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Exploratory analysis of the annual risk to life from debris flows

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Abstract. Debris flows are hazardous yet often unrecognised and poorly understood by the public and natural hazards community. Some catchments generate debris flows with average recurrence intervals (ARIs) <10 years, but most debris flow catchments have ARIs ranging from decades to millennia. Consequently, many debris flow catchments pose an underappreciated hazard, especially where there are dwellings on debris flow fans and other depositional areas.

Here, we describe how to use simple and well-accepted methods to:

- Make a preliminary identification of catchments that are susceptible to debris flows.
- Estimate the threshold ARI for debris flows in a catchment below which there is an unacceptable annual risk to life for the occupiers of any dwellings.
- Identify the "window of non-recognition" where debris flows are sufficiently infrequent within a catchment that it is not recognised as susceptible, yet frequent enough that the risk to life exceeds the accepted threshold.
- Explore the influence of the important parameters driving the annual risk to life from debris flows.

We show that, given precautionary but realistic assumptions about debris flow hazards and the vulnerability of dwellings and their occupants, catchments with no history of debris flow activity can pose an unrecognised and unacceptable risk to life.

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1 Introduction

Debris-flows are intense sediment-flood events occurring in steep, erodible catchments that can occur when heavy rainfall causes slope failures to deliver large quantities of fine sediment to stream channels. This input then causes sediments to be mobilised in the channel as discrete surge waves containing boulders and often trees that move rapidly down-channel to fan areas, where they can be destructive and potentially fatal. New Zealand is prone to such events because of its active tectonic, volcanic and hydrological setting and many steep, erodible catchments.

Debris flows are often unrecognised and underappreciated by the New Zealand public and within New Zealand's natural-hazard community. This is partly due to confusing terminology, with previous events referred to as "floods", "flash floods", or "slips" (McSaveney et al., 2005). However, the behaviour and impacts of debris flows are very different from conventional floods or landslips on a hillside. For the same amount of rain, a debris flow can have a much higher instantaneous discharge rate, contain much more and often much larger rock debris, and move faster than a flood in the same location. Therefore, in a given catchment, debris flows are usually far more hazardous and harder to manage than floodwater (McSaveney et al., 2005). At the same time, their flow behaviour means they can travel very large distances (up to or exceeding 10 km), impacting environments far from their sources. In contrast, potentially catastrophic slips and other landslides generally occur on steep slopes, and their impacts occur within a limited zone downslope from the landslide. Here we describe simple and well-accepted methods to 1) identify debris flow-susceptible catchments and 2) estimate the annual risk they pose to dwellings located on debris flow fans and, thus, the annual risk to life for the occupiers of those dwellings. We utilise these methods to show that even though debris flows may have average recurrence intervals (ARIs) of centuries or even millennia, their ability to cause great damage means the risk they pose to life can exceed acceptable levels. Nonetheless, the long ARIs for these events create an illusory sense of security so that their risk to life is not recognised.

2 Methods

2.1 Identifying debris flow catchments

Although there are catchments that generate debris flows with ARIs of a few years or less (see Davies et al., 2023, Table 1 for a summary), many have ARIs ranging from decades to millennia. Consequently, many debris flow-susceptible catchments have no record of debris flow activity, resulting in an underappreciated hazard.

Expert field investigation can discern evidence of past debris flow activity, but this is expensive in time and money and not always conclusive. Also, since debris flows can occur very infrequently, evidence of past debris flows may be obscured or removed by subsequent fluvial erosion and deposition processes.

The primary requirement for a debris flow to occur is a large volume of sediment, especially fine sediment, available for mobilisation by a triggering event. This requires a steep and erodible catchment so that hillslope processes can deliver sediment to the stream channel (Welsh and Davies, 2010). Thus, catchment gradient is an obvious factor likely to be associated with debris flow occurrence, and several indicator variables for debris flow susceptibility have been proposed based on catchment topography. The most commonly used is the Melton ratio (Melton-R), which measures a catchment's average steepness (Melton 1965). The Melton-R is calculated from:

$$\text{Melton-R} = H/(A^{0.5}) \tag{1}$$

where A is the map area of the catchment surface (m^2), and H is the elevation difference between the catchment's highest point and fan apex (m).

