Assessment of Sediment Load Reductions to Achieve Target Attribute States in the Streams and Rivers of the Auckland Region

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Executive Summary

The National Policy Statement for Freshwater Management 2020 (NPS-FM) requires Auckland Council (AC) set a target attribute state (TAS) for fine suspended sediment for all rivers and streams in the region and prescribe limits on resource use that will achieve these targets. As a first step in setting TASs and limits, this study has assessed sediment load reductions required to achieve options for several TASs in streams and rivers of the Auckland region.

Fine suspended sediment is a contaminant that affects ecosystem health by changing the optical characteristics of water (visual clarity and light penetration) as well as physical effects on aquatic animals such as gill clogging and abrasion. The NPS-FM fine suspended sediment attribute is quantified by observations of visual clarity based on measurements taken in the field as the horizontal sighting distance of a black disc, which therefore has units of metres (m). The fine suspended sediment attribute is defined (i.e., both the baseline state and the TASs) by the median value of monthly visual clarity observations in streams and rivers.

This study does not consider how the sediment load reductions would be achieved or whether the TASs are reasonable. Rather. it aims to inform AC about the magnitude of the load reductions needed for each option, how these vary across the region, and the uncertainty inherent in the assessments. In addition, this study does not consider sediment objectives for downstream estuarine receiving environments. Sediment load reductions required to meet any (yet to be identified) sediment-related outcomes in estuaries could be greater than the load reductions estimated in this report to achieve TASs in the region’s streams and rivers.

The analysis undertaken by this study utilised three models that were informed by regional river water quality monitoring data. These models were used to (i) estimate baseline visual clarity, (ii) estimate the absolute reductions in catchment sediment loads required to achieve TASs defined in terms of visual clarity, and (iii) estimate the catchment sediment load reduction required as a proportion of the baseline catchment sediment load. The estimated baseline visual clarity was combined with numeric criteria (i.e., required median visual clarity values) corresponding to each TAS and calculations were made of the amounts by which baseline loads would need to be reduced to allow the TASs to be achieved (i.e., the load reduction required). The study includes an assessment of the uncertainties associated with the input models describing baseline state and loads.

The study assessed sediment load reductions required to achieve three TAS options for rivers and streams across the region. The options for TASs are defined in terms of the lower thresholds for the A, B or C bands that are used as shorthand by the NPS-FM to define TASs. The three TAS options are defined by the uniform requirement of the A, B and C-band thresholds applied to all stream and river receiving environments across the region.

The sediment load reductions were evaluated for all individual river segments represented by GIS-based digital drainage network (version 2.4), which underlies the River Environment Classification in the Auckland region. The results for the individual receiving environments were aggregated to report on individual, stormwater Consolidated Receiving Environments (CREs, of this there are 11), Freshwater Management Units (FMUs, of which there are three), and the whole region.

The results for the three FMUs and the whole region are the most succinct and broad summaries of the load reductions required and are shown in Table A below. The load reductions that were assessed for the C-band TAS represent the national bottom line and represent the minimum that AC’s implementation of the NPS-FM would need to include to achieve acceptable sediment loads in the streams and rivers of the region. The study results indicate that a regional sediment load reduction of 6% (90% confidence interval 3% - 11%) is required to achieve at least the national bottom line for rivers (i.e., the C-band TAS) in the Auckland region. The load reductions required were largest for the A-band TAS and least for the C-band TAS. This is because the A-, B- and C-band TASs represent increasing levels of environmental quality and therefore increasingly stringent criteria. It should be kept in mind that the results vary considerably at the sub-regional scale and can be significantly higher in some catchments than shown in Table A below.

Monte Carlo analyses were used to estimate the uncertainties associated with three key components of the study: the estimated baseline visual clarity, the proportional reductions in suspended sediment load required to achieve TASs, and the baseline sediment loads. The Monte Carlo analyses simulated 100 ‘realisations’ of the load reduction calculations, which were then used to define the probability distributions of all estimates. The probability distribution describes the range over which the true values of the load reductions are expected to lie. Table A shows the best estimate of the load reduction as the mean value of these distributions, and the extreme lower and upper values were represented by the 5th and 95th percentiles of the distributions.

Table A. The sediment load reductions required for the three FMUs and the region for the TAS options as a proportion of the baseline sediment load (%). The load reductions are expressed as proportions of the baseline load and the values shown in parentheses are the 5th and 95th confidence limits for the reported values. Bands C to A define the TASs which in all cases are improvements to the baseline instream water quality.

TAS option	Sediment load reduction as proportion of baseline load (%)			
	Kaipara FMU	**Hauraki FMU**	**Manukau FMU**	**Region**
C-band	5 (1 - 13)	4 (2 - 8)	15 (7 - 25)	6 (3 - 11)
B-band	10 (4 - 23)	9 (6 - 13)	22 (15 - 32)	11 (7 - 16)
A-band	19 (7 - 40)	15 (10 - 22)	30 (22 - 40)	19 (12 - 28)

It is unlikely that the uncertainties associated with the assessments made by this study can be significantly reduced in the short to medium term (i.e., in less than 5 to 10 years). This is because, among other factors, the modelling is dependent on the collection of long-term water quality and sediment load data and reducing uncertainty would require data for considerably more sites than were available for the present study.

