DRAFT METHODOLOGY RECOMMENDATION:

Evaluating forest road networks to protect water quality in NSW

November 2020

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1 General 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.

2 Methodology recommendation

2.1 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[2], has been shaped by the feedback received from the technical panel review, steering committee meeting, and stakeholder workshop.

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.

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

2.2 Linking model implementation, field assessment and monitoring

The program includes two key parts outlined in separate section below.

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.

Field assessments to identify opportunities for improvement

Field assessments to collect data (model parameters and sediment delivery hazards) for identifying problematic parts of the road network and d*etermine how elements of road design and maintenance can be improved* to reduce sediment delivery. 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.

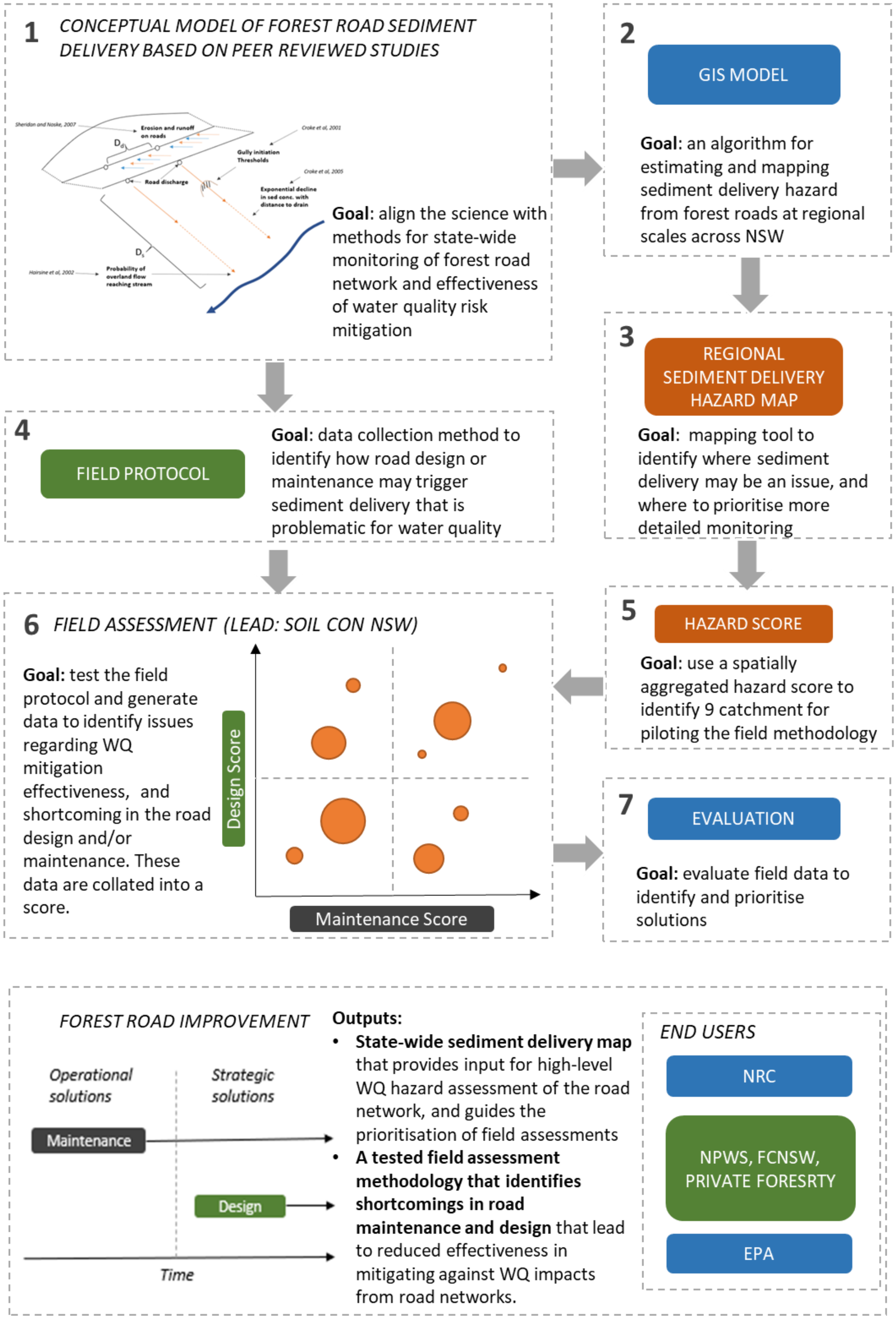


Figure 1. *Linking model implementation, field assessment and monitoring*

2.3 Task outline for field assessments

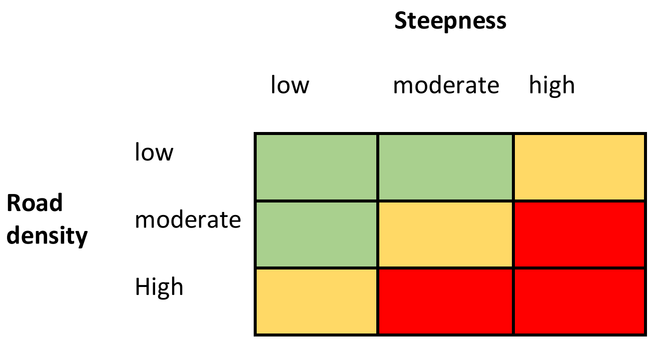
1. **State-wide mapping of sediment delivery hazard from forest road network**

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)

2. **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 1). For the field reconnaissance, 2-3 contrasting catchments will be selected.

Table 1. Matrix illustrating the link between topography, road density and sediment delivery hazard.



3. **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 2)?
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 2. 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.

6. 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 1 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 leads 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.

7. 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.

8. Field Survey and Demonstration Pilot

The field assessment will be led by Soil Conservation Service (Kurt Laboyrie).

9. Pilot documentation

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

3 Key considerations in development of methodology

3.1 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.

3.2 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.

3.3 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 2). 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.

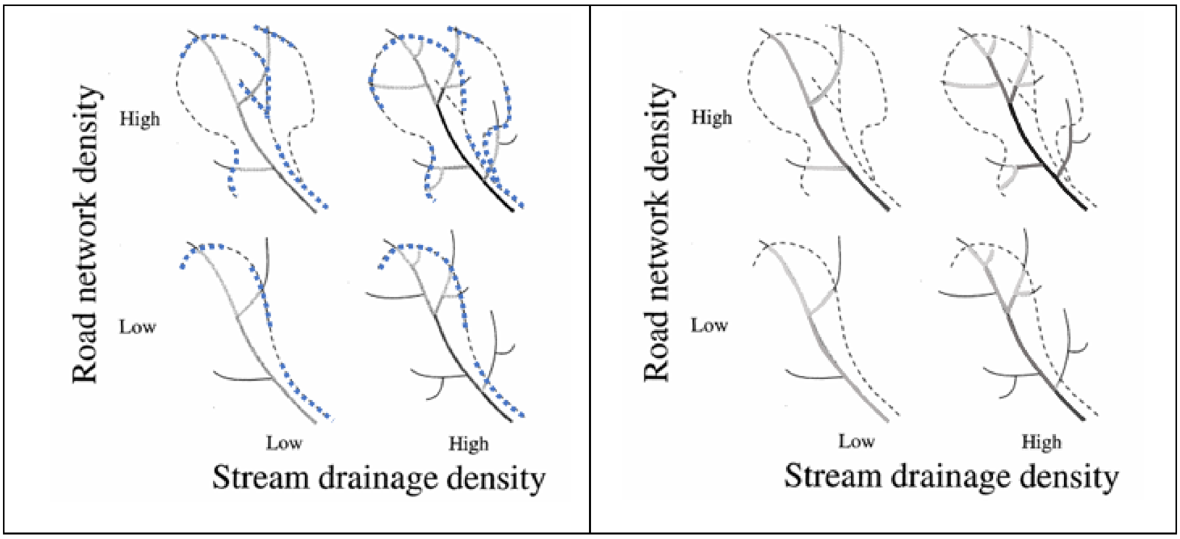


Figure 2. *Spatial association between drainage network and road networks provide a high-level indicator of potential road impacts on sediment delivery to streams. (left) Effect of increasing draining densities of the road network (dashed lined) and the stream network (solid line) on the number of road-segment 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).

3.4 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).

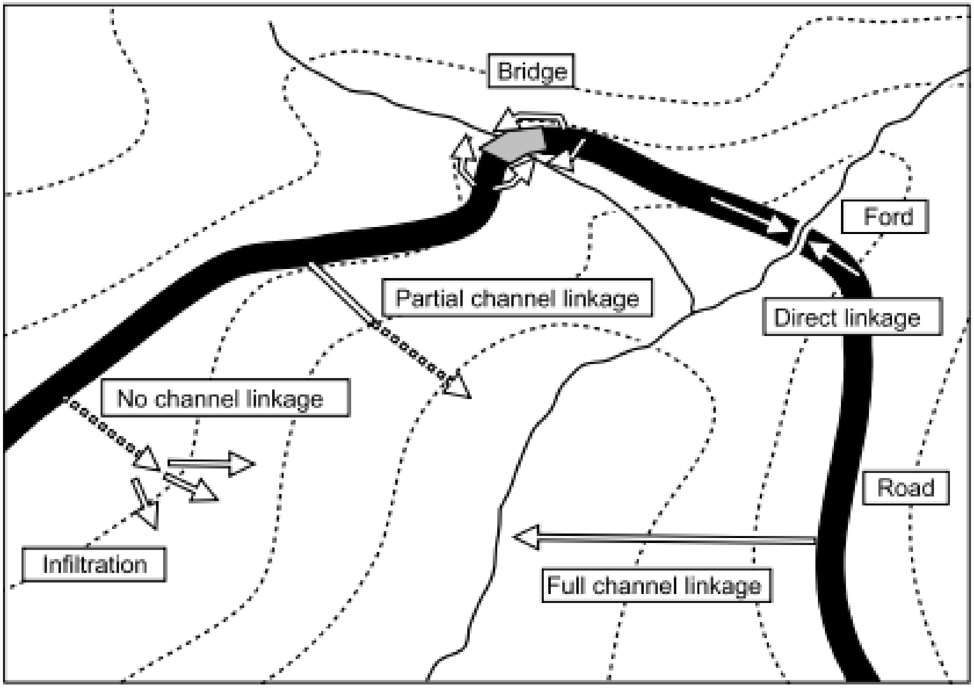


Figure 3. *The range of potential linkage categories within a forested catchment - from full channel, partial channel, and no channel linkage, to the direct linkage that occurs at a ford or bridge crossing. These categories can be used to determine the degree to which major sources like roads and tracks, are linked to stream (Croke et al, 1999).*

4 Sediment delivery model

4.1 Model overview

The conceptual model in (Figure 4) 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)

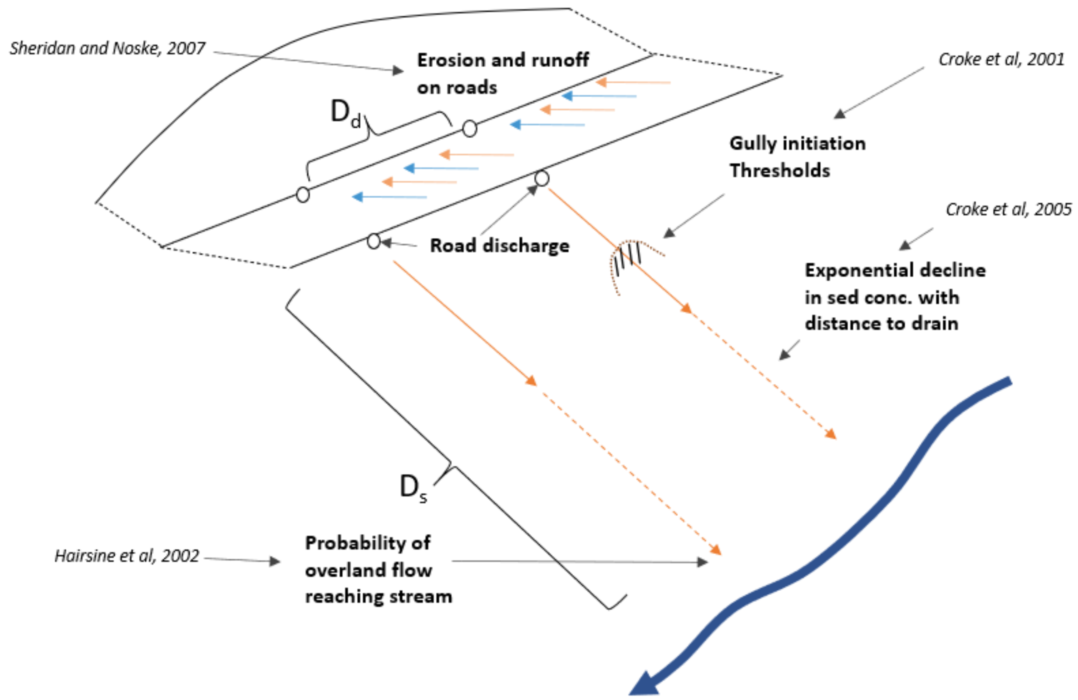


Figure 4. *How each key process relates to one another in the conceptual model*

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).

4.2 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 5).

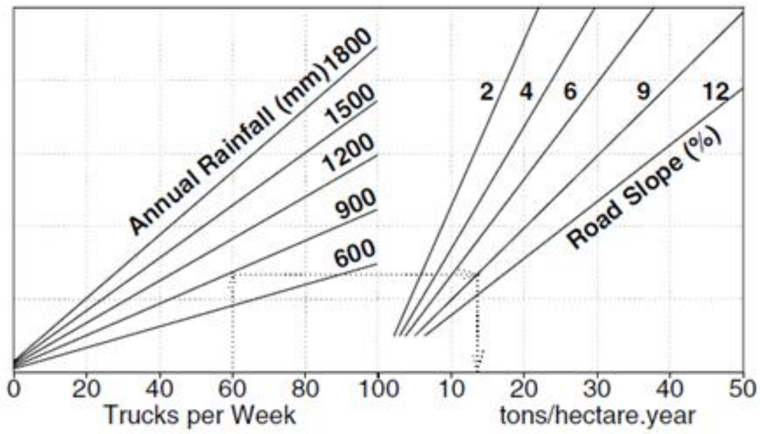


Figure 5. Nomogram for estimating the annual sediment load from gravel surfaced forest roads.

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.	

4.3 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 6).

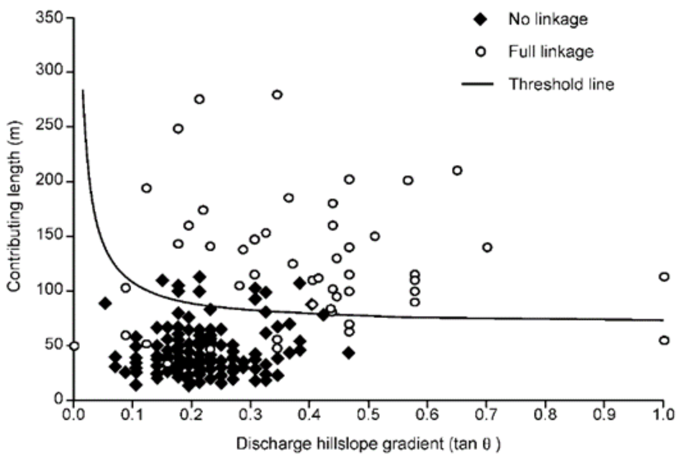


Figure 6. *Fitted threshold curve separating channelled and non-channelled road drains for the study area (Croke and Mockler 2001).*

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	

4.4 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 7).

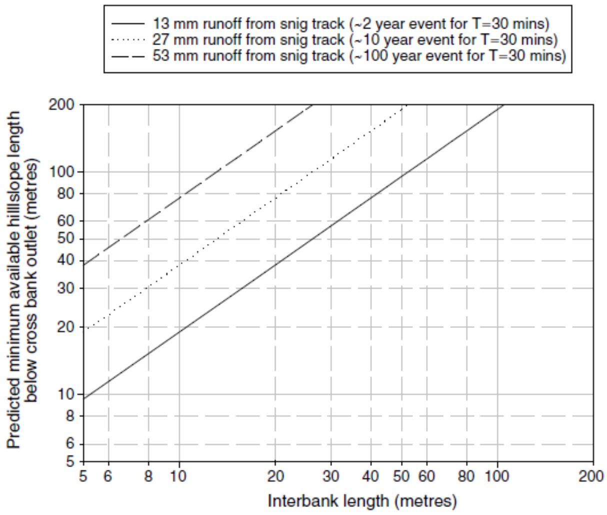


Figure 7. *An example of how interbank length performs under three different runoff rates. The greater the interbank or outlet spacing, the greater the length of drainage pathway required to avoid delivery to stream.*

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).

4.5 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 8). These relationships can be utilised to estimate the sediment concentration of plumes as they reach and or breakthrough to the stream.

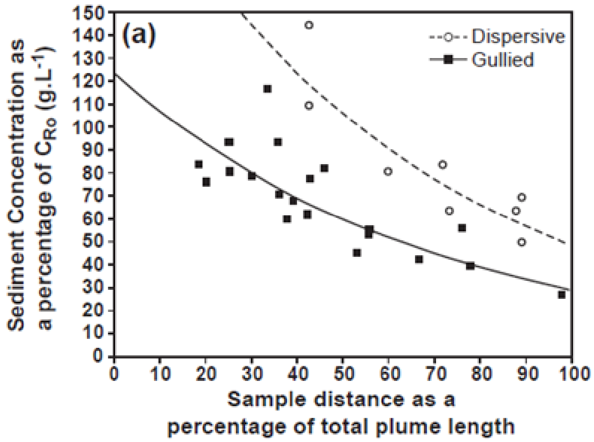


Figure 8. *The exponential relationship between initial sediment concentration for both dispersive and gullied pathways (Croke et al, 2005).*

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	

5 GIS implementation

5.1 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 9):

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.

