The forest road erosion toolbox: Modelling, mapping and treating sediment delivery from roads to waterways

Alex Sims[1], Petter Nyman[2], Kristen Thomson[2] and Richard Farr[2]

1 Alluvium Consulting, Dunedin, New Zealand, alex.sims@alluvium.com

2 Alluvium Consulting, Melbourne, VIC, Australia.

Key points

- Fine sediment from unsealed forest roads can be delivered directly to waterways, creating a persistent water quality and habitat risk.
- This risk occurs across large road networks but is usually concentrated at a smaller number of connected drains and crossings.
- The Forest Road Erosion Toolbox provides a spatial method for estimating sediment delivery, mapping risk hotspots, comparing drainage and maintenance scenarios, and undertaking preliminary culvert-capacity screening at road–waterway crossings.
- The tool can be used by forest managers, road managers, regulators and practitioners to prioritise field inspection, target maintenance and compare mitigation options across large, unsealed road networks.

Abstract

Fine sediment eroded from unsealed forest roads can degrade water quality and aquatic habitat when road runoff remains connected to the stream network. Forest managers, regulators and road managers need to assess this risk across road networks that can extend for many thousands of kilometres. Direct monitoring is costly, spatially limited and often unable to isolate the contribution of specific road segments, drains or one management action. This paper describes an ArcPro toolbox developed to assess sediment delivery risk from unsealed forest roads and to size road culverts. The toolbox implements published science on road erosion, runoff, gully initiation, overland flow connectivity and sediment concentration decline along flow paths. The toolbox builds on earlier work by Alluvium Consulting for the Natural Resources Commission in NSW, Forest and Wood Products Australia and the Arthur Rylah Institute, and on research from the CRC for Catchment Hydrology and related field programs. The toolbox includes a baseline sediment delivery model, a scenario-testing module and a culvert sizing module. The sediment delivery module models sediment generated from the road surface and the probability and magnitude of its delivery to waterways. It does not estimate total sediment yield from the surrounding forest catchment. Vegetation cover within the wider catchment is therefore not an input to that module, although the intervening hillslope affects road-to-stream connectivity and sediment deposition. The separate culvert module uses catchment-scale runoff and represents land cover through a user-selected runoff coefficient. Users provide a road network, a digital elevation model, and assumptions about road drainage. Outputs include spatial datasets, maps, tables and plots of sediment delivery (kgdesig) that can be used to prioritise maintenance, identify hotspots and to compare management scenarios. The model structure is modular, so erosion equations and regional parameters can be updated as new data become available.

Keywords

Forest roads, sediment delivery, hydrologic connectivity, culvert sizing, ArcPro, water quality, erosion risk

Introduction

Delivery of fine sediment from catchments to waterways can increase by orders of magnitude when unsealed road networks are introduced. In south-eastern Australian forested catchments, unsealed roads have been estimated to contribute 20 to 60 times more sediment than undisturbed forest on a unit-area basis (Motha et al., 2003). In managed forest catchments, fine-sediment delivery is therefore often disproportionately associated with unsealed roads rather than vegetated hillslopes. Roads combine compacted, low-infiltration surfaces with exposed sediment that remains available for erosion throughout the year, whereas sediment production from intact forest floor is generally much lower. Increased fine sediment delivery above background rates can degrade water quality, reduce habitat quality and have flow-on effects on the environmental values that depend on those waterways (Wood and Armitage, 1997; Croke and Hairsine, 2006). This risk is often acute in small headwater streams, including ephemeral streams. In these systems, sediment delivery during runoff events can occupy a large proportion of the period when the channel is flowing. The result is not only a short pulse of turbid water, but repeated event-scale sediment delivery into waterways with limited capacity to dilute, transport or recover between flows.

