:

	Min	Max	new
1	0	10	10
2	10	20	20
3	20	30	30
4	30	40	40
5	40	50	50
6	50	60	60
7	60	70	70
8	70	80	80
9	80	90	90
10	90	100	100
11	100	110	110
12	110	120	120
13	120	130	130
14	130	140	140
15	140	150	150
16	150	160	160
17	160	170	170
18	170	180	180
19	180	190	190
20	190	200	200
21	200	250	250
22	250	300	300
23	300	400	400
24	400	500	500
25	500	600	600
26	600	700	700
27	700	800	800
28	800	900	900
29	900	1000	1000
30	1000	80000	10000

Vector processing

The FCROADS geodatabase was provided to Alluvium by NRC under a data sharing agreement for modelling purposes only. To be utilised as such, the database was processed to allow for the extraction of suitable data in .csv format for excel based modelling.

The geodatabase contains attribute data for most road features, some of which are utilised to estimates of model parameters, such as traffic intensity. It also includes a variety of road types which fall outside the scope of the evaluation (i.e., sealed, snig or walking tracks). The database was therefore required to be processed in several ways prior to being utilised in the model. A summary of pre-processing steps is provided below.

FCROADS pre-processing

Initial processing involved the deletion of geodatabase features which bore attributes which suggested that they fell out of the scope of the evaluation. The features which were deleted included those in the screen shot below.

Process	Domain	Code - Description	N
Saved as shapefile			
Feature deletion	Display Road Class	1 - Highway, Freeway, Motorway	
Feature deletion	Display Road Class	2 - Sealed surface, Two or more	
Feature deletion	Display Road Class	3 - Sealed surface, One lane	
Feature deletion	Road Type	7 - Walking Track	
Feature deletion	Road Type	8 - Bridle Track	
Feature deletion	Road Type	9 - Walking Track, Horses Permitt	
Feature deletion	Surface	1 - Sealed	

The roads geodatabase file was extracted as a .shp file but then converted to a geopackage (.gpkg) file to enable faster processing times.

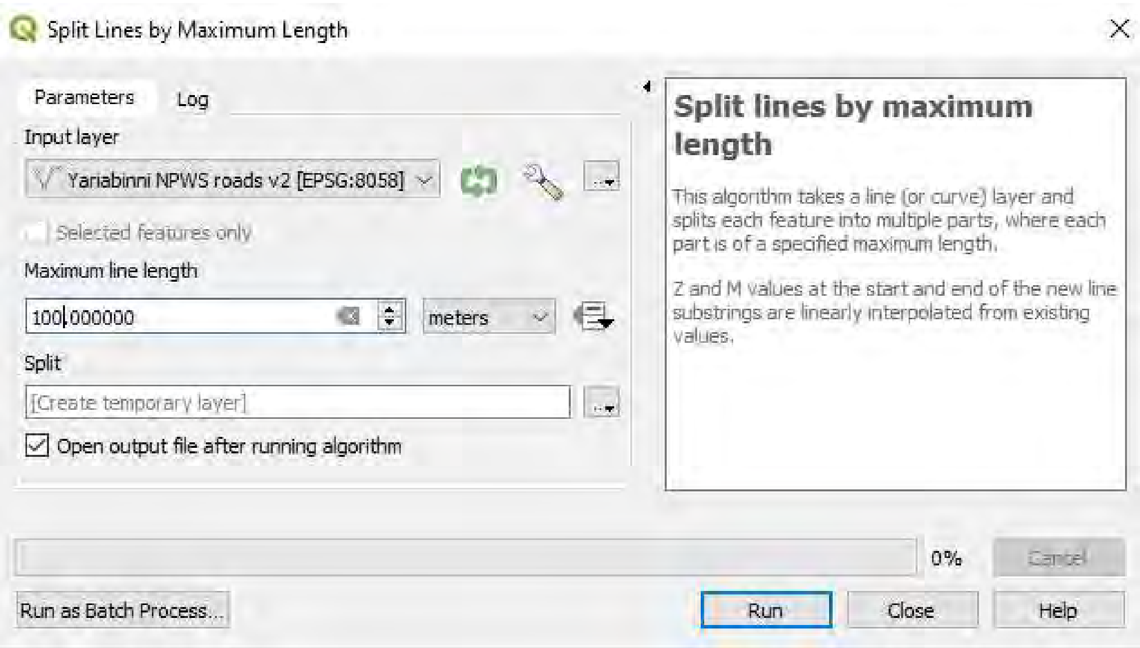
A unique ID was assigned to all features under the title 'OG_ID' - meaning Original ID.

Fix geometries and splitting roads layer by IFOA

All features had geometries fixed prior to being split by IFOA

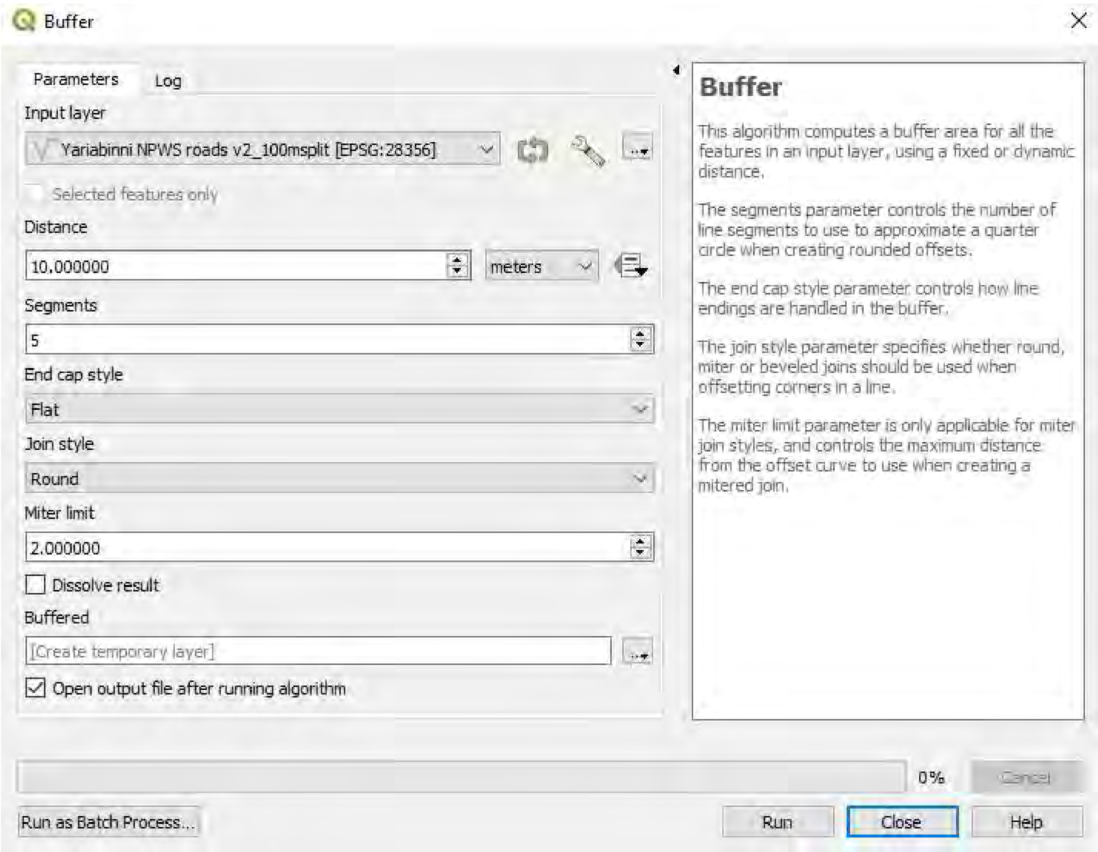
Split roads to 100m intervals

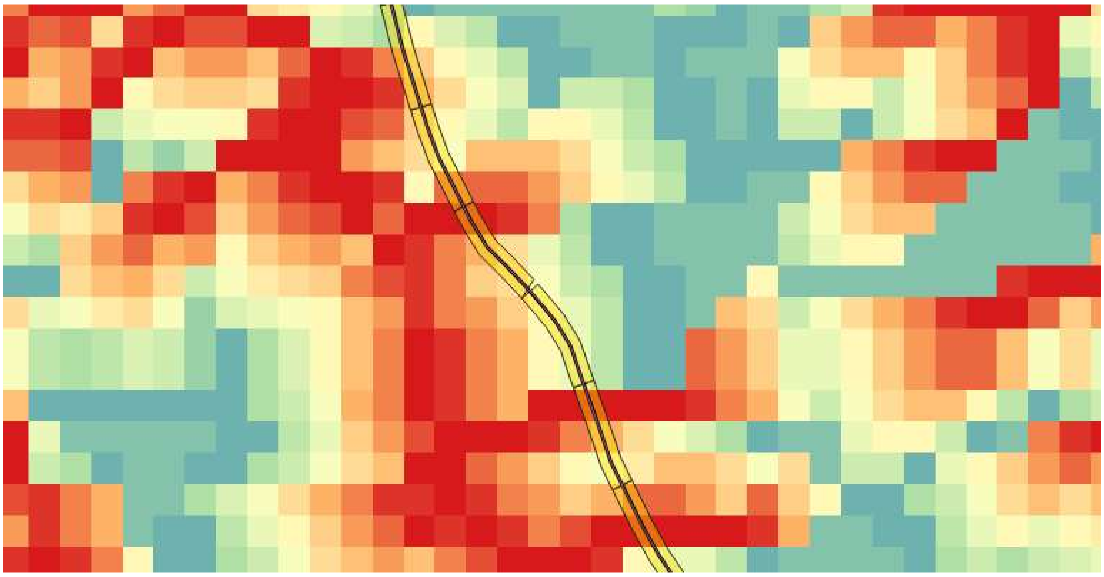
Each roads .gpkg file then had its features split into segments 100m or less. Each segment was assigned a unique ID 'SG_ID'.



Buffer segments

For each roads .gpkg file, the 'Buffer' tool is used to generate 10m buffer polygons for road segment (creating a total width of 20m). The end style should be set to flat, so that the buffers for each segment do not overlap considerably. Some overlap of polygons at road bends and intersections is unavoidable with this method but not critical.





Reprojection

Given the roads file needs to be in a flat projection (GDA94 Z55 or NSW LAMBERT) to be segmented into 100 metre lengths and buffered, the buffered road polygons require a reprojection into WGS84 format to overlay the WGS84 rasters to calculate their corresponding zonal statistics. The reason for reprojecting the road buffer .gpkg file rather than the raster layers themselves is that there is less error produced in reprojecting the vector file when compared to reprojecting a series of large state-wide raster layers.

