Manaaki Whenua
Landcare Research

Memorandum on implementing a national index for susceptibility to streambank erosion

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1 Introduction

The Ministry for the Environment (MfE) contracted Manaaki Whenua – Landcare Research (MWLR) to produce a geospatial dataset showing the susceptibility to streambank erosion for every river reach in the New Zealand digital river network. This work follows an earlier feasibility study by Smith (2020) that evaluated the potential for development of a national index that expressed the spatial variation in reach-scale susceptibility to streambank erosion.

The intended use of the national index for susceptibility to streambank erosion is to support the implementation of the updated National Policy Statement – Freshwater Management (NPS-FM 2020) by councils, particularly in relation prioritising interventions to reduce streambank erosion and evaluating the effects of those interventions in the future.

The national susceptibility index described by Smith (2020) provides a relative, spatial measure of susceptibility to bank erosion across the digital river network. The index considers the spatial variability in factors that may influence bank erosion at the reach scale. The requirement for a nationwide susceptibility index means that only spatial data sets available on a national scale may be used as inputs. As a result, the balance between model complexity, spatial resolution, and the level of available data were key considerations for index development (Smith 2020).

This technical memorandum describes the national implementation of the susceptibility index for streambank erosion outlined by Smith (2020) and includes recommendations on a) appropriate use of the index and b) additional work required to progress to national quantification of streambank erosion within catchment sediment budgets.

2 Index description and data requirements

2.1 Index description

The feasibility study by Smith (2020) outlined a susceptibility index for streambank erosion based on the Digital Network (DN v1) derived for the River Environment Classification v1 (REC v1). This allowed use of NIWA's Regional Flood Estimation Tool v2 (Henderson & Collins 2016; Henderson et al. 2018) that is based on DN v1. Subsequently, NIWA mapped the original flood estimation model onto the Digital Network v2 (used for REC v2) and this output was supplied by MfE to MWLR. As a result, the streambank erosion susceptibility index has been implemented using the REC v2.5 digital river network.

In contrast to the version of the index based on REC v1, here we include additional terms for a) channel sinuosity and b) the extent of digital river network intersection with mapped lakes in equation 1. The sinuosity term was initially excluded as sinuosity data was not available with REC v1. The index does not include a term representing erosion control works due to the lack of national-scale spatial data (Smith 2020).

An empirical approach for representing reach-average bank migration rate (M_j) forms the basis for computing the index of susceptibility to streambank erosion (Smith 2020). M_j can be calculated for each stream link in the digital river network as follows:

$$M_j = SP_j Sn_j T_j V_j \left(1 - PR_j\right)\left(1 - PL_j\right) \tag{1}$$

where SP_j is the stream power of the mean annual flood for the j-th stream link, Sn_j is the channel sinuosity rate factor of the j-th link, T_j is the soil texture-based erodibility factor of the j-th link, V_j is the valley confinement factor of the j-th link, PR_j is the proportional extent of riparian woody vegetation of the j-th link, and PL_j is the proportional extent of intersection with mapped lakes for the j-th link.

The conceptual basis for including each term in equation 1 is described by Smith (2020) and in further detail by Smith et al. (2019). Previous studies report increasing bank migration with increasing bankfull discharge, mean annual flood, and stream power (Hooke 1979; Nanson & Hickin 1986; Walker & Rutherfurd 1999; Dymond et al. 2016; Alber & Piégay 2017). Other factors, such as the cohesiveness of bank materials (Julian & Torres 2006), channel sinuosity (Nanson & Hicken 1983), valley confinement (Hall et al. 2007), and riparian woody vegetation (Abernethy & Rutherfurd 2000) are also important and result in high levels of spatial variability in bank erosion.

Stream power is the work done on the channel by the water per second per unit channel length. Stream power (SP_j) for the mean annual flood (MAF, $m^3 s^{-1}$) is approximated for each stream link by the product of MAF and channel slope. The interaction between channel sinuosity and bank migration rate is represented by a log-normal relationship to determine Sn_j. This function represents the positive-skew observed in the relationship between channel sinuosity and migration rate (Crosato 2009). The dimensionless Sn_j is calculated as:

$$Sn_j = \frac{1}{(Sinu_j - 1)\sigma\sqrt{2\pi}}\, e^{\left(-\frac{(ln\,(Sinu_j - 1) - \mu)^2}{2\,\sigma^2}\right)} \tag{2}$$

where $Sinu_j$ is sinuosity of the j-th stream link of the digital river network, and μ and σ are the mean and standard deviation parameters that determine the location and scale of the distribution. The μ and σ parameters are fitted using measurements of reach-scale bank migration rates (Smith et al 2019).

The texture of the bank material influences bank migration rates where more cohesive banks with higher silt and clay content tend to be more resistant to erosion (Hickin & Nanson 1984; Simon & Collison 2001; Wynn & Mostaghimi 2006). An empirical relationship based on percent silt + clay content (SC) is used to estimate the soil critical shear stress (τ_c) (Julian & Torres 2006) as follows:

$$\tau_c = 0.1 + 0.1779SC + 0.0028SC^2 - 0.0000234SC^3 \tag{3}$$

SC is obtained from spatial data on soil textural classes. The soil texture-based erodibility factor (T_j) is represented by a power function to characterise the relationship between τ_c and bank erodibility (Arulanandan et al. 1980; Hanson & Simon 2001; Julian & Torres 2006) for the j-th stream link:

$$T_j = c\tau_{cj}{}^{-d} \quad (4)$$

where the c and d parameters are fitted using bank migration rate data.

Floodplain extent and the level of valley confinement due to steep valley sides or exposed bedrock are factors that may limit lateral bank migration (Hall et al. 2007; De Rose & Basher 2011; Fryirs et al. 2016). A valley confinement factor (V_j) is calculated as

$$V_j = \left(1 - e^{\left(-15/SB_j\right)}\right)^{11} \quad (5)$$

using the mean slope in degrees (SB_j) of a buffer zone either side of the j-th stream link (Smith et al. 2019).

Woody riparian vegetation typically increases bank stability via the effects of root reinforcement and root cohesion (Abernethy & Rutherfurd 2000; Hubble et al. 2010; Polvi et al. 2014; Konsoer et al. 2015), as well as by increasing flow resistance (Thorne 1990) and by lowering bank water content that can improve bank stability (Simon & Collison 2002). The effect of riparian woody vegetation (PR_j) is represented by reducing bank migration rates proportional to the extent of woody riparian vegetation along the j-th stream link (equation 1).

Stream links in the digital river network pass through lakes. Therefore, the reach-average bank migration rate for those links intersecting lake polygons should reflect the proportional extent of intersection (PL_j). To accommodate some observed spatial misalignment between the digital stream network and mapped lakes, it is assumed that where $PL_j \geq 0.95$, then reach-average bank erosion is negligible and equates to zero. For values of PL_j less than 0.95, some bank erosion may occur along the section of channel not intersecting the lake. Hence, stream links that partially intersect lakes can produce non-zero values.

The index of susceptibility to streambank erosion (I_j) is computed by scaling M_j to the range 0−100 on a national basis to provide a relative measure of reach-scale susceptibility across all modelled stream links as follows:

$$I_j = \left(\frac{M_j - M_{min}}{M_{max} - M_{min}}\right) \times 100 \quad (6)$$

where M_{max} is set to the mean of the 10 highest values for M_j (for which I_j is set to 100) to avoid dependence on a single large value of M_j for calculating all index values. M_{min} corresponds to the minimum value (zero). This scaling procedure produces a simple, dimensionless index that can be used to compare bank erosion susceptibility for stream links across the REC v2.5 network.