Various studies have derived a range of threshold values for Melton-R, above which a catchment is deemed susceptible to debris flows. A typical threshold for debris-flow susceptibility is Melton-R >0.5 or >0.6 (Holm et al. 2016, Page et al. 2012, Welsh and Davies 2010, Wilford et al. 2004). However, in practice, there is no well-defined Melton-R threshold, with debris flows occurring in catchments with Melton-R values down to as low as Melton-R ~0.15 (e.g. Davies et al., 2023; Church and Jakob, 2020; McSaveney et al., 2005). In New Zealand, regional-scale mapping of catchment Melton-R (Welsh and Davies, 2010; Bloomberg and Palmer, 2022) suggests that significant areas of built environments in New Zealand may be subject to debris flow hazards, even where no previous events have been

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recorded. However, these regional reconnaissance-level studies require follow-up by agencies responsible for natural hazard management, i.e., detailed site investigation of potential debris flow hazards and risks at the site level.

Of particular concern are locations where debris flows pose a risk to life for occupants of dwellings on debris flow fans. The lack of a quantified ARI makes accurately calculating risk difficult. In this case, "…unquantified (or ignored) risks can lead to incomplete or irrational risk management" decisions (Strouth and McDougall, 2022).

2.2 Setting acceptable limits to risk to life from natural hazard impacts

Globally, the individual risk to life from natural hazard impacts is considered unacceptable at levels greater than about 10^{-3} to 10^{-4} per year (Taig et al., 2012). Where multiple deaths can occur, graphs showing the expected frequency and cumulative number of fatalities (F-N curves) can indicate societal risk and its tolerability (e.g. Fig. 1 in Porter and Morgenstern (2012)). Such graphs are widely used as indicators of acceptable risk limits for various hazards but vary in the thresholds for acceptable risk (Mona, 2014; Sim et al., 2022). Here, we follow Porter and Morgenstern (2012) to establish a maximum acceptable individual risk to life as 10^{-3} per year, which scales linearly with the maximum acceptable risk to multiple lives (10^{-3}/N per year, where N= number of fatalities).

Calculation of risk to life for a debris flow catchment

If the Melton-R value or other evidence suggests that a catchment may be susceptible to debris flows, and there are existing or proposed dwellings on the debris flow fan, then it is necessary to calculate the risk to life and evaluate its tolerability. To do this, we use a modified form of a commonly used calculation of the annual risk to life from exposure to a single landside (see Walker et al., 2007; Porter and Morgenstern, 2012; de Vilder et al., 2022):

$$\text{Risk} = PH * PS{:}H * PT{:}S * V * E \qquad (2)$$

where: PH = annual probability of the debris flow occurring; PS:H = spatial probability of impact on a dwelling if a debris flow occurs; PT:S = temporal probability that an individual occupant will be present when the debris flow impacts the dwelling; V = vulnerability, or probability of loss of life if the occupied dwelling is impacted; and E = number of occupants at risk, which is equal to 1 for the determination of individual risk.

PH can also be specified in terms of its inverse, the average recurrence interval ARI (years) for a debris flow occurrence.

We retain the notation but redefine some of the variables in Eq. 2 to reflect our understanding of the components of risk to life from debris flows. We redefine "Risk" as the maximum acceptable annual risk to life (RTLmax) and PH as PHmax, the value for the annual probability of a debris flow that will result in RTLmax, so that:

$$\text{RTLmax} = \text{PHmax} * \text{PS:H} * \text{PT:S} * V * E \tag{3}$$

$$\text{PHmax} = \text{RTLmax} / [\text{PS:H} * \text{PT:S} * V * E] \tag{4}$$

Eq. 4 allows PHmax to be calculated, given an accepted value for RTLmax and known or assumed values for PS:H, PT:S, V and E. If there is evidence that the annual probability of a debris flow occurring is greater than the calculated PHmax, then any occupants of dwellings on the debris flow fan will be subject to an unacceptable risk to life.

Eq. 4 also allows us to explore the effects of uncertainty about the values of its other parameters. These parameters and their uncertainties are discussed in the following sections.

