environment.nsw.gov.au

Post-fire debris flows in New South Wales

Susceptibility modelling and implications for management

Department of Climate Change,
Energy, the Environment and Water

Acknowledgement of Country

Department of Climate Change, Energy, the Environment and Water acknowledges the Traditional Custodians of the lands where we work and live.

We pay our respects to Elders past, present and emerging.

This resource may contain images or names of deceased persons in photographs or historical content.

Cover photo: Post-fire debris flow in the Tumut River, NSW. NearMap 2020

Published by:
Environment and Heritage Group
Department of Climate Change,
Energy, the Environment and Water
Locked Bag 5022, Parramatta NSW 2124
Phone: +61 2 9995 5000 (switchboard)
Phone: 1300 361 967 (Environment and Heritage enquiries)
TTY users: phone 133 677, then ask for 1300 361 967
Speak and listen users: phone 1300 555 727, then ask for 1300 361 967
Email info@environment.nsw.gov.au
Website www.environment.nsw.gov.au

ISBN 978-1-923200-07-4
EHG 2024/0101 April 2024

Find out more at:

environment.nsw.gov.au

Contents

List of tables

List of figures

Executive summary

This work forms part of the Water Quality – Bushfire Recovery project of the Water, Wetlands and Coastal Science Branch in the NSW Department of Climate Change, Energy, the Environment and Water (the department). The 2020 NSW Bushfire Inquiry made 76 recommendations with the aim, when bushfires like this occur again, to minimise loss of life and reduce damage to property and the environment.

Debris flows are extremely damaging and dangerous post-fire hazards that can cause significant short- and long-term impacts to rivers and aquatic ecosystems, water quality, and infrastructure. However, they are a relatively poorly understood process in New South Wales.

This report outlines the development of a post-fire debris flow susceptibility model for New South Wales to better characterise the spatial variability in debris flow likelihood after bushfire. The model outputs provide an important resource to improve predictions of these potentially destructive hazards that occur after fire. It has implications for land and water management in a range of contexts and tenures, including threatened aquatic species management, water quality, and risk assessments related to infrastructure and safety.

The key aims of the work were to:

- develop and compare predictive random forest classification and logistic regression models of debris flow likelihood, using observational debris flow data from the Tuross, Tumut and Lake Burragorang catchment areas
- map individual debris flows in sections of the Tuross River and Lake Burragorang catchment areas using high-resolution aerial imagery
- model a Budyko radiative index of dryness, or aridity index, across New South Wales at 30 m resolution (see NSW 30 m Aridity Index (NSW Government and DCCEEW 2023)), to enable fine-scale assessment of moisture balance, which was not possible with previously available coarse-resolution aridity datasets
- create a debris flow susceptibility map for forested areas across New South Wales.

1. Introduction

This work forms part of the 'Water Quality – Bushfire Recovery' project of the Wetlands and Coastal Science Branch in the NSW Department of Climate Change, Energy, the Environment and Water (the department). The 2020 NSW Bushfire Inquiry made 76 recommendations with the aim, when bushfires like this occur again, to minimise loss of life and reduce damage to property and the environment. Funding was provided to contribute to addressing recommendation 36 of the 2020 NSW Bushfire Inquiry: 'That government invest in long-term ecosystem and land management monitoring, modelling, forecasting, research and evaluation …'

The project aims to improve understanding of how bushfires impact NSW waterways and the relative sensitivity of different waterway types to bushfire impacts. The project also seeks to develop management tools to assist land and water managers to better prioritise areas for targeted management or intervention after fire. This report outlines the development of a post-fire debris flow susceptibility model for New South Wales, to better characterise the spatial variability in debris flow likelihood after bushfire.

1.1 Background

Bushfires are common throughout Australia, and although they are an essential part of many Australian ecosystems, they are often destructive, and their impacts can persist long after the fire is out.

Severe post-fire erosion, such as debris flows, occurs during intense rainfall following a bushfire and can reduce water quality and cause long-lasting impacts to downstream rivers and wetlands as well as enormous damage to infrastructure. Debris flows are fast-moving, powerful mass movements composed of a slurry of water, mud, rock, logs and debris with sediment concentrations often exceeding 40% (Nyman et al. 2011; Iverson 2014). They are runoff generated mass movements and once they generate enough momentum, scour straight, deep, trench-like channels down hillslopes and headwater hollows (Tang et al. 2019). In this way, they are distinct from landslide processes that occur due to high pore pressure in saturated soils (Abdollahi et al. 2023; Hakro and Harahap 2015).

Debris flow fan deposits form when energy within the flow is reduced, typically related to a reduction in slope or a reduction in flow confinement (Nyman et al. 2011; Iverson 2014). Debris flows mobilise huge amounts of sediment and are often associated with flash flooding in reaches downstream of the fan deposit. Although post-fire erosion is commonly considered merely a consequence of bushfires, debris flows are significant natural hazards in their own right, which can cause considerable damage to property and infrastructure and even loss of life in mountainous regions around the world (Jackson and Staley 2018).

Debris flows are hard to predict and often occur in remote and rugged bushland, making them difficult to study. Not all landscapes are susceptible to debris flows after fire, but where they do occur their impacts are disproportionately significant in terms of short-term water quality impacts and longer-term impacts on aquatic ecosystems in downstream creeks and rivers, and infrastructure such as roads (Fraser et al. 2022; Smith et al. 2011). Understanding the spatial variability in relative likelihood of debris flow activity is important to better characterise risks to water quality, infrastructure, and aquatic ecosystems.

Post-fire debris flow research is lacking in New South Wales with notable exceptions being the work done in the Warrumbungles following the 2013 Wambelong fire (Tulau et al. 2019a; Tulau 2019b), and recent debris flow mapping undertaken on behalf of the NSW Natural Resources Commission (NRC – NSW Government 2023). In Victorian catchments however, post-fire hydrological and geomorphic research has led to a strong theoretical understanding of debris flow processes in south-eastern Australia. Supported by extensive field data and predictive models (Nyman et al. 2013; Nyman et al. 2015; Nyman et al. 2021), this work has highlighted some of the key factors determining susceptibility to debris flows after fire, which are fire severity, slope, basement geology, soil erodibility, and aridity.

By leaning on these insights and using recently mapped debris flow datasets in New South Wales, this report summarises the process of developing a NSW-wide debris flow susceptibility map to better understand debris flow likelihood across the state. The key aims of the work are to:

- develop and compare predictive random forest classification and logistic regression models of debris flow likelihood, using observational debris flow data from the Tuross, Tumut and Lake Burragorang catchment areas
- map individual debris flows in sections of the Tuross River and Lake Burragorang catchment areas using high-resolution aerial imagery
- model a Budyko radiative index of dryness, or aridity index, across New South Wales at 30 m resolution (see NSW 30 m Aridity Index (NSW Government and DCCEEW 2023)), to enable fine-scale assessment of moisture balance, which was not possible with previously available coarse-resolution aridity datasets
- create a debris flow susceptibility map for forested areas across New South Wales.

Improving our understanding of the spatial variability in the susceptibility of landscapes to debris flows has significant implications for land and water management in the rugged, forested country of eastern New South Wales. In particular, the model outputs can inform assessments of future potential hazards to threatened aquatic species, remote infrastructure such as roads and properties, and drinking water reservoirs and infrastructure. Nonetheless, further work is required to optimise and improve the model in a range of different climatic and geomorphological regions across New South Wales, and to better quantify sediment loads and budgets related to debris flows.

1.2 Study areas

Four study areas across 3 catchments areas – Tumut, Tuross and Lake Burragorang – were used to develop an inventory of debris flow occurrence after the 2019–20 bushfires. High-resolution aerial imagery was used to accurately map discrete debris flow deposits and channel initiation points. Mapping of debris flows by NRC – NSW Government (2023) provided an inventory of debris flows in sections of the Tumut and upper Tuross river catchments in southern New South Wales. High-resolution NearMap imagery in the lower Tuross and Lake Burragorang catchments allowed further addition to this debris flow occurrence inventory (Figure 1).

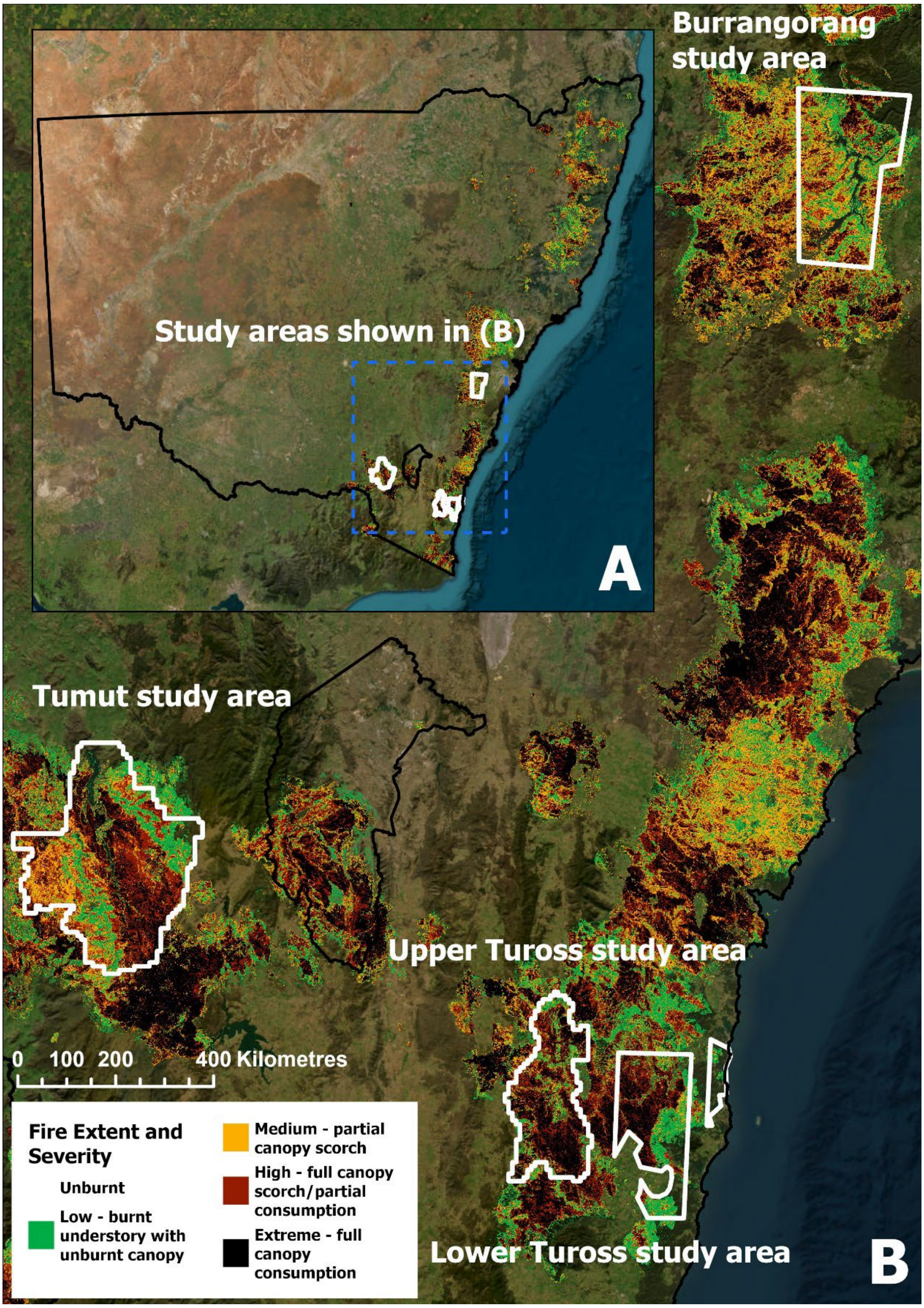

Figure 1 Study areas where mapping of debris flows using high-resolution aerial imagery was used to train the debris flow susceptibility model and 2019–20 fire extent and severity mapping. Source: NSW Government and DCCEEW (2020)