Unsealed road networks occur across private plantation forests, state forests, national parks and other managed catchments. They are built and used for fire access, recreation, plantation establishment, thinning, harvesting and historic native forest logging. Sediment risk changes through time as road use, traffic, surface condition, drainage condition and maintenance change (Sheridan et al., 2006; Sheridan and Noske, 2007). However, the road formation, drainage structures and crossings can persist in the catchment for decades. This means roads can remain as fine sediment sources long after their original purpose has changed or after active forestry use has ceased.

Unsealed forest and rural road networks extend across many thousands of kilometres, and risk is not distributed evenly across those networks. Sediment delivery depends on catchment factors such as slope, contributing area, drainage density and distance to stream. It also depends on rainfall intensity, soil type, geology, road surface condition and traffic (Sheridan et al., 2006; Sheridan and Noske, 2007). Superimposed on these catchment and climate controls is the design and condition of the road network itself, including road alignment, road width, crowning, drain spacing, table drains, relief culverts, mitre drains and stream crossings. These features control how runoff is generated, where it is concentrated, and whether fine sediment is conveyed from the road to the stream network (Croke and Mockler, 2001; Hairsine et al., 2002; Lane et al., 2006; Takken et al., 2008).

Sediment generated on a road surface is not automatically delivered to a waterway. A road segment may erode but have low delivery risk if runoff disperses onto stable forest floor and sediment is trapped before reaching a stream. Another segment may generate less sediment but deliver a high proportion of it because a drain, gully or crossing connects the road surface directly to the waterway. Sediment delivery risk is therefore controlled by both the amount of sediment produced on the road and the strength of the connection between the road drainage network and the stream network (Croke and Hairsine, 2006). The strength of this connection can be shaped by gully initiation thresholds, overland flow pathways and the decline in sediment concentration with increasing travel distance from the road outlet (Croke and Mockler, 2001; Hairsine et al., 2002; Croke et al., 2005; Lane et al., 2006).

Agencies and land managers responsible for unsealed road networks face a large mismatch between the resources available for maintenance and intervention and the extent of the road network requiring assessment. There is a need for a defensible and transparent way to prioritise where to intervene, based on the locations of highest sediment delivery risk and the greatest return on investment in terms of risk reduction. Field inspection and monitoring remain important, but they cannot cover every road, drain and crossing across large networks. Managers need an evidence-based desktop method that can screen road networks, prioritise field effort, and compare maintenance and intervention options on a consistent basis.

This paper describes an ArcGIS Pro toolbox built to address that need. The toolbox uses published science on road runoff, erosion and road-to-stream connectivity, including studies developed through the CRC for Catchment Hydrology and related field research (Croke and Lane, 1999; Croke and Mockler, 2001; Hairsine et al., 2002; Croke et al., 2005; Lane et al., 2006; Takken et al., 2008). It provides a spatial method for estimating sediment delivery risk from unsealed roads, testing road-drainage and maintenance scenarios, and undertaking preliminary hydraulic screening of culvert requirements at small headwater crossings.

Hydrologic processes in the model

Sediment delivery module

The toolbox is built around hydrologic connectivity. In this context, connectivity describes whether sediment-laden runoff generated on the road surface and discharged through road drains travels across the intervening hillslope and enters a nearby waterway. Connectivity and sediment delivery are calculated for a representative rainfall event, typically a nominated short-duration design storm. The module does not estimate runoff or sediment generated from the broader forest catchment, cleared coupes, hillslope gullies or other non-road sources. Connectivity between a segment of road and nearby waterway is a product of road design (for example whether the road is crowned), road position, road and hillside slope, spacing between road drains, the distance between a drain and waterways, and the ability of the intervening ground surface to infiltrate, disperse or store flow discharged from drains. Building the toolbox around the concept of connectivity follows earlier field and modelling work showing that delivery from forest roads is controlled by the links between drains and waterways via explicit runoff flow paths, not area-averaged concepts such mean erosion rate or road/waterway density (Croke and Mockler, 2001; Hairsine et al., 2002; Croke et al., 2005; Takken et al., 2008).