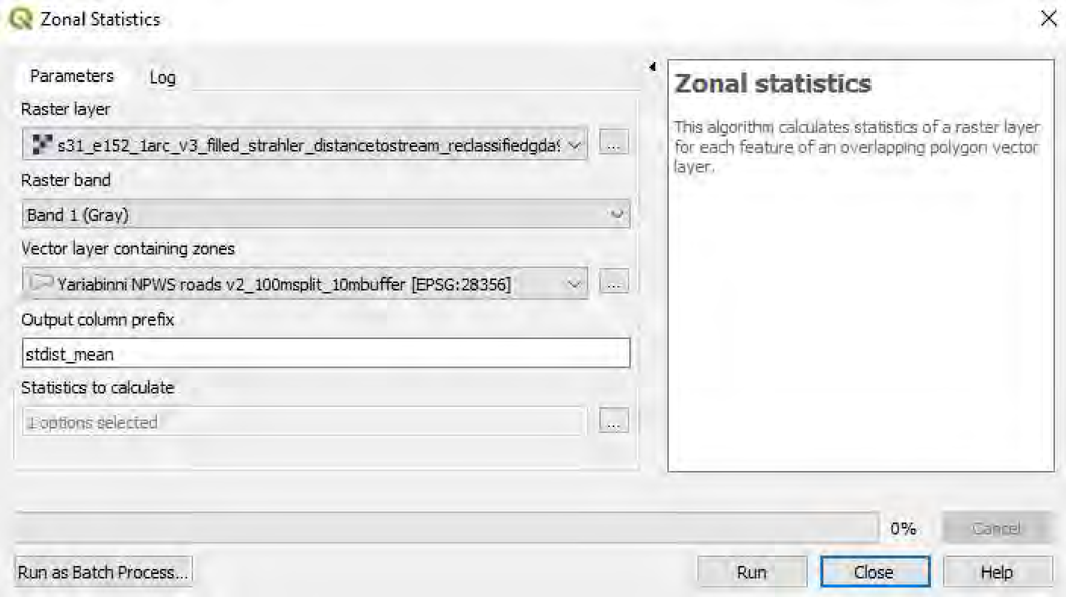
Raster Sampling

To gather the data corresponding to each 100m road segment the following approach is taken.

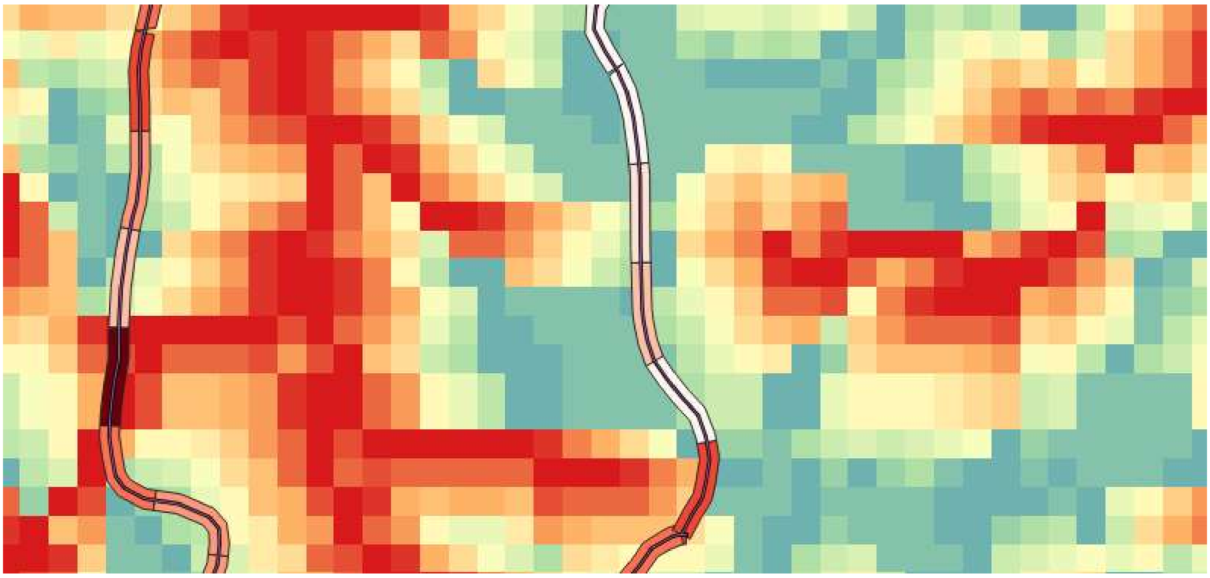
1. The roads dataset is split at 100m intervals (Section 2.3)
2. A 10m buffer is applied to each 100 segments (Section 2.4)
3. The mean value within the buffer area is calculated for each corresponding raster dataset (i.e., Distance to streams, rainfall intensity, terrain slope (D8)) and then added as attributes to the road segment vector file (Sections 3.1 to 3.4 below)

Zonal statistics (Mean distance to stream)

The zonal statistics tool calculates the mean value of any raster dataset that falls within a vector polygon. The mean distance to stream value within each of the road segment buffer feature is calculated using this tool. The tool allocates a mean distance to stream value to each buffer feature by creating a new output column.

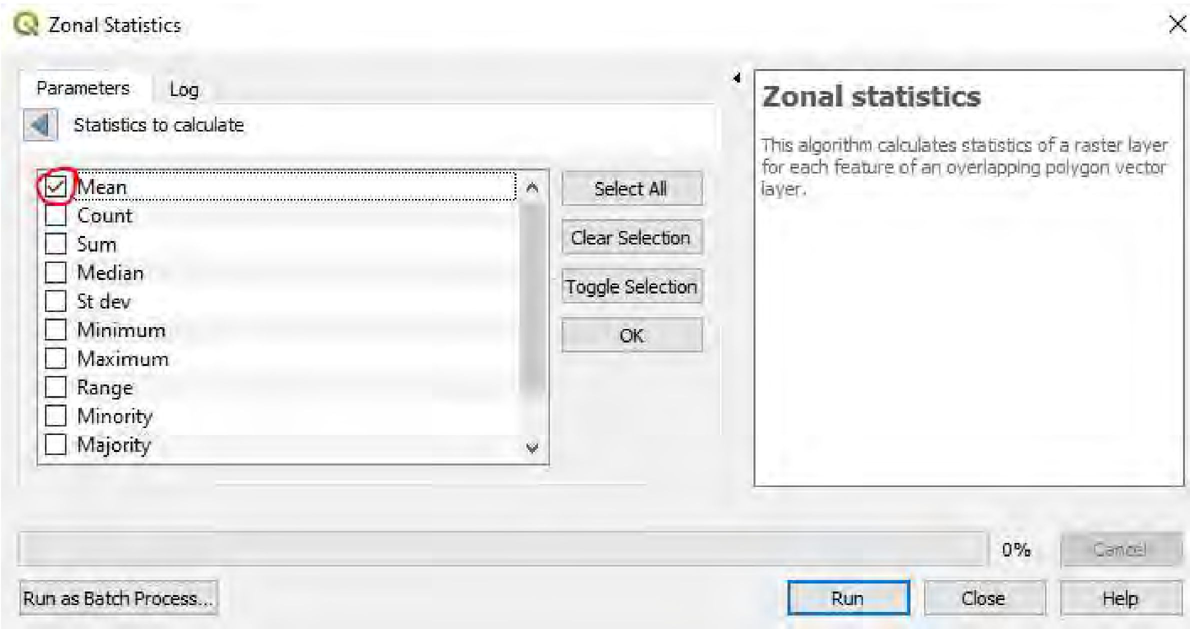


An example of the buffers coloured by mean distance to stream below:



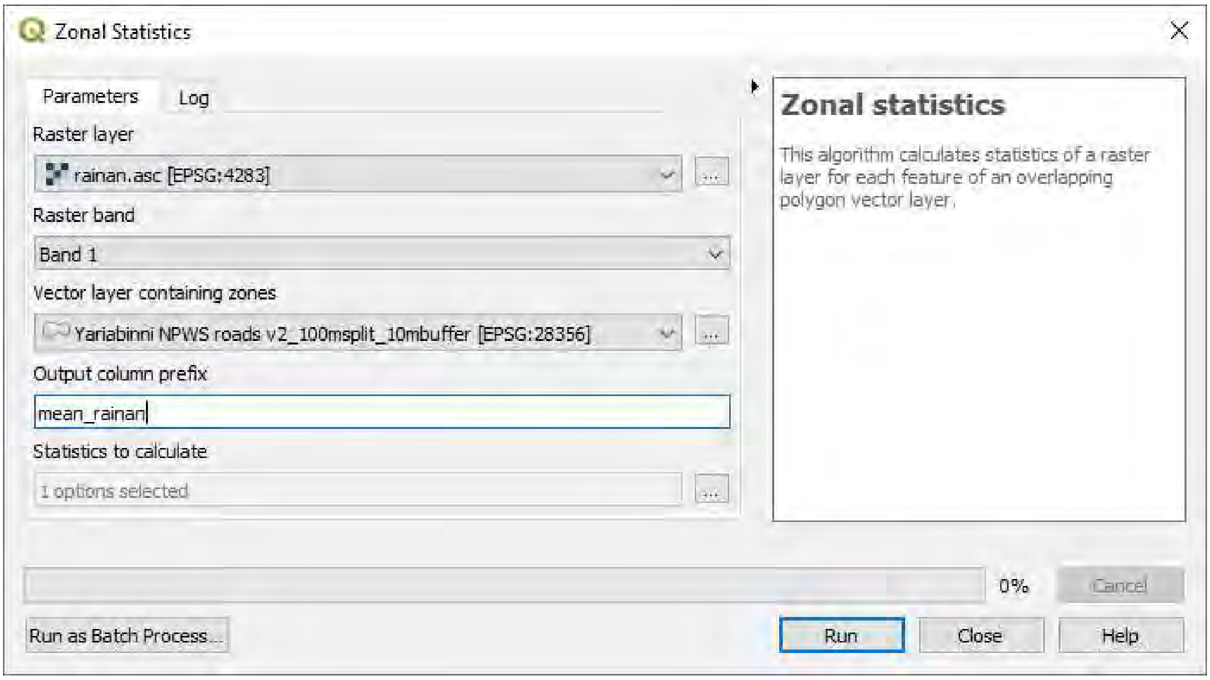
Zonal statistics (Mean surrounding slope)

The D8 slope as calculated from the TauDEM D8 flow directions tool in Step 1.2 provides the data for this calculation. The D8 slope tool calculates slope as the greatest drop across each cell/distance, presenting slope as a ratio (rise/run). The zonal stats tool is used to sample for the mean slope within each buffer zone. Ensure that 'mean' is selected in the 'statistics to calculate' tab (as shown below).



Zonal Statistics tool (Annual Rainfall)

The zonal stats tool is used again to allocate the mean annual rainfall value to each of the road segment buffer areas. The rainfall grid is 5km by 5km.