Fire severity classes: low severity – burnt understorey with unburnt canopy; moderate severity – partial canopy scorch; high severity – complete canopy scorch and partial canopy consumption; extreme severity – complete canopy consumption. B: Tumut and Upper Tuross study areas mapped by NRC – NSW Government (2023), lower Tuross and Lake Burragorang study areas mapped by the department in 2024 (this report).

1.2.1 Upper and lower Tuross study areas

The Tuross River rises in the Kybeyan Range, flowing east through the rugged and remote bushland of Wadbilliga National Park (see site details in Table 1). Its flow is unregulated and provides an important water source for Eurobodalla Shire Council, supporting dairy and beef grazing in its lower reaches, and oyster farming in the estuary. The Tuross River catchment was significantly impacted by the Badja fire, which burnt ~315,500 ha between 27 December 2019 and 5 March 2020. The upper and lower Tuross study areas were severely burnt, with large portions burnt at an extreme severity with >50% canopy removal, and most of the study areas experiencing partial canopy removal. The south-eastern region of the lower Tuross study area was burnt at a generally lower severity (Figure 1). Several large rainfall events during 2020 and 2021 (Figure 2) caused significant debris flow activity in the Tuross study areas and severe water quality impacts in the river and estuary.

Table 1 Characteristics of the upper and lower Tuross study areas

Attribute	Description
Climate	Mean annual rainfall is about 931 mm and is generally uniformly spread across the year.
Vegetation	Dry sclerophyll forests (shrubby sub-formation) dominate the area, accounting for 45% of the total forested area, followed by wet sclerophyll forests (shrubby sub-formation) (33%) and wet sclerophyll forests (grassy sub-formation) (10%).
Lithology	Sandstone dominates this region, constituting 60% of the study areas, followed by granite (35%), and granodiorite (10%).

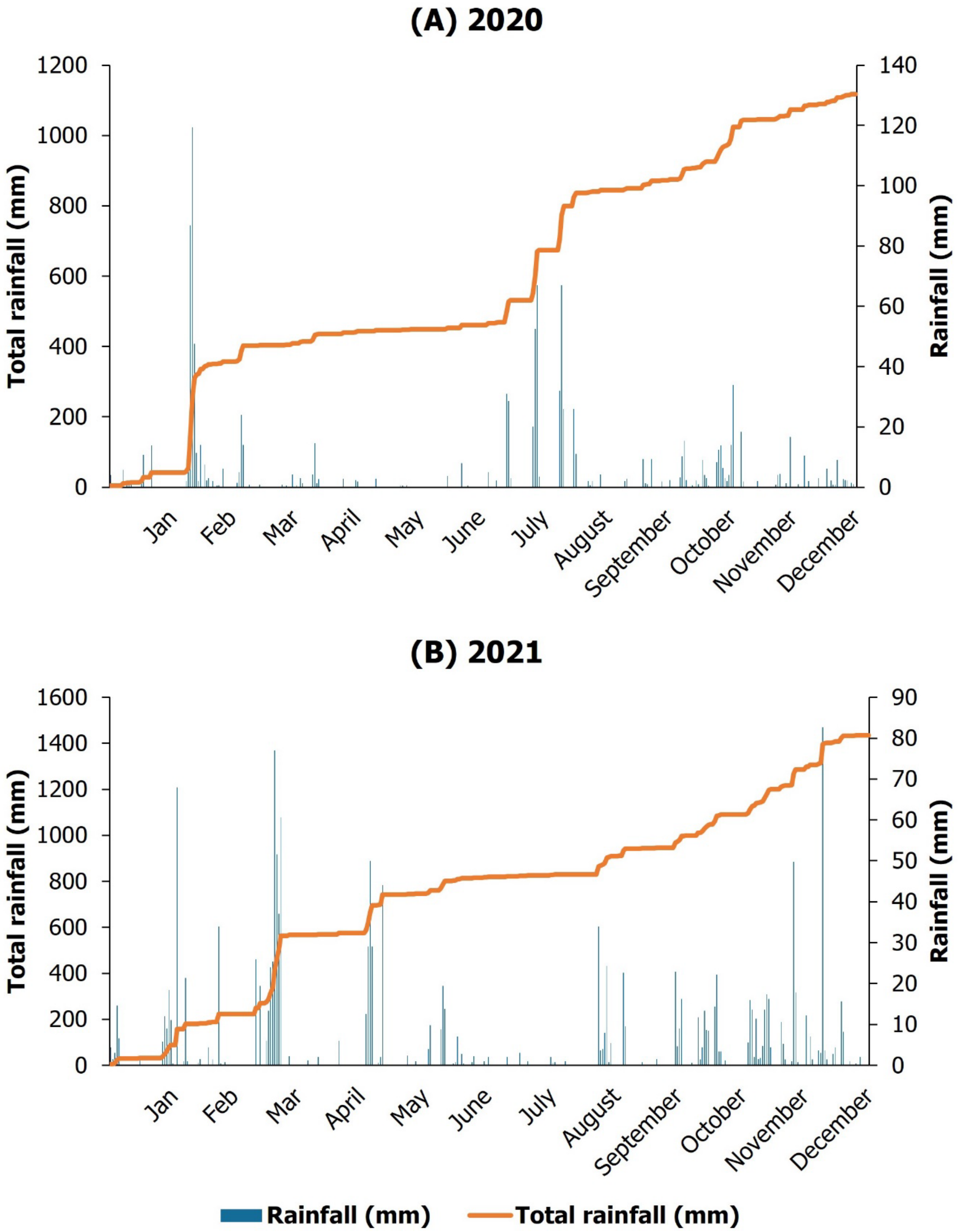

Figure 2 **Daily and cumulative rainfall (mm; station number 069054) in the Tuross study area in 2020 and 2021. Source: Bureau of Meteorology, Australia (2024)**

1.2.2 Tumut study area

The Tumut River is a tributary of the Murrumbidgee River and rises in the NSW Snowy Mountains (site details in Table 2). It is heavily regulated by 6 dams as part of the Snowy Mountains Hydroelectric Scheme. Within the Tumut study area there are 3 impoundments: Talbingo Reservoir, Jounama Pondage and Blowering Reservoir. The Tumut study area was impacted by the Dunns Road fire, which burnt ~334,000 ha between 27 December 2019 and 24 February 2020. The central portions of the study area in the Tumut Valley were significantly impacted with large regions of extreme severity burns with >50% canopy removal. The north-eastern and south-western regions of the study area were generally burnt by moderate or low severity fire (Figure 1). Numerous large rainfall events throughout 2020 and 2021 (Figure 3) caused significant debris flow activity in the Tumut study area.

Table 2 Characteristics of the Tumut study area

Attribute	Description
Climate	During the 24-year period from 1997 to 2022, the catchment's mean annual rainfall was 973 mm, with most of the rainfall occurring during winter (June to August).
Vegetation	Wet sclerophyll forests (grassy sub-formation) dominate the area, accounting for 91% of the total forested area, followed by dry sclerophyll forests (shrubby sub-formation) (5.8%) and dry sclerophyll forests (shrub/grass sub-formation) (3%).
Lithology	Granodiorite with 30% and granite with 24% dominate this region, followed by pyroclastic rocks (13%) and quartzite (12%).