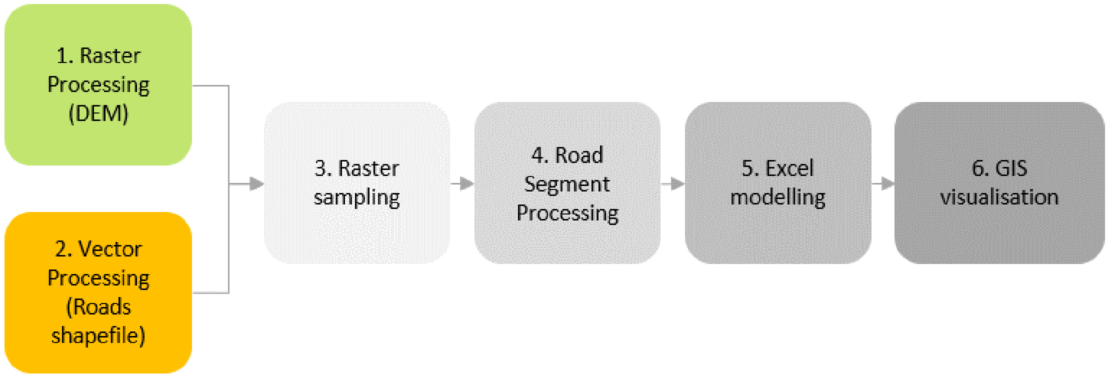


Figure 9. *An overview of the stages of data processing*

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.

5.2 GIS implementation: example outputs

To **demonstrate the model applications, the GIS workflow was implemented for section of Yarriabini National Park using the National Park Roads Dataset where roads were assigned widths of 5-8m, traffic set to 20-50 trucks** per week **and roads** surface **is gravel or** natural **earth. These values are assigned based on road type and are used for demonstration purposes only.** The model was implemented using a 1 in 10-year storm event.

There are four output from the modelling, shown in Figures 10-13:

- Sediment produced by road segment (t/ year) (Figure 10)
- Gully threshold exceedance (Y/N) (Figure 11)
- Volume of runoff reaching stream (m3) (Figure 12)
- Sediment delivered to streams (kg) (Figure 13)

This is a preliminary test run of the modelling approach for a small area and we have not evaluated the results in terms of how they correspond with literature values. The average sediment delivery (per unit areas of road) from the road network for a 1 in 10-year event is 3.4 tonnes per hectare. The maximum sediment delivery rate is 19.4 tonnes per hectare. As a first pass, these results appear to be in the right ballpark given published values from Sheridan and Noske (2007b) that show mean annual sediment yields from road crossing of 15.8 tonnes per hectare of road. A method for model verification will be developed in the next stages of the project.

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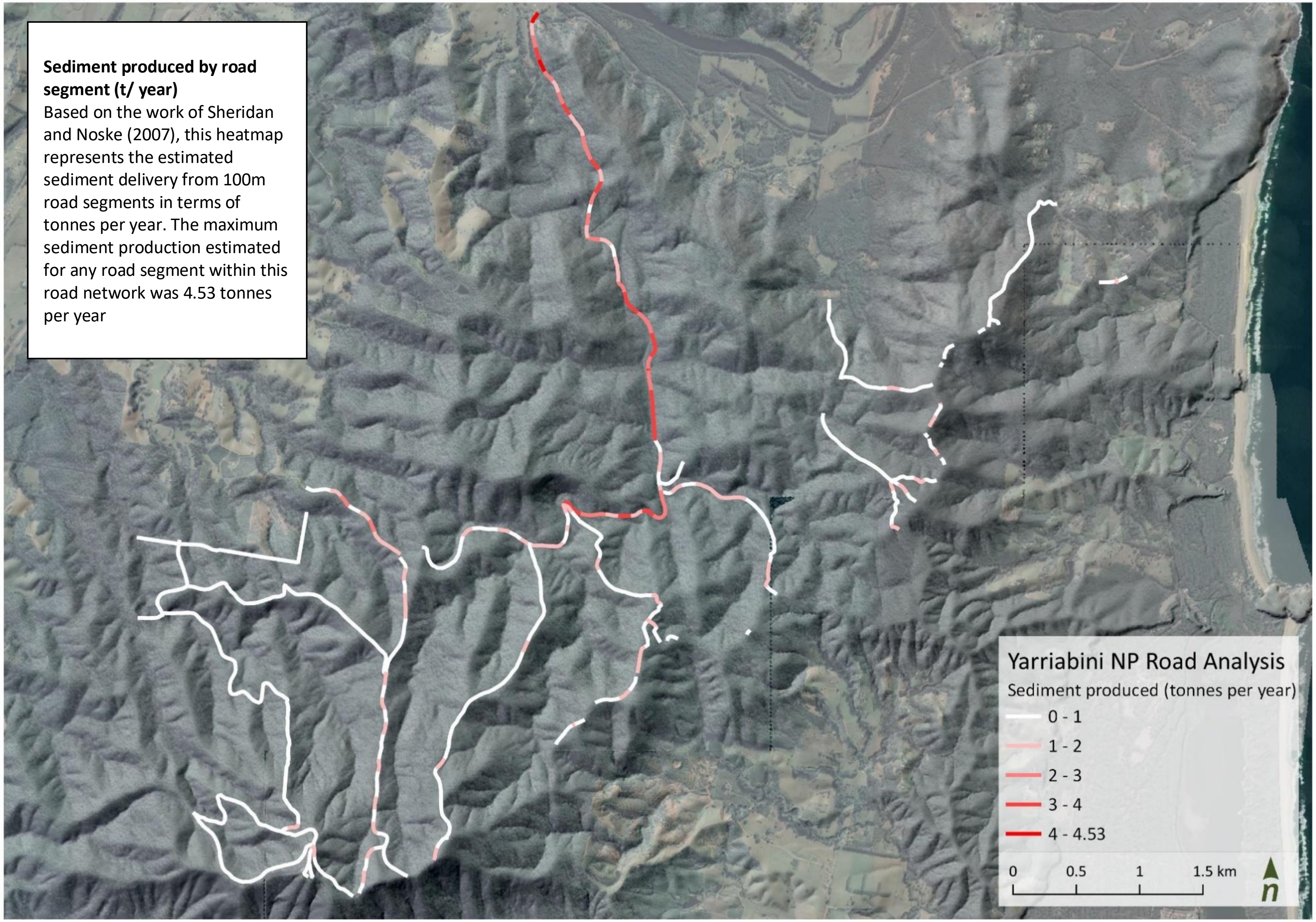

Figure 10. *Sediment produced per 100m segment of road in tonnes per year*

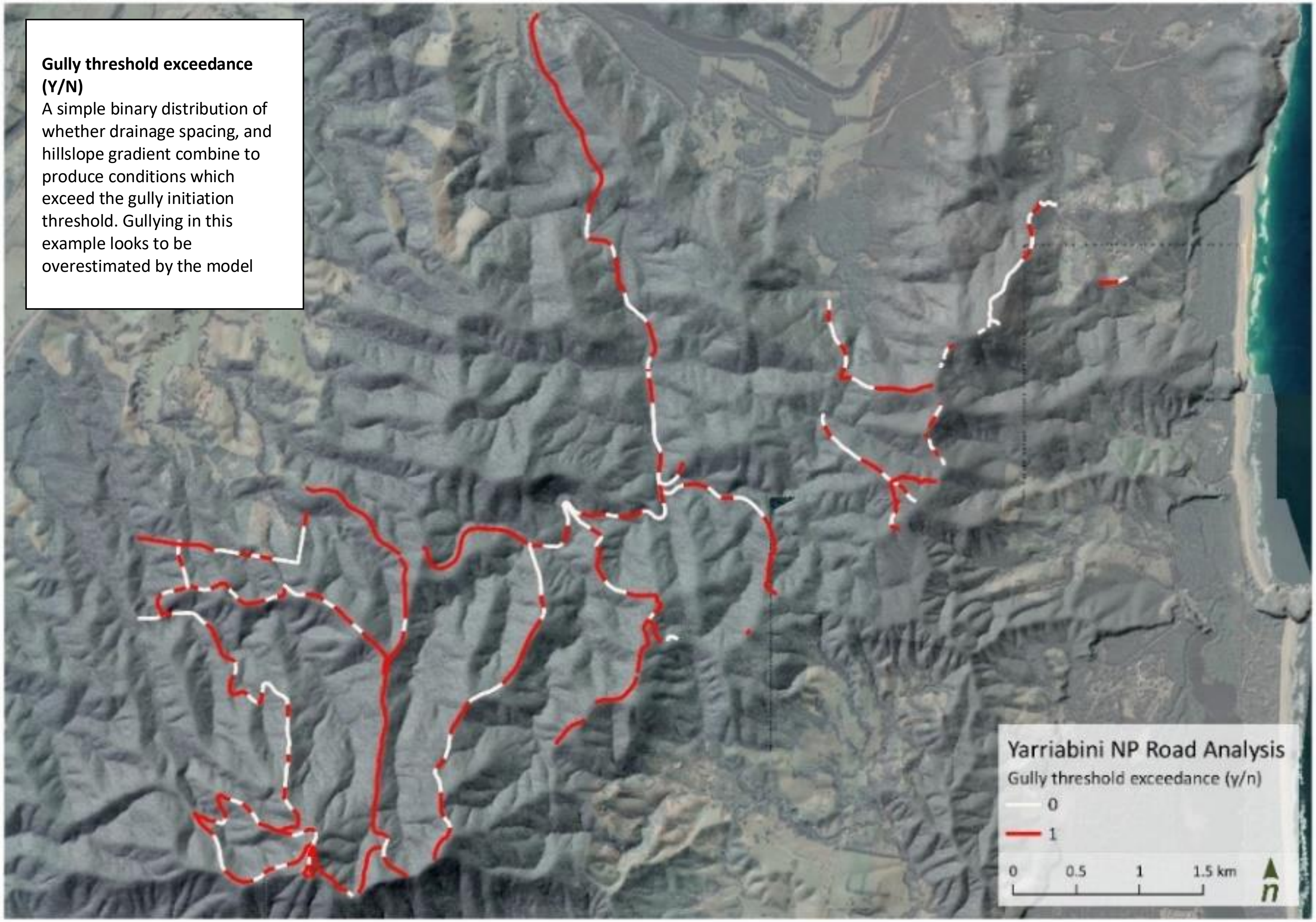

Figure 11. *A binary indicator of where the parameters associated with each 100m road segments exceed the gully initiation threshold (1 = yes, 0 = no)*

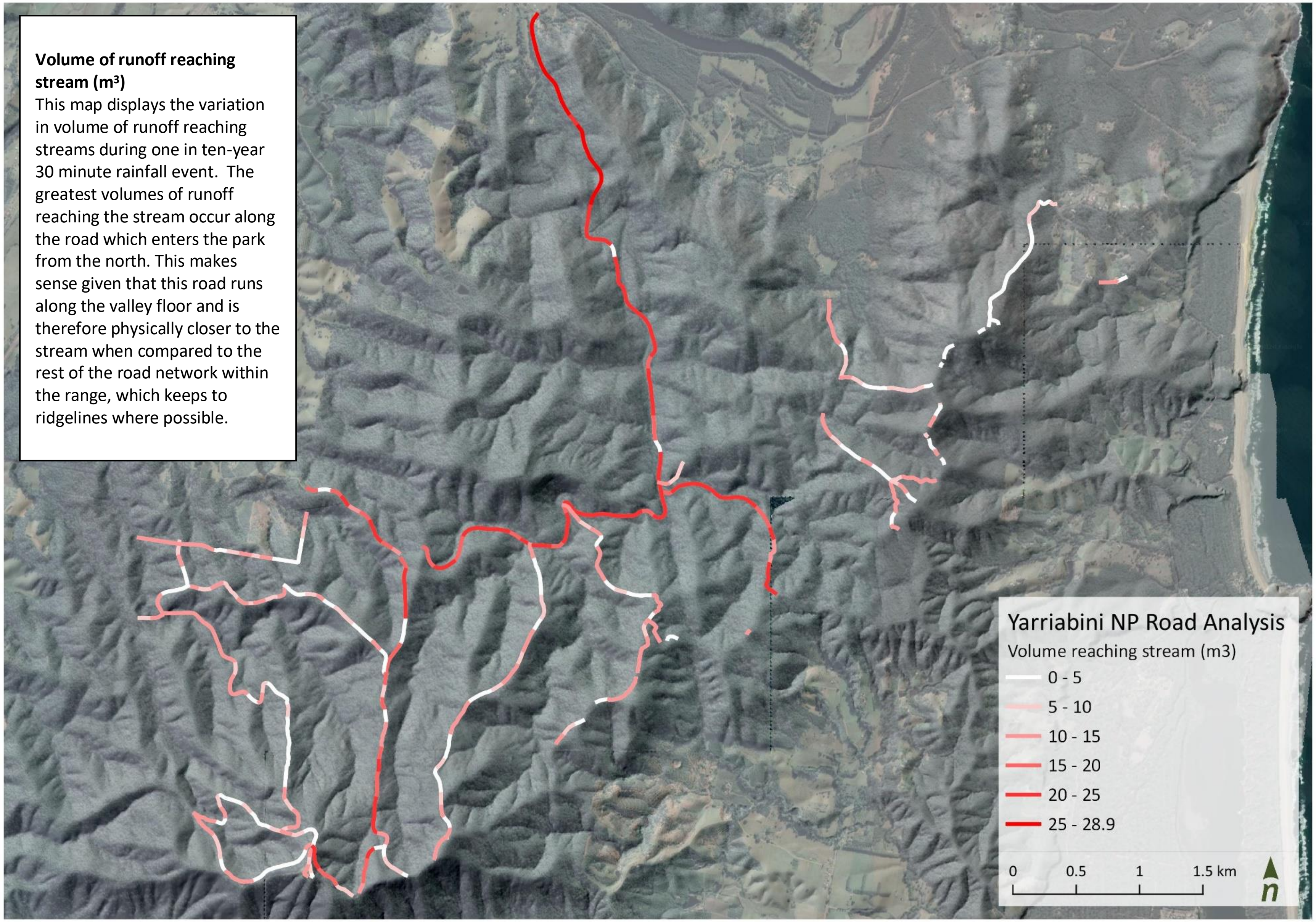

Figure 12. *Estimated volume of runoff reaching the stream during 30 min one in 10 year.*

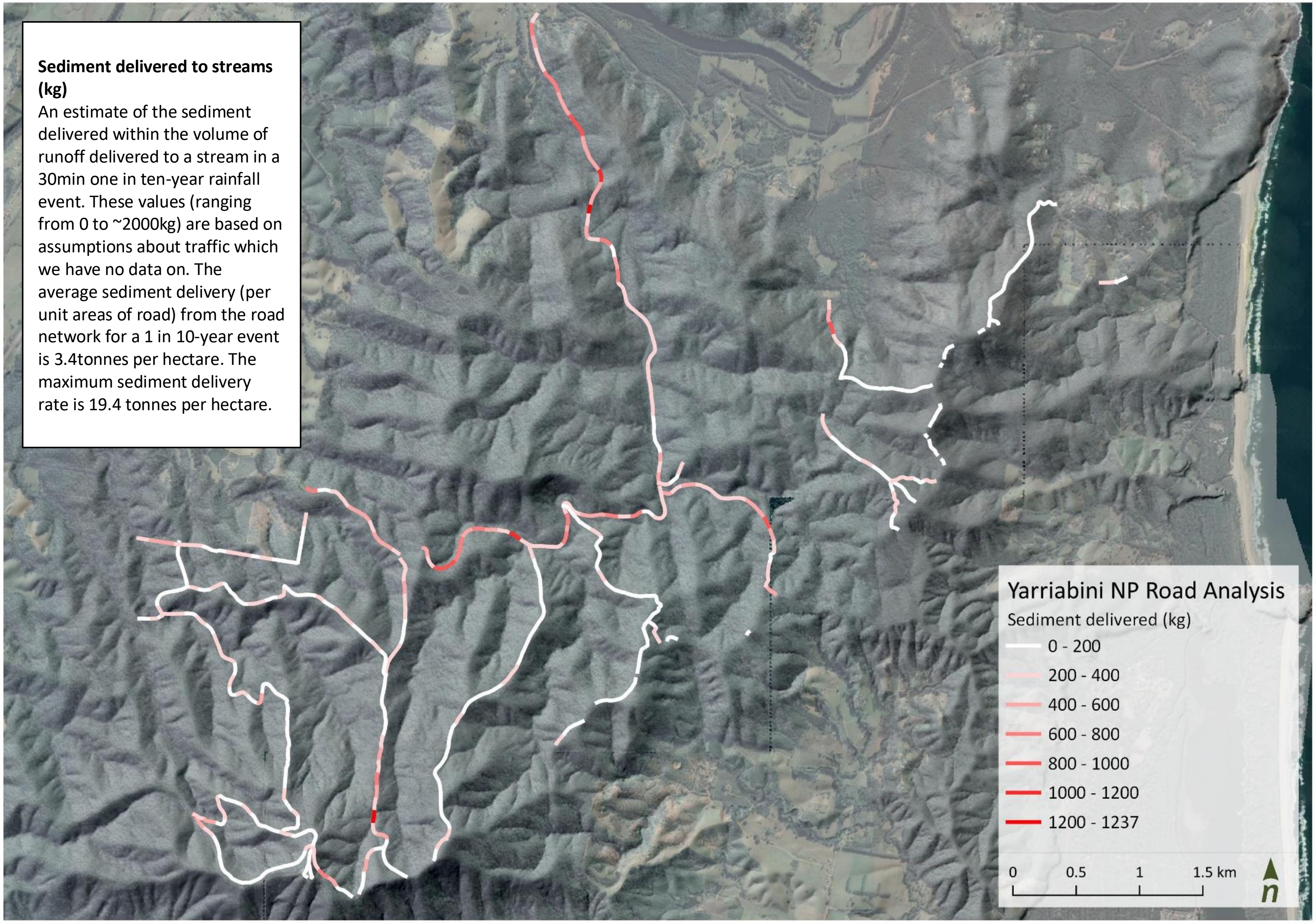

Figure 13. *An estimate of the sediment delivered within the volume of runoff delivered to a stream in a 30min one in ten-year rainfall event.*

5.3 What Next

Following NRC's review of the proposed methodology above, we envisage the following actions to proceed. These are largely in line with those outlined in Section 2.3:

- Update the methodology as per the recommendations made by NRC
- Rank a selection of accessible forest road catchments in terms of road density and their steepness
- Select two contrasting catchments for field reconnaissance
- Derive a sediment delivery hazard map for the two catchments using the proposed model
- Development of a field checklist for the field reconnaissance
- Conduct field reconnaissance to answer questions listed in Section 2.3.3

6 References

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Attachment A: Inputs and outputs

Table 3. Description of INPUT parameters utilised in the proposed methodology

Parameter	Category	Unit	Source/Derivation	Assumption(s)	Field Verification
SRTM 1 Arc Second Global	Terrain	Degrees (WGS84)	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	Ascii grid	http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp		
Rainfall intensity	Climate	mm/0.5 hours	http://www.bom.gov.au/water/designRainfalls/ifd/ (one in 10-year event)		
Terrain Slope	Terrain	degrees	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 the downstream slope.	Does taking the mean slope over a 100m length (+ 10m buffer) adequately capture downslope gradients near stream crossings? Difficult to field verify efficiently.
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	Road width may need verification if the road classification criteria are not reliable, considering differences in management and practice from region to region, park to park.