2.2 Data requirements

Data sets required to calculate the index for susceptibility to streambank erosion for every stream link are summarised below:

- **Mean annual flood** predicted for each stream link by NIWA's Regional Flood Estimation Tool v2 (Henderson & Collins 2016; Henderson et al. 2018) and mapped onto the REC v2.5 digital river network. Data on stream link sinuosity is obtained from REC v2.5.
- **National 15 m DEM** for calculating channel slope and valley confinement. The resolution of the national DEM is a limitation, particularly for lowland reaches, where channel slopes tend to be overestimated. This could be improved with the future availability of LiDAR nationally.
- **Freshwater Ecosystems of New Zealand (FENZ)** database (Leathwick et al. 2010) for determining the proportional extent of stream link intersection with mapped lakes (PL_j).
- **Channel polygons** produced by combining Land Cover Database (LCDB) v5.0 'river' and 'gravel and rock' land cover classes with the Land Information New Zealand (LINZ) river polygons from 1:50,000 scale mapping. This required removal of LCDB 'gravel and rock' areas located beyond the extent of the channel network. The resulting channel polygons better represents wider channels, particularly those with areas of exposed gravel, and improves spatial alignment between channel banks and mapped woody vegetation.
- **Spatial silt and clay (SC) content** estimated from soil textural classes compiled from the Fundamental Soil Layers (FSL) (Newsome et al. 2008). FSL was used instead of S-Map due to its national coverage. FSL soil texture data are not unavailable for the Gisborne District. Therefore, mean SC content was estimated for each NZ Soil Class (NZSC) in the Gisborne District based on SC data summarised by NZSC from other regions. The FSL is the lowest resolution spatial input to the model with mapping completed at 1:63,360/1:50,000 scale as part of the NZ Land Resources Inventory (Newsome et al. 2008).
- **National woody vegetation cover** obtained from classification of 2002 satellite imagery with 15-m resolution (EcoSat Woody; Dymond & Shepherd 2004). EcoSat Woody was intersected with the union of the buffered (15-m) LINZ centrelines and channel polygons to determine the proportional extent of riparian woody vegetation. This mapped stream network is used in preference to the REC2 digital network because it exhibits better planform accuracy and improved spatial correspondence between channel position and riparian woody vegetation. The 2018 New Zealand Land Cover Database (LCDB v5.0) is not used, despite being more recent, because it has a minimum mapping unit of 10,000 m^2 versus 225 m^2 for EcoSat. This makes LCDB less suitable for characterising the narrow corridors of woody vegetation often found along channel banks.
- **Calibration data** comprising measurements of reach-scale bank migration rates (mean = 0.45 m y^{-1}; range = 0.02 – 4.4 m y^{-1}, n = 68 stream links) used to fit parameter values for the sinuosity (equation 2) and erodibility (equation 4) factors. Parameter values were determined by minimising the mean square error between predicted and observed values [R^2 = 0.73 relative to 1:1 line; root mean square error

(RMSE) = 0.39 m y^{-1}]. Bank migration rate data were obtained from reach-scale mapping of channel change in the Manawatū and Kaipara catchments (Spiekermann et al. 2017a; Smith et al. 2019). For comparison, separate calibrations for the Manawatū and Kaipara catchments produced RMSEs of 0.69 and 0.10 m y^{-1}, respectively, which reflects in part the difference in mean measured migration rates (Manawatū = 1.4 m y^{-1}; Kaipara = 0.14 m y^{-1}).

3 National susceptibility index for streambank erosion

MfE requested MWLR provide recommendations on appropriate use of the susceptibility index. This followed discussion about the scope of work, during which it was agreed that MWLR would not spatially aggregate and summarise index results. Instead, we provide guidance on approaches for visualisation and comparison of index values, and outline limitations for consideration when evaluating index results.

3.1 Recommendations for index use

Index visualisation

The index exhibits a high level of positive skew (Fig. 1). Most values are low and correspond with the large number of first (n = 303,266) and second order (n = 139,944) stream links in the REC v2.5 digital river network (total link n = 593,517) while a smaller number of typically higher order stream links exhibit larger index values (Fig. 2). First and second-order streams are characterised by low mean annual flood values compared with higher order links, which typically results in low susceptibility compared with higher-order channels. Therefore, a proportionally small number of stream links exhibit higher susceptibility when comparing across the national river network.

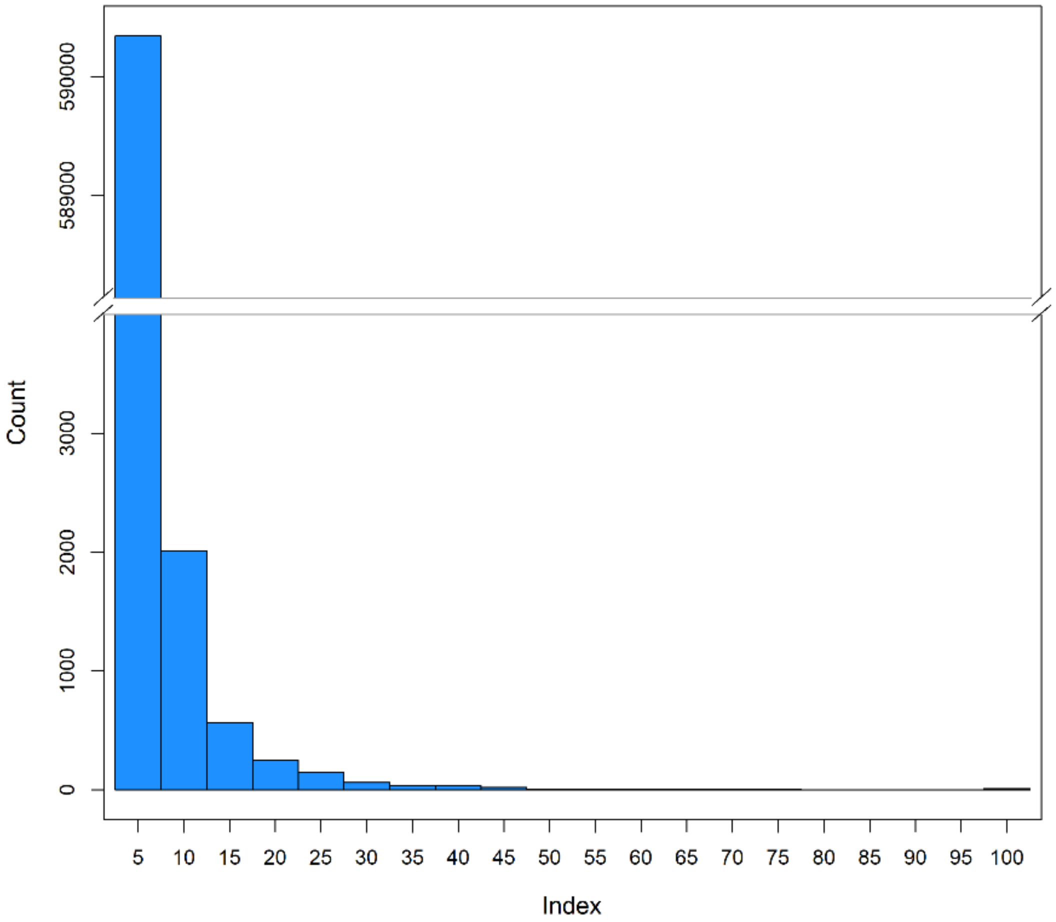

Figure 1. Histogram of susceptibility index values based on 20 equal-sized bins. The choice of bin size is arbitrary. Note the break in the y axis.

Rapid visualisation of differences in higher index values (of most interest for targeting bank erosion mitigation) on a national scale may be best achieved with the Jenks Natural Breaks optimization method (available in most GIS software). The Jenks classification minimises deviations from within-class means while maximising the difference in means between classes. If adopting Jenks classification on a national scale, we suggest using 8 classes but leaving the lowermost class blank to better highlight higher susceptibility stream links.

However, Jenks classification is data-specific and unsuitable for comparing subsets of index values (e.g. subset by region and mapping discrete regional results for comparison). Alternatively, higher index values may be selected for display based on an exceedance threshold approach (described below) that better supports comparison between different spatial aggregations.

