Assessment of the impact of class 1 drainage lines exclusion zone settings on the ingress of sediment from harvested compartments to the drainage network

Document no: DRAFT
Version: 3-1

Natural Resources Commission

Coastal IFOA monitoring program: assessment of class 1 drainage line exclusion zone settings
10 May 2024

Assessment of the impact of class 1 drainage lines exclusion zone settings on the ingress of sediment from harvested compartments to the drainage network

Client name:	Natural Resources Commission		
Project name:	Coastal IFOA monitoring program: assessment of class 1 drainage line exclusion zone settings		
Document no:	DRAFT	**Project no:**	IA295900
Version:	3-1	**Project manager:**	James J. Shelley
Date:	10 May 2024	**Prepared by:**	James J. Shelley, Craig A. Clifton, Petter Nyman (Alluvium), and Conan Peterson
Document status:	DRAFT	**File name:**	Class 1 drainage lines monitoring_final report DRAFT for TC_clean

Document history and status

Version	Date	Description	Author	Reviewed	Approved
Draft 0-1	20/10/23	Final report - draft	James J Shelley	Craig Clifton Petter Nyman	Craig Clifton Petter Nyman
Draft 1-0	7/11/23	Final report – draft	James J Shelley	NRC	Bryce Gorham
Draft 2-0	28/11/23	Final report – draft	James J Shelley	Jackie Croke (independent)	Bryce Gorham
Draft 3-0	8/5/24	Final report – draft	James J Shelley	Technical Committee	

Distribution of copies

Version	Issue approved	Date issued	Issued to	Comments
Draft 0-1	Craig Clifton	20/10/23	Bryce Gorham	For internal review prior to distribution among the NRC and technical committee
Draft 1-0	Craig Clifton	7/11/23	Bryce Gorham	For review prior to distribution among the technical committee
Draft 2-0	Craig Clifton	28/11/23	Jackie Croke	For external review prior to distribution among the technical committee
Draft 3-0	Craig Clifton	14/5/24	The Technical Committee	For review by the technical committee
Draft 3-1	Craig Clifton	24/6/24	Bryce Gorham	Includes edits in responses to TC comments

Jacobs Australia Pty Limited

32 Cordelia Street
PO Box 3848
South Brisbane, QLD 4101
Australia

T +61 7 3026 7100
F +61 7 3026 7300
[Website]

Executive summary

Background

The Coastal Integrated Forestry Operations Approval (Coastal IFOA) was approved by the NSW Government in late 2018. It establishes Conditions and Protocols being the regulatory settings to enable forestry operations on NSW State Forest and Crown timber land and includes provisions for the protection of the environment and for threatened species conservation. The Coastal IFOA included changes in riparian protections around Class 1 drainage lines from the previous forestry approvals. The Coastal IFOA Protocol 38: Monitoring Program includes consideration of riparian protections on Class 1 drainage lines (headwater steams). The Coastal IFOA requires the NSW Forest Monitoring Steering Committee (the Steering Committee), independently chaired by the Natural Resources Commission (the Commission), to oversee the design and implementation of the Coastal IFOA monitoring program.

The *Waterway and wetland health monitoring strategy* was developed to guide this part of the effectiveness monitoring component of the monitoring program. It specified the monitoring question regarding riparian protections around Class 1 drainage lines to be *"Are the exclusion zone conditions for Class 1 classified drainage lines effective in minimising the impact on waterway condition?"*.

The exclusion zone conditions (often referred to as settings) require that a riparian 'buffer zone' comprising both a Riparian Exclusion Zone (REZ) and a Ground Protection Zone (GPZ) be left around Class 1 drainage lines. The Coastal IFOA riparian protections are outlined in order of occurrence in the table below.

Coastal IFOA Riparian protections - Buffer zones for Class 1 drainage lines

	Class 1 drainage line
Buffer Zone	**REZ – 5m (most often) or 10m**
	GPZ –10m.
	Harvest / general operational area

After the release of the monitoring plan and central monitoring question, discussions between the Commission and the Steering Committee representatives on a cross agency Technical Working Group led to the development of a secondary, related monitoring question focussed on assessing whether GPZs perform as well as REZs in minimising the impact on waterway condition. Specifically, this question was, "*Are ground protection zones that have been accessed by machinery as effective at preventing track derived overland flow reaching the stream network as riparian exclusion zones?*".

Jacobs was engaged by the Commission to design and implement a repeatable and scientifically valid field survey that answers these questions, allowing for a wholistic assessment of the effectiveness of the exclusion zone conditions being the settings (focussed on the buffer zone) applied to Class 1 drainage lines in achieving the goals of the Coastal IFOA that predominantly focus on preventing sediment from forestry operations reaching the headwater stream network.

Methods

The methods employed in this study aim to provide a quantitative basis for assessing the effectiveness of buffer zones (REZs and the GPZs) in preventing connectivity of overland flow between harvested forestry compartments and the stream network across a range of environmental settings in the Coastal IFOA region. As the effectiveness of the buffer zones in achieving this function is dependent on several factors such as the intensity of rainfall generating runoff and potentially the degree of disturbance from machinery access, it is not a simple yes or no question. Our methodology aims to provide framework that supports stakeholders in determining the risk of connectivity they are comfortable with in the context of our assessment.

We used the volume-to-breakthrough (vbt) model of Hairsine *et al.* (2002) to make inferences about the distance that overland flow generated from compacted surfaces (including tracks) would travel through buffer zones during rainfall events of varying magnitude. Central to this model is the *vbt5* measurement that describes the volume of water required to create an overland flow plume that travels 5m downslope from the discharge point, accounting for flow pathways, infiltration and depressional storage. To measure the *vbt5* we pumped water from a water cart through a hose and released it in REZs and GPZs across the Coastal IFOA region to simulate overland flow originating from a crossbank outlet during a rainfall event. The release of water was regulated by a rotameter so that it discharged at 3.0 Litres per second (L s^{-1}) which reflects the discharge magnitude measured in the study of Hairsine *et al.* (2002) and is that expected from cross bank exits. The *vbt5* was recorded in each case. Soil bulk density and local hillslope topographic gradient were also recorded to see if they influenced the *vbt5* value.

We then used these *vbt5* measurements as parameters in the equations presented in Hairsine *et al.* (2002) to predict overland flow plume distances across Class 1 drainage line buffer zones in the Coastal IFOA region. Subsequently, we used the distribution of plume lengths to determine the probability that track-derived overland flow from crossbank outlets diverted towards the buffer zone would reach the stream network in a worst-case scenario where outlets discharged directly into the buffer zone. We modelled overland flow plume lengths generated under four storm intensities and four varying contributing track areas (i.e. the area of track between crossbank outlet which helps determine outflow volume). In this way the results provide a framework from which decision makers can assess the effectiveness of current buffer zones in disconnecting track-derived overland flow from the stream network where the risk is highest and determine if they are appropriate. In addition, we investigated whether environmental variables with known influence on soil hydrology (i.e. forest class, riparian zone slope, soil bulk density, and mean annual wetness) may influence plume length and therefore the likelihood that plume length will exceed the width of a buffer zone.

Results and Discussion

In total we collected and analysed 116 data points across 30 sites in 11 forests situated between the northern and southern extent of the Coastal IFOA region. These measurements are a strong foundational dataset from which to draw conclusions about the effectiveness of the buffer zones around Class 1 drainage lines in preventing the ingress of sediment into streams in this region (the primary monitoring question). The subset of this dataset, which included paired GPZ and REZ sites for investigating the secondary study question, was comprised of 45 data points (22 GPZ, 23 REZ) across six sites in three forests. This was considered to present a suitable "pilot study" that provides insight into any differences in hydrological processes operating in GPZs versus REZs but is insufficient to draw definitive conclusions at the regional level.

With the above in mind, the comparison of buffer zone effectiveness between REZs and GPZs (study Question 2) did not provide evidence indicating that they have differing capacity for capturing track derived overland flow (and sediment) at the sites visited. Nor did they provide evidence that buffer zones settings are inadequate in this respect. Regardless, suggested best management practices on access could be considered to mitigate the effect of machinery compaction on runoff generation in the GPZ.

The assessment of the probability that buffer zones would be exceeded by overland flow plumes under different storm intensities and track crossbank spacings, in different rainfall zones (study Question 1), made clear the degree to which these factors can influence connectivity. This work substantiates the importance of maintaining riparian buffers in the timber harvesting context. In the worst-case scenario tested, where track crossbanks are widely spaced (e.g. greater than 30m apart) current buffer zones are largely inadequate regardless of the magnitude of rainfall events, particularly in moderate to high rainfall regions. Where crossbank are closer together (e.g. 10m apart), buffer zone effectiveness improves dramatically, but only to about the intensity of a 1 in 10-year rainfall event in low to moderate rainfall regions. In high rainfall regions such as Coffs Harbour the 15m buffer zones are largely ineffectual at preventing connectivity between high-risk crossbank outlets and the stream network.

Finally, the results indicated the effectiveness of Class 1 buffer zones in capturing track derived overland flow is similar across the Coastal IFOA region and is not influenced by hillslope or regional environmental factors lending support to the broad applicability of our results.

What constitutes a desired probability of effectiveness is left to forestry regulators to decide using the framework we have provided in this investigation. Importantly though, (1) the distance between crossbanks, and (2) the total distance of the flow path between the closest crossbank outlet and the stream network can be altered to achieve a desired level of exclusion zone setting effectiveness. This provides mangers with a relatively simple mechanisms with which to decrease the probability of connectivity, if deemed necessary.

Based on our results, to achieve optimal reduction of hydrological connectivity we recommend that (1) close spacing of cross banks should be implemented in high-risk runoff scenarios where tracks drain close to the buffer zone, (2) a management scenario to manage for should be determined (i.e. what rainfall event, what track spacing will be implemented, and what probability of effectiveness is acceptable), (3) the total length of the flow path between the crossbank outlet and the stream network should be increased to achieve the desired probability of effectiveness based on this management scenario, and (4) the necessary flow path length should be region specific to account for substantial differences in regional rainfall volumes and risk of connectivity. Increasing the total flow path could be effectively done by leaving an appropriate distance between the crossbank outlets and the buffer zone.

Contents

Tables

Figures

Glossary of Terms

Buffer Zone	A protected area of vegetation that applies to each side of a drainage line (measured from the bankfull level), inclusive of the Ground Protection Zone and Riparian Exclusion Zone.
Compartment	An area of forest designated for *forestry operations* inclusive of exclusion zones and boundary tracks.
Crossbank	A hump of earth constructed across a track, log dump or road to baulk the flow of water so that it can be diverted.
Crossbank outlet	The point at which overland flow discharges from the base of the crossbank in a downslope direction.
Extraction	The transport of logs from the point of felling to the log dump.
Ground Protection Zone	A strip of vegetation or groundcover that must be retained adjacent to specified riparian features or ESAs set out in Division 3, Chapter 5 of the Coastal Integrated Forestry Operations Approval, where modified harvesting practices are required to minimise soil disturbance.
Harvest area	An area of land that is subject to active harvesting operations or forest products operations exclusive of exclusion zones
Machinery tracks	Marks left in the ground by heavy machinery such as skidders; typically from dual caterpillar tracks. Distinct from a constructed 'track' (see definition below).
Overland flow	Surface flow generated by rainfall, also referred to as runoff.
Riparian Exclusion Zone	A protected area that applies to each side of a drainage line (measured from the bankfull level) where harvesting operations are excluded as specified in condition 95 and 96 of the Coastal Integrated Forestry Operations Approval.
Snig and Snigging	The practice of hauling or dragging a log to a log dump, landing or stockpile using a skidder (or similar machine).
Track	A constructed snig track or an extraction track.

1. Introduction

1.1 Project background

The Coastal Integrated Forestry Operations Approval (Coastal IFOA) was approved by the NSW Government in late 2018. It establishes the conditions and settings to enable forestry operations on NSW State Forest and Crown timber land and includes provisions for the protection of the environment and for threatened species conservation. The overarching intent of the Coastal IFOA is to deliver a contemporary outcomes-based regulatory framework that reduces the costs associated with implementation and compliance and improves clarity and enforceability. As part of the modernisation process, changes were made to riparian protections including those applying to Class 1 drainage lines, which can be characterised as ephemeral headwater streams.

The Coastal IFOA includes a monitoring program requirement under Protocol 38 (NSWEPA 2023). The NSW Forest Monitoring Steering Committee oversees this monitoring program which was approved in March 2020. Class 1 drainage lines were included in an effectiveness monitoring component of the program to answer the overarching question "are the Coastal IFOA conditions effectively meeting its objectives and outcomes?". The Waterway and wetland health monitoring plan was developed in October 2020 to guide the program and has specified the central monitoring question to be "Are the exclusion zone conditions for Class 1 classified drainage lines effective in minimising the impact on waterway condition?". The exclusion zone conditions (settings) focused on in the context of this study relate to the Riparian exclusion zone (REZ) and Ground protection zone (GPZ) that are herein collectively referred to as the buffer zone.

Following the release of the monitoring plan, discussion between the Commission and the Steering Committee TWG representatives led to the development of a second, related monitoring question focussed on assessing whether ground protection zones (GPZs) perform as well as riparian exclusion zones (REZs) in minimising the impact on waterway condition. Specifically, this question was, "Are ground protection zones that have been accessed by machinery as effective at preventing track-derived overland flow reaching the stream network as riparian exclusion zones?".

Jacobs was engaged by the Commission, as per the RFQ for this project, to design and implement a repeatable and scientifically valid field survey and report on the ongoing performance and contribution of the buffer zone, comprised of the REZs and GPZs, to achieve the Coastal IFOA outcome statement for riparian protection. It was agreed that the key measure of buffer "effectiveness" would be the performance of buffers in preventing overland flow, which carries sediment, reaching the stream network as this is a key consideration for maintaining exclusion zones and is the primary goal of IFOA guidelines (Croke and Hairsine 2006; Stutter et al. 2019; Alluvium 2020a). As for the "impact on waterway condition" being assessed, the deleterious effect of fine sediment on water quality and aquatic communities is well documented (see review in Shelley *et al.* 2023), and it is implied that increased sediment beyond natural levels due to runoff from forestry areas would impact on these values. Building on the framework in Nyman *et al.* (2023), Jacobs proposed an experimental methodology to conduct this work and detailed the theory behind it in a previous report (Jacobs 2023a). That methodology was further developed in discussion with the technical committee which led to a more detailed methods report (Jacobs 2023b).

This report builds upon the previous two reports. While the main details regarding the context of the study and the approach taken are presented herein so that the report can be understood on its own, the main purpose of this document is to describe the study as it was ultimately conducted, detail the results, and discuss how they can be interpreted in the context of the study questions and management of riparian zones around Class 1 drainage lines more broadly.

1.2 Exclusion zones as a sediment mitigation tool

In forestry compartments, harvested slopes and associated infrastructure such as roads and tracks can present significant sources of erosion that may lead to sediment transport into streams as a result of rainfall events (Croke *et al.* 1999; Wallbrink and Croke 2002). As such, the risk of sediment transport to streams from timber harvesting operations and the effectiveness of methods for mitigating this risk have received substantial research attention.

Research has informed a range of forestry management practices aimed at controlling the risk of sediment laden overland flow from harvest areas connecting with the stream network, and they have been shown to be highly effective (Croke and Hairsine 2006). These practices include buffer zones (e.g. REZs and GPZs) along waterways, design measures and drainage for roads (e.g. crossbank spacing), snig/extraction tracks, landings and crossings, minimum separation distance of infrastructure from streams, and slope and seasonal harvesting restrictions (FPA 2020).

Of these measures, the maintenance of exclusion zones in the riparian strip/buffer zone along and around waterways has historically received significant research attention (see reviews in Alluvium 2020b and Shelley *et al.* 2023). In part, this attention is due to the range of functions riparian vegetation provides, such as: maintaining stream channel stability, providing habitat for fauna, regulating light and temperature in the stream environment, and acting as a filter for sediment and nutrient laden overland flow between the areas of disturbance and the stream network (Parkyn 2004; Croke and Hairsine 2006; Stutter *et al.* 2019). Minimising the ingress of sediment laden overland flow into the stream network is generally the key consideration when establishing exclusion zone settings. Being at the bottom of the landscape and immediately bordering waterways, the exclusion zone is the last management intervention in place preventing such ingress (Croke and Hairsine 2006; Stutter *et al.* 2019; Alluvium 2020a).

Over roughly the last two decades, studies of the capacity of buffer zones to capture and infiltrate surface overland flow conducted in Victoria have often taken a combined field measurement and predictive modelling approach. These studies focussed on the risk posed by crossbank outlet discharge from roads and tracks. Field-based experiments are conducted that simulated crossbank discharge into riparian zones and the resulting data is used in hydrological models that describe the distance that an overland flow plume (runoff) will travel, and its volume, in a given environmental setting and for a given storm magnitude (see methods in Hairsine *et al.* 2002; Sheridan *et al.* 2007). These studies can also provide an indication of the probability that an exclusion zone of a given width/setting will be exceeded by the plume, and by how much, allowing for a quantitative assessment of its effectiveness in disconnecting track-derived overland flow from the stream network under different scenarios (e.g. different rainfall magnitudes, impacted by bushfire, different landscapes). Among these studies, Nyman *et al.* (2023) developed a framework for prescribing buffer zone widths based on this output that is also relevant here. These experiments leverage the considerable body of forestry research that exists, describing the main sources and drivers of erosion and overland flow in south-eastern Australian forests, in particular:

- The influence of rainfall magnitude;
- The main sources of erosion and overland flow in forestry compartments; and
- The influence of hillslope and landscape factors (e.g. soil permeability, aridity, and slope).

Prior to this project there has been insufficient data to conduct a quantitative assessment of the effectiveness of buffer zones in disconnecting forestry track-derived overland flow from the stream network in NSW where environmental context can differ substantially to Victoria, and where exclusion zone settings are different. Here we applied the methods outlined in Hairsine *et al.* (2002), Sheridan *et al.* (2007), and Nyman *et al.* (2023) to assess the effectiveness of exclusion zone settings (i.e. the currently prescribed buffer zone) in the Coastal IFOA in reducing sediment connectivity between harvest areas and the stream network.

2. Methods

2.1 Overview

The effectiveness of exclusion zones in reducing sediment delivery to streams was determined using the concept of hydrological connectivity (Croke and Hairsine, 2006). The connectivity describes the likelihood that sediment will be transported from its source (typically a track, boundary track, or road) to a waterway. The higher the connectivity, the higher the likelihood of sediment delivery from these compacted surfaces to a stream. In this study we combined field measurements and modelling to assess the level of connectivity across different Coastal IFOA regions and evaluate the implications for the effectiveness of current buffer zones around Class 1 drainage lines in preventing the ingress of sediment into streams.

To assess connectivity across the region we conducted volume-to-breakthrough (vbt) experiments that simulate the movement of overland flow from a point source (e.g. a crossbank outlet on a track) through a riparian buffer zone (both GPZs and REZs). The vbt can be viewed as a metric of connectivity that quantifies the volume of overland flow that may enter an area before a discharge is observed at the downslope boundary of that area. The volume at the downslope boundary is a combination of water lost to overland flow through infiltration, water stored above ground in depressional storage and water in transit between the upper and lower boundary of the area (Hairsine *et al.* 2002). The measurements capture the combined effect of vegetation, surface roughness and infiltration capacity in buffer zone performance. The *vbt* concept has been successfully applied in a range of forest settings to determine the likelihood of sediment being transported across buffers and into waterways (Lane *et al.* 2006; Sheridan *et al.* 2007; Takken *et al.* 2008; Nyman *et al.* 2023).

Using (1) the vbt metric, and (2) estimates of overland flow generated between crossbanks on tracks during varying rainfall intensities in different areas of the Costal IFOA region, the length and volume of an overland flow plume emanating from a crossbank outlet can be modelled under a range of scenarios (Hairsine *et al.* 2002). These results are used to determine the probability that a buffer zone of a given width would prevent the plume from reaching the stream network.