Probability of impact on a dwelling if a debris flow occurs (PS:H)

If a debris flow occurs, it will likely discharge onto a debris flow fan, a depositional area where a steepland catchment disgorges onto a lower-slope landform. Initially, the debris flow will follow the existing active stream channel. However, changes in the active-channel position, termed avulsions, pose a severe threat to dwellings on fans. This is because mitigation measures (e.g., check dams, bunds) are usually applied to active channels and cannot prevent damage from flows that establish a new channel pathway (de Haas et al., 2018). Thus, a dwelling on the fan can still be impacted, even if it is far from existing stream channels.

Furthermore, the path(s) followed by the avulsing debris flows are difficult to predict. A very conservative assumption is, therefore, PS:H =1. In other cases where debris fans may be small or truncated by wave action or river flows, dwellings are often sited on the fan apex and PS:H =1 is near-certain.

Temporal probability that an individual will be present when the landslide occurs PT:S

In New Zealand, the average proportion of time an individual spends within a residential dwelling is 0.69 (Khajehzadeh and Vale, 2017). However, this average value may not apply

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during high-intensity rainfall events when debris flows are most likely. At such times, dwelling occupants may self-evacuate or be evacuated by the authorities. Alternatively, during the event, the proportion of time spent in the dwelling may be close to 1, as its occupants shelter in place. We use a value of PT:S =0.69 for this study, recognising that actual values are likely to be binomial (one or zero) during high-intensity rainfall events.

Probability of an individual death if dwelling impact occurs (V)

This parameter is critical but has considerable uncertainty. Firstly, it depends on debris flow intensity in terms of volume, depth, composition and velocity. While somewhat governed by catchment area and topography, debris flow volumes may vary by at least two orders of magnitude between the median and 99th percentile for catchments of the same area (de Haas and Densmore, 2019; Marchi et al., 2019). Other factors, such as rainfall intensity and the volume of landslide material available for mobilisation as debris flows, are difficult to estimate or predict but likely to be important drivers of debris flow intensity.

Our model assumes a single annual probability threshold for a debris flow that is an unacceptable risk to life for occupiers of a dwelling in a debris flow catchment. A more complex formulation would account for the reality that debris flows of different magnitudes/intensities may come from the same catchment, with larger, more intense events having lower frequencies. For example, Strouth and McDougall (2022) estimate separate model parameter values for each landslide frequency-magnitude scenario, then integrate these to estimate an overall risk to life.

Also important to the value of the V parameter is the vulnerability of the impacted building, which can depend on construction methods and materials (e.g., a light timber-framed dwelling vs a modern dwelling constructed from permanent materials.)

Finally, it may depend on chance or timing. For example, out of caution, occupants may move to a less vulnerable part of the dwelling during a high-intensity rainfall event. Conversely, if the debris flow occurs in the middle of the night, a person sleeping in a bedroom on the upslope side of a dwelling may have no warning or chance to avoid the full force of impact.

Bell and Glade (2004) published values for the risk of death to an individual in the open (0.1 to 0.5) and within a building (0.02 to 0.25) for "low-magnitude" to "high-magnitude" events, respectively. Following Jakob (2005), we assume that the risk of death for an individual in an impacted building is V =0.1. Note that if we chose a value of V=1.0 (it is certain the occupant of an impacted dwelling would die), then the threshold for PHmax would be an order of magnitude lower, assuming we use the same threshold RTLmax (0.001 in this study).

The number of occupants at risk (E)

The PHmax value is based on the RTLmax value for an individual. We used the NZ occupancy rate for usually resident households to calculate the PHmax for debris flow fans with multiple dwellings and/or occupants (N(O)=2.67, Statistics NZ (2023)). N(O) is multiplied by the number of dwellings on a debris flow fan (N(dwellings/catchment)) to calculate the number of individuals occupying that fan (E). In a specific case study, this number – like all corresponding values PS:H, PT:S and V – can be replaced by local data. Note that the maximum acceptable annual probability of debris flows PHmax becomes progressively smaller with increasing E. In other words, the risk to life will increase with increasing E, and the acceptable-risk threshold for the annual probability of debris flows should be reduced. At the same time, some factors may reduce the risk to life with increasing E. If the larger numbers of people E are dispersed over multiple dwellings on a fan, and if the debris flow path and deposition area are restricted to part of the fan, some dwellings may not be impacted. Thus, the decrease in PHmax might not scale linearly with increasing E since PS:H is less if averaged over all the dwellings. Similarly, with multiple inhabitants, V may vary with location within the dwelling of the different inhabitants at the time of debris flow impact.