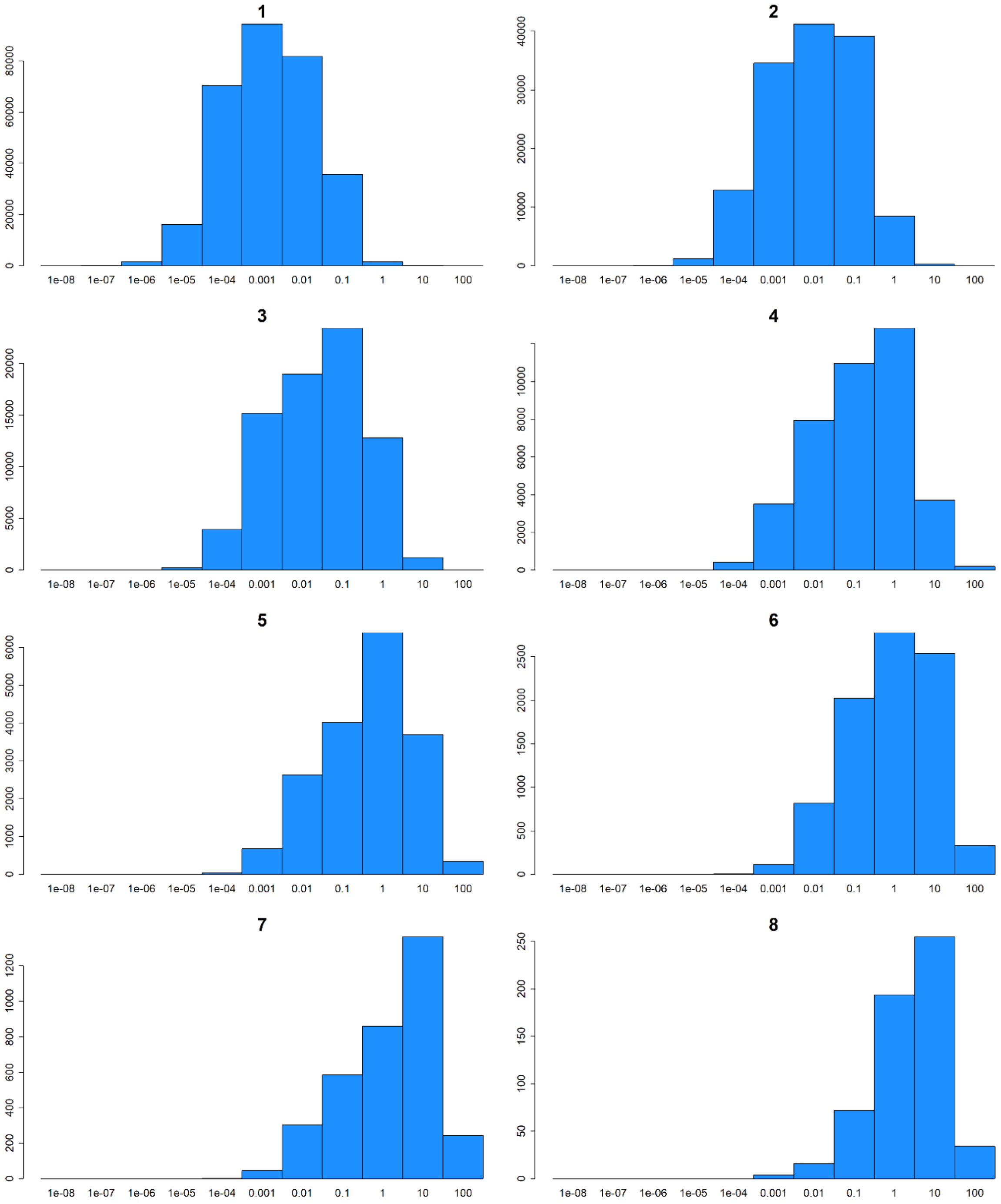

Figure 2. Histograms of susceptibility index values by REC v2.5 stream order (1-8). Bins follow a log-scale on the x axis while count data are shown on the y axis (note differences in y-axis scale). The plots exclude stream links (representing 1.4% of all links) with an index value of 0 (mostly lake intersecting links).

Index aggregation

Comparison of index values should not focus on individual stream links. This is because index values for individual links may be uncertain due to a) errors in underlying spatial data (see the discussion of limitations below), and b) the potential for missing spatial information (e.g. erosion control works) to result in predicted susceptibility that is not fully representative of contemporary conditions. Higher levels of spatial aggregation reduce sensitivity to index values for individual stream links.

For comparison between catchments or regions, we recommend that aggregations of index values be made on a 'like-for-like' basis. For example, computing mean index values for certain catchments may complicate comparison due to differences in catchment size and stream order. Larger catchments might appear to have a low index value when averaged overall but exhibit high levels of within-catchment variability.

Given the increase in index values with stream order (Fig. 2) associated with the general downstream increase in stream power of the mean annual flood, we recommend that order be used for summarising index values. For instance, mean index values could be computed by stream order for each sea-draining catchment to enable ranking of catchments by index results based on stream order.

Some natural areas experience high bank erosion rates due to high stream powers and the presence of erodible banks. These are notable along some mid-reaches of the steep rivers draining to the west coast from the Southern Alps, including areas with native forest along banks. These river reaches located within natural areas could be excluded from subsequent analysis as unsuitable for mitigation based on a mask (e.g. Department of Conservation estate). This would allow ranking of catchments or regions to be based on stream links located within areas deemed to be mitigatable.

Index exceedance thresholds

Comparison of index values may be based on the percentage of index values that exceed a given threshold value (Fig. 3). National index values corresponding to selected percent exceedance thresholds and the associated cumulative number and length of REC2 links are summarised in Table 1. This analysis enables the selection of stream links with index values that exceed some chosen level (e.g. upper 0.1, 1, 5%). For example, the upper 1% of stream links on a national scale equal or exceed an index value of 2.816 and correspond to *n* = 5,935 links and 4,375 km of channel (Table 1). For the upper 5% of links, the corresponding index value is 0.337 and this captures 21,768 km of channel. The upper 5% of stream links with higher bank erosion susceptibility are shown in Figure 4.

The index for susceptibility may also be visualised based on stream order and percent exceedance thresholds. For example, Figure 5 shows REC v2.5 stream links with a stream order ≥ 5 and an index value ≥ 0.337 (upper 5%) on a national scale. Stream links with lower index values are colour coded blue (0 < index < 0.337) or grey (index = 0) in Figure 5. Those links with an index of 0 generally fully intersect lakes, while very low index values may result from partial intersection with lakes.

Percent exceedance thresholds could form the basis for ranking bank erosion susceptibility by stream order and sea-draining catchment. For example, stream links that equal or exceed a pre-defined threshold value (e.g. upper 1% or 5% nationally) could be identified and the proportion of threshold-exceeding stream length computed relative to the total stream length by stream order present within each sea-draining catchment. This could then form the basis for ranking catchments for prioritisation. Alternatively, the proportion of threshold-exceeding stream length could be calculated relative to total length by stream order present in each region for regional-scale comparison.

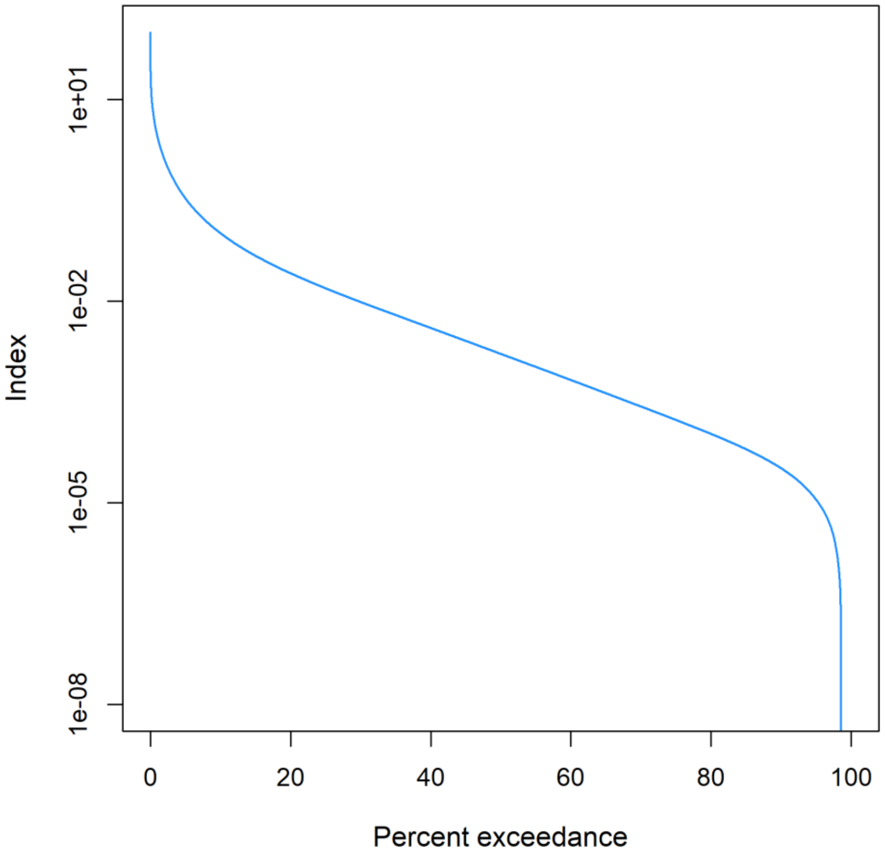

Figure 3. Plot of percent exceedance versus index for susceptibility to streambank erosion. The plot excludes stream links with an index value of 0 (mostly lake intersecting) so does not reach 100%. Note the y-axis log scale.