These results are ultimately used to develop a framework for deciding on a level of connectivity that is acceptable in Class 1 drainage lines in the Coastal IFOA region given a range of rainfall and crossbank spacing scenarios. The framework is based on the assumption that high magnitude rainfall events will lead to a degree of connectivity between harvest areas and the stream network in some instances, so it is prudent to evaluate this risk and assess the degree to which it is acceptable.

The method is based on a worst-case scenario where that the point source discharge is being directed straight into the buffer zone, which can occur on tracks that run down the hillslope to the buffer zone or run parallel to the buffer zone along the harvest area boundary, and/or boundary tracks (tracks bordering the harvest area used for vehicle access to the compartment and sometimes snigging) that run parallel to drainage lines. As such it is considered a simulation of a high-risk scenario and the results should be interpreted in that context.

Study sites were chosen in different hydroclimate settings (e.g. different forest types, with soils of different bulk density, and different mean annual rainfall) that were predicted to represent some of the highest risk and lowest risk settings for overland flow generation in the region. These predictions are based on previous research from southeast Australia that points to forest type, bulk density, and moisture regimes being key predictors of soil hydraulic properties, overriding other factors such as geology and soil texture (Inbar *et al.* 2020; Noske *et al.* 2016; Sheridan *et al.* 2015; Nyman *et al.* 2014; Nyman *et al.* 2023). We supplemented GIS datasets describing such environmental heterogeneity with field measurements of soil bulk density and site slope. By collecting data across a wide geographic traverse of the Coastal IFOA region we expect to incorporate this heterogeneity into our assessment of buffer zone effectiveness.

2.2 Site selection

2.2.1 Criteria for site selection

2.2.1.1 Project criteria

Project criteria were laid out in the RFQ and establish conditions around which the experiment had to conform to. These included:

- Sites must be on Class 1 drainages as classified by LiDAR – obtained topography data and/or ground-truthed by the Forestry Corporation of NSW (FCNSW).
- Sites must have been harvested during the period the current Coastal IFOA rules were in place (excluding operations conducted under transitional arrangements in accordance with Protocol 40) and provide representation of all Coastal IFOA sub regions and harvesting regimes.
- The sample of sites/harvest plans considered must be a random sample of the available sites recently harvested. The timing window for field survey relative to completion of harvesting operations should be as close as practicable to the completion of operations, but is limited to 12 months to best determine disturbance levels (retention, stabilisation/rehabilitation and preferential flow paths).
- Each harvest plan selected must be assessed at multiple buffer zone (REZ and GPZ) sites.
    - Sites are to be selected from available sites that meet the criteria
    - At each site the survey needs to consider the spatial variation of disturbance within the operational area

2.2.1.2 Additional design and operational criteria

Within the pool of available sites that met the project criteria, further criteria were set that were derived from the requirements of the study design and logistical constraints of the experiment. These criteria stipulated that study sites must:

- Represent settings with a high risk of overland flow generation. Previous studies have indicated that arid areas with high bulk density pose a greater risk of generating runoff, and areas that exhibit these conditions typically have low rainfall (e.g. Noske *et al.* 2016; Nyman *et al.* 2023). The opposite is expected in high rainfall areas with low bulk density soil. We used GIS mapping to identify sites with high and low runoff risk.
- Contain both undisturbed Buffer zones (where neither the GPZ & REZ were accessed), and disturbed Buffer zones (where the GPZ was accessed), where possible.
- Be safely accessible by tracks/roads, and on foot between the vehicle and the site of water release.
- Be within 60 m of the safe operating location of a water cart, so a 60 metre hose can reach the discharge location
- Not include riparian zones in topographic hollows that are frequently saturated due to natural sub surface water flows.

2.2.2 Data used in site selection

The FCNSW supplied GIS shapefiles with the following features related to harvesting activities that have occurred within the last year (e.g. Figure 2-1):

- Harvest plan boundaries
- Drainage lines and classifications (e.g. Class 1)
- Ground-truthed Class 1 channels, any reclassification (e.g. where a Class 1 drainage was reclassified as a drainage feature), and the location where the Class 1 channel head was located
- Road and vehicle tracks
- Harvest progress depicted by 25 m^2 grid squares where GIS tracking data indicate the passage of harvesting machines.

The harvest progress grid was used to identify sites where the GPZ may have been accessed by machinery. These sites were then ground truthed to confirm that they had been accessed in the field.

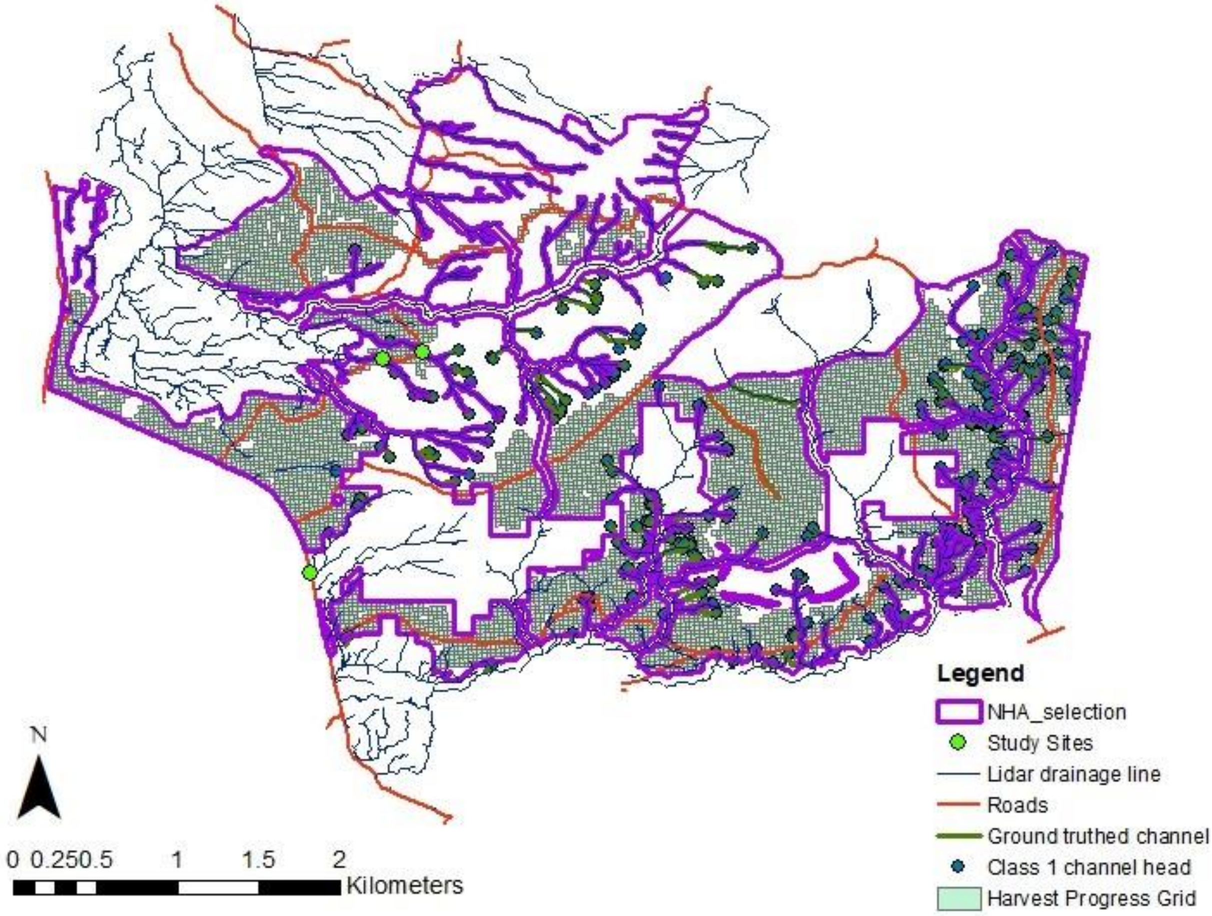

Figure 2-1 Example map of a forest plan area showing the FCNSW GIS data layers used in the site selection process.

In addition, we used the following publicly available datasets to guide site selection:

- Australian Soil Bulk Density Index 0-5 cm (Viscarra Rossel *et al.* 2014)
- Australian Soil Bulk Density Index 5-15 cm (Viscarra Rossel *et al.* 2014)
- NSW Aridity/Wetness Index - High resolution 30 meter (New South Wales Department of Planning and Environment 2023)
- NSW State Vegetation Map (NSW OEH 2017)

2.3 Study sites

In total we conducted *vbt* experiments at 30 sites across 11 forests (and 12 harvest plan areas) within the Coastal IFOA region between the 11/7/23 and the 28/7/23 (Table 2-1; Figure 2-1). The sites typically corresponded with the areas identified in the draft methods, but several changes had to be made given difficulty in accessing sites and other schedule changes. The most notable changes included not going to the Burrowan or Styx River plan areas but adding sites in the Bagawa and South Brooman plan areas. Overall, the geographic spread of the sites aligned closely with the plan and each site was in a plan area that had experienced timber harvesting activity within the last year. The sites effectively spanned the full longitudinal breadth of the region and represented a wide range of forest types from coastal, hinterland, and tableland areas.

2.3.1 General description of undisturbed riparian exclusion zones

Seven far north coast sites were located between Grafton and Casino (Double Duke, Gibberagee, Camira, and Bom Bom) in a region defined by high aridity (according to the aridity/wetness index), but which had high mean annual rainfall. The sites were composed of dry sclerophyll forests and forested wetlands. The Forested Wetlands (Double Duke and Gibberagee) were swampy (moist), low elevation, sand dominated forests that had experienced moderate intensity burns in 2020. Groundcover was thick and dominated by grasses with some bracken. In addition to *Eucalyptus*, *Melaleuca* was present at the Double Duke sites. The slopes leading to the stream channels were particularly low. The Dry Sclerophyll Forests (Camira and Bom Bom) were also low elevation, but the forest was more open and appeared drier. Camira had a thick ground cover of grasses and some sedges, and the topsoil (i.e. 0-5cm) was composed of a light brown sand and silt layer. It was also affected by wildfire in 2019/20. Bom Bom was in a dry forest with a hard, consolidated, light brown silt/clay dominated A-horizon. Groundcover mainly consisted of moderately dense grass cover and leaf litter, and there was a considerable amount of bare earth.

A further 12 sites were situated on the mid north coast between Coffs Harbor and Port Macquarie (Bagawa, Bulls Ground, and Orara East) in a high rainfall coastal region. Each site supported wet sclerophyll forest. Bagawa had a thick bracken dominated understory, moderately deep but unbroken leaf layer, and dark loamy topsoil. The Bulls Ground sites were characterised by a moderately thick groundcover dominated by forbs and grasses with some sedge and vines. With the addition of a thin leaf layer and a considerable amount of woody debris, there was little to no bare soil. The topsoil was dark and loamy. Orara East sites were noticeably damp even though there had been no effective rain for some time. The understory was dominated by ferns and some palm trees. There was a thick leaf litter layer, and the topsoil was dark, loamy, and granular.

In the southern section of the Coastal IFOA region, the experiment was run at three sites in two coastal forests near Batemans Bay (Boyne and South Brooman). The Boyne sites supported wet sclerophyll forest with an understory of tussock grasses, vines, and cycad palms. There was a thick leaf litter layer and light brown, soft, crumbly topsoil dominated by silt and clay. The site appeared to be impacted by low intensity fire in 2020. The South Brooman site was also in wet sclerophyll forest, in a steep fern covered valley with dense vine grown and a thick mat of wire grass and organic debris covering the ground. It appeared to be impacted by low intensity fire in 2020. The topsoil was dark brown and damp even though there had been no rain for some time.

In the mountains inland from Batemans Bay, the experiment was run at three high elevation sites in Currowan plan area. Two of these sites were in wet sclerophyll forests, while one was in a dry sclerophyll forest. The wet sclerophyll sites occurred in steep valleys with a thick undergrowth of ferns, fern trees, vines, and shrubs. The ground was covered in a thick mat of wire grass and leaf litter. The topsoil was either light or dark brown, loamy, and soft underfoot. Currowan 1 differed from Currowan 2 in that Banksias were prominent and it showed signs of a light burn. The dry sclerophyll site (Currowan 3) had been more heavily burnt in 2020. The understory was dominated by young acacia regrowth and the groundcover was a thin layer of leaves. The topsoil was light brown, aggregated and crumbly.

On the far south coast in the southernmost East Boyd State Forest, the experiment was run at five sites over two planning regions. Both wet and dry sclerophyll forests were visited, although their general features were much the same. Each of the sites had been moderately to severely burnt during the 2020 bushfires and the understory was dominated by tussock grasses and Casuarina regrowth. Groundcover was a thinnish layer of leaf litter and woody debris and the topsoil was soft, crumbly, and light brown.

2.3.2 Description of accessed Ground Protection Zones (GPZs)

Ground Protections Zones that had been accessed by forestry machinery were identified at six sites. In this section we provide a description of these GPZs, and images of the sites are provided in Appendix A. We note that these sites were paired with REZs which are described in the section above and this section focusses on describing ground disturbance in the GPZ. Generally speaking, the area accessed in the GPZs was quite discrete (up to 30m in length) and ground disturbance was limited. Trees were harvested, but the base and root balls remained intact. Sources of ground compaction were machinery tracks and log drag marks. These were minor when compared to the constructed tracks in the general harvest area, but still formed flow paths during the experiments. For the most part, the disturbed areas were covered in woody debris and/or piles of harvesting debris (also referred to as slash) had been purposefully placed in the zone, presumably as part of stabilisation measures aimed at intercepting flow from the adjoining harvest area. The disturbance did not lead to any appreciable signs of erosion (e.g. rilling, gullying, or slumping). No rehabilitation efforts were observed, although it may have been determined that the level of disturbance didn’t warrant rehabilitation efforts. Site specific descriptions are as follows.

Within the Camira GPZ the ground cover consisted of grasses and sedges that had been disturbed by a skidder which had left multiple track marks while harvesting and dragging a few select trees from the zone. Some of the understory had also been incidentally disturbed but overall, the degree of disturbance was considered moderate. No appreciable evidence of erosion was observed. No obvious efforts had been made to stabilise the disturbed area, although harvest debris was scattered over the ground. Finally, no rehabilitation efforts were observed.

At Bagawa the GPZ retained a relatively thick groundcover of bracken, vines, and forbes. There was also a fairly light cover of woody debris and some moderate piles of slash left in the zone. Machinery tracks were evident at a single entry/exit point and drag marks from log extraction were present. Some of the understory had also been incidentally disturbed and overall, the degree of disturbance was considered moderate. No appreciable signs of erosion and no rehabilitation measured were observed.

The area of GPZ access at Orara East 1 was largely covered in a matt of woody debris including substantial piles of slash that had been placed in the zone. The ground was damp although it hadn’t been rained for some time. Predominantly ferns and grasses were growing up through the debris. Machinery tracks were present at a single entry/exit point into the zone where trees had been removed and drag marks were apparent where the skidder had pulled a tree out to the adjacent road. Overall, the degree of disturbance was the most substantial of the accessed GPZ sites that were visited, but there were still no appreciable signs of erosion.

Bulls Ground 1 was characterised by a moderately thick groundcover dominated by forbs and grasses with some sedge and vines, with a thin leaf layer. Some select trees had been harvested from the outer few meters of the GPZ without the machine accessing the GPZ, so the ground was effectively undisturbed. There was also some minor disturbance of the understory around the harvested trees. Smallish piles of harvesting debris (also referred to as slash) had been deliberately placed in the GPZ. Overall, the degree of disturbance was considered low. No appreciable evidence of erosion was evident, and perhaps subsequently no rehabilitation efforts were observed.

Bulls Ground 3 had moderately thick groundcover in parts made up mainly of bracken and grasses, although there was a thick layer of woody debris and leaves covering much of it. Native plant regrowth was emerging through the debris. Some select trees had been harvested from the outer few meters of the GPZ without the machine accessing the GPZ, so the ground was effectively undisturbed. There was some disturbance of the understory in the harvested area and slash piles had been placed in the zone. Overall, the degree of disturbance was considered low. No appreciable evidence of erosion was evident, and no rehabilitation efforts were observed.

Bulls Ground 4 was largely covered in a thick matt of woody debris including substantial piles of slash that had been placed in the zone. Native plant regrowth was occurring through the debris, including bracken, grasses, and eucalypts. Machinery tracks were present in the zone where trees had been removed emanating from a single entry/exit point. There was also disturbance of the understory in the harvested area. The degree of disturbance was considered moderate. Regardless, no appreciable signs of erosion were evident.

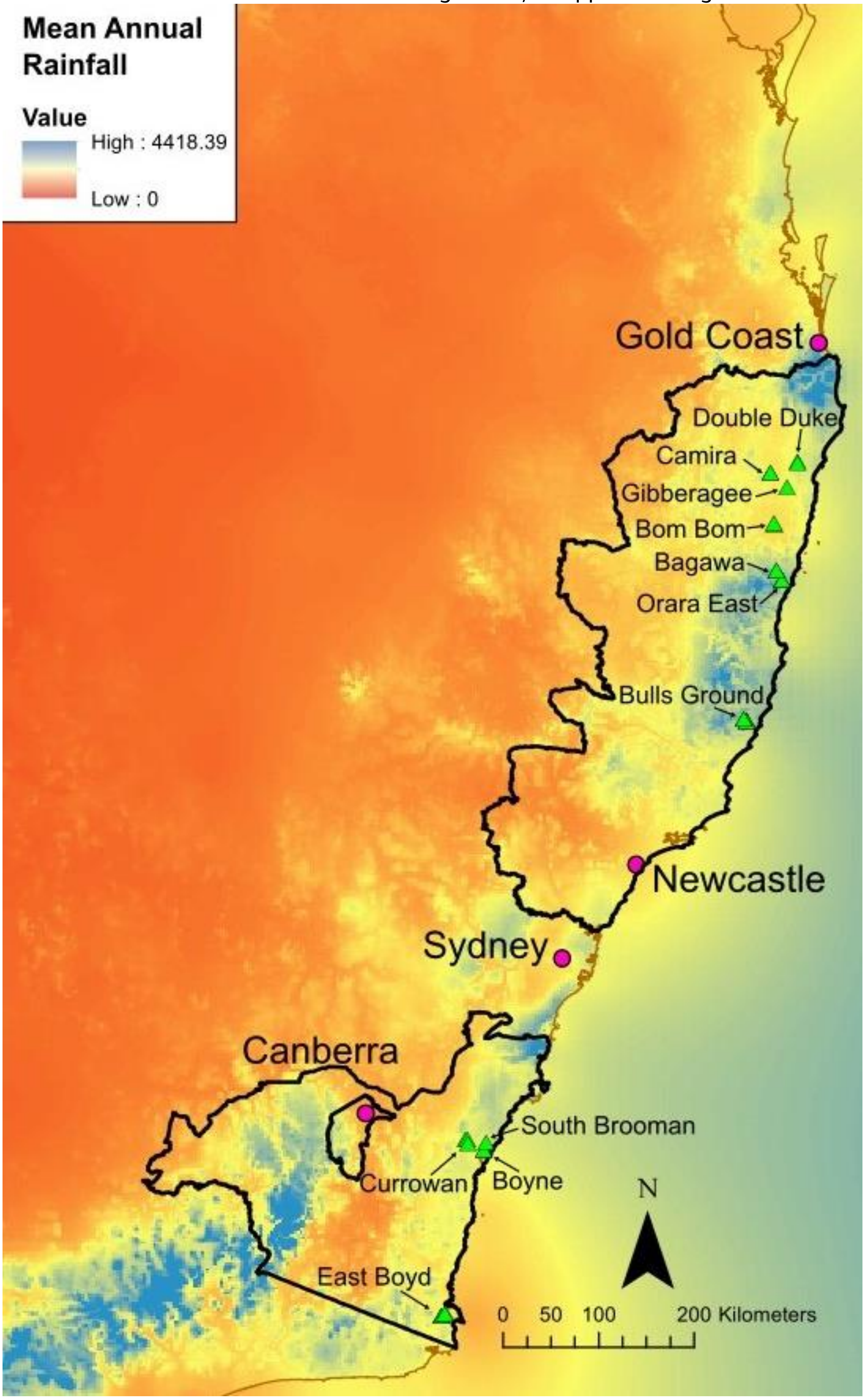

Figure 2-2 Map of the Coastal IFOA region (outlined in black) on the NSW coast. Study sites visited as part of this project are indicated by green triangles. The names of each forestry planning region are given as well as major cities. The heat map represents mean annual rainfall across the region.

