Assessment of the impact of Class 1 drainage line exclusion zone settings on the ingress of sediment to stream

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Key Points

- The maintenance of riparian buffer zones is a critical forest harvesting measure that helps capture runoff before it reaches the stream network, so any changes in buffer zone rules/settings must be assessed to ensure they still perform this function.
- We developed an assessment framework that considers the importance of drain spacings on tracks, rainfall intensity, and regional rainfall patterns in determining the effectiveness of riparian buffer zones in capturing runoff.
- The most practical and effective measure for reducing the risk of runoff connecting between forest harvesting compartments and the stream network is maintaining sufficient distance between high-risk runoff areas (e.g. track drains) and the stream.

Abstract

Recent changes in the regulatory settings for forestry operations on State Forest and Crown timber land in eastern NSW included changes in riparian buffer zone protections around Class 1 drainage lines. The Natural Resources Commission (NRC) instigated a monitoring program to assess the effectiveness of the settings in minimising the ingress of sediment-laden runoff into the stream network. This project was undertaken to design and implement a repeatable and scientifically valid monitoring program to address this need.

We used the volume-to-breakthrough (vbt) model of Hairsine *et al.* (2002) to make inferences about the distance that runoff draining from forestry 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 5 metres downslope from the discharge point, accounting for infiltration. To measure the *vbt5* we pumped water from a water cart and released it in riparian buffer zones across eastern NSW to simulate forestry track discharge during a rainfall event.

The assessment made clear the degree to which rainfall intensity and snig track crossbank outlet (i.e. track drain) spacings influence the probability that buffer zones would be exceeded. Where snig track crossbank outlets are widely spaced (> 30m) current buffer zones are largely inadequate regardless of the magnitude of rainfall events. Where crossbank outlets are closer together, buffer zone effectiveness improves dramatically. The results provide a framework for assessing how effective buffer zones are at achieving the function of capturing sediment-laden runoff.

Keywords

Volume to breakthrough, runoff, snig track, forestry, crossbank, drainage outlet, zero order stream, headwater stream

Introduction

In forestry compartments, harvested slopes and associated infrastructure such as roads and snig tracks can present significant sources of erosion that may lead to sediment transport into streams following rain (Croke *et al.*, 1999; Wallbrink & 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 surface runoff 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 along waterways, design measures and drainage for roads, 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 riparian buffer zones along and around waterways where harvesting is excluded has historically received significant research attention (see reviews in Alluvium, 2020b and Shelley *et al.*, 2023). At least 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 runoff between the areas of disturbance and the stream network (Parkyn, 2004; Croke & Hairsine, 2006; Stutter *et al.*, 2019). That said, minimising the ingress of sediment-laden surface runoff into the stream network is generally the key consideration when establishing riparian buffer zone settings.

Over roughly the last two decades, studies of the capacity of buffer zones to capture and infiltrate surface runoff conducted in Victoria have often taken a combined field measurement and predictive modelling approach. These studies focussed on the risk posed by drain discharge from roads and tracks. Field-based experiments are conducted that simulated crossbank discharge into buffer zones and the resulting data is used in hydrological models that describe the distance that an overland 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 runoff 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 in Victoria based on this modelling output that is directly relevant to this study question. These experiments leverage the considerable body of forestry research that exists, describing the main sources and drivers of erosion and runoff in south-eastern Australian forests, in particular (1) the influence of rainfall magnitude; (2) the main sources of erosion and runoff in forestry compartments; and (3) 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 surface runoff from the stream network in NSW where environmental context can differ substantially to Victoria. 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 currently buffer zone settings in the Coastal IFOA in reducing sediment connectivity between forestry compartments and the stream network.

Methods

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 snig track, boundary track, or road) to a waterway. The higher the connectivity, the higher the likelihood of sediment delivery to a stream. In this study we combined field measurements and modelling to assess the probability of connectivity across different Coastal IFOA regions and use that information to evaluate the effectiveness of current buffer zones settings around Class 1 drainage lines in preventing the ingress of sediment carrying runoff into the stream network.