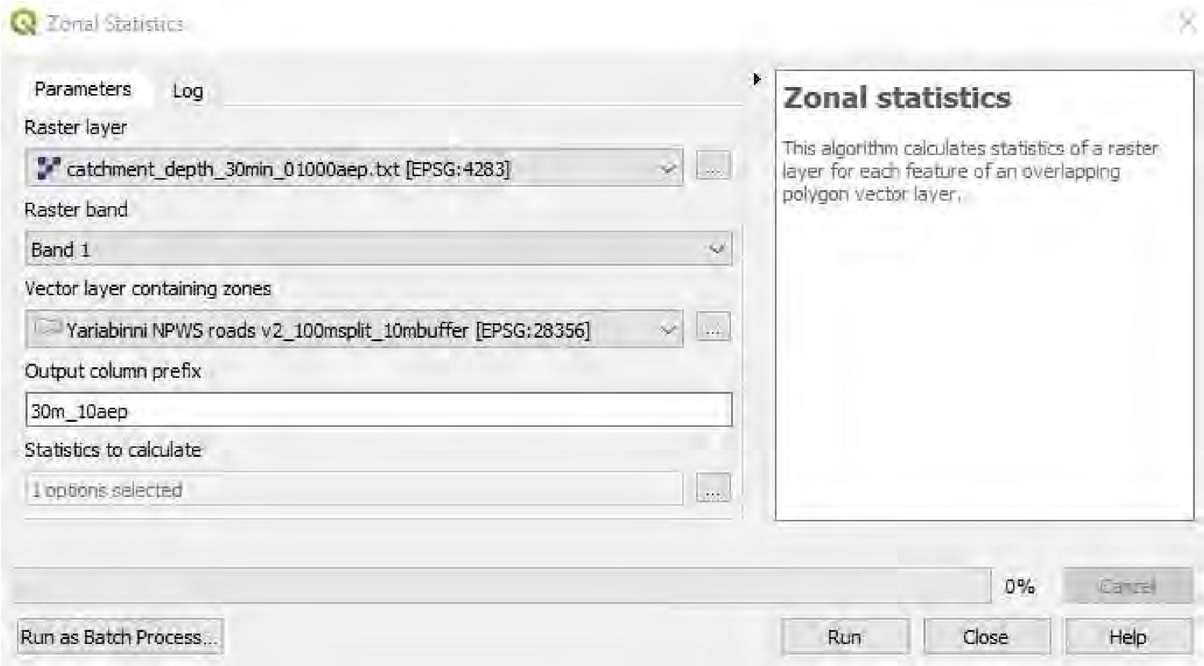


Zonal Statistics (Rainfall Intensity)

The zonal stats tool was used to gather the mean rainfall intensity value for each buffered 100m road segment.

The rainfall grid is 2.5km by 2.5km. Given that a state-wide design rainfall grid was not available from BOM, grids were extracted systematically across the state and then merged to produce a state-wide grid for a one in ten-year 30-minute design rainfall.

Grids available here: http://www.bom.gov.au/water/designRainfalls/



Road segment Processing (line shapefile)

Road Slope

Road segment slope can is calculated by taking the difference in elevation between the two endpoints of each road segment, divided by the segment length.

*Note*SRTM data is available from multiple sources. Elevation data should be derived from a SRTM dataset that is as accurate as possible. In some cases, the USGS data may not have decimal places, but the ELVIS datasets do. So, with the USGS SRTM data was used for the distance to streams calculations, the ELVIS SRTM datasets will be used for the road slope derivations.

In the example below the slope is calculated as a percentage. This will need to be converted to degrees later to inform the drain spacing guidelines.

https://gis.stackexchange.com/questions/273440/calculate-slope-of-line-segments-with-qgis

10

In the QGIS Processing Toolbox, there are GRASS tools `v.split.length` and `v.drape` (using QGIS 2.18.16).

Before starting;

0.) make sure your DEM and road data are projected onto the same CRS.

Then, following your summary workflow:

1.) split line (forest road) into equal lengths segments

`v.split.length` will give you a new layer `Split by length` by default.

2.) convert segments to 3D shapes (Interpolate shape tool)

`v.drape` will give you a new `3D vector` layer.

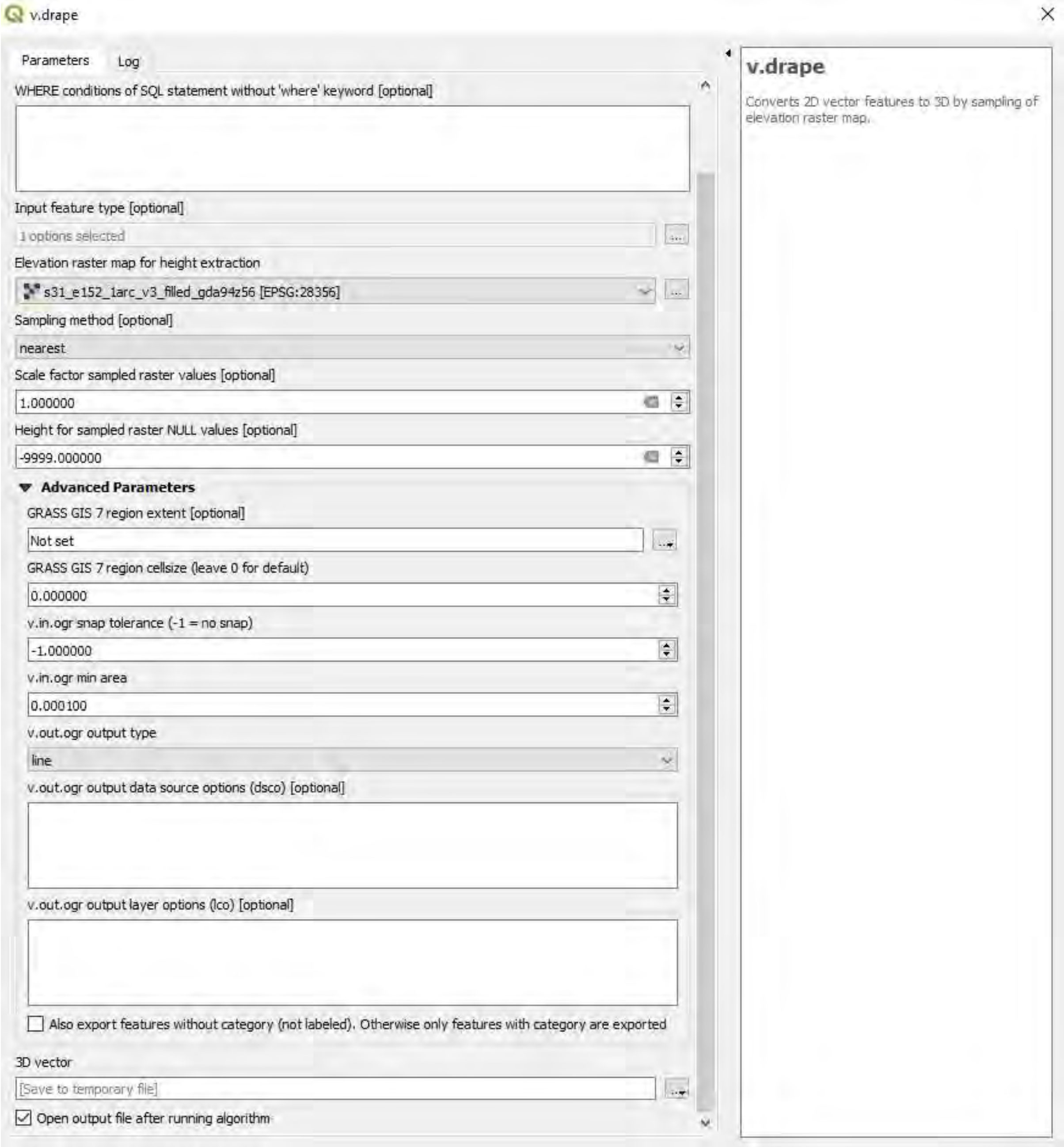
3.) calculate slope of each segment with the field calculator

```
abs(z(start_point($geometry)) - z(end_point($geometry)))/$length*100
```

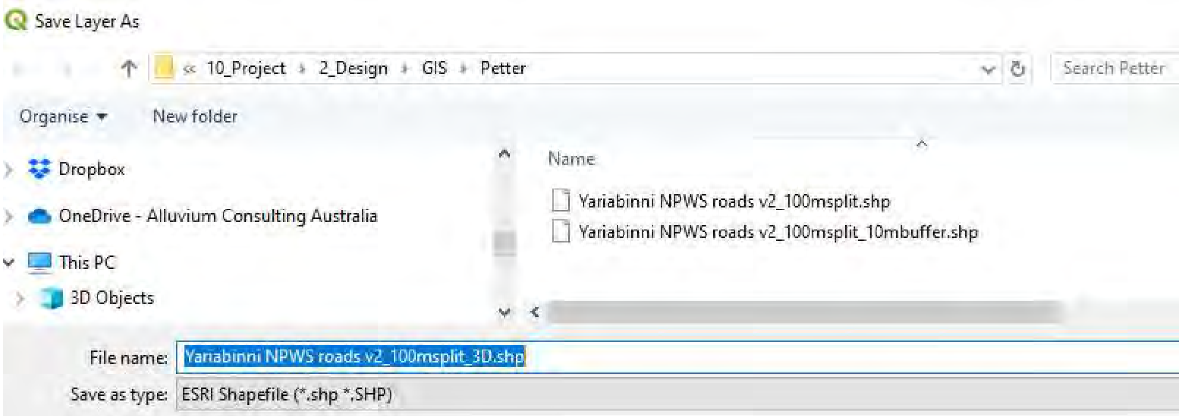
share improve this answer follow

answered Mar 3 '18 at 20:17
Kazuhito
24.1k 5 40 116

First i struggeld with the v.drape tool. The tool did run but i wouldn't generate any outcome. I realized only then that the file path contained a 'ü' letter and thats why it didn't work. Thanks for your help everybody. – Quarantane Mar 5 '18 at 10:31



Save the output 3D road file and label appropriately – as below:



The slope is then converted into degrees using the following formula in the calculator

((atan("seg_slope"/100))/pi())*180

Yarrabinni NPWS roads v2_100msplit_3D — Features Total: 401, Filtered: 401, Selected: 0

	SAPEquipID	AssetName	d_SubtypeC	d_AssetTyp	d_AssetMat	d_Branch	d_LGA	Comments	LengthM	VerDate	Length_m	seg_slope	sslope_deg
380	1270593	Way Way Creek...	Vehicle Trail	2WD	Bitumen Seal	North Coast	Nambucca	NULL	1760.490000000...	2020/05/01 00:0...	1761	1.471403165045...	0.843
381	1270595	Way Way Creek...	Vehicle Trail	2WD	Gravel	North Coast	Nambucca	NULL	167.3000000000...	2020/05/01 00:0...	167	7.822857735607...	4.473
382	1270595	Way Way Creek...	Vehicle Trail	2WD	Gravel	North Coast	Nambucca	NULL	167.3000000000...	2020/05/01 00:0...	167	4.026026839986...	2.305
383	1273335	Nursery Trl - 03	Vehicle Trail	4WD	Natural	North Coast	Kempsey	Field checked h	1535.690000000	2020/05/01 00:0	1536	0.301663031345	0.173

Please note the derivation of road slopes can lead to unrealistic values where very short road segments traverse raster cell boundaries. In these cases, the difference in the height between the endpoints can be unrealistic, leading to very high slope values. Overall, however, these high slope values make up a minor percentage (2-3%) of the reconnaissance dataset which can be identified and deleted.

Drainage spacing:

For the purposes of the statewide assessment the NPWS spacing policy was used for all forest road segments irrespective of tenure.