Table 2-1 Study site details. Forestry Disturbance, Elevation, Mean slope, and Mean bulk density measurements were taken in the field. The remaining data was taken from the following sources: 'Vegetation Class' (NSW State Vegetation Map; NSW OEH 2017); 'Harvest Date' (FCNSW Harvest Progress Grid 2023); 'Mean Annual Rainfall' (Average annual, seasonal and monthly rainfall maps; Bureau of Meteorology 2023); 'Soil Composition' (Soil and Landscape Grid of Australia 0-5cm; Grundy *et al.* 2015); 'Wetness Index' (NSW Aridity/Wetness Index - High resolution 30 meter; New South Wales Department of Planning and Environment 2023). Measured variables are denoted with an asterisk (*), while modelled variables are denoted with a hat (^).

Plan Name	Site Name	Latitude / Longitude	Vbt5 (number of samples)	Vegetation Class	Harvest Date	Forestry Disturbance*	Elevation (m)*	Mean Annual Rainfall (mm)^	Soil Comp. (%)*	Mean Slope (°)*	Mean Bulk Density (g/cm^3)*	Wetness Index^
DOUBLEDUKE	Double Duke 1	-29.15300 153.19393	2	Coastal Floodplain Wetlands	18/1/23	Undisturbed	44	1290	Sand: 71 Silt: 14 Clay: 15	7	0.600 (n=2)	1.52
DOUBLEDUKE	Double Duke 2	-29.16434 153.18962	2	Coastal Floodplain Wetlands	11/12/22	Undisturbed	33	1290	Sand: 74 Soil: 13 Clay: 14	2	0.604 (n=2)	1.46
CAMIRA	Camira - GPZ	-29.25575 152.93547	3	Clarence Dry Sclerophyll Forests	8/5/23	Multiple machinery tracks; Vegetation removed/disturbed	89	1108	Sand: 74 Silt: 14 Clay: 12	4	0.660 (n=2)	1.75
CAMIRA	Camira - REZ	-29.25581 152.93554	3	Clarence Dry Sclerophyll Forests	8/5/23	Undisturbed	89	1108	Sand: 74 Silt: 14 Clay: 12	3.5	0.660 (n=2)	1.75
GIBBERAGEE	Gibberagee	-29.39395 153.09206	3	Coastal Floodplain Wetlands	24/5/23	Undisturbed	72	1165	Sand: 76 Silt: 13 Clay: 11	3	0.640 (n=3)	1.65
BOM BOM	Bom Bom 1	-29.75055 152.97133	5	Clarence Dry Sclerophyll Forests	30/9/22	Undisturbed	54	1021	Sand: 65 Silt: 15 Clay: 20	12	0.670 (n=5)	1.84

Plan Name	Site Name	Latitude / Longitude	Vbt5 (number of samples)	Vegetation Class	Harvest Date	Forestry Disturbance*	Elevation (m)*	Mean Annual Rainfall (mm)^	Soil Comp. (%)*	Mean Slope (°)*	Mean Bulk Density (g/cm^3)*	Wetness Index^
BOM BOM	Bom Bom 2	-29.73060 152.96860	3	Clarence Dry Sclerophyll Forests	29/11/22	Undisturbed	58	1021	Sand: 68 Silt: 13 Clay: 18	4	0.574 (n=2)	1.84
BAGAWA	Bagawa - REZ	-30.17944 152.99313	3	North Coast Wet Sclerophyll Forests	2/3/23	Undisturbed	186	1622	Sand: 62 Silt: 21 Clay: 17	18	0.835 (n=3)	1.25
BAGAWA	Bagawa - GPZ	-30.17955 152.99303	4	North Coast Wet Sclerophyll Forests	2/3/23	Disturbed GPZ Machinery track; Log drag marks; Vegetation removed/disturbed; small amount of slash	186	1622	Sand: 62 Silt: 21 Clay: 17	18	1.020 (n=4)	1.25
ORARA EAST	Orara East 1 - REZ	-30.26706 153.04386	5	North Coast Wet Sclerophyll Forests	10/2/23	Undisturbed	143	1754	Sand: 61 Silt: 21 Clay: 19	15	0.713 (n=3)	1.35
ORARA EAST	Orara East 1 - GPZ	-30.26685 153.04385	5	North Coast Wet Sclerophyll Forests	10/2/23	Disturbed GPZ One minor machinery track; Vegetation removed/disturbed; slash piles	143	1754	Sand: 61 Silt: 21 Clay: 19	17	0.807 (n=5)	1.35
ORARA EAST	Orara East 2	-30.26680 153.04270	4	North Coast Wet Sclerophyll Forests	5/5/23	Undisturbed	160	1754	Sand: 60 Silt: 21 Clay: 19	25	0.667 (n=3)	1.35

Plan Name	Site Name	Latitude / Longitude	Vbt5 (number of samples)	Vegetation Class	Harvest Date	Forestry Disturbance*	Elevation (m)*	Mean Annual Rainfall (mm)^	Soil Comp. (%)*	Mean Slope (°)*	Mean Bulk Density (g/cm^3)*	Wetness Index^
BULLS GROUND	Bulls Ground 1 - REZ	-31.59317 152.71118	5	North Coast Wet Sclerophyll	16/3/23	Undisturbed	46	1393	Sand: 68 Silt: 20 Clay: 12	10	0.637 (n=5)	1.31
BULLS GROUND	Bulls Ground 1 - GPZ	-31.59320 152.71080	3	North Coast Wet Sclerophyll	16/3/23	Disturbed GPZ Vegetation removed/disturbed; slash piles; largely undisturbed ground	46	1393	Sand: 68 Silt: 20 Clay: 12	10	0.797 (n=3)	1.31
BULLS GROUND	Bulls Ground 2	-31.59490 152.71060	5	North Coast Wet Sclerophyll	16/3/23	Undisturbed	43	1393	Sand: 67 Silt: 20 Clay: 13	12	0.631 (n=5)	1.26
BULLS GROUND	Bulls Ground 3 - REZ	-31.59488 152.71072	4	North Coast Wet Sclerophyll	16/3/23	Undisturbed	43	1393	Sand: 67 Silt: 20 Clay: 13	9.5	0.662 (n=4)	1.22
BULLS GROUND	Bulls Ground 3 - GPZ	-31.59470 152.71040	3	North Coast Wet Sclerophyll	16/3/23	Disturbed GPZ Vegetation removed/disturbed; slash piles; largely undisturbed ground	43	1393	Sand: 67 Silt: 20 Clay: 13	9.5	0.713 (n=3)	1.22
BULLS GROUND	Bulls Ground 4 – REZ	-31.57770 152.68580	3	Northern Hinterland Wet Sclerophyll Forests	14/2/23	Undisturbed	77	1393	Sand: 58 Silt: 26 Clay: 16	15.5	0.951 (n=3)	1.36

Plan Name	Site Name	Latitude / Longitude	Vbt5 (number of samples)	Vegetation Class	Harvest Date	Forestry Disturbance*	Elevation (m)*	Mean Annual Rainfall (mm)^	Soil Comp. (%)*	Mean Slope (°)*	Mean Bulk Density (g/cm^3)*	Wetness Index^
BULLS GROUND	Bulls Ground 4 - GPZ	-31.57770 152.68580	4	Northern Hinterland Wet Sclerophyll Forests	14/2/23	Disturbed GPZ Vegetation removed/disturbed; slash piles; ground disturbed from machinery access	77	1393	Sand: 58 Silt: 26 Clay: 16	15.5	0.951 (n=4)	1.36
SOUTH BROOMAN	South Brooman	-35.56510 150.25790	5	Southern Lowland Wet Sclerophyll Forests	10/8/22	Undisturbed	57	1096	Sand: 71 Silt: 14 Clay: 15	28	0.711 (n=5)	1.33
BOYNE	Boyne 1	-35.63730 150.24000	3	Southern Lowland Wet Sclerophyll Forests	1/11/22	Undisturbed	44	1031	Sand: 65 Silt: 19 Clay: 16	15	0.690 (n=3)	1.91
BOYNE	Boyne 2	-35.63694 150.23319	5	Southern Lowland Wet Sclerophyll Forests	14/11/22	Undisturbed	61	1031	Sand: 69 Silt: 17 Clay: 14	20	0.575 (n=4)	2.01
CURROWAN	Currowan 1	-35.53830 150.06630	5	South Coast Wet Sclerophyll Forests	8/8/22	Undisturbed	416	944	Sand: 66 Silt: 18 Clay: 17	22	0.912 (n=3)	0.96
CURROWAN	Currowan 2	-35.57520 150.08830	5	Southern Lowland Wet Sclerophyll	15/12/22	Undisturbed	187	981	Sand: 67 Silt: 18 Clay: 16	30	0.673 (n=4)	0.95

Plan Name	Site Name	Latitude / Longitude	Vbt5 (number of samples)	Vegetation Class	Harvest Date	Forestry Disturbance*	Elevation (m)*	Mean Annual Rainfall (mm)^	Soil Comp. (%)*	Mean Slope (°)*	Mean Bulk Density (g/cm^3)*	Wetness Index^
CURROWAN	Currowan 3	-35.53730 150.08470	5	South East Dry Sclerophyll	1/8/22	Undisturbed	444	983	Sand: 66 Silt: 17 Clay: 17	17	0.970 (n=5)	1.84
EASTBOYD 173A	East Boyd 1	-37.19522 149.84018	4	South East Dry Sclerophyll	16/6/22	Undisturbed	130	836	Sand: 76 Silt: 13 Clay: 11	9	0.622 (n=4)	1.96
EASTBOYD 173A	East Boyd 2	-37.19815 149.83524	3	South Coast Wet Sclerophyll	8/6/22	Undisturbed	112	836	Sand: 72 Silt: 15 Clay: 13	17	0.649 (n=3)	1.70
EASTBOYD 22A	East Boyd 3	-37.17210 149.87990	4	South East Dry Sclerophyll	21/7/22	Undisturbed	136	836	Sand: 71 Silt: 16 Clay: 13	8	0.690 (n=4)	2.05
EASTBOYD 22A	East Boyd 4	-37.17860 149.86870	4	South East Dry Sclerophyll	14/6/22	Undisturbed	117	808	Sand: 76 Silt: 13 Clay: 10	19	0.672 (n=4)	0.87
EASTBOYD 173A	East Boyd 5	-37.19887 149.83529	4	South Coast Wet Sclerophyll	8/6/22	Undisturbed	91	836	Sand: 75 Silt: 14 Clay: 11	19	0.632 (n=4)	0.86

2.4 Field measurements

2.4.1 Volume to breakthrough (vbt) experiments

The volume to breakthrough (vbt) method quantifies the volume of water required to reach a specified distance downslope and provides a quantitative assessment of the extent to which hillslopes can absorb overland flow. The *vbt5* metric is the volume of water absorbed when the plume reaches 5 meters downslope of the discharge point. The volume is calculated from time and rate of discharge from the delivery hose. We used *vbt5* as a parameter in an analytical model for simulating plume lengths and volumes. It integrates soil hydraulic properties and surface roughness caused by vegetation and microtopography.

For each experiment, water was applied to the hillslope at a rate of 3.0 L s^{-1}, by pumping water from a water cart and metering the flow rate using a rotameter (Figure 2-3). This rate is representative of culvert discharges measured in large storm events in forest environments (Sheridan and Noske, 2006) and has been adopted in other *vbt* experiments (Lane et al. 2006; Nyman 2009; Nyman et al. 2023). The use of a steady discharge in this study differs from that used in Hairsine et al. (2002), where overland flow was generated on tracks so that discharge rates varied through time. The discharge was set to this rate as it is a sensible rate at which to operate the experiment and because it generally resembles the type of overland flow conditions expected at a crossbank outlet following a 1 in 10-year 30 min storm event on a 5m wide and 15m long segment of track. Water was delivered to the hillslope via a delivery hose which was placed on the ground with the discharge point facing upslope in order to reduce flow energy and concentration. In this way the flow resembled the concentrated flow that leaves a track cross bank and enters a rough near-natural surface. A measuring tape was be used to mark the 5m point downslope from the discharge point.

Figure 2-3 General setup of the volume-to-breakthrough experiment. A) depicts the water cart with the water pump attached to the back with the red hose leading into the buffer zone; B) shows the red hose connecting to the rotameter which controls the flow released though the black hose; C) shows the black hose laid out at the top of a *vbt5* run (marked by pink tape) with the measuring tape indicating the distance from the discharge point.

At each site where it appeared the GPZ was accessed for harvesting, we defined the GPZ and REZ by measuring back 5 to 15m from the channel bank, from the point of bank full width (which we determined ourselves) (Figure 2-4 Scenario 1). We acknowledge that this measurement is difficult and somewhat open to interpretation but were also guided by what areas had been disturbed by machinery. The 5 meters closest to the channel, where the buffer zone is undisturbed, was treated as the REZ. The experiment was run in the REZ first (Figure 2-4 Scenario 1, Step 1) as it meant the overland flow plume wouldn't impact on the upslope GPZ before the experiment was run there (Figure 2-4 Scenario 1, Step 2). Furthermore, if the GPZ had not been disturbed by the access of harvesting machinery, the whole buffer zone was treated as an undisturbed REZ for the purpose of running the experiment (Figure 2-4 Scenario 2). A 20 m wide cross-slope line was measured, and replicates were placed at even intervals (e.g. 4 m apart if 5 replicates are being done) although, there were some restrictions on placement due to length of available hose and the presence of large debris at flow initiation points. Between two and five replicates (median = 4) were conducted at each site based on water availability (i.e. how much water was available in the water tank and the duration of the flows taken to determine *vbt5*).

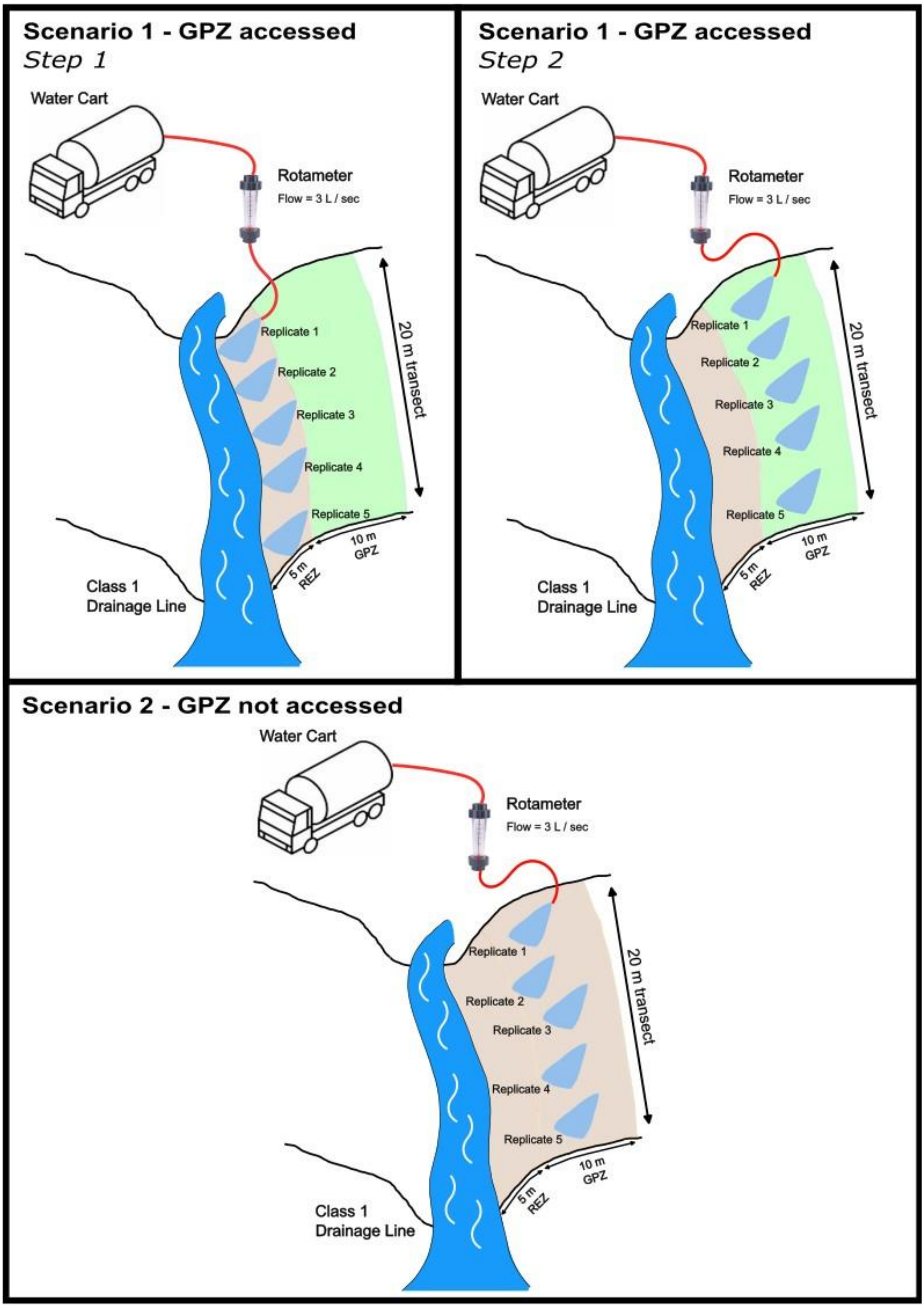

Figure 2-4 Schematic outlining the layout of the volume-to-breakthrough experiment. In these scenarios, sections of the buffer zone that haven't been disturbed by machinery are shaded red, while sections disturbed by machinery (i.e. an accessed GPZ) are shaded green. In Scenario 1 the GPZ has been accessed by forest harvest machinery and the experiment is run sequentially in both the REZ and GPZ sections. In Scenario 2 the GPZ was not accesses and the transect was placed anywhere in the 15m zone near the Class 1 drainage line.

2.4.2 Hillslope properties

At each site, soil bulk density of the topsoil and slope measurements were collected to inform an assessment of links between hillslope properties and variation in the overland flow plumes. The slope was measured at each *vbt5* run using a clinometer from the discharge point to the 5m mark.

For bulk density, a cylindrical sediment core (7.5 cm deep, 4.4 cm diameter) was taken immediately above each *vbt5* measurement and placed in a zip lock back for later processing. In this way the *vbt5* measurements were directly related to the bulk density of the soil. Bulk density processing was conducted at the University of Melbourne's School of Ecosystem and Forest Sciences laboratories. The soil was oven-dried at 105°C for 48 hours, then weighted to obtain the dry weight of the soil. Bulk density (g cm^3) was calculated as the ratio of mass to volume. There were 2-5 replicate soil cores at each site.

Unfortunately, following sample collection, the microorganisms in the soil consumed the site labels within 14 bags and those samples could not be attributed to a site or replicate. These samples were discarded. In total 103 usable bulk density readings were collected alongside corresponding *vbt5* measurements with data collected for each site.