The volume-to-breakthrough (vbt) experiment simulates the movement of surface runoff from a point source (e.g. the snig track drain) through riparian buffer zones. The method assumes that the point source discharge is being directed straight into the buffer zone, which can occur on snig tracks that run down the hillslope to the buffer zone or run parallel to the buffer zone along the compartment boundary, and/or boundary tracks (tracks bordering the harvest compartment 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.

The experimental approach is based on the concept of volume to breakthrough. The vbt is the volume of runoff 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 exclusion zone performance. As a metric of connectivity, 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).

Study sites

The following sites selection criteria were adhered to in order to ensure they fit with the objectives of the study:

- Sites must be on Class 1 drainages as classified by lidar 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 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 and must have been harvested in the last 12 months.

In total we conducted vbt experiments at 30 sites across 12 harvest plan areas within the Coastal IFOA region between 11 July 2023 and the 28 July 2023 (Figure 1). The sites effectively spanned the full longitudinal breadth of the study region and represented a wide range of forest types from coastal, hinterland, and tableland areas.

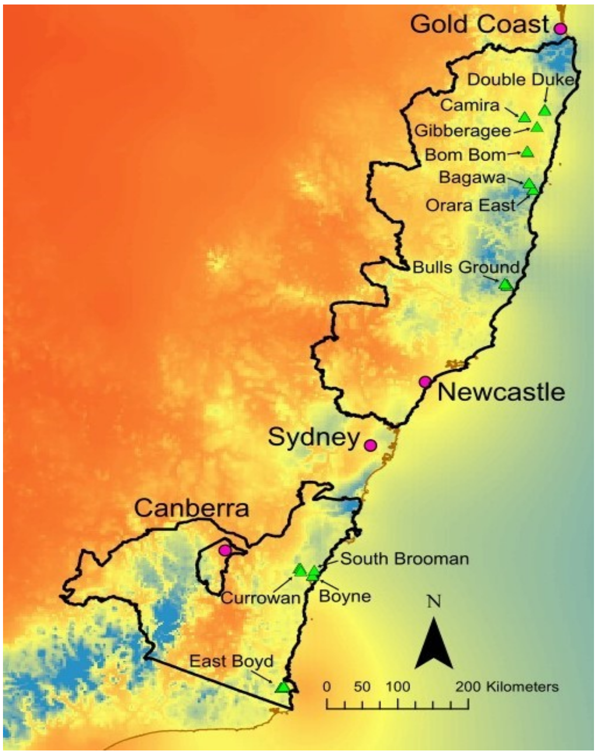

Figure 1 Map of the Coastal IFOA region (outlined in black) on the NSW coast. Study sites visited as part of this project are indicated by green triangles. The names of each forestry planning region are given as well as major cities. The heat map represents mean annual wetness across the region with blues indicating wetter areas and yellows and oranges indicating less wet areas.

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 method was applied to obtain the *vbt5* metric. The *vbt5* metric is the volume of water absorbed when the plume reaches 5 metres 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. This rate is representative of culvert discharges measured in large storm events in forest environments (Sheridan & Noske, 2007) 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), in which runoff was generated on snig tracks so that discharge rates varied through time. The discharge rate was selected to mimic the type of runoff conditions expected at an outlet/drain following a 1 in 10-year 30 min storm event on a 5m wide and 15m long segment of snig 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 diffuse overland flow that is typical of snig track drainage. A measuring tape was used to mark the 5m point downslope from the discharge point.

Runoff plume modelling

In order to quantify the degree of connectivity expected between snig track drains 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 runoff reaching the stream by diffuse overland flow from a drain outlet. It estimates both the volume of flow that reaches a given point (e.g. 15m from the drain) and the maximum distance the plume would travel before complete infiltration. The model integrates volume-to-breakthrough measurements which describe the volume of runoff that enters an area before discharge is observed at the downslope boundary of that area.

