# Post-fire debris flow mapping in the Tumut and Tuross Catchments

**Technical report**

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**Natural Resources Commission**

# Post-fire debris flow mapping in the Tumut and Tuross Catchment

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## Contents

# Summary

Large bushfires in southeast (SE) Australia during the summer of 2019/20 resulted in changes to catchment conditions, leading to increased sediment delivery into waterways. These have, in turn, impacted aquatic ecosystems such as coastal lagoons, wetlands, rivers and reservoirs. The impacts have been significant, yet there is a paucity in data needed to understand the drivers behind large sediment delivery events or 'sediment slugs' which are detrimental to waterway health. The lack of data has meant that there has been limited opportunity to leverage existing research in SE Australia (from Victoria in particular) to test and apply predictive models and risk assessment tools to landscapes in NSW.

The objective of this project is to build a dataset for NSW that can be used in evaluating and modelling the impacts of bushfire on sediment delivery to waterways. The project uses an existing methodology for mapping erosion events that was developed in earlier research projects in Victoria and ACT. The mapping focuses on identifying the location of post-fire generated debris flows, which is a threshold driven erosion process that has the potential to generate very high sediment loads (more than 100 t/ha) in a few hours.

The project was designed to capitalize on the opportunity for data collection that emerged with a large and high-severity bushfire followed by several periods of intense rainfall. Our understanding of large episodic erosion events after bushfire is limited and there are few datasets available to provide the insight necessary to advance our knowledge on the processes and their impacts. The window of opportunity for collecting this type of data is narrow, as vegetation recovery tends to obscure erosion features within 1-2 years of bushfire events.

The data associated with this analysis can be accessed at the TERN Data Discovery Portal, and this work will also be shared on the NSW Government's central resource for Sharing and Enabling Environmental Data (SEED). The data will inform further empirical analyses as well as the development and testing of post-fire catchment risk assessment tools. Such tools and the additional insight that can be gained from further data analysis will provide a means for managing risk to water supply reservoirs and other critical infrastructure, and for optimizing forest management activities to reduce the likelihood of triggering adverse impacts from fire-related erosion.

The methodology uses aerial imagery to identify locations of post-fire debris flows that are likely to pose risk to waterways and infrastructure. The erosion events are identified by mapping channel initiation points (CIPs) and debris flow fans. Channel initiation points are typically located at the base of steep hillslopes and represent the point in the landscape where the erosive force of overland flow exceeds the threshold for channel sediments to mobilize. Together, the data on channel initiation points and debris flow fans, reflect the intensity with which post-fire debris flow processes are operating in a catchment.

For NSW catchments, this is the first time that post-fire debris flows have been systematically mapped and linked to fire severity and other landscape attributes. The mapping complements previous work in the Warrumbungles National Park, where debris flows were identified as an important post-fire erosion process[1]. With the erosion mapping, geoprocessing and spatial analyses, the project has delivered a comprehensive inventory of post-fire channel incision and debris flows in catchments that are representative of much of the non-sandstone dominated parts of the SE NSW region.

The study mapped debris flows in two catchments:

- **Tumut Catchment**. The Tumut catchment was impacted by the Dunns Road Fire. The fire burned 334,000 hectares. It started from lightning on December 27, 2019. The fire was officially extinguished on February 24, 2020. Imagery was obtained for an area covering about 1735km$^2$. This study determined there were 785 channel initiation points (CIP) and 211 fan deposits in the Tumut study area. The overall CIP density in the study area is 0.45 CIPs per km$^2$. Within 1km grids, the density ranged from 0 to 22 CIPs per km$^2$. With a

[1] Tulau, M.J., Nyman, P., Young, M., Morand, D., Mcinnes-Clarke, S.K. and Noske, P., 2019, December. Mass Movements of Warrumbungle National Park, New South Wales, Australia. In Proceedings of the Linnean Society of New South Wales (Vol. 141).

density of 22 CIPs per $km^2$, this landscape has been subject to post-fire erosion events that produce sediment yields that are up 40 times above the annual erosion rate that would be expected from an undisturbed catchment. When assessed at the scale of the 1km grid, the data suggests that about 10% of the study area has been impacted by sediment delivery events associated with the mapped CIPs and the downstream channel erosion that they have triggered.

- **The Tuross Catchment.** The Tuross catchment was impacted by the Badja Fire, which was ignited by a lightning strike on December 27, 2019. The fire burned 315,500 hectares. The fire was extinguished in March after heavy rainfall. Imagery was obtained for an area covering about 737$km^2$. This study identified 273 CIPs and 146 fan deposits. The overall CIP density in the study area is 0.37 CIPs per $km^2$. Within 1km grids, the density ranged from 0 to 11 CIPs per $km^2$. With a density of 11 CIPs per $km^2$, the landscape is subject to post-fire erosion events that produce sediment yields that are up 20 times above the annual erosion rate expect from an undisturbed catchment. When assessed at the scale of the 1km grid, the data suggests that about 12% the study area has been impacted by sediment delivery events associated with the mapped CIPs and the downstream channel erosion that they have triggered.

The exploratory analysis demonstrates that the debris flow processes operating in the two case study catchments are very similar to observations from eastern Victoria, where models of post-fire debris flow have been developed and tested, and where risk assessment processes are well established. There are consistent trends in the landscape attributes that are associated with channelized erosion in headwaters and debris flow occurrence. The post-fire erosion processes that have been documented in this study contrast with what has been documented previously in southeast NSW, where research effort to date have been focused largely on the Hawkesbury sandstone landscapes in the Sydney Basin.

Some key findings with respect to landscape effects on CIPs and erosion by debris flows include:

- The importance of fire severity in influencing debris flow frequency. The frequency of debris flows increases markedly when a bushfire results in crown scorch and crown burn.
- The importance of forest type. In this study, dry forests have much higher frequency of debris flow than wetter forest types. This is consistent with observations in Victoria that show that debris flows occur more regularly in dry forest types. In previous work, the link between forest types, contrasting moisture regimes, and debris flows has been developed further by considering the effects of aridity which is an important proxy for soil hydraulic properties (bulk density, infiltration capacity) and therefore erosion response. Drier moisture regimes mean lower porosity and therefore less infiltration. The link between aridity and soil properties might partially explain the higher debris flow frequency in Tumut when compared to the Tuross study area. By linking the occurrence of extreme erosion events such as debris flows to landscape attributes that have been mapped, we provide a basis for more focused efforts to mitigate risk as part of fire management or post-fire response.
- The importance of lithology. Post-fire debris flows appear to be more common on sedimentary and volcanic terrain and less common on granitic terrain. This result is consistent with observations from fire-affected catchments in Victoria. Considering geology in assessments of post-fire erosion risk, will lead to more focused efforts around management and mitigation.
- The study did not analyze erosion processes at a spatial resolution that would support conclusive remarks with regards to the role of forest roads on post-fire erosion. There is anecdotal evidence from the 2019/20 bushfire and other burned areas that roads trigger increased flow concentration and therefore increased likelihood of gully initiation. The analysis in this report found some correlation between road density and the density of channel initiation by debris flows in the Tumut study site. However, at the spatial resolution of this assessment, the local effects of roads are likely to be masked by variability in fire severity and terrain, which emerge as more important factors contributing to debris flows at the landscape scale. The datasets in this report should be explored further to determine if there are local features related to roads and forest management that have an impact on debris flow occurrence and channelized erosion.

- Areas within the catchments classified as softwood plantations or agricultural land do not have higher debris flow frequency than native forest. Thus, at the scale of our analysis, it seems debris flow frequency does not appear to be affected by intensive land use. Factors such as slope, and fire severity appear to be more important at the scale of the fire footprint. More detailed examination of the data might reveal localized effects of land use, whilst controlling for other factors.

In terms of landscape controls on debris flow occurrence in the study areas, there is strong similarity with catchments in eastern Victoria. This means that the conceptual frameworks of risk assessment and the modelling tools developed within those frameworks might be transferrable from the Victorian forest management settings to the type of landscapes represented by the Tumut and Tuross catchments. It might therefore be beneficial to apply and test existing models and risk assessment tools to these settings in SE NSW. Those tools will help inform catchment managers, land managers, and water utilities about hotpots for erosion risk and potential management intervention that can be pursued to reduce the chance of those hotspots burning at high fire severity.

More generally, regarding bushfire, forest management and sediment delivery to waterways, this study points to the importance of considering episodic erosion events when establishing baselines and setting management objectives and strategies. Sediment transport and availability in waterways are functions both persistent background sediment sources (e.g. undistributed forests, roads, streambank erosion) and episodic sources that are typically related to stochastic processes. The role of episodic events is particularly relevant in the current environment, where climate change is likely to cause intensification in the processes (high intensity rainfall and bushfire) that govern the frequency of threshold driven erosion events such as debris flows and landslides. Generating data and models to improve understanding of how erosion regimes might play out into the future under different land use and forest management scenarios should be a priority for research.

In view of the findings in this report, and the current state of knowledge in NSW regarding bushfire, forest management and sediment delivery, we propose the following priorities for research and model development:

- **Recommendation 1**: Use the debris flow inventory from this study and supporting datasets to conduct empirical analyses that quantify the relative importance of fire severity, terrain, aridity, geology, and anthropogenic factors in causing variability in debris flow frequency. Calculating a high-resolution aridity data layer for NSW, would assist with such an analysis, given that it is likely to be a key landscape attribute contributing to variability in debris flow frequency.
- **Recommendation 2**: Develop conceptual models of sediment dynamics in forested catchments of NSW, which aim to identify dominant erosion processes operating in different geomorphic and hydroclimatic settings, and how these dynamics may play out over the longer term with predicted changes in rainfall, bushfire, and different land management scenarios.
- **Recommendation 3.** Initiate new research programs for quantifying sediment sources and building sediment budgets for forested catchments, with a view to provide a longer-term perspective on the implications of forest management, bushfire and rainfall regimes for water quality and sediment dynamics in waterways of NSW.
- **Recommendation 4**: Facilitate a process for knowledge exchange and data sharing amongst relevant agencies and researchers. This will avoid duplicating efforts, it will lead to better research outcomes and result in improved efficiency in research and model development. There are models and risk assessment frameworks already in place that are used routinely by Victorian fire and land management agencies to manage erosion risk associated with bushfire and planned fire. Working to implement and test these models for the areas covered by this study would fast track the uptake of existing research and improve management of post-fire erosion risk in NSW.
- **Recommendation 5:** Develop water quality monitoring programs coupled with debris flow field surveys to better understand the ecological implications in space and time of sediment pulses from post-fire erosion.

This will provide insights into how bushfires play out as disturbance agent in aquatic ecosystems, both in terms of water quality and sedimentation, and thereby help guide and prioritize efforts to mitigate risk with well-targeted forest and waterway management activities.

# 1. Introduction

## 1.1 Project background

Large bushfires in SE Australia during the summer of 2019/20 have resulted in changes to catchment conditions. Runoff rates and sediment delivery have increased, and these have affected ecosystems, including coastal lagoons and wetlands, rivers and reservoirs (Biswas et al, 2021; Silva et al, 2020).

The consequences are clearly documented, but the processes and landscape controls that dictate where consequential impacts occur remain largely unknown. Across burned areas, the impacts of post-fire hydrology on waterways and water quality depends on a range of factors including landscape attributes, fire severity, post-fire rainfall events, land-use history, and degree of connectivity between the bushfire impacted areas and the waterway values at risk.