2.5 Data analysis

2.5.1 Influence of exclusion zone settings and vegetation type on volume-to-breakthrough

Within the overall dataset of *vbt5* measurements and related modelled plume lengths, it was anticipated that there may be groupings of data with statistically different distributions that correspond with hypothesised drivers of runoff risk. For instance, it was considered possible that overland plumes travel further through GPZs than REZs due to ground compaction from machinery and/or the impact of felled trees on the ground. Furthermore, based on a similar study conducted in Victoria (Nyman *et al.* 2023), it was hypothesised that overland plumes may travel further through dry forests where hydroclimatic conditions limit ground infiltration than they would through wet forests. To help achieve the stated objectives of the project and to provide further insight into factors influencing buffer zone effectiveness, we tested the following hypotheses using linear and generalised linear models applied to the field measurements.

Hypothesis 1 = Overland plumes travel the same distance through GPZs as they do through REZs.

Hypothesis 2 = Overland plumes travel the same distance through Dry Sclerophyll forests as they do through Wet Sclerophyll forests.

Prior to the analysis *vbt5* distribution was checked for normality and subsequently log transformed to improve normality. To test for differences in *vbt5* volumes between GPZs and REZs (*Hypothesis 1*) we conducted an analysis of variance (ANOVA) using the *aov* R package. *Vbt5* was used as the response variable and buffer zone area (GPZ or REZ) was used as the grouping variable. Furthermore, to investigate whether the number of replicate samples taken in the field were sufficient to provide the statistical power needed to detect change using the ANOVA test, we conducted a power analysis of the paired GPZ/REZ data in the *pwr* R package. In a hypothesis test, statistical power is the probability that the test will detect an effect that actually exists. To calculate the sample size needed to achieve a given level of power the test was parameterised as follows: 'number of groups' (2), 'number of samples' (calculated from the power analysis), 'effect size' (0.45- calculated from the dataset), 'significance level' (0.05), 'power' (varied manually). We investigated the level of 'power' achieved given the number of samples gathered in the field. We considered that power ≤ 0.8 provides an acceptable level of confidence, which is a commonly adopted threshold (Cohen, 1988).

To test *Hypothesis 2* we conducted another ANOVA, with the model comparing *vbt5* volumes (response variable) measured in six of the 'vegetation classes' sampled that represent wet and dry sclerophyll forests (*Dry Sclerophyll***:** Clarence Dry Sclerophyll, South East Dry Sclerophyll; *Wet Sclerophyll*: North Coast Wet Sclerophyll, Northern Hinterland Wet Sclerophyll, South Coast Wet Sclerophyll, Southern Lowland Wet Sclerophyll). While not a wet or dry sclerophyll forest, the Coastal Floodplain Wetlands vegetation class was sampled due to the limited pool of sites that fit each of our site selection criteria in the areas we were focussed on, so we included this class in the analysis. If a model detected a significant difference between vegetation classes overall, a post-hoc test was used to determine exactly which classes were different from one another using Tukey's Honestly Significant Difference test (Tukey's HSD).

2.5.2 Hillslope and landscape scale influences on volume-to-breakthrough

We investigated relationships between the *vbt5* measurements and the continuous hillslope (bulk density and slope) and landscape (wetness) variables of focus in this study. The prospect was that if strong relationships could be identified the variables could be used to better understand buffer zone suitability more broadly across the Coastal IFOA region where sampling hasn't been conducted. This was considered a value add to the project and not part of the central aims. The following hypotheses were tested for each variable.

Slope. Flow velocity tends to increase with slope and diffuse overland flow plumes might be expected to travel faster when slopes are steeper leading to less time for infiltration. This may lead to longer flow plumes.

Hypothesis 3 = Hill slope will be negatively correlated with *vbt5* measurements.

Soil bulk density. Soil bulk density measurements are inversely proportional to the porosity (i.e. the absorbency) of the soil. Low bulk density values indicate high porosity and a higher capacity to absorb surface water, and high values indicate low porosity and a lesser capacity to absorb surface water.

Hypothesis 4 = Soil bulk density will be negatively correlated with *vbt5* measurements.

Average Annual Wetness index (aka Aridity). The average annual wetness index is the ratio between precipitation and potential evapotranspiration (rainfall / potential evapotranspiration). An index of 1 indicates areas where annual rainfall and evapotranspiration are equal. Index above 1 indicates a wet area where annual rainfall exceeds annual evapotranspiration and below 1 indicates a dry area where evapotranspiration is potentially greater than the prevailing rainfall. Wetness, also referred to in the literature as aridity (the inverse of wetness), has been linked to soil hydraulic properties (Noske *et al.* 2016). In these studies, a low wetness index has been attributed to lower infiltration rates, so a negative correlation with *vbt5* was expected.

Hypothesis 5 = Average annual wetness index scores will be negatively correlated with *vbt5* measurements.

Our investigation of groupings within the *vbt5* dataset (detailed in Section 0) ultimately revealed that most measurements taken were part of the same distribution. As such, we analysed the whole dataset together in the assessment of the influence of hillslope variables. Linear regression was implemented using the *lm* function in R to investigate the relationship between *vbt5* volumes and each of the above hillslope and landscape variables. Each of the predictor variables were $\log_{10}$ transformed in each analysis to minimize effects of non-normality.

Sand content: Sand content may also influence the porosity of the soil and we considered investigating it too. However, we ran a Spearman's rank correlation test to check for autocorrelation with bulk density (also a soil property) and found that they were significantly autocorrelated (Spearman's Þ = -0.43, p = <0.001). Based on this result we omitted sand content from further analysis.

2.5.3 Exclusion zone exceedance modelling

To quantify the degree of connectivity expected between track crossbank outlets discharging into buffer zones and the stream network, we used the *vbt5* model of Hairsine *et al.* (2002). This model was developed to predict the probability of road and track-derived overland flow reaching the stream by diffuse overland flow from a crossbank outlet. It estimates both the volume of flow that reaches a given point (e.g. 15m from the crossbank outlet) and the maximum distance the plume would travel before complete infiltration. The model integrates volume to breakthrough measurements which describe the volume of overland flow that enters an area before discharge is observed at the downslope boundary of that area.

Firstly, the volume of overland flow that discharges into the crossbank outlet, V_{in} (m^3), is calculated as per Equation 1. In this equation *CA* is the contributing track area (m^2), *R* is the rainfall rate (mm h^{-1}), *I* is the infiltration rate (mm h^{-1}) and *t* is the duration of the event. By altering the *CA* and *R* parameters in this equation, we investigated different contributing track area and different rainfall scenarios in different areas of the Coastal IFOA. This allowed us to assess exclusion zone performance under low to high-risk scenarios and to provide insight into how reducing crossbank spacing can reduce discharge from outlets and ultimately plume lengths. These scenarios are described in Section 2.5.4. The *I* parameter was set at 30 mm h^{-1} based on the mean apparent infiltration rate of tracks measured by Croke *et al.* (1999) during field-based rainfall simulator experiments. The *t* parameter was set to reflect 30-min rainfall events.

$$V_{in} = CA * (R - I) * \frac{t}{1000}$$ Equation 1

Figure 2-5 Image of a track with the 'contributing track area' described in Equation 1 outlined in blue.

Once the volume exiting the track crossbank outlet was modelled, the volume of flow reaching the stream though the exclusion zone (V_{out}) is estimated through Equation 2. In this equation, *D* is the distance from the outlet to the stream. The *vbt5* parameter is the volume of breakthrough value for a 5 m long hillslope segment. Initial investigations of the *vbt5* results indicated that they were likely part of the same distribution (with an exception dealt with in Section 3.3) and it would be appropriate to treat them as a single randomly distributed term. So, to broaden the applicability of our results we fitted a truncated normal distribution to the *vbt5* field measurements (with the lower boundary set to zero as *vbt5* measurements can't be negative) and modelled the volume of flow exceeding a 15m buffer zone based on 1000 random samples taken from that distribution. Further to this, as we are predicting plumes (and their volumes) longer than 5m, we treated the theoretical 15m buffer zone as a sequence of spatially independent 5-m long plumes in series, each of which has a distinct *vbt5* (i.e. capacity to store overland flow) taken randomly from the normal distribution, described by the μ*vbt5* parameter (Hairsine *et al.* 2002). The *D* parameter was set at 15m to reflect buffer zone widths for Class 1 drainage lines in the Coastal IFOA region. As our results indicated that GPZs and REZs exhibited similar hydraulic properties (i.e. *vbt* measurements were from the same statistical distribution; see Section 3.2), we treated the whole buffer zone (GPZ and REZ components) as a single unit.

$$V_{out} = V_{in} - D * \frac{\mu vbt5}{5}$$ Equation 2

We then generated a cumulative probability distribution of exclusion zone exceedance by (1) sorting flow volumes (V_{out}) in ascending order, (2) calculating the sample probability of each measurement ($p_i = 1/n$), where *n* is the total number of samples, and (3) calculating the cumulative sum of those probabilities. We produced probability of exceedance functions by plotting P against V_{out}.past the 15m buffer zone (x)

$$P(V_{out} > x) = 1 - \sum_{i=1,2,3\ldots}^{n} p_i$$

Equation 3

Finally, to investigate what exclusion zone setting widths would be required to reduce the probability of connectivity with adjacent streams to less than10% (which we arbitrarily set) we modelled the distance that flow would travel through a continuous riparian zone (i.e. the plume distance; l_{pred}), for each µ*vbt5* measurement, using the approach of Hairsine *et al.* (2002). These results are discussed in the Discussion:

$$\mu\, l_{pred} = 5 \frac{V_{out}}{\mu v b t 5}$$

Equation 4

2.5.4 Model scenarios

The V_{in} model (Equation 1) was used to assess buffer zone effectiveness given (1) rainfall events of varying intensity experienced in areas of the coastal IFOA region with differing rainfall regimes, and (2) variable crossbank spacings on tracks as recommended in the Coastal IFOA guidance on track spacings.

2.5.4.1 Rainfall intensity

Four rainfall scenarios were used that represent 30-min rainfall events with recurrence intervals of 5, 10, 20, and 50 years. 30-minute design storms were obtained from the intensity-frequency-duration (IFD) grids available from the Bureau of Meteorology (BoM). We used the maximum 30-minute intensity (I30) for each individual site as input to the V_{in} model. In this way buffer zone effectiveness can be evaluated under a range of common to less commonly experienced rainfall events. In summary we used the following scenarios:

- I30 rainfall event with a 1 in 5-year recurrence interval
- I30 rainfall event with a 1 in 10-year recurrence interval
- I30 rainfall event with a 1 in 20-year recurrence interval
- I30 rainfall event with a 1 in 50-year recurrence interval

2.5.4.2 Regional rainfall volume

Rainfall intensity scenarios (i.e. parameter *R*) were derived for three areas of the Coastal IFOA region that experience substantially different annual rainfall volumes in order to better understand buffer zone effectiveness across the whole region. We chose locations which lie in low, moderate, and high rainfall areas to derive the rainfall volumes from including:

- Low rainfall setting (Eden)
- Moderate rainfall setting (Grafton)
- High rainfall setting (Coffs Harbour)

2.5.4.3 Contributing track area (area between crossbanks)

. The Coastal IFOA Drainage Spacing Guidance specifies maximum distances between drains depending on the track slope; tracks with higher slopes have lower maximum distances allowed between drains (Table 2-2; NSWEPA 2020). Drainage spacings can be implemented at any distance below the maximum, which provides for considerable variation across harvesting operations. Track widths are set at 5m and due to the requirements for machinery size and construction. This width was typical of field observations. Coastal IFOA settings do not regulate track width, so a reasonable approach has been taken noting the variability of widths being used in practice.

Table 2-2 NSW EPA Coastal IFOA guidance for track drainage/crossbank spacing. The table describes the maximum distance of water flow or potential water flow along track surfaces (measured along the ground surface) between crossbanks on tracks of varying slope. This table is reproduced from the NSWEPA Coastal IFOA Guidance – Track Drainage Space Guidance (NSWEPA 2020).

Track slope (degrees)	Maximum distance (metres)
5	100
10	60
15	40
20	25
25	20
30	15

Crossbank spacings encountered on tracks during the field program ranged between 20m and 30m, with track widths being consistently 5m. We believe this reflects the reality that tracks approaching buffer zones often occur on steeper slopes (>15°). As such, we chose contributing track area scenarios that encompass the maximum crossbank spacings allowed on tracks between 15° (contributing area = 40m x 5m) and 30° (contributing area = 15m x 5m) slope. In addition, we investigated discharge on 10m x 5m to assess how further reducing crossbank spacings may decrease the amount of overland flow surpassing 15m buffers in the Coastal IFOA region. In summary, we investigated the following scenarios:

- Contributing track area 40m x 5m (200m^2)
- Contributing track area 30m x 5m (150m^2)
- Contributing track area 15m x 5m (75m^2)
- Contributing track area 10m x 5m (50m^2)

2.6 Probabilistic framework for assessing the effectiveness of buffer zones in preventing sediment connectivity between harvest areas and the stream network

This study aims to provide a quantitative basis for assessing the effectiveness of buffer zones around Class 1 drainage lines in preventing connectivity between areas of overland flow generation within forestry compartments and the stream network across a range of environmental settings in the Coastal IFOA region. The analytical approach uses the hydrological measurements collected within buffer strips across the Coastal IFOA region. The measurements simulate the overland flow process that connect overland flow generating areas (e.g. log landings, track, and other compacted surfaces) with the stream network. As such, they are directly related to the performance of the buffer zone in reducing delivery of sediment to streams.

We used the results from the fieldwork and analyses detailed above to develop a framework for deciding the level of connectivity that is acceptable in Class 1 drainage lines in the Coastal IFOA region. The framework is based on the assumption that high magnitude rainfall events will lead to a degree of connectivity between harvest areas and the stream network in some instances, so it is prudent to evaluate this risk and assess the degree to which it is acceptable. The outcome is defined in terms of the probability that overland flow plumes will/won't exceed the width of the buffer zone given a certain high rainfall event for a given area falling on a certain track area between crossbanks.

For example, it might be decided that buffer zones should prevent overland flow connectivity between harvest areas and the stream network 80% of the time, in a 1 in 10-year rainfall event. The implication is that it is acceptable for the buffer zone to be exceeded 20% of the time during a 1 in 10-year rainfall event. The results show that in such a scenario the buffer zone is only exceeded 8% of the time (so is effective 92% of the time), and when exceedances do occur only a small volume of the generated overland flow will reach the stream via the overland pathway, carrying with it a small portion of the fine sediment generated on the compacted surfaces.

In this way we can investigate both the probability buffer zones may be exceeded under various scenarios and how that risk may be reduced by standard practices such as reducing cross bank spacings, increasing the distance between cross bank outlets and buffer zones, and/or increasing the width of the buffer zone.

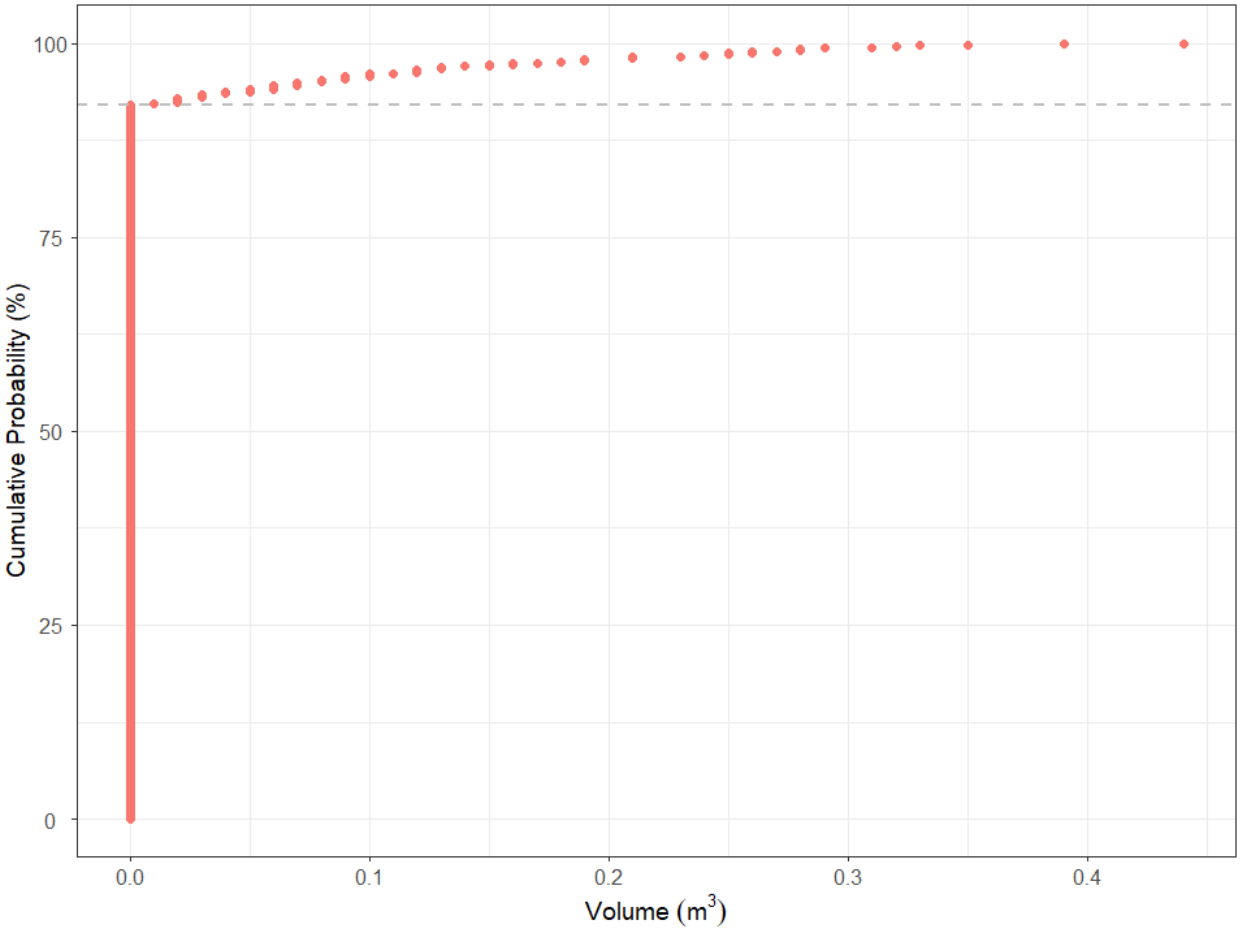

Figure 2-6 Risk based approach to assessing buffer zone effectiveness. In this example case, the results indicate the probability of surface runoff traveling greater than 15m through the buffer zone, and by what volume, during a single 1 in 10-year rainfall event where track drains are spaced 10m apart. Each volume estimate (red dot) was derived from a *vbt5* measurement in the field. If the volume is zero, the data implies that the 15m buffer zone would not be exceeded. All volumes greater than zero (above the grey dotted line) indicate exceedances of varying amounts.

3. Results

3.1 Overview

In total 116 *vbt5* experiments were run across 11 forests situated between the northern and southern extent of the Coastal IFOA region. The results of these experiments are shown in Figure 3-1. The *vbt5* volumes ranged between 88L and 2282L, with the mean being 277L and the median 233L. The values are heavily skewed to the left of the graph with the vast majority of *vbt5* values being less than 600L. However, several measurements greater than 1000L occur to the right of the plot suggesting a non-normal and potentially bimodal distribution. These results and are explored further in Section 3.3.