Using the overarching concept of connectivity, the toolbox models three distinct but closely related processes:

1. **Erosion from the road surface**. Unsealed roads are compacted, trafficable surfaces with low infiltration compared with undisturbed forest soils. Rainfall can produce surface runoff, and that runoff can entrain fine sediment from the road surface, particularly where increased traffic, greater road grade and poor road condition predispose the road surface to erosion. The toolbox uses published road erosion relationships as the starting point for estimating sediment generated from road segments, including work on sediment delivery from different forest road types (Sheridan and Noske, 2007). The relationship estimates traffic-related fine-sediment generation and delivery, not rutting, rilling or deeper gully erosion, and excludes non-road catchment sources.
2. **Runoff from the road surface**. Runoff in this module is calculated from the contributing road surface draining to each outlet, rather than from the surrounding catchment. Drain spacing and road width determine the runoff delivered to each drain outlet. Wider drain spacing increases the catchment of each drain and allows more runoff and sediment to accumulate before flow is discharged from the road. Shorter spacing can the reduce contributing catchment area to a drain, as can road crowning, which sheds some proportion of runoff to the hillslope as diffuse, concentrated flow.
3. **Overland flow delivery**. Not all runoff that leaves a road reaches a stream. Flow can infiltrate, spread or pond on hillslopes and valley floors. Earlier work represented the probability of overland flow reaching streams as a function of discharge from the drain and the terrain of the hillslope between the drain and the waterway (Hairsine et al., 2002; Lane et al., 2006). The toolbox uses that concept to predict the length of the sediment-laden plume discharged from a drain, and then compares that with the calculated distance between the drain and waterway to determine whether a plume reaches a waterway or is dissipated on the intervening hillslope.
4. **Gully initiation**. The model makes a binary prediction of whether runoff from a road outlet is sufficient to initiate a gully and modifies the effective plume travel distance accordingly. It does not model sediment production from pre-existing catchment gullies. Concentrated flow leaving a road drain can incise a flow path if slope, contributing area and discharge exceed a threshold determined from experimental field data compiled by Croke and Mockler (2001). Once a gully forms, the flow path becomes more efficient at transferring water and sediment downslope.

Gully initiation is important because it can convert a diffuse, low-delivery runoff pathway into a direct road-to-stream link. The model makes a binary prediction on gully presence or absence and then modifies the plume length and travel distance accordingly.

5. **Sediment concentration decline**. Field studies show that sediment concentration can decline as runoff travels away from a road because sediment is deposited or filtered along the flow path (Croke et al., 2005). This is the mechanism behind many road buffer and drainage practices. The model represents this decline so that the concentration of sediment in any plumes that do reach the stream account for deposition on the intervening hillslope.

The relationship between these processes is shown in Figure 1.