This report can help inform the process for deciding on limits to resource use, by providing an assessment of the approximate magnitude of sediment load reductions needed to achieve several options for TASs, with a quantified level of confidence for each option. The NPS-FM requires regional councils to have regard to these and other things when making decisions on setting limits. This report shows that these decisions will ultimately need to be made in the face of uncertainty.

1 Introduction

The National Policy Statement for Freshwater Management 2020 (NPS-FM, NZ Government, 2023) requires Auckland Council (AC) to set a target attribute state (TAS) for suspended fine sediment for all rivers and streams in the region and prescribe limits on resource use that will achieve these targets. As a first step in this process, this study has predicted baseline state of the suspended fine sediment attribute in streams and rivers in the Auckland region, and assessed the reductions in sediment load that would be required to achieve three options for TASs that are defined in accordance with the NPS-FM. The purpose of the study to inform AC about: (i) where the options for TASs are currently being achieved, and (ii) where this is not the case, the size of the gap between baseline sediment loads and loads that would allow the TAS options to be achieved. This report does not describe how the load reductions can be achieved or whether the TASs are reasonable. These decisions need to be made by other processes but should be informed by the results of this study.

High loads of suspended fine sediment discharged to aquatic ecosystems can have several types of impacts. Suspended fine sediments change the optical characteristics of water (visual clarity and light penetration), which impacts on the 'visual habitat' of animals and the aesthetic and recreational value of water bodies. Reduced light penetration can inhibit growth of aquatic plants and algae leading to ecosystem impacts including significant changes to ecosystem structure. Sediments suspended in the water column can also have physical effects on animals such as gill clogging and abrasion, effects on some migratory fish species and effects on food quality and quantity. Deposition of fine sediment on the beds of rivers, lakes and estuaries degrades benthic habitat and can result in burial and suffocation of benthic ecosystems. Deposited sediment also degrades the aesthetic and recreational value of waterbodies. Consequently, managing the sediment to achieve TASs in streams and rivers is a requirement of the NPS-FM.

The NPS-FM fine suspended sediment attribute is quantified by observations of visual clarity based on measurements taken in the field as the horizontal sighting distance of a black disc, which therefore has units of metres (m). The fine suspended sediment attribute is defined (i.e., both the baseline state and the TASs) by the median value of monthly visual clarity observations in streams and rivers.

The study assesses sediment load reductions required to achieve three potential TAS options for rivers that are defined based on the National Objectives Framework (NOF) appended to the NPS-FM. The study includes an assessment of the uncertainties of the sediment load reduction estimates. The uncertainty assessment is based on combining the uncertainties of the various input models that describe baseline sediment loads and baseline visual clarity. The analysis methodology is based on two previous national-scale studies of nitrogen load reduction requirements (MFE, 2019; Snelder *et al.*, 2020), studies of sediment loads and load reduction requirements that were undertaken to inform the 2020 update to the NPS-FM (Hicks, Haddadchi, *et al.*, 2019; Hicks, Semadeni-Davies, *et al.*, 2019) and a recent study of the state of New Zealand's aquatic receiving environments compared to the NPS-FM 'bottom lines' (Snelder *et al.*, 2023). The NPS-FM also requires consideration of downstream receiving environments such as estuaries but does not prescribe what type of attributes should be used or how acceptable states should be quantified. This study only assessed the sediment load reduction requirements to achieve TAS for streams and rivers.

The analyses described in this report do not consider how the sediment load reductions would be achieved; this will be the subject of subsequent studies. The current report therefore only aims to inform AC about the magnitude of the required load reductions and how these vary across the region. This information establishes target load reductions that can be used as a basis for comparing the efficacy of actions that could be modelled in a future scenario testing process.

2 Methods

2.1 Overview

The analyses undertaken by this study used available river water quality and hydrological data and several extant models (Figure 1). The modelling is based on a spatial framework that represents the Auckland surface water drainage network (i.e., streams and rivers) and the associated catchments.

Conceptually, sediment loads derive from catchments and are transported downstream by the drainage network where their concentration determines the visual clarity in stream and river receiving environments (

Figure 1). Models that are fitted to observations of visual clarity and sediment loads at long term state of environment (SOE) monitoring sites are used to predict the baseline visual clarity and loads of sediment at each segment of the drainage network, each of which represents a river receiving environment. For this study,, loads of suspended fine sediment were obtained from modelling undertaken by NIWA for the Ministry for the Environment (MfE) in support of the 2020 update to the NPS-FM (Hicks, Semadeni-Davies, *et al.*, 2019).

The *criteria* to achieve TAS in stream and river receiving environments are primarily defined in terms of visual clarity. The analysis converts the visual clarity criteria into an equivalent annual sediment load that is called the *maximum allowable load* (MAL, i.e., the load that will allow the TASs to be achieved). The compliance of streams and rivers with the visual clarity criteria is assessed by comparison to baseline visual clarity. Receiving environments with visual clarity that are less than or greater than the criteria are non-compliant or compliant, respectively. The baseline annual sediment loads are compared to the MAL and where the baseline load is higher, the difference is the *local excess load* (i.e., the amount by which the baseline sediment load at a receiving environment would need to be reduced to achieve the TAS).