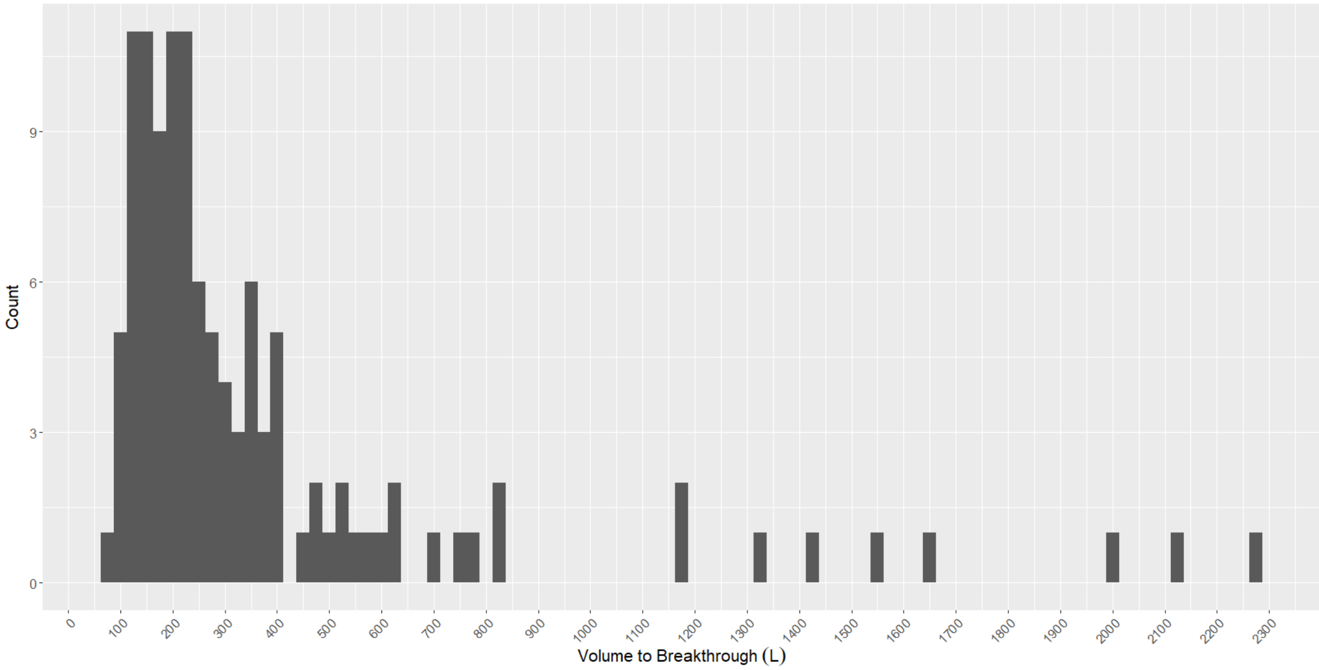

Figure 3-1 Frequency histogram depicting all volume to breakthrough results collected as part of this study. Histogram bins = 25L.

3.2 Assessment of differences in hydraulic properties between Ground Protection Zones and Riparian Exclusion Zones

To test whether plumes travel further through disturbed GPZs than through undisturbed REZs we applied an ANOVA to the data. The results of the ANOVA indicated that *vbt5* values (and thus plume lengths) were higher at GPZ sites than REZ sites, but the difference was not statistically significant (ANOVA, df = 1, F = 3.85, p = 0.058). The power analysis determined that the dataset had sufficient power (0.84) to detect change, implying that the results can be used to make reasonable conclusions. The results indicate that within the population of samples tested, plumes are likely to travel similar distances through GPZ and REZ zones (Figure 3-2). Given that these results indicate that all *vbt5* samples are from the same distribution we combine GPZ and REZ measurements in all following analyses.

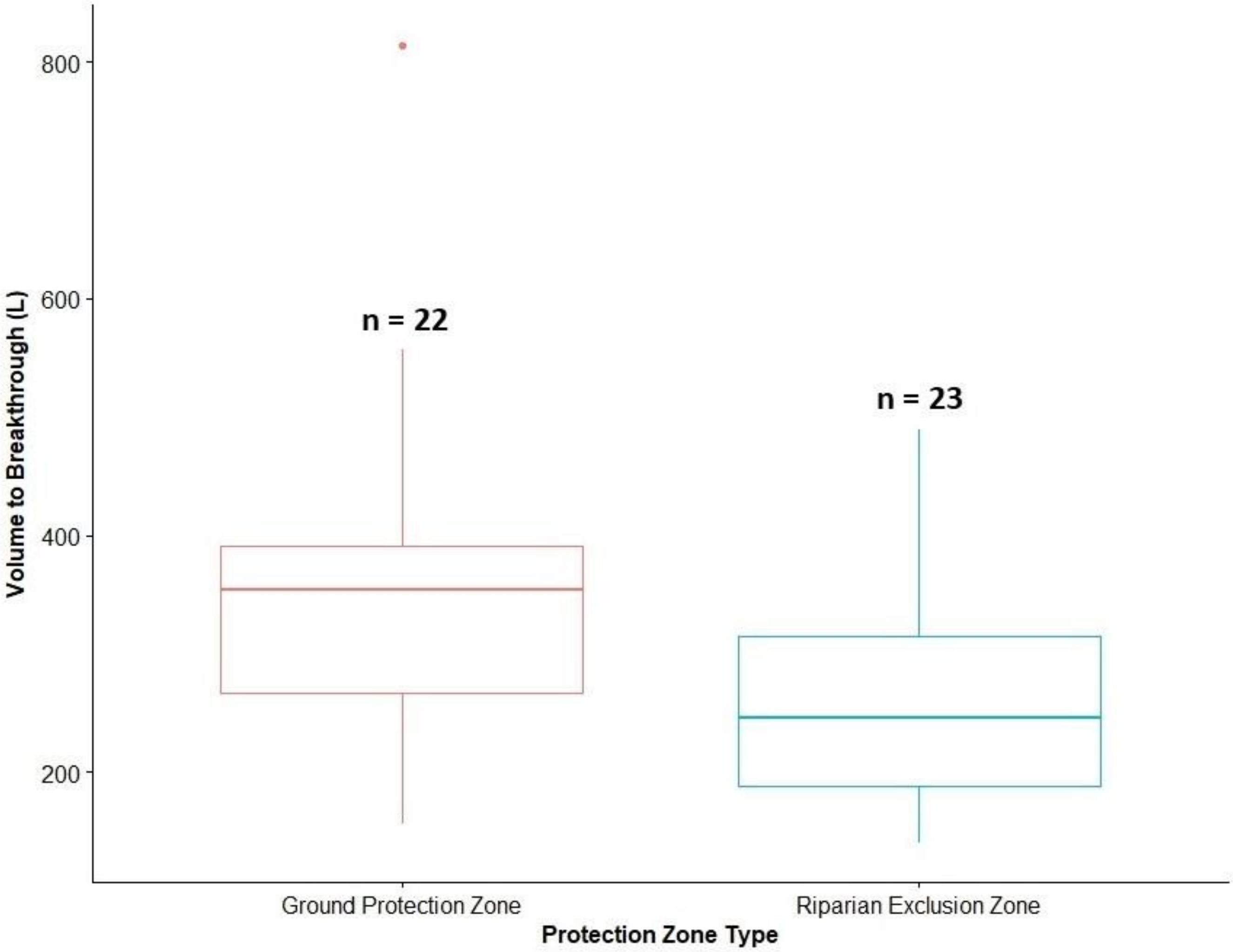

Figure 3-2 Box plots showing the distribution of volume-to-breakthrough measurements in Ground Protection Zones and Riparian Exclusion Zones in the Coastal IFOA region. Horizontal lines in each box represent the 75 percentile, mean, and 25 percentile values respectively, while vertical lines indicate the range of values beyond this. Individual dots indicate outlier values. The number of samples (n) used in the analysis, collected from six sites (see Table 2-1), are also presented.

3.3 Assessment of differences in *vbt5* between different forest types

To test whether plumes travel further through different vegetation types, as defined in the NSW State Vegetation Type Map, an ANOVA was applied to all *vbt5* results and their associated vegetation categories.

The analysis of vegetation class also indicated significant differences in the dataset (ANOVA, df = 6, F = 36.88, p = <0.001). The post-hoc Tukey's HSD analysis indicated that this result was driven by significant differences between Coastal Floodplain Wetlands and each of the other vegetation classes. Coastal Floodplain Wetlands was the only vegetation class sampled within the Forested Wetlands vegetation form, so the results are the same as those for Forested Wetlands. The mean *vbt5* volume for Coastal Floodplain Wetlands was between 1238.85 and 1488.19 L greater than each of the other vegetation classes (p = <0.001 for each comparison). Each of the other vegetation classes exhibited similar *vbt5* volumes (p = >0.05 for each comparison) (Figure 3-3).

The results indicate that plumes would travel the same distance through most of these vegetation classes with the exception of Coastal Floodplain Wetlands, where plumes would travel significantly shorter distance than in those other vegetation classes.

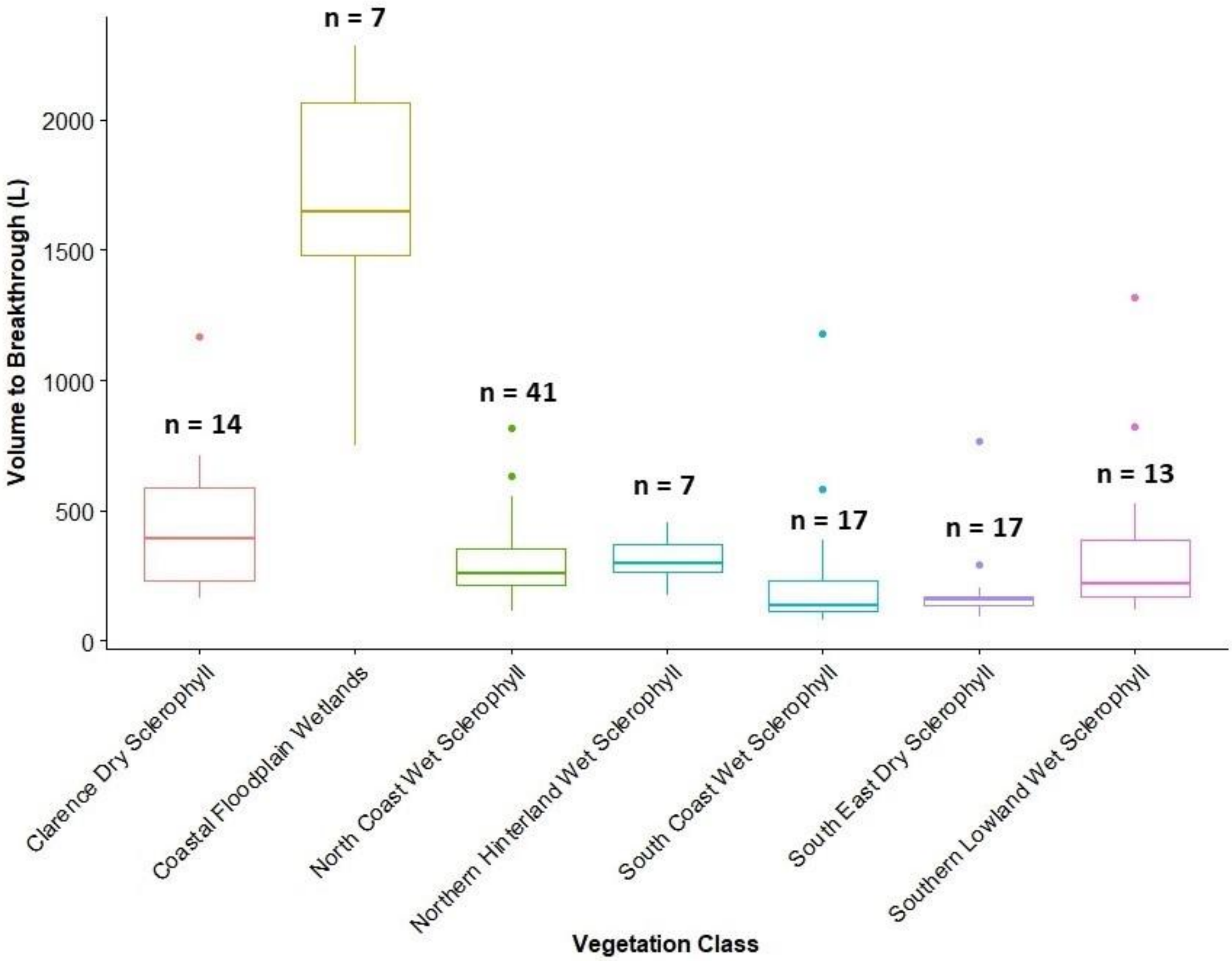

Figure 3-3 Box plots showing the distribution of volume-to-breakthrough measurements in each of the vegetation classes visited in the Coastal IFOA region. Horizontal lines in each box represent the 75 percentile, mean, and 25 percentile values respectively, while vertical lines indicate the range of values beyond this. Individual dots indicate outlying values. The number of samples (n) used in the analysis, collected from 30 sites (see Table 2-1), are also presented.

It is clear from these results that the Coastal Floodplain Wetlands are largely responsible for the skewed *vbt5* distribution for the dataset, as highlighted in Figure 3-4. The potential implication for statistical analysis is that data from that Vegetation Class represents a separate normal distribution to the rest of the dataset and should be treated separately. As such, we excluded Coastal Floodplain Wetlands from further analysis and focussed on the core distribution.

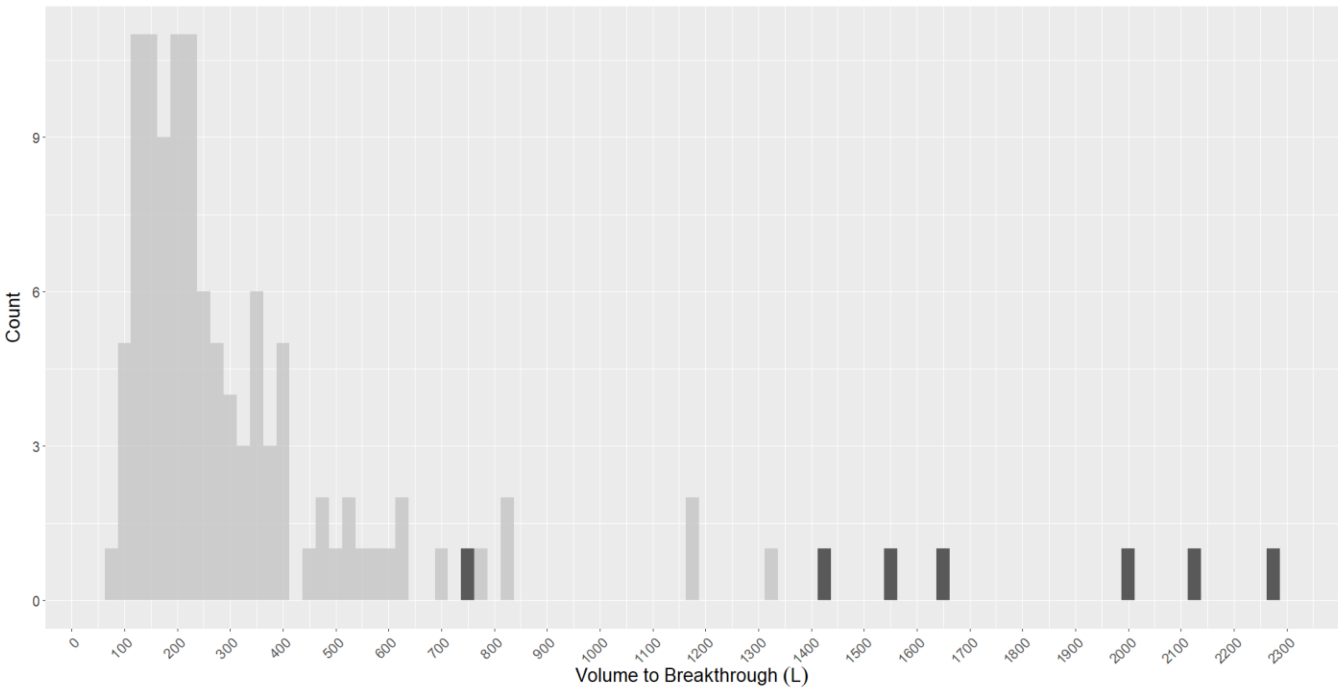

Figure 3-4 Frequency histogram depicting all volume to breakthrough results collected as part of this study with results from Coastal Floodplain Wetlands highlighted dark grey. Histogram bins = 25L.

3.4 Assessment of hillslope and landscape influences on *vbt5*

We investigated the influence of slope and landscape features on vbt5 field measurements through linear regression to help identify variables that may be used to predict plume lengths, and thus buffer zone effectiveness, more broadly across the Coastal IFOA region. Data collected from Coastal Floodplain Wetlands was excluded from the analysis as they present extreme outlier values that potentially belong to a separate distribution, and the results are likely driven by different processes than those from the wet and dry sclerophyll forests. The results are presented in Figure 3-5.

The results indicated that there is a statistically significant negative relationship between slope and *vbt5* volume (R^2 = -0.280, p = 0.003; Figure 3-5A). The R^2 value indicated that the model didn't fit the data particularly well but the trajectory did conform with expectations (*Hypothesis 3*).

A non-significant negative relationship between bulk density and *vbt5* volume was also identified (R^2 = -0.093, p = 0.365; Figure 3-5B). While the direction of the relationship conformed with expectations (*Hypothesis* 4), bulk density did not explain the variance in the vbt5 volumes well.

Finally, a positive, non-significant relationship was found between Mean Annual Wetness Index values and *vbt5* volume (R^2 = 0.120, p = 0.213; Figure 3-5C). So, while the trajectory of the relationship was consistent with *Hypothesis 5* Mean Annual Wetness did not explain variance in the *vbt5* volumes.

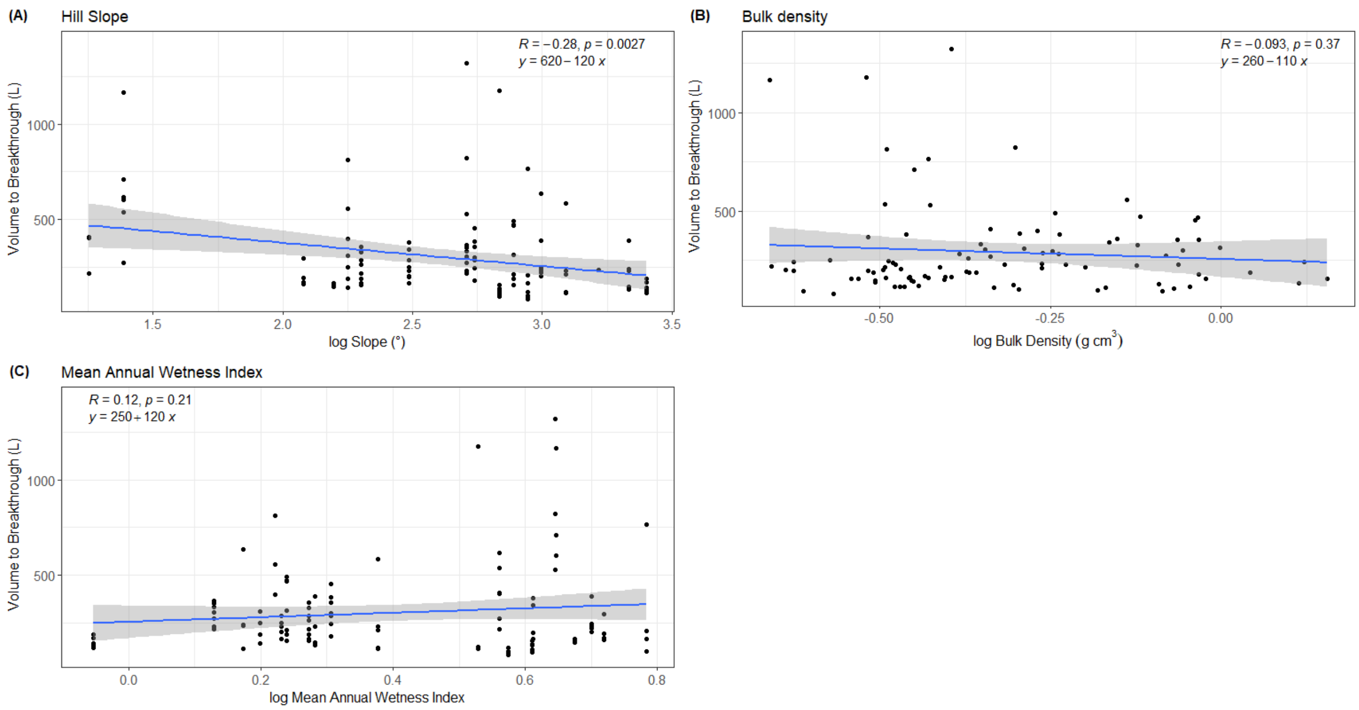

Figure 3-5 Linear regressions of A) Hillslope, B) Bulk density, and C) Mean annual wetness index against *vbt5* volume. Each of the predictor variables in on the log scale. For each regression the R^2, p-value, and regression equation (y) are indicated on the figure.

