TOOLBOX FOR MODELLING SOURCES, PATHWAYS, AND DELIVERY OF SEDIMENT IN FORESTED WATER SUPPLY CATCHMENTS

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ABSTRACT
Forested catchments are a key asset for water security. We have developed a package of modelling tools that quantify sediment delivery risks from bushfires, forestry operations, and unsealed road networks within a unified water quality risk framework. By combining landslide and sheetwash models, road-to-stream connectivity models, and bushfire impacts on vegetation and soils, it translates complex catchment processes into management-ready outputs. The toolbox produces risk maps and catchment-scale estimates of sediment delivery, which can be directly linked to water quality. The package equips utilities and catchment managers with defensible, science-based insights to optimise investment in management to safeguard drinking water and protect waterways.

INTRODUCTION

Sediment and associated contaminants generated from land disturbance are among the most significant threats to drinking-water security, aquatic ecosystem health, and the long-term viability of land management practices. Across forested and fire-prone landscapes, three drivers emerge as key risks:

- Bushfires – intense rainfall on burnt slopes produces rapid ash, nutrient, and sediment delivery to streams (Smith et al, 2009; McGuire et al, 2015).
- Timber harvesting – vegetation removal increases susceptibility to landslides and sheetwash erosion during the “window of vulnerability” post-harvest (Phillips et al, 2024)
- Unsealed road networks – chronic sediment inputs delivered via hydrologically connected drains and culverts (Croke et al 1999, Hairsine et al, 2002).

Individually, each process has been studied, and there is a wealth of knowledge and models available in the peer-reviewed literature. However, the knowledge and modelling capability are not accessible operationally by those working in the water and catchment management sectors.

In this project, we consolidate the science and modelling capability into a consistent, modular integrated modelling package that quantifies sources, pathways, and delivery of sediment to receiving waters. The approach directly links physical erosion processes to water-quality risk and management levers, creating a defensible risk basis for utilities, regulators, and forest managers.

THE TOOLBOX DESIGN

The tool was developed from syntheses of data and concepts in the peer-reviewed literature, drawing on decades of research in Australia and elsewhere on forest hydrology and geomorphology. Its development has been driven by emerging needs amongst land and water management sectors for bespoke tools that are framed around risk and built from the bottom up based on the dominant processes that contribute towards risk.

Common features that have informed our design are the need to 1) move away from predicting spatially averaged annual sediment loads and instead capture the episodic and patchy patterns of erosion and sediment delivery, and to 2) represent the erosion and sediment delivery processes in ways that capture the management levers that are relevant for mitigation. For example, when predicting erosion from forest road networks, we need models that capture the drainage design elements that dictate how runoff accumulates and drains off the road surface. That is where we can make a difference through adjustments to management practice.

The tools have been scripted using Python and developed into libraries that users can implement with minimal coding expertise required. The library integrates three complementary modules that predict sediment delivery in response to the impacts from bushfire, timber harvesting, and forest road networks (Figure 1).

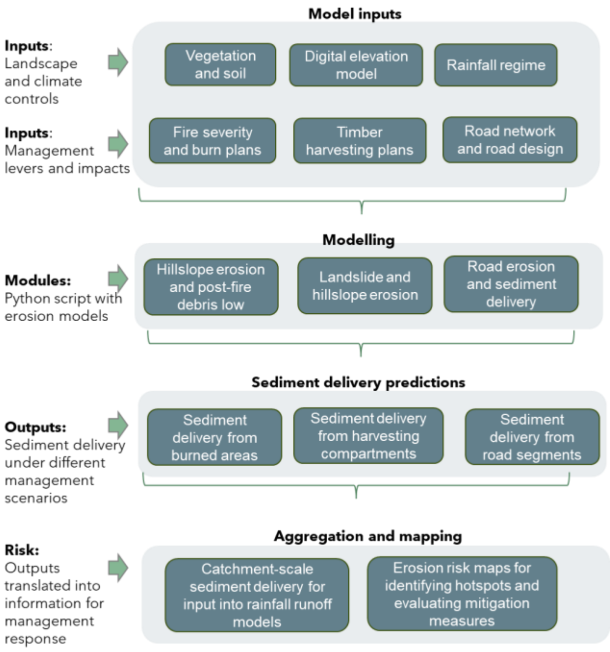

Figure 1: Overview of the toolbox

Each module is developed as a standalone library, allowing for flexibility in implementation. Outputs are developed into susceptibility maps and event-based sediment delivery predictions for design storms or time series of rainfall. Rainfall is needed as input to all the tools and can be obtained from observations, stochastic rainfall generators or intensity-frequency-duration curves. For the bushfire module, the outputs can be integrated into water resources models such as eWater Source, and the aim is to achieve this integration for the other modules as well. For all the modules, the terrain, flow accumulation and drainage networks are generated from either SRTM 1-second hydrologically enforced DEM from Geoscience Australia (default), or from a lidar-derived DEM.