Table 1. Susceptibility index values and the cumulative number of REC v2.5 stream links and length of link corresponding to selected percent exceedance levels on a national scale

Percent exceedance	Index value	Cumulative N REC2 links	Cumulative length of REC2 links (km)
0.01	41.396	59	34.2
0.02	31.688	118	71.3
0.05	21.609	296	193
0.1	15.123	593	396
0.2	9.923	1,187	828
0.5	5.295	2,967	2,151
1	2.816	5,935	4,375
2	1.278	11,870	8,610
5	0.337	29,675	21,768
10	0.102	59,351	45,573
20	0.026	118,703	97,080
50	0.002	296,759	236,128

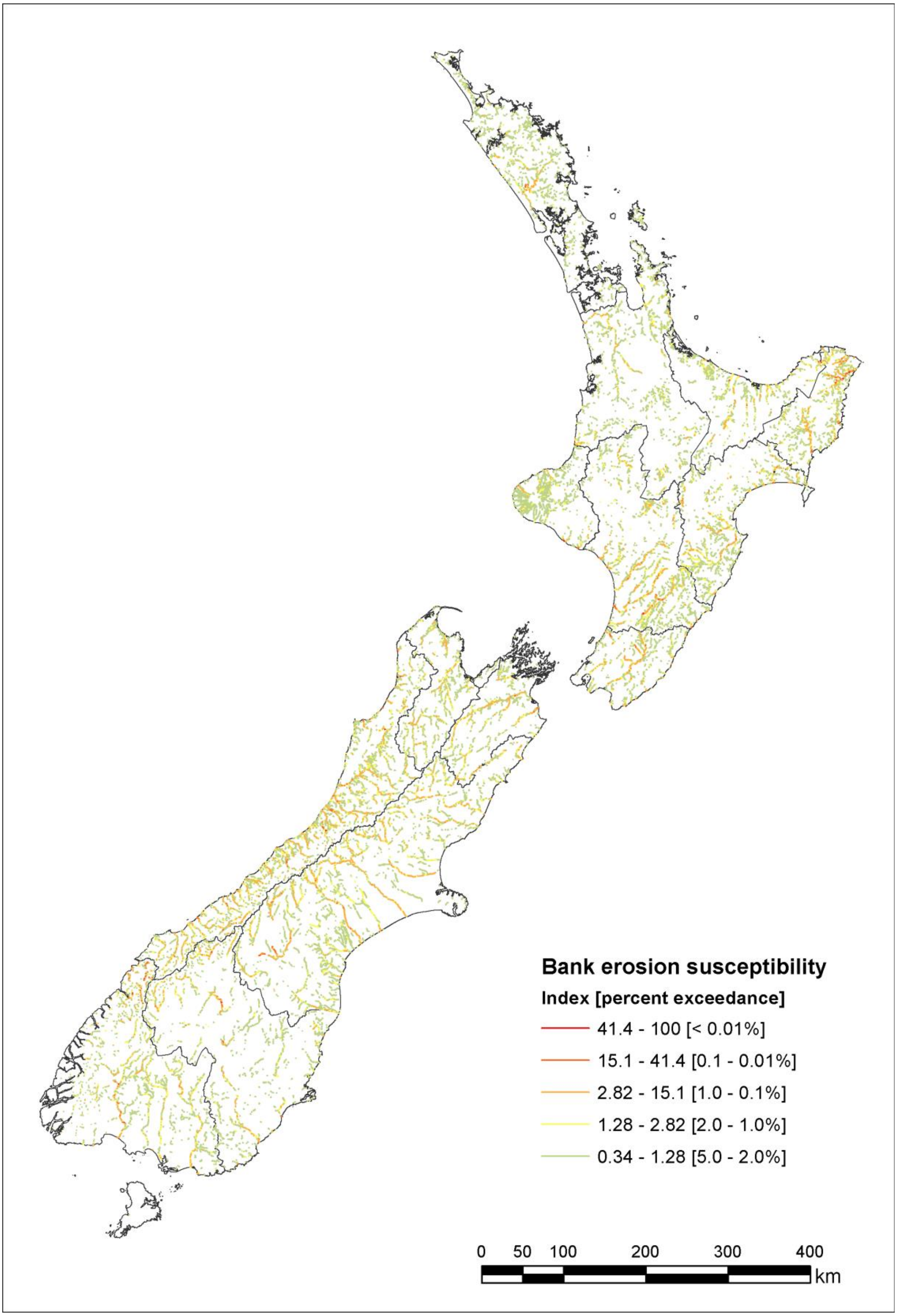

Figure 4. National map of streambank erosion susceptibility index values for the REC v2.5 digital river network displaying stream links with an index value ≥ 0.337 that equates to the upper 5% of ranked links (Table 1) that exhibit the highest susceptibility. Region boundaries are shown in black.