3.5 Probability of Class 1 drainage line buffer zones preventing track-derived overland flow reaching the stream network

To test the effectiveness of buffer zones around Class 1 drainage lines in the Coastal IFOA region we modelled the length of flow plumes exiting track crossbank outlets, based on a sampling of a truncated normal distribution fitted to the *vbt5* measurements, and calculated the probability that those plumes would exceed the prescribed 15m riparian buffer zone in three areas of the coastal IFOA region that experience low, moderate, and high annual rainfall volumes relative to the region. The results can be viewed as the probability that the buffer zones will be effective in preventing track derived overland flow from reaching the stream network in a worst-case scenario where a cross bank discharges directly into the buffer zone. We investigated the probability of exceedance under four rainfall scenarios (storms with 1 in 5-year, 1 in 10-year, 1 in 20-year, and 1 in 50-year recurrence intervals) and four contributing track area scenarios (contributing track area is 5 x 10m, 5 x 15m, 5 x 30m, and 5 x 40m). In total 1000 modelled plume lengths were used in the analysis.

3.5.1 Low rainfall setting (Eden)

The town of Eden was chosen to represent a low rainfall area within the Coastal IFOA region. The exceedance probability results are presented in Table 3-1 and Figure 3-6. During a 1 in 5-year storm there is a 100% chance that the buffer zone will prevent connectivity between a track crossbank outlet and the stream network if the track drains are spaced 10m or 15m apart (contributing track area 5 x 10m). While there is a slight chance that an overland flow plume may exceed the buffer where tracks are 30m (1% chance) and 40m (2% chance), the volume of water modelled to reach the stream network is small 0.001 to 0.002m^3 (i.e. 2 Litres).

During a 1 in 10-year storm there is a 97 to 99% chance that a buffer zone will prevent connectivity with the stream network where track crossbank outlets are spaced 10m or 15m apart. Furthermore, the mean modelled volume exceedance was quite low 0.001 to 0.004m^3. If crossbank outlet spacings are 30m apart there is a substantially greater probability of track-derived overland flow exceeding the buffer (33%), with the mean exceedance volume being 0.068m^3. Where crossbanks spacings are the widest investigated, 40m, there is an 67% chance that the buffer zone will exceeded, with the modelled mean exceedance being 0.208m^3.

During a 1 in 20-year storm the probability that the buffer zone would prevent connectivity between a track crossbank outlet and the stream network is 95% where crossbanks spacings are 10m apart, with the mean modelled exceedance volume being 0.006m^3. Where crossbanks spacings are 15m apart there is a 19% probability that the buffer zone would be exceeded, with the mean exceedances volume being 0.033m^3. If 30m or 40m spacings are allowed between crossbank outlets, the probability of exceedance and volume of water reaching the stream network increases greatly to 91% (0.442m^3) and 99% (0.887m^3) respectively.

In the largest storm event modelled (1 in 50-year recurrence) the buffer zones are predicted to be effective less than 80% of the time in all scenarios. Where the crossbanks spacings are the smallest (10m apart), the probability that the buffer zone would be exceeded was 21%, with mean exceedance volume being 0.037m^3. Allowing for 15m crossbanks spacing would mean that the buffer zones are expected to be exceeded 64% of the time by a mean volume of 0.189m^3. With crossbanks spaced 30m or 40m apart the buffer zones are expected to be ineffective in preventing track-derived overland flow from reaching the stream network and the mean modelled volumes reaching the network were quite high (1.177 and 1.897m^3 respectively).

Table 3-1 Probability that a 15m wide buffer zone on a Class 1 drainage line in the near the town of Eden will be exceeded by a flow plume coming off an immediately adjacent track crossbank outlet given various rainfall recurrence and contributing track area scenarios. The results are presented as a probability (%) based on 1000 random samples from the truncated normal distribution of vbt measurements, followed by the mean (± standard deviation) volume of flow (m^3) that is modelled to reach the stream if the buffer is exceeded.

Rainfall recurrence	Dimensions of contributing track area (m)			
	5 x 10	5 x 15	5 x 30	5 x 40
1 in 5-year	0 [0.000 ± 0.000]	0 [0.000 ± 0.001]	1 [0.001 ± 0.008]	2 [0.002 ± 0.018]
1 in 10-year	1 [0.001 ± 0.008]	3 [0.004 ± 0.025]	33 [0.068 ± 0.130]	67 [0.208 ± 0.226]
1 in 20-year	5 [0.006 ± 0.033]	19 [0.033 ± 0.088]	91 [0.442 ± 0.290]	99 [0.887 ± 0.318]
1 in 50-year	21 [0.037 ± 0.094]	64 [0.189 ± 0.216]	100 [1.177 ± 0.319]	100 [1.897 ± 0.319]

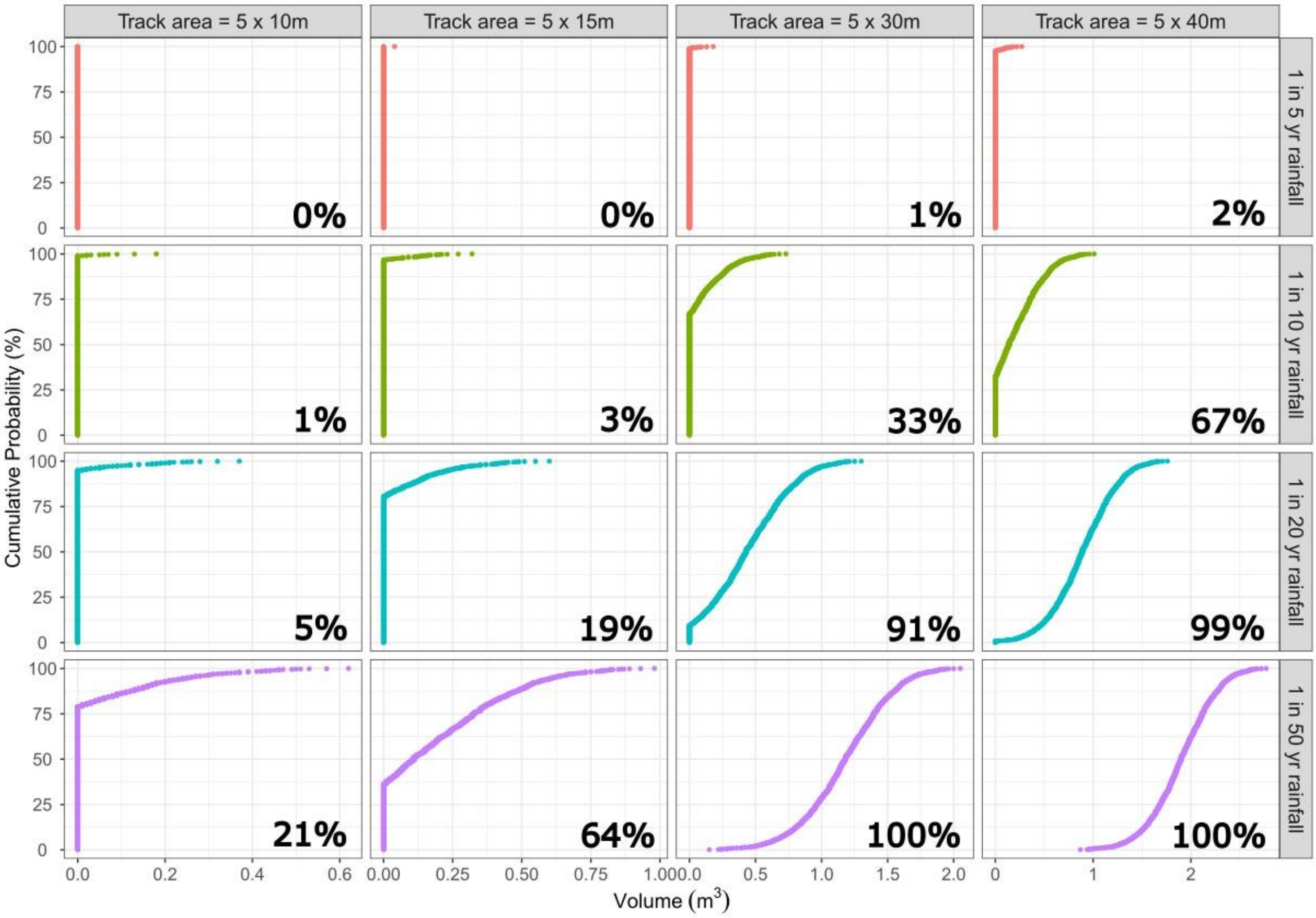

Figure 3-6 Probability of exceedance functions, based on predicted plume lengths and volumes, describing the probability that overland flow from track crossbank outlets adjacent to Class 1 drainage line buffer zones in the Coastal IFOA region near the town of Eden will exceed the buffer zone. The results are presented as the volume (m^3) of water that is predicted to exceed the buffer zone in each scenario. A result of 0.0 m^3 means the buffer zone was not exceeded. The probability that buffer zones will be exceeded in each scenario is printed in bold on each figure. Four different rainfall scenarios are presented with increasing recurrence intervals, and four different scenarios describing increasing crossbank spacings on the contributing track area are presented.

3.5.2 Moderate rainfall setting (Grafton)

The moderate rainfall setting was based around Grafton. The exceedance probability results are presented in Table 3-2 and Figure 3-7. During a 1 in 5-year storm there is a greater than 92% chance that the buffer zone will prevent overland flow connecting between a track crossbank outlet and the stream network if the track crossbanks are spaced 10m or 15m apart, with the mean volume of water predicted to reach the stream network is 0.002 to 0.011m^3. If drains were spaced 30m apart there would be a substantially large probability of exceedance (62%) by a mean volume of 0.182m^3. Finally, if drains were spaced 40m apart there would be a 92% chance that the buffer zone would be exceeded by a mean volume of 0.470m^3.

During a 1 in 10-year storm there is a 92% chance that a buffer zone will prevent connectivity with the stream network where track crossbank outlets are spaced 10m apart. The mean modelled volume exceedance was 0.011m^3. When crossbank outlet spacings are 15m apart, there is a much larger probability of exceedance (31%), with a mean volume predicted to reach the stream network being 0.0.061m^3 in each plume. If crossbanks were spaced 30m or 40m apart there would be essentially ineffective in preventing track derived overland flow reaching the stream network (97 to 100% probability of exceedance) and the mean volume of water reaching the stream is also quite high 0.651 and 1.187m^3.During a 1 in 20-year storm the probability that the buffer zone would prevent connectivity between a track crossbank outlet and the stream network is less than 80% in all crossbanks spacing scenarios. Where crossbanks spacings are 10m apart there is a 22% probability that the buffer zone will be exceeded by a mean volume of 0.039m^3. Where crossbanks spacings are 15m apart there is a 65% probability that the buffer zone would be exceeded by a mean volume of 0.195m^3. If 30m or 40m spacings are allowed between crossbank outlets, the buffer zones are not expected to prevent connectivity and the mean volume of water reaching the stream network is predicted to be 1.207 to 1.937m^3 in each plume.

In the largest storm event modelled (1 in 50-year recurrence) and where the crossbanks spacings are the smallest (10m apart), the probability that the buffer zone would be effective at preventing overland flow reaching the stream network is 48%, with mean exceedance volume being 0.136m^3. Where crossbank spacings were 15m to 40m apart there was a very high probability of exceedance (94 to 100%), by quite large volumes of water 0.516 to 2.977m^3 in each plume.

Table 3-2 Probability that a 15m wide buffer zone on a Class 1 drainage line in the near the town of Grafton will be exceeded by a flow plume coming off an immediately adjacent track crossbank outlet given various rainfall recurrence and contributing track area scenarios. The results are presented as a probability (%) based on 1000 random samples from the truncated normal distribution of vbt measurements, followed by the mean (± standard deviation) volume of flow (m^3) that is modelled to reach the stream if the buffer is exceeded.

Rainfall recurrence	Dimensions of contributing track area (m)			
	5 x 10	5 x 15	5 x 30	5 x 40
1 in 5-year	2 [0.002 ± 0.017]	8 [0.011 ± 0.047]	62 [0.182 ± 0.213]	92 [0.470 ± 0.294]
1 in 10-year	8 [0.011 ± 0.047]	31 [0.061 ± 0.123]	97 [0.651 ± 0.311]	100 [1.187 ± 0.319]
1 in 20-year	22 [0.039 ± 0.097]	65 [0.195 ± 0.220]	100 [1.207 ± 0.319]	100 [1.937 ± 0.319]
1 in 50-year	52 [0.136 ± 0.187]	94 [0.516 ± 0.300]	100 [1.987 ± 0.319]	100 [2.977 ± 0.319]

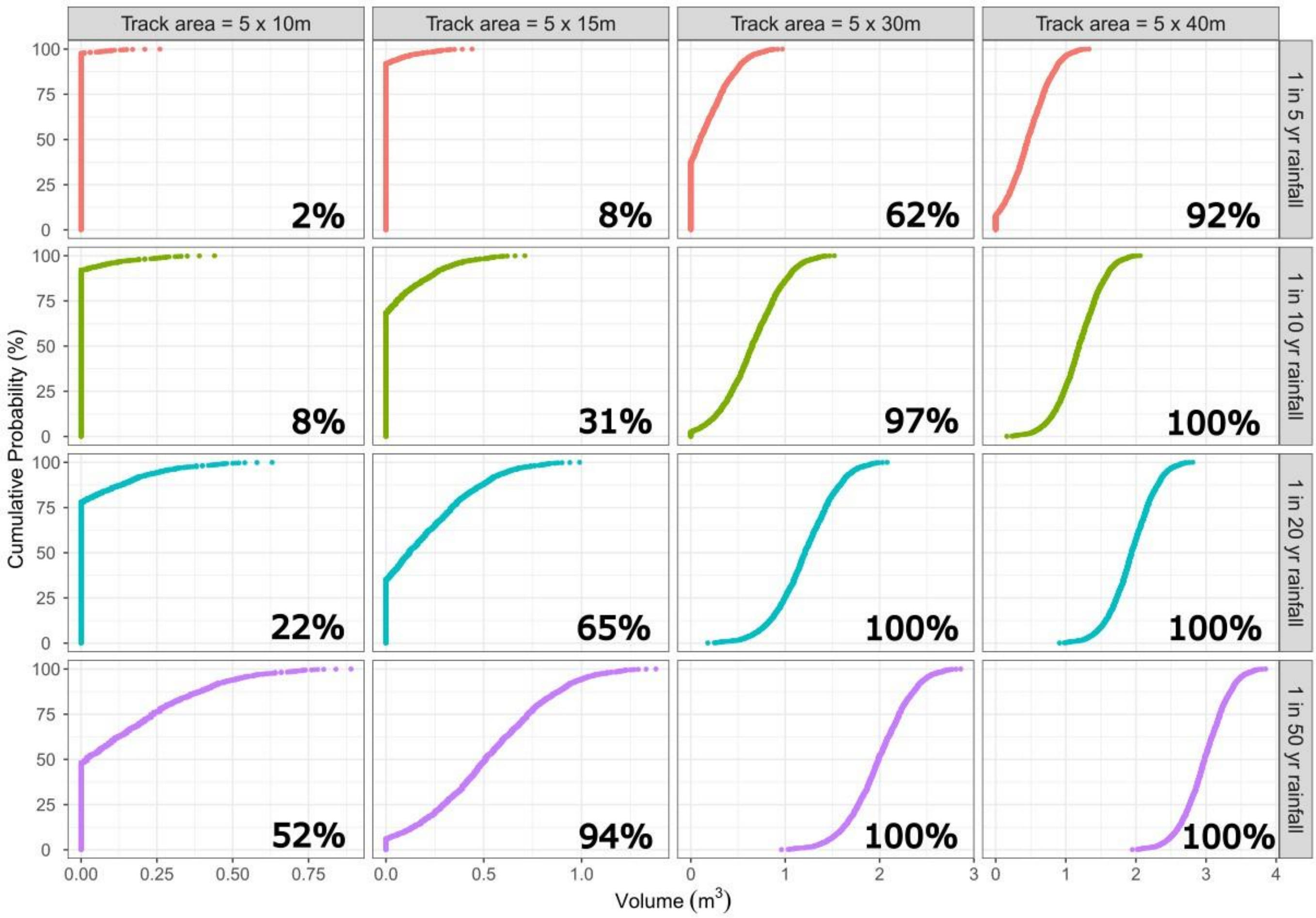

Figure 3-7 Probability of exceedance functions, based on predicted plume lengths and volumes, describing the probability that overland flow originating from track crossbank outlets adjacent to Class 1 drainage line buffer zones in the Coastal IFOA region near the town of Grafton will exceed the buffer zone. The results are presented as the volume (m^3) of water that is predicted to exceed the buffer zone in each scenario. A result of 0.0 m^3 means the buffer zone was not exceeded. The probability that buffer zones will be exceeded in each scenario is printed in bold on each figure. Four different rainfall scenarios are presented with increasing recurrence intervals, and four different scenarios describing increasing crossbank spacings on the contributing track area are presented.

3.5.3 High rainfall setting (Coffs Harbour)

Coffs Harbour was used to represents a high rainfall area within the Coastal IFOA region. The exceedance probability results are presented in Table 3-2 and Figure 3-7. During a 1 in 5-year storm there is an 75% chance that the buffer zone will prevent overland flow connecting between a track crossbank outlet and the stream network if the crossbanks are spaced 10m apart (contributing track area 5 x 10m). In cases where overland flow exceeds the buffer, the mean volume of water predicted to reach the stream network is 0.0.047m^3. If the drains were spaced 15m apart there would be a 70% chance of that the buffer zone would be exceeded by a mean volume of 0.229m^3. If drains were spaced 30m or 40m apart the buffer zone aren't expected to prevent connectivity and the mean volume of water reaching the stream network in each plume is predicted to be very high (1.317 and 2.077m^3 respectively).

During a 1 in 10-year storm there is a less than 36% chance that a buffer zone will prevent connectivity with the stream network under all crossbank spacing scenarios, with the buffers being essentially ineffective where crossbank spacing are 15m or larger. The mean modelled volume reaching the stream network in each plume was between 0.461 and 4.687m^3.

During a 1 in 20-year or 1 in 50-year storm event the buffers are predicted to be largely ineffective under all track spacing scenarios (91 to 100%). Furthermore, the volume of water reaching the stream in each plume is predicted to be quite high, especially where wider crossbank spacings are in place (0.461 to 6.627m^3).

Table 3-3 Probability that a 15m wide buffer zone on a Class 1 drainage line in the near the city of Coffs Harbor will be exceeded by a flow plume coming off an immediately adjacent track crossbank outlet given various rainfall recurrence and contributing track area scenarios. The results are presented as a probability (%) based on 1000 random samples from the truncated normal distribution of vbt measurements, followed by the mean (± standard deviation) volume of flow (m^3) that is modelled to reach the stream if the buffer is exceeded.