Sediment delivery associated with bushfire is episodic and patchy in space. These features need to be understood and quantified to provide benchmarks for evaluating impacts of forest management on sediment transport and waterway health. Establishing such benchmarks and providing context around bushfire, climate change and impacts on waterways is a recommendation from a recent review by Alluvium (2020) funded by the Forest Monitoring and Improvement Program. The review, which focused on timber harvesting and impact on waterways, pointed to the need for more contextual data on sediment delivery from forests, with emphasis on the erosion events that occur when catchments have been disturbed by bushfire. Improved understanding of sediment delivery from forests and its links to fire regimes and landscape attributes will lead to more informed management of soil and water resources in forested catchments. The empirical data and subsequent model development can highlight where in the landscape there are opportunities for risk mitigation and how those can be realized through changes in land management practices.

## 1.2 Objectives

The objective of this project is to build a dataset on post-fire debris flows for NSW that can be used in evaluating and modelling the impacts of bushfire on sediment delivery from post-fire debris flows. The project uses a methodology (from Nyman et al, 2015) for mapping post-fire debris flows using aerial imagery, that was developed in earlier research projects in Victoria and ACT. Data collected using this type of methodology has formed the basis for significant advances in our understanding of catchment response to bushfire and in the development of predictive models (see for example Nyman et al 2022; Kean et al, 2019; Nyman et al 2019, Rengers et al, 2016). The work will provide a basis for improved understanding of post-fire erosion processes and form important context around forest management in NSW, bushfire, and implications for water resources. The project focuses on the Tumut and Tuross Catchments in southern NSW.

The methodology and analyses are documented such that future data collection efforts provide datasets that are consistent with management application and research efforts currently underway in Victoria and ACT (Alluvium, 2019, Sheridan et al, 2022). As such, the project seeks to provide an opportunity for leveraging existing knowledge and accelerate the uptake of research for application to catchments in NSW, where the knowledge on threshold driven post-fire erosion processes, such as debris flows, is lacking.

# 2. Background on bushfire and erosion risk

## 2.1 Bushfire impacts on catchments and forest hydrology

Bushfire has large implications for catchment and water resources management. There are two key mechanisms by which bushfire can impact on catchment hydrology in temperate forests of SE Australia.

First, there is the immediate post-fire increase in surface runoff where reduced vegetation cover and water repellent soils result in much more overland flow during rainstorms. More overland flow in the post-fire period means more erosion, debris flows and dangerous flash-flooding from hillslopes and steep upland drainage networks. In the event of intense rainfall, high concentrations of sediment and nutrients enter streams, rivers, and reservoirs. Bushfire-effects on surface runoff and erosion in eucalypt dominated forest typically last for 2-4 years (Noske et al, 2016, Wilkinson et al, 2009, Tomkins et al 2007, Prosser and Williams, 1998). In undisturbed conditions, the forest of SE Australia are typically dominated by wet area hydrology, which means most of the surface runoff is generated from the saturation excess and not infiltration excess (Hortonian) runoff.

Second, over longer timeframes, there may be a change in the catchment water balance as vegetation recovers and new plants grow to replace those damaged or destroyed by fire. Increased water use by plants may result in reduced runoff reaching rivers. The extent of change in plant-water use and streamflow depend on forest type, fire severity and fire extent. Stand-replacing fires in mountain ash or alpine ash forest (which regenerate from seed after fire) can result in a temporary increase in water yield (for a few years), followed by major reduction in in yield (up to 50% reduction) lasting for several decades (Cornish and Vertessy, 2001). In mixed-species eucalyptus forests the effects are much less dramatic with reduction in streamflow being of relatively low magnitude and short-lasting (Nolan et al 2015). Recent research suggests that more generally, across both ash forest (obligate seeders) and other temperate forests of Australia, the changes in streamflow due to bushfire are highly variable (Benyon et al; 2023; Khaledi et al, 2022) and largely depended on post-fire rainfall and post fire vegetation dynamics which varies form one bushfire to another.

This project investigates aspects related to the erosion caused by increased surface runoff in the first two years following a major bushfire event.

## 2.2 Post-fire erosion processes – hillslopes and steep gullies as sediment sources in burned forests

Surface runoff leading to widespread erosion of topsoil and upland drainage networks are key triggering mechanisms for water quality impacts from bushfire (Biswas et al, 2021; Smith et al, 2011; Lyon and O'Connor, 2008). This erosion process has been found to be strongly linked to fire severity and soil hydraulic properties (der Sant et al., 2018; Moody et al., 2015), which can vary significantly at relatively fine spatial scales. The timing of short duration, high intensity rainfall events, is also critical in determining if major erosion events occur after bushfire. A large proportion of sediment delivery to the ACT Cotter water supply reservoir following the 2003 bushfire stemmed from erosion of topsoil and steep channels during short intense thunderstorms (Wasson et al., 2003).

Bushfire-related impacts on waterways and water quality are often patchy and episodic (Miller et al, 2003). This notion of patchiness and episodicity in post-fire impacts, implies that much of the sediment that is supplied to river networks originate from threshold driven erosion processes at the spatial and temporal intersection of high intensity rainfall events and recently burned areas, where the thresholds for large erosion events are low. This characterization of risk (that it is largely embedded in low-frequency, high magnitude events) is supported by research from burned forests of SE Australia, which suggest that sediment slugs and water quality impacts often stem from a discrete sediment source that is mobilized during high intensity rainfall (Silva et al, 2020, Nyman et al, 2020; Smith et al, 2011, Lyon and O'Connor, 2008).

Debris flows are an important process for sediment delivery. Debris flows, a threshold-driven process that causes widespread erosion (or scour) of headwater channels, has been identified as an important process of post-bushfire sediment generation and delivery (Nyman et al., 2015). It was one of the key processes contributing to water contamination in the Cotter reservoir following the 2003 bushfire (Wasson et al., 2003; White et al., 2006). Gully erosion by debris flows is triggered by surface runoff. Intense rainfall and steep terrain are key controlling factors. The most severely burnt, dry (west and north facing) slopes are the most likely source of debris flows after bushfire, because these slopes have poorly structured soils and are more prone to surface runoff generation (Noske et al, 2016; der Sant, 2018). The timescale of recovery of hillslope processes is in the order of 5 years, but most of the erosion occurs within the first few years after bushfire (Noske et al., 2016), as readily available hillslope sediment becomes depleted (Nyman et al., 2013). Sediment fans deposited at the base of headwater gullies can act as sediment sources for long periods of time after the initial bushfire disturbance (Lancaster and Casebeer, 2007).

# 3. Methodology

## 3.1 Study area

### 3.1.1 The Tumut Catchment

The catchment of the upper Tumut River was impacted by the Dunns Road Fire. The fire burned 334,000 hectares. It started from lightning on December 27, 2019. The fire was officially extinguished on February 24, 2020.

The Tumut River drains into the Talbingo and Blowering Dams. These dams store water for electricity generation in the Snowy Mountains Hydro-Electric Scheme and for agriculture in the Murrumbidgee Irrigation Area. The dams also supply water for stock and household needs for landholders and towns along the Tumut and Murrumbidgee Rivers.

The catchment received several large rainfall events in the first few months after the bushfire and this triggered widespread erosion. Daily rainfall at Talbingo is shown in Figure 3-2.

Post-fire aerial Imagery was captured for an area of about 1735km$^2$. Imagery was collected in the period between 3/1/2021 and 9/10/2021 (Table 3-2).

Table 3-1. Summary of catchment attributes in the Tumut River study area

| Attribute | Description |
|---|---|
| Climate | Temperate oceanic climate. Mean annual rainfall in the study area ranges from 950 to 1350 mm., with wet winters (June – August) and drier in summers (December-March). |
| Lithology | Mainly igneous felsic (intrusive) in the southwest and northeast. A mix of igneous volcanic and sedimentary siliciclastic in Tumut Valley and in the southeast. |
| Vegetation | Mostly native forest. Some areas cleared for plantation and agriculture in the northwest of the study area. Dry Sclerophyll Forest is the most common forest type at lower elevation. Subalpine Woodland dominates at higher elevation. Patches of Wet Sclerophyll Forest are located in the west. |
| Fire severity[1] | Large band of extreme fire severity fire (with full canopy consumption) along the Tumut Valley. Large area of moderate (partial canopy scorch) and low severity (burnt understory, unburnt canopy) fire in the west and northeast of the study area. |

[1]From FESMv3 (https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm)

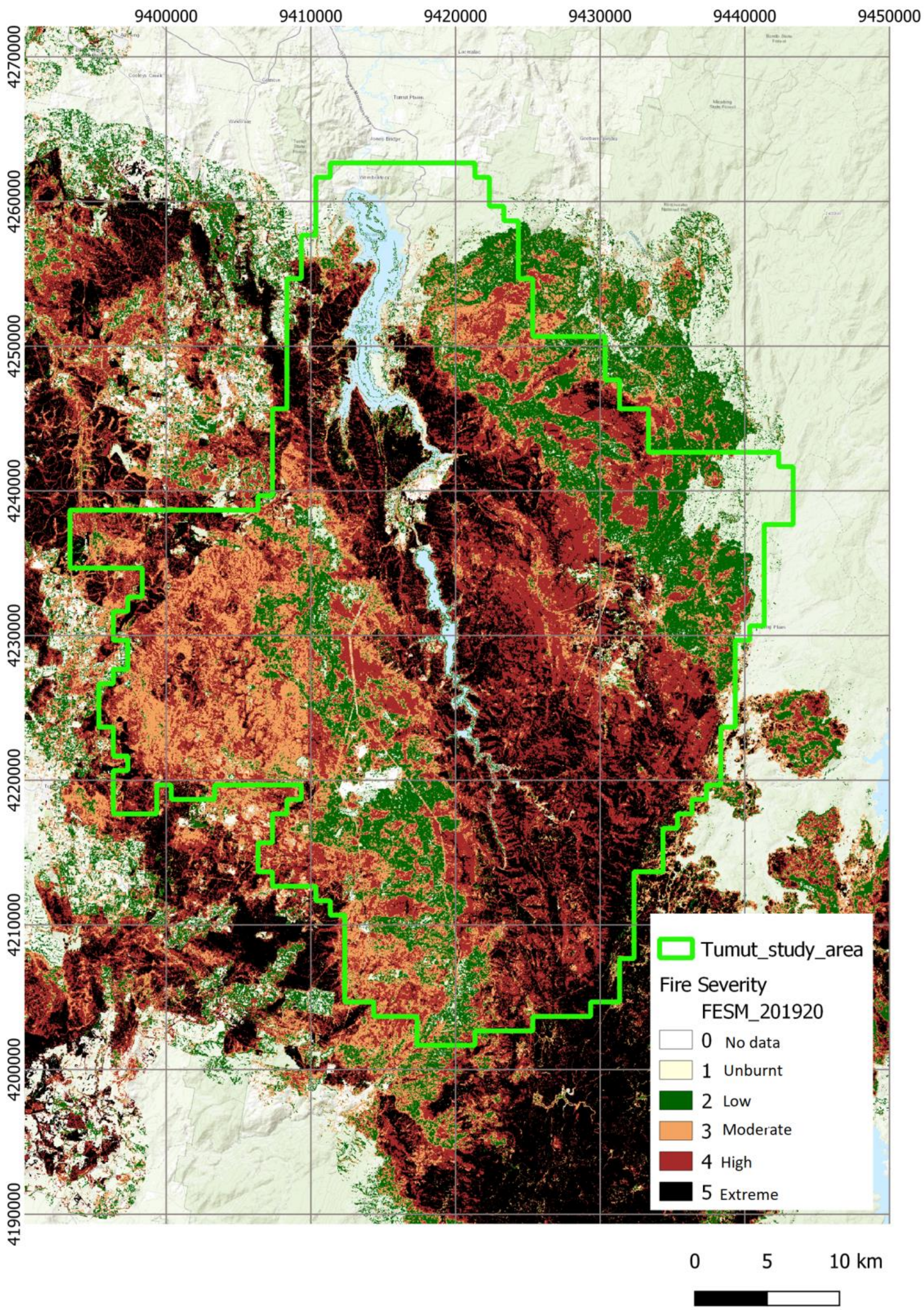
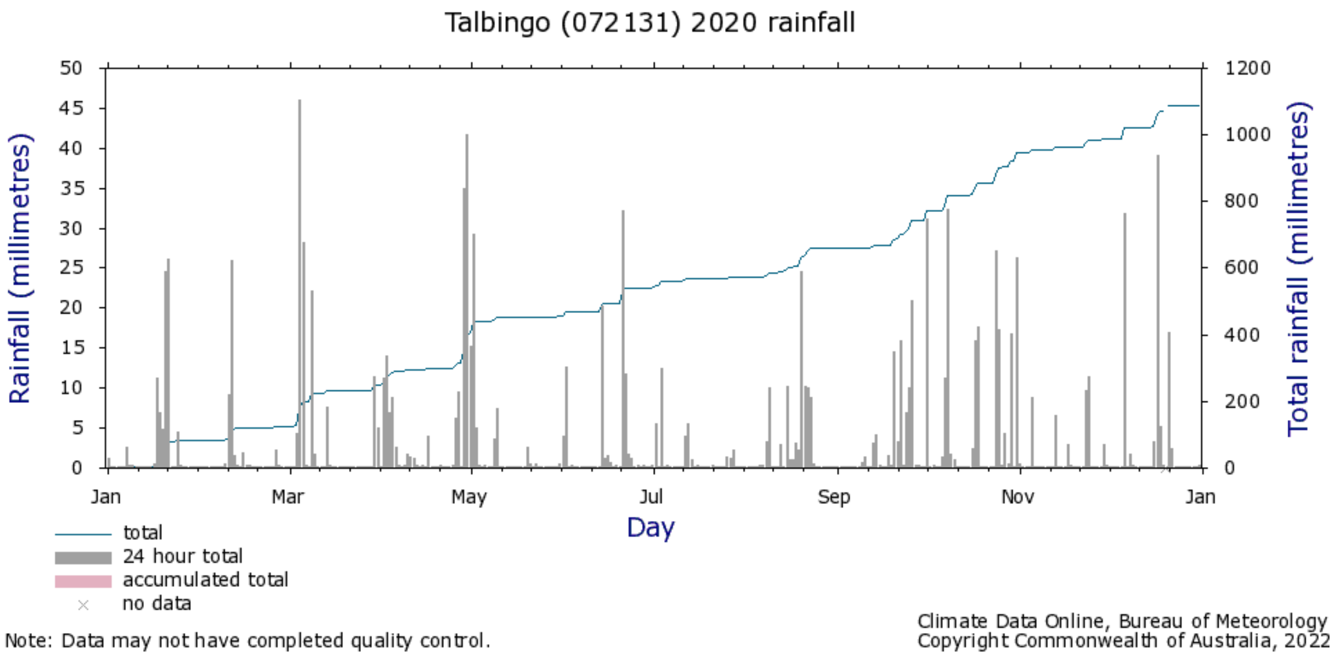