Firstly, the volume of runoff that discharges into the drain, V_{in} (m^3), is calculated as per Equation 1. In this equation *CA* is the contributing snig 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 snig track area and rainfall scenarios to assess buffer zone performance under low to high-risk scenarios and to provide insight into how reducing drainage spacing can reduce discharge from drains and ultimately plume lengths. These scenarios are described in the sections below. The *I* parameter was set at 30 mm h^{-1} based on the mean apparent infiltration rate of snig tracks measured by Croke *et al.* (1999) during field-based rainfall simulator experiments. The *t* parameter was set to reflect 30-min rainfall events.

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

Once the volume exiting the snig track drain 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 drain to the stream and *vbt5* is the volume of breakthrough measured for a 5 m long hillslope segment (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.

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

Initial investigations of the *vbt5* results indicated that they were likely part of the same distribution (with an exception discussed in Results section) 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 not be negative) and modelled the volume of flow exceeding a 15m buffer zone based on 1000 random samples taken from that distribution.

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}.from the 15m buffer zone (x):

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

Finally, to investigate what exclusion zone setting widths would be required to reduce the probability of connectivity with adjacent streams to less than 10% (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 *vbt5* measurement, using the approach of Hairsine *et al.* (2002):

$$l_{pred} = 5\frac{V_{out}}{vbt5} \qquad \text{Equation 4}$$

Model scenarios

The V_{in} model (Equation 1) was used to assess buffer zone effectiveness given (1) rainfall events of varying intensity, and (2) variable drainage spacings on snig tracks as permitted under Coastal IFOA protocols.

Rainfall

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

Contributing snig track area (area between drains)

We chose contributing track area scenarios that encompass the maximum drainage spacings allowed on tracks between 15° (contributing area = 40m x 5m) and 30° (contributing area = 15m x 5m) slope in the Coastal IFOA area. These were commonly encountered around Class 1 drainage lines. In addition, we investigated discharge on 10m x 5m to assess how further reducing drainage spacings may decrease the amount of runoff surpassing 15m buffers. 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)

Results

In total 116 *vbt5* experiments were run across 11 forests situated between the northern and southern extent of the Coastal IFOA region. The *vbt5* volumes ranged between 82L and 1321L, with the mean being 299L. 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 snig track crossbank outlets/drains, 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 and high annual rainfall volumes relative to the region. This can also be viewed as the probability that the buffer zones will be effective in preventing track derived runoff from reaching the stream network. We investigated the probability of exceedance under four rainfall scenarios and four contributing snig track area scenarios as detailed above. In total 1000 modelled plume lengths were used in the analysis.

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 Figure 5.