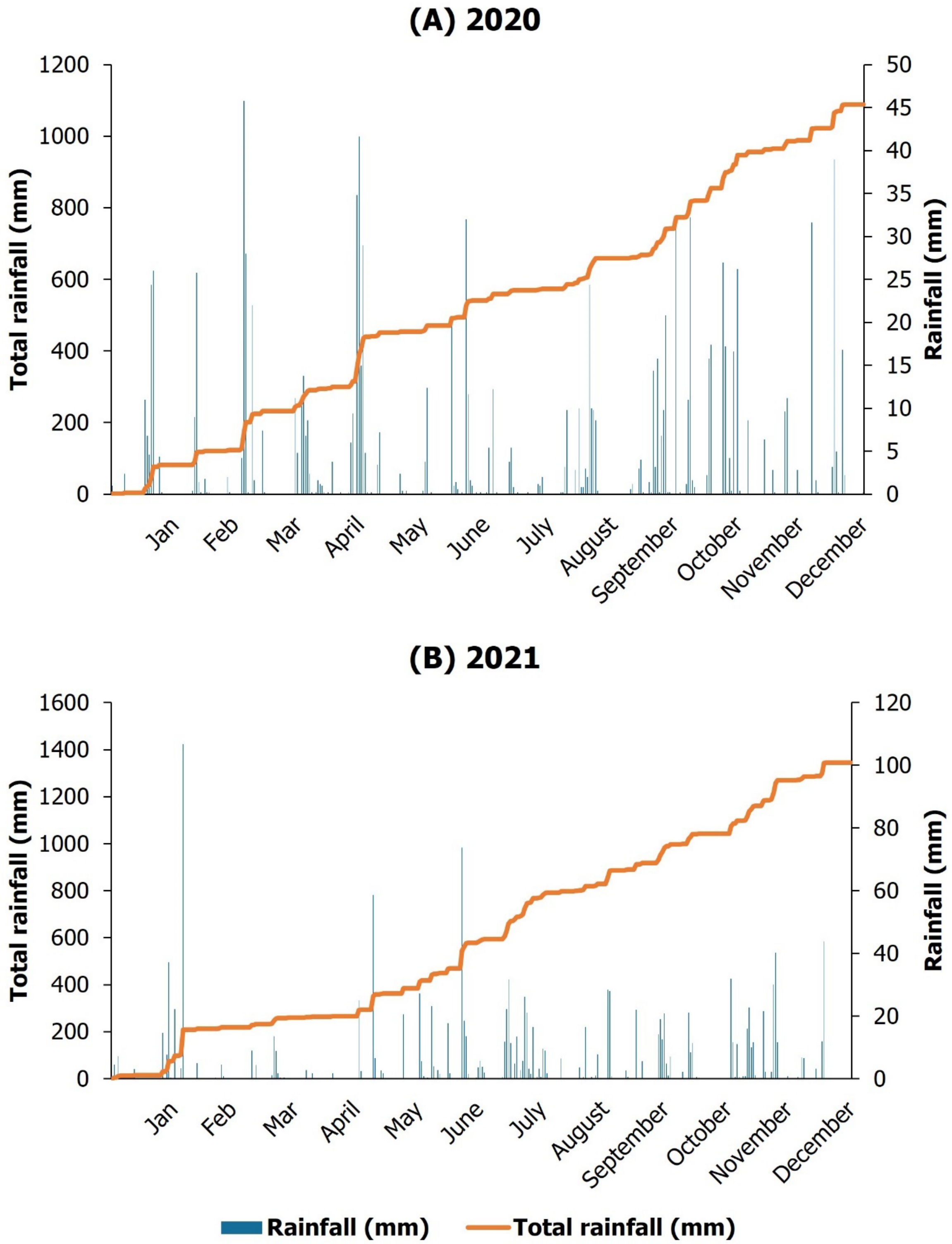

Figure 3 Daily and cumulative rainfall (mm; station number 072131) in the Tumut study area in 2020 and 2021. Source: Bureau of Meteorology, Australia (2024)

1.2.3 Lake Burragorang study area

Lake Burragorang in the Greater Blue Mountains World Heritage Area is one of the main reservoirs providing drinking water for Sydney. The dam impounds several major tributaries of the Nepean River, including the Coxs, Wollondilly, Nattai and Kedumba rivers (Table 3). The Lake Burragorang study area was impacted by the Green Wattle Creek fire which burnt ~280,000 ha between 27 November 2019 and 10 February 2020. Much of the study area was burnt by moderate-severity fire with partial canopy scorch, with numerous smaller pockets of extreme fire severity particularly in the north-eastern and southern regions of the study area. Four significant rainfall events occurred in 2020 and 2021 (Figure 4), which caused significant debris flow activity in the study area and water-quality impacts in the reservoir.

Table 3 **Characteristics of the Lake Burragorang study area**

Attribute	Description
Climate	During the 128-year period from 1895 to 2023, the region's mean annual rainfall was 970 mm, and was generally uniformly spread across the year with a slight increase in summer rainfall.
Vegetation	Dry sclerophyll forests (shrub/grass sub-formation) with 44% and dry sclerophyll forests (shrubby sub-formation) with 43% dominate the area, followed by wet sclerophyll forests (shrubby sub-formation) (9.1%) and rainforests (1.5%).
Lithology	Sandstone dominates this region, constituting 77%, followed by granite (13%).

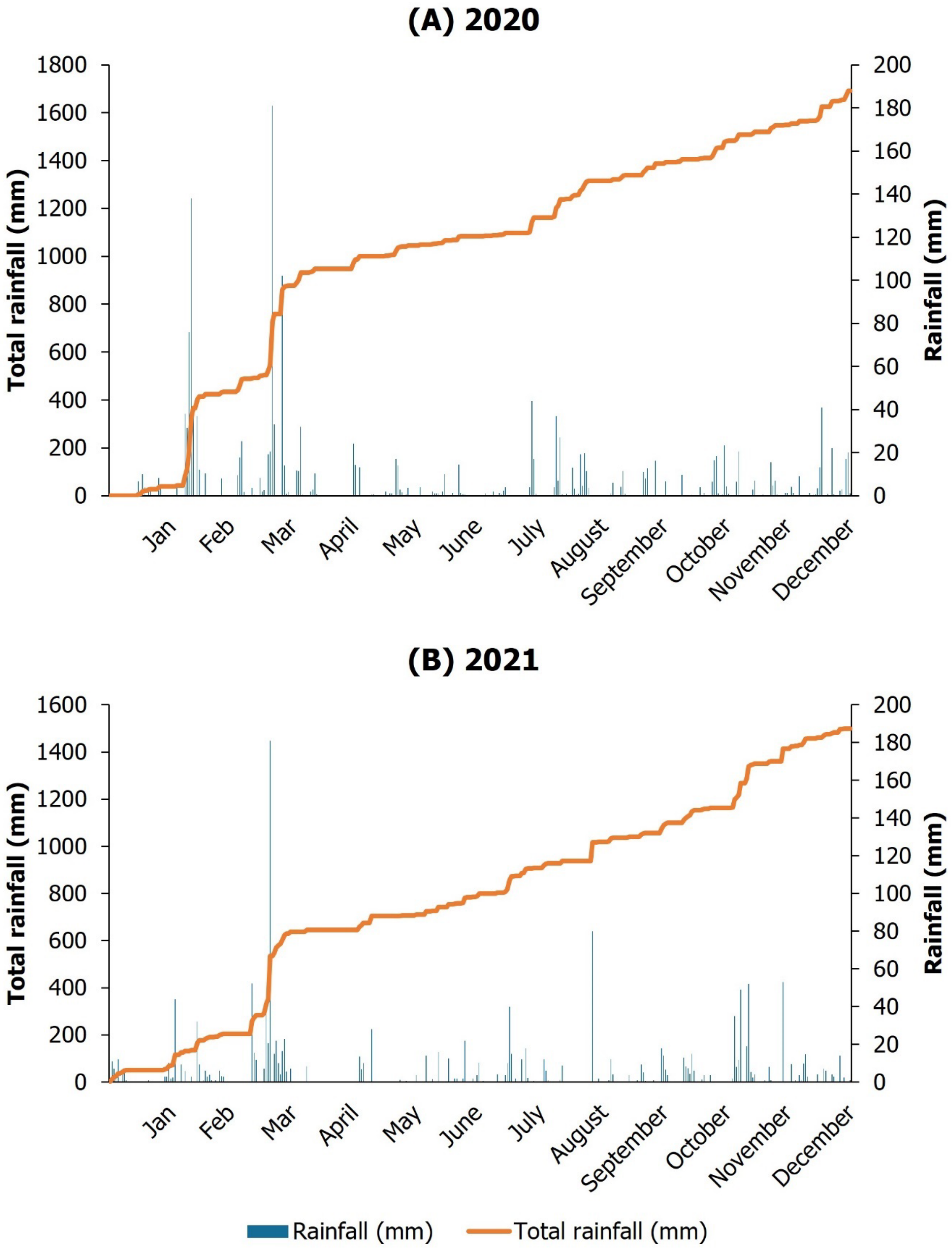

Figure 4 **Daily and cumulative rainfall (mm; station number 063036) near the Lake Burragorang study area in 2020 and 2021. Source: Bureau of Meteorology, Australia (2024)**

2. Debris flow susceptibility modelling method

Random forest classification and logistic regression are 2 modelling approaches that have been used widely in debris flow and landslide susceptibility mapping (Cannon et al. 2010; Staley et al. 2016; Smith et al. 2021). For this project, both approaches were undertaken using the debris flow occurrence inventory from the Tuross, Tumut and Burragorang study areas. Their predictive performance was assessed and compared to determine the most appropriate method for creating a NSW-wide debris flow susceptibility map. There are limitations and assumptions inherent in the approach, which are discussed below. Nonetheless, the model output has numerous potential usages in a range of management contexts.

2.1 Random forest

Random forest classification is a powerful machine learning algorithm that combines the strength of multiple decision trees to improve accuracy and handle complex problems (James et al. 2023). Random forest creates hundreds of individual decision trees. Each tree considers only a random subset of features (predictive variables) and training data to individually make a prediction. The final prediction from the random forest is typically determined by the most common prediction among the various decision trees. Unlike logistic regression, the random forest itself doesn't have an underlying statistical model with a specific equation or mathematical formula that captures the entire relationship between the features and the target variable (binary debris flow data). Key assumptions of a random forest are:

- the errors contained within individual decision trees within the forest are assumed to be independent of each other
- no strong multicollinearity of predictive variables (features).

2.2 Logistic regression

Logistic regression is a multivariate statistical analysis used to determine the probability of a binary outcome based on a set of relevant independent, predictor variables (James et al. 2023). Event and non-event observations from a target study area are required for the training and validation of the logistic regression. Observations need to be accompanied by relevant continuous or discrete predictor variables. Debris flow susceptibility was modelled using the following equations.

$$P = \frac{e^{y}}{1 + e^{y}}$$

$$y = \beta_1 \ + \ \beta_2 X_1 \ + \ \beta_3 X_2 \ \ \ldots + \ \beta_n X_n$$

P is the probability of debris flow, β1, β2 … βn are constants derived by the logistic regression, and *X1*, *X2* … *Xn* are predictive variables.

Key assumptions of a logistic regression are:

- dependant variable is binary
- observations are independent of one another
- no multicollinearity between predictor variables
- independent variables linearly related to the log odds
- no strongly influential outliers in the predictive variables
- a large sample size – a general guideline is that you need a minimum of 10 cases with the least frequent outcome for each independent variable in your model.

2.3 Debris flow occurrence inventory

2.3.1 Debris flow mapping

High-resolution (~7 cm) NearMap acquisitions of aerial imagery across a broad swathe of the central Tuross catchment and Lake Burragorang region allowed mapping of discrete post-fire debris flows (Figure 1, Table 4). This inventory of known debris flow occurrences was supplemented by debris flow mapping undertaken by the NRC (NRC – NSW Government 2023) in another region of the Tuross catchment and in the Tumut catchment. The combined inventory was used to train and calibrate the models (Figure 1, Table 4).