Figure 3-1. Study area in the Tumut Catchment (green outline showing the extent of aerial imagery capture) (737km$^2$) and the fire severity mapped from Sentinel 2 satellite imagery. Fire severity categories described in the FESM dataset (https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm)



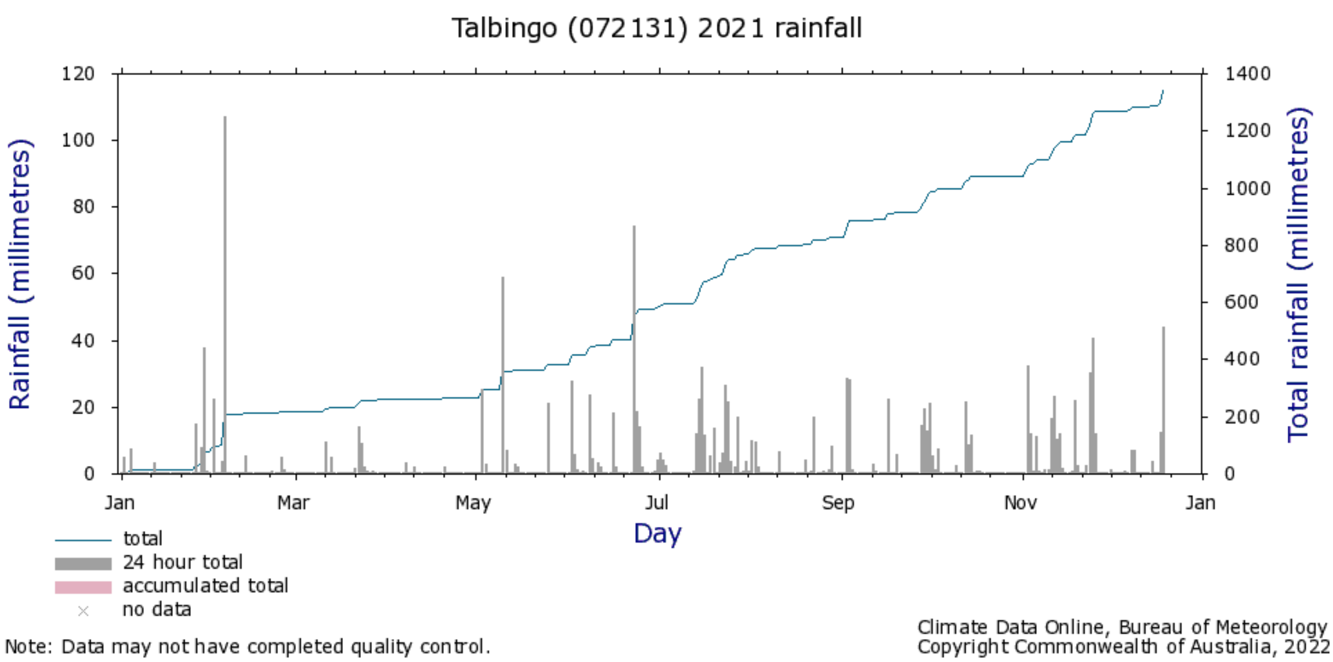




Figure 3-2. Rainfall in year 1 (top) and year 2 (bottom) at Talbingo in the Tumut Catchment.

Table 3-2. Imagery files for the Tumut Catchment.

| Imagery file | Date of capture |
|---|---|
| BloweringErosion_A_Xmap_2021_0926_RGB_120mm_LCC.tif | 26/9/2021 |
| BloweringErosion_B_Xmap_2021_0926_RGB_120mm_LCC.tif | 26/9/2021 |
| BloweringErosion_C_Xmap_2021_0926_RGB_120mm_LCC.tif | 26/9/2021 |
| BloweringErosion_D_Xmap_2021_1009_RGB_120mm_LCC.tif | 9/10/2021 |
| BloweringErosion_E_Xmap_2021_1009_RGB_120mm_LCC.tif | 9/10/2021 |
| BloweringErosion_F_Xmap_2021_1009_RGB_120mm_LCC.tif | 9/10/2021 |
| BloweringErosion_G_Xmap_2021_1009_RGB_120mm_LCC.tif | 9/10/2021 |
| BloweringErosion_H_Xmap_2021_1009_RGB_120mm_LCC.tif | 9/10/2021 |
| FireDamage_MaragleSF_South_2021_0228_RGB_18cm_LCC.tif | 28/2/2021 |
| FireDamage_MaragleSF_North_2021_0228_RGB_18cm_LCC.tif | 28/2/2021 |
| GreenHills_Post-Fire_2021_0228_19cm_LCC.tif | 28/2/2021 |
| FireDamage_BagoSF_South_2021_0103_RGB_14cm_LCC.tif | 3/1/2021 |
| FireDamage_BagoSF_MidWest_2021_0103_RGB_14cm_LCC.tif | 3/1/2021 |
| FireDamage_BagoSF_North_2021_0103_RGB_14cm_LCC.tif | 3/1/2021 |
| FireDamage_BagoSF_SouthEast_2021_0103_RGB_17cm_LCC.tif | 3/1/2021 |
| FireDamage_BagoSF_Mid_2021_0103_RGB_14cm_LCC.tif | 3/1/2021 |

### 3.1.2 The Tuross Catchment

The catchment in the upper Tuross River was impacted by the Badja Fire, which was ignited by a lightning strike on December 27, 2019. The fire burned 315,500 hectares. The fire was extinguished in March after heavy rainfall.

The Tuross River and its tributaries are unregulated, with no major storages to capture and control flows. The catchment supports important freshwater and estuarine ecosystems, and it provides water supply for Eurobodalla Shire Council, agriculture and oyster farming.

The catchment received several large rainfall events in the first few months after bushfire and this triggered widespread erosion and water quality impacts in the Tuross River and its estuary.

Post-fire aerial Imagery was captured for an area of about 737km$^2$. Imagery was collected in the period between 17/1/2022 and 14/02/2022 (Table 3-2).

Table 3-3. Summary of catchment attributes in the Tuross River study area.

| Attribute | Description |
|---|---|
| Climate | Temperate oceanic climate. Mean annual rainfall in the study area ranges from 800 to 1000 mm., with a relatively even spread of rainfall through the year. |
| Lithology | Mainly sedimentary siliciclastic in the south. Mainly igneous felsic (intrusive) in the north. |
| Vegetation | Native forest throughout. Wet Sclerophyll Forest at high elevation and where water availability is high due to drainage. Grassy Woodland and Dry Sclerophyll Forests in the foothills. |
| Fire severity[1] | Large area of extreme fire severity in the south and the northeast of the study area (full canopy consumption). Nearly all of the study area is fire severity category 3 (partial canopy scorch) or higher. |

[1]From FESMv3 (https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm)