Rainfall recurrence	Dimensions of contributing track area (m)			
	5 x 10	5 x 15	5 x 30	5 x 40
1 in 5-year	25 [0.047 ± 0.107]	70 [0.229 ± 0.234]	100 [1.317 ± 0.319]	100 [2.077 ± 0.319]
1 in 10-year	64 [0.189 ± 0.216]	97 [0.651 ± 0.311]	100 [2.267 ± 0.319]	100 [3.347 ± 0.319]
1 in 20-year	91 [0.461 ± 0.293]	100 [1.147 ± 0.319]	100 [3.277 ± 0.319]	100 [4.687 ± 0.319]
1 in 50-year	100 [0.927 ± 0.319]	100 [1.877 ± 0.319]	100 [4.727 ± 0.319]	100 [6.627 ± 0.319]

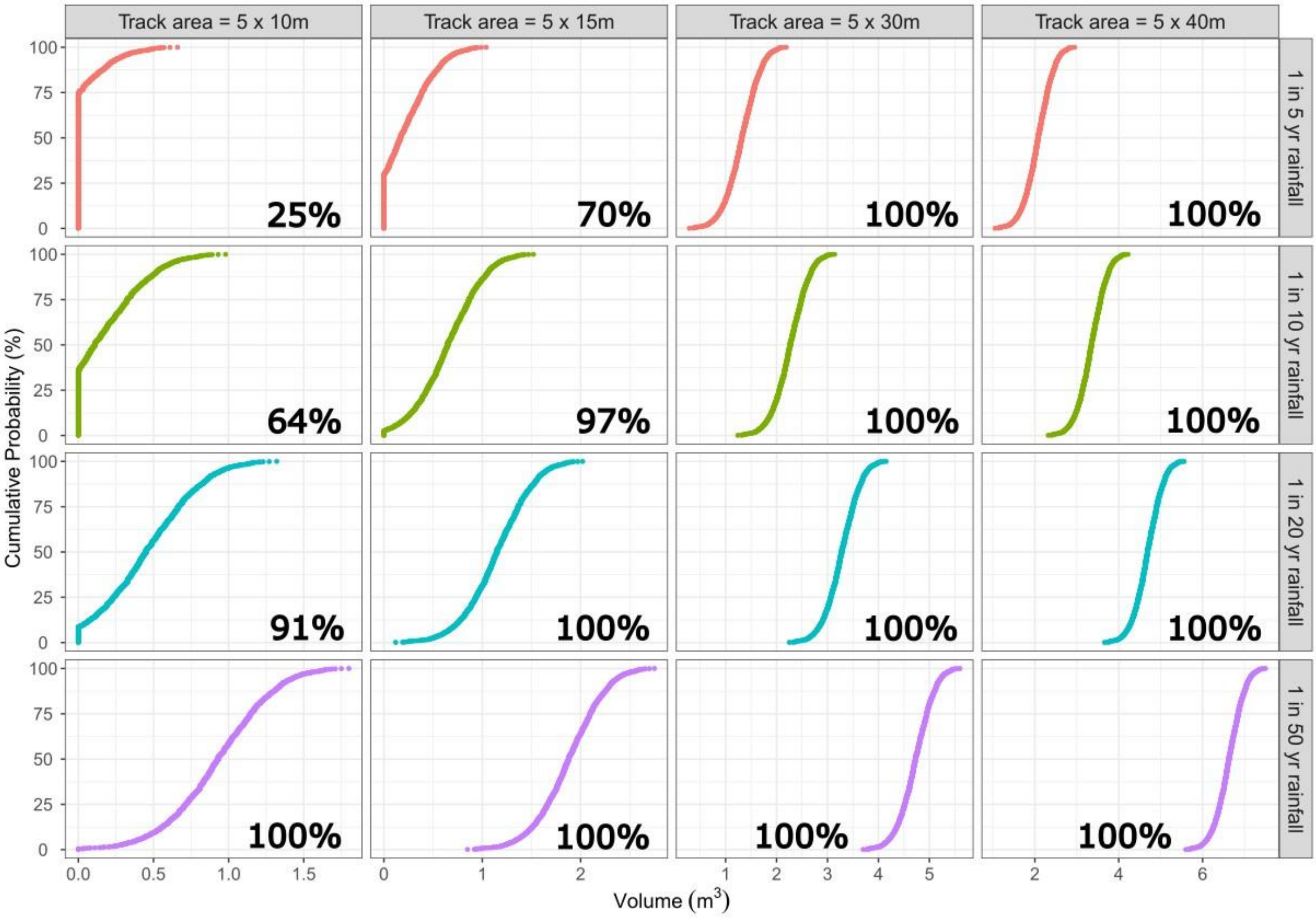

Figure 3-8 Probability of exceedance functions, based on predicted plume lengths and volumes, describing the probability that overland flow from track crossbank outlets adjacent to Class 1 drainage line buffer zones in the Coastal IFOA region near the city of Coffs Harbour will exceed the buffer zone. The results are presented as the volume (m^3) of water that is predicted to exceed the buffer zone in each scenario. A result of 0.0 m^3 means the buffer zone was not exceeded. The probability that buffer zones will be exceeded in each scenario is printed in bold on each figure. Four different rainfall scenarios are presented with increasing recurrence intervals, and four different scenarios describing increasing crossbank spacings on the contributing track area are presented.

4. Discussion

In this study we combined field measurements and modelling to assess the distance overland flow emanating from track crossbank outlets travels through riparian buffer zones bordering Class 1 drainage lines in the Costal IFOA region. In total we collected and analysed 116 data points across 11 forests situated across the northern and southern extents of the region. The dataset is significant in relation to the local and global forestry literature and considered a strong foundation from which to make inferences regarding buffer zone effectiveness. We used the distribution of the results to address two key questions that are pertinent to assessing the effectiveness of exclusion zone conditions/settings in this context: (1) are current buffer zones effectively meeting their objectives and outcomes? and (2) are ground protection zones as effective at preventing surface overland flow as riparian exclusion zones? In addition, we interrogated the data collected to see if overland flow plumes, and subsequently the risk that the exclusion zones settings would not disconnect track derived overland flow from the stream network, correlates with landscape and hillslope variables encountered in this study. We discuss these findings and there interpretation below.

4.1 Are ground protection zones effective at preventing overland flow reaching the stream network at riparian exclusion zones?

We measured *vbt5* at multiple paired GPZ and REZ sites and compared them to see if accessed GPZs are as effective at preventing overland flow reaching the stream network as intact riparian exclusion zones. The results showed that *vbt5* volumes, and thus plume lengths, generated within GPZs are similar to those generated within REZs. In fact, *vbt5* volumes tended to be larger in GPZs meaning plume lengths would be less. While the ability to project the findings over the whole Coastal IFOA is inherently limited by the sample size (6 sites), the results show that that GPZs and REZs have similar capacity to infiltrate overland flow at the study sites.

The result might be considered counterintuitive, given that GPZs are subject to varying degrees of disturbance from machinery access, tree fall, and snigging which act to compact the ground and reduce surface water infiltration (Figure 4-1). However, it was apparent in the field that not all types of disturbance reduce infiltration, and some types of disturbance may act to increases infiltration. For instance, *vbt5* volumes were notably lower (plumes longer) when the flow ran downslope along machinery tracks and drag marks from logs. However, where such tracks were perpendicular to the hillslope (across the contour), they tended to capture the flow and redirect or hold it, allowing more time for infiltration.

Further to this, tree crowns and other slash were often left in the GPZ which in some cases acted to intercept flow and redistribute it in much the same way as intact vegetation and fallen debris would. While we recorded the types of disturbance encountered for each *vbt5* run, insufficient data was collected to make any statistical inferences regarding these results. However, the conclusions conform with common sense and could be considered for additions to best management practices regarding access to GPZs. For example, it could be stated that machinery should access the zone obliquely to avoid creating flow pathways that point directly towards the stream and avoid entering the GPZ while facing directly downslope. A degree of variability in plume length is also expected in intact riparian zones where trees and branches fall naturally, leading to a mosaic of flow pathways with lower and higher infiltration rates relative to the site. This appeared to be reflected in the dataset as variance across the REZ and GPZ sites was similar.

Figure 4-1 Examples of some of the types of ground disturbance observed in ground protection zones including piles of slash, machinery tracks, a berm created by machinery movement, and an impact mark from a fallen tree.

4.2 What landscape and hillslope variables influence plume length?

To better understand the environmental factors influencing *vbt5* volume, and thus buffer zone effectiveness, we explored potential relationships between a range of landscape and hillslope variables. These included vegetation class (as defined in the NSW State Vegetation Type Map), hillslope, bulk density, and mean annual wetness.

Overall, *vbt5* volumes were quite consistent across the Coastal IFOA region, with some notable exceptions. These included sites in Double Duke and Gibberagee State forests where the mean *vbt5* volume was 1278L ± 529L compared 299L ± 225L across all other sites. Each of these sites were within the Coastal Floodplain Wetlands vegetation class and Forested Wetlands vegetation form. They were low lying, swampy sites within the Clarence River and Bungawalbin Creek floodplains and were characterised by sandy soils with relatively low bulk density (0.624 ± 0.026), and low sloping riparian zones (range 2-7°). They were unique among the forest types included in this study which were otherwise dry and wet sclerophyll forests. The observed infiltration rate of these sandy soils was particularly high which, in combination with the flat landscape, were likely key drivers behind the high *vbt5* values. The results indicate that a very large rainfall event would be needed to generate a flow plume that would exceed a 15m buffer zone in such settings. On the other hand, the results suggest that overland flow plume length is expected to be similar across all other vegetation classes investigated.

The consistency in *vbt5* volumes observed elsewhere contributed to a lack of strong relationships between *vbt5* volumes and landscape and hillslope variables which varied substantially over the large study area. The strongest relationship observed was with slope. This negative relationship matched the hypothesised response (*Hypothesis 3*), was statistically significant, and received an R^2 value of -0.29. The result is somewhat at odds with other recent *vbt5* studies that have not found a strong relationship between hillslope and plume length, suggesting that soil and vegetation properties which influence infiltration exert a stronger influence (Lane *et al.* 2006; Nyman *et al.* 2023). However, these studies were focussed on lower order streams that typically occur in steeper valleys where hillslopes were always greater than 10°. Class 1 drainage lines are headwater streams and by nature small water bodies and often have not eroded steep gullies. Consequently, the slope approaching the channel is often quite low (i.e. less than 10°). Where the slope was less than 10° in this study, we observed that the plumes travelled noticeably more slowly, and the flow paths were less defined with the plume tending to diverge and spread out allowing more time for infiltration. A similar effect has been shown on forestry tracks where steeper slopes have been shown to increase the initiation of concentrated flow and gullying at drain outlets (Croke and Mockler 2001).

The trend observed between *vbt5* volume and bulk density was not significant, although the negative trajectory did match expectations (*Hypothesis 4*). Bulk density is associated with the porosity and infiltration rate of soil, so it was expected that more water would be needed to generate an overland flow plume where bulk density is low (more porous) compared to sites where bulk density was high. A stronger relationship between *vbt5* volume and bulk density was observed in a similar study conducted in Victoria, although the results here suggest the utility of bulk density by itself helping to predict the propensity of a landscape to generate overland flow is limited and perhaps dependant on environmental context (Nyman *et al.* 2023). It may also be the case that other factors such as slope may act to uncouple the relationship. This is not uncommon in environmental datasets where a single “master” variable is rarely responsible for an observed response. Rather, multiple factors work in concert.

No significant trend was observed between mean annual wetness and *vbt5*. Soil erosivity and infiltration capacity has been shown to be strongly influenced by the aridity of the landscape (i.e. dryness of the climate at a given location). As such, aridity has been investigated as a determinant of overland flow generation and erosion. For instance, Noske *et al.* (2016) showed that post-bushfire runoff and erosion processes in Eucalypt forests in south-east Australia are highly variable, with the magnitude of response being strongly linked to hillslope aridity. Van der Sant *et al.* (2018) further evaluated the relationship between landscape aridity and post-bushfire runoff. They found that average and peak runoff was significantly correlated with aridity, being two times higher at the most arid site than the least arid site, and peak runoff being up to 1000 times different between those sites. However, each of these studies focussed on recently burnt catchments. In unburnt, undisturbed forests, aridity-driven variation in soil surface hydrology and overland flow generation is expected to be lesser than burnt and disturbed forests as the vegetation stabilises soil, encourages infiltration, and reduces erosion (Cerdà and Doerr 2005; Noske *et al.* 2016). The absence of a relationship here supports this assertion.

In summary, we found that the propensity of riparian buffer zones around Class 1 drainage lines to generate overland flow plumes is remarkably similar across the large Coastal IFOA region. Furthermore, no particularly strong correlation was found between *vbt5* volume and the environmental variables tested. Exceptions such as Coastal Floodplain Wetlands exist where the ability of the landscape to generate overland flow plumes may by substantially more or less than observed on this project. However, given the degree of coverage achieved as part of the field campaign and the consistency of the results, it would appear that those examples are few within the context of typically harvested forest types. This result would imply that the current uniform approach to Class 1 exclusion zone settings in the Coastal IFOA region is warranted.

4.3 Are the exclusion zone conditions (settings) for Class 1 classified drainage lines effective in minimising the impact on waterway condition?

Whether or not an exclusion zone of a given setting is effective in preventing connectivity between a harvest area and the stream network is not a simple yes or no question. The Coastal IFOA does not set a performance metric for buffers zones other than that the conditions are designed to meet the outcomes statement for riparian protection. Buffer zone effectiveness in preventing track derived overland flow reaching the stream network is influenced by within compartment management practices such as the placement and orientation of tracks and the spacing of drainage outlet on tracks, and ultimately the amount of rainfall that is generating overland flow (Croke and Hairsine 2006; Lane *et al.* 2006). Each of these influencing factors vary in space and time, adding complexity to any assessment of exclusion zone setting effectiveness. Research focussed on understanding areas of sediment capture and loss in forestry compartments has identified that overland flow via crossbanks outlets from compacted tracks pose the main risk of connectivity (Wallbrink and Croke 2002). In instances where tracks are orientated downhill towards the exclusion zone or run parallel to stream channels, track-derived overland flow doesn't is effectively directed straight into the buffer zone and the risk that the overland flow plume will reach the stream is directly related to the distance the plume can travel before infiltrating into the ground (Figure 4-3).

With this in mind we used the *vbt5* model of Hairsine *et al.* (2002) to model overland flow plume distances across Class 1 drainage line buffer zones in the Coastal IFOA region and used the distribution of plume lengths to determine the probability that track-derived overland flow from crossbank outlets pointed into the buffer zone would reach the stream network (i.e. the red arrows in Figure 4-2). We investigated plume lengths generated under four storm intensities and four contributing track areas (i.e. the area of track between crossbank outlet) in low, moderate, and high rainfall areas of the Coastal IFOA region. In this way the results provide a framework from which decision makers can assess the adequacy of current buffer zone settings in preventing the ingress of sediment laden overland flow into the stream network.

We do not attempt to set a threshold here that specifies an acceptable probability that current buffer settings will prevent connectivity. Such a value needs to be derived following robust discussion between forestry stakeholders, using these results as context. Discussions regarding an acceptable threshold should consider that these results represent the performance of current buffer zones under a high-risk scenario, that is, when a snig-track or boundary track crossbank discharges directly into the buffer zone during a high rainfall event. This scenario perhaps most often occurs on tracks that lead to stream crossings or those that follow the boundary of the harvest areas, running parallel to drainage lines.

The results show the substantial impact that storm intensity and contributing track area have on exclusion zone setting effectiveness, as well as regional rainfall patterns. In low rainfall areas current exclusion zone settings have a moderate to high probability of effectively preventing overland flow connectivity (> 80% probability) given a range of crossbank spacings and rainfall event magnitudes (up to 1 in 20-year rainfall event). In moderate rainfall regions a moderate probability of effectiveness (>78% probability) is achieved where 10m crossbank spacings are implemented during 1 in 5 to 1 in 20-year rainfall events. However, in high rainfall areas the probability that the current exclusion zone settings will effectively prevent connectivity is very low, being ≤75% in all scenarios and largely ineffective where crossbank spacings were 15m or greater. These results show the degree to which crossbank spacings can improve buffer zone effectiveness, and the limits of the mechanisms influence. It is clear that minimising crossbanks spacings on tracks that approach the buffer zone is critical to maximising the effectiveness of the buffers in preventing overland flow reaching the stream network. While implementing 10m spaced crossbank outlet on all tracks regardless of slope may be difficult, these narrow spacings would only be necessary where tracks are in close proximity to the buffer zone (unless the track is particularly steep). For example, a best management practice could be put in place advising that when a track is within so many metres of the riparian buffer zone, 10m crossbank spacings should be implemented.

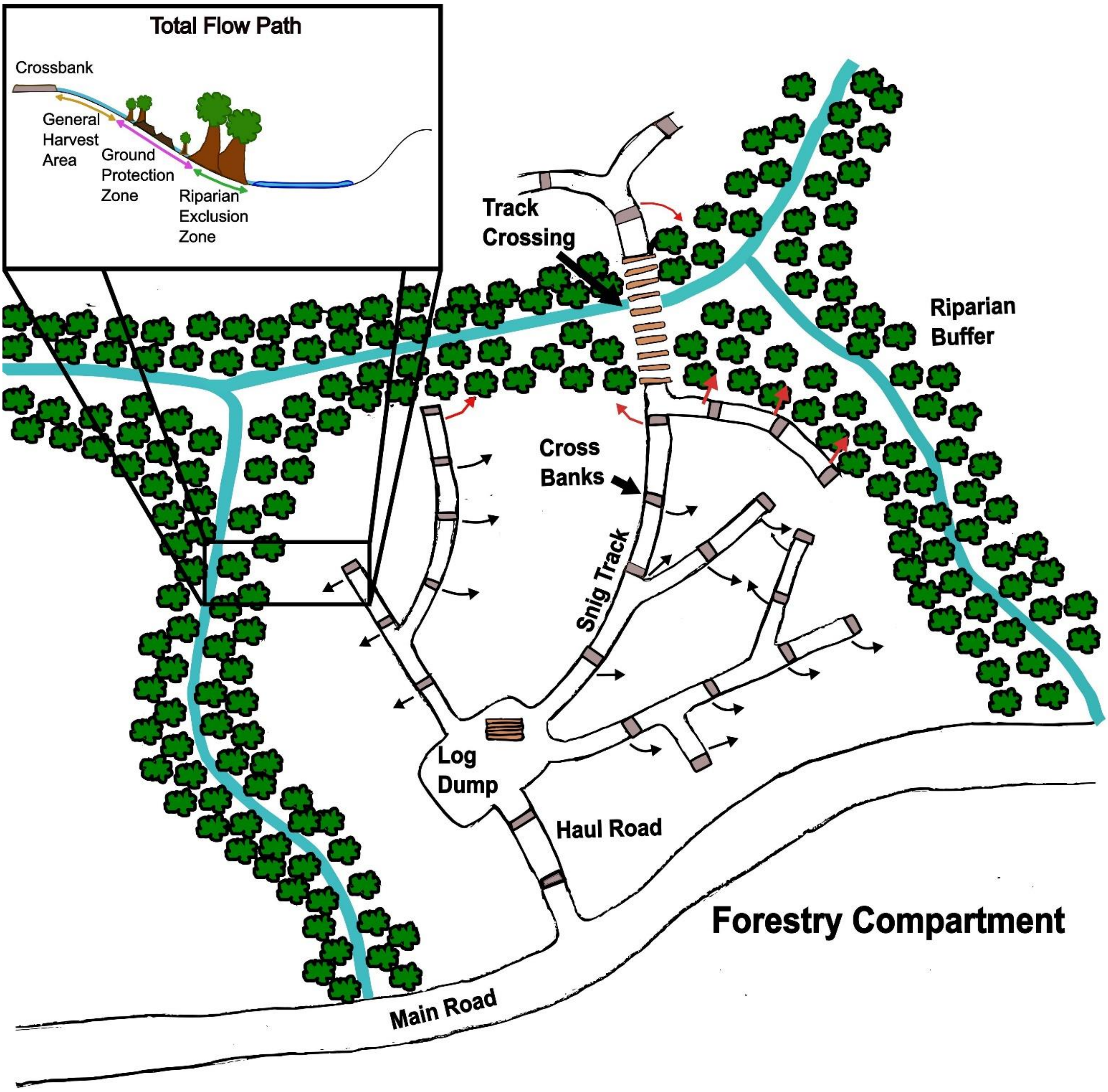

Figure 4-2 A schematic showing features potentially present in the harvest area of forestry compartments in the NSW Coastal IFOA region and areas of overland flow generation on tracks. The narrow arrows indicate overland flow generation at crossbanks on tracks (where most overland flow is generated within the compartment), with red arrows indicating high risk areas where overland flow is most likely to connect with the stream network, specifically where tracks approach the riparian buffer zone. The inset image shows the elements of the total flow path that runoff from the crossbank travels through before reaching the stream network.