The *point load reduction* required at any receiving environment (i.e., any point in the drainage network) is the minimum load reduction that ensures the sediment load at that, and all upstream, receiving environments do not exceed the MAL. The point load reduction required differs from the local excess load, in that it considers the excess load of all upstream receiving environments. Thus, a receiving environment may have a local excess load of zero but, if it is situated downstream of receiving environments that have local excess loads, it will have a point load reduction required that reflects a reconciliation of those upstream local excess loads. Load reductions required were quantified for the 11 Stormwater Consolidated Receiving Environment (CRE) catchments, three freshwater management units (FMU), and for the whole region as both absolute and relative quantities. The absolute sediment load reduction required is expressed as a kilo tonnes per year (kt yr^{-1}) and as a yield per year (t km^{-2} yr^{-1}). The relative load reduction required is calculated as the load reduction required (baseline load – MAL) divided by the baseline load and expressed as a percentage. The benefit of expressing the load reduction required in relative terms is that it is a comparable quantity across CRE catchments and FMUs.

The final step of the analysis identifies critical points, their catchments (critical catchments), and the critical catchments' excess load. This begins by identifying critical points in each sea-draining catchment. A *critical point* is defined as a receiving environment for which the ratio of the baseline sediment load to MAL is not exceeded by any upstream receiving environment (McDowell *et al.*, 2018). The catchment upstream of the critical point is the *critical point catchment*. Within a single sea-draining catchment there is at least one critical point (the terminal segment, i.e., river mouth), but there can be many critical points distributed throughout the catchment. The *critical catchment excess load* indicates the sediment load reduction required at the critical point to allow all receiving environments upstream of the critical point (i.e., in the critical catchment) to achieve their TASs. The critical catchment excess load can be expressed as an absolute (excess) yield (the excess load divided by the total area of the upstream catchment; mass km^{-2} yr^{-1}), or as a proportion of the baseline load (i.e., excess load/baseline load; %).

The process of identifying the critical points is as follows. The terminal segment of every sea-draining catchment (the river mouth) is defined as a critical point, the baseline load to MAL ratio is noted, and the local excess load is assigned as the critical catchment excess load. From the terminal segment, the baseline load to MAL ratio at successive upstream receiving environments are obtained. At each receiving environment, the baseline load to MAL ratio is compared with the same ratio for the downstream critical point. If the baseline load to MAL ratio at the receiving environment is greater than that of the downstream critical point, the receiving environment is defined as a critical point (in addition to the already identified downstream critical points) and local excess load for the receiving environment is assigned as the excess load. If the baseline load to MAL ratio at the receiving environment is less than that of the downstream critical point, the critical point and critical catchment excess load are unchanged. The process continues upstream to the catchment headwaters. More details of the process of defining critical points are provided by Snelder *et al.* (2020). The results of the critical points analysis are visualised by mapping critical catchments coloured by their excess loads.