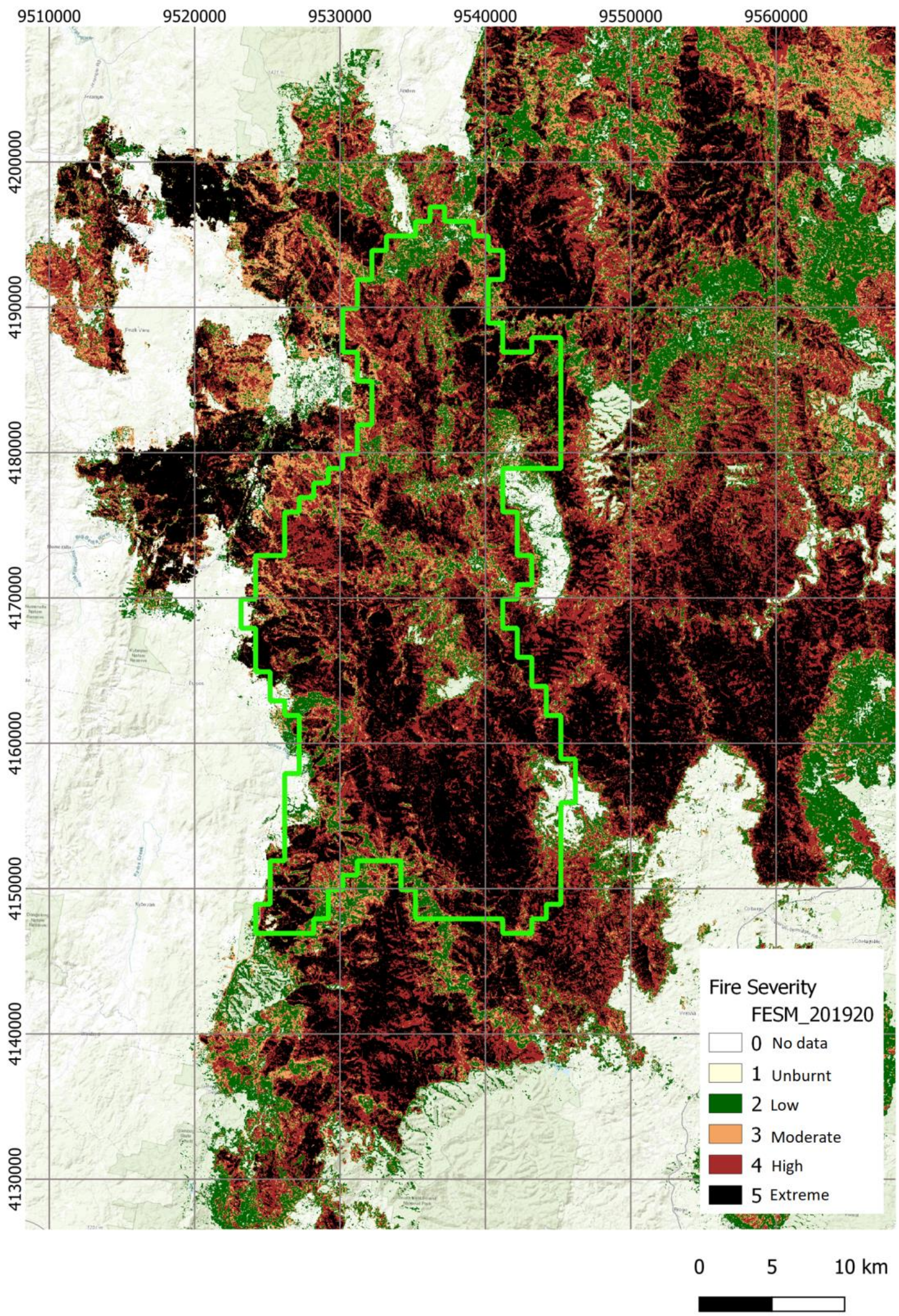
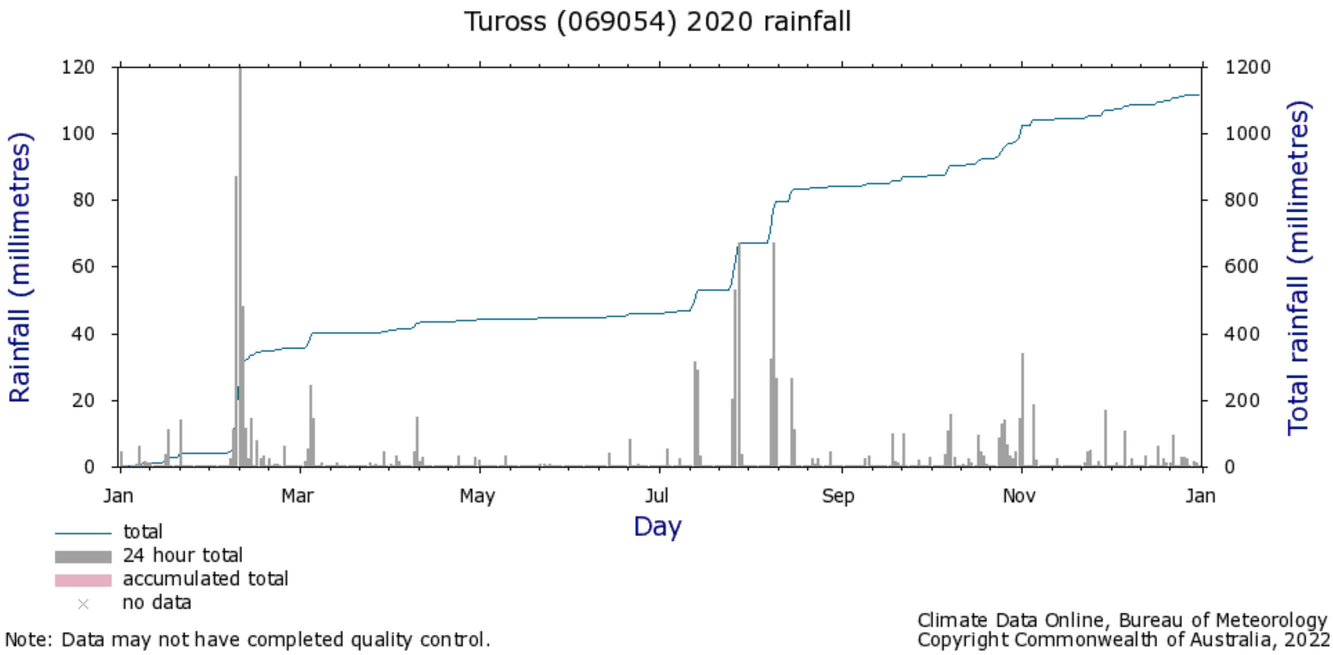



Figure 3-3. Study area in the Tuross Catchment (green outline showing the extent of aerial imagery capture) (737km$^2$) and the fire severity mapped from Sentinel 2 satellite imagery. Fire severity categories described in the FESM dataset (https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm)



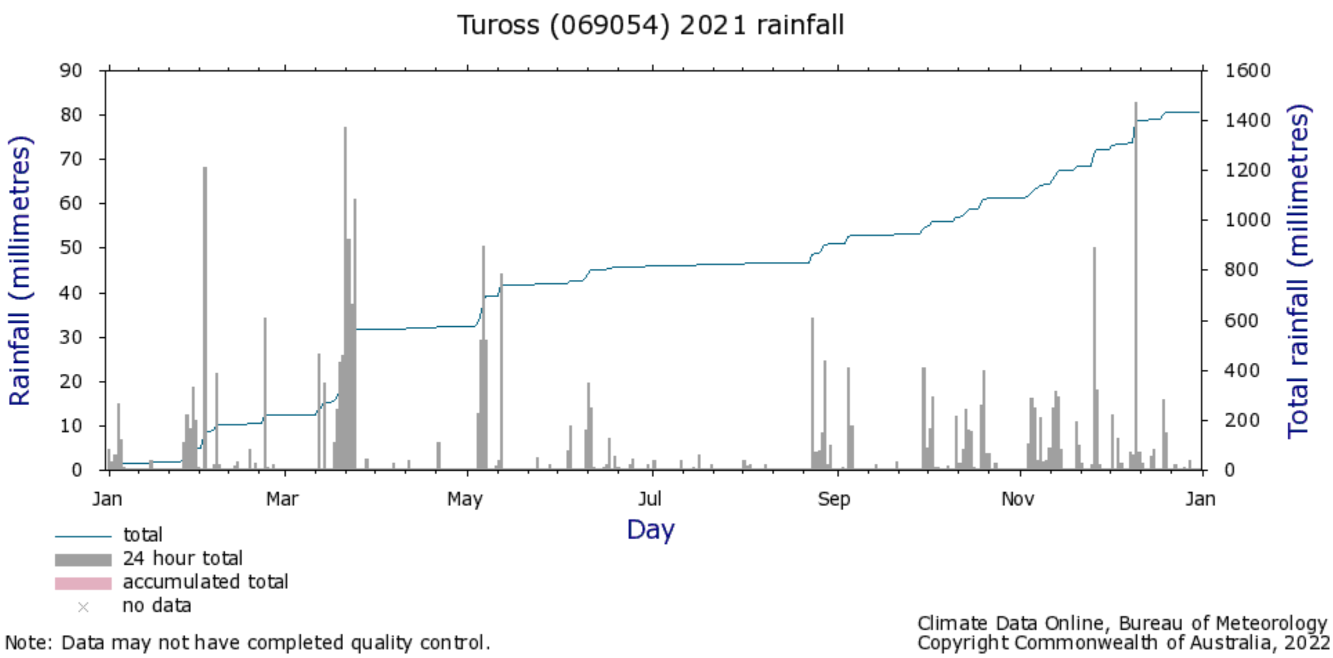




Figure 3-4. Rainfall in year 1 (top) and year 2 (bottom) at Tuross in the Tuross Catchment.

Table 3-4. Imagery files for the Tuross Catchment.

| Imagery file | Date of capture |
| --- | --- |
| Xmap_Tuross_Block1_1_RGB_2022_0117_15cm_LCC.tif | 17/01/2022 |
| Xmap_Tuross_Block1_2_RGB_2022_0117_15cm_LCC.tif | 17/01/2022 |
| Xmap_Tuross_Block1_3_RGB_2022_0117_15cm_LCC.tif | 17/01/2022 |
| Xmap_Tuross_Block1_4_RGB_2022_0117_15cm_LCC.tif | 17/01/2022 |
| Xmap_Tuross_Block2_1_RGB_2022_0214_12.5cm_LCC.tif | 14/02/2022 |
| Xmap_Tuross_Block2_2_RGB_2022_0214_12.5cm_LCC.tif | 14/02/2022 |
| Xmap_Tuross_Block2_3_RGB_2022_0214_125mm_LCC.tif | 14/02/2022 |
| Xmap_Tuross_Block2_4_RGB_2022_0214_12cm_LCC.tif | 14/02/2022 |
| Xmap_Tuross_Block2_5_RGB_2022_0214_12.5cm_LCC.tif | 14/02/2022 |
| Xmap_Tuross_Valley1_RGB_2022_0214_75mm_LCC.tif | 14/02/2022 |

## 3.2 Mapping channel initiation points and fans

### 3.2.1 Imagery considerations

Erosion response within the study area is determined by mapping fans and channel initiation points (CIP) from the aerial imagery (Figure 3-5). We adopt the method outlined in Nyman et al. ( 2015) for mapping the location of fans and channel initiation points from aerial imagery. Satellite imagery provides an alternative source of data for mapping erosion events. Products such as GeoEye (resolution ~40cm) or Planet Imagery (resolution ~ 50cm) have been used for landslide mapping. The cost of GeoEye Imagery is in the order of \$20-25 per $km^2$, similar to the cost of aerial imagery. Products such as RapidEye, Sentinel and Landsat have also been used in mapping of geomorphological features. However, the resolution of these (5-20m) is insufficient to detect the channel heads that this study is looking to map.

Aerial imagery provides high resolution products that can be captured during conditions (time of day, sun angle) when constraints on detecting erosion features are minimized. Furthermore, with aerial imagery, each point in the landscape is imaged many times during capture as neighboring photos overlap each other significantly. This results in between five and twenty different view-angles (i.e. from camera perspective) for every location/observation. This is a big advantage when attempting to discern the detail of erosion features. For example, from directly above, erosion features may be obscured by a tree crown, but with a view-angle of say 30 degrees, it is possible to see more of what is under the tree crown. Ortho-mosaics, however, provide only one view-angle for every location.

### 3.2.2 Mapping methodology

The presence of depositional fans and scoured channel features reflect the intensity with which surface runoff and debris flow processes are operating. In the study by Nyman et al (2015), the mapped fans and channel heads were assumed to represent the occurrence of post-fire debris flows, supported by field verification.

In the development of their methodology, comparison of aerial imagery interpretation with the field surveys showed that debris flows could be identified with high confidence, with a mean accuracy of 0.95 and a precision of 0.89 (true negative rate 0.77; true positive rate 0.94) as long as deposits were larger than 10 $m^2$ (Nyman et al, 2015). For deposits with surface area of 10 $m^2$ (typically located in small 1st order headwaters) there was more uncertainty in the observations. The geologic and geomorphic setting in the Tumut and Tuross study catchments are similar to those in Nyman et al (2015) and the methodology is therefore assumed to be transferable. Field observations from the study areas could be used to verify this assumption.