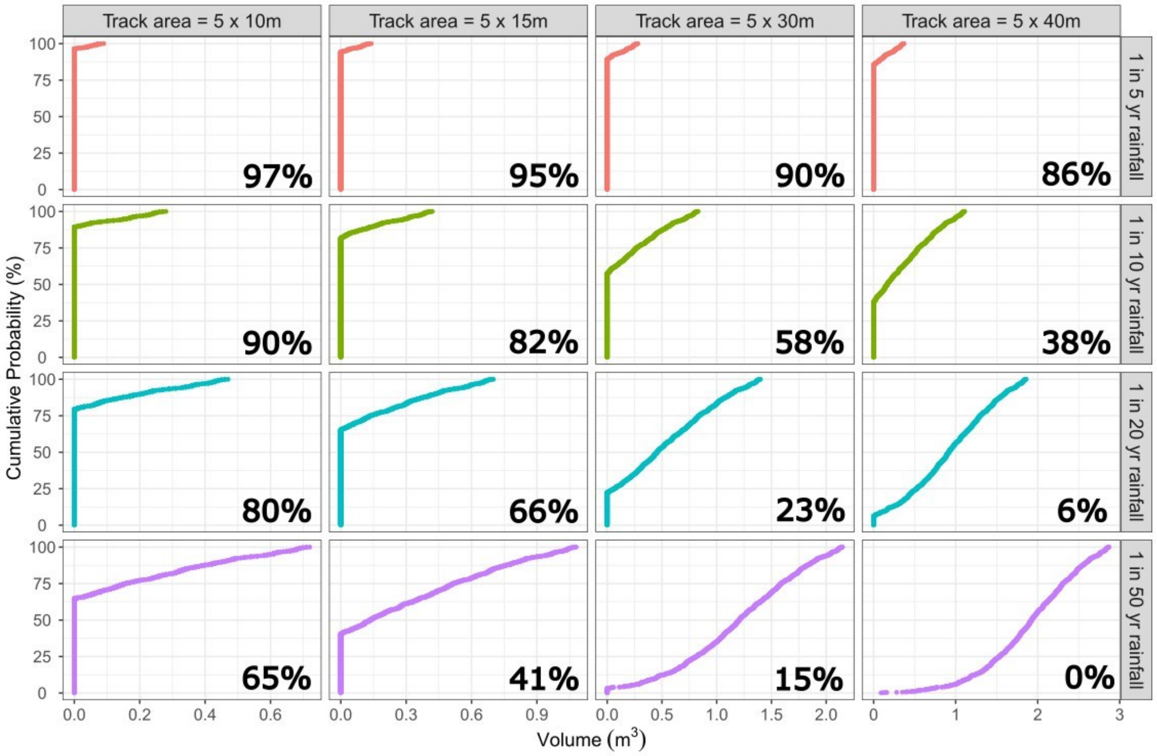

Figure 5 Probability of exceedance functions, based on predicted plume lengths and volumes, describing the probability that runoff from snig track crossbank outlets/drains adjacent to Class 1 drainage line buffer zones in the Coastal IFOA region near the town of Eden will exceed the buffer zone. The 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 not 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 drainage spacings on the contributing snig track area are presented.

High rainfall setting (Eden)

Coffs Harbour was used to represents a high rainfall area within the Coastal IFOA region. The exceedance probability results are presented in Figure 6.