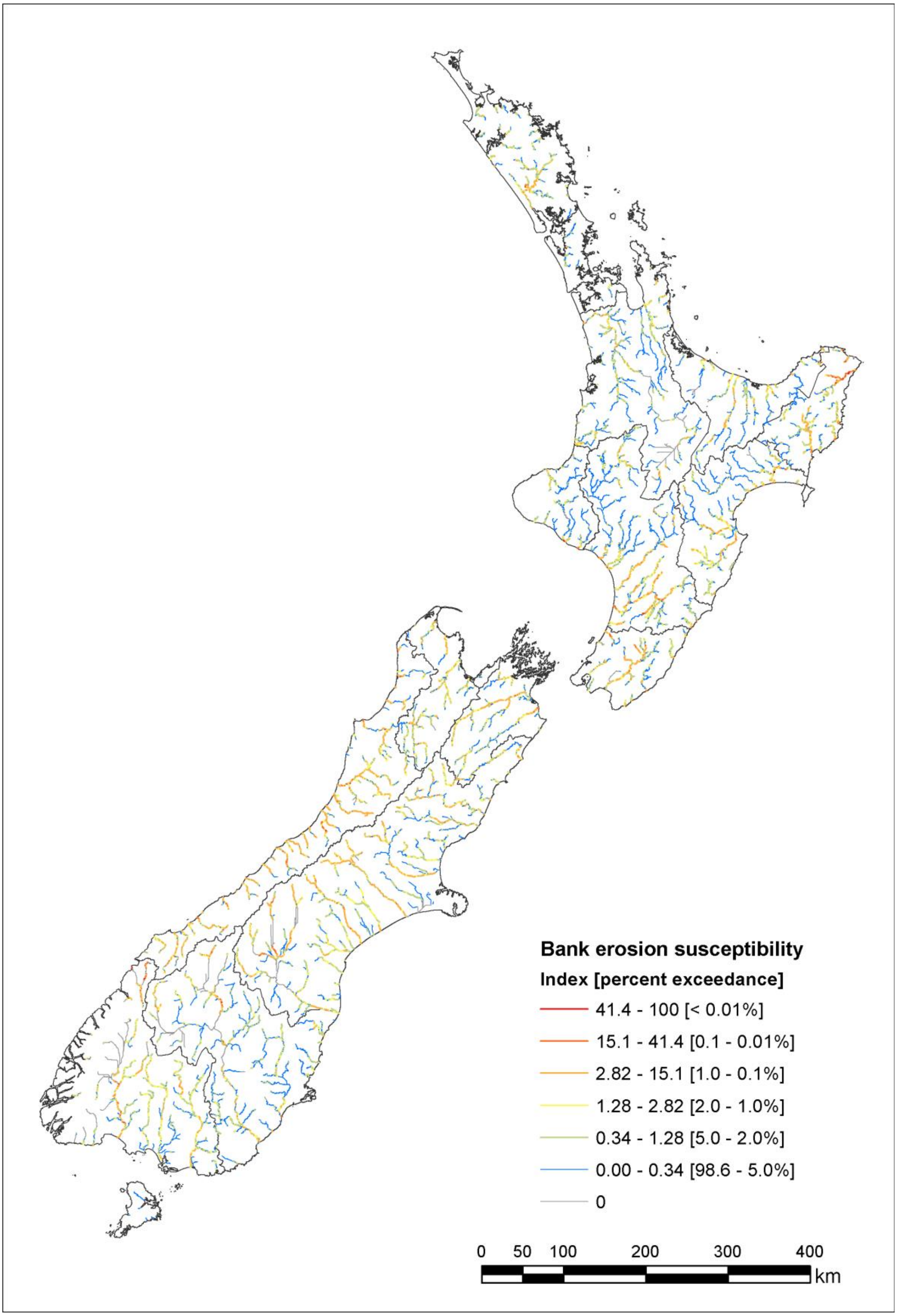

Figure 5. National streambank erosion susceptibility index and corresponding percent exceedance values for the REC2.5 digital river network displaying only Strahler 5th-order and above-stream links for visualisation. Links with index values of zero fully intersect lakes. The colour scheme discriminates the upper 5% of ranked index values (refer Table 1) that exhibit the highest susceptibility (excluding blue and grey links). Region boundaries are shown in black.

3.2 Index limitations

Limitations associated with the derivation of the index for susceptibility to streambank erosion are outlined below. These include several limitations previously identified in Smith (2020) as well as additional points for consideration alongside index results. The index provides a relative measure of the spatial variation in reach-scale susceptibility to bank erosion. It does not show variation in the magnitude of sediment loads generated by bank erosion. Further work required to quantify bank erosion derived sediment loads is discussed in the next section.

- **Model calibration data.** Bank migration rate data for calibration are limited to mapped reaches within the Manawatū and Kaipara catchments. Although this data set spans a range of observed reach-scale bank migration rates, riparian woody vegetation extents, and bank erodibility values for the mapped reaches, it does not represent the wider range of channel forms and conditions present nationally. For instance, no data are available for braided rivers. Future data collection needs to support national quantification of bank erosion are discussed in section 4.
- **Erosion control works or recent riparian planting.** The index does not capture the effect of erosion control works (e.g. riprap) or riparian plantings after 2002 when high-resolution national woody vegetation cover mapping was completed. As a result, stream links with higher index values would have reduced susceptibility if these interventions were considered. This is notable in some lowland reaches where river engineering works ensure little or no channel movement whereas higher index values may be predicted due to the absence of these effects when calculating the index. This is also relevant in urban areas and other locations where the effects of channelisation may alter susceptibility but are not represented. Future implementations of the index could include both erosion control works and riparian plantings once national-scale spatial data are available. This is consistent with the approach outlined by Smith et al (2019) where spatial data on erosion control works and riparian plantings was included in bank erosion modelling for catchment sediment budgets.
- **Spatial correspondence between riparian woody vegetation and channel banks.** Accurate spatial representation of narrow corridors of riparian woody vegetation along stream networks is a challenge. Spatial errors in both the planform and extent of modelled stream networks and the classification of woody vegetation cover in the riparian zone will contribute to over- and underestimation of susceptibility in places. This error could be reduced with national LiDAR coverage to derive improved river network geometry from higher resolution digital elevation models (DEMs) and riparian woody cover from canopy height models (CHM). Use of LiDAR-derived DEMs would also improve the accuracy of slope information.
- **Streambank erodibility.** Given the absence of national data on the silt + clay content of bank material that may be used to estimate bank erodibility, it was necessary to infer this property from national soil texture maps. This is important because a) FSL based soil texture data are the lowest resolution input to the index, and b) these data do not capture localised variations in bank material texture or locations where channels have incised into bedrock. More generally, the lack of national data on spatial patterns in reach-scale bank material composition (including gravel content) is an important limitation in the representation of bank erodibility.

- **Mean annual flood estimation.** The index depends on the spatial estimation of MAF based on NIWA's Regional Flood Estimation Tool v2 (Henderson & Collins 2016; Henderson et al. 2018). Therefore, errors in MAF propagate into the predicted index values. Factors such as reservoir flood control or flow diversions not represented in the estimated MAF also affect bank erosion susceptibility. Likewise, the effect of impervious surfaces in urban areas is not represented in the prediction of MAF and may contribute to under-estimation of susceptibility in some highly urbanised catchments. On the other hand, projections of changes in MAF under climate scenarios (e.g. Collins et al 2018) might be used to predict possible future changes in susceptibility.
- **Bank erosion in tidal reaches.** Higher index values occur in the lowermost reaches of rivers that extend into the tidal zone in some instances. This tends to reflect high predicted MAF values, lower riparian woody vegetation, and sometimes sandy channel material with low silt + clay content. It may also reflect the lack of representation within the index of erosion defences in these locations that prevent channel change. Furthermore, no account is made for possible tidal effects on bank erosion rates (Fagherazzi et al. 2004).
- **Limited applicability to low order streams.** Previous model calibration was limited to stream orders 3−7. Application to lower order streams has not been tested due to insufficient levels of observable lateral change in channel banks on these streams when mapping from repeated high-resolution aerial photographs. Generally, the model predicts low index values for streams below third order due to lower estimated MAF and greater levels of valley confinement.
- **Role of woody vegetation in bank erosion for low-order streams.** The role of woody riparian vegetation in bank erosion for low-order streams is uncertain. Wider channels were observed under forest compared to pasture for second-order streams in the Waikato region and this was attributed to suppression of ground vegetation cover by canopy shading (Davies-Colley 1997). However, the effectiveness of riparian woody vegetation in promoting bank stability may increase as catchment size increases and channels widen, reducing the potential effect of canopy shading (Hughes 2016). This is consistent with studies that show increased bank stability with the presence of woody vegetation (e.g. Abernethy & Rutherfurd 2000; Hubble et al. 2010; Konsoer et al. 2015).
- **Livestock impacts on streambanks.** Livestock trampling and foraging impacts on streambanks are not captured by the index. This is a difficult factor to represent because of the localised and temporally variable nature of livestock access to channel banks, which may vary at paddock, farm, and catchment scales. Notably, livestock grazing was reported to show no effect on channel form for wider, higher-order streams in Southland compared to narrow (<2 m), low-order streams under intensive grazing (Williamson et al 1992).

4 Requirements for national quantification of bank erosion

Quantification of streambank erosion contributions to catchment suspended sediment loads on a national scale requires significant further work. In this section, we outline the scope of work needed by identifying the data and analysis requirements to enable national prediction of sediment loads from bank erosion. Our approach builds on the bank erosion model described by Smith et al (2019) that formed the basis for computing national susceptibility to streambank erosion. This model predicts mean annual net suspended sediment loads from reach-scale bank erosion based on the REC v2 digital river network. The model was developed as an improvement on the previous representation of bank erosion in the SedNetNZ sediment budget model (Dymond et al 2016).

However, neither the bank erosion model nor SedNetNZ were initially designed to predict loads at national scale. This is due to limitations associated with available spatial data, erosion process understanding, and the erosion rate data required for model calibration. To date, applications of SedNetNZ focus on regional-scales and make use of spatial datasets held by many councils, such as for erosion control, riparian planting, riparian fencing, stopbanks, as well as hydrological data (e.g. Spiekermann et al. 2017b; Smith et al. 2020; Neverman et al. 2021a, b). The advantage of SedNetNZ relates to the representation of sediment load contributions by erosion process, whereas other models with national coverage, such as NZeem® (Dymond et al. 2010) or the updated suspended sediment load estimator (Hicks et al. 2019) predict total suspended sediment loads or yields but provide no information on erosion process-specific contributions to load.

To achieve national quantification of suspended sediment loads from streambank erosion, we need to overcome impediments to national-scale application of the bank erosion model. The scope of work outlined below anticipates two phases. The first phase focuses on data collection, analysis and modelling needed to represent bank erosion nationally. The second phase anticipates the future availability of national-scale LiDAR coverage that would be required to achieve further improvements beyond phase 1.

Once improved and applied nationally, predictions of bank-derived mean annual net suspended sediment loads could be combined with existing national models of suspended sediment load to provide information on the relative load contribution of bank erosion.