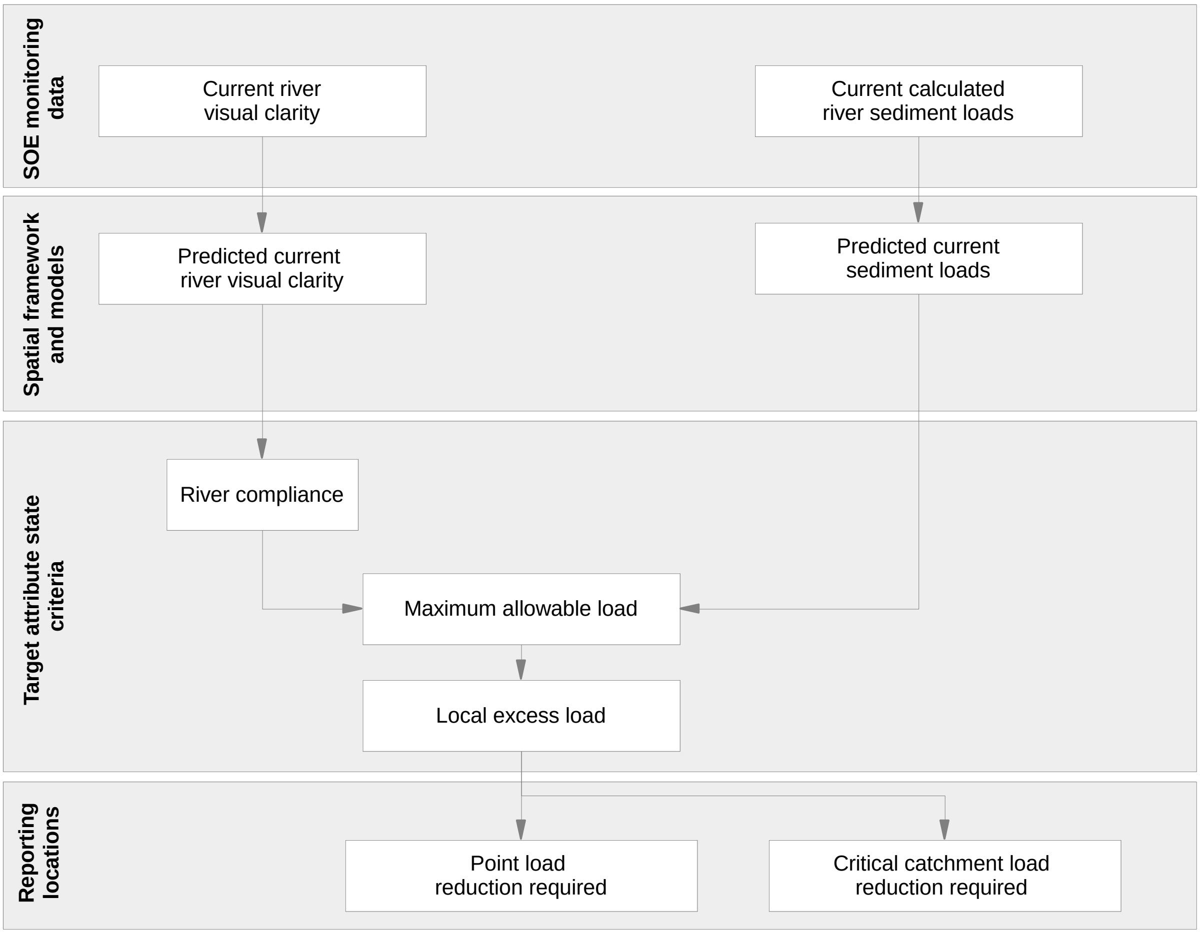

Figure 1. Schematic diagram of the assessment of sediment load reductions required to achieve TASs.

The following sections describe the various components of the analysis shown in Figure 1 in more detail.

2.2 Spatial framework

The study area comprised the catchments of rivers of the Auckland region that discharge to the ocean within the region's boundary (Figure 2). However, to increase the number of SOE monitoring sites that could be used to construct a spatial model of baseline visual clarity, the model domain extended to catchments of rivers of the neighbouring Northland and Waikato regions (Figure 2).

The drainage network and river receiving environments of the model domain (including the Auckland region study area) were represented by the GIS-based digital drainage network (version 2.4, hereafter DN2.4), which underlies the River Environment Classification (REC; Snelder and Biggs, 2002). The digital network was derived from 1:50,000 scale contour maps and represented the rivers within the model domain as 95,200 segments of which 10,856 were assigned to the Auckland region (Figure 2). Segments were bounded by upstream and downstream confluences, each of which is associated with a sub-catchment. The terminal segments of the river network (i.e., the most downstream points in each drainage network that discharge to the ocean) were identified. The position in the network of branching segments is indicated by the stream order (Strahler, 1964). A segment of order one is a headwater stream and when two segments of the same order merge, the next downstream segment is given a number that is one higher. The highest order segments in the Auckland region were order six whereas the highest order segments in the model domain were associated with the main-stem of the Waikato River which are order eight.

In general, Auckland's streams and rivers discharge to the ocean within the Auckland regional boundary. However, on the southern boundary of the Auckland region there are four catchments, comprising 162 network segments that discharge to the Waikato Region (Figure 3). Of these, the two eastern-most catchments are located entirely within the Auckland region boundary until their main stems cross the southern Auckland region boundary. The two western-most catchments have tributaries that are located within the Waikato region boundary that drains into the main-stem in the Auckland region, and the main-stem then crosses the southern Auckland region boundary. All relevant segments were included in the analyses and the load reductions required for the four catchments are included as part of the overall load reduction requirements for the region. The contributions of these four catchments to load reduction requirements for the region, and the other spatial units defined in this study, can be quantified and isolated from the figures provided if necessary.