Table 4 Mapping details of the 4 study areas

	Lower Tuross	Upper Tuross	Tumut	Burragorang
Mapped by	DCCEEW 2024	NRC – NSW Government (2023)	NRC – NSW Government (2023)	DCCEEW 2024
Area of imagery (km^2)	719	737	1,735	1,082
Date(s) of imagery	12/03/20 and 23/01/21	Acquisitions between 17/01/22 and 14/02/22	Acquisitions between 03/01/21 and 09/10/21	17/01/21
Number of channel initiation points mapped	770	273	781	451
Number of 2 ha watersheds associated with debris flows	291	192	585	493

Debris flows have characteristic forms that can be reliably mapped using suitably high-resolution aerial imagery (~10 cm or better; Adams et al. 2016; NRC – NSW Government 2023). The typically straight, deeply scoured channels formed by the debris flows can be easily identified in aerial imagery as pale scars across the landscape. Mapping of debris flows was undertaken following methods developed by Nyman et al. (2015), whereby 2 key features were mapped as point features in an ArcGIS environment (Figure 5A):

- debris flow fans – the point at which sediment deposition becomes the dominant feature rather than scour. In some cases, debris flows discharge directly into a larger stream and there is no clear depositional fan. In these cases, the debris flow deposit was mapped at the location it discharges into the larger river
- channel initiation points – the point where the hillslope sheet flow transitions into channelised debris flows.

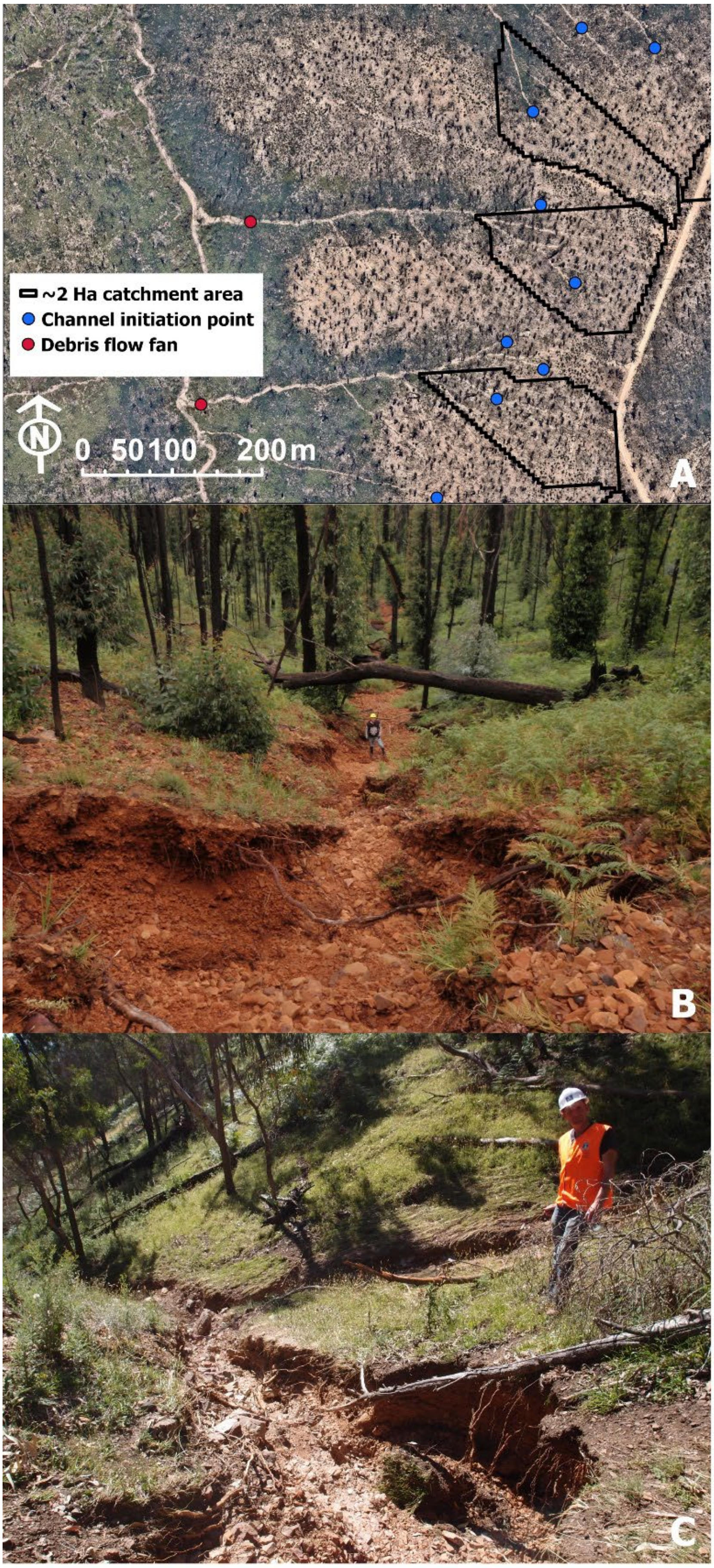
~2 Ha catchment area
Channel initiation point
Debris flow fan
N
0 50100 200m
A
B
C

Figure 5 **A: Mapping of channel initiation points and debris flow fans using high-resolution imagery. B and C: Debris flow channels looking downstream; these images are from debris flows in Victoria, not those mapped in New South Wales. Photos: Petter Nyman/Alluvium.**

2.3.2 Linking to functional units

Functional units, representing the typical area above a debris flow initiation point, were defined to provide a consistent area from which landscape attributes could be extracted. The functional units are convergent, zero-order headwater catchments, approximately 2 ha in size (Figure 5). Two-hectare headwater catchments were used because research in Victoria has demonstrated that debris flow processes largely operate in these small headwater environments (Nyman et al. 2015; Nyman et al. 2020).

The rationale for defining these functional units is described in Langhans et al. (2016). For each functional unit, presence or absence of debris flows was recorded by assigning a binary score of 1 (debris flow) or 0 (no debris flow). A headwater catchment is associated with a debris flow if a channel initiation point occurred within the 2 ha area, or if it occurred in the first-order drainage line downstream. A flow accumulation raster, created from mosaics of 5 m digital elevation models (DEMs), was used to determine if a headwater catchment was hydrologically linked to a downslope channel initiation point.

The inventory of debris flow observations across the Tumut, Tuross and Burragorang study areas includes 2,275 channel initiation points associated with 1,561 debris flow-producing headwater catchments, and 43,191 headwater catchments where debris flows did not occur (NRC – NSW Government 2023) (Table 4).

2.3.3 Predictor variables

Research over the past decade, predominantly in the Victorian High Country, has identified some of the key factors that determine the susceptibility of a landscape to debris flows (Nyman et al. 2011; Nyman et al. 2015; Sheridan et al. 2015). These are fire severity, slope, basement geology, soil erodibility, and aridity (Table 5). Average values of the predictor variables in Table 5 for each ~2 ha catchment were used in the random forest and logistic regression models.

Table 5 **Predictor variables of models**

Predictor variable	Rationale	Publicly accessible link	References
Fire severity	Fire severity is a fundamentally important predictor of debris flow susceptibility. It is generally understood that debris flows are more likely to occur where there has been partial or complete canopy removal during fire (Wondzell et al. 2003).	Fire Extent and Severity (FESM) 2019/20	NSW Government and DCCEEW 2020
Slope	Slope is an important factor determining debris flow susceptibility, as steeper slopes contribute to higher energy runoff during high-intensity rainfall.	NSW-wide 5 m DEM	Joint Remote Sensing Research Program portal, resampled from Elvis LiDAR elevation data (ICSM 2023)
Geology	Geology plays an important role in debris flow susceptibility with sandstone based lithologies appearing more susceptible than granitic or other volcanic rock types, though more work is required over a range of different landscapes to fully understand the influence of basement geology on debris flow susceptibility.	NSW Seamless Geology	NSW Government and Department of Regional NSW 2018
Soil erodibility (K-factor)	The K-factor is a component of the widely used Revised Universal Soil Loss Equation (RUSLE) relating to soil erodibility. It is estimated from soil mapping and soil profile data.	NSW soil erodibility K-factor	NSW Government and DCCEEW 2018; for method: Yang et al. 2017
Aridity	Aridity is related to the balance between precipitation and potential evapotranspiration and provides an indication of moisture balance across the landscape. Through its influence on soil hydraulic properties, aridity has been shown to be an important factor determining the susceptibility of hillslopes to severe post-fire erosion (Sheridan et al. 2015). Locally drier slopes – equator-facing slopes for example – have been shown to have	NSW 30 m Aridity Index	NSW Government and DCCEEW 2023

	lower infiltration rates and the post-fire vegetation recovery is slower than polar-facing slopes with higher average moisture balances, allowing a longer window within which a high-intensity rainfall event can trigger severe erosion. To allow fine-scale assessments of variations in aridity to inform the predictive logistic regression model, a high-resolution 30 m aridity index (also known as the Budyko radiative index of dryness) for NSW was developed following Nyman et al. (2015).	

2.4 Model training and validation

Given their proximity and similarity of geographic characteristics, the data from the upper and lower Tuross study areas were combined for model training and validation. This meant that 3 regions were used for model training and cross-validation. To avoid the influence of an imbalanced dataset on training the models, an equal number of debris flow-producing watersheds and non-debris flow-producing watersheds were sampled to produce the training data for the random forest and logistic regression models. Once the models were trained, validation of the model was undertaken by running the model on a subset of the debris flow inventory to determine how well the model correctly identifies debris flow occurrence and non-occurrence.

An assessment of the performance of the model was undertaken by evaluating receiver operator characteristic (ROC) curves and the calculation of area under the curve (AUC) scores (James et al. 2023) (see Table 7, Figure 6). The AUC score provides a measure of how well the model accurately predicts true events (true positives) versus false predictions (false positives). An AUC score of 50% indicates a model has zero discriminatory performance, while an AUC score >80% indicates very good discrimination and >90% is excellent. To assess how well the models predict debris flow occurrence in regions outside of the areas they were trained, 3 separate training and validation scenarios were undertaken:

1. Tuross and Tumut debris flow observations were used to train both models. An equal number of debris flow and randomly selected non-debris flow watersheds (1,068 each) were used for training. The models were subsequently validated by predicting debris flow occurrence in the Burragorang region.
2. Tuross and Burragorang debris flow observations were used to train both models. An equal number of debris flow and randomly selected non-debris flow watersheds (976 each) were used for training. The models were subsequently validated by predicting debris flow occurrence in the Tumut region.
3. Finally, Tumut and Burragorang debris flow observations were used to train models. An equal number of debris flow and randomly selected non-debris flow watersheds

(1,078 each) were used for training. Again, these models were subsequently validated by predicting debris flow occurrence in the Tuross region.

After the 3 scenarios were run (see model performance metrics in the following section (Table 7)), a further validation step was performed. Splitting the debris flow inventory from all study areas into a training dataset incorporating 80% of debris flow-producing watersheds (i.e. 1,248 debris flows) and validation dataset of 20% (i.e. 313 debris flows) of debris flow-producing watersheds allowed assessment of the predictive power of the model when debris flow observations from all 3 regions were incorporated into model training.