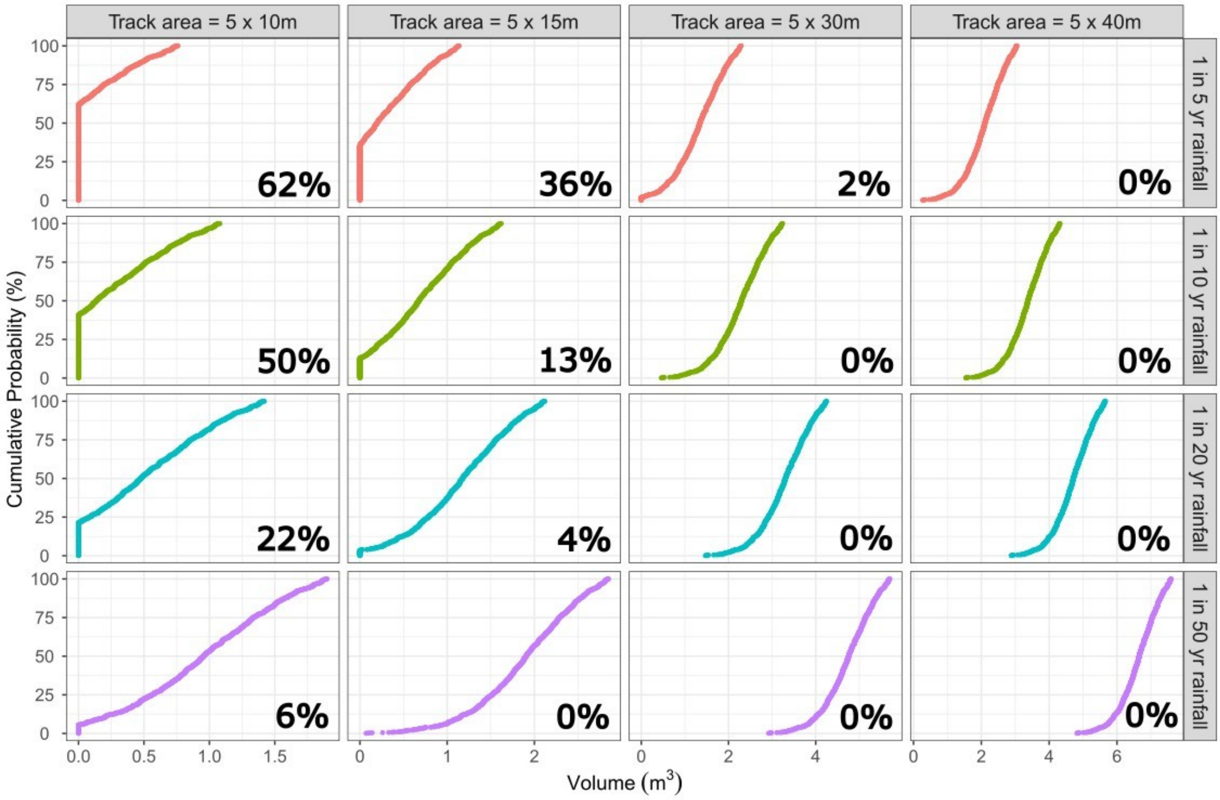

Figure 6 Probability of exceedance functions, based on predicted plume lengths and volumes, describing the probability that runoff from snig track crossbank outlets/drains adjacent to Class 1 drainage line buffer zones in the Coastal IFOA region near the city of Coffs Harbour will exceed the buffer zone. 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 not 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 drainage spacings on the contributing snig track area are presented.

Discussion

Whether or not a buffer zone is effective in preventing runoff connectivity between a forestry compartment and the stream network is not a simple yes or no question. The Coastal IFOA does not set a performance metric for buffers zones to meet. Furthermore, the effectiveness in achieving this role is influenced by within compartment management practices such as the placement and orientation of tracks and the spacing of drains on tracks, and ultimately the amount of rainfall that is generating surface runoff (Croke & Hairsine, 2006; Lane *et al.*, 2006). Each of these influencing factors vary in space and time, adding complexity to any assessment of buffer zone effectiveness. Research focused on understanding areas of sediment capture and loss in forest compartments has identified that runoff via drains from highly compacted snig tracks pose the main risk of connectivity (Wallbrink & Croke, 2002). In instances where snig tracks are orientated downhill towards the exclusion zone or run parallel to stream channels, track runoff is effectively directed straight into the buffer zone and the risk that the runoff plume will reach the stream is directly related to the distance the plume can travel before infiltrating into the ground.

With this in mind we used the *vbt5* model of Hairsine *et al.* (2002) to model runoff plume distances across Class 1 drainage buffer zones in the Coastal IFOA region and used the distribution of plume lengths to determine the probability that snig track-derived runoff from crossbank outlet/drains pointed into the buffer zone would reach the stream network. We investigated plume lengths generated under four storm intensities and four contributing snig track areas (i.e. the area of snig track between crossbank outlet/drains), across low and high rainfall areas in 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-runoff into the stream network.

The results show the substantial impact that storm intensity and contributing track area have on exclusion zone setting effectiveness, as well as regional rainfall. Generally speaking, in low rainfall areas current exclusion zone settings have a moderate to high probability of effectively preventing runoff connectivity (> 82% probability) given a range of crossbank spacings and rainfall event magnitudes (up to 1 in 20-year rainfall event). However, in high rainfall areas the probability that the current exclusion zone settings will be effective is very low, being <62% in all scenarios and essentially ineffective where crossbank spacings were 30m 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 crossbank spacings on tracks that approach the buffer zone is critical to maximising the effectiveness of those zones in preventing runoff reaching the stream network.

Regardless, under the assumption that 10m snig track crossbank spacings are the shortest that can be practically implemented on tracks, in high rainfall regions current buffer zones are only effective as, or more often than not (i.e. effective more than 50% 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 drains and the stream network. To some degree, snig tracks already end metres before the riparian zone, although the degree to which this is the case is unknown and there are no established rules around where a snig track should end in relation to the exclusion zone in the Coastal IFOA. Therefore, it is recommended that rules be established to ensure an appropriate distance is kept.

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