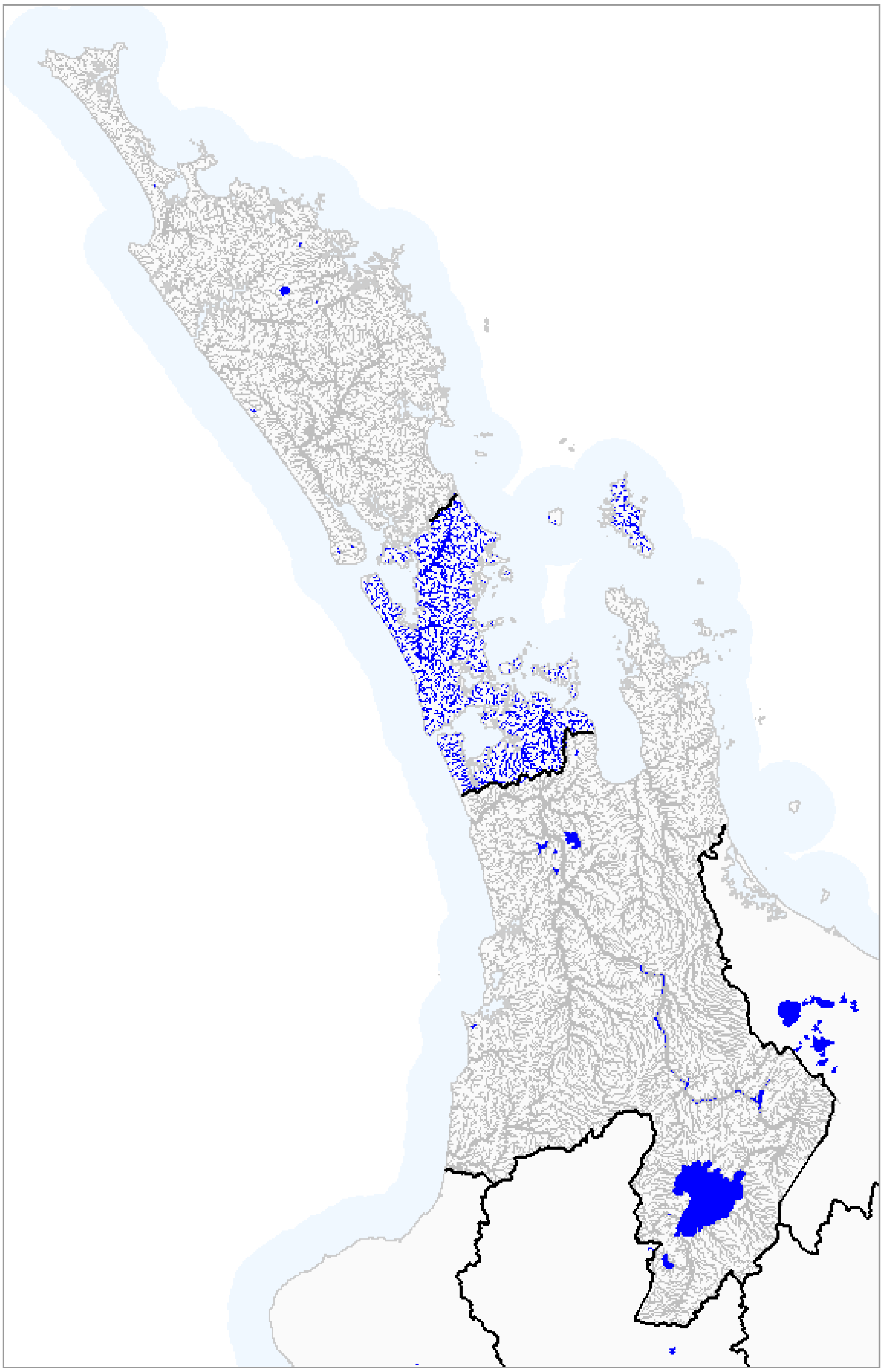

Figure 2. Representation of streams and rivers in the model domain by the spatial framework used in this study. Rivers in the Auckland region (i.e., the study area) are represented by the blue lines and in the Northland and Waikato regions as grey lines. Note that this map shows only segments of order two or greater but all segments (i.e., including those of order one) represented by DN2.4 in the Auckland region were included in the load reductions analyses.

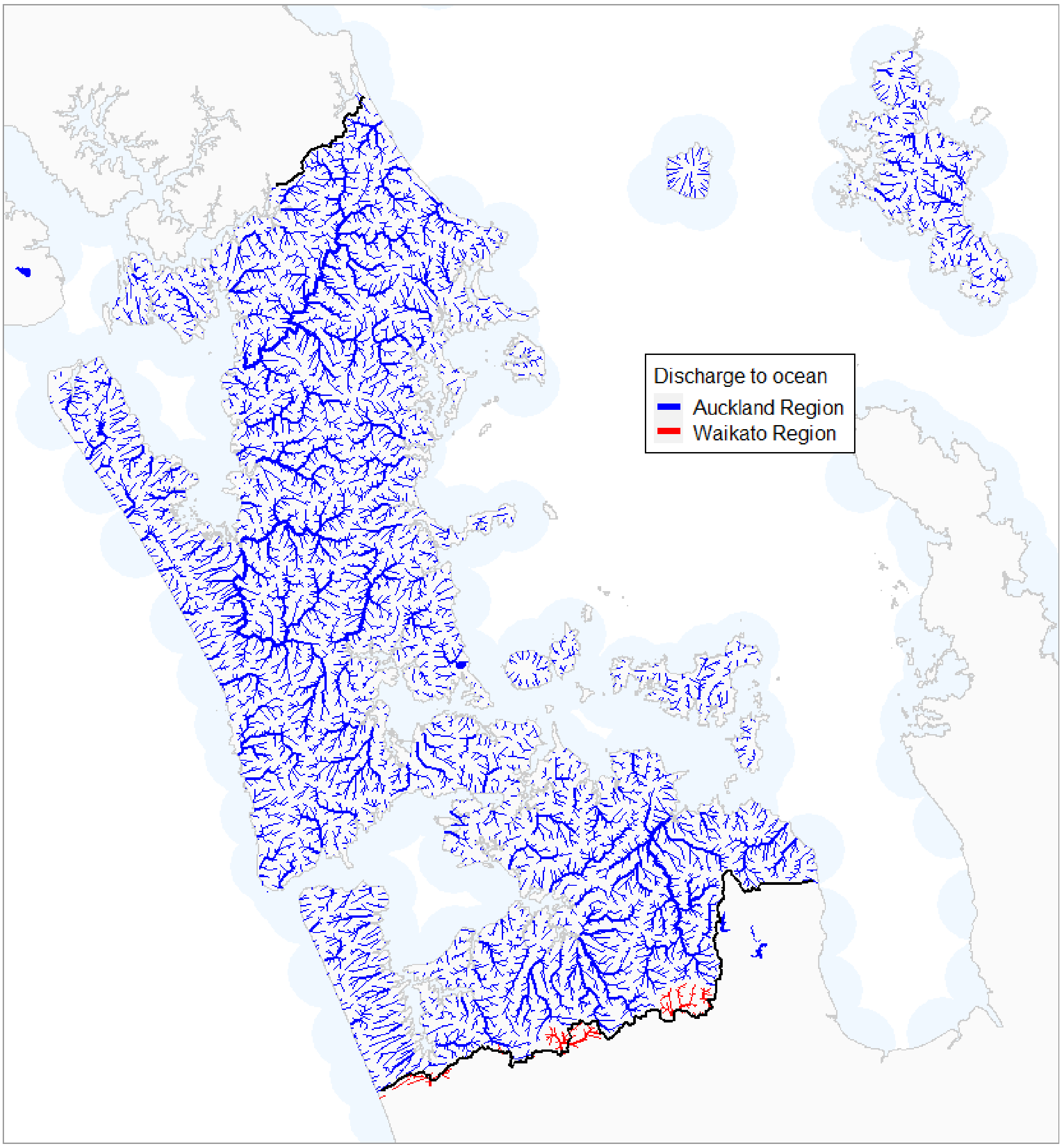

Figure 3. River segments included in study area. Rivers that drain to the ocean within the Auckland regional boundary are represented by blue lines. Rivers that drain into the Waikato region, but which were included in the study area, are shown as red lines. All rivers and catchment areas shown were included in the load reduction analyses. Note that this map shows all segments, (i.e., including those of order one), represented by DN2.4.