2.4.1 Modelling results and performance

All 5 of the predictor variables were significant predictors in both the random forest and logistic regression models ($p < 0.001$; Table 6). Random forest feature importance values sum to 1 and indicate the relative ranked importance of different variables in determining debris flow occurrence. Slope (0.27) emerged as the dominant factor, closely followed by fire severity (0.26). Aridity (0.18) is the third most important predictor, indicating the influence of local-scale moisture availability on debris flow susceptibility (Table 6).

Logistic regression odds ratios do not provide an indication of ranked importance of predictor variables but indicate how changes in predictor variables are associated with increased or decreased odds of occurrence. Where the odds ratio is >1, increases in the variable are associated with increases in the odds of debris flow occurrence. Similarly, beta (β) coefficients indicate interactions between predictors and the probability outcome, in this case debris flows. The positive coefficients indicate that increases in a predictor variable are associated with an increase in odds ratios of event outcomes and a higher probability of debris flow. The magnitude of beta coefficients represents the strength of relationship between predictors and debris flow occurrence (Table 6). Both models perform well and highlight that the chosen predictor variables are important drivers of debris flow likelihood, which aligns well with insights into the drivers of debris flow susceptibility gained in Victoria (Nyman et al. 2013; Nyman et al. 2015; Nyman et al. 2021).

Table 6 **Results of fitting random forest and logistic regression models to the binary data on debris flow occurrence in Tumut, Tuross and Burragorang study areas**

	Random forest[a]		Logistic regression[b]		
Predictor variable	p-value	Feature importance	p-value	β coefficient	Odds ratio
Aridity	<0.001	0.18	<0.001	0.72	2.07
FESM	<0.001	0.26	<0.001	4.30	1.32
Slope	<0.001	0.27	<0.001	0.18	1.20
Geology	<0.001	0.10	<0.001	30.64	2.04
K-factor	<0.001	0.175	<0.001	0.82	2.28

[a] Coefficient of determination (R^2 score) goodness of fit test: 0.91. R^2 score provides an evaluation metric in the range 0–1 indicating goodness of fit. A score higher than 0.9 shows very good correlation between the model's prediction and actual values and reflects excellent model fit. Sum standard error for random forest variables: 0.01

[b] Hosmer–Lemeshow goodness of fit test; Chi-square statistic: 3.5, p-value = 0.94. The Hosmer–Lemeshow test assesses the goodness of fit of the logistic regression model by comparing the number of observed events to the number of predicted events. The null hypothesis is that the model predicted events are significantly different from the observed events. Therefore, a high p-value indicates good model fit. Sum standard error for random logistic regression: 0.6

The random forest model produced slightly better predictive performance than the logistic regression when validated within the study areas that were used to train the model (Table 7). However, the logistic regression model outperformed the random forest model in the 3 validation scenarios whereby the models were validated in a region outside of the study areas used to train the model (Table 7). Smith et al. (2021) found the same discrepancy between random forest and logistic regression when comparing their ability to predict landslide susceptibility in New Zealand. Predictive models must strike a balance between generality and specificity. Generality refers to a model's ability to be accurately extrapolated beyond the regions in which it was trained. Specificity refers to how well it performs within the regions it was trained on. The random forest model may be too specific in that it overfits to the training dataset and struggles to generalise to other situations. Both models display very good discriminatory performance with AUC scores ≥80% (Table 7, Figure 6), however given the improved performance of the logistic regression model when predicting debris flows outside of the region that the model was trained on, this model was chosen to develop the NSW debris flow susceptibility map.

Table 7 **Results of training, validation and calibration of fitting random forest and logistic regression models**

			AUC	
	Training areas	**Validation area/s**	**Random forest**	**Logistic regression**
1	Tuross + Tumut	Burragorang	65%	66%
2	Tuross + Burragorang	Tumut	79%	86%
3	Tumut + Burragorang	Tuross	76%	81%
4	80% (Tuross + Tumut + Burragorang)	20% (Tuross + Tumut + Burragorang)	86%	81%
5	Tuross + Tumut + Burragorang	Tuross + Tumut + Burragorang	86%	80%

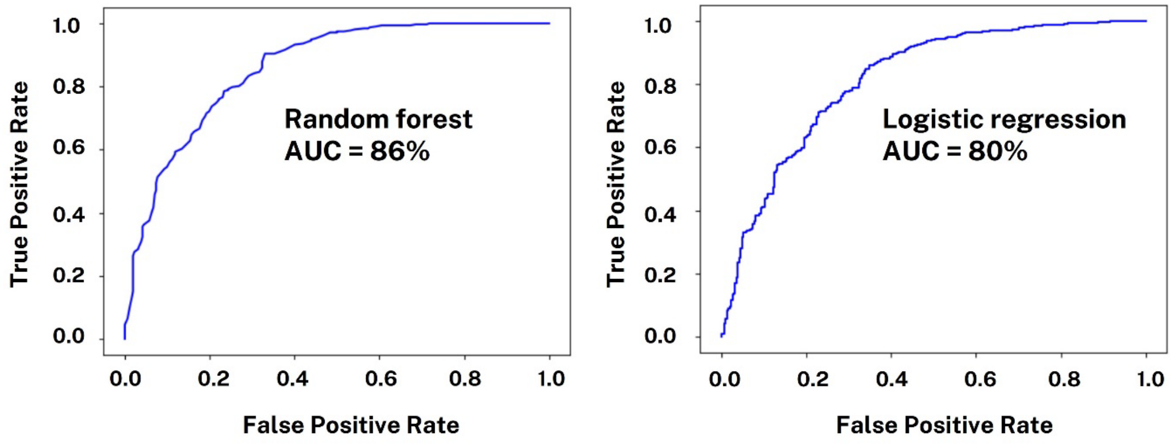

Figure 6 **Receiver operator characteristic (ROC) curves and area under curve (AUC) for random forest and logistic regression of re-calibration samples trained with 1,561 debris flow and 1,561 randomly selected non-debris flow in 3 study areas for extrapolating across New South Wales**

3. NSW-wide debris flow susceptibility

3.1 NSW debris flow susceptibility map

The logistic regression model was trained using the entire debris flow occurrence inventory and was extrapolated to develop a NSW-wide debris flow susceptibility map (Figure 7). Predictor variable datasets for slope, aridity, geology and soil erodibility are available for the whole of New South Wales and can be calculated for all ~2 ha headwater catchments across the state, allowing extrapolation of the debris flow susceptibility model.

Debris flow probabilities were not estimated for the whole state but were calculated for forested regions where debris flow processes typically occur. The probability predictions were conducted across 98 local governments areas (LGAs), as listed in Table A1. Fire severity was held constant at 5 – extreme fire severity, canopy consumption – in order to estimate debris flow probability across the forested areas of the state assuming extreme severity fire. Assuming a worst-case scenario allows a 'forward-looking' susceptibility model that allows assessments of the relative likelihood of debris flow activity across all areas of New South Wales that may experience future bushfire.

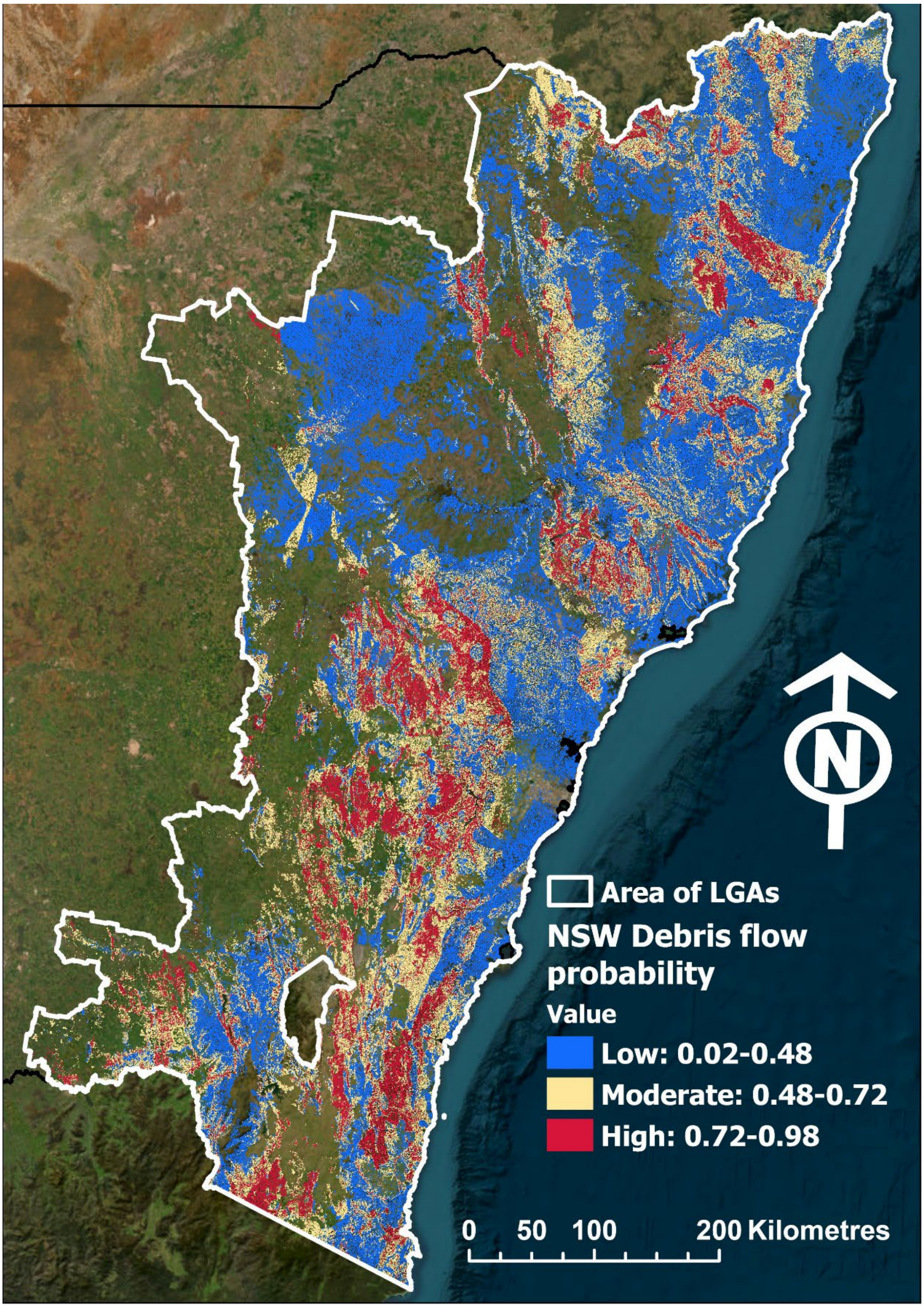

Figure 7 **NSW debris flow susceptibility map based on logistic regression model in the 98 LGAs of eastern New South Wales (see Table A1)**

3.2 Assumptions and accuracy

The logistic regression model was validated in 4 study areas across 3 relatively small mountainous regions of south-east New South Wales, with narrower ranges of predictor variables compared to the variability seen across the state (Table 8). Extrapolating beyond these ranges introduces uncertainty to the results. As such, regions with key predictor variables outside of these ranges (e.g. the northern NSW tablelands) are considered to have a lower confidence in their probability estimates, whereas confidence in the debris flow probabilities for the south-eastern NSW ranges, where the model was trained and validated, is higher. Model outputs for 2 ha catchments mapped in the riparian areas, floodplains and rangelands of western New South Wales were removed from the final model output. These low relief regions are not susceptible to debris flow processes, however with their considerably higher aridity values than the eastern tablelands, the logistic regression model anomalously classified some of these regions as having a high probability of debris flow activity. There might be additional artifacts, stemming from the modelling, that need to be assessed on a case-by-case basis when the map is used in hazard assessments.