Drain spacing	Road attribute	metres	Drain spacing polices/guidelines for NPWS	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	Drain spacing requires field verification. Could be done initially by drive-by GPS way pointing. A more efficient means may be by car-based LiDAR. Anecdotal information from road maintenance/management may also be useful.
Traffic intensity	Road attribute	Number of trucks	Intensity is an arbitrary estimate based on road type: 20 trucks per week for 4wd roads and 50 for 2wd. Traffic intensity datasets are likely to be available for National Parks. Other proxies for intensity may be possible through a discussion with agency reps	The values currently attributed are arbitrary and require revision.	Traffic monitoring devices are relatively low cost and easy to set up, potential for the pilot study. Anecdotal information from road maintenance/management may also be useful.
Road Slope	Road attribute	rise/run	Calculated by taking the height of road segment endpoints as per the SRTM DEM	100m distances for slope measurements are fine scale enough	In some cases, especially at stream crossings, the variability in slope may not be captured as only the endpoints of each segment are used to calculate slope. Is there a need to determine slope more consistently around stream crossings at a resolution greater than 100m? As this is where connectivity is the greatest.

Distance to stream	Road attribute	metres	TauDEM processing of SRTM DEM using the Distance to Streams tool. The tool requires both a stream raster (Strahler order) and D8 flow directions	Need to agree on what constitutes a stream. Follow IFOA conditions? Check data with Forest NSW	This will be difficult to determine in the field considering time constraints. The DEM and the processing is robust enough to not require verification of this critical parameter, providing that there is agreement on stream/distance threshold
Axels per week	Road attribute	Variable	A calculation based on number of trucks	We assume there are 9 axles per truck	A distribution of vehicle types, perhaps based on traffic monitoring data or local knowledge, could provide for higher resolution estimations of the number of axles per (truck/vehicle).
Infiltration rate	Hydrology	millimetres/hour	From Croke et al 2006		
Volume to breakthrough vbt5	Hydrology	m^3	From Hairsine et al 2002		
				What about roads which are depressed within the landscape, leading to a larger 'contributing area'?	
Area threshold	Hydrology	m^2	Based on a calculation with a constant as derived in Croke and Mockler		

Table 4. Description of outputs produced and utilised as part of the proposed methodology

Parameter	Category	Unit	Source/Derivation	Assumption(s)	Field Verification

Slope adjustment factor	Output	constant	Sheridan and Noske 2007		
Sediment delivery	Output	tonnes/Ha/year	Sheridan and Noske 2007		
Volume	Output	m^3	Calculated using the rainfall intensity, infiltration rate and the area of road segment	Using infiltration rate from (Croke et al 2006)	
Predicted mean volume of overland flow reaching stream - dispersive	Output	m^3	Based on dV/dL = 0.065		
Predicted mean volume of overland flow reaching stream -gullied	Output	m^3	Based on dV/dL = 0.065 and a 3X increase in plume length with gullies (Croke et al, 2005)		
Mean plume length dispersive	Output	m		Contains a constant	
Mean plume length gullied	Output	m		Contains a constant	
Gully (y=1 & n=0)	Output	constant	If the road contributing area and slope exceeds a certain threshold then a gully (1) is attributed, if not then (0), no gully.	(Croke and Mockler)	
Road contributing area	Output	m2	Length of the road segment (100m) and road width (as above)	It is assumed that the contributing area is only the road itself, however it is more likely that the area includes part of the drainage pathways either side of the road as well as the cut slope, if there is one.	Road width will need to be verified in the field, perhaps some adjustment mechanism to be included to account for extra catchments.

Road surface area	Output	Ha	The above road contributing area value converted to Hectares	As for Road Contributing Area	As for Road Contributing Area
Sediment generation	Output	tonnes/year	Utilises the sediment delivery values from the Sheridan and Noske calculations and multiplying them by the Road surface area.		
Sediment generation	Output	grams/year	Conversion of above value		
Initial sediment concentration	Output	grams/litre	Based on the above value divided by the width of the rad and a constant derived in Hairsine et al., 2002.		
Percentage of plume length -gullied	Output	%			
Percentage of plume length dispersive	Output	%			
Sediment concentration at stream - gullied	Output	Kilograms/ m^3	Based on exponential decay functions derived in Croke et al., 2005.		
Sediment concentration at stream - dispersive	Output	Kilograms/ m^3	Based on exponential decay functions derived in Croke et al. 2005.		
Sediment delivered	Output	kg			Water quality monitoring of specific outlets of pilot site catchments can, if utilised in conjunction

Attachment B: Processing steps

The processes contained within the six-stage approach as outlined in Figure 9 are detailed in the following flow diagrams (Figure 14 toFigure 18). 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.

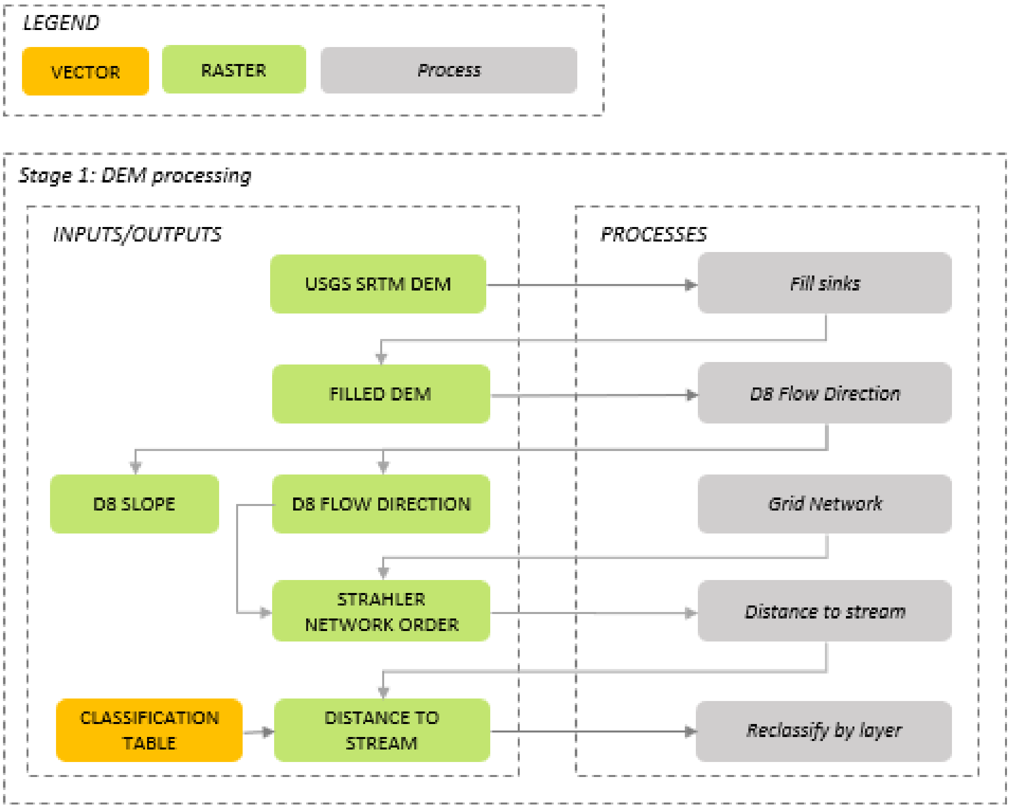


Figure 14. *Stage 1 outlines the process of condtioning the Digital Elevation Model to calculate distance to streams.*

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.

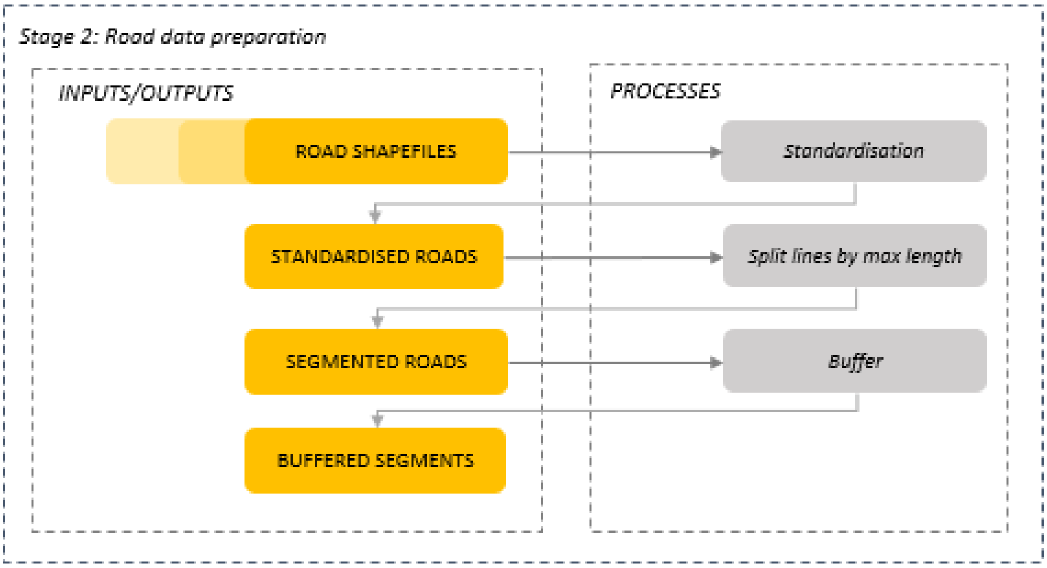


Figure 15. *Stage 2 prepares the road vector file into segments and buffer zones for subsequent stages.*

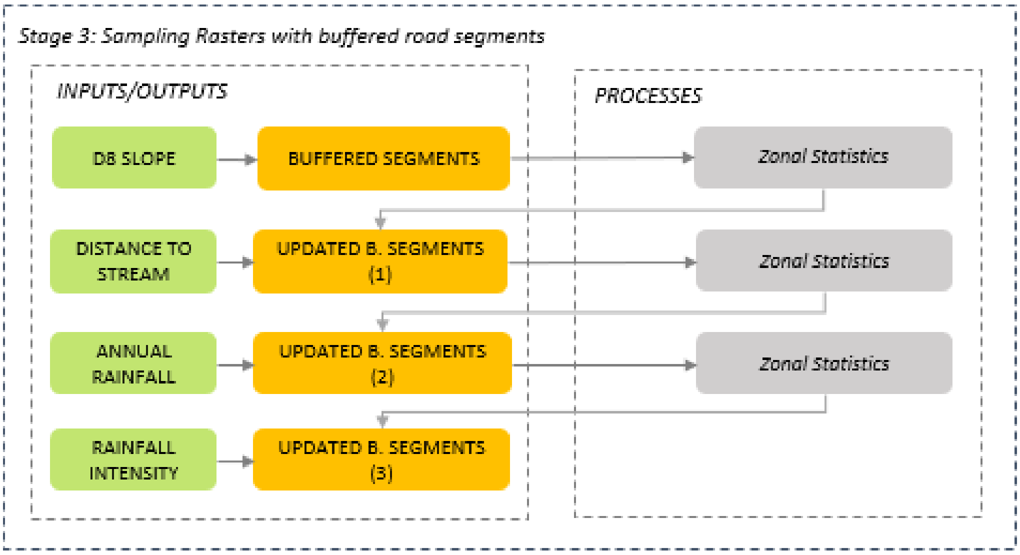


Figure 16. *Stage 3 utilises the zonal statistics tool to gather the mean values of raster datasets for each buffered road segment.*

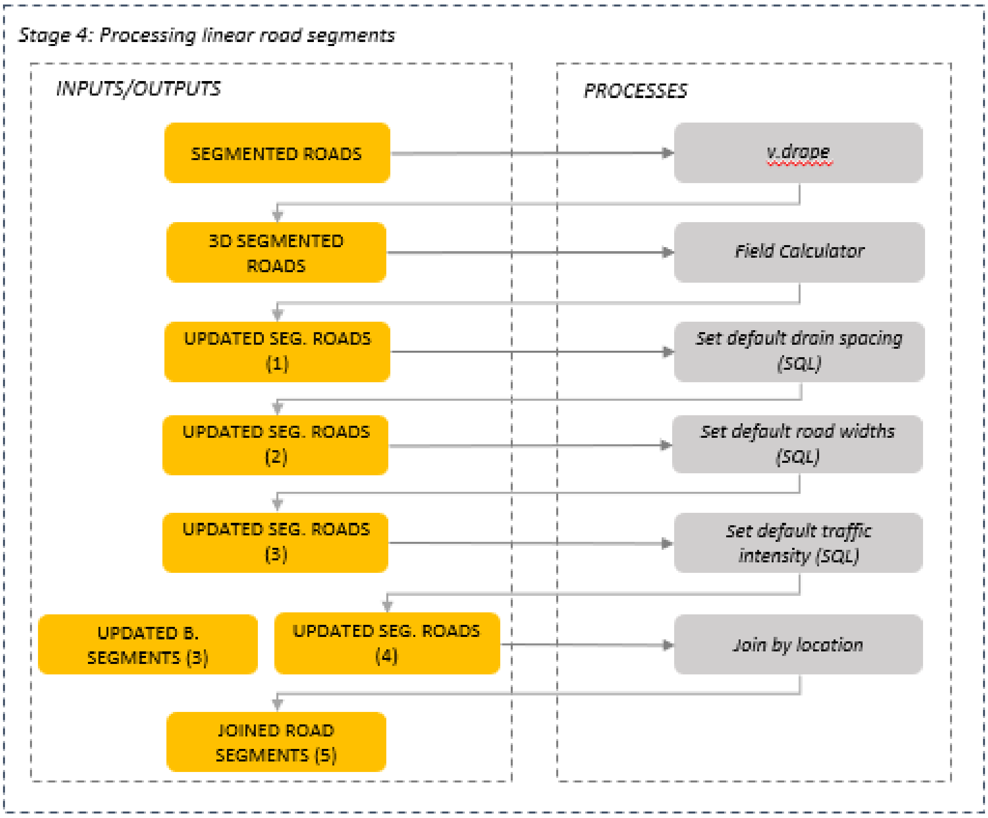


Figure 17. *Stage 4 takes the segmented road lines and poplulates their attribute table with key parameters, including those from the buffered road segments, which sampled the raster datasets.*

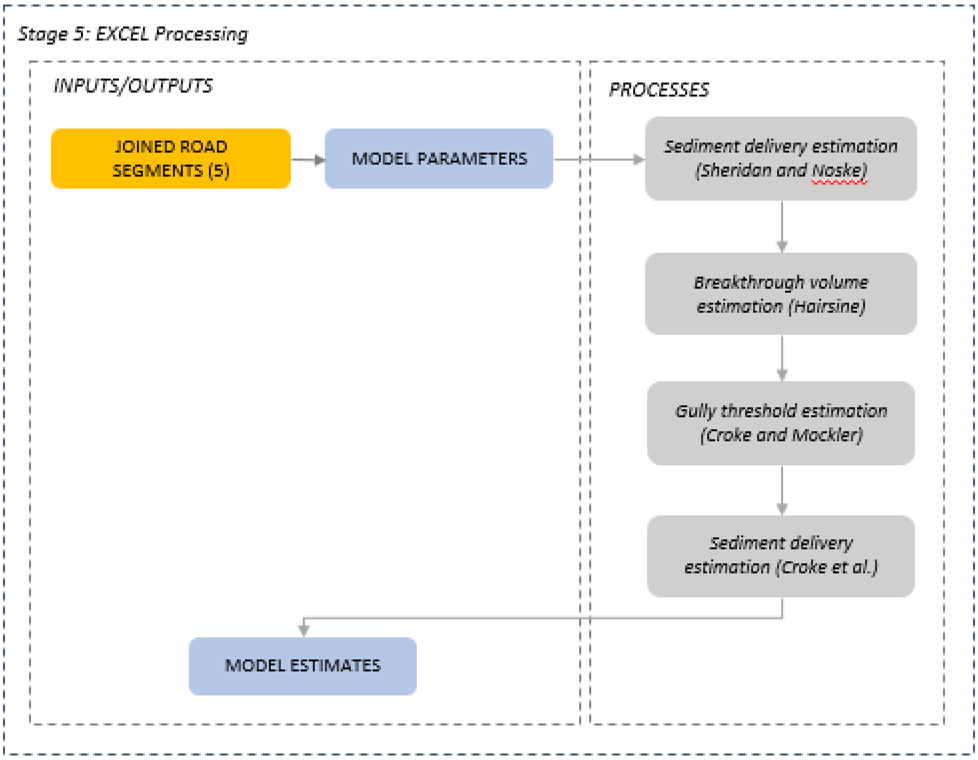


Figure 18. *Stage 5 takes the attribute data from the parameterised road segments shapefile into Excel to feed the model equations sourced from the literature mentioned.*

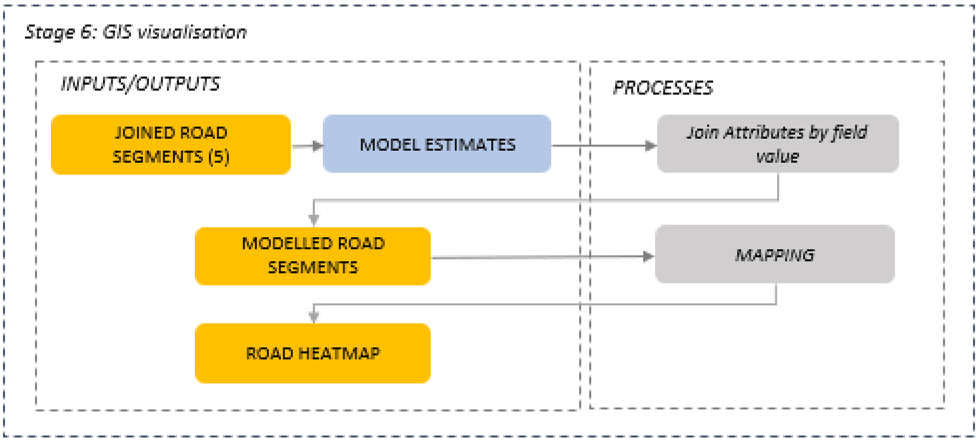


Figure 19. *Stage 6 joins the processed model outputs and reintegrates them with their corresponding road segments in GIS to produce a heatmap of modelled values.*

Attachment C: Detailed workflow in QGIS

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 20) and described in the main document.