The results of the analyses carried out in this study can be reported at any spatial scale from individual receiving environments (i.e., river segments) to the whole study area. Summaries of the load reductions required as mass per year (kilo t yr^{-1}) were produced for the region, the three FMUs (Figure 4) and the CRE catchments (Figure 5). These summaries were evaluated by obtaining the load reductions required at the terminal segments of the summary area (i.e., the downstream-most segment of FMUs, or the network of segments intersecting the coastline for catchments of estuaries or the region as a whole).

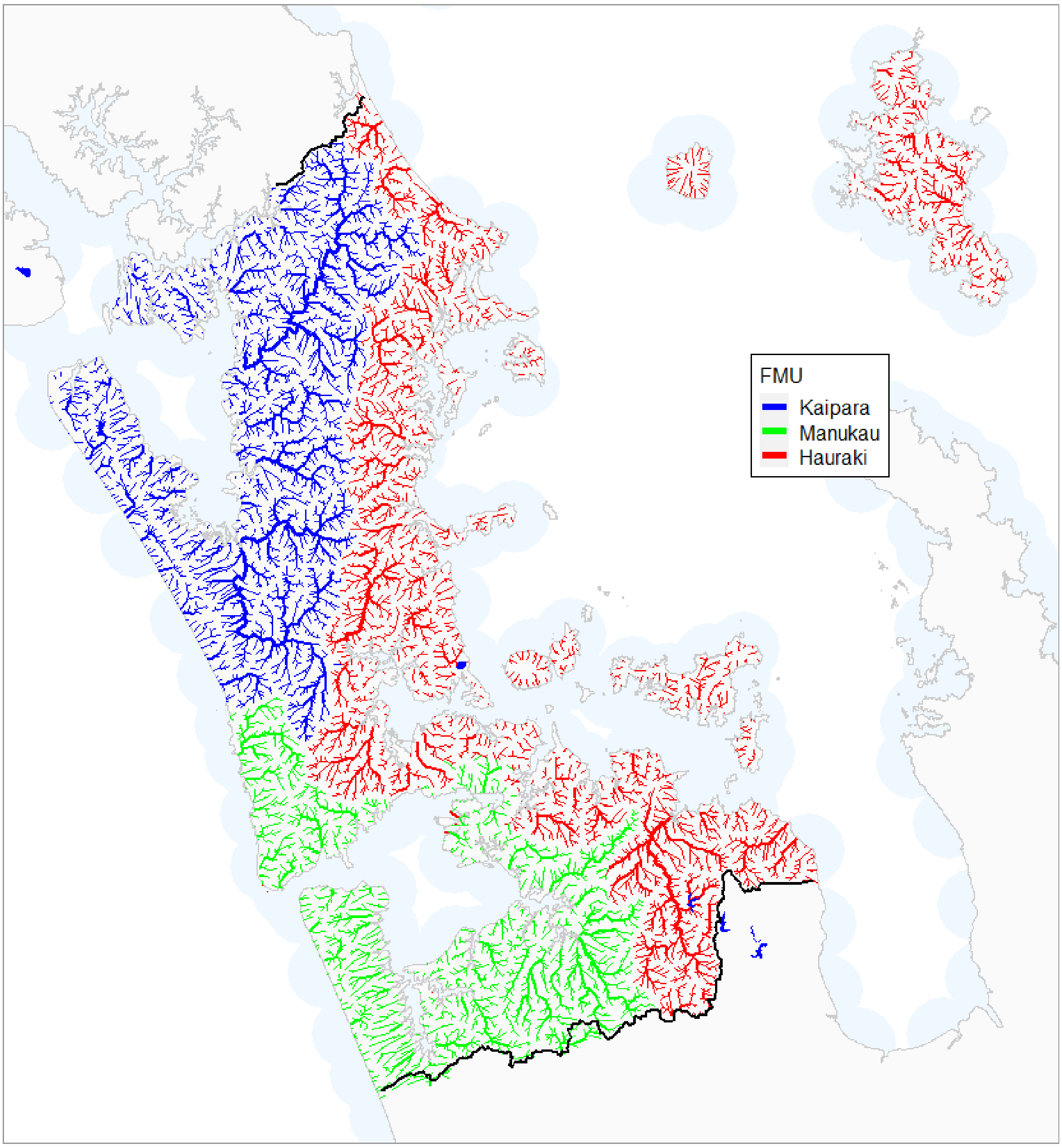

Figure 4. River segments included in the study area categorised by their assigned Freshwater Management Unit (FMU). Note the rivers that drain into the Waikato region are included in the Hauraki and Manukau FMUs in the load reduction analyses. Note that this map shows all segments (i.e., including those of order one) represented by DN2.4.