Table 8 **Descriptive statistics for the predictor variables (features) used in Tuross, Tumut and Burragorang study areas for training the model versus NSW forested areas**

	Debris flow inventory training dataset (Tuross, Tumut and Burragorang regions)				**NSW-wide[a]**			
Predictor variable	Min.	Max.	Mean	Std dev.	Min.	Max.	Mean	Std dev.
Slope	0.001	52.583	20.697	9.808	0	50.997	10.152	9.302
Fire severity	0.002	5	3.773	1.2	N/A	N/A	N/A	N/A
Aridity	0.368	2.719	1.708	0.395	0.173	8.224	2.26	0.92
Geology[b]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Soil K-factor	0	0.067	0.043	0.007	0	0.07	0.048	0.01

[a] Note that this refers to forested areas within New South Wales, not the entirety of the state. The following forested types were included for the debris flow susceptibility map: dry sclerophyll forests (shrub/grass sub-formation), dry sclerophyll forests (shrubby sub-formation), forested wetlands, rainforests, wet sclerophyll forests (grassy sub-formation), and wet sclerophyll forests (shrubby sub-formation) (NSW State Vegetation Type Map, NSW Government and DCCEEW (2022)). Additionally, man-made plantation forestry, which encompasses environmental forestry, hardwood and softwood plantation, was incorporated into the debris flow susceptibility map using the NSW Landuse 2007 dataset captured by Landsat ETM/TM data (NSW Government and DCCEEW 2007).

[b] Eight geology types were included in the models training: sandstone (8), quartzite (7), pyroclastic rocks (6), granite (5), granodiorite (4), siltstone (3), slate (2), tonalite (1). Geology ordinal values (the numbers in brackets) were assigned according to the counts of debris flows within each dominant lithology in the training/calibration areas (Tuross, Tumut and Burragorang). All other lithologies were considered zero.

Debris flow susceptibility was classified into 3 susceptibility scores – low, moderate and high – based on statistical analysis of the probability values (0–1) for each 2 ha watershed. Youden's J statistic test was employed to define the cut-off between low and moderate probability classes (Ruopp et al. 2008). This test leverages sensitivity (true presence/presence) and specificity (true absence/absence) to pinpoint an optimal cut-off value. Using predicted and real data from the fourth set of the fitted logistic regression model (Table 7), a cut-off value of 0.48 was calculated. To further classify debris flow probability, K-means algorithm (Guo et al. 2021) was used to cluster probabilities that met or exceeded the initial cut-off of 0.48. By defining 2 clusters and calculating their centroids, a second cut-off point of 0.72 was identified. This enabled us to categorise probabilities into 3 distinct groups:

- low (0 to 0.48) – significant debris flow activity not expected
- moderate (0.48 to 0.72) – debris flow activity possible
- high (0.72 to 1) – highly susceptible to significant debris flow activity.

3.2.1 Warrumbungles debris flows

Assessment of the debris flow susceptibility map in regions outside of the areas used to train the model provides confidence that the model incorporates the key factors determining the likelihood of debris flow activity. There are few well-documented occurrences of debris flows in New South Wales, however after the 2013 Wambelong fire in the Warrumbungle Range, significant debris flow activity caused damage to National Parks and Wildlife Service infrastructure and significantly impacted waterways (Tulau et al. 2019a; Tulau et al. 2019b). The NSW debris flow susceptibility map developed by the logistic regression model identifies much of the Warrumbungle National Park as highly susceptible to debris flow activity after severe fire (Figure 8B). Conversely, the random forest model output does not highlight the Warrumbungle Range as particularly susceptible to debris flows, reflecting perhaps the lack of generality of the random forest model in identifying debris flow susceptibility beyond the training dataset (Figure 8A). An appropriate debris flow channel initiation point dataset does not exist to cross-validate the model and produce performance metrics such as an AUC score, however the model broadly identifies the mountainous region as susceptible to debris flows, which accords with recent experience in the Warrumbungles.

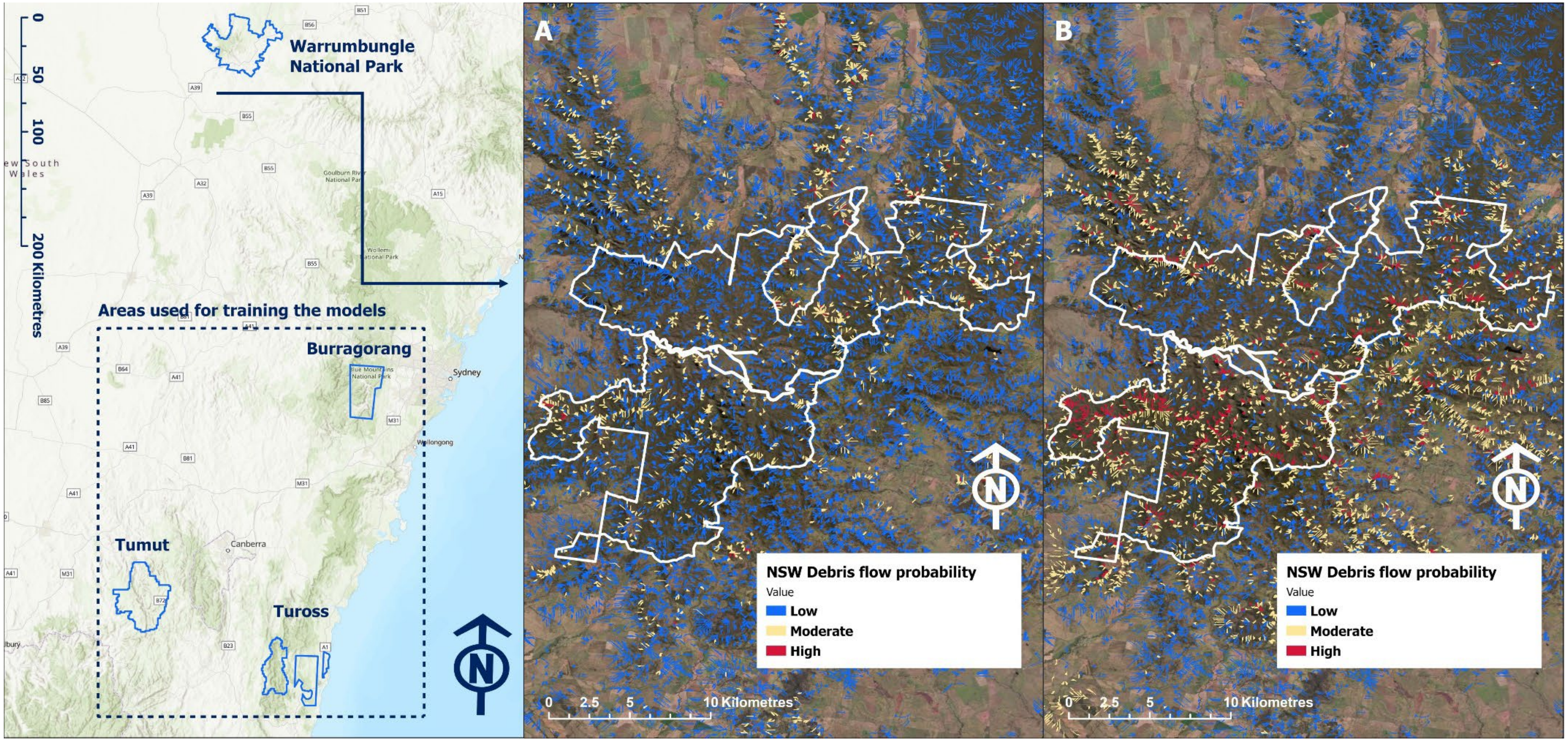

Figure 8 Debris flow susceptibility in the Warrumbungle National Park, New South Wales. A: Random forest model output. B: Logistic regression model output

4. Benefits for management

The prevention, preparedness, response and recovery (PPRR) cycle is a well-known approach to disaster management that places emphasis on pre-planning and preparation for emergencies but also the need for effective response and recovery strategies.

The NSW debris flow map allows for a high-level assessment of the spatial variability in debris flow likelihood in forested country in New South Wales. This information can assist in a range of ways in the bushfire prevention and preparedness stages before bushfires occur, and also during the recovery stages.

4.1 Prevention and preparedness

The NSW debris flow susceptibility map provides a high-level indication of debris flow hazard across the landscape assuming a high-severity fire (i.e. canopy removal). This can help to guide management actions designed to increase the resilience of priority assets such as threatened species habitat, water reservoirs or critical infrastructure from potential post-fire erosion impacts.

It is unlikely that the occurrence of severe bushfires and post-fire debris flows can be directly reduced at large scales. However, by understanding key factors that drive debris flow occurrence and how their likelihood varies across the landscape, it may be possible to manage some of the risks and impacts in critical areas. Debris flows are significantly more likely to occur where fire has caused partial or complete canopy removal. Hazard reduction burning is one of the few tools that exist to manage fire risk at the landscape scale and may be a tool that, along with strategic firebreaks, reduces the chance of crowning fire and therefore subsequent debris flow risk. Even then, the effectiveness of landscape-scale prescribed burning on reducing the severity of subsequent bushfires is uncertain, particularly during extreme fire weather (Price et al. 2015; Hislop et al. 2020).