Bushfire

- Uses data on landscape attributes and fire severity simulate ash, nutrient, and sediment pulses following fire (Table 1).
- Uses empirical data from post-fire runoff studies, coupled with rainfall–erosion thresholds, to quantify loads at the catchment outlet (Table 1).
- Supports rapid post-event scenario testing for utilities managing degraded source water.
- Event-based, capturing erosion from rainplash/sheetwash as well as rilling and scouring, which occur when critical stream power thresholds are exceeded.
- Produces predictions of sediment delivery to streams from hillslopes and gullies within the fire footprint (Figure 2).

Table 1: Inputs to the bushfire impact module

Key inputs	Source
Fire severity	The difference Normalised Difference Burn Ratio (dNBR), calculated using Sentinel satellite imagery.
Soil properties	Soil and Landscspe Grid of Australia available from TERN
Landscape aridity	Aridity index calculated from local rainfall, temperature and radiation
Background soil erodibility	Obtained from CSIRO database on RUSLE factors
Fire impact factors	From various research papers describing the relationship between fire, runoff and erosion (Biswas, 2020)

Timber harvesting

- Combines a statistical landslide susceptibility model (trained on observations) with a RUSLE-based sheetwash model (Table 2).
- Accounts for slope-to-stream connectivity through sediment delivery ratio, which varies with vegetation cover and slope.
- Captures the elevated “window of vulnerability” post-harvest, when root strength declines and regrowth has not yet stabilised soils.
- Outputs exceedance curves showing the probability and duration of turbidity thresholds being exceeded, informing harvest scheduling and treatment cost analysis.

Table 2: Inputs to the timber harvesting module

Key inputs	Source
Landslide inventory	Mapped landslides following events with known rainfall intensities (Betts et al, 2023)
Time since harvest and planned logging rotations	Spatial data from forestry operators or publicly available datasets (e.g. Logging history overlay)
Surface soil erodibility of in logged areas	From research describing the relationship between soil erodibility and timber harvesting activities (Marden et al, 2006)
Landslide response to harvesting	From research describing the relationship between hillslope stability and timber harvesting activities (Phillips et al, 2024)

Forest road networks

- Segments unsealed roads based on topographic highs and lows and applies empirical runoff/erosion relationships to represent erosion and sediment delivery.

- Accounts for road-to-stream connectivity using a model of infiltrating overland flow plumes on hillslopes.
- Incorporates road design parameters (drain spacing, culvert placement, road width) and connectivity decay with distance to streams.
- Produces spatial risk maps and supports cost–benefit prioritisation of maintenance and culvert upgrades

Table 1: Inputs to the forest roads erosion module

Key inputs	Source
Road network	From national databases or road networks held by agencies
Drainage structures	From road inventories, design guidelines, or field surveys
Hillslope hydrology	From field measurements that characterised the behaviour of overland flow plumes (Hairsine et al, 2002)
Erodibility of compacted road surfaces	From various research papers describing the relationship between sediment generation and road attributes such as slope, traffic and local climate (Sheridan and Noske, 2007)

ILLUSTRATIVE CASE STUDIES

Bushfire in Melbourne’s drinking water catchments

The city of Melbourne sources nearly all of its drinking water from forested catchments. These catchments support some of the most flammable forests on earth. When they are burned, the catchments represent a major risk to the treatability of source water. Erosion from burned catchments leads to increased delivery of sediment, nutrients and other constituents into water reservoirs. These can cause increased costs of supplying water or even disruption to the supply.

Water utilities and fire managers can greatly benefit from having insights into the magnitude of impact and what this means for the delivery of water quality constituents. Together, these provide a means for 1) post-fire risk mapping and response and 2) scenario-based planning to improve preparedness through fuel and catchment management activities.

To date, the model has been used to identify locations for installing sediment control measures, including debris nets and post-fire hillslope mulching. The model has also been paired with a fire regime simulator to understand how fire and fuels can be best managed to achieve water quality outcomes that minimise treatment cost and risk of water supply disruptions. A model of reservoir hydrodynamics has been developed for the reservoir, allowing catchment managers and reservoir operators to examine the implications of post-fire erosion and mitigation activities for water quality at the reservoir offtake, after dilution and settling within the reservoir (Nyman et al, 2020).