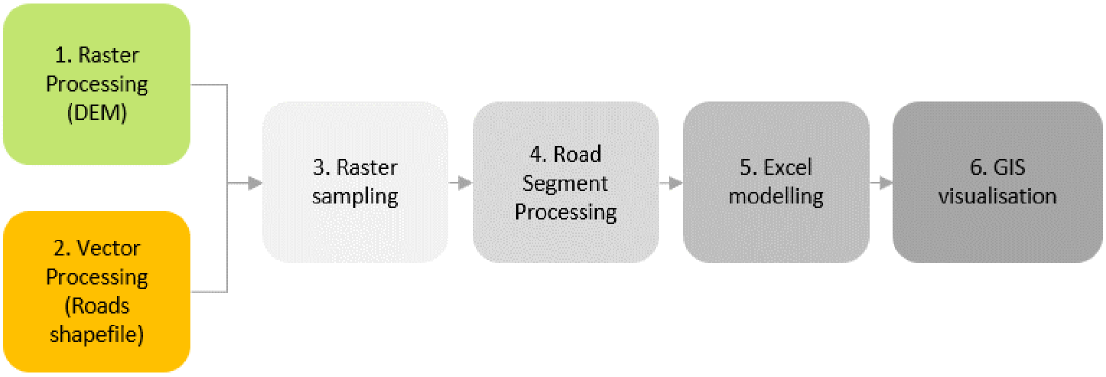
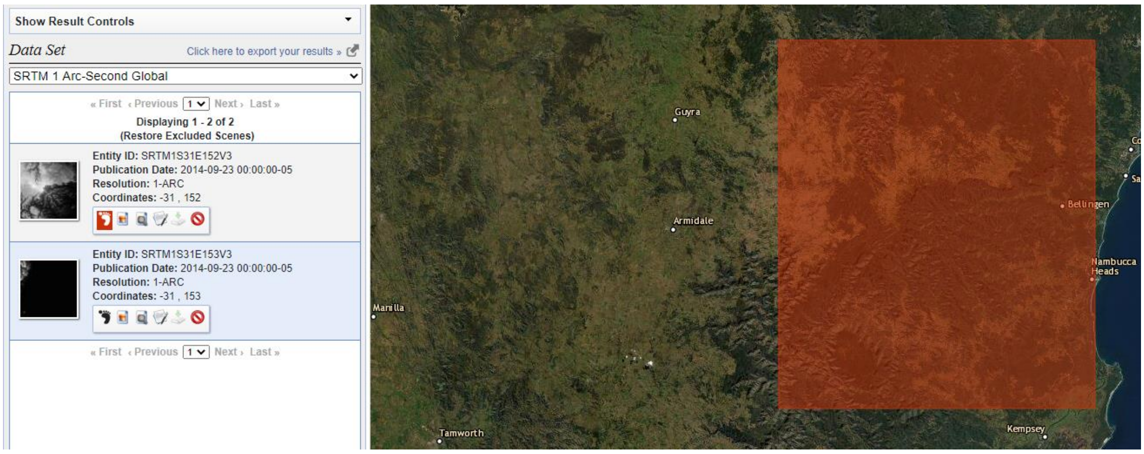


Figure 20. *Processing stages*

1 Raster Processing

1.1 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 util you have produced your final product. 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.

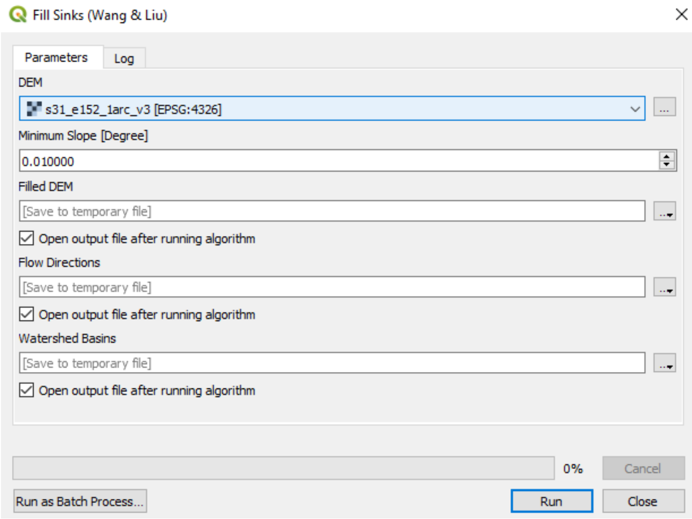
NOTE: TauDEM requires a partly manual installation to work on QGIS. Details provided in the link below:

https://gis.stackexchange.com/questions/272797/adding-taudem-provider-to-qgis-3

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

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

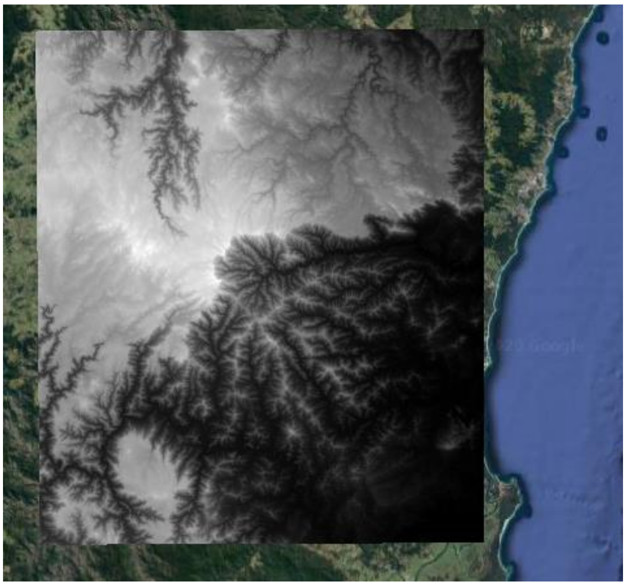
1.2 Fill Sinks

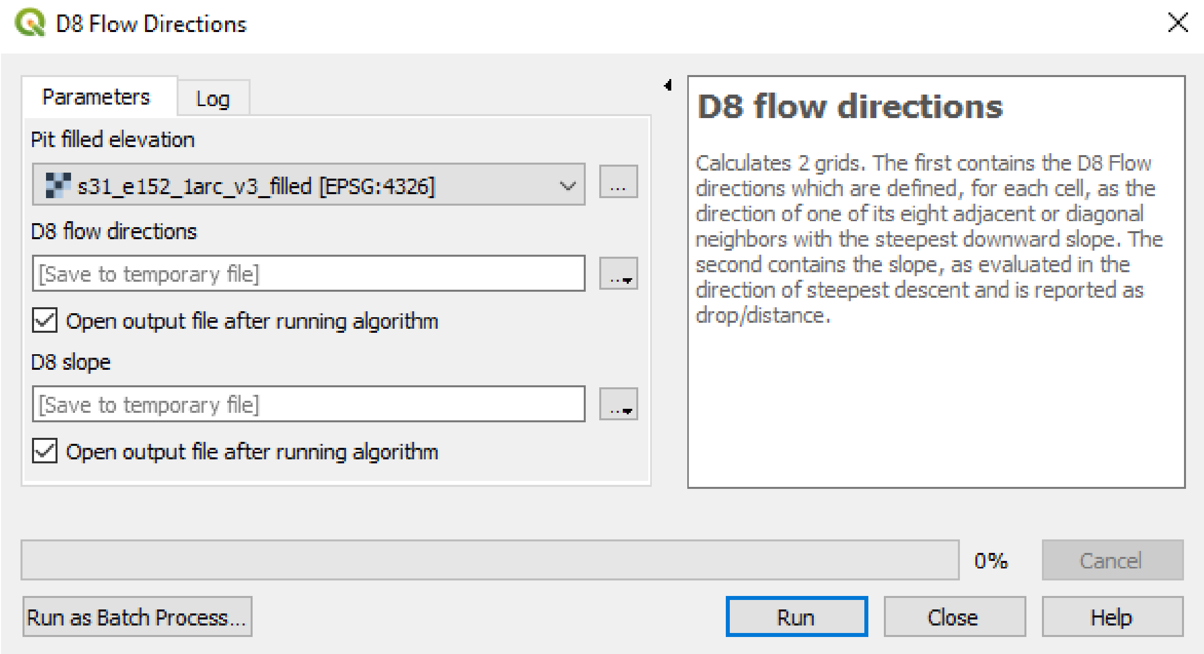


1.3 D8 Flow Direction

The pit filled raster is fed into the *D8 Flow Direction* tool

INPUT:

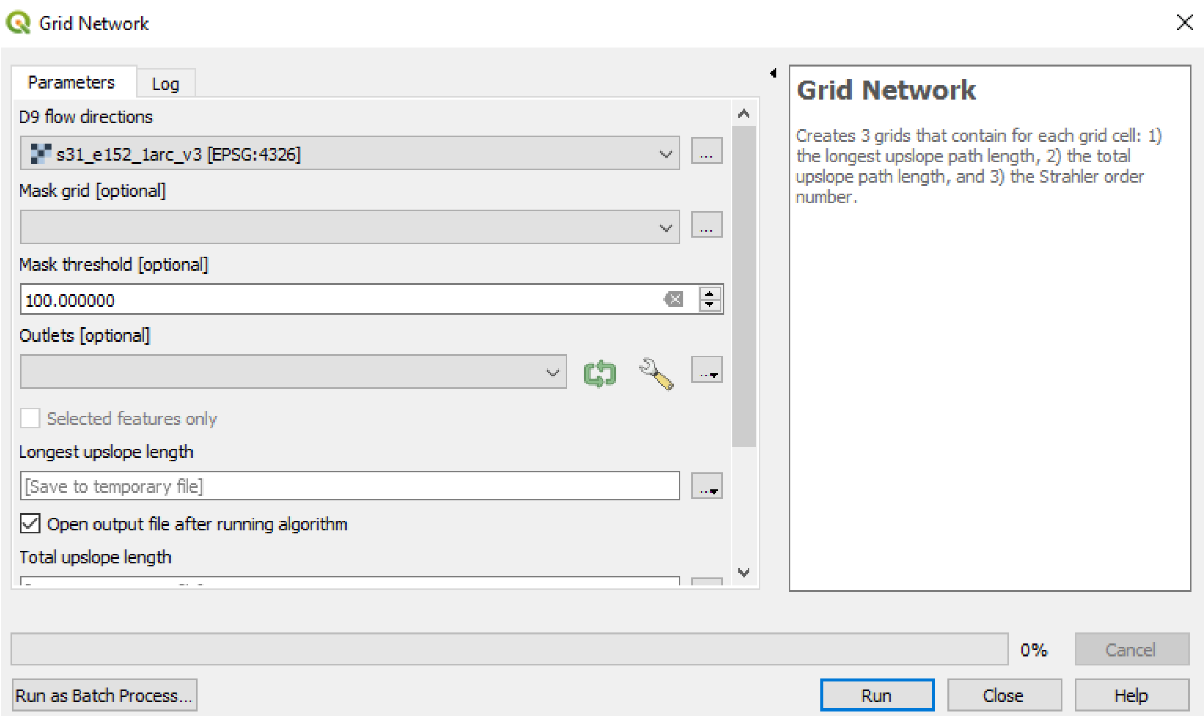




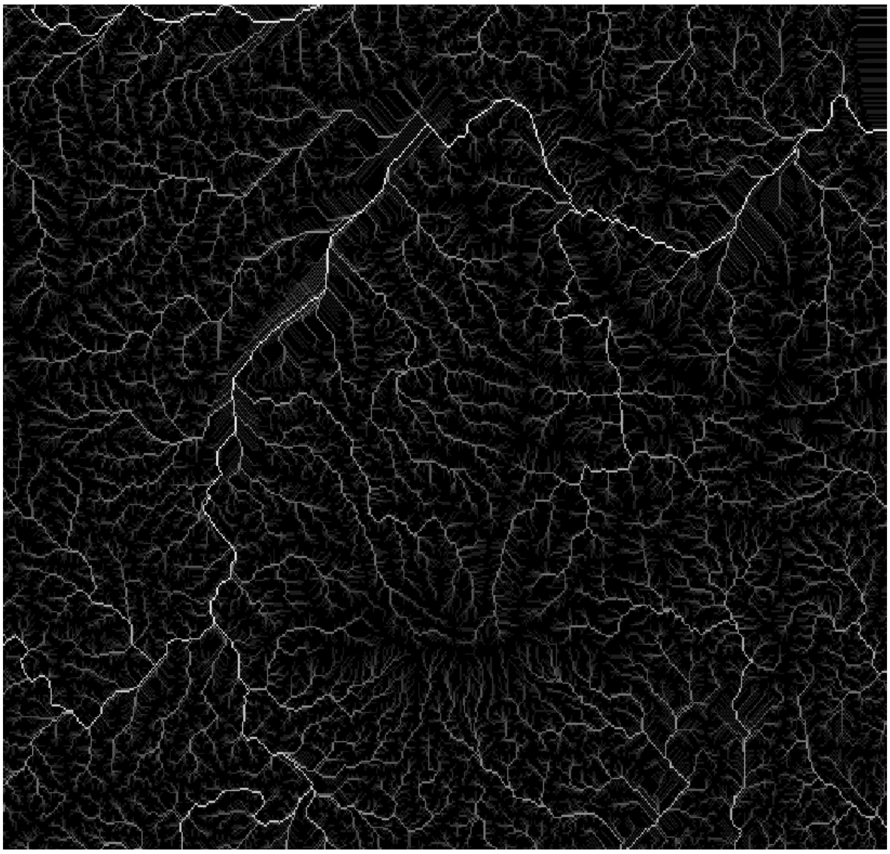
1.4 Grid Network

The D8 flow directions output grid is fed into the *Grid Network tool*.

https://hydrology.usu.edu/taudem/taudem5/help53/GridNetwork.html

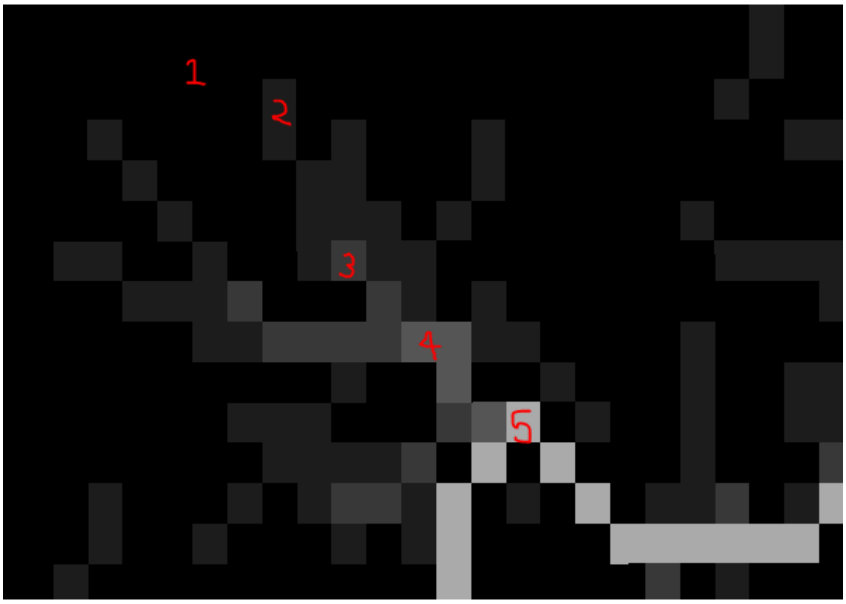


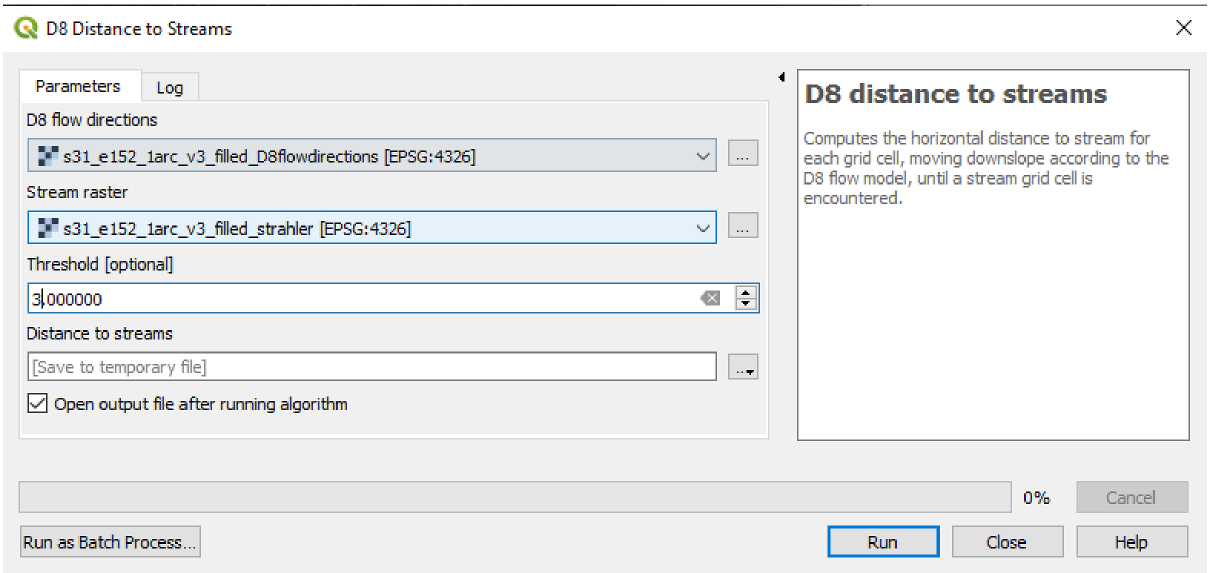
OUTPUT: A fully connected stream network is the desired result, as shown below. If the stream network is disconnected, there is likely to an issue with the previous stages.