4.2 Response and recovery

The emergency response efforts during a bushfire and its aftermath are rightfully focused on protecting life and property. In this respect, post-fire erosion concerns are not front and centre of firefighting efforts, though in drinking water catchments this may be more of a consideration for incident management teams. In the weeks to months following fire, debris flow susceptibility maps may assist management efforts. In particular, given the inherent link between debris flow activity and downstream flash flooding, pre-emptive decisions can be made regarding closure of certain roads, campgrounds or recreational areas, as well as targeted safety and emergency warnings, if heavy rainfall is forecast over recently burnt firegrounds that are susceptible to debris flows.

Over recovery timeframes, debris flow susceptibility models can be run using updated fire extent and severity mapping to understand debris flow risk specific to a fire rather than assuming high-severity fire across the landscape as the logistic regression model does. This may help to guide field assessment of post-fire erosion and prioritisation of management or monitoring efforts. Additionally, the downstream impacts of debris flows can persist for many years. These impacts are typically related to the propagation of coarse sediment slugs or sand sheets that can homogenise channel beds by infilling pools and the interstitial spaces in gravel bed rivers. Understanding which rivers may be most likely to experience these long-term impacts can assist prioritisation of riparian rehabilitation and aquatic species management projects.

Once a debris flow has formed, anything short of a highly engineered structure is unlikely to meaningfully reduce its erosive energy and sediment mobilisation. Targeted on-ground works such as debris racks, sediment barriers and check dams can reduce the impact of debris flows, by trapping sediment and dissipating the energy of the flow. These measures, however, are expensive and are generally only effective at very localised scales, so are typically associated with targeted protection of individual key assets. Also, if they are not addressing erosion rates at the source, these engineering approaches are unlikely to significantly reduce the amount of fine sediment (silt and mud) transported by debris flows that cause water quality issues in downstream rivers, estuaries and reservoirs. Mulching, aerial seeding and log erosion barriers on hillslopes in recently burnt areas are methods that may help to reduce runoff and erosional energy that generate debris flows (Santi et al. 2006; Anjozian 2009). When concentrated in smaller areas of <2 km^2, these methods have been found to reduce debris flow volumes in some settings, though unfortunately effectiveness diminishes at steeper slopes (>23°) that are typically associated with debris flow activity (Santi et al. 2006). Debris flow mitigation strategies have not been comprehensively investigated in an Australian setting. Nonetheless, even with mixed results, given that these approaches are most likely to have success at small scales, prioritisation tools such as the NSW debris flow susceptibility map are critical.

5. Recommendations for future updates

The NSW debris flow susceptibility map represents an initial effort to model post-fire debris flow likelihood at a large scale across New South Wales. For reasons noted in this report, it is only suitable for high-level assessment of relative susceptibility to post-fire debris flows. In some areas, particularly northern New South Wales, there is lower confidence in the accuracy of the debris flow probability estimates. It is also not suitable for assessment of risks to individual sites or assets. Nonetheless, for broader, sub-catchment-scale assessments of risks posed by post-fire debris flows, the susceptibility maps have numerous applications in the management of waterways, water resources and remote infrastructure.

Further research and optimisation will improve the accuracy and applicability of these datasets across New South Wales, including:

- future uses of this model involving running the model with a different assumed fire severity to investigate the likelihood of debris flow activity under different fire severities. Also, future modelling could incorporate fire extent and severity mapping from a particular fire season, to determine the likelihood of debris flows associated with that fire season
- improved understanding of post-fire erosion processes in regions outside of south-eastern New South Wales and eastern Victoria, informed by field data and advanced modelling approaches. The northern tablelands of New South Wales are influenced more by tropical climate modes and typically have wetter coastal ranges. Associated variations in aridity and soil hydraulic properties may significantly influence post-fire erosion processes in these regions
- quantification of sediment loads associated with post-fire debris flows to better understand the magnitude of impacts on catchment sediment budgets and the cascading impacts on water quality, river geomorphology and hydrology, and aquatic ecosystems
- aligning debris flow modelling with water quality monitoring to inform the development of coupled erosion and water quality models that can more accurately account for landscape-scale heterogeneity of erosion responses after fire
- developing methods to allow fine-scale assessments of debris flow risk at a site scale to assist management of key threatened species habitats, sensitive waterway types and/or infrastructure assets.

6. Conclusions

Debris flows are destructive post-fire hazards that can significantly impact aquatic ecosystem health, communities and infrastructure. The development of high-resolution aerial imagery has highlighted significant debris flow activity in parts of New South Wales that were impacted by the 2019–20 Black Summer bushfires. By building an inventory of debris flow occurrences and insights developed by debris flow research in Victoria, this project developed predictive debris flow susceptibility models for New South Wales.

Both the random forest and logistic regression models performed well, however the logistic regression model performed better when extrapolating to areas outside of those in which the models were trained. The NSW debris flow susceptibility map developed represents the first modelling effort to map post-fire debris flow susceptibility across New South Wales. With projections of increasingly severe and longer bushfire seasons over coming decades, the threat of post-fire debris flows is likely to increase into the future (Di Vergilio et al. 2019; Herold et al. 2021). Additional work is required to fully understand this threat, to predict not only where they might occur but also the short- and long-term impacts they may have.

7. Acknowledgements

This work was undertaken as a component of the NSW DCCEEW Water Quality – Bushfire Recovery project to assist in addressing recommendation 36 of the 2020 NSW Bushfire Inquiry. The authors gratefully acknowledge input and assistance from the NSW Natural Resources Commission, Alluvium, and the University of Melbourne in the development of the NSW post-fire debris flow susceptibility map and in reviewing this report.

8. References

Abdollahi M, Vahedifard F and Tracy FT (2023) ‘Post-wildfire stability of unsaturated hillslopes against rainfall-triggered landslides’, *Earth’s Future*, 11(3):p.e2022EF003213, doi: 10.1029/2022EF003213.

Adams M S, Fromm R and Lechner V (2016) ‘High-resolution debris flow volume mapping with unmanned aerial systems (UAS) and photogrammetric techniques’, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41:749–755, doi: 10.5194/isprs-archives-XLI-B1-749-2016.

Anjozian L-N (2009) ‘That liquefaction of her clothes: mitigating debris flows in the post-wildfire landscape’, *Joint Fire Science Program Briefs*, Issue 52, http://digitalcommons.unl.edu/jfspbriefs/52.

Bureau of Meteorology, Australia (2024) Climate Data Online, accessed 15 March 2024, http://www.bom.gov.au/climate/data/index.shtml?bookmark=201

Cannon SH, Gartner JE, Rupert MG, Michael JA, Rea AH and Parrett C (2010) ‘Predicting the probability and volume of postwildfire debris flows in the intermountain western United States, *GSA Bulletin*, 122(1–2), pp.127–144, doi: https://doi.org/10.1130/B26459.1.

Di Virgilio G, Evans JP, Blake SA, Armstrong M, Dowdy AJ, Sharples J and McRae R (2019) ‘Climate change increases the potential for extreme wildfires’, *Geophysical Research Letters*, 46(14):8517–8526.

Fraser AM, Chester MV and Underwood BS (2022) ‘Wildfire risk, post-fire debris flows, and transportation infrastructure vulnerability’, *Sustainable and Resilient Infrastructure*, 7(3):188–200, doi: 10.1080/23789689.2020.1737785.

Guo Z, Shi Y, Huang F, Fan X and Huang J (2021) ‘Landslide susceptibility zonation method based on C5.0 decision tree and K-means cluster algorithms to improve the efficiency of risk management’, *Geoscience Frontiers*, 12(6):101249, doi: 10.1016/j.gsf.2021.101249.

Hakro MR and Harahap ISH (2015) ‘Laboratory experiments on rainfall-induced flowslide from pore pressure and moisture content measurements’, *Natural Hazards and Earth System Sciences Discussions*, 3(2):1575–1613.

Herold N, Downes SM, Gross MH, Ji F, Nishant N, Macadam I, Ridder NN and Beyer K (2021) ‘Projected changes in the frequency of climate extremes over southeast Australia’, *Environmental Research Communications*, 3(1):011001.

Hislop S, Stone C, Haywood A and Skidmore A (2020) ‘The effectiveness of fuel reduction burning for wildfire mitigation in sclerophyll forests’, *Australian Forestry*, 83(4):255–264.

ICSM (Intergovernmental Committee on Surveying and Mapping) (2023) *Elvis – Elevation and Depth - Foundation Spatial Data*, Intergovernmental Committee on Surveying and Mapping, accessed 1 February 2023, https://elevation.fsdf.org.au.

Iverson RM (2014) ‘Debris flows: behaviour and hazard assessment’, *Geology today*, 30(1):15–20, doi: 10.1111/gto.12037.

Jackson ME and Staley DM (2018) ‘The deadly Montecito post-fire debris flow of January 9, 2018 and the successes and challenges of post-fire debris-flow prediction and early warning’, in *AGU Fall Meeting Abstracts*, vol. 2018, pp. NH34C-01.

James G, Witten D, Hastie T, Tibshirani R and Taylor J (2023), *An introduction to statistical learning: With applications in python*, Springer Nature.

Langhans C, Smith HG, Chong DM, Nyman P, Lane PN and Sheridan GJ (2016) ‘A model for assessing water quality risk in catchments prone to wildfire’, *Journal of Hydrology*, 534:407–426, doi: 10.1016/j.jhydrol.2015.12.048.

NRC (Natural Resources Commission) – NSW Government (2023) NSW Forest Monitoring and Improvement Program Post-Fire Debris Flow Mapping in the Tumut and Tuross Catchments, version 1.0, Terrestrial Ecosystem Research Network (dataset), doi: 10.25901/j1b2-ae38.

NSW Government and DCCEEW (State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water) (2007) *NSW Landuse 2007*, accessed from The Sharing and Enabling Environmental Data Portal 8 February 2024, datasets.seed.nsw.gov.au/dataset/nsw-landuseac11c.

NSW Government and DCCEEW (State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water) (2018) *Modelled Hillslope Erosion over New South Wales*, accessed from The Sharing and Enabling Environmental Data Portal 21 November 2023, datasets.seed.nsw.gov.au/dataset/aea6e148-2c60-4de3-8233-2bc7ade4b4d2, doi: 10.25948/5f0bd19c72d76.

NSW Government and DCCEEW (State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water) (2020) *Fire Extent and Severity Mapping (FESM) 2019/20*, accessed from The Sharing and Enabling Environmental Data Portal 21 November 2023, datasets.seed.nsw.gov.au/dataset/f7eb3f73-5831-4cc9-8259-8d1f210214ac.