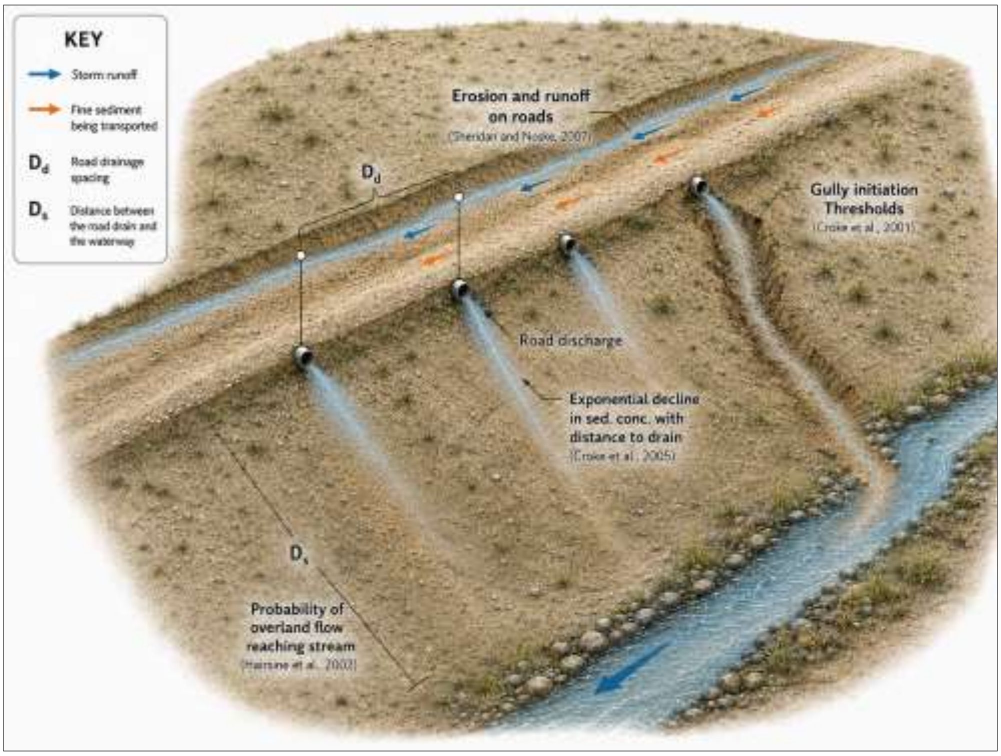

Figure 1 Conceptual model for road-waterway connectivity

Culvert sizing module

Crossings of first- and second-order streams commonly occur in steep headwater terrain, where road approaches are also steep and can efficiently route runoff and sediment directly to the channel. Undersized culverts increase sediment-delivery risk to downstream waterways by impounding water upstream, increasing the likelihood of outflanking – where a new channel is scoured around the culvert, or overtopping, which strips sediment from the road surface directly above the culvert. Flow overtopping a culvert can trigger scour on the downstream side, causing a headcut to develop and then migrate upstream, undermining the culvert and adjacent banks. These processes can destabilise the crossing, creating an additional, concentrated source of sediment from waterway erosion and completely connect the adjacent roads to the waterway. Appropriate culvert sizing is therefore a core part of the Forest Road Erosion Toolbox because it reduces the likelihood that stream crossings become failure points in the road drainage network due to undersized culverts.

This module is separate from the road-sediment calculation described in the previous section. The culvert sizing module represents the hydrological process by which rainfall over the upslope catchment is converted to an estimate of peak discharge at a road–waterway crossing. It implements the Rational Method to estimate peak discharge from the contributing catchment area, design rainfall intensity and an assumed runoff response for the upslope landcover (vegetation cover is represented by a runoff coefficient, which can be modified by the user). This provides an estimate of the flow that must be conveyed through the crossing under nominated design rainfall events. The resulting discharge is then used to calculate appropriate dimensions for either box or circular culverts, allowing culvert requirements to be rapidly screened for small headwater stream crossings where the Rational Method is suitable. The culvert sizing module does not account for or represent sediment delivery to the culverts. The resulting discharge is used to calculate preliminary dimensions for box or circular culverts at small headwater crossings where the Rational Method is applicable. These outputs are intended for network-scale screening and comparison, not as a substitute for site-specific hydraulic design, road-safety assessment, geotechnical assessment, debris allowance, fish-passage design or professional engineering certification. The culvert sizing module is shown conceptually in Figure 2.