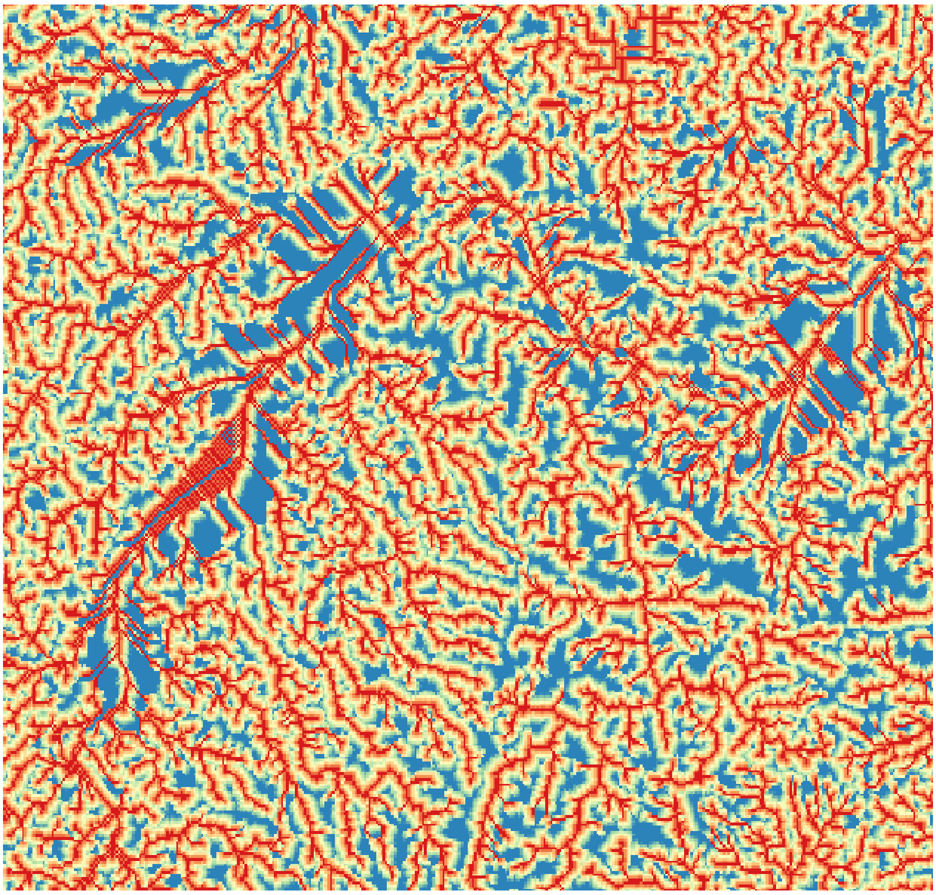
1.5 Distance to stream

Both preceding outputs can be utilised in the D8 Distance to Stream tool. The threshold responds to the stream order values, which in this case is 3 (as shown below).





OUTPUT:



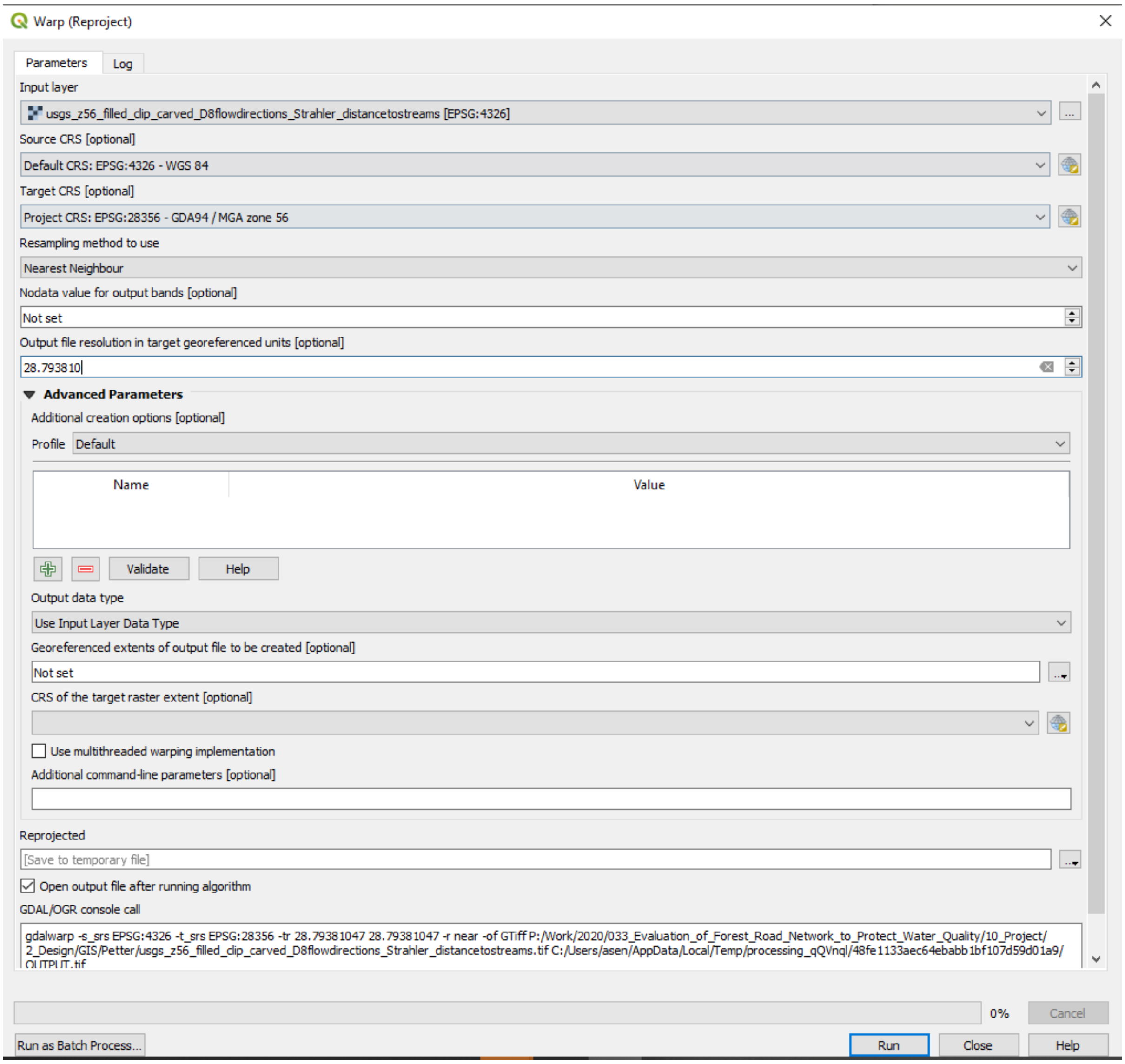
1.6 Reclassify by layer

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.

However, prior to running a reclassification of cell values, the raster layer needs to be flattened and therefore reprojected into the appropriate zone via the warp tool, as in the example shown below:

Note that the cell size has been set to the same size as the previously downloaded projected SRTM dataset from USGS earth explorer downloads page.

Also note that now that the distance to streams layer is reprojected, that a slight warping takes place from WGS84 to GDA94z56 (Figure 1).



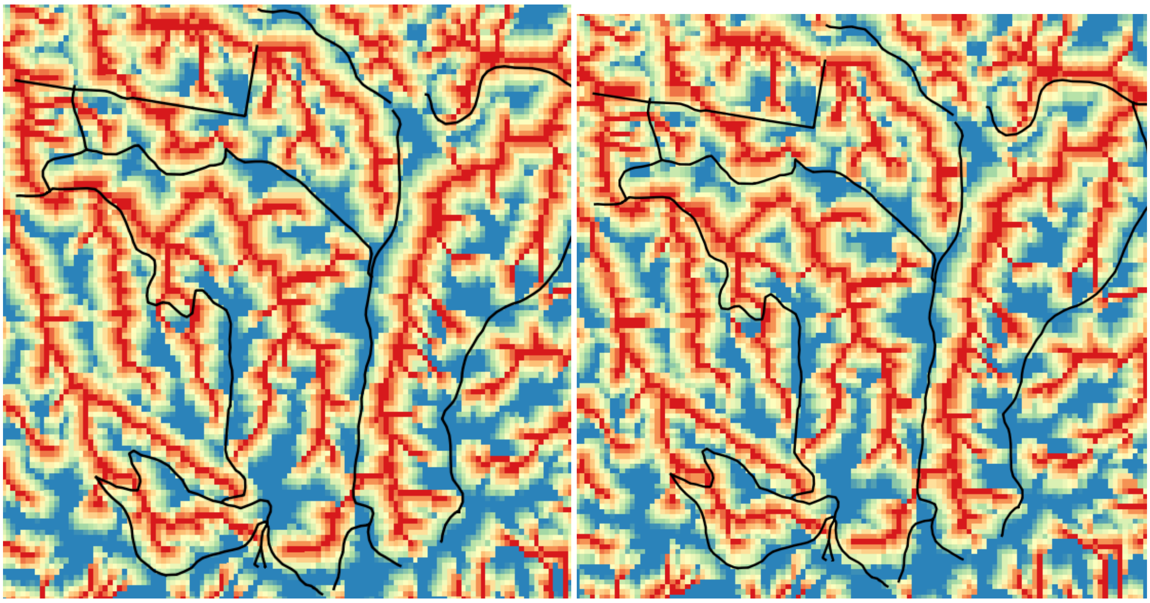
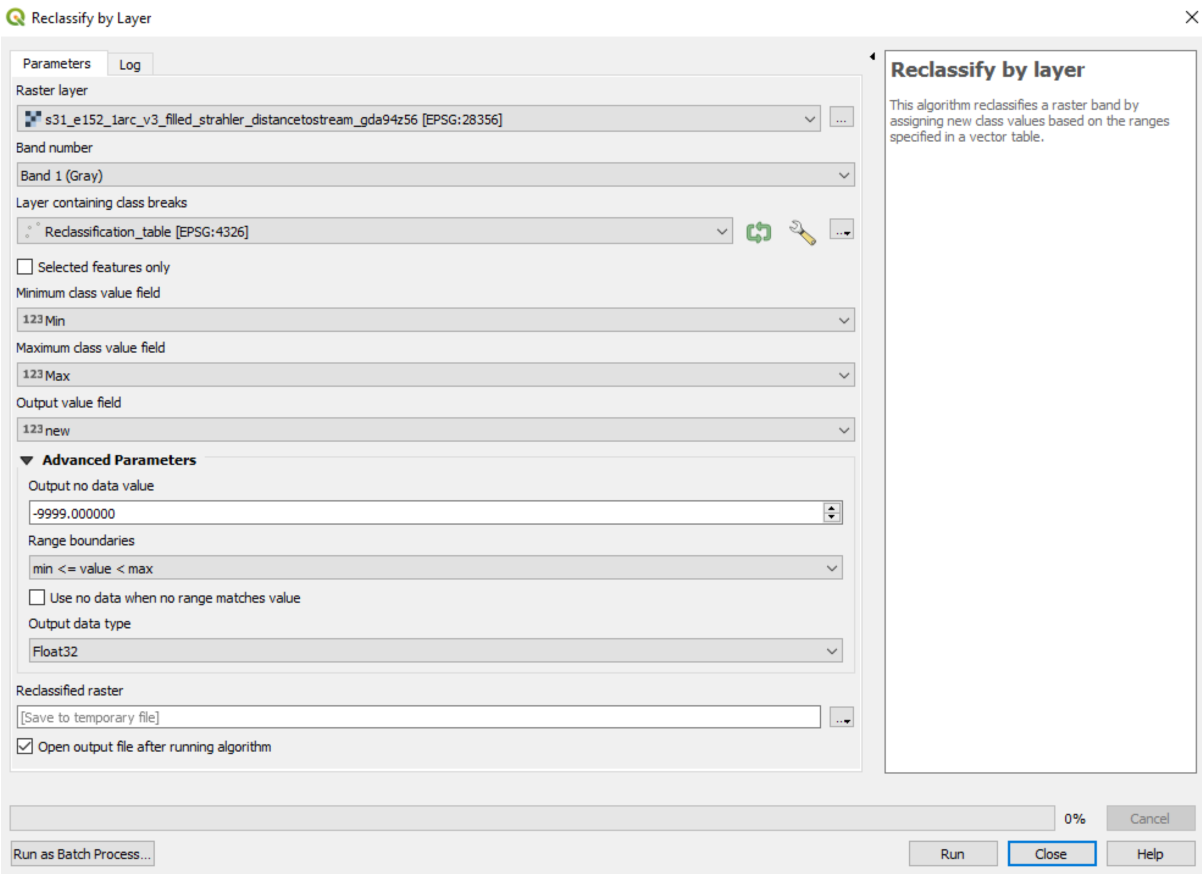
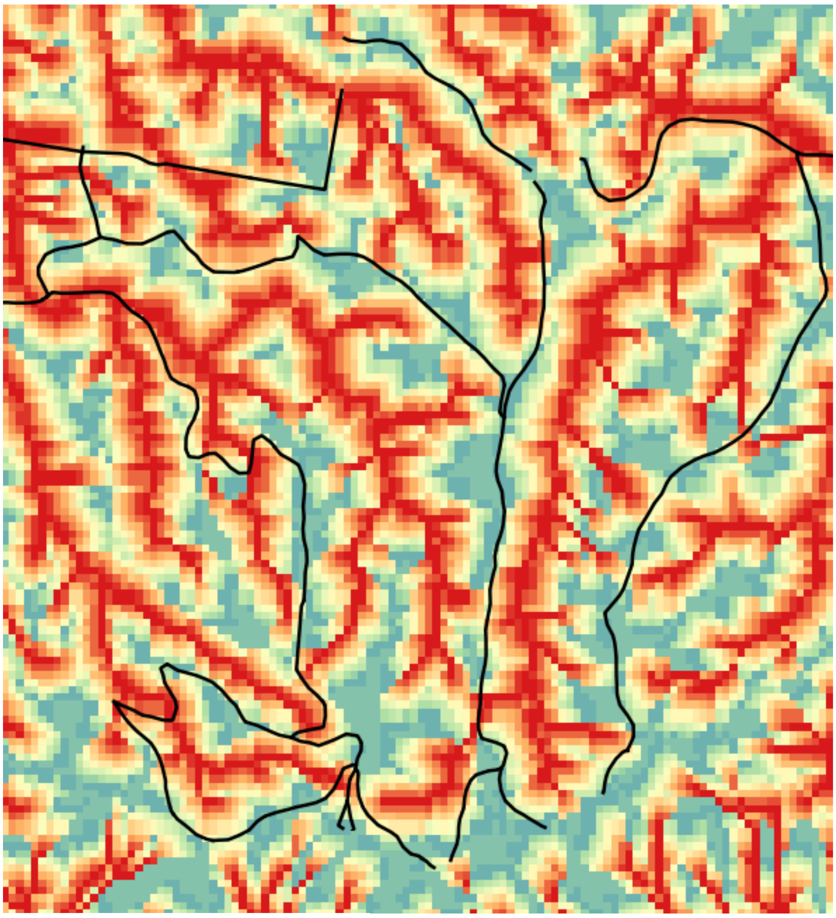


Figure 21. *WGS84 on the left and GDA94z56 to the right*



Reclassified projected distance to stream layer as per the reclassification vector file (below)