For National Parks, drain spacing is subject to variation according to soil class/erosion risk. Given that classification of erosion risk is undertaken at the local scale, drainage spacing in this example does not take soil class into account.

A possible proxy for soil class could be the RUSLE K layer.

	Spacing (m) by tenure/region					
Road Grade (degrees)	Plantation	Brigalow Nandewar and South Western Cypress IFOAs	PNF (Northern and Southern Regions)	PNF (River Red Gum Region)	PNF (Cypress and Western Hardwood Region)	National Parks
1	250	175	150	250	175	250
2	200	175	150	200	175	200
3	150	175	150	150	175	150
4	125	100	100	125	100	125
5	100	100	100	100	100	100
6	90	80	60	90	80	90
7	80	80	60	80	80	80
8	70	80	60	70	80	70
9	65	60	60	65	60	65
10	60	60	60	60	60	60
11	55	40	40	-	40	55
12	50	40	40	-	40	50
13	45	40	40	-	40	45
14	40	40	40	-	40	40
15	40	40	40	-	40	40
16	38	25	30	-	25	-
17	36	25	30	-	25	-
18	34	25	30	-	25	-
19	32	25	30	-	25	-
20	30	25	30	-	25	-
21	28	20	-	-	20	-
22	26	20	-	-	20	-
23	24	20	-	-	20	-
24	22	20	-	-	20	-
25	20	20	-	-	20	-

- The maximum drainage spacing approach varies across tenures
- Plantation Forestry takes on **generic spacing approach**
- Some IFOAs and PNF areas take **regional approaches**
- Other IFOAs (such as Riverina Red Gum and probably CIFOAs) adopt **site specific spacing approach**, as do public roads (Blue Book 1 and 2)
- Fire trails and National Parks take a **middle road , using soil erodibility/class** to guide drain spacing.
- In some tenures, such as the Brigalow and Cypress IFOA regions, the spacing relates to environmental values/geographic attributes, yet the basis for the spacing is not referenced.

	Drain spacing by soil class			
Road Grade (degrees)	Soil Class A	Soil Class B	Soil Class C	Soil Class D
0-8	70 to 90m	60 to 70m	20 to 30m	*
8 to 12	60 to 70m	50 to 60m	*	*
12 to 16	40 to 60m	*	*	*
16 to 20	30 to 40m	*	*	*
20 to 22	20m (to 30m**)	*	*	*

A SQL expression can deliver the drain spacing according to the calculated road slope.

CASE

WHEN "sslope_deg" >= 0 AND "sslope_deg" <=1 THEN '250'

WHEN "sslope_deg" >1 AND "sslope_deg" <=2 THEN '200'

WHEN "sslope_deg" >2 AND "sslope_deg" <=3 THEN '150'

```
        WHEN "sslope_deg" >3 AND "sslope_deg" <=4 THEN '125'

        WHEN "sslope_deg" >4 AND "sslope_deg" <=5 THEN '100'

        WHEN "sslope_deg" >5 AND "sslope_deg" <=6 THEN '90'

        WHEN "sslope_deg" >6 AND "sslope_deg" <=7 THEN '80'

        WHEN "sslope_deg" >7 AND "sslope_deg" <=8 THEN '70'

        WHEN "sslope_deg" >8 AND "sslope_deg" <=9 THEN '65'

        WHEN "sslope_deg" >9 AND "sslope_deg" <=10 THEN '60'

        WHEN "sslope_deg" >10 AND "sslope_deg" <=11 THEN '55'

        WHEN "sslope_deg" >11 AND "sslope_deg" <=12 THEN '50'

        WHEN "sslope_deg" >12 AND "sslope_deg" <=13 THEN '45'

        WHEN "sslope_deg" >13 AND "sslope_deg" <=14 THEN '40'

        WHEN "sslope_deg" >14 AND "sslope_deg" <=15 THEN '40'

        WHEN "sslope_deg" >15 AND "sslope_deg" <=20 THEN '10'

END
```

Width

The attribute column named 'Formation_width' in the FCROADS dataset was used to inform the width of the road segment used in the model. attribute provides 28 categories of road width (ranging from -2 to 13). Given the normal width of a road ranges between 3 to 10m, we assume that unit of measurement in this category is metres.

The distribution of these widths across the road types in the dataset was briefly analysed to understand the distribution of widths across the dataset. It was discovered that most unsealed roads (67%) sit in the 3m category with about 4.5% of roads listed below 3m, most of these were in the 0m category. Consequently the processed roads file was modified so that a 3m width was applied to all roads that sat below 3m.

Traffic Intensity

Traffic intensity has been applied in a generic fashion across the State, despite it being likely that traffic will greatly vary in accordance with tenure management and proximity to population centres. Sheridan and Noske (2007) quantify traffic intensity in terms of truck axles per week. We use the same metric.

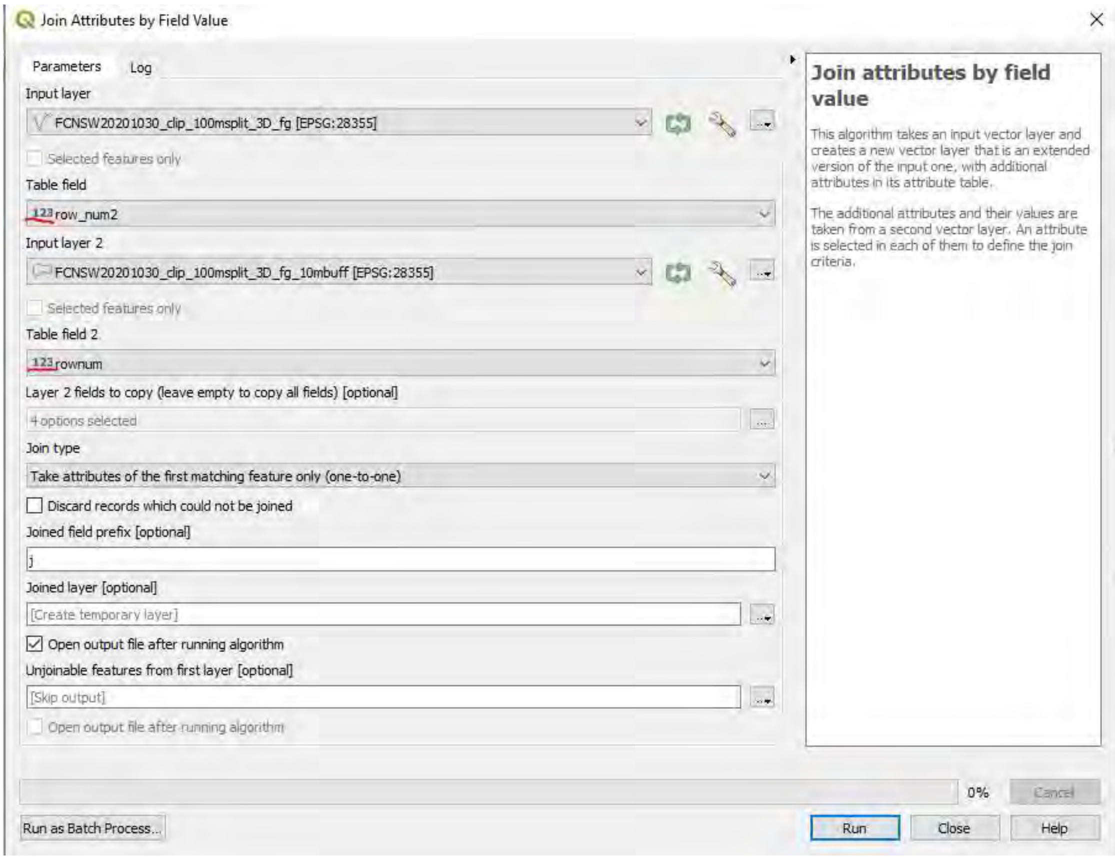
At this stage, traffic intensities have been allocated in accordance to different combinations of attribute categories which serve as indicators for trafficability and intensity of use. These indicators are 'LaneCount' and 'Trafficability' and 'Road type'. A variety of combinations of these three indicators are utilised to ensure the entire dataset gets an estimate of traffic intensity as either low (90) medium (360) or high (630 axles per week). Due to not all indicators being present for all road features, some 'catch all' allocations are used in the SQL code which are quite obviously rudimentary.

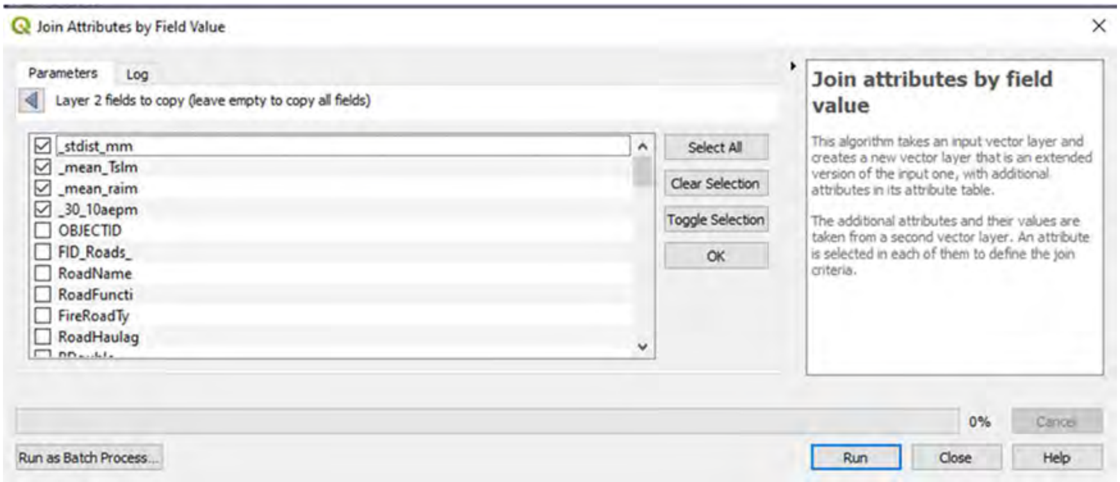
```
CASE

WHEN  "LaneCount" = '1' AND  "Trafficabi" = '3' THEN 90

WHEN  "LaneCount" = '0' AND  "Trafficabi" = '3' THEN 90

WHEN  "LaneCount" = '1' AND  "Trafficabi" = '1' THEN 360

WHEN  "LaneCount" = '1' AND  "Trafficabi" = '2' THEN 360

WHEN  "LaneCount" = '2' AND  "Trafficabi" = '2' THEN 630

WHEN  "LaneCount" = '2' AND  "Trafficabi" = '1' THEN 630

WHEN  "LaneCount" = '2' AND  "Trafficabi" = '3' THEN 360

WHEN  "LaneCount" = '-2' AND  "Trafficabi" = '3' THEN 90

WHEN  "LaneCount" = '-2' AND  "Trafficabi" = '2' THEN 360

WHEN  "LaneCount" = '0' AND  "Trafficabi" = '1' THEN 360

WHEN  "LaneCount" = '0' AND  "Trafficabi" = '2' THEN 90

WHEN  "LaneCount" = '0' AND  "Trafficabi" = '0' THEN 90

WHEN  "LaneCount" = '-2' AND  "Trafficabi" = '1' THEN 360

WHEN  "LaneCount" = '-1' AND  "Trafficabi" = '2' THEN 90

WHEN  "LaneCount" = '-1' AND  "Trafficabi" = '3' THEN 90

WHEN  "LaneCount" = '-1' AND  "Trafficabi" = '1' THEN 90

WHEN  "LaneCount" = '-2' AND  "Trafficabi" = '0' THEN 90

WHEN  "RoadType" = '6' AND  "Trafficabi" = '0' THEN 90

WHEN  "RoadType" = '2' AND  "Trafficabi" = '0' THEN 90

WHEN  "Trafficabi" = '-2' THEN 90

WHEN  "Trafficabi" = '-1' THEN 90

END
```