Under the assumption that 10m track crossbank spacings are the shortest that can be practically implemented on tracks, in moderate to high rainfall regions (e.g. Coffs Harbour) current buffer zones are only effective 36% of the time during 1 in 10 year rainfall events or less. To further improve exclusion zone setting effectiveness, other management mechanisms would need to be adjusted or implemented, such as increasing the distance between the track crossbank outlets and the stream network. This would be most easily achieved by establishing a minimum distance between crossbank outlets and the buffer zone, thus increasing the total flow path of the overland flow plume, to allow for further infiltration in the general harvest area (see Figure 4-2 inset). In support of this, volume to breakthrough experiments run in the general harvest area by Hairsine *et al.* (2002) yielded very similar *vbt5* results to those recorded here in the riparian buffer zone (mean 336L ± 189L compared to 299L ± 225L here, omitting Coastal Forested Wetlands), indicating that the general harvest area between the crossbank outlet and the buffer would have a similar infiltration capacity to the riparian buffer zone. Complimentary practices, such as adding large woody debris (e.g. tree crowns or root balls) to Class 1 drainage lines in recently harvested compartments, could also be implemented to aid in sediment capture and storage (Walsh *et al.* 2020).

Assuming a 15m wide buffer is in place, this dataset can be used to guide what additional distance is needed between the crossbank outlet and the buffer to achieve an agreed upon probability of success. By way of example, Figure 4-3 shows that in a compartment with 10m spacings between crossbanks, a total flow path distance of 18m is needed to capture overland flow 85% of the time during a 1 in 10-year rainfall event (based on our dataset). Accounting for the 15m buffer, the track crossbank outlets should exit no closer that 3m to the buffer to allow the full 18m of slope for infiltration. Similar calculations could be made for any scenario or probability threshold once the desired management framework is decided upon. We note that any such inferences should account to the limitations of the dataset as outlined in Section 4.4.

Most often tracks already end many metres before the buffer zone, although there are no rules around where a track should end in relation to the zone in the Coastal IFOA and the typical distance they lie from it is unknown. It follows that it may be necessary to establish rules that ensure an appropriate distance is kept to reduce connectivity risk where the risk is unacceptably high (e.g. where regional rainfall volumes are high). It is acknowledged that any change in the Coastal IFOA conditions or protocols is not an insignificant step to take and that the distribution of connectivity risk is not yet fully understood (i.e. does the risk warrant a change in the conditions or protocols?). To this point, the interpretation of findings would benefit from a better understanding of how close tracks typically approach riparian buffer zones in the Coastal IFOA. Such information could be gathered by investigating harvesting machinery tracking data and satellite imagery, or perhaps through Drone or LiDAR surveys. This information would enable a reassessment of the probability that the buffer would be exceeded by track derived flow if the crossbanks are typically situated, say 10m away from the buffer. We note that the reassessment could be easily done using this dataset. Alternately, a detailed description of the distribution of modelled plume lengths across the Coastal IFOA region (which vary with regional rainfall) would describe what total flow path lengths are needed to ensure, say 80% of plumes do not connect with the stream network if crossbanks are spaced say, 15m apart. The results could be used to establish a regionally specific minimum distance between crossbanks and buffer zones. This would be a simpler approach that would provide an understanding of what distance is needed between the crossbanks and the buffer zones to adequately reduce connectivity risk regardless of what is currently being done, and the analysis could be done using this dataset. The information gain from either approach would facilitate the integration of the concept of the "total flow path distance" into the assessment of exclusion zone setting effectiveness broadening the applicability of the results by moving the focus away from the worst-case scenario approach taken here.

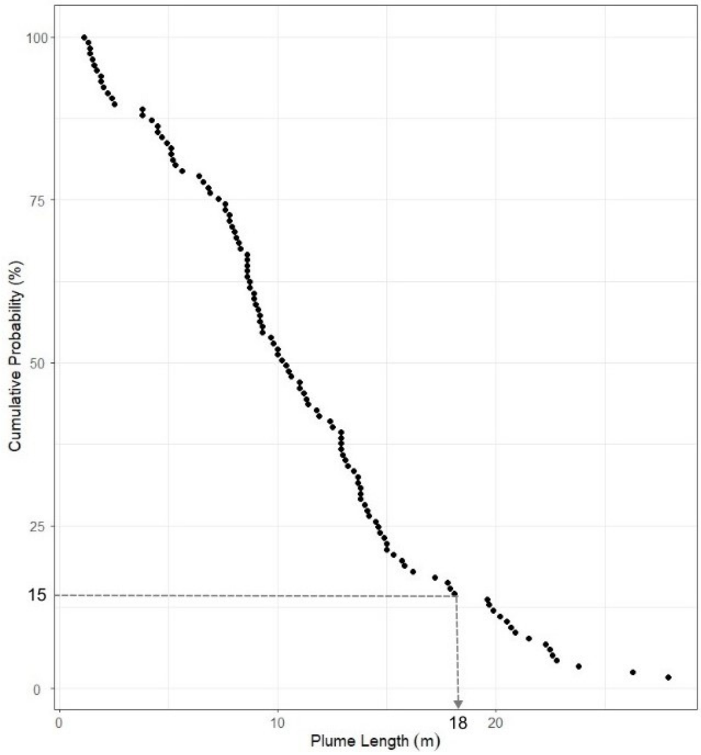

Figure 4-3 A probability of exceedance function describing the probability that overland flow from track crossbank outlets adjacent to Class 1 drainage line buffer zones in the Coastal IFOA region will travel a certain distance. In this scenario (1 in 10-year rainfall event and 10 m spacing between crossbanks), there is a 100% probability that a plume will travel at least 1.1m and a 1.7% probability it will travel 27.9m. The grey dashed line indicates that a total flow path length of 18m would be needed to prevent a runoff plume reaching the stream network 85% of the time.

4.4 Limitations and considerations regarding the method and dataset

The method used to collect this data (rainfall/overland flow simulation using a tanker hose) has in recent years been criticised as they fail to address the natural variability in rainfall intensities (Dunkerley 2021a, 2021b). The 'intensity profile' of rainfall refers to peaks in rainfall intensity, rate of change of rainfall intensity, and rainfall intermittency over the course of an event. Dunkerley (2021a) suggests that when using rainfall simulation to explore and understand infiltration, overland flow, soil detachment, and other important land surface processes, it is desirable to reproduce the intensity profile of rainfall in a way that corresponds as closely as possible with the characteristics of natural rainfall in each particular study location. However, most rainfall/ overland flow simulation studies to date, including this one, have applied fixed rates to their simulations rather than variable ones. This is due at least in part to a general lack of understanding of regionally specific rainfall intensity profiles and the difficulty of simulating those profiles in the field, which requires bespoke equipment.

With this in mind, constant rainfall intensities have been shown to result in lower rates of overland flow, and lower peak overland flow rates, than variable intensity rainfall with the same mean intensity. This is likely because overland flow is typically shallower and slower in constant-intensity rain than in variable-intensity rain (Mutchler and Hansen 1970; Dunkerley 2021a). In the context of this study, this implies that the results are more likely an underestimate of overland flow volume and plume length and the probability of effectiveness should be a considered conservative estimate. None the less, we recognise limitations of using fixed flows in our study and note that describing and analysing the intensity profile of rainfall and its relevance to overland flow processes offers scope for development of the analytical methods applied. We suggest that any such work should attempt to compare constant flow rate results against the variable rate results as a starting point.

It is also important to reiterate is that due to difficulties finding appropriate study sites, the comparison between GPZs and REZs is based on a limited number of measurements and a limited number of sites that mostly lie around the central coast of NSW. On this point we note the following:

- the power analysis indicated that there were sufficient replicates to detect significant differences in *vbt5* values between GPZs and REZs based on the effect size estimated from our dataset,
- our broader analysis of *vbt5* values across the region indicated that harvested forests have similar hydraulic properties (i.e. the *vbt5*s belong to the same normal distribution) so there isn't an expectation that the different environmental conditions experienced in other parts of the Coastal IFOA would lead to different *vbt5* values in GPZs, which implies our results are representative of the region,
- each of the GPZ sites had been harvested in the last five months meaning that they provide a true representation of the disturbance expected (little regeneration had taken place).

These points suggest that the dataset and the findings provide reasonable insight into the second study question. That said, a more representative sampling of the Coastal IFOA region would provide greater confidence in the results and more replicates and sites would better capture the variability in *vbt5* values related to impact type and severity in GPZs. With this in mind we refrain from making definitive conclusions regarding the second study question. Rather we interpret the results as having not provided evidence that GPZs and REZs exhibit differing capacity to capture overland flow and the sediment it carries. That is to say, we did not find evidence that the GPZ setting in Coastal IFOA buffer zones influences the risk of sediment being transported into streams based on the assessment framework presented in this report. The veracity of the results would benefit greatly from additional fieldwork. However, we recommend that any further investigations into the impact of GPZ settings on runoff connectivity risk (or similar processes) should be contextualised by an investigation into the frequency of GPZs access and how this is distributed across the Coastal IFOA. This would aid in study design and it will provide an understanding of the magnitude of the risk that accessed GPZs *may* pose stream health, thus providing a gauge by research funding for the topic could be prioritised.

Finally, an important consideration when interpretating the results is that the *vbt5* data underlying the exceedance probability estimates represent individual plumes emanating from high-risk crossbank outlets (i.e. track crossbanks pointed into the buffer zone), although the number and distribution of these crossbanks is unknown so the overall impact that buffer exceedance has on the stream network is not quantifiable. This poses a limitation to the interpretation of the findings. As discussed above it is possible to overcome this issue through an analysis of satellite imagery and or drone or LiDAR data to determine forestry areas with more or less of these high-risk areas. This would add important context to the results and would allow for more nuance in the management response.

4.5 Conclusions and recommendations

This study achieved its stated aims, albeit the primary study question was answered with greater confidence than the second. Overall, the results present a robust assessment of the effectiveness of the current exclusion zone conditions (settings) in preventing the ingress of sediment into streams. The methods employed are repeatable and can be built upon to broaden the applicability of the results across other regions or to further investigate questions around overland flow and sediment delivery risk.

The limited size of the GPZ/REZ comparison dataset meant that definitive conclusions regarding differences in the effectiveness of the two settings in capturing sediment laden overland flow were not possible. Based on the dataset though, no evidence was found indicating that they perform the function differently. As such, no evidence was found to suggest that the buffer zones prescribed in the current exclusion zone settings are inadequate in that respect. Regardless, suggested best management practices on access could be considered to mitigate the effect of machinery compaction on overland flow generation in the GPZ. Furthermore, the results indicated that the propensity for forests in the Coastal IFOA region to generate overland flow is similar across the region. With few exceptions, the landscape and hillslope factors investigated had little impact on overland flow distance. The slope of the riparian buffer zone appears to influence plume length, although the relationship is too weak to accurately predict connectivity risk. It is therefore recommended that it be treated as part of the natural heterogeneity of the region.

Coastal Forested Wetlands appear to have particularly high infiltration rates compared to other forest types and overland flow generation is very low. However, this type of forest is uncommon in the context of the Coastal IFOA being largely confined to floodplains which contain significant areas of high conservations status vegetation communities that are not managed for harvesting. As such, tailored management settings are unlikely to be warranted. Finally, the results made clear the degree to which exclusion zone setting effectiveness is dependent on (1) the total flow path distance between track crossbank outlets and the stream network, (2) the distance between track crossbanks, and (3) the magnitude of the rainfall event causing overland flow. Both the distance between crossbanks and distance of the flow path between the crossbank outlet and the stream network can be altered to achieve a desired probability of effectiveness.

For optimal reduction of hydrological connectivity we recommend that (1) close spacing of cross banks should be implemented in high-risk scenarios where tracks or boundary tracks drain close to the buffer zone (e.g. Figure 4-2), (2) a management scenario should be decided upon to manage for (i.e. what rainfall event, what track spacing will be implemented, and what probability of effectiveness is acceptable), (3) the total length of the flow path between the crossbank outlet and the stream network should be increased to achieve the desired probability of effectiveness base on this management scenario, and (4) the necessary flow path length should be region specific to account for substantial differences in regional rainfall volumes and risk of connectivity. Increasing the total flow path could be effectively done by leaving an appropriate distance between the crossbank outlets and the buffer zone.

5. References

Alluvium (2020a). Evaluating forest road networks to protect water quality in NSW (Issue September).

Alluvium (2020b). Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests. Report for the Natural Resources Commission.

Cerdà A, Doerr SH (2005). Influence of vegetation recovery on soil hydrology and erodibility following fire: an 11-year investigation. International Journal of Wildland Fire, 14(4), 423-437.

Cohen, J (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Lawrence Erlbaum

Croke J, Hairsine P, Fogarty P (1999). Sediment transport, redistribution and storage on logged forest hillslopes in south‐eastern Australia. Hydrological Processes, 13(17), 2705-2720.

Croke JC, Hairsine PB (2006). Sediment delivery in managed forests: a review. Environmental Reviews 14, 59–87.

Croke J, Mockler S (2001). Gully initiation and road‐to‐stream linkage in a forested catchment, southeastern Australia. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 26(2), 205-217.FPA, 2020

Dunkerley DL (2021a). The importance of incorporating rain intensity profiles in rainfall simulation studies of infiltration, runoff production, soil erosion, and related landsurface processes. Journal of Hydrology, 603, 126834.

Dunkerley DL (2021b). Light and low-intensity rainfalls: A review of their classification, occurrence, and importance in landsurface, ecological and environmental processes. Earth-Science Reviews, 214, 103529.

FPA (2020) *Forest Practice Code*. Forest Practices Authority, Hobart.

Grundy MJ, Rossel RV, Searle RD, Wilson PL, Chen C, Gregory LJ (2015). Soil and landscape grid of Australia. Soil Research, 53(8), 835–844.

Hairsine PB, Croke JC, Mathews H, Fogarty P, Mockler SP (2002). Modelling plumes of overland flow from logging tracks. Hydrological Processes 16, 2311–2327.

Inbar A, Nyman P, Lane PN, Sheridan GJ (2020). The role of fire in the coevolution of soils and temperate forests. Water Resources Research 56(8): e2019WR026005.

Jacobs (2023a). Proposed approach to the assessment of the impact of class 1 drainage line exclusion zones on the ingress of sediment to streams. Report to the Natural Resources Commission.

Jacobs (2023b). Assessment of the impact of Class 1 drainage lines exclusion zones on the ingress of sediment to streams: a description of methods. Report to the Natural Resources Commission.

Lane PNJ, Hairsine PB, Croke JC, Takken I (2006). Quantifying diffuse pathways for overland flow between the roads and streams of the Mountain Ash forests of central Victoria Australia. Hydrological Processes: An International Journal 20, 1875–1884.

Mutchler CK, Hansen LM (1970). Splash of a waterdrop at terminal velocity. Science, 169(3952), 1311–1312.

New South Wales Office of Environment and Heritage (2017). The NSW state vegetation type map: methodology for a regional scale map of NSW plant community types. Sydney, Australia: NSW OEH.

New South Wales Department of Planning and Environment (2023), NSW Aridity Index - High resolution (30 meter), accessed from The Sharing and Enabling Environmental Data Portal [https://datasets.seed.nsw.gov.au/dataset/d7052ea2-e207-4b06-aeb5-565d657e107d], date accessed 2023-10-17.]

New South Wales Environmental Protection Agency (NSWEPA) (2020) Coastal IFOA Guidance – Track Drainage Space Guidance. Parramatta, Australia: NSW EPA.

New South Wales Environmental Protection Agency (NSWEPA) (2023) Coastal Integrated Forestry Operations Approval – Protocols. Parramatta, Australia: NSW EPA.

Noske PJ, Nyman P, Lane PNJ, Sheridan GJ (2016). Effects of aridity in controlling the magnitude of runoff and erosion after wildfire. Water Resources Research 52, 4338–4357.

Nyman P (2009) The effectiveness of the 2007 Salvage Harvesting Prescriptions in addressing the risk of pollutant delivery to streams. Report to the Department of Sustainability and the Environment. Department of Forest and Ecosystem Science, The University of Melbourne.

Nyman P, Sheridan GJ, Smith HG, Lane PN (2014). Modeling the effects of surface storage, macropore flow and water repellency on infiltration after wildfire. Journal of Hydrology. 513, 301-313.

Nyman P, Shelley JJ, Raadik TA, Lyon JP, Noske PJ, Lane PNJ, Freeman M, and Fitzpatrick B (2023). Optimising timber harvesting buffer widths to benefit the timber industry and the aquatic environment – Data Report. Arthur Rylah Institute for Environmental Research Technical Report Series. Department of Environment, Land, Water and Planning. Heidelberg, Victoria.

Parkyn S (2004). Review of riparian buffer zone effectiveness. Ministry of Agriculture and Forestry Wellington, New Zealand.

Shelley JJ, Freeman M, Raadik TA, Lyon JP, Nyman P, Noske PJ, Lane PNJ, Garnick S, and Fitzpatrick B (2023). A review of literature relevant to buffer width prescriptions in southeast Australia: Managing the risk of forestry derived sediment impacts on aquatic communities. Arthur Rylah Institute for Environmental Research Technical Report Series. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Sheridan GJ, Lane PNJ, Noske PJ (2007). Quantification of hillslope runoff and erosion processes before and after wildfire in a wet Eucalyptus forest. Journal of Hydrology 343, 12–28.

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

Stutter M, Kronvang B, Ó Huallacháin D, Rozemeijer J (2019). Current insights into the effectiveness of riparian management, attainment of multiple benefits, and potential technical enhancements. Journal of Environmental Quality 48, 236–247.

Takken I, Croke J, Lane P (2008). A methodology to assess the delivery of road runoff in forestry environments. Hydrological Processes: An International Journal 22, 254–264.

Viscarra Rossel RV, Chen C, Grundy M, Searle R, Clifford D, Odgers N, Holmes K, Griffin T, Liddicoat C, Kidd D (2014): Soil and Landscape Grid National Soil Attribute Maps - Bulk Density - Whole Earth (3" resolution) - Release 1. v6. CSIRO. Data Collection. Bioregional Assessment Programme 2013.

Wallbrink PJ, Croke J (2002). A combined rainfall simulator and tracer approach to assess the role of Best Management Practices in minimising sediment redistribution and loss in forests after harvesting. Forest ecology and management, 170(1-3), 217–232.

Walsh P, Jakeman A, Thompson C (2020) Modelling headwater channel response and suspended sediment yield to in-channel large wood using the Caesar-Lisflood landscape evolution model. Geomorphology 363:107209.

Appendix A. Images of ground protection zones sites

Camira GPZ



Bagawa GPZ



Orara East 1 GPZ



Bulls Ground 1 GPZ



Bulls Ground 3 GPZ

Bulls Ground 4 GPZ