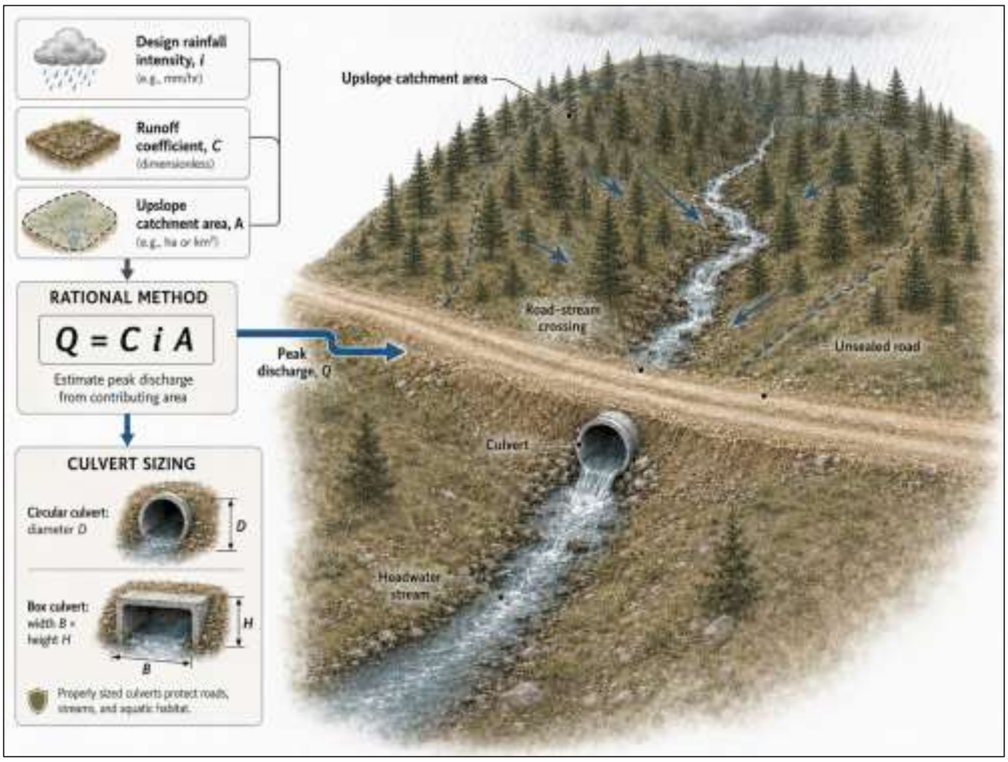

Figure 2 Overview of the culvert sizing module

Model interface and output

The Forest Roads Erosion Toolbox is implemented as an ArcGIS Pro toolbox that converts spatial inputs into a network-scale assessment of road runoff, road–waterway connectivity, sediment delivery risk and culvert sizing requirements. At the simplest level, the user supplies a road network and an underlying digital elevation model. The terrain surface may be a coarse regional DEM or a higher resolution LiDAR-derived DEM where available. Higher resolution DEMs improve the representation of short flow paths between roads, drains and waterways, which is important because road–waterway connectivity often depends on local topography that is poorly resolved in coarser terrain data.

The toolbox can be used as a desktop screening tool, a scenario-testing tool, or an existing-condition assessment tool. In desktop mode, it identifies where sediment delivery risk is likely to be highest across a road network. In scenario mode, users can test the effect of alternative drain spacing, road crowning and surface cover assumptions, represented through runoff coefficients. In existing-condition mode, users can supply field-surveyed drain locations to assess the sediment delivery potential of the actual road network. These uses can be staged: a baseline desktop run can identify likely hotspots, guide field surveys, and then be rerun with surveyed drainage data to refine the assessment. The relationship between inputs and outputs of both of the model modules is shown schematically in Figure 3.