National quantification of bank erosion – phase 1

Phase 1 focuses on acquiring essential data needed for national-scale bank erosion modelling. This lack of representative data for model calibration and validation is currently the main impediment to national quantification of bank erosion. The following points could form the focus for targeted national-scale data collection and analysis:

- **Measurement of reach-scale bank migration rates from repeated high-resolution aerial imagery obtained by regional councils.** Data collection could focus on representing the range in river forms and channel conditions that exist nationally. These data are essential to underpin model calibration and validation following the method described by Smith et al. (2019) that would enable national assessment of model predictive performance.

- **Development of a sub-model for predicting reach-scale mean bank heights for use in estimating bank erosion suspended sediment loads nationally.** Bank height (H_j) is required to compute gross mean annual suspended sediment load (t y^{-1}) from bank erosion (B_j), where $B_j = \rho M_j H_j L_j$, ρ is the bulk density of bank material (t m^{-3}), M_j is the modelled reach-average bank migration rate from equation 1 (m y^{-1}), and L_j is the reach length (m).
- **Quantification of reach-scale bank sediment accretion.** Estimating bank accretion allows us to account for sediment storage that offsets gross erosion and determine the net sediment load from bank erosion. Currently, net bank erosion is estimated as one-fifth of gross erosion based on measurements from the Waipaoa River catchment only (De Rose & Basher 2011). More data are needed to represent how bank accretion varies spatially and by river form to improve prediction of net bank-derived suspended sediment loads.

Table 2 links the required data, their source and use in the model, and the specific improvements that will likely result during phase 1. This work will include development of statistical sub-models for reach-scale mean bank height and bank accretion that relate these measurements to spatial variables (e.g. flow statistics, slope, riparian woody vegetation, etc.) available nationally to enable prediction across the REC v2 digital river network. The resulting predictions of bank height and bank accretion will be incorporated into the bank erosion model, which will be calibrated and validated using the new bank migration rate data. The approach in phase 1 would meet MfE's requirement for a national REC v2 based estimate of mean annual suspended sediment loads from bank erosion.

Table 2. Summary of phase 1 data requirements, use, source, and resulting improvements that would enable progress to national quantification of streambank erosion within catchment sediment budgets

Data	Use	Source	Improvements
Reach-scale bank migration rates	National calibration of sinuosity and bank erodibility factors following method by Smith et al. (2019) and validation of bank migration rate predictions required for quantifying sediment loads from bank erosion.	Mapping of reach-scale channel planform change from existing repeated, high-resolution (<0.5 m) regional aerial photography spanning an approximate 10-year interval for change detection.	• Increase national representativeness of migration rate data to span a wider range in river channel forms (e.g. wandering, braided etc) and channel conditions (e.g. extent of riparian woody vegetation, bank erodibility). • Ability to quantify uncertainty in model predictions of reach-scale bank migration rates based on cross-validation using national scale data.
Reach-scale bank height	Sub-model to predict spatial variation in reach-scale mean bank height on national scale for use in calculating bank erosion loads.	Extract bank height data from LiDAR DEMs (where coverage is available) and relate to spatial variables with national coverage.	• Improve accuracy in prediction of mean bank height at reach-scale for use in estimating bank erosion sediment loads. • Ability to quantify uncertainty in mean bank height predictions based on cross-validation.
Reach-scale bank accretion	Sub-model to predict reach-scale bank accretion for use in computing net sediment loads from bank erosion.	Repeated LiDAR surveys of river corridors (where available). Use to quantify reach-scale volumetric change by differencing DEMs and relate to spatial variables.	• Improve estimate of net bank erosion using bank accretion data from repeated LiDAR surveys of river corridors. • Ability to quantify uncertainty in reach-scale accretion used to estimate net bank erosion based on measured reaches.

National quantification of bank erosion – phase 2

While phase 1 could deliver significant improvements in the underpinning measurement data and enable national-scale modelling of sediment loads from bank erosion for the first time, the model will still be dependent on the availability and resolution of national spatial datasets. For instance, in the absence of national LiDAR coverage (excludes most of the Horizons and Otago regions),[1] we are not currently able to improve model inputs for channel slope or sinuosity on a consistent national basis.

Assuming complete national LiDAR coverage is achieved in the future, then further progress could be made to improve national bank erosion quantification beyond that outlined above. National LiDAR coverage would enable derivation of a new digital river

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[1] Map of current and forthcoming regional LiDAR coverage: https://www.linz.govt.nz/data/linz-data/elevation-data

network based on a higher-resolution national DEM to replace the current REC v2 digital network. This new digital river network could then form the basis for computing channel slope, planform, and sinuosity on a national scale with improved accuracy. Mean annual flood estimates would need to be re-computed by NIWA for the LiDAR DEM-based digital network for use in the bank erosion model. National LiDAR coverage could also allow quantification of riparian woody vegetation from canopy height models (CHMs) and improve representation of the alignment between the channel network and riparian woody vegetation. These revised model inputs could then replace previous inputs, which, combined with the data-driven improvements outlined in phase 1, could further enhance both the representation of factors influencing bank erosion and the prediction of suspended sediment loads from bank erosion on a national scale.

5 Conclusion

This memorandum presents the first national index for susceptibility to streambank erosion developed in New Zealand. The approach outlined in the feasibility study by Smith (2020) has been refined and fully implemented across the REC v2.5 digital river network. The index of susceptibility provides a quantitative basis for comparing and prioritising catchments for management interventions, such as riparian planting, to reduce streambank erosion. It may also form the basis for assessing the impact of these interventions in the future.

We believe the index for susceptibility to streambank erosion represents an important step in the longer-term effort to better quantify the contribution of streambank erosion to catchment suspended sediment loads on a national scale. To achieve this ambition will require future investment in targeted data collection and analysis to overcome important barriers to progress. We have outlined key focus areas that would support this progress and provide a more data-driven basis for national-scale modelling of suspended sediment loads from streambank erosion.

6 Acknowledgements

We thank the Ministry for the Environment for funding this work, and Stephen Fragaszy for input to the development of the proposal and feedback on the technical memorandum. We acknowledge NIWA for supplying mean annual flood estimates for the REC v2 digital river network that were made available by MfE for use in this project. Andrew Neverman is thanked for reviewing an earlier draft of the memorandum.

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Appendix 1

Smith H 2020. Memorandum on the technical feasibility of developing a national index for susceptibility to streambank erosion. Manaaki Whenua – Landcare Research Contract Report LC3769 prepared for the Ministry for the Environment.

Memorandum on the technical feasibility of developing a national index for susceptibility to streambank erosion

Manaaki Whenua – Landcare Research contract report number: LC3769

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1. Scope

The Ministry for the Environment contracted Manaaki Whenua – Landcare Research (MWLR) to examine the technical feasibility of developing a national index for spatial variation in susceptibility to streambank erosion. The intended use of this index is to provide a quantitative and consistent basis for assessing susceptibility to streambank erosion that can be used to support the prioritisation and targeting of riparian land management interventions for sediment control.

The approach for developing a susceptibility index for streambank erosion outlined in this technical memorandum is based on components of the improved bank erosion model described by Smith, Spiekermann et al. (2019) that express susceptibility. This bank erosion model adopts a conceptual, steady-state modelling approach that aims to better represent the spatial variability in factors influencing bank erosion at the river-reach scale, such as stream power, the extent of riparian woody vegetation, valley confinement, and the composition of bank material that influences bank erodibility.

The requirement for a nationwide susceptibility index means that only spatial data sets available on a national scale can be used as inputs. As a result, the balance between model complexity, spatial resolution, and the level of available data forms a key consideration in developing the susceptibility index for streambank erosion.

2. National streambank erosion susceptibility index

This analysis is based on factors controlling bank migration rate, which is interpreted as largely a response to the susceptibility to bank erosion. Previously, Smith, Spiekermann et al. (2019) represented the bank migration rate (m y^{-1}) as a function of a set of spatial factors known to influence bank erosion. Various studies report increasing bank migration with increasing bankfull discharge, mean annual flood, and stream power (Hooke 1979; Nanson & Hickin 1986; Walker & Rutherfurd 1999; Dymond et al. 2016; Alber & Piégay 2017). Other factors, such as the cohesiveness of bank materials (Julian & Torres 2006), valley confinement (Hall et al. 2007), and riparian woody vegetation (Abernethy & Rutherfurd 2000), are also important, resulting in high levels of spatial variability in bank erosion.