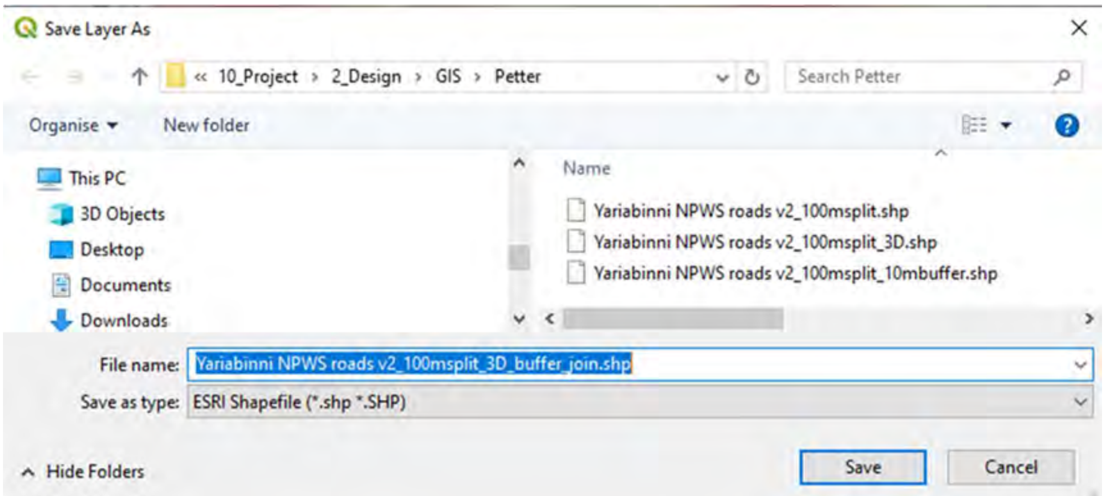
Excel Modelling

To run the model in excel, the values which have been calculated in the buffer zones for each road segment are joined back to the 3D road segment shapefile so that all that inputs can be exported in one simple spreadsheet.

The join type settings are important – a one to one join by unique identifier (such as Segment ID) should suffice. Ensure that the join field is in the same data type for the join to work. Run the join function and save the joined layer with an appropriate name.


Join Attributes by Field Value
Parameters
Log
Input layer
FCNSW20201030_clip_100msplit_3D_fg [EPSG:28355]
Selected features only
Table field
row_num2
Input layer 2
FCNSW20201030_clip_100msplit_3D_fg_10mbuff [EPSG:28355]
Selected features only
Table field 2
rownum
Layer 2 fields to copy (leave empty to copy all fields) [optional]
4 options selected
Join type
Take attributes of the first matching feature only (one-to-one)
Discard records which could not be joined
Joined field prefix [optional]
j
Joined layer [optional]
[Create temporary layer]
Open output file after running algorithm
Unjoinable features from first layer [optional]
[Skip output]
Open output file after running algorithm
Join attributes by field value
This algorithm takes an input vector layer and creates a new vector layer that is an extended version of the input one, with additional attributes in its attribute table.
The additional attributes and their values are taken from a second vector layer. An attribute is selected in each of them to define the join criteria.
0%
Cancel
Run as Batch Process...
Run
Close
Help


Join Attributes by Field Value
Parameters
Log
Layer 2 fields to copy (leave empty to copy all fields)
_stdist_mm
_mean_Tslm
_mean_raim
_30_10aepm
OBJECTID
FID_Roads_
RoadName
RoadFuncti
FireRoadTy
RoadHaulag
Select All
Clear Selection
Toggle Selection
OK
Join attributes by field value
This algorithm takes an input vector layer and creates a new vector layer that is an extended version of the input one, with additional attributes in its attribute table.
The additional attributes and their values are taken from a second vector layer. An attribute is selected in each of them to define the join criteria.
0%
Cancel
Run as Batch Process...
Run
Close
Help



Please Note It is important at this stage that the dataset is checked for blanks, as there will likely be many due to the partitioning of roads into segments. As most road lengths are not even multiples of 100m, there will be offcuts ranging from 0m- to ones less than 100m, though the majority (>90%) will likely sit within 90-100m. To clean the data of the errors that typically arise from such impossibly short segments, all road segments less than 1m were deleted from each regional roads dataset at this stage in the processing sequence.

Model Calculations

Four different empirical models are applied to estimate the amount of sediment delivered to a stream. These are detailed in the main document; their formulae are translated into excel functions to generate estimates of sediment delivery for each road segment.

Discretisation

Sediment delivery hazard and mitigation potential values are discretised into 5 categories based on the analyses outlined in the main report. Ratings are as outlined below.

Avg. Sed. del. per m. (kg)	Sediment delivery hazard
0 - 0.2	1. Very Low
0.2 - 2	2. Low
2 - 5	3. Moderate
5 - 10	4. High
> 10	5. Very High

Avg. Sed. del. per m. (kg)	Mitigation Potential
0 - 0.2	1. Very Low
0.2 - 1	2. Low
1 - 4	3. Moderate
4 - 8	4. High
> 8	5. Very High

The SQL expression below was employed to assign BEST CASE hazard categories to the added column named ‘sdhazard_best_case’.

CASE

WHEN "sd_dw_kg_avg_per_m" <=0.2 THEN 1

WHEN "sd_dw_kg_avg_per_m" > 0.2 AND "sd_dw_kg_avg_per_m" <=2 THEN 2

WHEN "sd_dw_kg_avg_per_m" > 2 AND "sd_dw_kg_avg_per_m" <=5 THEN 3

WHEN "sd_dw_kg_avg_per_m" > 5 AND "sd_dw_kg_avg_per_m" <=10 THEN 4

WHEN "sd_dw_kg_avg_per_m" > 10 THEN 5

END

The SQL expression below was employed to assign WORST CASE hazard categories to the added column named ‘sdhazard_worst_case’

CASE

WHEN "sd_dw_kg_avg_per_m_1" <=0.2 THEN 1

WHEN "sd_dw_kg_avg_per_m_1" >0.2 AND "sd_dw_kg_avg_per_m_1" <=2 THEN 2

WHEN "sd_dw_kg_avg_per_m_1" >2 AND "sd_dw_kg_avg_per_m_1" <=5 THEN 3

WHEN "sd_dw_kg_avg_per_m_1" >5 AND "sd_dw_kg_avg_per_m_1" <=10 THEN 4

WHEN "sd_dw_kg_avg_per_m_1" >10 THEN 5

END

The SQL expression below was employed to assign mitigation potential categories to the added column named ‘mitigation_potential’

CASE

WHEN "Diff_p_m_kg" <=0.2 THEN 1

WHEN "Diff_p_m_kg" >0.2 AND "Diff_p_m_kg" <=1 THEN 2

WHEN "Diff_p_m_kg" >1 AND "Diff_p_m_kg" <=4 THEN 3

WHEN "Diff_p_m_kg" >4 AND "Diff_p_m_kg" <=8 THEN 4

WHEN "Diff_p_m_kg" >8 THEN 5

END

GIS Visualisation

In order visualise the modelled outputs, the GIS software typically requires numerical values. If there is text in the column of data to be displayed, the GIS platform will assume that the entire column is composed of text therefore be unable to arrange the discretise the data in numerical fashion.

To avoid this issue:

1. Check for any 'DIV' values in the excel spreadsheet to exported as CSV. As when it is joined to the shapefile in QGIS it will be allocated a 'text' field type – this will affect your ability to display the results.

)978	17.70293	8.680355	7.2207	775.9411
)254	15.44776	8.782748	7.479251	981.3676
0	0	-46.8248	-46.8248	#DIV/0!
3843	371.6528	1.377848	0.028878	27.71247

2. Save values as CSV
3. Add CSV to GIS workspace
4. Use the join Attributes by field value tool to join the CSV to the road's shapefile by 'Seg_ID'.

Once joined. The GIS software should allow for data visualisation through inbuilt discretisation and display functions.

Attachment D Field assessment methods

Attachment D: Field assessment methods and post processing steps

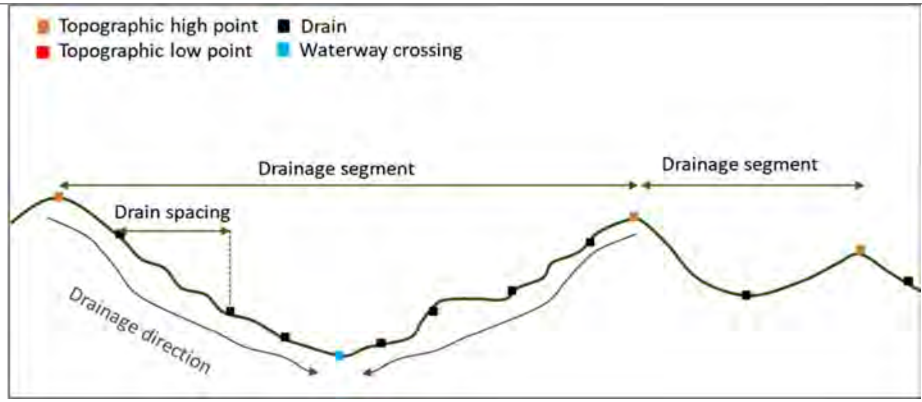
Purpose of the field assessment

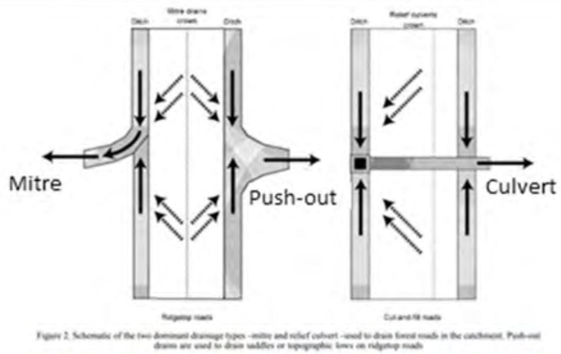
The purpose of the field assessment is to more accurately define the location of drains and waterway crossings in a road network, the condition of those drains and importantly, the road catchment area that contributes flow to each drain.