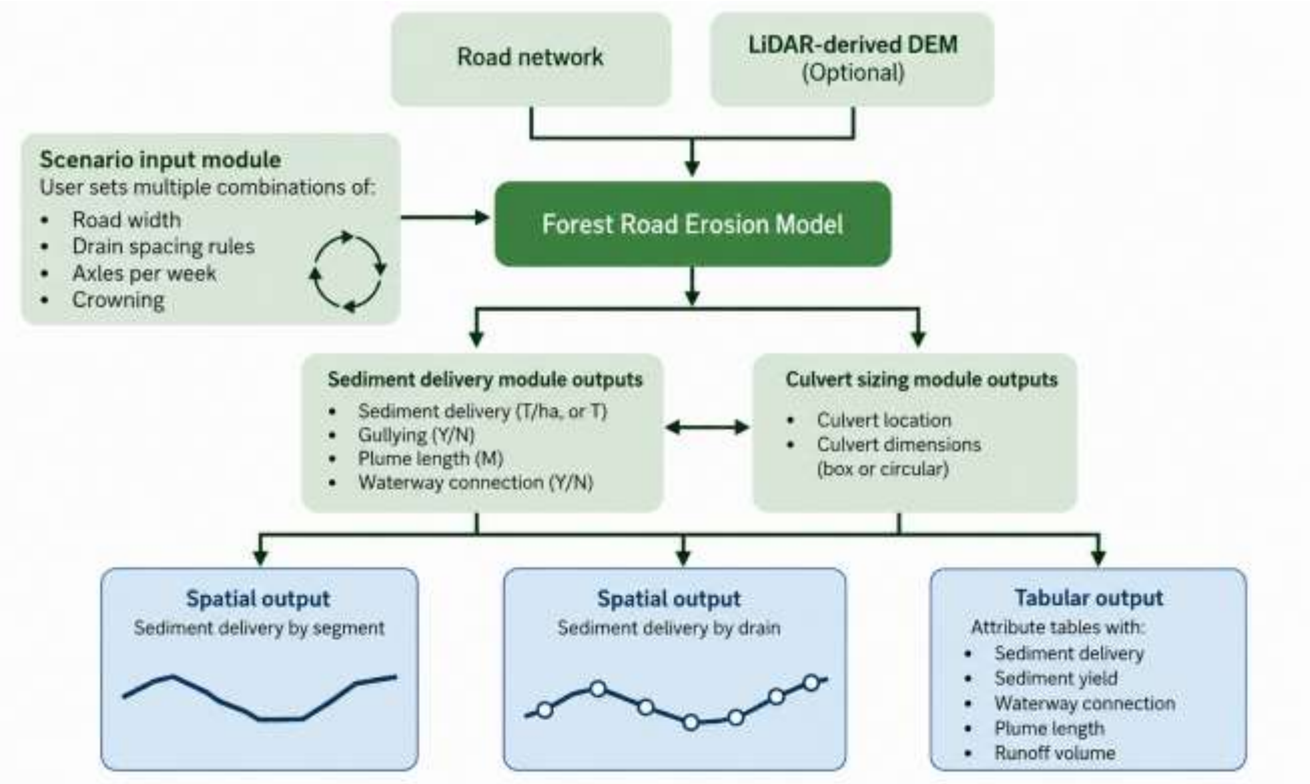

Figure 3 Forest Roads Erosion Toolbox workflow, input and output data

The toolbox derives the drainage network and flow pathways from the terrain surface, identifies road–waterway crossings, and segments the road network into contributing road units draining to individual outlets. Where drain locations are not supplied, drain points are generated from the road alignment, topography and assumed drain spacing. Where surveyed drains are supplied, those locations are used directly. The model then estimates runoff volume, plume length, road–waterway connection status, sediment concentration and sediment delivery for each road segment and associated drain under the selected design storm.

The outputs are spatial vector datasets with attribute tables attached to road segments, drain points and crossing points. These can be displayed as colour-coded road lines or drain points showing relative sediment delivery potential, connectivity status, plume length, runoff and sediment mass. The same output structure supports scenario comparison, allowing users to assess how changes in drain spacing, road crowning or runoff coefficient alter the magnitude and spatial pattern of sediment delivery. Results can also be exported or summarised by road class, sub-catchment, coupe, tenure or management unit to support network-scale reporting and prioritisation.

For the culvert sizing module, the toolbox uses the derived drainage network and road alignment to identify potential road–waterway crossings. It then delineates the contributing catchment area upslope of each crossing, estimates design peak discharge, and converts that discharge into recommended dimensions for box or circular culverts. This provides a mapped crossing dataset that can be reviewed alongside the sediment delivery outputs, allowing hydraulically sensitive crossings and sediment delivery hotspots to be considered within the same ArcGIS Pro workflow. An example of the model interface is shown in Figure 4.