NSW Government and DCCEEW (State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water) (2022) *NSW State Vegetation Type Map*, accessed from The Sharing and Enabling Environmental Data Portal 25 January 2024, datasets.seed.nsw.gov.au/dataset/95437fbd-2ef7-44df-8579-d7a64402d42d.

NSW Government and DCCEEW (State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water) (2023) *NSW Aridity Index – High resolution (30 meter)*, accessed from The Sharing and Enabling Environmental Data Portal 21 November 2023, datasets.seed.nsw.gov.au/dataset/d7052ea2-e207-4b06-aeb5-565d657e107d.

NSW Government and Department of Regional NSW (State Government of NSW and Department of Regional New South Wales) (2018), *NSW Seamless Geology*, accessed from The Sharing and Enabling Environmental Data Portal 21 November 2023, datasets.seed.nsw.gov.au/dataset/5d6e177a-9a78-490c-a570-47c38bbb4399.

Nyman P, Box WA, Stout JC, Sheridan GJ, Keesstra SD, Lane PN and Langhans C (2020) ‘Debris-flow-dominated sediment transport through a channel network after wildfire’, *Earth Surface Processes and Landforms*, 45(5):1155–1167.

Nyman P, Sheridan GJ, Moody JA, Smith HG, Noske PJ and Lane PN (2013) ‘Sediment availability on burned hillslopes’, *Journal of Geophysical Research: Earth Surface*, 18(4):2451–2467, doi: 10.1002/jgrf.20152.

Nyman P, Sheridan GJ, Smith HG and Lane PN (2011) ‘Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia’, *Geomorphology*, 125(3):383–401, doi: 10.1016/j.geomorph.2010.10.016.

Nyman P, Smith HG, Sherwin CB, Langhans C, Lane PN and Sheridan GJ (2015) ‘Predicting sediment delivery from debris flows after wildfire’, *Geomorphology*, 250:173–186, doi: 10.1016/j.geomorph.2015.08.023.

Nyman P, Yeates P, Langhans C, Noske PJ, Peleg N, Schärer C, Lane PNJ, Haydon S and Sheridan GJ (2021) ‘Probability and consequence of postfire erosion for treatability of water in an unfiltered supply system’, *Water Resources Research*, 57(1), 2019WR026185, doi: 10.1029/2019WR026185.

Price OF, Penman TD, Bradstock RA, Boer MM and Clarke H (2015) ‘Biogeographical variation in the potential effectiveness of prescribed fire in south-eastern Australia’, *Journal of Biogeography*, 42(11):2234–2245.

Ruopp MD, Perkins NJ, Whitcomb BW and Schisterman EF (2008) ‘Youden Index and optimal cut-point estimated from observations affected by a lower limit of detection’, *Biometrical Journal: Journal of Mathematical Methods in Biosciences*, 50(3):419–430, doi: 10.1002/bimj.200710415.

Santi P, Higgins J, Cannon S and DeGraff J (2006) *Evaluation of Post-Wildfire Debris Flow Mitigation Methods and Development of Decision-Support Tools*, United States Geological Survey technical report, Joint Fire Science Program.

Sheridan GJ, Nyman P, Langhans C, Cawson J, Noske PJ, Oono A, Van der Sant R and Lane PNJ (2015) ‘Is aridity a high-order control on the hydro–geomorphic response of burned landscapes?’, *International Journal of Wildland Fire*, 25(3):262–267, doi: 10.1071/WF14079.

Smith HG, Sheridan GJ, Lane PN, Nyman P and Haydon S (2011) ‘Wildfire effects on water quality in forest catchments: A review with implications for water supply’, *Journal of Hydrology*, 396(1–2):170–192, doi: 10.1016/j.jhydrol.2010.10.043.

Smith HG, Spiekermann R, Betts H and Neverman AJ (2021) ‘Comparing methods of landslide data acquisition and susceptibility modelling: Examples from New Zealand’, *Geomorphology*, 381:107660, doi: 10.1016/j.geomorph.2021.107660.

Staley DM, Negri JA, Kean JW, Laber JM, Tillery AC and Youberg AM (2016) *Updated logistic regression equations for the calculation of post-fire debris-flow likelihood in the Western United States: U.S. Geological Survey Open-File Report 2016–1106*, 13 pp., doi: 10.3133/ofr20161106.

Tang H, McGuire LA, Rengers FK, Kean JW, Staley DM and Smith JB (2019) 'Developing and testing physically based triggering thresholds for runoff-generated debris flows', *Geophysical Research Letters*, 46(15):8830–8839, doi: 10.1029/2019GL083623.

Tulau MJ, McInnes-Clarke SK, Yang X, McAlpine RA, Karunaratne SB, Zhu Q and Morand DT (2019a) 'The Warrumbungle Post-Fire Recovery Project – raising the profile of soils', *Soil Use and Management*, 35(1):63–74.

Tulau MJ, Nyman P, Young M, Morand D, Mcinnes-Clarke SK and Noske P (2019b) 'Mass movements of Warrumbungle National Park, New South Wales, Australia', in *Proceedings of the Linnean Society of New South Wales*, vol. 141.

Wondzell SM and King JG (2003) 'Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions', *Forest Ecology and Management*, 178(1-2):75–87, doi: 10.1016/S0378-1127(03)00054-9.

Yang X, Gray J, Chapman C, Zhu Q, Tulau M and McInnes-Clarke S (2017) 'Digital mapping of soil erodibility for water erosion in New South Wales, Australia', *Soil Research*, 56(2):158–170, doi: 10.1071/SR17058.

Appendix A: Local government areas considered for the debris flow probability prediction map

Table A1 **Local government areas considered for the debris flow probability prediction map. Ninety-eight out of 131 LGAs in New South Wales were included in the prediction.**

no.	LGA name	Council name
1	Albury City	Albury City Council
2	Armidale Regional	Armidale Regional Council
3	Ballina	Ballina Shire Council
4	Bathurst Regional	Bathurst Regional Council
5	Bayside	Bayside Council
6	Bega Valley	Bega Valley Shire Council
7	Bellingen	Bellingen Shire Council
8	Blacktown	Blacktown City Council
9	Blayney	Blayney Shire Council
10	Blue Mountains	Blue Mountains City Council
11	Burwood	Burwood Council
12	Byron	Byron Shire Council
13	Cabonne	Cabonne Shire Council
14	Camden	Camden Council
15	Campbelltown	Campbelltown City Council
16	Canada Bay	City of Canada Bay Council
17	Canterbury-Bankstown	Canterbury-Bankstown Council
18	Central Coast	Central Coast Council
19	Cessnock	Cessnock City Council
20	City of Parramatta	City of Parramatta Council
21	Clarence Valley	Clarence Valley Council
22	Coffs Harbour	Coffs Harbour City Council
23	Coonamble	Coonamble Shire Council
24	Cootamundra-Gundagai Regional	Cootamundra-Gundagai Regional Council
25	Cowra	Cowra Shire Council
26	Cumberland	Cumberland Council
27	Dubbo Regional	Dubbo Regional Council
28	Dungog	Dungog Shire Council
29	Eurobodalla	Eurobodalla Shire Council
30	Fairfield	Fairfield City Council
31	Georges River	Georges River Council
32	Gilgandra	Gilgandra Shire Council
33	Glen Innes Severn	Glen Innes Severn Shire Council
34	Goulburn Mulwaree	Goulburn Mulwaree Council

no.	LGA name	Council name
35	Greater Hume Shire	Greater Hume Shire Council
36	Gunnedah	Gunnedah Shire Council
37	Gwydir	Gwydir Shire Council
38	Hawkesbury	Hawkesbury City Council
39	Hilltops	Hilltops Council
40	Hornsby	The Council of the Shire of Hornsby
41	Hunters Hill	The Council of the Municipality of Hunters Hill
42	Inner West	Inner West Council
43	Inverell	Inverell Shire Council
44	Kempsey	Kempsey Shire Council
45	Kiama	The Council of the Municipality of Kiama
46	Ku-Ring-Gai	Ku-Ring-Gai Council
47	Kyogle	Kyogle Council
48	Lake Macquarie	Lake Macquarie City Council
49	Lane Cove	Lane Cove Municipal Council
50	Lismore	Lismore City Council
51	Lithgow City	Lithgow City Council
52	Liverpool	Liverpool City Council
53	Liverpool Plains	Liverpool Plains Shire Council
54	Maitland	Maitland City Council
55	Mid-Coast	Mid-Coast Council
56	Mid-Western Regional	Mid-Western Regional Council
57	Mosman	Mosman Municipal Council
58	Muswellbrook	Muswellbrook Shire Council
59	Nambucca Valley	Nambucca Valley Council
60	Narrabri	Narrabri Shire Council
61	Newcastle	Newcastle City Council
62	North Sydney	North Sydney Council
63	Northern Beaches	Northern Beaches Council
64	Oberon	Oberon Council
65	Orange	Orange City Council
66	Penrith	Penrith City Council
67	Port Macquarie-Hastings	Port Macquarie-Hastings Council
68	Port Stephens	Port Stephens Council
69	Queanbeyan-Palerang Regional	Queanbeyan-Palerang Regional Council
70	Randwick	Randwick City Council
71	Richmond Valley	Richmond Valley Council
72	Ryde	Ryde City Council
73	Shellharbour	Shellharbour City Council
74	Shoalhaven	Shoalhaven City Council
75	Singleton	Singleton Council
76	Snowy Monaro Regional	Snowy Monaro Regional Council
77	Snowy Valleys	Snowy Valleys Council
78	Strathfield	Strathfield Municipal Council
79	Sutherland Shire	Sutherland Shire Council
80	Sydney	Council of the City of Sydney

no.	LGA name	Council name
81	Tamworth Regional	Tamworth Regional Council
82	Tenterfield	Tenterfield Shire Council
83	The Hills Shire	The Hills Shire Council
84	Tweed	Tweed Shire Council
85	Unincorporated – Sydney Harbour Area	Unincorporated
86	Upper Hunter	Upper Hunter Shire Council
87	Upper Lachlan Shire	Upper Lachlan Shire Council
88	Uralla	Uralla Shire Council
89	Wagga Wagga	Wagga Wagga City Council
90	Walcha	Walcha Council
91	Warrumbungle	Warrumbungle Shire Council
92	Waverley	Waverley Council
93	Willoughby	Willoughby City Council
94	Wingecarribee	Wingecarribee Shire Council
95	Wollondilly	Wollondilly Shire Council
96	Wollongong	Wollongong City Council
97	Woollahra	Woollahra Municipal Council
98	Yass Valley	Yass Valley Council