Drain assessment

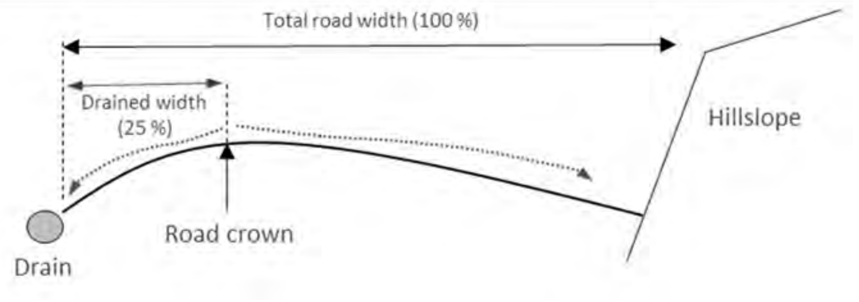
A summary of the measurements made at each drain, the units of measurements and additional explanation are provided in Table 20.

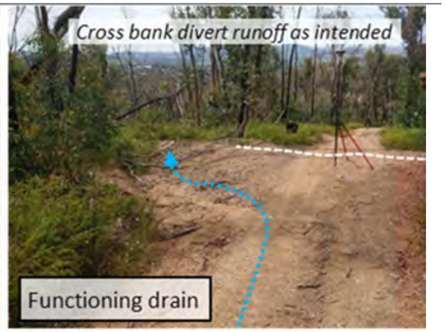
Table 20. Field measuremnts made at each drain, units of measuremnt and additonal explaantion

Measurement	Units and measurement notes	Photo/diagram
Drain or crossing location and Point ID	Marked at intersection of drain and road edge, or intersection of waterway and road. Point ID to match Point ID assigned by survey method.	
Feature type	Drain Waterway crossing Topographic High Topographic low	

Measurement	Units and measurement notes	Photo/diagram
Drain type	Mitre Pushout Culvert Cros bank	 

Measurement	Units and measurement notes	Photo/diagram
Road slope	Unit: degrees Measurement: measured adjacent drain or at a point upslope representative of the area of road contributing flow to the drain. If road slope is highly variable near drains necessary, the average slope of the larger segment can be used.	
Road width	Unit: Metres Measurement: gravel road width adjacent drain. If road width is highly variable, the average width of the larger segment can be used.	

Measurement	Units and measurement notes	Photo/diagram
Road crowning	Unit: Percent Measurement: percentage of road area that contributes flow to drain, varies between 0 (drain ineffective) 25, 50, 75 or 100 (no crowning)	
Drain slope	Degrees, measures on hillslope along a representative section of drain outlet pathway.	
Drain outlet	0= Dispersive, no gully, or gully is less than 30 cm deep. 1 = Gullied, gully greater than 30 cm deep present at drain outlet.	 

Measurement	Units and measurement notes	Photo/diagram
Drain blockage factor	0 = Unblocked, drain is functioning as intended. 1 = Blocked, sediment or debris accumulated in drain and prevent drain functioning as intended.	
Drain bypass factor	0 = Not bypassed, drain functioning as intended and upslope flow is diverted to adjacent hillslope via drain 1= Drain bypassed and upslope flow is diverted around drain and down road.	 

Post-processing field data

This section summarises the desktop GIS based processing steps that transform the field measurements into model inputs. Overall, the postprocessing steps are:

Step 1: Assign RTK point locations and elevations to each drain point (import, join by attribute of point name).

Step 2: Define road segments: a segment is between two topographic high points, or between a topographic high point and a top low (such as a crossing). The workflow used to calculate the distance between drains within a segment, accounting for bypassed drains is outlined below.

Calculating the linear catchment of a road forest drain: Workflow and processes

This document describes the process used to estimate the linear catchment distance for each drain within a forest road (or a segment of it).

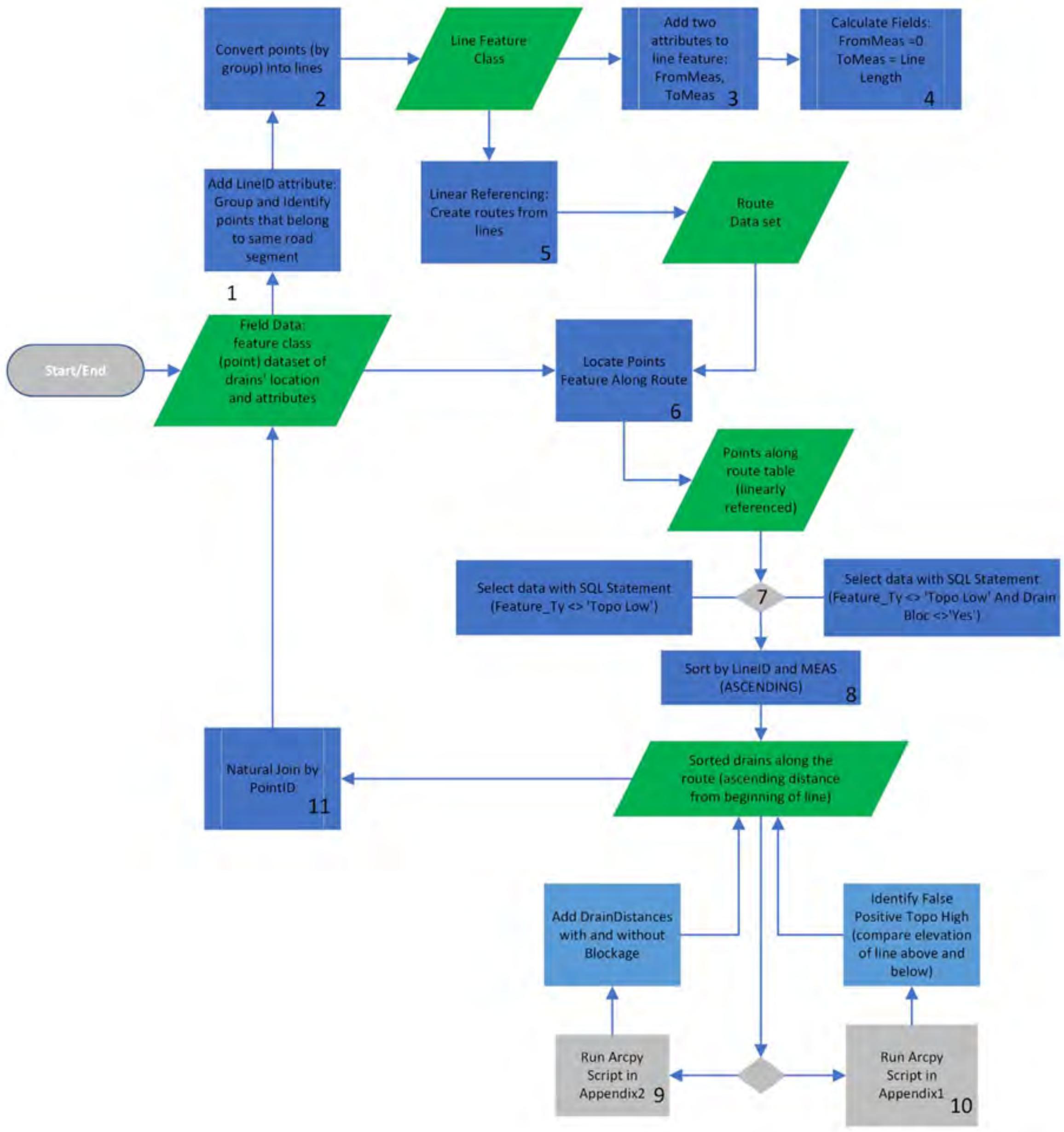


Figure 74. *Workflow and Process*

The workflow and processes implemented and illustrated in Figure 1 below was implemented using ArcGIS Pro version 2.9.3. It is however reproducible using any version of ArcGIS Desktop application currently supported by ESRI, including ArcMap applications (i.e., 10.8 and newer).

Data Requirements:

Input data consist of surveyed drain data (locational data collected in the field) captured as point feature class (spatial point dataset) and the following attributes are relevant for the calculations:

1) Feature Type: classification of point data (e.g., topo high, topo low, drain, crossing)
2) Drain Blockage: yes/no
3) Elevation
4) Sequence order of the drains along road (in this instance, it is identified by point id). If not available, the order will be assigned to the order/sequence of the data entry (i.e., ObjectID) as the true sequence of drains along the road. ***NB:*** *This is important because the sequence of points will be used to create lines connecting the points. Failing to comply with this requirement will create a zig-zag effect of the drains alignment as illustrated in Figure 2.*

Automation
Note that when the number of drains is small, and the number of distance calculations is also small, manually measuring the distance between points along a road may be simplest and fastest. However, when the number of drains is large this task becomes very time consuming. ArcGIS Scripts, which can be implement in ArcMap or ArcGIS Pro, ca be used to automate the steps outlined in this attachment. Scripts automate the drain distance calculations and speed up this step significantly.

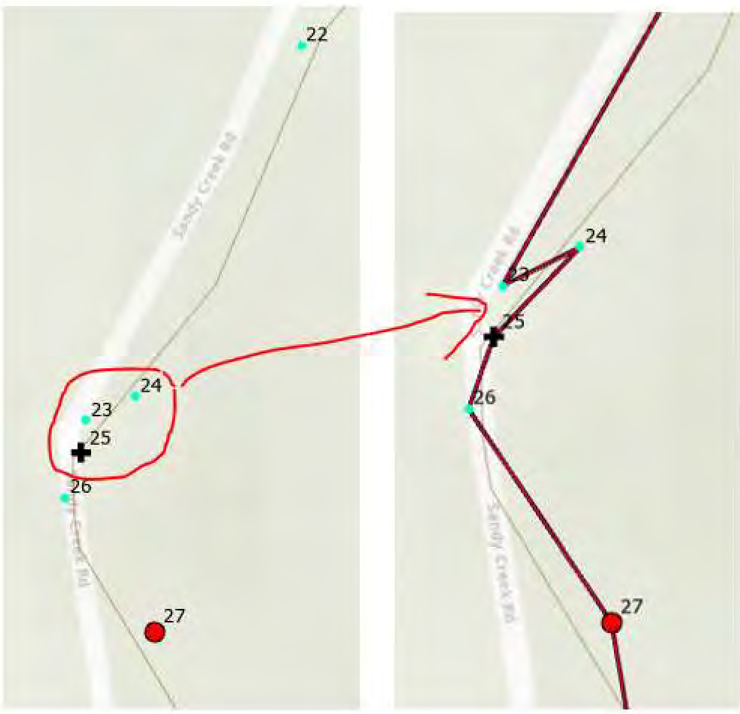


Figure 75. *Understanding data requirements and consequences of fail to comply*

Workflow and Processes description

Please refer to the workflow diagram for the steps taken to derive the drain distance linear catchment.

Step1: Group drains by road (or road segment)

The drain grouping is assigned by detecting sequence of drains along a common road (or segment of), as illustrated in Figure 3.

This must be done by adding a road id or “LineID” as an attribute of the combined point data, as illustrated in the left-hand side of Figure 3.