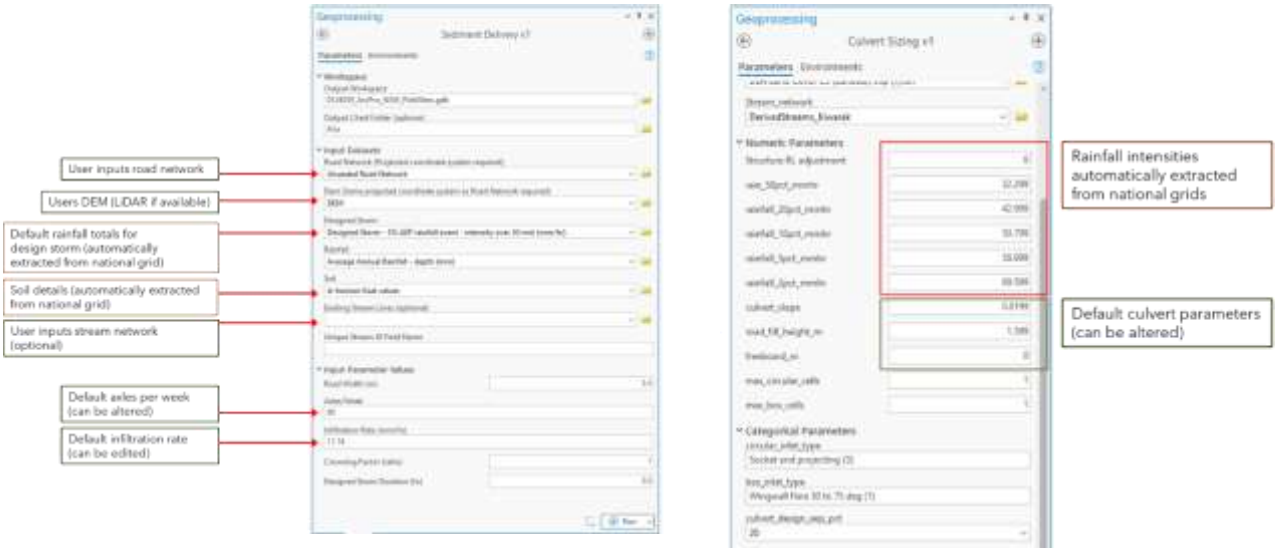

Figure 4 The user interface of the Roads erosion and culvert sizing modules

Example model output

The example outputs below show application of the toolbox to roads in Kirawak Forest, NSW. In this example, drain locations were modelled using assumed road-drain spacing consistent with Forest Practices Code Part 1, which specifies drainage spacing based on road slope. The first image shows predicted sediment delivered to waterways during the 30-minute design event from individual road drains, highlighting discrete drain outlets with higher delivery potential. The second image aggregates the same results to road segments, showing where sediment delivery risk is concentrated along the road network and where maintenance or drainage interventions would most likely reduce delivery to waterways.

Conclusions

Persistent fine sediment delivery from unsealed roads remains a practical waterway-management problem because sediment risk is generated across large road networks but delivered through a smaller number of connected drains, crossings and road segments. Road managers need to manage this risk at network scale, often with limited field data, constrained maintenance budgets and many kilometres of road requiring assessment. The toolbox provides a consistent way to estimate the quantum of sediment delivery risk, map how that risk is distributed, and identify the hotspots that matter most for waterway protection. This allows managers to prioritise field inspection and maintenance, compare the relative sediment-delivery consequences of alternative drainage and maintenance scenarios, and identify crossings where preliminary hydraulic screening indicates that culvert capacity warrants further assessment The value of the tool is not that it replaces field judgement, but that it focuses that judgement where it is most useful and gives managers a defensible basis for comparing risk, treatment options and investment across large unsealed road networks.