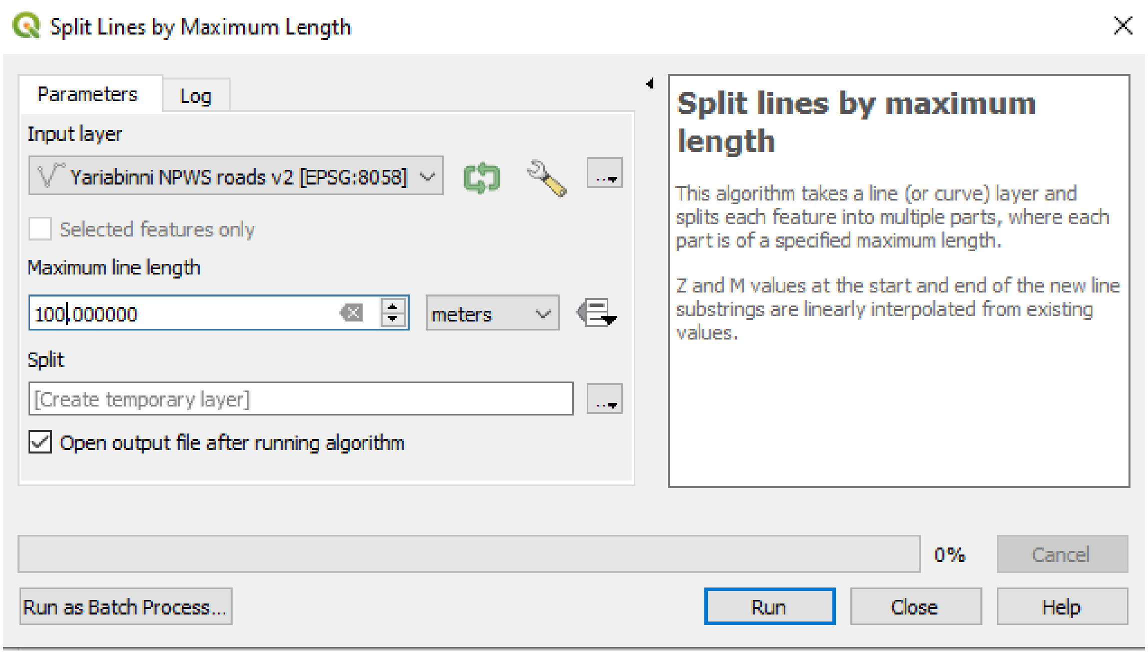
Reclassification_table — Features Total: 23, Filtered: 23, Se

	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	1000	1000
23	1000	1545	1600

2 Vector processing

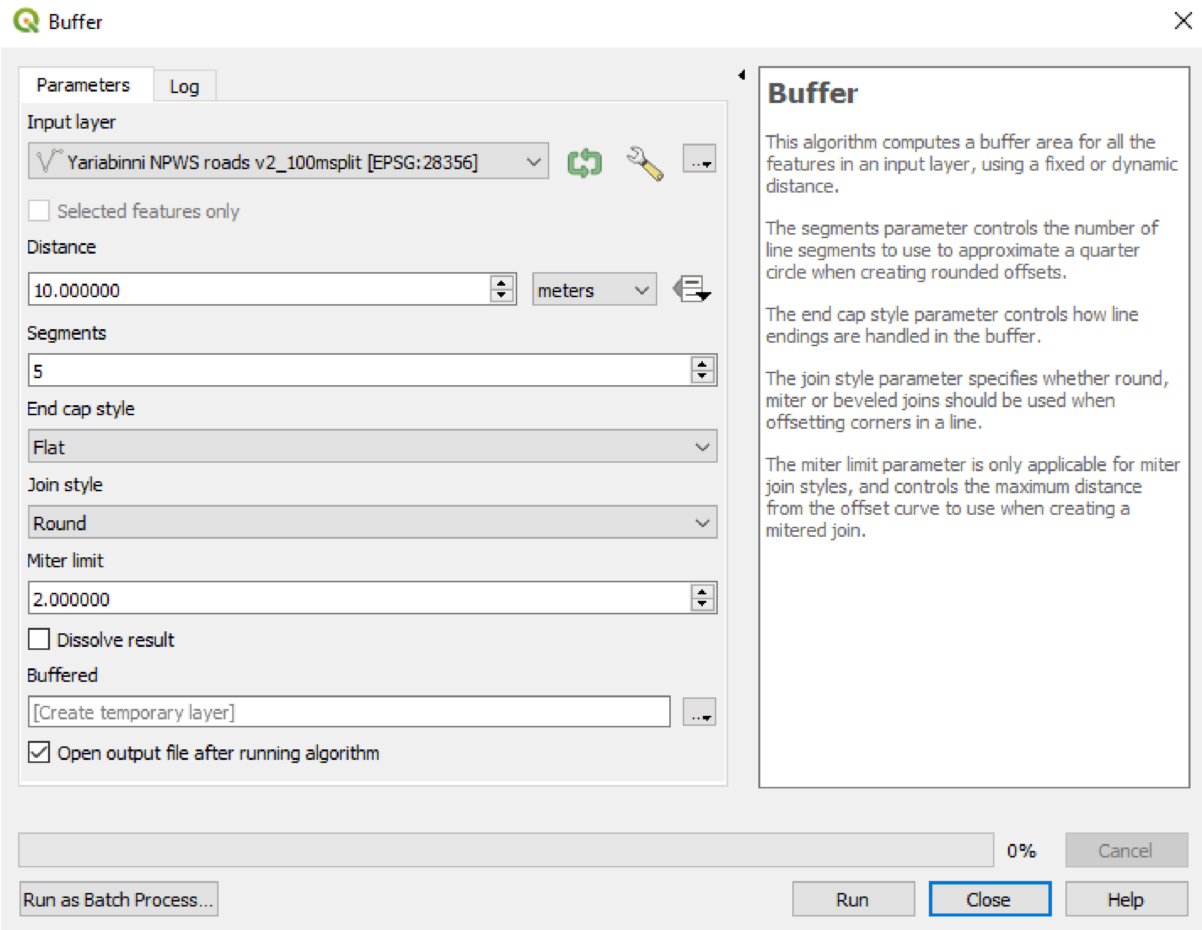
2.1 Split roads to 100m intervals

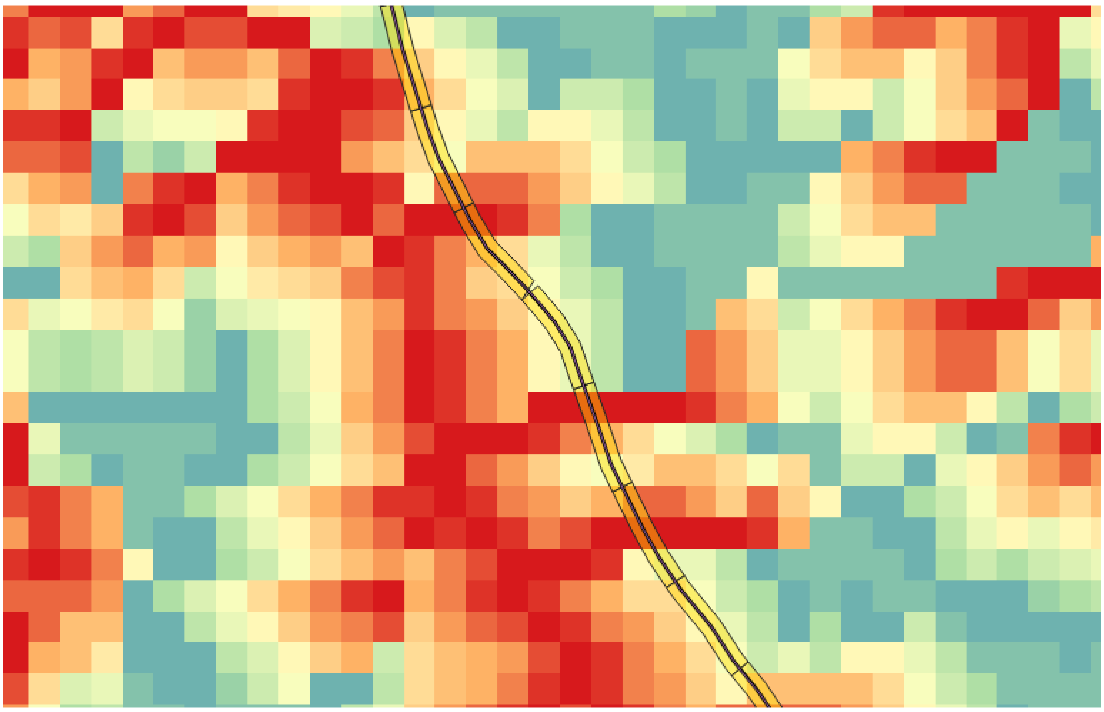
Split distance will affect overall processing time. We have chosen 100m for this example.



2.2 Buffer segments

The Buffer tool generates 10m buffer polygons for each 100m road segment. Make sure the end style is set to flat, so that the buffers for each segment don't overlap.





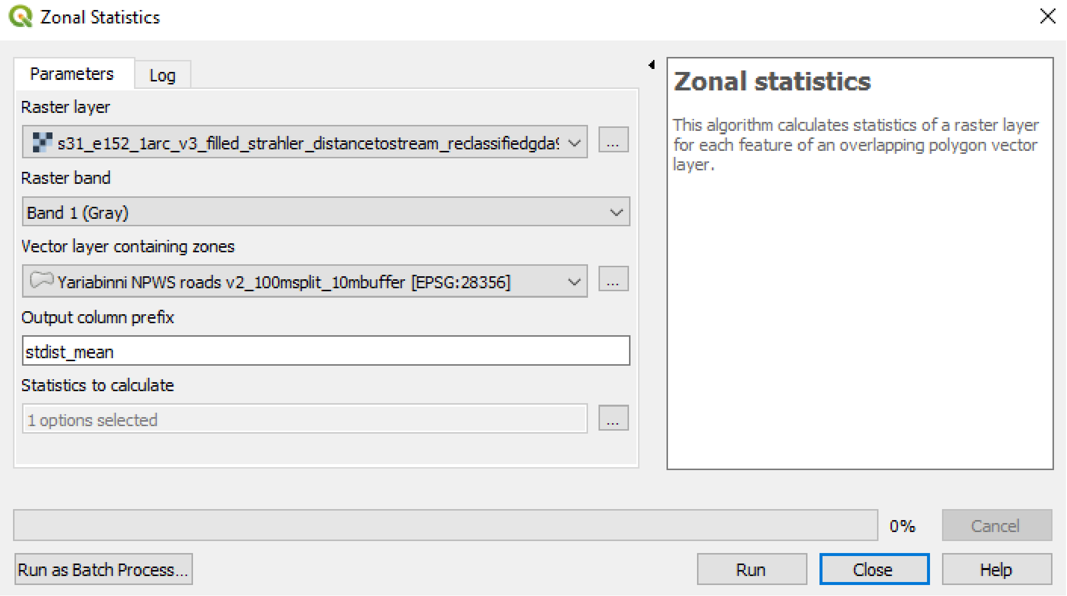
3 Raster Sampling

To gather data which corresponds to each stretch of road the following approach is taken.

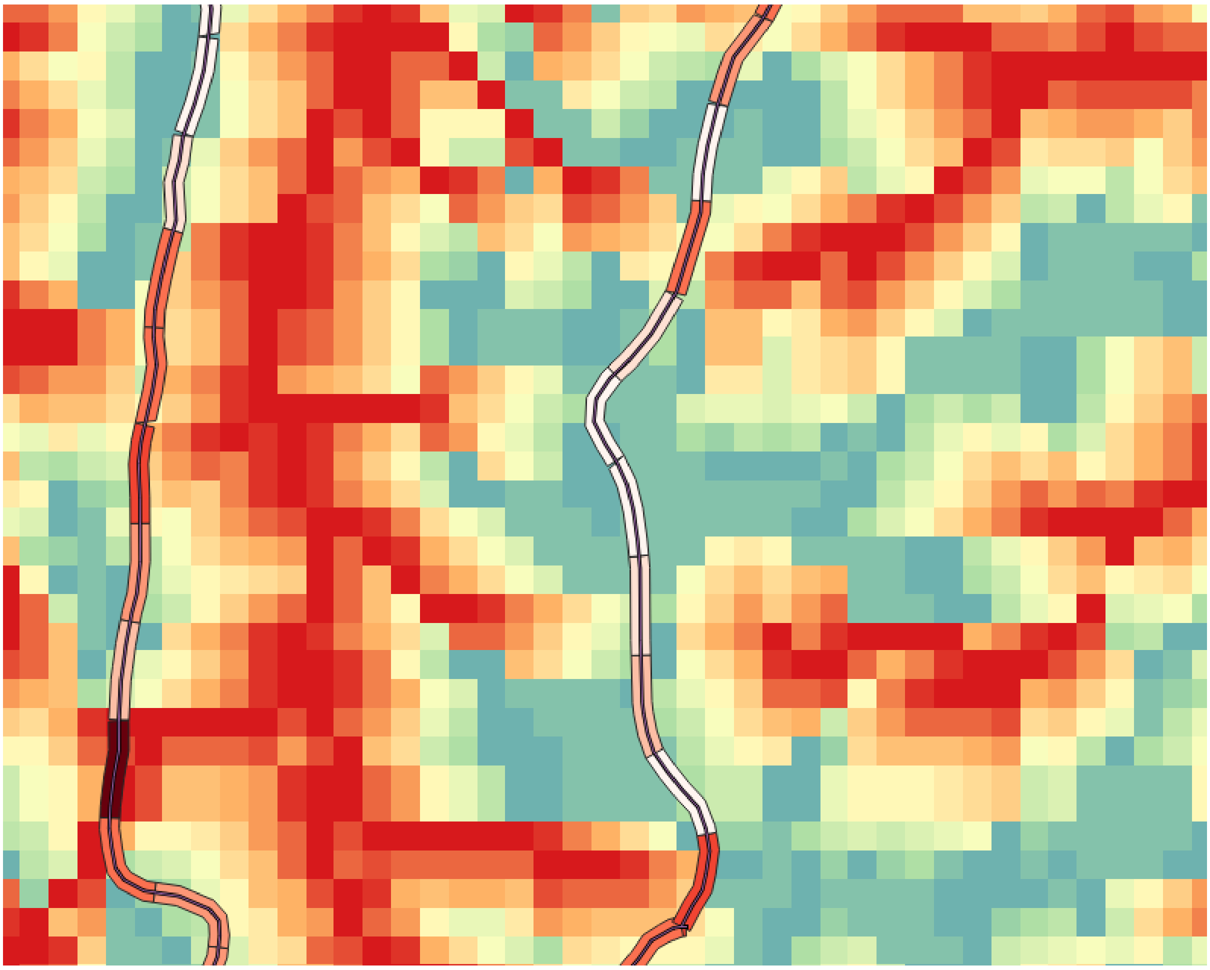
1. The sample PWS roads dataset is split at 100m intervals
2. A 10m buffer is applied to each 100 segments.
3. The mean value of each buffer zone is taken for each corresponding raster dataset (i.e. Distance to streams, rainfall intensity, terrain slope (D8) and then added as attributes to the road segment vector file

3.1 Zonal statistics (mean distance to stream)

The zonal statistics tool can calculate the mean distance to stream value within each of the road segment buffer zones. A mean distance value is allocated to each buffer feature.

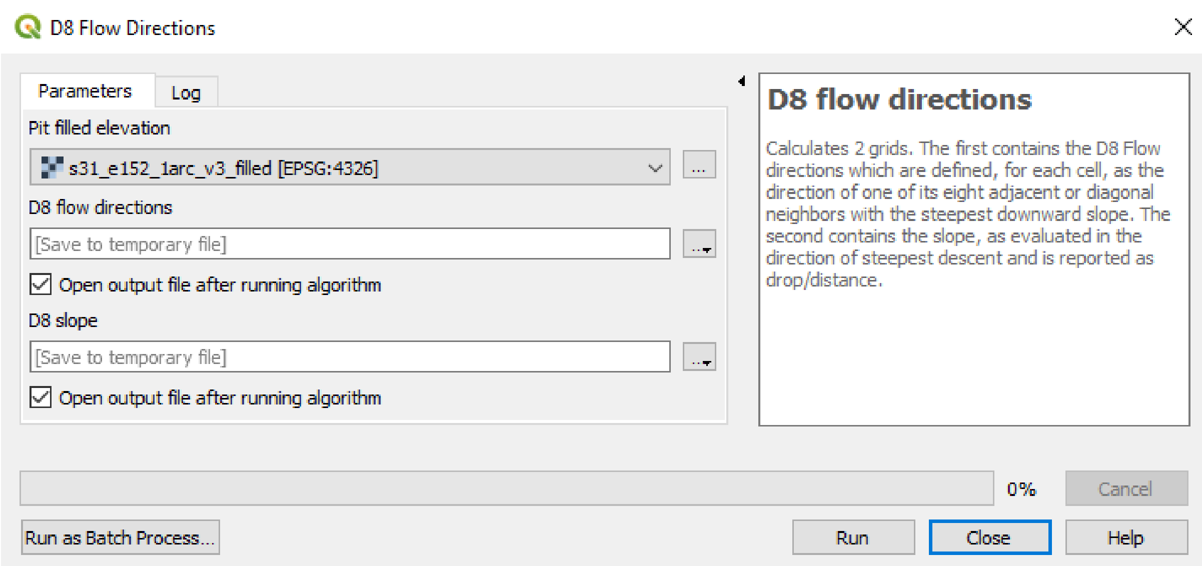


An example of the buffers coloured by mean distance to stream below:

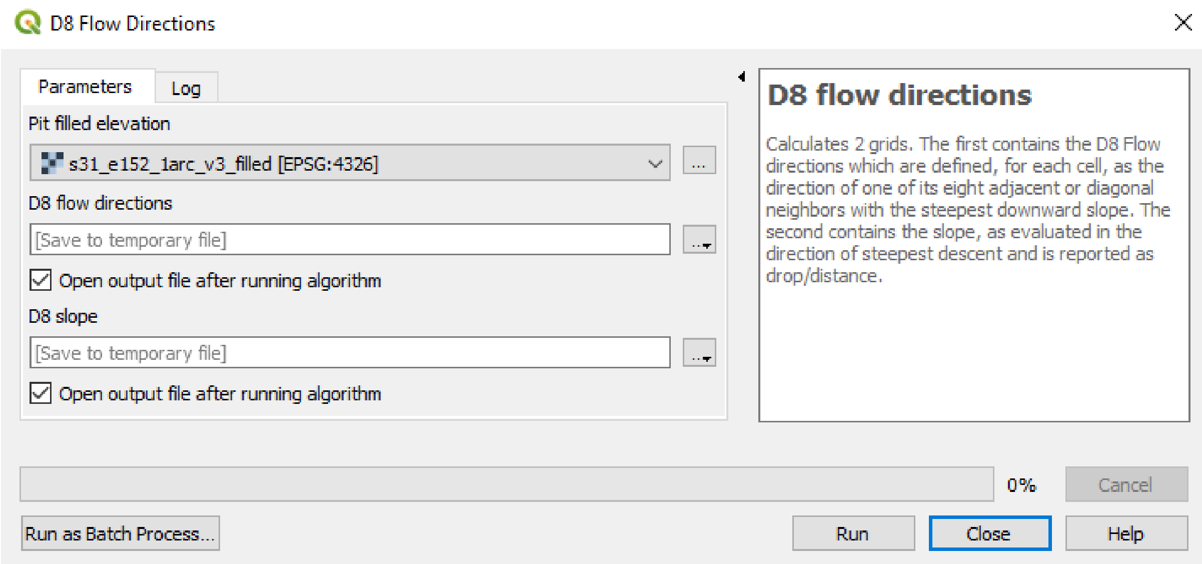


3.2 Zonal statistics (mean surrounding slope)

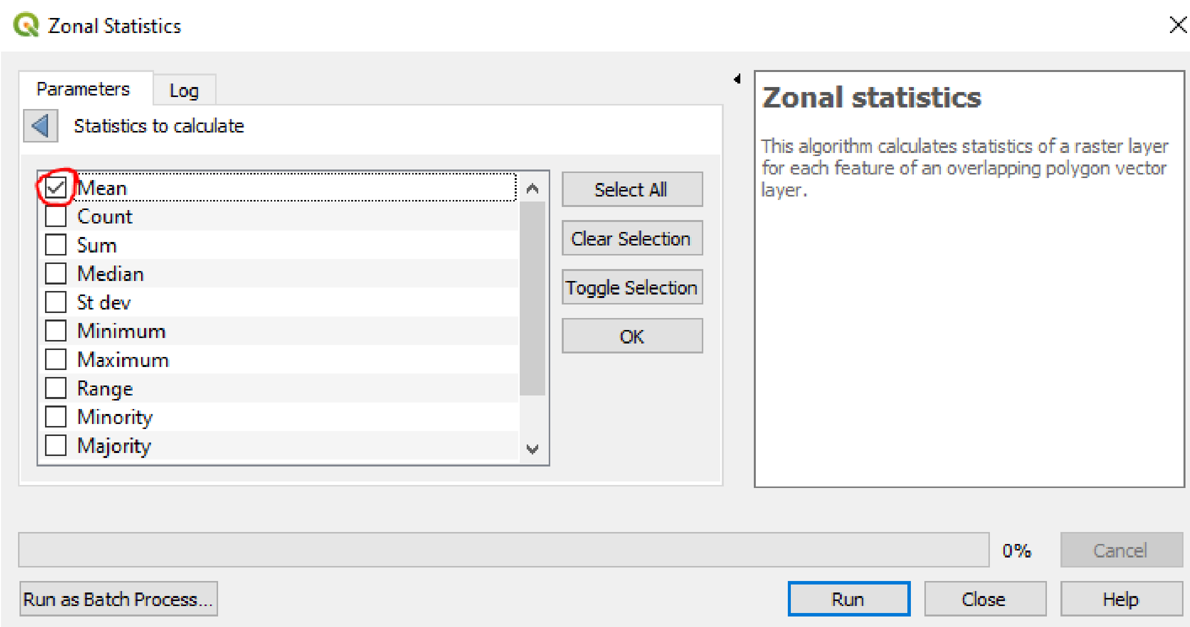
We can use D8 slope as calculated from the TauDEM D8 flow directions tool in Step 1.2. The tool produces a slope raster which calculates slope as the greatest drop across each cell/distance.



The zonal stats tool can then sample for the mean slope within each buffer zone, as shown below.



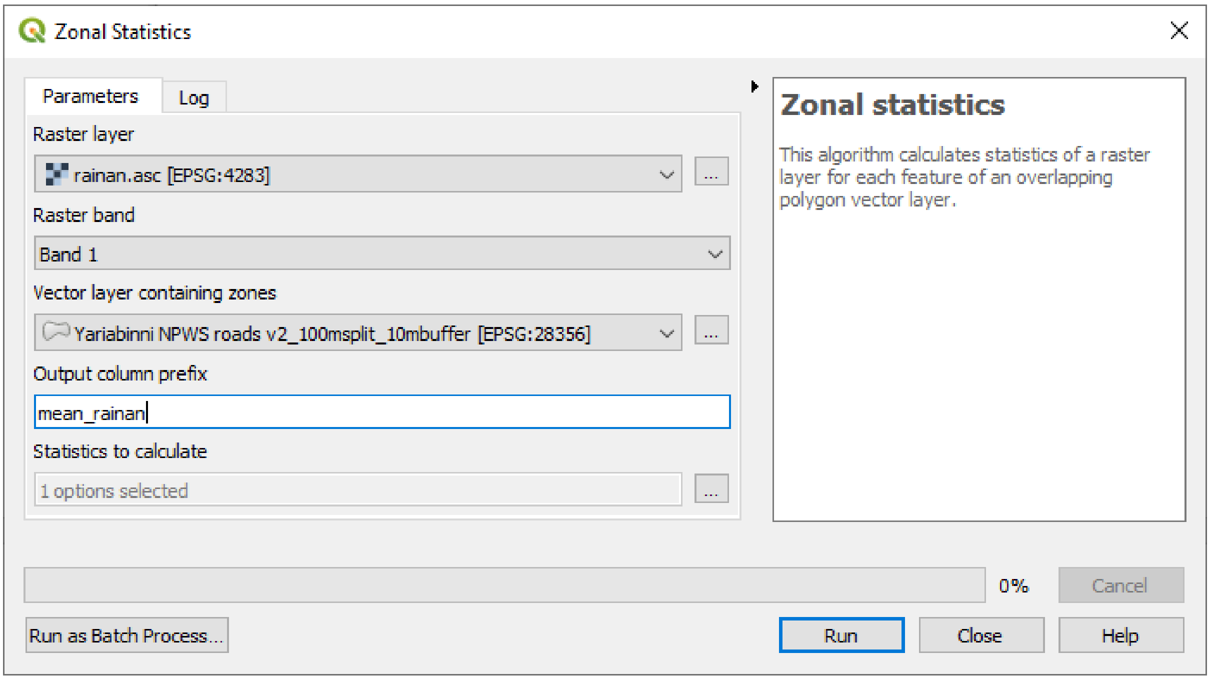
Make sure 'mean' is selected in the 'statistics to calculate' tab.



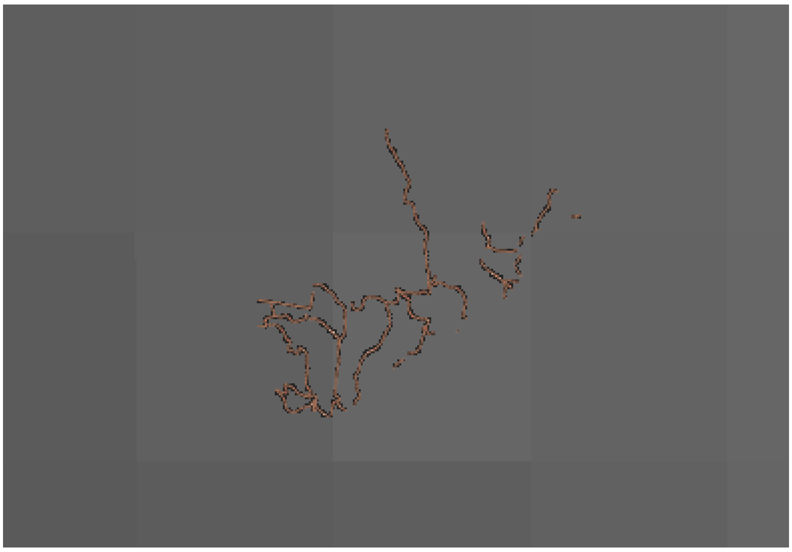
The D8 tool calculates slope as a ratio (rise/run)

3.3 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.



The grid cells in relation to the study area roads below.



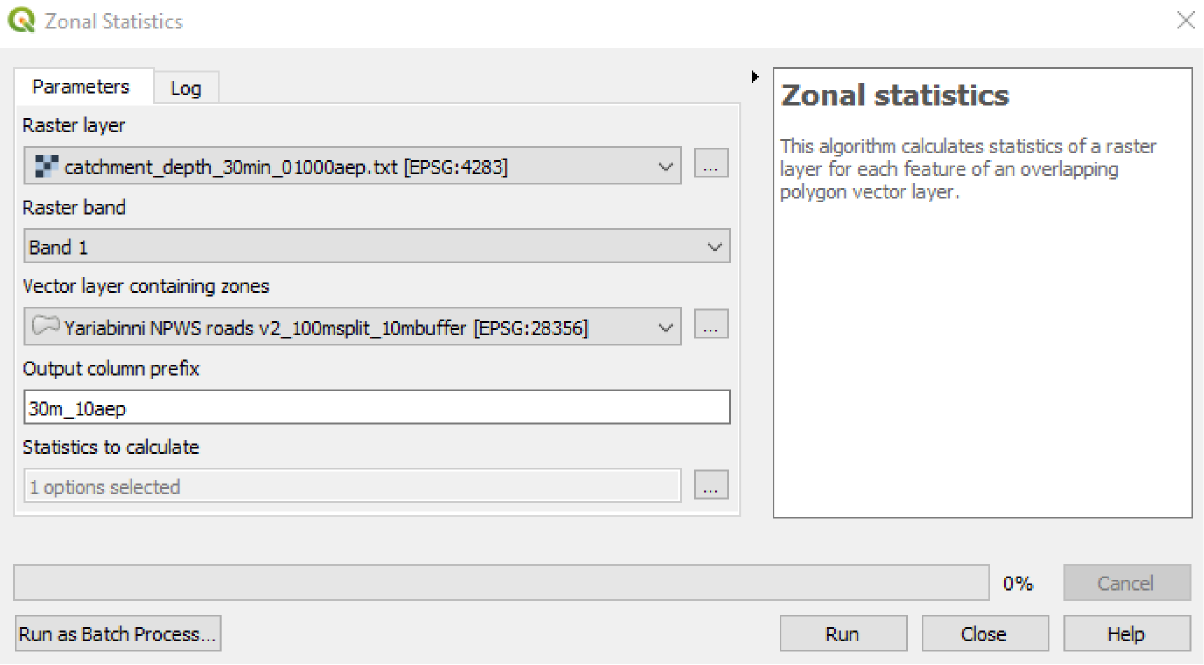
3.4 Zonal Statistics (Rainfall Intensity)

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

The grid is 2.5km by 2.5km.

Grids available for sites only. An enquiry will need to be made about sourcing a grid across the entire state for the broadscale analysis.

http://www.bom.gov.au/water/designRainfalls/revised-ifd/?coordinate_type=ddExt&latitude1=-30.886&longitude1=152.833&latitude2=-30.709&longitude2=153.051&sdmin=true&sdhr=true&sdday=true&extent=true



Example of grid in relation to study area below

4 Road segment Processing (line shapefile)

4.1 Road Slope

Road slope can be calculated by taking the elevation of both endpoints of each line and the distance between. This is a rough measure but close enough given this is a state-wide analysis.

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.

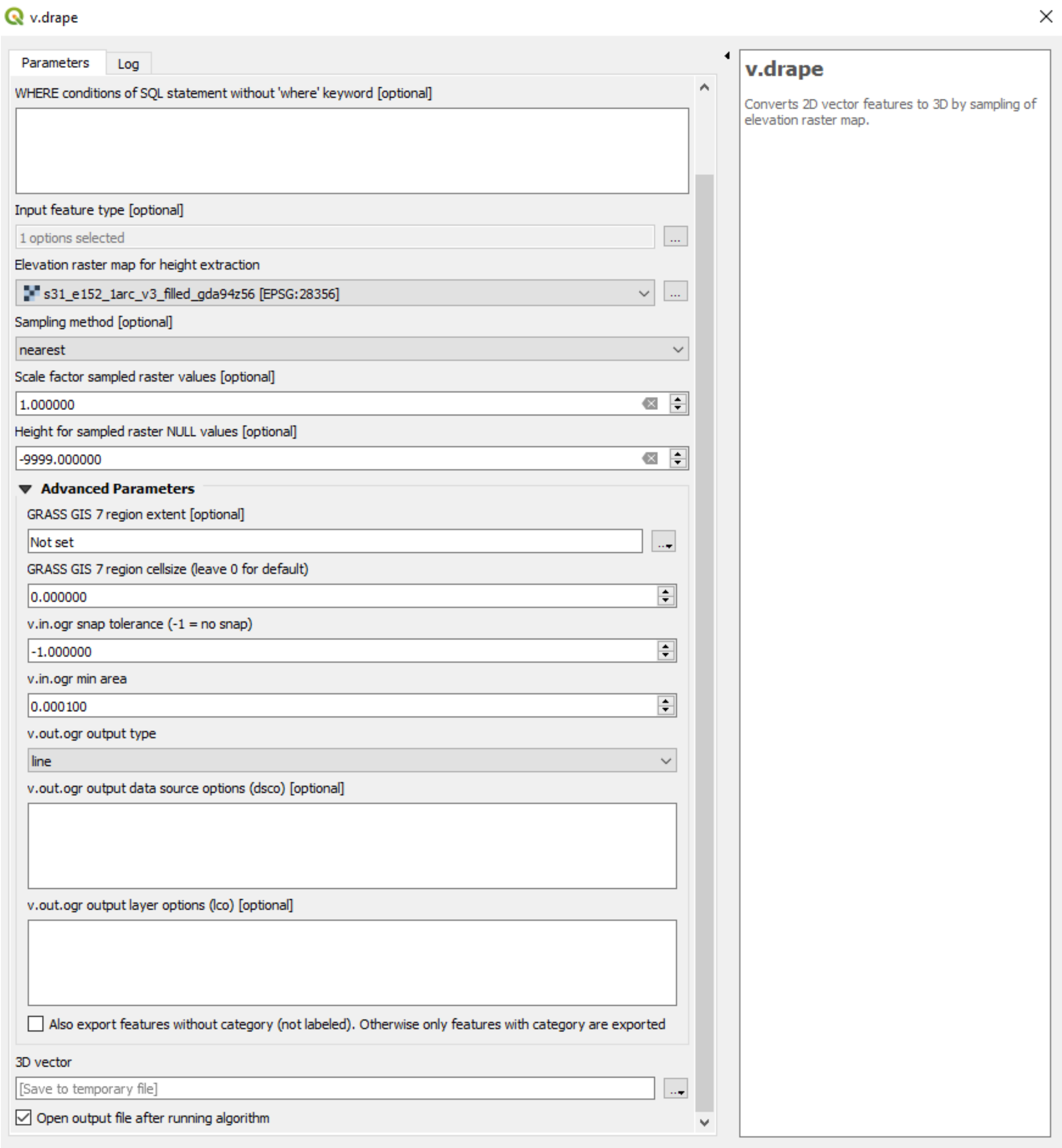
3.) calculate slope of each segment with the field calculator

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

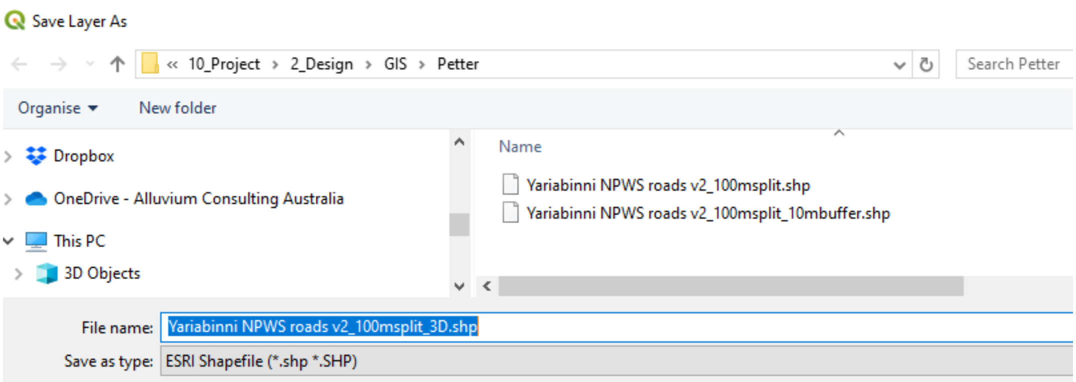
share improve this answer follow

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. – Quarantäne 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

Yariabinni 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 b	1535.690000000	2020/05/01 00:0	1536	0.301663031345	0.173

4.2 Drainage spacing:

The drainage spacing for the sample area can be assumed from the relevant spacing policy.