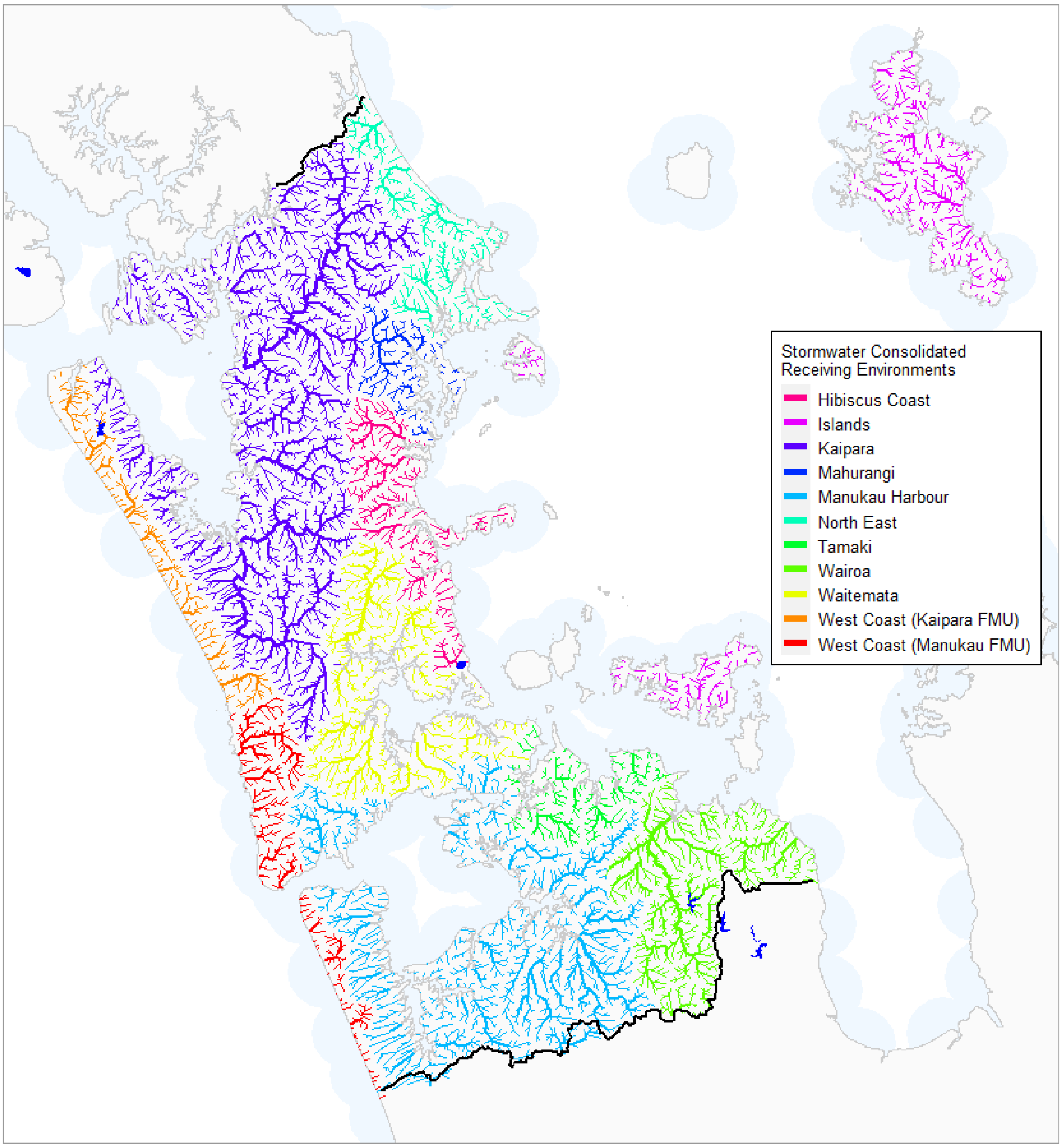

Figure 5. River segments included in the study area categorised by their assigned CRE catchments. Note the rivers that drain into the Waikato region (see Figure 3) are included in the Wairoa and Manukau Harbour CREs in the load reduction analyses. Note that this map shows all segments (i.e., including those of order one) represented by DN2.4.

2.3 Estimated baseline visual clarity

Estimates of the baseline median visual clarity were made for all network segments in the Auckland region (Figure 3) for the baseline assessment period defined as 1 July 2012 to 30 June 2017 (5 years) by statistical regression modelling. This approach was identical to that used for several previous national and regional water quality modelling studies (e.g., Whitehead, 2018). . The models in this study were fitted to SOE monitoring site data pertaining only to monitoring sites in the Northland, Auckland and Waikato regions. The combination of the three regions was a compromise between having sufficient sites to adequately model median visual clarity and to minimise regional bias in predictions made by larger scale (e.g., national scale) models. A type of regression model called a random forest (RF) was fitted to the observed monitoring site median values.

The regression model predictor variables describe various aspects of each site's catchment including the climate, geology, and land cover which were obtained from the Freshwater Environments of New Zealand database (Wild *et al.*, 2005). The predictor variables also included five predictors that quantified the density of pastoral livestock in 2017 to indicate land use intensity (Table 1). The pastoral livestock density predictors were based on publicly available information describing the density of pastoral livestock provided from the agricultural production census (APC) provided by Statistics New Zealand. These predictors improve the discrimination of catchment land use intensity compared to descriptions of the proportion of catchment occupied by different land cover categories (e.g., Whitehead, 2018). The densities of four livestock types (dairy, beef, sheep and deer) in each catchment were standardised using 'stock unit (SU) equivalents', which is a commonly used measure of metabolic demand by New Zealand's livestock (Parker, 1998). These five predictors express land use intensity as the total stock units and the stock units by each of the four livestock types divided by catchment area (i.e., SU ha^{-1}). Further details are provided by Snelder *et al.* (2021).