The steps for mapping erosion include:

1) A 1km grid is generated and superimposed over the aerial imagery.
2) Within each grid cell, the depositional fans are located and marked.
3) Scoured drainage lines above these fans are identified. The scour lines show up as pale-coloured linear features. These drainage lines, and the catchment above them, are considered to be the sediment sources contributing to the fan. We used all the evidence available in the image (colour, texture, shading, etc.) to discriminate eroding channels from those that are not. The head of the scour lines are then identified and marked as the channel initiation points.
4) In some settings there are distinct scour lines and channel heads without a depositional fan, because the sediment has deposited directly into larger river systems. In these situations, the channel initiation points are still mapped, but they will not have a depositional fan associated with them.
5) Once all the features are mapped, the data are aggregated into metrics of debris flow density, by counting the number of channel heads in each 1$km^2$ grid cell.

Figure 3-5. Mapping of debris flow fans (green markers) and channel initiation points (red markers).

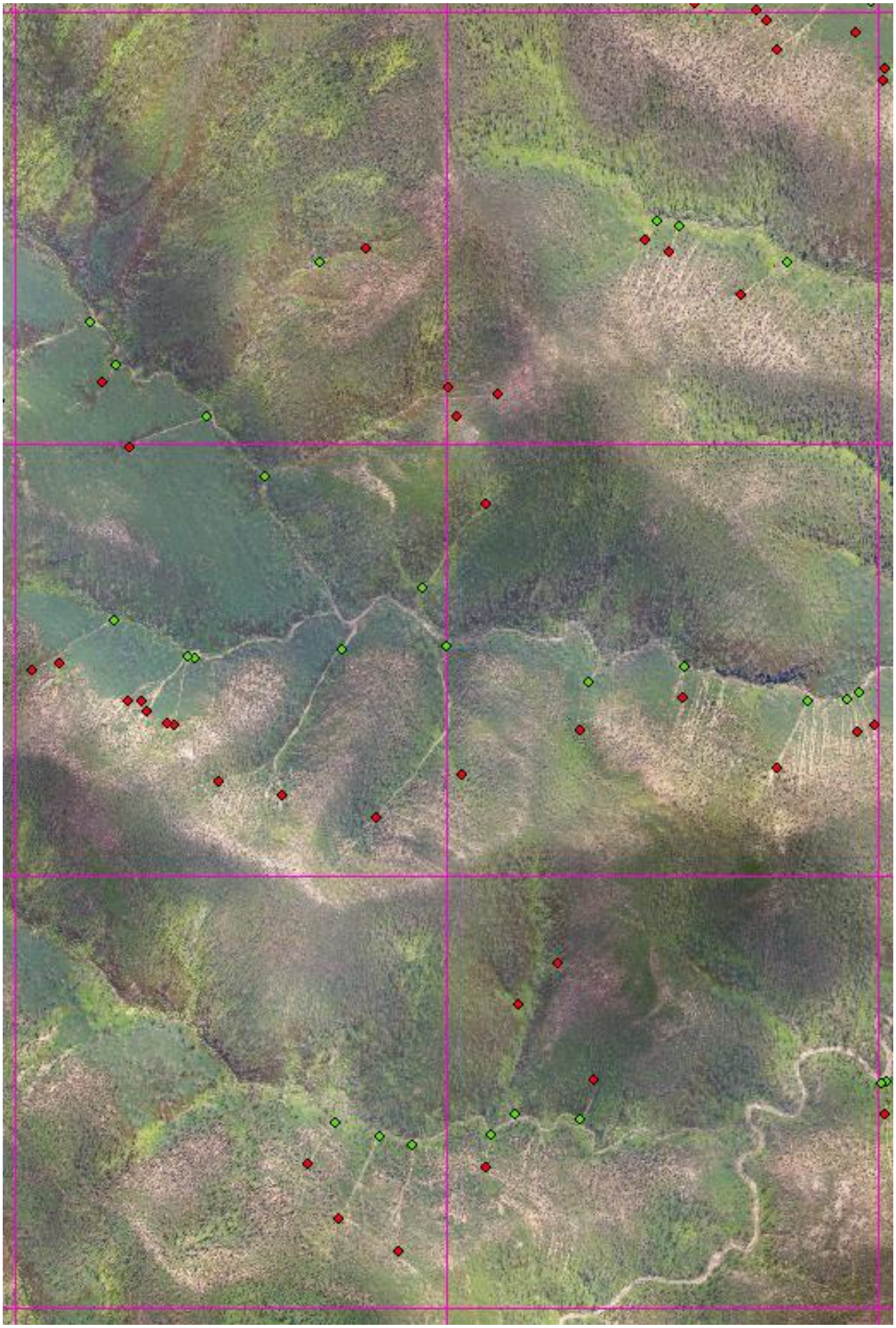


Figure 3-6. Debris flow fans (green) and channel initiation points (red) within 1km² grids.

### 3.3 Identifying controls on debris flow occurrence

We developed a database with debris flow density alongside information on attributes that may be linked to post-fire debris flow susceptibility. The role of these attributes in causing spatial variation in debris flow density was determined as part of the exploratory analysis. More comprehensive analysis and modelling are needed to fully exploit these data (and other datasets) and build on the capacity for benchmarking, understanding, and predicting impacts of post-fire erosion on catchment values. We note that higher resolution data on RUSLE parameters and slope are available for NSW catchments, and these can be used in future analyses.

Table 3-5. List of attributes used to examine spatial variation in debris flow susceptibility,

| Attribute | Data source and relevance to debris flow susceptibility |
|---|---|
| Fire severity | Fire severity has been found to be a key factor contributing to debris flow susceptibility. Increased fire severity means more surface runoff and less resistance to erosion. Both normalized burn ratio (dNBR) or fire severity categories have been used to relate erosion to fire impact. In this study we have characterized fire severity using the NSW Fire Extent and Severity Mapping (FESM). https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm. The FESM severity classes include: unburnt, low severity (burnt understory, unburnt canopy), moderate severity (partial canopy scorch), high severity (complete canopy scorch, partial canopy consumption), extreme (full canopy consumption). |
| Slope | Slope is linked to peak flows and channel initiation thresholds. A slope layer was produced from the SRTM-derived 1 Second Digital Elevation Models Version https://data.gov.au/dataset/ds-ga-aac46307-fce8-449d-e044-00144fdd4fa6/details?q= |
| Aridity | Aridity is an important proxy for soil hydraulic properties and has been used as an input to susceptibility models for post-fire debris flows. Aridity is the balance between rainfall and potential evapotranspiration (PET). For this study the aridity layer was measured using rainfall and PET layers from BoM (resolution = 5km). http://www.bom.gov.au/climate/data-services/maps.shtml |
| RUSLE K-factor | The K-factor in the Revised Universal Soil Loss Equation (RUSLE) is related to soil erodibility. Typically, it is developed from information on geology and soil texture. Data is available from CSIRO at 1km resolution https://data.csiro.au/collection/csiro:19354 |
| RUSLE R-factor | The R-factor in the Revised Universal Soil Loss Equation (RUSLE) is related to rainfall erosivity. It says something about the long-term properties of rainfall with respect to the energy available to erode and transport sediment. Data is available from CSIRO at 1km resolution https://data.csiro.au/collection/csiro:19354 |
| RUSLE LS-Factor | The LS-factor in the Revised Universal Soil Loss Equation (RUSLE) is related to topography. It says something about the slope steepness and slope lengths, both which are important for sediment transport . Data is available from CSIRO at 1km resolution https://data.csiro.au/collection/csiro:19354 |
| Vegetation class | Vegetation class describes aspect of land use and is a proxy for climate and forest productivity. Vegetation was described using Vegetation Formations and Classes of NSW. https://datasets.seed.nsw.gov.au/dataset/vegetation-classes-of-nsw-version-3-03-200m-raster-david-a-keith-and-christopher-c-simpc0917 |
| Lithology | Lithology is related to landform and soil erodibility and was described using national surface geology mapping product. https://data.gov.au/dataset/ds-dga-48fe9c9d-2f10-49d2-bd24-ac546662c4ec/distribution/dist-dga-018c87e5-404a-44e5-821c-fc309ca0e9be/details?q= |

# 4. Results

## 4.1 Data outputs

The study has produced an inventory of fans and channel initiation points, which have been combined with ancillary data on landscape attributes which are linked to debris flow susceptibility. This report provides an overview of some of these data. More in-depth analysis and model development are needed to fully exploit the datasets generated by the project.

To facilitate further analysis, research and model development the report has been delivered together with a series of data products that can be easily brought into future projects. These will be hosted on the Terrestrial Ecosystem Research Network (TERN) Data Discovery Portal https://portal.tern.org.au/ - and accessible through SEED.

The data include:

- The shapefiles marking the locations of debris flow fans and channel initiation points for both study sites. There are six shapefiles:
  - CIP_tumut.shp — Channel initiation points in the Tumut study area
  - Deposits_tumut.shp — Debris flow deposits in the Tumut study area
  - Tumut_StudyArea.shp — Outline of study area covered by the aerial imagery
  - CIP_tuross.shp — Channel initiation points in the Tuross study area
  - Deposits_tuross.shp — Debris flow deposits in the Tuross study area
  - Turosst_StudyArea.shp — Outline of study area covered by the aerial imagery
- The shapefile containing the grids with debris flow density metrics and associated data on landscape attributes as listed in Table 3-5. There are two files:
  - GRID_tumut.shp — 1km grid with counts of channel heads and landscape attributes
  - GRID_tuross.shp — 1km grid with counts of channel heads and landscape attributes
- Folders containing all the aerial imagery that was used to map post-fire debris flow (as per Table 3-2and Table 3-4).

## 4.2 Data summary: Tumut Catchment

There were 785 channel initiation points (CIP) and 211 fan deposits in the Tumut study area. The overall CIP density in the study area is 0.45 CIPs per km$^2$. Within 1km grids, the density ranges from 0 to 22 CIPs per km$^2$. When assessed at the scale of the 1km grid, the data suggests that about 10% of the study area has been impacted by sediment delivery events associated with the mapped CIPs and the downstream channel erosion that they have triggered.

The relationships between CIPs and landscape attributes are summarized below:

- There is significant clustering of CIPs and fans along the central Tumut valley (Figure 4-1).
- Key factors contributing to this clustering are likely to be fire severity and slope. There appears to be a clear relationship between these two factors and CIP density (Figure 4-2). The CIP density increases once fire severity reaches around 3 (moderate fire severity). For slope, the threshold for increased CIP density is

around10 degrees. Forest type is also an important factor with dry forests being more susceptible to debris flow than wetter forest types (Table 4-1).

- Aridity appears to have little influence on CIP density. Likewise, there appears to be no real significant relation between RUSLE factors and CIP density (Figure 4-2).
- Dry forests are over-represented in terms of the CIP density. That is, when compared against the area comprising wet and dry forest, the CIPs are more common in dry forest types (0.58 CIPs per $km^2$). Commensurate with this result, CIPs are relatively less common in wet forests (0.03 CIPs per $km^2$).
- Burned areas classified as cleared forest, which includes plantations and agriculture, have lower susceptibility to debris flow when compared to burned dry native forest (Table 4-1). As such, it seems that intensively managed forests are no more susceptible to debris flows than native forest.
- CIP density is higher in metamorphic lithology when compared to igneous (Table 4-1). This indicates that the geological setting has an impact on the susceptibility of burned areas to post-fire debris flows. Assessment and response to post-fire erosion risk should therefore consider geology as factor that can help focus efforts where the risk is high.