A simplified empirical approach for representing bank migration rate (M_j) is outlined here and could form the basis for computing the index of susceptibility to streambank erosion. M_j can be calculated for each stream link within the national River Environment Classification (REC) network as follows:

$$M_j = SP_j T_j V_j \left(1 - PR_j\right) \tag{1}$$

where SP_j is the stream power of the mean annual flood for the j-th stream link, T_j is the soil texture-based erodibility factor of the j-th link, V_j is the valley confinement factor of the j-th link, and PR_j is the proportional extent of riparian woody vegetation of the j-th link. This approach excludes terms for channel sinuosity and erosion control works that were included in the model by Smith, Spiekermann et al. (2019) due to limits on data available at the national scale.

Stream power is the work done on the channel by the water per second per unit channel length. Stream power (SP_j) for the mean annual flood (MAF, $m^3 s^{-1}$) is estimated for each REC stream link by the product of MAF and channel slope. This does not include the density of water (1000 kg m^{-3}) and acceleration due to gravity constants (9.81 m s^{-2}) that form part of the gross stream power equation, as these provide no information on spatial variation that will improve prediction.

The texture of the bank material influences bank migration rates (Hickin & Nanson 1984; Wynn & Mostaghimi 2006). More cohesive banks with higher silt and clay content tend to be more resistant to erosion (Simon & Collison 2001; Julian & Torres 2006). Therefore, an empirical relationship based on percent silt + clay content (*SC*) may be used to estimate the soil critical shear stress (τ_c) (Julian & Torres 2006) as follows:

$$\tau_c = 0.1 + 0.1779SC + 0.0028SC^2 - 0.0000234SC^3 \qquad (2)$$

SC is obtained from spatial data on soil textural classes. The soil texture-based erodibility factor (T_j) can then be represented by a power function to characterise the relationship between τ_c and bank erodibility for the *j*-th stream link:

$$T_j = c{\tau_{cj}}^{-d} \qquad (3)$$

where the *c* and *d* parameters are fitted using bank migration rate data. The use of a power function is based on experimental (Arulanandan et al. 1980) and field (Hanson & Simon 2001; Julian & Torres 2006) observations of the relationship between stream bank or bed critical shear stress and erodibility.

Floodplain extent and the level of valley confinement are factors that may limit lateral bank migration (Hall et al. 2007; De Rose & Basher 2011). The presence of steep valley sides and/or exposure of bedrock influence the spatial patterns of erosion and deposition (Fryirs et al. 2016). A valley confinement factor (V_j) may be computed as per Smith, Spiekermann et al. (2019) using the mean slope in degrees (SB_j) of a buffer zone [4 × 15 m digital elevation model (DEM) pixel width] either side of the *j*-th stream link:

$$V_j = \left(1 - e^{\left(-15/SB_j\right)}\right)^{11} \qquad (4)$$

Woody riparian vegetation typically increases bank stability via the effects of root reinforcement and root cohesion (Abernethy & Rutherfurd 2000; Hubble et al. 2010; Polvi et al. 2014; Konsoer et al. 2015). Woody vegetation can also increase roughness and flow resistance, thereby reducing the boundary shear stress acting on the bank surface (Thorne 1990). In addition, woody vegetation has hydrological effects on bank stability. For example, woody vegetation was found to be more effective than grass cover at lowering soil water content, due to increased canopy interception and evapotranspiration, thus improving bank stability (Simon & Collison 2002). The effect of riparian woody vegetation (PR_j) may be represented at the stream link scale by reducing bank migration rates proportionally to the extent of woody riparian vegetation along the *j*-th stream link (equation 1).

The index of susceptibility to streambank erosion (I_j) could be computed by scaling M_j to the range 0−1 on a national basis to provide a relative measure of susceptibility across all modelled stream links as follows:

$$I_j = \frac{M_j - M_{min}}{M_{max} - M_{min}} \qquad (5)$$

where M_{max} and M_{min} correspond to the maximum and minimum values for M_j, respectively. This scaling procedure produces a simple, dimensionless index that can be used to compare erosion susceptibility for stream links across the REC network.

3. Spatial data requirements

The spatial data sets required to calculate the susceptibility index for streambank erosion include regional mean annual flood (MAF) statistics, the REC and Land Information New Zealand (LINZ) digital stream networks, national 15 m DEM, the Fundamental Soil Layers (FSL) (Newsome et al. 2008), and mapped woody vegetation cover (Dymond & Shepherd 2004). The index can be computed for every REC stream link, which average 700 m in length, and therefore can provide a high level of spatial detail.

However, it should be noted that the spatial detail is constrained by the resolution of the individual input layers (e.g. FSL) not the REC stream network. The 15 m resolution of the national DEM is a limitation for determining channel slope and valley confinement, particularly for lowland reaches, where channel slopes tend to be overestimated. This could be improved with the future availability of LiDAR nationally.

Stream power is computed using MAF, estimated from NIWA's Regional Flood Estimation Tool v2 (Henderson & Collins 2016; Henderson et al. 2018) and channel slope. This tool provides flood statistics for all stream links based on analysis of data from 640 river gauging stations but is only available for version 1 of REC.[2] Hence the susceptibility index is based on the REC1 stream network rather than REC2. An attempt to join the REC1 flood statistics to the REC2 stream network proved unsatisfactory, with too many stream links being assigned incorrect flood statistics, in part due to the increase in the number of links in the REC2 network compared to REC1.

Use of the REC1 stream network represents a trade-off between the nationwide availability of MAF estimates for all stream links for REC1 versus improvements in the spatial representation of the stream network in REC2. At present, spatial representation of most hydrological variables continues to be based on REC1 (for a discussion of this issue, see the FAQs for NZRivermaps;[3] Booker & Whitehead 2017). If NIWA's regional flood estimation is updated to REC2, then the susceptibility index for streambank erosion could be updated using the REC2 stream network. Reach-level sinuosity information is also available for REC2 but not REC1, so this could be included in the susceptibility index if it were updated to REC2.

Spatial data on silt + clay (SC) content used to determine the soil texture-based erodibility (T_j) factor can be estimated from soil textural classes compiled from the FSL. To calibrate T_j, a combined data set comprising measured reach-scale bank migration rates from the Manawatu and Kaipara catchments is used to fit parameter values (Spiekermann et al. 2017; Smith, Spiekermann et al. 2019). This calibration data set was used in previous applications of the full bank erosion model in Southland (Smith, Herzig et al. 2019) and Hawke's Bay (Smith et al. 2020).

Spatial information on riparian woody vegetation is obtained from satellite imagery and intersected with the LINZ digital stream network (comprising streams lines and polygons) obtained from 1:50,000 topographic mapping. The mapped stream network is used in preference to the DEM-derived channel network in REC because it exhibits better planform accuracy, which should improve spatial correspondence between channel position and riparian woody vegetation.

In addition, to better represent wider channels, particularly braided channels with large areas of exposed gravel, LCDB v5 'river' and 'gravel and rock' land cover classes can be used to produce a revised river polygon layer. Mapped 'gravel and rock' areas located beyond the extent of the channel network need to be removed, which is a significant task at a national scale. This approach will enable better representation of wide channels with exposed gravel beds and will improve the alignment between channel banks and mapped woody vegetation when quantifying the reach-scale extent of riparian woody vegetation cover.

The proportion of riparian woody vegetation can be computed from the intersection of the digital stream network with a 15 m buffer and a classified map of 2002 woody vegetation cover (called EcoSat Woody), which was derived from Landsat TM at 15 m resolution (Dymond & Shepherd 2004). The 2018 New Zealand Land Cover Database (LCDB) is not used, despite being more recent, because it has a

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[2] https://data-niwa.opendata.arcgis.com/datasets/nz-flood-statistics-henderson-collins-v2-layer

[3] https://shiny.niwa.co.nz/nzrivermaps/

minimum mapping unit of 10,000 m^2 versus 225 m^2 for EcoSat. This makes LCDB less suitable for characterising the narrow corridors of woody vegetation often found along channel banks.

4. Regional example

A preliminary implementation of the susceptibility index has been completed to demonstrate feasibility and provide a visualisation of possible outputs. This focuses on the Horizons Region. Figure 1 shows the spatial variation in index values (range 0−1) across the REC1 stream network for this region. For display purposes, only those stream links equating to third order and above are shown. The outputs in Figure 1 require further updating before these can be finalised. This includes re-calibration of the soil-texture-based erodibility component of the index (described below).