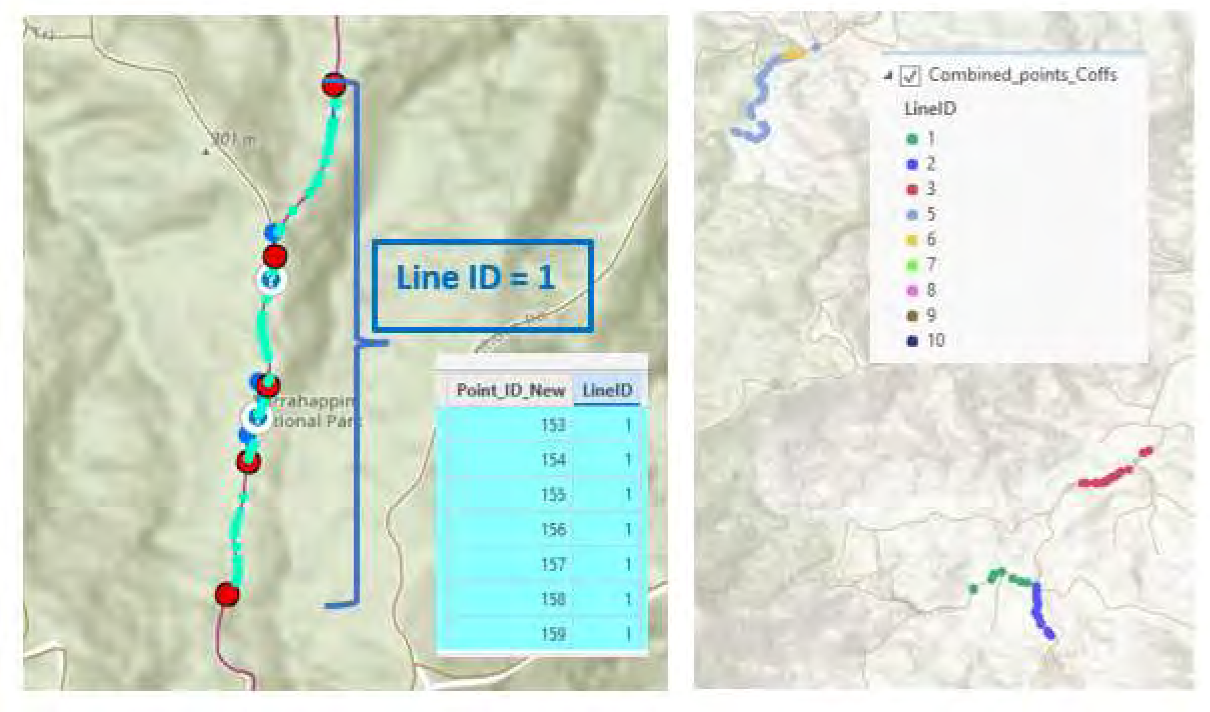


Figure 76. *Identifying Drains by Road*

Step2: Combine points into Lines

Run the “Points to Line” geoprocessing tool of ArcGIS.

- “Line Field” should be set to use the attribute added/created in step 1 above.
- Use the attribute that identifies the sequence of drains along the road. This is option and if not identified, it will default to the sequence of the data (ObjectID). See notes in item 4 of Data requirements.

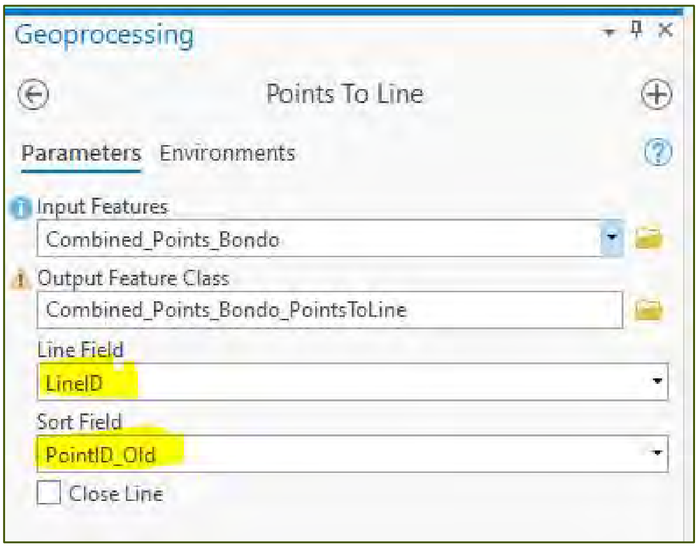


Figure 77. *Step 2 - Convert points to Line in ArcGIS*

Step 3 and 4: Add attributes to the Line dataset and calculate values

Add two attributes (Type DOUBLE) to the dataset generated in step 2 and assign values as specified below. They are:

- FromMeas and assign value zero
- ToMeas and assign the length of the line as value

Steps 5, 6 and 7: Linear Referencing drains along the line

Linear Referencing system is a method of spatial referencing commonly applied in engineering and construction, in which the locations of physical features (in this case drains) along a linear element (say a road, pipe or cables) are positioned relative to the length of the linear element. In our case, we will position the drains along the line (that represents the forest road). Each drain will be assigned a 'MEAS' (i.e. measurement) which is the distance of that drain along the line, relative to the start of the line (from MEAS = 0). Hence, the distance between 2 drains is given by the MEAS difference between these drains. See illustration in Figure 5.

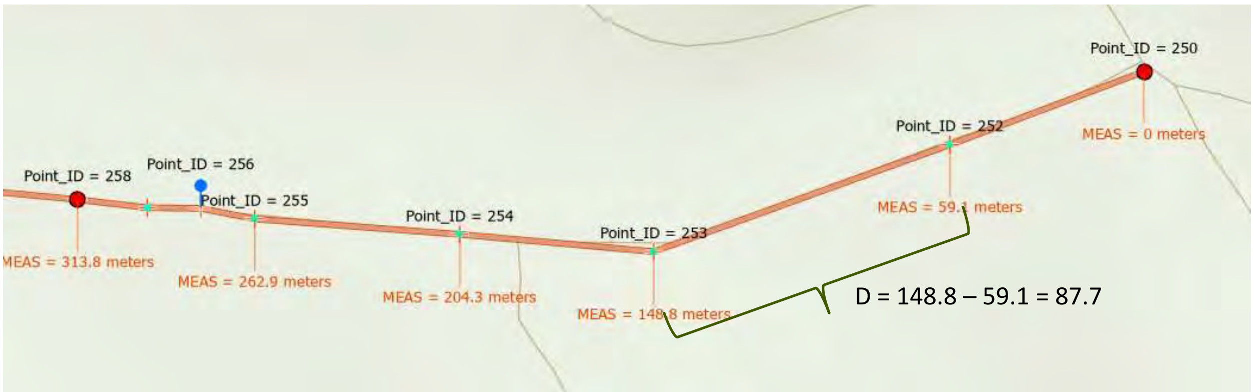


Figure 78. Linear Referencing drains along line representing forest road

The distances between drains are given by the estimates created in step 2. A relative distance measurement for each drain will be given by the distance of each drain to the start of the line (zero mark).

** NB: if the distance between drains along the road is required (as opposed to Euclidean distance then replace the line created in step 2 with the actual road segment).

Step 5: Create Routes from Line – run the geoprocessing tool "Create Routes" from the Linear Referencing toolbox in ArcGIS with the settings illustrated in Figure 6.

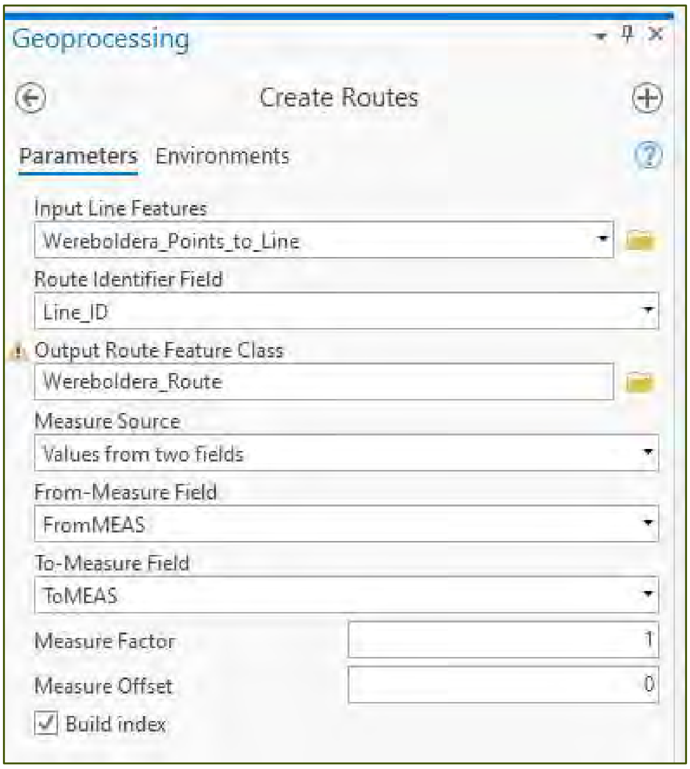


Figure 79. *Create Routes using line data*

Step 6. Locate Features Along Routes: run the geoprocessing tool "Locate Features Along Routes" from the Linear Referencing toolbox in ArcGIS with the settings illustrated in Figure 7.

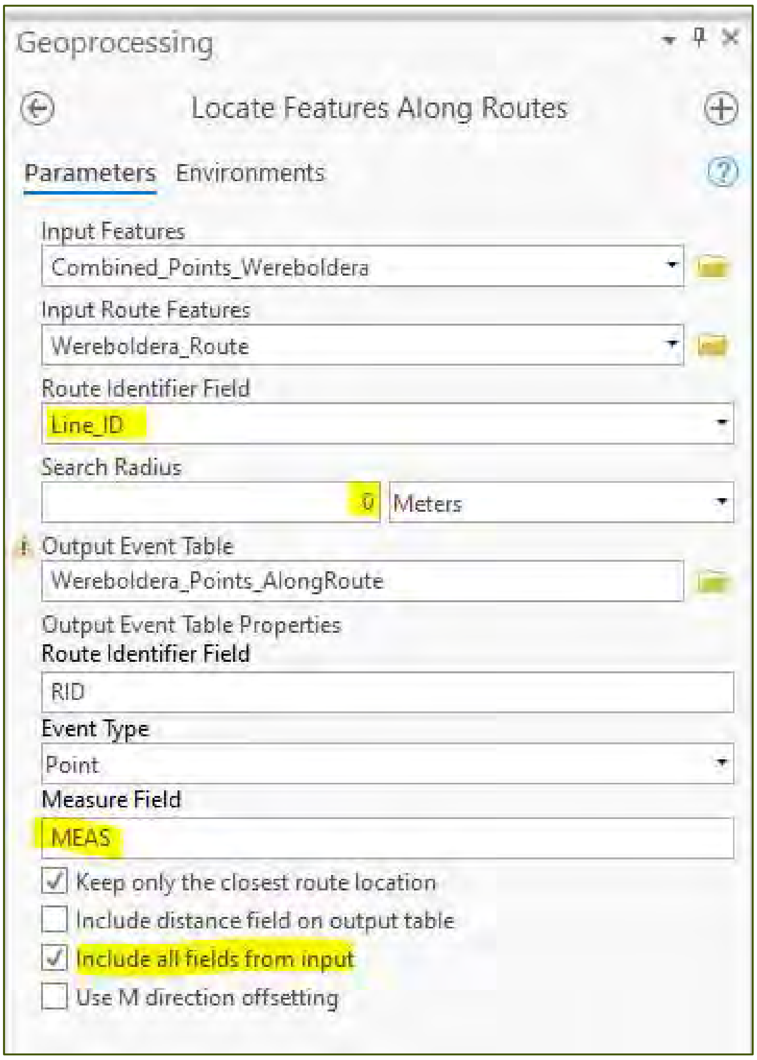


Figure 80. *Locate Features Along Routes geoprocessing tool in ArcGIS*

Step 7: Select drains and other feature types to include in the drain catchment distance analysis.