While these points are valid, we use single assumed values for PS:H and V to keep our model simple and account for the worst-case scenarios where entire fans are inundated, and multiple dwellings are impacted to an extent that is life-threatening for all inhabitants.

The estimated annual probability of debris flow occurrence (PH)

Calculating PHmax provides a standard for comparison with estimated PH (annual probability of a debris flow occurring). There is an unacceptable risk to life for debris flow catchments where estimated PH > calculated PHmax. However, estimated PH can have wide confidence limits or be completely uncertain since ARIs may be centuries or even millennia in magnitude. This means that no debris flows may have occurred in living or even historical memory for most catchments, so data to estimate ARIs are sparse or lacking.

This lack of certainty is a serious problem since 1) PH is an important driver of annual risk to life from debris flows, 2) the lack of observations means estimates of PH may have confidence limits that are so wide as to make the estimates uninformative, and 3) in rapidly-

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developing countries like New Zealand, the expansion of land use into hitherto-unutilised areas means that debris-flow hazard may be unrecognised. Of course, with very long ARIs (very low PH), the risk to life may be acceptably low. However, there may be a "window of non-recognition" where ARIs are long enough that the debris flow hazard is not yet recognised but short enough that the risk to life is still unacceptably high. The second application of our model is identifying any such window.

2.3 Analysis using Bayesian inference

We used Bayesian inference to estimate PH for debris flow events. All statistical analysis was done in programme R (R Core Team, 2021).

Bayesian analysis combines expert opinion in the form of the prior distribution with the observed evidence to produce a posterior distribution. There are few formal estimates of PH for New Zealand catchments. However, for two well-studied debris flow events of sufficient intensity to be life-threatening, evidence suggested ARIs were 200-500 years (McSaveney et al., 2005; Page et al., 2012).

We have thus used a conjugate beta-binomial model with the beta prior PH ~ Beta ($a=18.73$, $b= 5599.75$), where the parameters a and b were chosen to correspond to the prior 95% credible interval of (1/500,1/200) for PH.

Assuming a catchment where zero debris flows have been recorded over a given period (e.g. the last 150 years), the conjugate posterior distribution corresponding to an observation of 150 event-free years is then PH|data ~ Beta ($a=18.73$,$b= 5749.75$). We have used this result to estimate the posterior probability that PH > PHmax for that catchment. We then compared estimated PH with the PHmax values for a range of dwellings per catchment (1, 2,5, 20 and 100). Where estimated PH>PHmax, the risk to life was classified as unacceptable.

We also estimated the probability of a "window of non-recognition" where ARIs are long enough that the debris flow hazard is not recognised but short enough that the risk to life is still unacceptably high. For three defined periods (50, 100 and 150 years), we estimated the posterior predictive distributions for the probabilities of outcomes where zero debris flows occurred during the period since, for these outcomes, the debris flow susceptibility of the catchment would likely be unrecognised (assuming no expert investigation of the catchment). This assumes that if at least one debris flow had occurred in a catchment during the specified period, it would have been recorded, and the catchment's susceptibility would have been clearly recognised.

Note that while we have used 50, 100 and 150-year periods, these methods can be used with any time period. The criterion for the choice of time period is how far back it is likely that a debris flow occurrence would be remembered and recorded. In regions where human settlement is very recent, an appropriate time period might be considerably shorter than 150 years.

3 Results

3.1 Estimation of PHmax and comparison with estimated PH

Table 1 shows the calculated values for PHmax assuming the upper limit for acceptable risk to an individual life (RTLmax) is 0.001, probability of impact PS:H =1.0 and probability of individual death if a debris flow impacts an occupied dwelling V =0.1. It also shows the inverse of PHmax, the minimum ARI threshold for risk to life.