Table 4-1. Channel initiation points in relation to vegetation classification and geology

| Attribute | Area | # of CIPs | % of area | % of CIPs | CIP density |
|---|---|---|---|---|---|
| *Vegetation* | | | | | |
| Wet forest | 316 | 9 | 18 | 1 | 0.03 |
| Dry forest | 1162 | 672 | 67 | 86 | 0.58 |
| Cleared | 242 | 104 | 13 | 13 | 0.43 |
| *Lithology* | | | | | |
| Igneous | 1345 | 548 | 78 | 70 | 0.41 |
| Metamorphic | 355 | 231 | 21 | 29 | 0.65 |

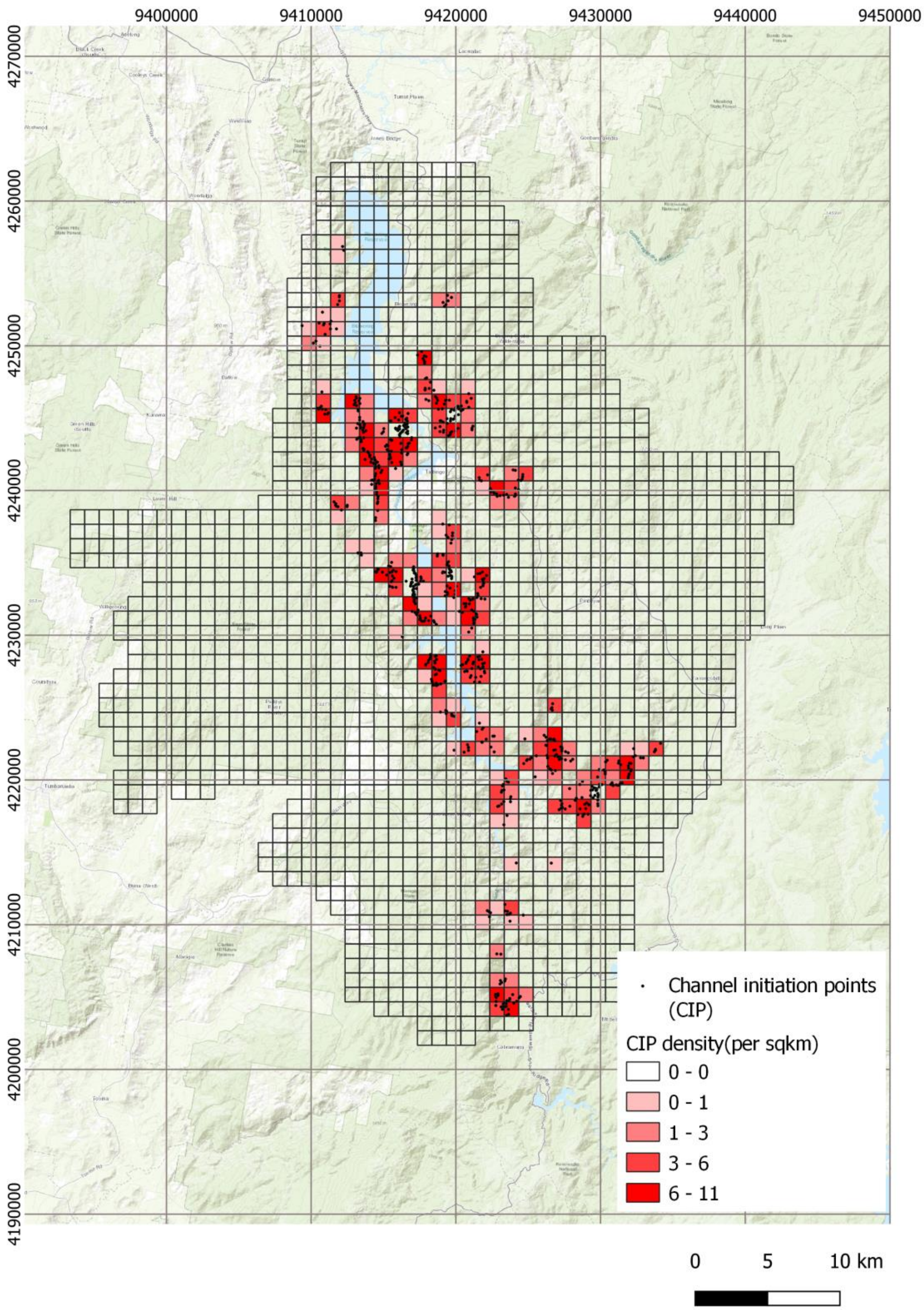



Figure 4-1. Distribution of channel initiation points (CIP) in the Tumut study area. The red color gradient is the number of CIPs per $km^2$. Black dots are individual CIPs.

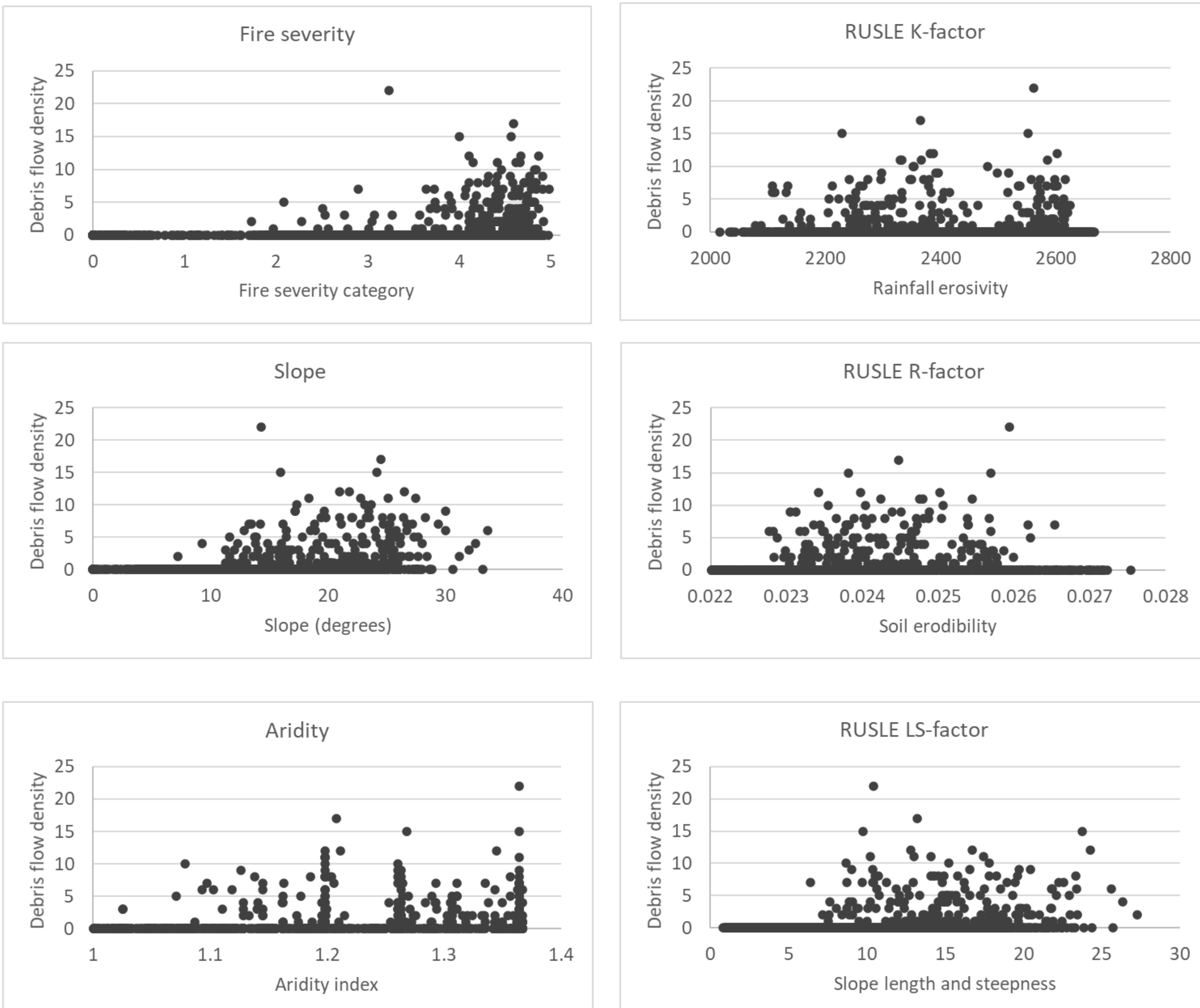



Figure 4-2. Association between landscape attributes and CIP density in the Tumut study area. A skewed distribution in the datapoints indicates a relationship between density and a landscape attribute. Fire severity is clearly an important influence on CIP density.

## 4.3 Data summary: Tuross Catchment

There were 273 channel initiation points (CIP) and 146 fan deposits in the Tuross study area. The overall CIP density in the study area is 0.37CIPs per $km^2$. Within the 1km grids, the density ranges from 0 to 11 CIPs per $km^2$. When assessed at the scale of the 1km grid, the data suggests that about 12% of the study area has been impacted by sediment delivery events associated with the mapped CIPs and the downstream channel erosion that they have triggered.

The relations to landscape attributes are summarized below:

- There is significant clustering of CIPs and fans in the southern part of the study area (Figure 4-3).
- Key factors contributing to this clustering are likely to be fire severity and slope. There appears to be a clear relationship between these two factors and CIP density (Figure 4-4). The CIP density increases once fire severity reaches a threshold of around 4 (high severity). For slope, the threshold for increases in CIPs is around 20 degrees.
- Aridity appears to have little influence on CIP density. Likewise, there appears to be no real significant relation between RUSLE factors and CIP density (Figure 4-4).
- Dry forests are over-represented in terms of the CIP density. That is, when compared against the area comprising wet and dry forest, the CIPs are more common in dry forest types (0.55 CIPs per $km^2$). Commensurate with this result, CIPs are under-represented in wet forests (0.15 CIPs per $km^2$).
- CIP density appears to be much higher in metamorphic lithology when compared to igneous (Table 4-2).

Table 4-2. Channel initiation points in relation to vegetation classification and geology

| Attribute | Area | # of CIPs | % of area | % of CIPs | CIP density |
|---|---|---|---|---|---|
| *Vegetation* | | | | | |
| Wet forest | 208 | 31 | 33 | 11 | 0.15 |
| Dry forest | 441 | 241 | 60 | 88 | 0.55 |
| Cleared | 20 | 0 | 3 | 0 | 0.00 |
| *Lithology* | | | | | |
| Igneous | 372 | 10 | 50 | 4 | 0.03 |
| Metamorphic | 364 | 263 | 49 | 96 | 0.72 |