Linear drain catchment analysis is performed considering 2 scenarios:

1) All drains are considered and distances between them calculated, whether or not the drains are blocked.
2) Blocked drains are eliminated from the analysis to estimate the actual linear catchment of unblocked drains.

For the analysis described in 1) we will eliminate from the output table generated in Step 6 “Topo low feature type, as shown in Figure 8.

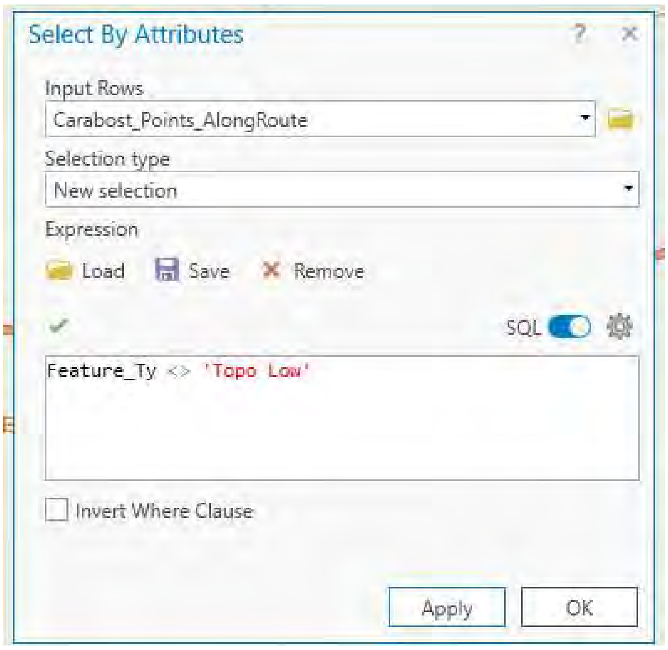


Figure 81. *Features to be included in the drain linear catchment distance*

Step 8: Sort table selection (if applicable). Sort the table by LineID (if applicable) and MEAS in ASCENDING order, as shown in Figure 9.

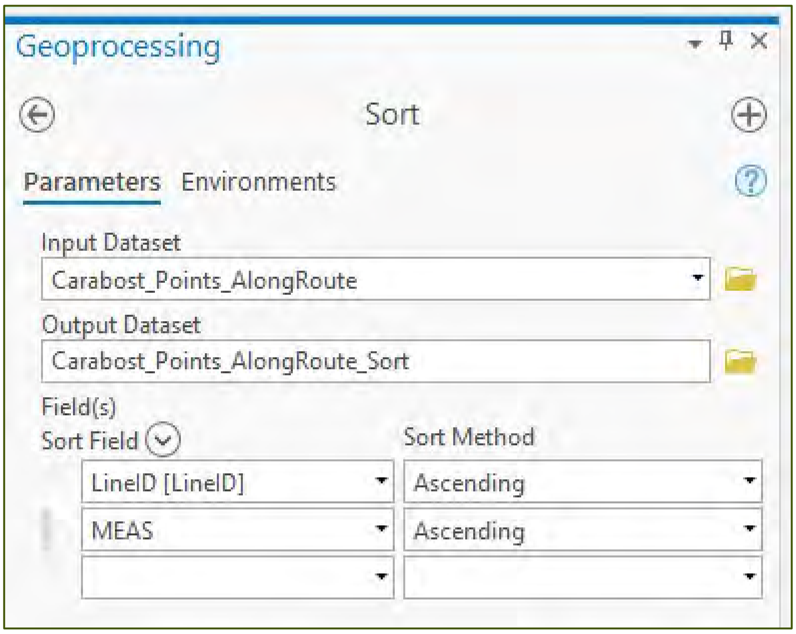


Figure 82. *Sort Table*

Step 9: Calculate the drain linear distance catchment

There is no standard tool within standard GIS systems to generate this output, therefore a script has been developed to execute this calculation specified as per domain expert specification. In summary, the drain linear distance catchment of any given drain/crossing is given by the sum of distances of its adjacent drains, if adjacent drains are at a higher elevation point.

To derive the drain linear distance catchment with observed blocked drains, repeat Steps 7 through 9 with a minor adjustment to exclude blocked drains from the analysis (see Figure 10 for the SQL query to select drains that are not blocked).

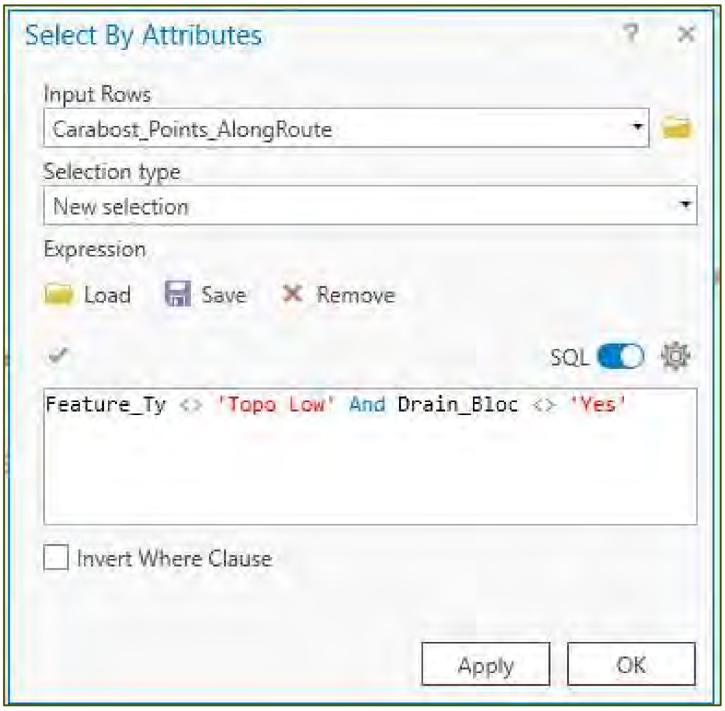


Figure 83. *Drains not blocked*

Please notice that the whole process has been scripted in arcpy for convenience and efficiency. Scripts are available upon request.

Step 10: Additional data check performed:

Verify if points recoded as "Topo High" are indeed at the highest elevation point when compared to the 2 adjacent neighbour points. If not (i.e. any of the 2 neighbours have higher elevation), add a field to the table of attributes "Topo High_Validation" and tag recorded point as "false positive?". See example illustrated in Figure11 below. NB: this process has been automated using arcpy script. Code snippet in Appendix 1.

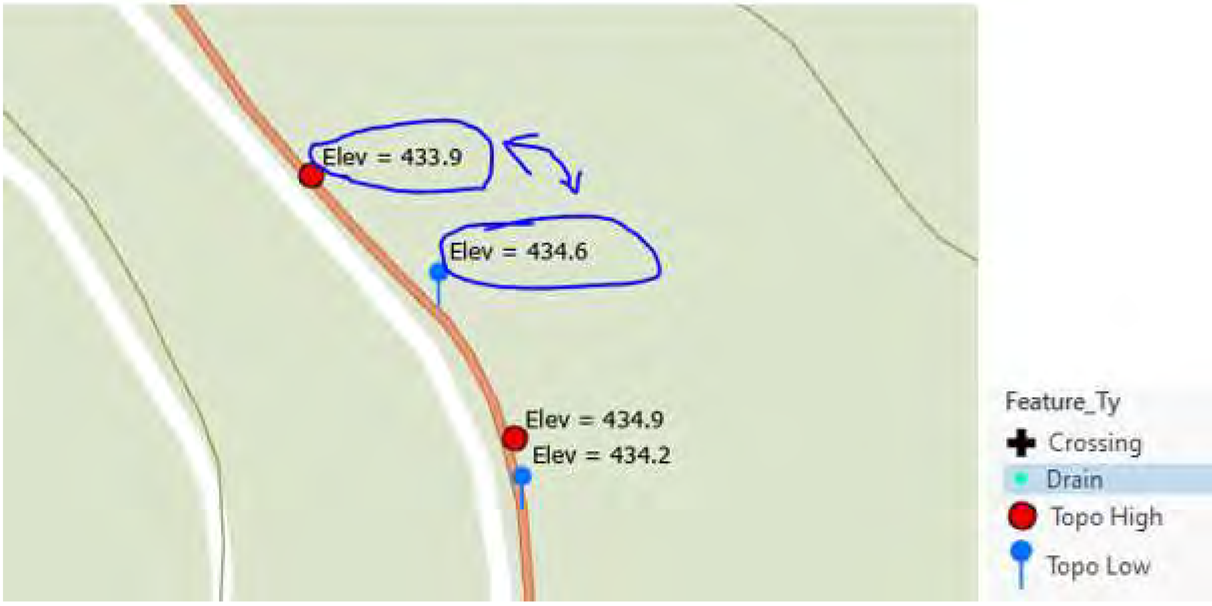


Figure 84. *Example of False Positive "Topo High" – Field Data collection error*

Assign stream distance, rainfall intensity, mean annual rainfall and traffic intensity

- **Assign stream distance values to drains:** The GIS processing step required to calculate the distance to stream value for each drain are summarised in Attachment C. Once the distance to stream raster has been generated, distance to stream values can be extracted where the raster intersects with georeferenced drains, and the distance values assigned to each drain. The most efficient means of assigning the distance to stream data to each drain is to use the 'Add Z information' OR 'Extract surface values' tools in ArcGIS or the equivalent in QGIS.
- **Assign mean annual rainfall and rainfall intensity values to drains:** Mean annual rainfall and rainfall intensity for the nominated storm event (which was set to a 1 year AEP 30 minute duration storm for both the statewide and local sediment delivery model in this project) can be downloaded from the BOM website by uploading drain points as a csv - http://www.bom.gov.au/water/designRainfalls/revised-ifd/. Note that there is a limit of 50 csv point per upload and if a large area with many drains are being surveyed., using the option to download gridded data and then extracting rainfall intensity values from the grid may be more efficient. Mean annual rainfall values can be obtained by first downloading gridded mean annual rainfall data for the region of interest from the BoM: http://www.bom.gov.au/climate/averages/climatology/gridded-data-info/gridded-climate-data.shtml, and then extracting the mean annual rainfall values from the grid to each drain using the 'Add Z information' OR 'Extract surface values' tools in ArcGIS or the equivalent in QGIS
- **Traffic intensity:** has been assigned using simple relationships between road width and the assumed number of trucks in the statewide model. For the purposes of the local model, an average value of 90 axles per week was chosen for the demonstration pilot. Users can set whatever traffic intensity value is most appropriate for the local area and types of roads surveyed. The traffic intensity value is assigned in the excel model and is straightforward to change.