As the number of dwellings per catchment increases towards 100, PHmax becomes very small. Thus, while PHmax ~0.0054 (ARI =184 years) is the threshold acceptable risk to life where there is one dwelling in a single debris flow catchment, PHmax ~ 0.001 (ARI =1000 years) can still mean an unacceptable risk to life where there are more than five dwellings (>10 individuals).

Table 1. Parameters used to calculate PHmax, the maximum acceptable annual probability of a debris flow occurring.

<table>
<tr><th colspan="4">Parameter</th><th>Symbol</th><th>Value</th></tr>
<tr><td colspan="4">Maximum annual acceptable individual risk to life</td><td>RTLmax</td><td>0.001</td></tr>
<tr><td colspan="4">Probability of impact on a dwelling if a debris flow occurs</td><td>PS:H</td><td>1.0</td></tr>
<tr><td colspan="4">Probability of individual death if a dwelling impact occurs</td><td>V</td><td>0.1</td></tr>
<tr><td colspan="4">Average no of occupants per dwelling (NZ residential)</td><td>N(O)</td><td>2.67</td></tr>
<tr><td colspan="4">Average proportion of time that the dwelling is occupied</td><td>PT:S</td><td>0.69</td></tr>
<tr><th colspan="6">Calculation of PHmax</th></tr>
<tr><td>N (dwellings/catchment)</td><td>1</td><td>2</td><td>5</td><td>20</td><td>100</td></tr>
<tr><td>E (individuals/catchment)</td><td>2.67</td><td>5.34</td><td>13.35</td><td>53.4</td><td>267</td></tr>
<tr><td>PHmax</td><td>0.00543</td><td>0.00271</td><td>0.00109</td><td>0.000271</td><td>0.0000543</td></tr>
<tr><td>Min. acceptable ARI (yrs)</td><td>184</td><td>368</td><td>921</td><td>3,685</td><td>18,423</td></tr>
</table>

The upper acceptable threshold for the annual probability of a debris flow (PHmax) can be used to explore the risk to life from debris flows by comparing it with estimated PH from Bayesian inference. Unacceptable risk to life occurs where the estimated annual probability of a debris flow PH exceeds the PHmax thresholds in Table 1.

Figure 1 shows how PHmax for a single dwelling can be compared with 1) the prior distribution and 2) a posterior distribution that assumes zero observations in a catchment for a 150-year period.

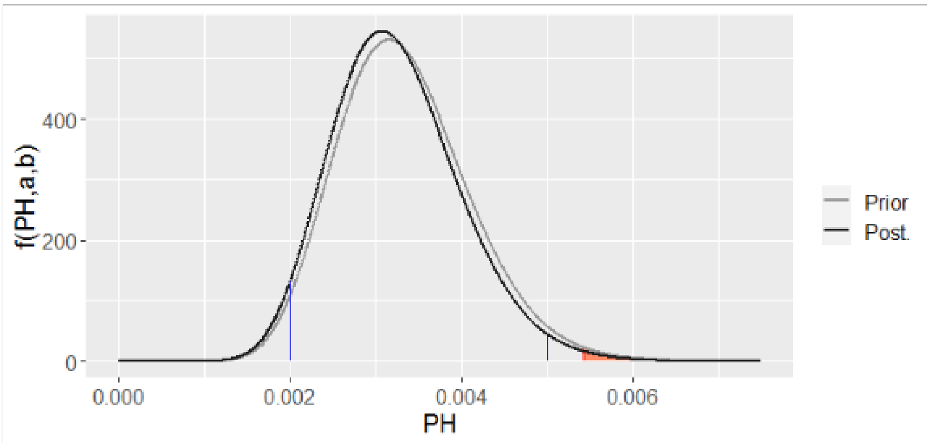

Figure 1: Prior (grey) and posterior (black) probability distribution for PH. The blue vertical lines indicate the 1/500 and 1/200 reference points for the prior. The orange area under the curve corresponds to the posterior probability that PH>PHmax for a single dwelling where PHmax=0.00543.

Using the posterior distribution, the posterior probability that PH > PHmax is the area under the black curve to the right of the right-hand blue vertical line (PHmax=0.00543 for a single dwelling, Table 1). Here, the posterior probability=0.0060; therefore, it is highly unlikely that PH > PHmax.