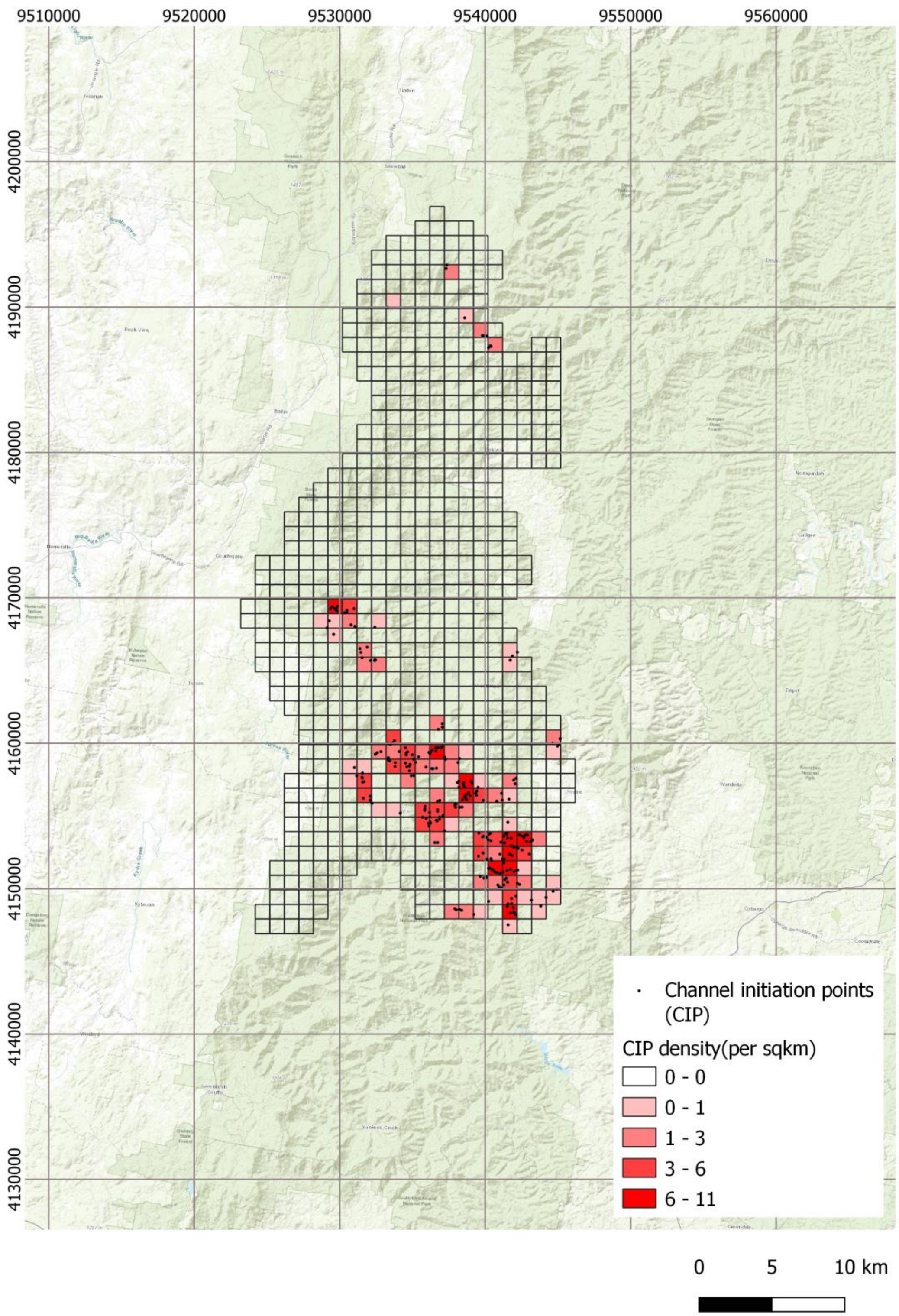



Figure 4-3. Distribution of channel initiation points (CIP) in the Tuross study area. The red color gradient is the number of CIPs per km$^2$. Black dots are individual CIPs.

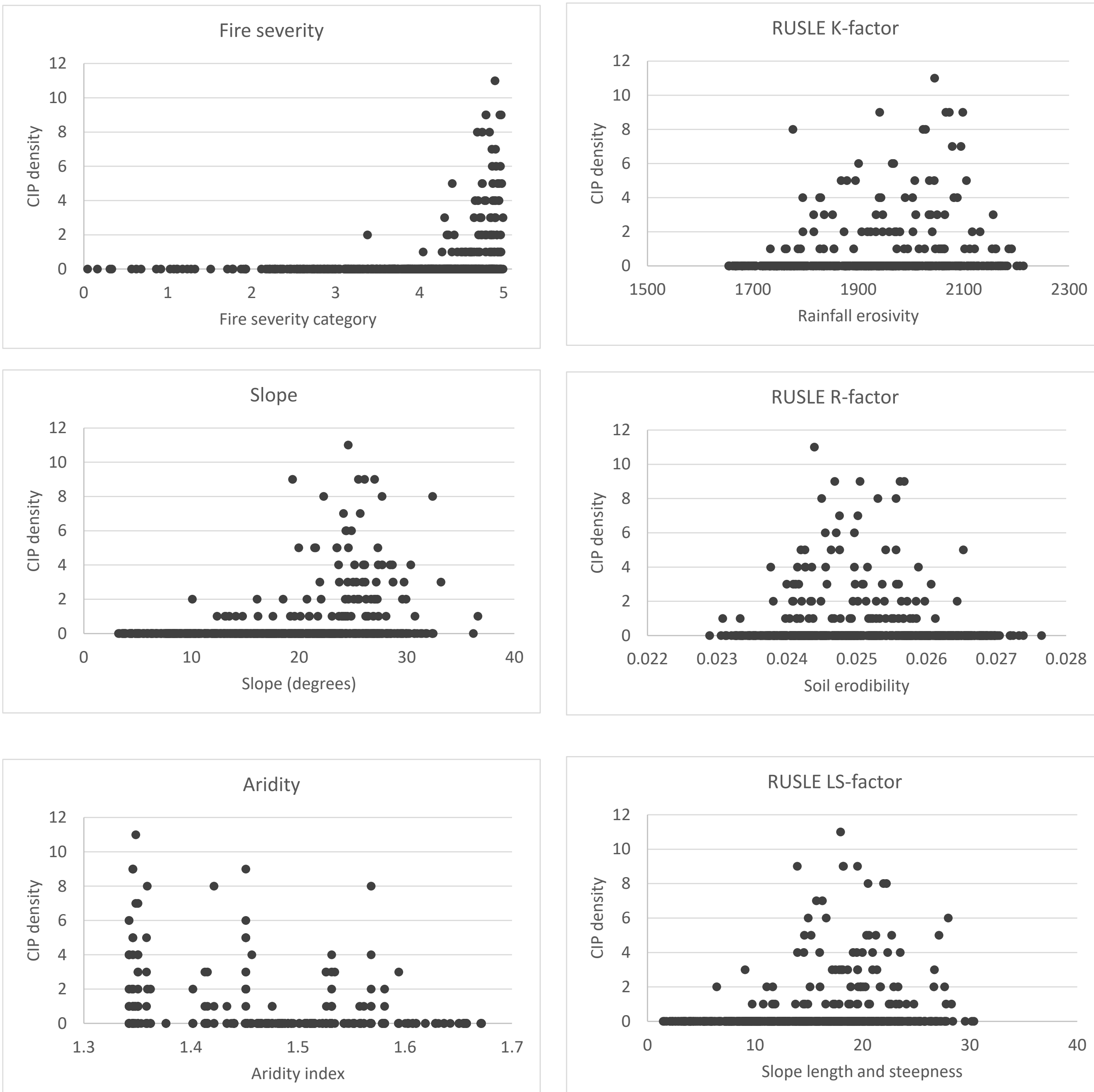



Figure 4-4. Association between landscape attributes and CIP density in the Tuross study area. A skewed distribution in the datapoints indicates a relationship between density and a landscape attribute. Fire severity is clearly an important control.

## 4.4 Data summary: Impact of roads on debris flow frequency

Channel initiation point (CIP) density was plotted alongside data on the length of forest roads in each grid cell (Figure 4-5). The aim of this analysis was to provide a high-level screening of the potential link between the forest road network and the frequency of debris flows. We note that the analysis was performed at a relatively coarse resolution and that more detailed analysis is needed to provide more accurate insights into the impact of roads on channel incision and debris flow at the scale of individual headwaters.

In the Tuross study area, there is no evidence of any link between the two. Most of the erosion events that were mapped occurred in remote areas with few roads. In the Tumut study area, there is more data from areas where there is a high density of forest roads. When analyzed for individual grids (black markers) the background variability is high and there is no evidence that roads have any impact. However, when averaging the road length for different levels of CIP density there is a trend in the data, where CIP density increases with road length density.

We note that this analysis is not conclusive. There needs to be a more local scale analysis of the data generated in this report to tease out the relative impacts of roads versus other factors in causing high magnitude runoff events, which trigger channel incision and debris flows in these systems.

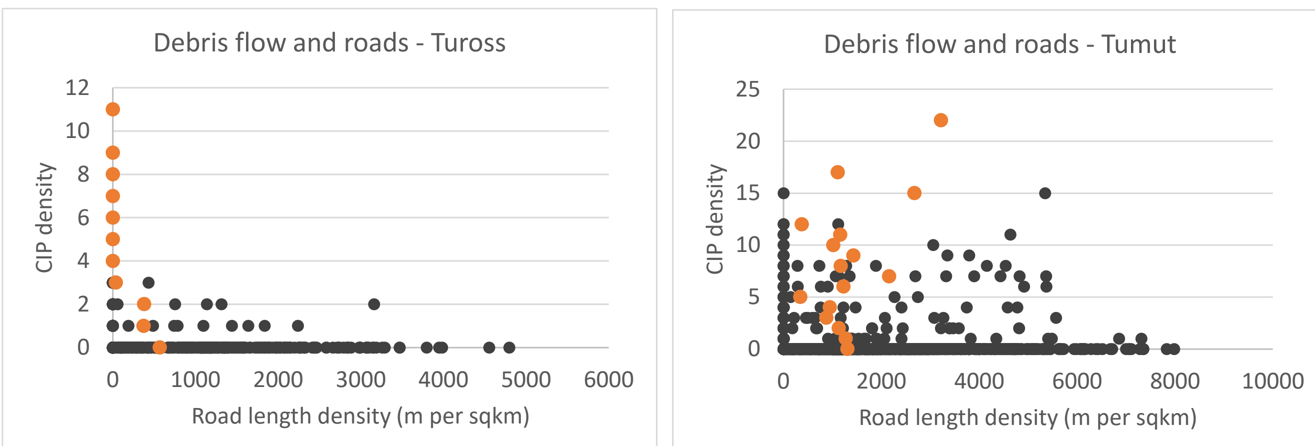



Figure 4-5. Association between road length density in each grid and the CIP density in the Tuross (left) and Tumut (right) study areas. Black markers are data pairs from each grid. The orange markers are the averages of road length density for each level of CIP density.

# 5. Discussion

## 5.1 Channel incision and debris flow generation from surface runoff after bushfire

From the erosion mapping, geoprocessing and spatial analyses, the project has produced a comprehensive inventory of post-fire debris flows in the two study catchments, which are representative of large proportion of the dissected uplands in the southeast NSW region. The widespread and intense bushfires, combined with several episodes of intense rainfall, has meant that the landscape in this region of NSW was primed for some of the most widespread and extreme erosion responses ever documented. The impacts have been significant, yet there has been a paucity of data required to understand the drivers behind these events. Moreover, the lack of data has meant that there has been limited opportunity to leverage existing research in SE Australia (Victoria in particular) and apply predictive models (e.g. Nyman et al, 2021, Langhans et al, 2016) and risk assessment tools (Sheridan et al, 2011) to NSW landscapes.

Previous research on post-fire erosion in NSW has largely focused on catchments in the sandstone-dominated landscapes of the Sydney Basin (e.g. Wilkinson et al, 2009, Blake et al 2009, Tomkins et al, 2007). In that geomorphic setting, flat sandstone ridgetops are bordered by steep side slopes often with cliffs in upper parts and a network of old valley-side gullies. Lower-gradient sandy foot slopes are adjacent to the river network. The research in the Sydney basin has been critical to our understanding of sediment transport processes after fire in sandstone landscapes, and highly relevant given the critical role these catchments serve as water supply to the Greater Sydney Region (Wilkinson et al, 2007). The work generally suggests that the dominant post-fire sediment sources in their study catchments were ridgetop and steep side slope units, where ash, burnt litter and soil was transported by surface wash when rainfall intensities were sufficient to produce overland flow.

It has been noted in work from the western US and in SE Australia that geology plays an important part in determining the degree with which bushfire impacts erosion processes (Nyman et al, 2019, Meyer et al 2001, Larsen et al, 2007). The processes that trigger runoff-generated debris flows after bushfire are linked to the downslope accumulation of surface runoff and sediment on steep hillslopes, where a process referred to as sediment bulking leads to channel incision and the formation of channelized debris flows (Langhans et al, 2017, Gabet, 2003). This process has been observed to occur regularly in the dissected uplands of Victoria, in severely burned catchments without any prior anthropogenic disturbance (Nyman et al, 2019, Langhans et al, 2017). These landscapes are soil mantled and have long (100m - 250m) and steep (30-35 degrees) hillslopes that converge into channels that store large volumes of colluvial sediments that are available for erosion and transport (Nyman et al, 2015).