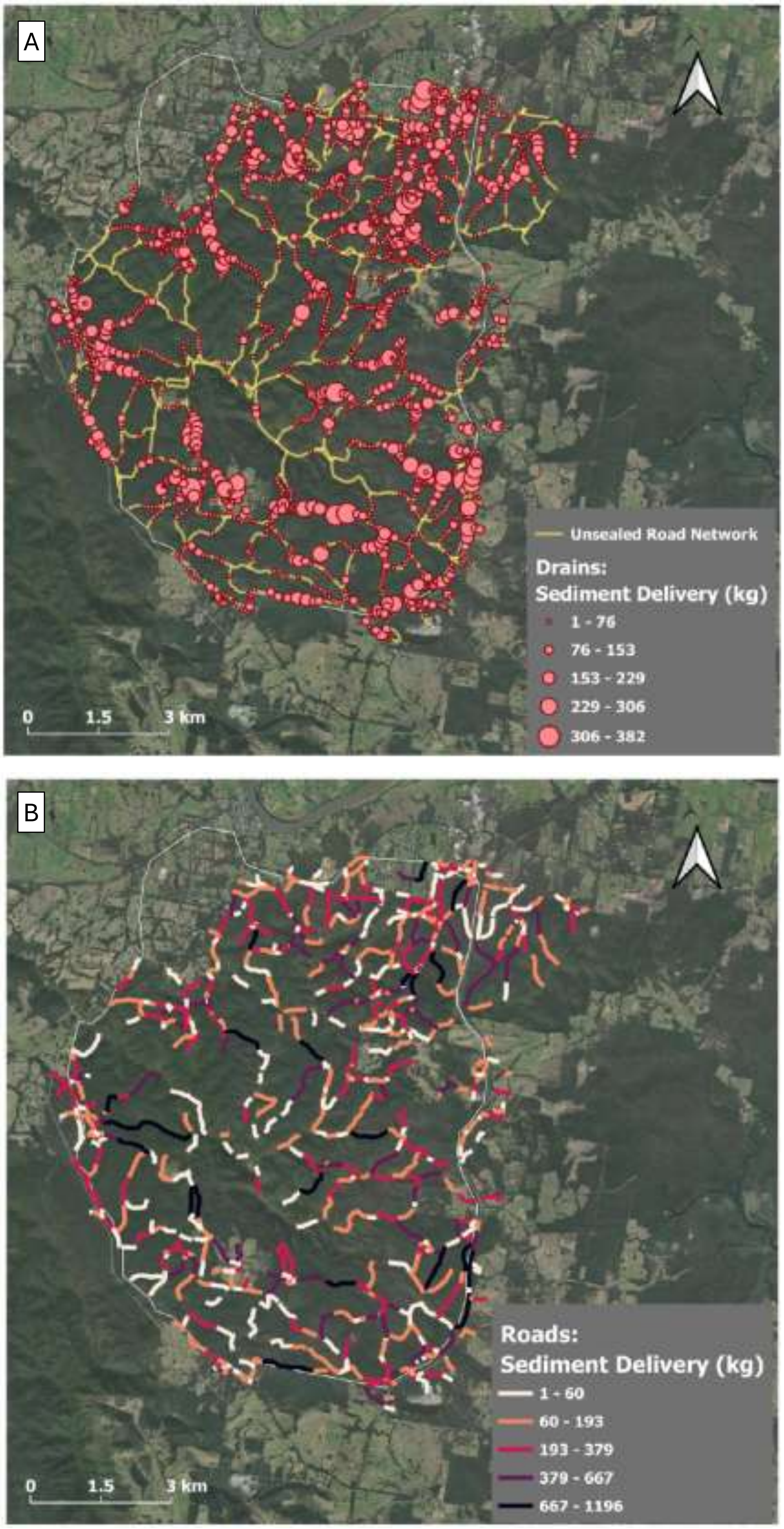

Figure 5 Predicted sediment delivered to waterways during the 30-minute design event, shown for (a) individual road drains and (b) aggregated road segments, Kirawak Forest, NSW

Acknowledgements

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