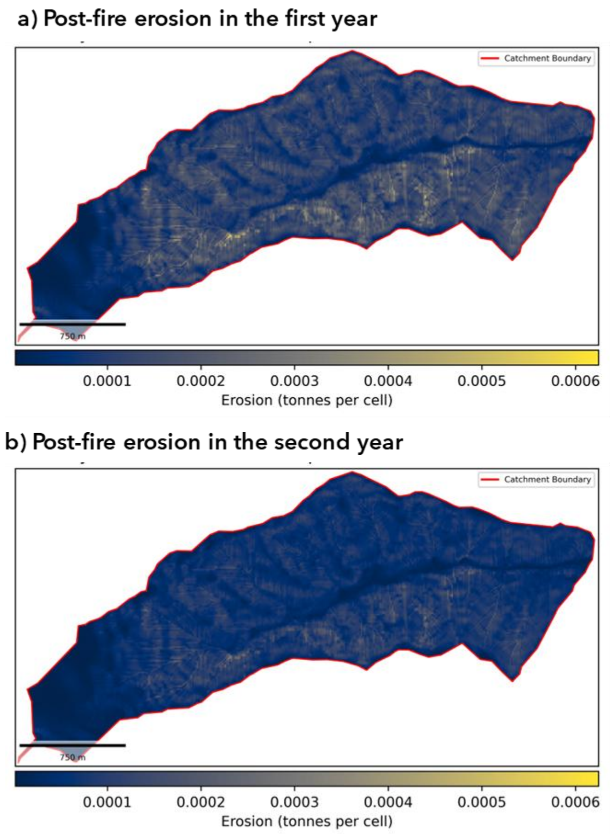

Figure 2: Example outputs (maps) showing hillslope erosion rates in the first (top) and second (bottom) year after bushfire

Timber harvesting in Auckland's drinking water catchments

Since 2017, the Hūnua Forest outside of Auckland has been managed to begin the transition of an exotic forest into native forest cover. This follows concerns being raised about previous commercial forest activity within the catchment, and about the viability of ongoing commercial forest management within one of Auckland’s main water supply catchments. From 2025, 695 hectares of forest within the catchment area of Cosseys Reservoir, Upper Mangatawhiri Reservoir, and Wairoa Reservoir could be harvested at a rate of up to 160 ha per year, over 5 years, based on the estate harvest plan. The harvest area will primarily be within the Cosseys Reservoir catchment. Vegetation removal and land disturbance associated with harvesting are a concern for Watercare due to the increased likelihood of erosion within these areas during the post-harvest vegetation recovery period. Erosion triggered by rain events within the Hūnua Ranges has previously been concentrated within areas that were recently harvested (Lee, 2020)

The model of post-timber harvest erosion has enabled Watercare to evaluate the risk that forest harvesting poses to water treatability in the Cosseys, Wairoa, and Upper Mangatawhiri Reservoirs. The modelling framework integrates validated, event-scale models that simulate sediment generation and delivery under varying rainfall intensities and harvest scenarios. While the models have been validated against published sediment yield data and historical events, it is important to note that landslide processes are inherently complex and threshold-driven.

The impact of harvesting is captured in the landslide model by upscaling the landslide probability predicted by the baseline (Figure 3) model for each year within the approximately five-year-long window of vulnerability post-harvest (up to a maximum probability of 1). The upscaling of landslide probability is based on the post-harvest landslide density data presented in Phillips et al., 2024. This data was used to extract scaling factors, proportional increases in landslide probabilities for each year post-harvest.

Watercare are using the model to examine different options regarding the scheduling of forestry activities, to ensure harvest areas are not causing disturbance to the point where water quality impacts incur costs to water treatment. The timing, location and size of harvesting compartments can optimised to minimise impacts. The tool allows for scenarios to rapidly assesses and visualised.