From our interpretation of the aerial imagery that was acquired in this project, it seems that runoff-generated debris flows are an important erosion process in some areas within the two study sites. There are large clusters of CIPs, particularly in areas burned at high severity, and these are often associated with clearly visible fans that have deposited into waterways. The coalescence of rills above the CIPs and the evidence of widespread hillslope erosion (Figure 3-5) suggest the triggering mechanisms are similar to those observed in eastern Victoria (Nyman et al, 2011, Langhans et al, 2017). The exploratory analysis demonstrates that there are large similarities between eastern Victoria and the two study regions (Tumut and Tuross) in the landscape controls on CIPs.

Some key findings with respect to landscape controls include:

- The importance of fire severity in influencing debris flow frequency. The frequency of extreme erosion events increases markedly when bushfire results in crown scorch and crown burn. This is consistent with earlier work from SE Australia (Nyman et al, 2015), indicating marked shifts in erosion response when fire severity go from understory burns to crown fire.
- The importance of forest type. In this study, dry forests that have been impacted by fire have much higher frequency of debris flow than wet forest types. This is consistent with observation in Victoria that the

moisture regime is an important proxy for soil and therefore erosion response (Noske et al, 2022; Nyman et al, 2015; Noske et al, 2016). Aridity index, determined from the ratio of potential evapotranspiration (PET) to precipitation, has been used as a metric that capture the impact of local moisture regimes on post-fire surface runoff and erosion in SE Australian catchments (Noske et al, 2016; der Sant, 2081). In Victoria, this index has been calculated at 20m resolution (Nyman et al, 2014), commensurate with the topographic variability (slope and aspect) which drives variability in local PET. The aridity data used in this study, which is calculated at much coarser resolution (5km), did not appear to be a good predictor, most likely due to fine scale variation from solar exposure (aspect, slope) not being represented. In NSW such high-resolution data on aridity are not currently available.

- The importance of lithology. Post-fire debris flows appear to be less common on granitic terrain when compared to sedimentary lithologies. This is consistent with observations from Victoria (Nyman et al, 2019) and elsewhere (Meyer et al 2001).
- The spatial resolution of our analysis is not suited for drawing conclusion regarding the impacts of forest roads on debris flow initiation. However, there appears to be some correlation in forest road density and debris flow density in the Tuross catchment. Moreover, anecdotal observations from the 19/20 bushfires, and from other bushfire events, suggest forest roads do contribute to the generation of concentrated overland flow and formation of channelized erosion. More work, focusing on individual headwaters and detailed information on road drainage (e.g. from lidar and field surveys), would be needed to determine to what degree the road network may exacerbate the post-fire debris flow response.
- In the areas of the Tumut Catchment where native vegetation has been cleared for plantations, there appeared to be no more CIPs than in dry native forests elsewhere in the study area. However, we note that our analyses related to road impacts and the role of land use is conducted at a relatively coarse spatial resolution. More detailed investigation would be needed to evaluate land use impacts at the hillslope or small catchment scales. Furthermore, the findings are confined to the forest of southern NSW and should not be generalized more broadly.

Erosion estimates from Nyman et al (2015) suggest an erosion rate from debris flows in first-order headwaters to be between 150 t/ha and 200 t/ha. First order headwaters, which comprise the channel initiation point and the first-order channel, are typically between 5 and 10 ha in size. Each headwater with a channel initiation point is therefore likely to generate sediment loads between 750 and 2000 t. This includes all sediments ranging in grain size from clay through to boulders. With this estimate, the debris flow sediment loads from a 1km grid cell is between 1.5 and 4 t/ha (when the density is around 20 CIPs per $km^2$). The background erosion rate in undisturbed forested catchments in SE Australia is typically 0.1- 0.2 t/ha/year (Lane et al, 2006; Smith et al, 2011). This means that in the areas subject to intense debris flow activity, the sediment delivery from small headwater catchments during these individual events accounts for somewhere between 7 and 40 years of background rates. The overall area subject to these processes is relatively small however, with channel initiation points observed in only 10-12 % of the grid cells.

This study focused on the mapping of sediment sources and has used estimates of erosion rates from earlier work to infer larger scale sediment yield from debris flows. With additional data on erosion and deposition in headwater catchments, there are opportunities to examine in more detail the role of debris flows in contributing to larger-scale sediment dynamics (e.g. Pelletier and Orem, 2014). In future studies, the mapping of erosion events could be coupled with repeat lidar survey and sediment sampling along the stream network to obtain a stronger basis for linking debris flow mapping with larger scale sediment delivery and transport.

The increase in debris flow susceptibility with high fire severity bushfire suggests that bushfire is important to landform development and long-term sediment yields in these systems. The links between landscape formation, bushfire and episodic erosion has been documented previously in Australia and elsewhere (Orem and Pelletier, 2016; Smith et al, 2012; Kirchner et al, 2001). With predictions of increased fire activity in southeast Australia due to climate change (Canadell et al, 2021), it will be important to consider what the implications might be for future soil stability, erosion and sediment transport. Considering episodic events, such as debris flows, which are not typically captured in instrumented catchments, will be critical for developing an understanding of how bushfire impacts on catchment processes under increasing fire activity. This understanding of bushfire, episodic events and longer-term sediment dynamics provides context for assessing future trajectories in catchment and waterway health, and for evaluating the effectiveness of different land management strategies in reducing risk to catchment values.

In the future, the role of burned areas in delivering sediment to waterways will depend in part on the fire regimes that these forests are subject to. Both climate change and fire management are likely to dictate what the future might hold in terms of bushfire activity (Morgan et al 2020; Bowman et al, 2020). The density of channel initiation points and the prevalence of debris flows is strongly associated with high severity fires, where the crowns are partially or completely burned. In a future with higher occurrence of days with high and very high forest fire danger index (FFDI), the conditions that will sustain these types of bushfires occurring will increase (Canadell et al, 2021). Rainstorm intensities are also projected to increase as a result of a warming climate (Guerreiro, 2018). Together, the likely increase in fire activity and the intensification in rainfall are likely to trigger an increase in debris flow frequency across SE Australia (Nyman et al, 2019). Furthermore, in a drying climate there may be larger areas that are prone to high-magnitude erosion events as forest ecosystems, and the soil that they support, become less resilient to the impacts of fire.

## 5.2 Future directions for post-fire debris flow research

With respect to the erosion processes that we have focused on in this report, there is a strong similarity with catchments in eastern Victoria. This means that the conceptual frameworks of risk and the modelling tools developed within those frameworks (e.g. Lanhgans et al, 2016, Nyman et al 2021) are likely to be transferrable from the Victorian setting to some of the non-sandstone dominated landforms of NSW. This has important implications for focusing future research effort and development of models that will complement other post-fire erosion modelling efforts in NSW (e.g. Neris et al, 2021; Yang et al, 2020).

There is significant merit in seeking out collaborations that draw on the existing knowledge base to test and refine debris flow models for application to NSW catchments. Model development should be carried out alongside empirical research that looks to quantify the controls on erosion processes in headwaters and their links to sediment transport at larger scales. Further empirical research on debris flow processes, in a contemporary context, is critical to help support the development of predictive models and tools for risk assessment that can inform improvement to land management practices.

***Recommendation 1:*** *Use the debris flow inventory from this study and supporting datasets to conduct empirical analyses that quantifies the relative importance of fire severity, terrain, aridity, geology, and anthropogenic factors in causing variability in debris flow frequency. Calculating a high-resolution aridity data layer for NSW, would help such an analysis, given that it is likely to be a key landscape attribute contributing to variability in debris flow frequency.*

This report shows that post-fire debris flows can be an important erosion process in burned areas of southern NSW. In the locations where the debris flows occur, they are likely to be a major source of sediment being delivered to streams in the post-fire period. This is because they have very high sediment yields compared to other erosion processes. However, at larger scales and over longer timeframes, the relative importance of post-fire debris flows relative to other erosion processes is unclear. Other important sources of sediment include sheet erosion from burned areas, erosion from forest roads and timber harvesting areas, and channel erosion along streams and rivers during floods. To place these different sediment sources into a broader geomorphic context, and to identify management implications, there is a need for further research that seeks to develop models of sediment dynamics, supported by empirically derived sediment budgets, for forested catchments of this region. This research must be developed with a view to discriminate between sediment derived from different sources (roads, burned areas, undisturbed forests) over time frames that are sufficiently long such that the episodic events such as debris flows and floods are considered.

Previous research using sediment tracers and suspended sediment sampling over a relatively short timeframe (1-2 years) found unsealed forest roads to be an important sediment source from forested catchments when assessed on a per unit area basis (Motha et al, 2002, 2003). Building on this work and complementing the approach with additional tracers to discriminate between burned and unburned areas, as well as surface and subsurface sources, would provide the data needed to build and validate models that look to inform longer term management of soil and water resources in in forested catchments of NSW. Using sediment cores from lakes and other depositional setting (e.g. fans and swamps) as a archive of past sediment delivery from forested catchments would be one avenue for providing a longer term perspective on sources, processes and links to land management and climate.

***Recommendation 2:*** *Develop conceptual models of sediment dynamics in forested catchments of NSW, which aim to identify important erosion processes operating in different geomorphic settings and how these dynamics may play out over the longer term with predicted changes in rainfall, bushfire , and different land management scenarios..*

***Recommendation 3:*** *Initiate new research programs for quantifying sediment sources and building sediment budgets for forested catchments, with a view to provide a longer-term perspective on the implications of forest management, bushfire and rainfall regimes for water quality and sediment dynamics in waterways of NSW*

There are ongoing research programs in Victoria and NSW on post-fire erosion. These involve researchers from University of Melbourne, Victorian Department of Environment Land, Water and Planning (DELWP), Macquarie University, and NSW Department of Planning and Environment. These research programs are focusing on the landscape response to the 2019/20 bushfires, with emphasis on post-fire debris flows as a risk to water quality. The data produced in this project should be brought into these projects to help fast track the development of post-fire risk assessment tools that specifically address at erosion risk from burned areas

***Recommendation 4:*** *Facilitate a process for knowledge exchange and data sharing amongst relevant agencies and researchers. This will avoid duplicating efforts, it will lead to better research outcomes and result in improved efficiency in research and model development. There are models and risk assessment frameworks already in place that are used routinely by Victorian fire and land management agencies to manage erosion risk associated with bushfire and planned fire. Working to implement and test these models for the areas covered by this study would fast track the uptake of existing research and improve management of post-fire erosion risk in NSW.*

The implication of post-fire debris flows for waterway health is poorly established. This report and previous work provide insights into where debris flow occur and the volumes of sediment that one might expect to be delivered from an event. How this sediment impacts on receiving waterways in terms of water quality, habitat and ecosystem function has not been quantified. There is therefore a need for empirical research which look to link erosion in burned headwaters with geomorphic and water quality responses in rivers and estuaries. Identifying catchments for focused research and monitoring is the first step in building stronger links between erosion in headwaters and ecosystem processes in downstream waterways and estuaries.

***Recommendation 5:*** *Develop water quality monitoring programs coupled with debris flow field surveys to better understand the ecological implications in space and time of sediment pulses from post-fire erosion. This will provide insights into how bushfires play out as disturbance agents in aquatic ecosystems, both in terms of water quality and sedimentation, and thereby help guide and prioritize efforts to mitigate risk with well-targeted forest and waterway management activities.*

# 6. References

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