Note that for multiple dwellings in a catchment, PHmax ranges from 0.00271 (two dwellings) down to 0.0000543 (100 dwellings) (Table 1). The posterior probabilities that PH > PHmax are 0.7526, 1.0000, 1.0000 and 1.0000 for 2, 5, 20 and 100 dwellings respectively. Therefore, depending on the number of dwellings, it is likely to be almost certain that PH > PHmax.

3.2 Estimating the "window of non-recognition"

The probability distributions for the probability of 0 events in 50, 100 and 150 years were used to identify a "window of non-recognition" where ARIs are long enough that the debris flow hazard is not recognised but short enough that risk to life is still unacceptably high. Bear in mind that these distributions are based on the prior 95% credible interval of (1/500,1/200) for the PH of a life-threatening debris flow event in a catchment.

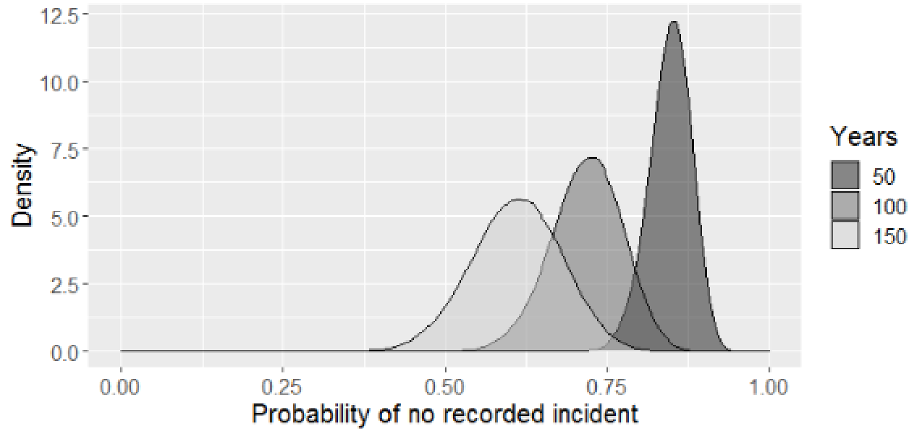

Figure 2: The probability distribution for the probability of 0 events in 50, 100, and 150 years, given prior estimates of PH.

Figure 2 shows the mean probability that no life-threatening debris flow occurs within 150 years is 0.61, with 95% credibility intervals of 0.47 and 0.74. A 150-year historical record is unlikely in a newly settled country like New Zealand. If the time interval for historical records is reduced to 100 or even 50 years, the proportion of catchments with zero debris flow occurrences is even higher. This analysis suggests there is a very good chance that catchments may have no recorded debris flow activity over long periods yet pose an unacceptable and unrecognised risk to life from debris flows.

4 Discussion

4.1 Uncertainty in parameter values

The model parameters (Eq. 4) determining the PHmax were based on reported values in the literature. All have uncertainty, but some appear to have higher uncertainty than others. The probability of impact on dwellings if a debris flow occurs (PS:H) is assumed to be 1. Where the fan is small and/or dwellings are sited in the likely path for a debris flow, this is a credible assumption. If dwellings are sited at a distance from the flow path, it is a matter of whether the debris flow avulses, and if it does, does it travel towards dwellings sited on the fan? Debris flow avulsion is poorly understood, and patterns of deposition on debris-flow fans have been monitored or reconstructed on only a few natural debris-flow fans (de Haas et al., 2018).

The probability of an individual death if dwelling impact occurs (V) and the temporal probability that an individual will be present when the landslide occurs (PT:S) are even more uncertain, depending on the interaction of debris flow intensity, dwelling vulnerability and human behaviour. The temporal probability that an individual will be present depends on human behaviours such as evacuation, sheltering in place, diurnal variations in occupancy, or seasonal variations in occupancy, as found with holiday homes. In New Zealand, given the large number of debris flow impacts on dwellings within the last 15 years with no fatalities (albeit with injuries and lucky escapes), the values for V (0.1) and PT:S (0.69) may be too high. However, given the risk-to-life implications of these parameters, we have erred on the side of caution.