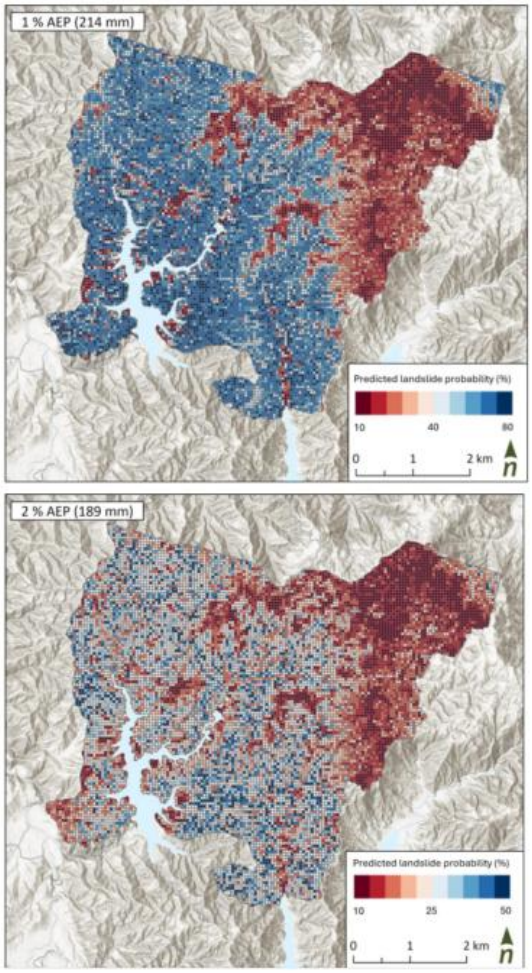

Figure 3: Landslide probabilities predicted for rainfall events with different daily totals corresponding to annual exceedance probabilities of 1% (top) and 2% (bottom).

Forest road networks senstive coastal catchment of coastal NSW

The NSW forestry sector is operating under conditions (or codes) that are designed to minimise impacts on environmental values. Regarding water quality and catchment health, the management of unsealed forest road networks is a key focus area. Unsealed roads are a significant contributor of sediment to streams in forested systems (Motha et al, 2003; Croke and Hairsine, 2006). However, with the right designs and maintenance regimes, the contribution of roads to sediment delivery can be greatly reduced. Through road drainage design and maintenance, the erosion from road surfaces and the connectivity between roads and the stream network can be minimised such that sediment delivery does not have adverse impacts on water quality (Croke and Hairsine, 2006). Forest road networks are extensive and it is therefore impractical to monitor all roads in terms of their environmental performance. Models are useful in that they offer opportunities to quantify and map risk without having to conduct detailed field surveys.

Our model provides forest managers with a tool that generates water quality risk profiles for forest road networks, as well as providing insights on the effectiveness of road design and drainage in reducing risk. The tool takes information on road placement, drainage structures, rainfall and topography to quantify the mass of sediment that could be delivered to streams. The user can modify parameters to examine how changes to drainage controls modify patterns of erosion and sediment delivery. Results can be visualised in different ways to understand the

- Risk of sediment delivery from specific segments along the road network
- Risk from the entire road network above a specific point on the waterway.
- Changes in these risks under different road designs and management practises

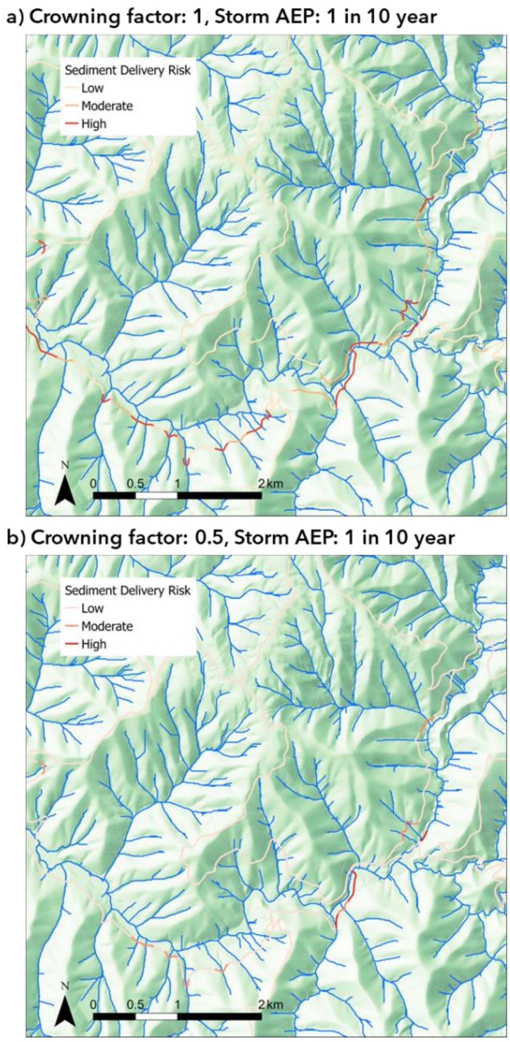

Figure 4: Segmented forest road network showing sediment delivery potential as determined from road attributes and connectivity with streams.

CONCLUSION

Collectively, the models form a consistent, transparent architecture that translates diverse erosion processes into management-ready risk metrics, supporting operational decisions, regulatory compliance, and long-term investment strategies (Figure 1). The team has worked closely with forest managers, water utilities, and fire managers to ensure the model functionality is aligned with the type of questions and management levers that can be deployed to mitigate risks. Some key opportunities for integration with management include:

- Post-fire risk assessment in water supply catchments
- Evaluating the effectiveness of prescribed burning and mitigation strategies in forestry operations
- Optimising scheduling of timber harvesting to minimised impacts on erosion and water quality
- Designing and maintaining forest road networks to benefit waterways and water quality

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