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
```

Note: Even though slopes above 16 deg aren't viable according to some road guidelines – some road slopes are calculated to have slopes above this threshold, thus the expression attempts to capture these with very low numbers, in this case -10m.

4.3 Width

The following road widths have been applied to the three different types of road (Natural, Gravel or Sealed).

ASSUMPTION: These widths are arbitrary based on best guess, however a dive into road design specs or at least a discussion with Kurt could refine these

d_AssetMat	Width
Natural	5
Gravel	8
Bitumen Seal	10

A SQL expression can assign road widths based on road characteristics:

```
CASE

    WHEN  "d_AssetMat" = 'Natural' THEN 5

    WHEN  "d_AssetMat" = 'Gravel' THEN 8

    WHEN  "d_AssetMat" = 'Bitumen Seal' Then 10

END
```

4.4 Traffic Intensity

Traffic intensity at this stage is allocated generic values based on whether the road is classified as 4wd or 2wd. It is assumed that 2wd roads are used more frequently than 4wd vehicles.

Traffic intensity numbers denote number of trucks per week

d_AssetTyp	Traf_int
2WD	50

4WD	20

CASE

WHEN "d_AssetTyp" = '2WD' THEN 50

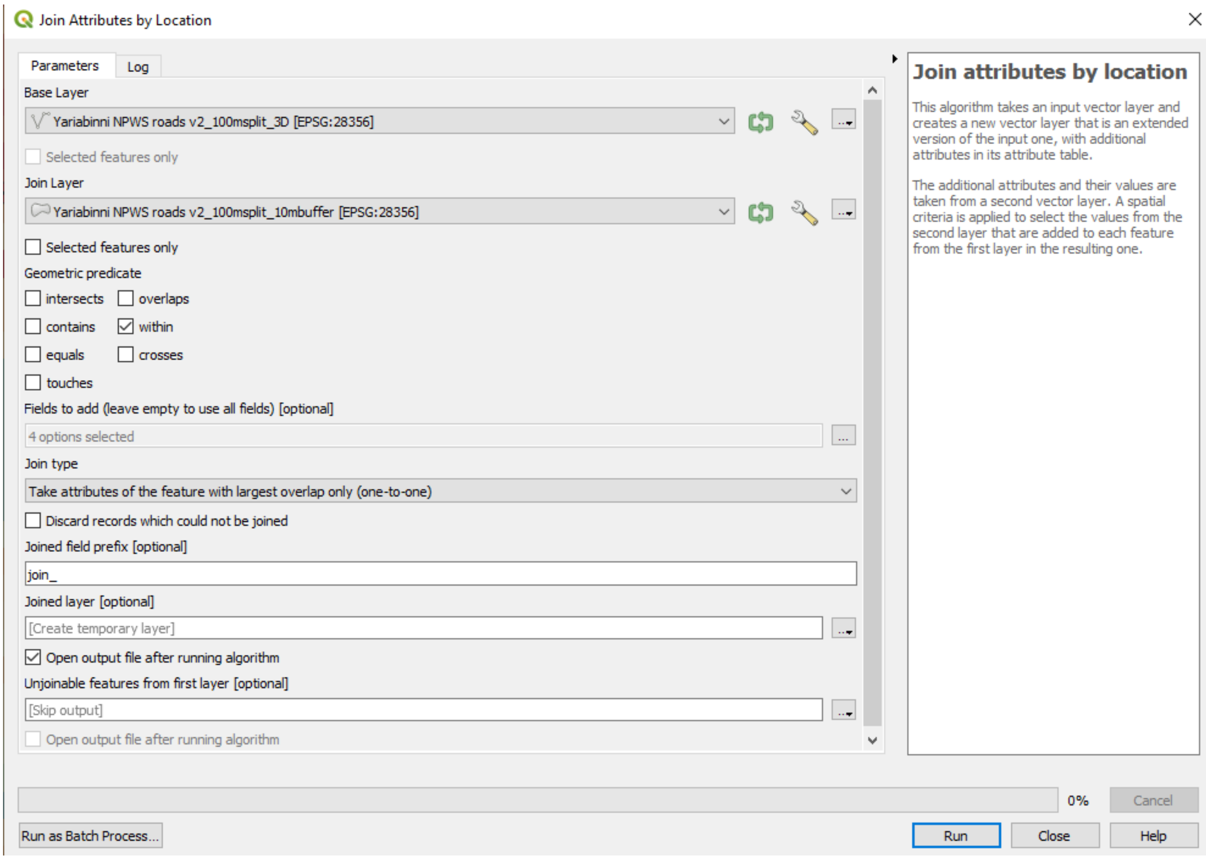
WHEN "d_AssetTyp" = '4WD' THEN 20

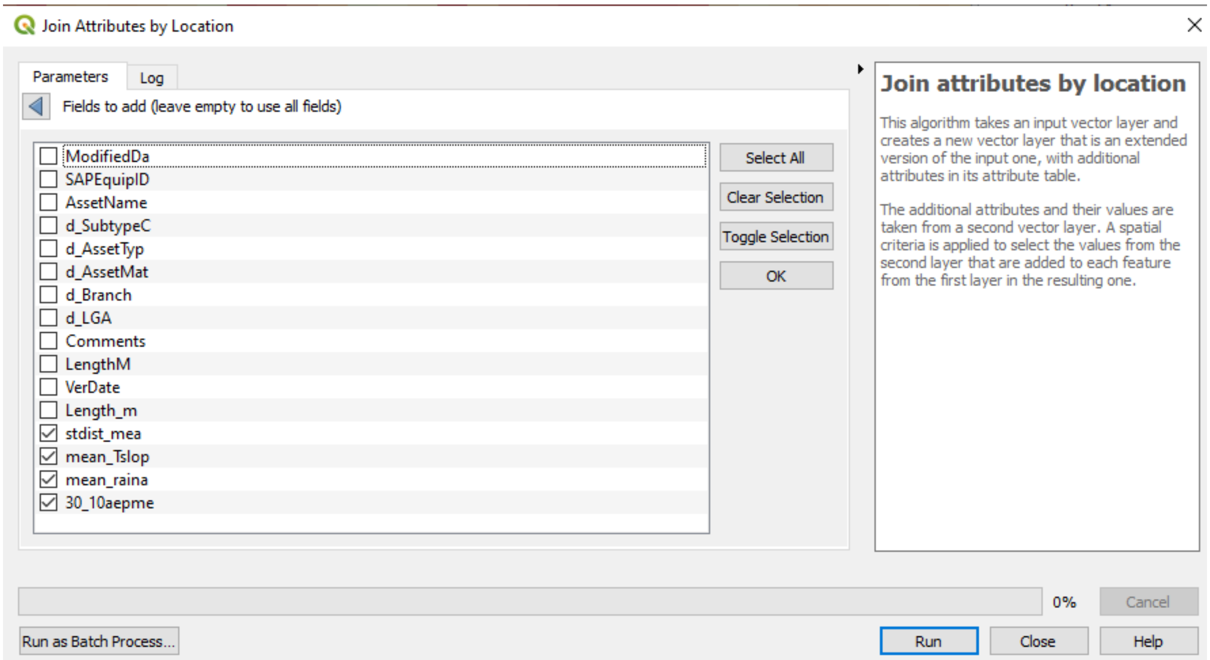
END

5 Excel Modelling

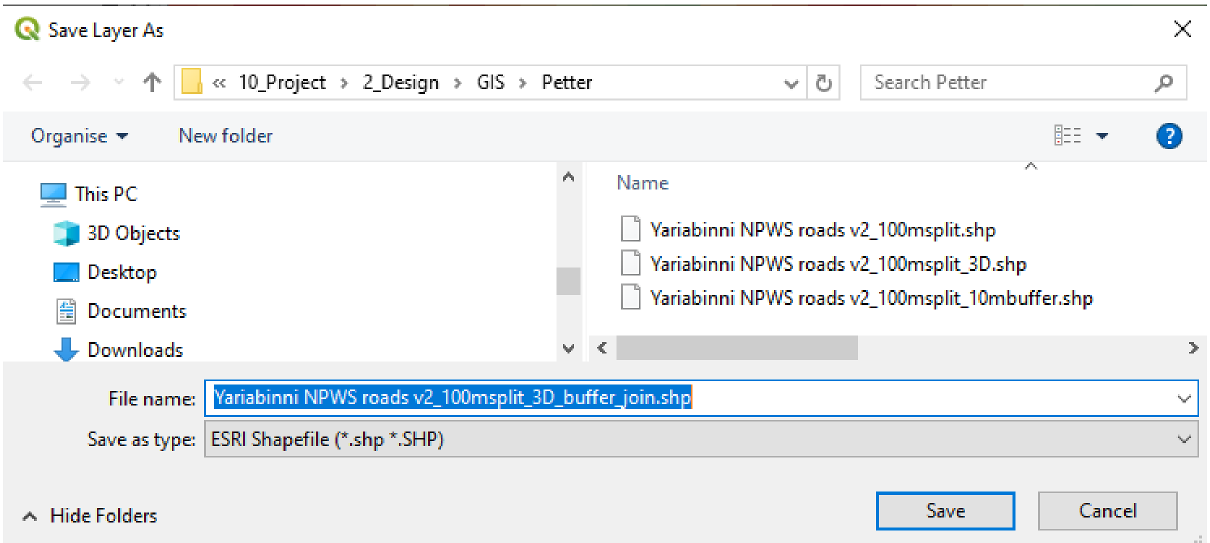
To run the model in excel, the values which have been calculated in the buffer zones for each road segment are joined back to the 3D road segment shapefile so that all that inputs can be exported in one simple spreadsheet.

The join type settings are important – a one to one join with the shape with the largest overlap will collect the correct information.





Run the join function and save the joined layer with an appropriate name:



5.1 Model Calculations

Four different empirical models developed from the following Australian studies are applied to estimate the amount of sediment delivered to a stream. These are detailed in the main document.

6 GIS Visualisation

1. Check for any DIV values in the result sheet 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.

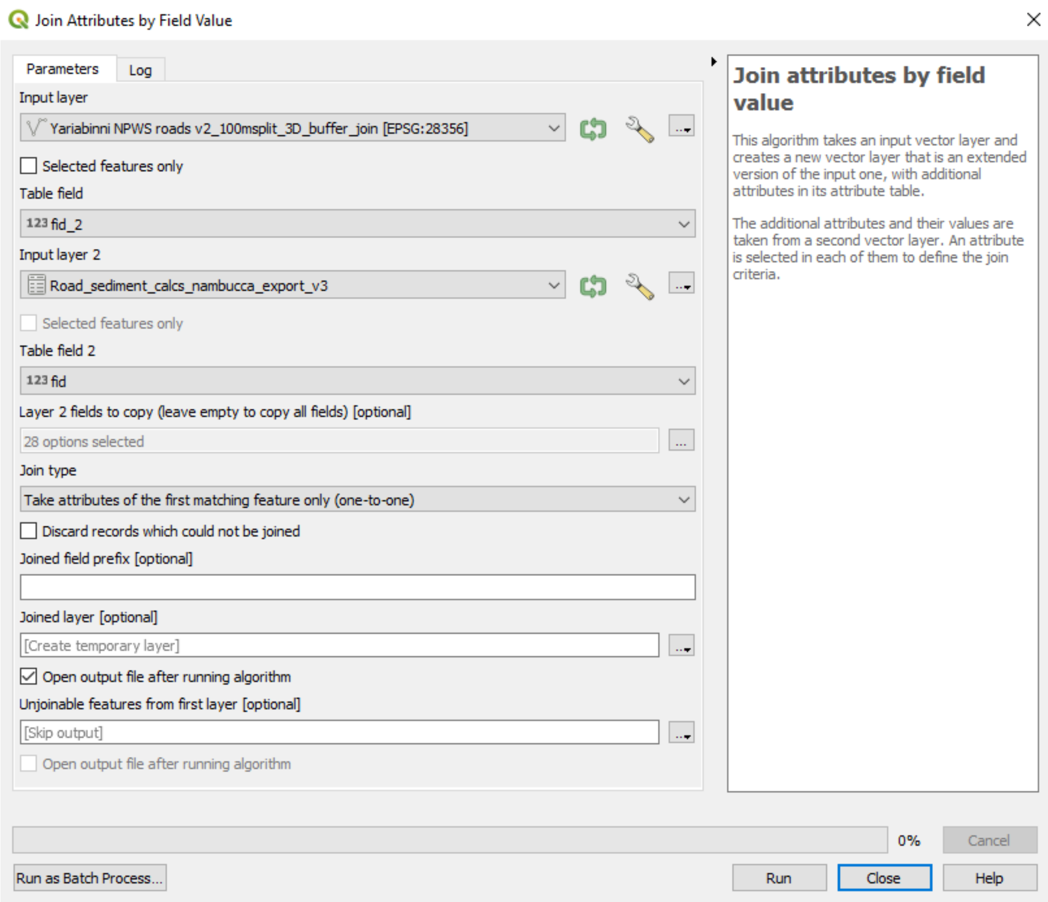
978	17.70293	8.680355	7.2207	775.9411
254	15.44776	8.782748	7.479251	981.3676
0	0	-46.8248	-46.8248	#DIV/0!
843	371.6528	1.377848	0.028878	27.71247

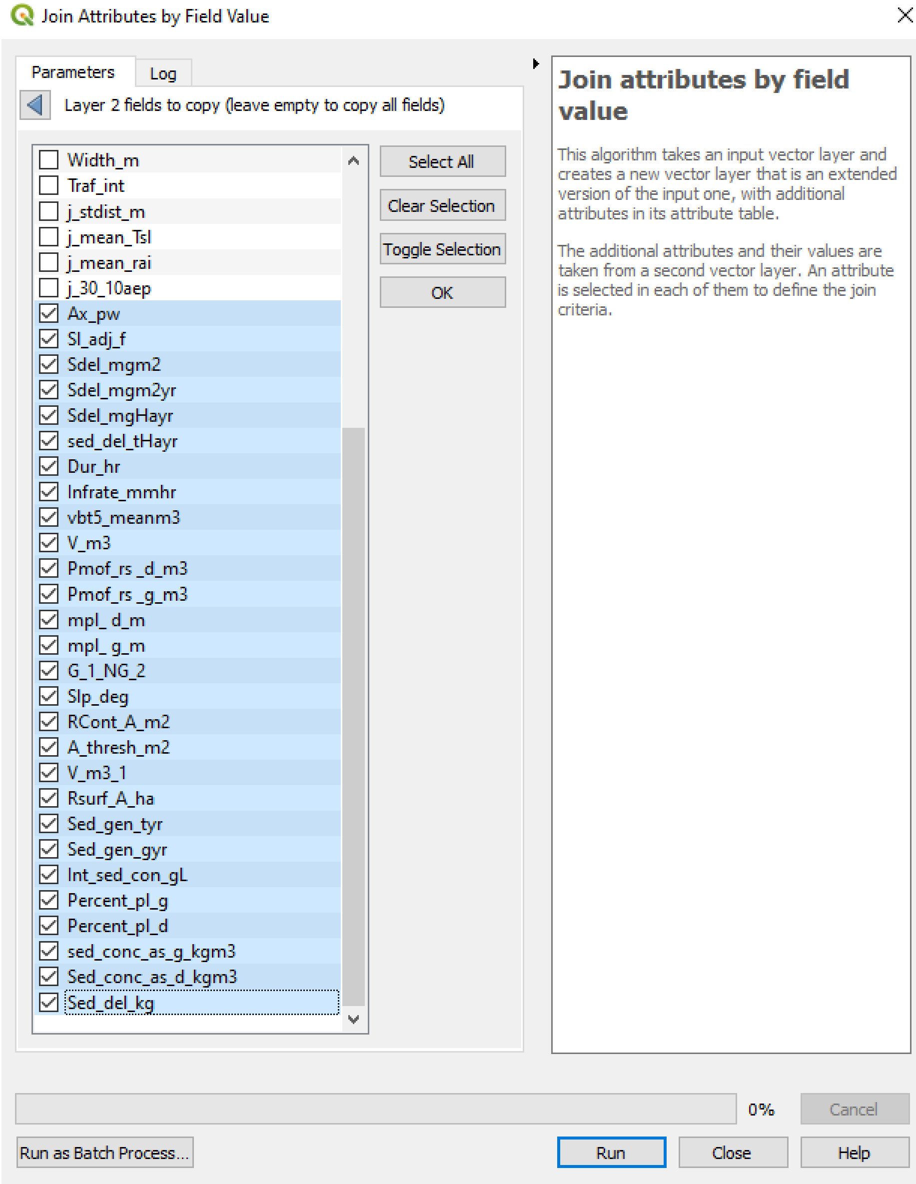
2. Save values as CSV
3. Add CSV to GIS workspace
4. Use the join Attributes by field value

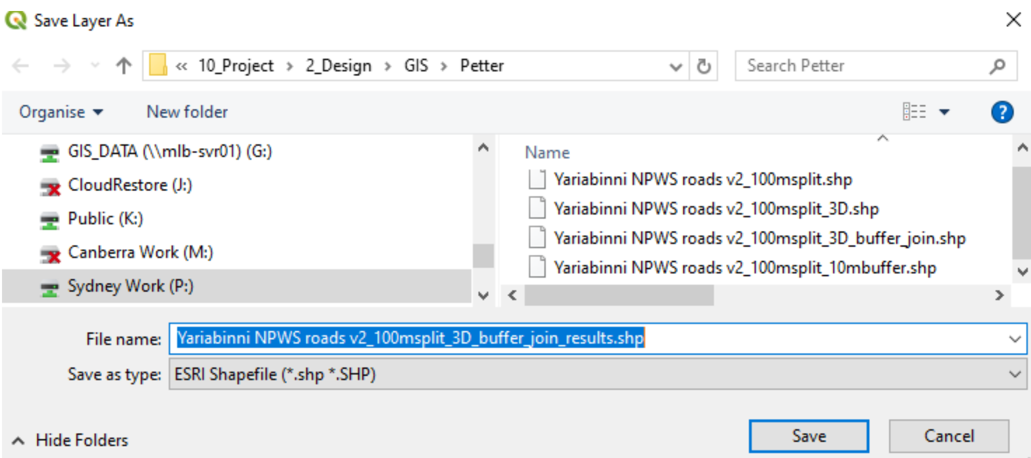
6.1 Join outputs to roads shapefile

Note: The join layer contains a unique identifier 'fid' that was created when the road was split into 100 segments. This unique ID is likely not to work in the join function as it is set as a 'Double' field type rather than an 'Integer'.

To get around this, create a new unique field ID called fid_2 and set the field type to 'integer'. The join should work if each field in the joining columns are of the same type.







6.2 Mapping

Once joined. Use Layout manager to display the modelled values.