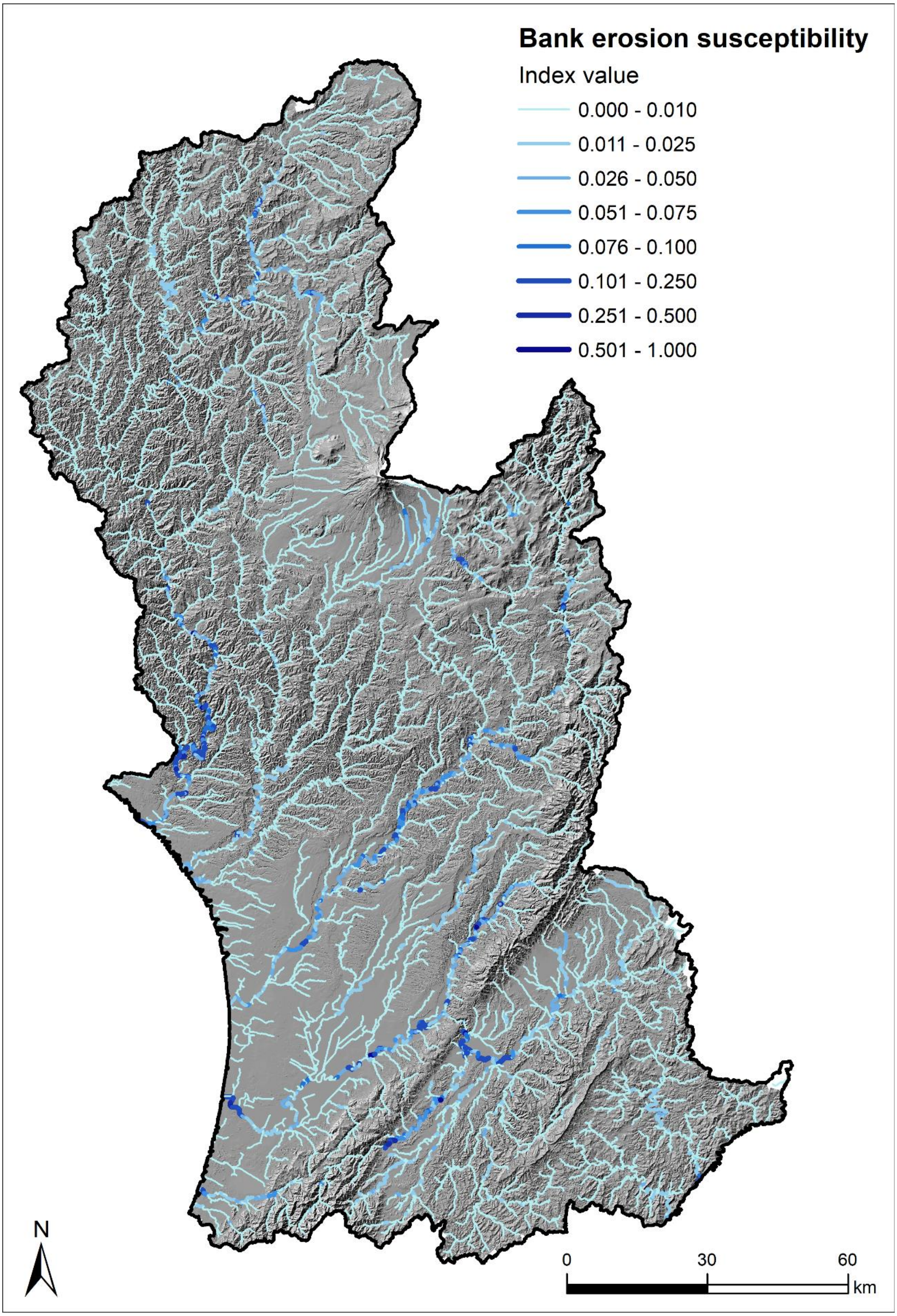

Figure 6: Map of preliminary streambank erosion susceptibility index values for the REC1 network (displaying third-order and above stream links for visualisation) in the Horizons region. Underlying hill shade is based on 15 m DEM. The index values displayed do not account for recent riparian plantings or erosion control works.

5. National implementation and catchment comparison

Before computing the index across the national REC network, some further data pre-processing is required. This includes:

- recalibrating the parameters for the soil-texture-based erodibility factor (T_j) using MAF values from NIWA's regional flood estimation tool, rather than the MAF obtained from regional regression relationships with mean annual discharge, q_j (i.e. $MAF_j = aq_j{}^b$) that were used previously
- refining the nationwide representation of channel extent based on LINZ river polygons using data from LCDB5 (as described above) to improve the spatial correspondence between channel margins and mapped woody vegetation cover
- updating the 2002 woody vegetation cover map with a recent map of woody cover (due for completion and release by MWLR this year) − the national index could be supplied initially with 2002 woody cover and then updated once the more recent national woody vegetation map becomes available.

FSL soil particle size data is unavailable for the Gisborne District, so an alternative approach to estimating this input will be needed for implementation to ensure consistency with results for the rest of the country.

Another consideration relates to how the index values are aggregated for comparison between catchments and regions nationally. While mean index values could be computed for catchments, this might provide a misleading basis for comparison. For instance, larger catchments might appear to have a low index value when averaged overall but exhibit high levels of within-catchment variability. Comparing between stream orders could help, in part, to provide a more 'like-for-like' basis for the comparison (i.e. compare mean index values by stream order between catchments). Furthermore, some natural areas experience high bank erosion rates due to high stream powers and erodible banks. These could be excluded as being unsuitable for mitigation in some areas (e.g. Department of Conservation estate).

6. Index limitations

The proposed index of susceptibility provides a simplified view of streambank erosion. While the index can be computed for the REC stream network on a national scale using available data, there are some important limitations that warrant consideration.

- The accurate spatial representation of narrow corridors of riparian woody vegetation along stream networks is a challenge. Spatial errors in both the planform and extent of modelled stream networks and the classification of woody vegetation cover in the riparian zone will contribute to over- and underestimation of susceptibility in places.
- Data available for calibrating the soil-texture-based erodibility factor are limited to mapped reaches within the Manawatu and Kaipara catchments. Although this data set spans a range of observed reach-scale bank migration rates, riparian woody vegetation extents, and bank erodibility values for the mapped reaches, it does not represent the full range of channel conditions present nationally. For instance, no data are available for braided rivers.

- Previous model calibration was limited to stream orders 3−7. Application to lower order streams has not been tested due to insufficient levels of observable lateral change in channel banks on these streams when mapping from repeated aerial photographs. Generally, the model predicts low migration rates for streams below third order due to lower estimated MAF and greater levels of valley confinement.
- In addition, the role of woody riparian vegetation in bank erosion for low-order streams is uncertain. Wider channels were observed under forest compared to pasture for second-order streams in the Waikato region and attributed to suppression of ground vegetation cover by canopy shading (Davies-Colley 1997). However, the effectiveness of riparian woody vegetation in promoting bank stability may increase as catchment size increases and channels widen, reducing the potential effect of canopy shading (Hughes 2016).
- The index does not capture the effect of erosion control works (e.g. riprap) or recent riparian plantings. As a result, some stream links with higher susceptibility would have low susceptibility if these factors were considered.
- The effect of livestock trampling and foraging on streambanks is not captured by the index. This is a difficult factor to represent because of the localised and temporally variable nature of livestock access to channel banks, which may vary at the paddock, farm and catchment scales. Notably, livestock grazing was reported to show no effect on channel form for wider, higher-order streams in Southland compared to narrow (<2 m), low-order streams under intensive grazing (Williamson et al. 1992).

7. Summary

- The development of a national index of susceptibility to streambank erosion is feasible. An approach has been outlined here that could be implemented nationwide using the REC stream network and available spatial data sets. Important considerations are the interpretation of index values and ensuring a consistent basis for their comparison between catchments and regions.
- Although the index provides a reach-averaged basis for determining spatial patterns in bank erosion susceptibility, it does not replace the need for local assessments of where to target riparian planting. This requires consideration of factors not captured by the index, such as the specific location of bank erosion within a reach, the presence of erosion control works, the space available for planting, and exactly what and where to plant at each site.

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