4.2 Limitations of the model

Our model assumes a single annual probability threshold for a debris flow that is an unacceptable risk to life for occupiers of a dwelling in a debris flow catchment rather than a more complex and realistic model that integrates a range of debris flow frequency and intensity scenarios.

An example of this limitation of our model is the "window of non-recognition" estimate, where catchments may exhibit no debris flow activity over long periods yet pose an unacceptable and unrecognised risk to life from debris flows. Of course, this analysis is based on limited data for ARIs of two life-threatening debris flow events. For catchments with lower ARIs, the proportion of unrecognised catchments with zero occurrences will be smaller, and that of recognised catchments with occurrences ≥1 will be larger. At the same time, these more frequent debris flows may not be life-threatening, leading to complacency about the actual risk to life in the catchment. This was the case for Matatā township in the eastern Bay of Plenty, New Zealand. Four debris flows had occurred at Matatā since 1860 before a major debris-flow disaster in 2005, which destroyed 27 dwellings and damaged 87 properties, fortuitously with no fatalities (McSaveney et al., 2005).

Despite these limitations, we have chosen a simple model because reliable data are scarce, and most model parameters are subject to considerable uncertainty. More importantly, our conceptual approach highlights the dangers of complacency about the risk to life from debris flows. Using simple concepts and Bayesian inference, we can show that, given precautionary but realistic assumptions about debris flow hazards and the vulnerability of dwellings and their occupants, unrecognised catchments with no history of debris flow activity can pose an unacceptable risk to life. Parameters subject to uncertainty (debris flow ARIs, probability of debris flow impact, dwelling vulnerability, occupancy during debris-flow triggering rainfall events) must be priorities for research to better understand the risk to life from debris flows. Land-use planning for future developments in a catchment cannot rely on the fact that no debris flows have been recorded. There is a need to do site analyses and to think carefully about the siting of dwellings or other structures that people may occupy.

5 Conclusions

Debris flows are a potentially dangerous natural hazard for any dwelling on an alluvial fan at the mouth of a steepland catchment. However, debris flow-susceptible catchments may be unrecognised because debris flows can occur very rarely in a given catchment. Even where reconnaissance studies using morphometric indices (e.g., Melton-R) indicate a significant potential hazard, the long annual recurrence intervals (ARIs) for some debris flow catchments mean their annual probability of occurrence (PH) is difficult to estimate reliably. Thus, there is a danger that their risk may be considered negligible.

Here, we have handled this difficulty by inverting the problem. Instead of trying to estimate PH for debris flows in a specific catchment, we have back-calculated a maximum acceptable annual probability PHmax to meet accepted thresholds for maximum risk to life. This has allowed us to:

1. Compare the threshold PHmax with two New Zealand studies where the probability distribution of PH can be estimated from field evidence. Given conservative assumptions about the probability of impact on dwellings and the probability of mortality for an impacted dwelling, we have shown that for catchments with more than one dwelling, PH can exceed PHmax.
2. Estimate the "window of non-recognition" where debris flows within a catchment may be so infrequent that it is not recognised as susceptible, yet the risk to life from debris flows exceeds the accepted threshold. We have shown that a significant

proportion of debris-flow-susceptible catchments will fall within this window, even assuming up to 150 years of written or oral history recording debris flows within the catchment.

3. Explore the influence of the important parameters underlying the annual risk to life from debris flows. The observed frequency of deaths in New Zealand dwellings from debris flow impacts, although admittedly a very small sample, appears to be lower than the assumed value in this study, suggesting that these key parameters need further research.
4. Nevertheless, catchments not recognised as debris-flow-capable can pose risks to life that are unacceptable by orders of magnitude. In these cases, the variation in risk due to the risk parameters (PS: H, V, PT:S) is likely to be insufficient to change the risk acceptability significantly.

Author contributions. MB and TD conceptualized and designed the study, including a literature review and preliminary analyses. EM performed statistical analyses, produced figures, and contributed to the writing and reviewing of the manuscript. TR and DP contributed to the writing and reviewing of the manuscript. MB revised and edited the text. The authors have no competing interests.

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