The RF models were fitted to site median visual clarity values calculated from the monitoring site data. A total of 166 river SOE water quality monitoring sites were used to fit the models (Figure 6). Of the 166 sites, 33, 35 and 98 were located in the Auckland, Northland and Waikato regions, respectively. The data pertaining to the individual observations for the Northland and Waikato sites were obtained from data that was collated for a national analysis prepared for the Ministry for the Environment (MFE) by Whitehead *et al.* (2021). The data pertaining to the individual observations for the Auckland sites were obtained from data that was collated for a study prepared for AC by Fraser (2023).

The statistical precision of the median statistic that is estimated from the individual observations depends on the variability in the visual clarity observations and the number of observations. For a given level of variability, the precision of the median increases with the number of observations. As a general rule, the rate of increase in the precision of compliance statistics slows for sample sizes greater than 30 (i.e., there are diminishing returns on increasing sample size with respect to precision (and therefore confidence in the assigned grade) above this number of observations; McBride, 2005). Therefore, we retained the sites that had at least 80% of months with observation (48 months) for the five-year baseline period and calculated the median values.

Table 1. Predictor variables used in spatial models.

Predictor	Abbreviation	Description	Unit
Geography and topography	usArea	Catchment area	m^2
	usLake	Proportion of upstream catchment occupied by lakes	%
	usElev	Catchment mean elevation	m ASL
	usSlope	Catchment mean slope	degrees
	segAveElev	Segment mean elevation	degrees
Climate	usAvTWarm	Catchment averaged summer air temperature	degrees C x 10
	usAvTCold	Catchment averaged winter air temperature	degrees C x 10
	usAnRainVar	Catchment average coefficient of variation of annual rainfall	mm y^{-1}r
	usRainDays10	Catchment average frequency of rainfall > 10 mm	days $month^{-1}$
	usRainDays20	Catchment average frequency of rainfall > 20 mm	days $month^{-1}$
	usRainDays100	Catchment average frequency of rainfall > 100 mm	days $month^{-1}$
	segAveTCold	Segment mean minimum winter air temperature	degrees C x 10
Hydrology	MeanFlow	Estimated mean flow	$m^3 s^{-1}$
	nNeg	Mean number of days per year on which flow was less than that of the previous day	$Year^{-1}$
	MALF7	Mean annual 7-day low flow divided by the mean flow	Unitless
	FRE3	Mean number of events per year that exceeded three times the long-term median flow	$Year^{-1}$
	JulFlow	Mean daily flow for July divided by the mean daily flow	Unitless
	FloodFlow	Log10 mean annual 1-day maximum flow divided by the mean daily flow.	Unitless
Geology*	usHard	Catchment average induration or hardness value	Ordinal*
	usPhos	Catchment average phosphorous	Ordinal*
	usParticleSize	Catchment average particle size	Ordinal*
	usCalcium	Catchment average calcium	
Land cover	usIntensiveAg	Proportion of catchment occupied by combination of high producing exotic grassland, short-rotation cropland, orchard, vineyard and other perennial crops (LCDB3 classes 40, 30, 33)	Proportion
	usIndigForest	Proportion of catchment occupied by indigenous forest (LCDB3 class 69)	Proportion
	usUrban	Proportion of catchment occupied by built-up area, urban parkland, surface mine, dump and transport infrastructure (LCDB3 classes 1,2,6,5)	Proportion
	usScrub	Proportion of catchment occupied by scrub and shrub land cover (LCDB3 classes 50, 51, 52, 54, 55, 56, 58)	Proportion
	usWetland	Proportion of catchment occupied by lake and pond, river and estuarine open water (LCDB3 classes 20, 21, 22)	Proportion
	usBare	Proportion of catchment occupied by bare ground (LCDB3 classes 10, 11, 12,13,14, 15)	Proportion
	usExoticForest	Proportion of catchment occupied by exotic forest (LCDB3 class 71)	Proportion
Stocking density data	SUTotal_2017	Stock unit density for all stock types in 2017 (i.e., total stock units)	SU ha^{-1}
	PropDairy_2017	Proportion of total stock unit density attributable to dairy cows in 2017	Proportion
	PropBeef_2017	Proportion of total stock unit density attributable to beef cows in 2017	Proportion
	PropSheep_2017	Proportion of total stock unit density attributable to sheep in 2017	Proportion
	PropDeer_2017	Proportion of total stock unit density attributable to deer in 2017	Proportion

Prior to fitting the RF model, the site median clarity values were log (base 10) transformed to increase the normality of their distributions. Note that although RF models make no assumptions about data distributions, normalising the response variable improves model performance (Snelder *et al.,* 2018).

Unlike linear models, RF models cannot be expressed as equations. However, the relationships between predictor and response variables represented by RF models can be represented by importance measures and partial dependence plots (Breiman, 2001; Cutler *et al.*, 2007). The importance of the predictor variable is indicated by the degree to which prediction accuracy decreases when the response variable is removed[1]. A partial dependence plot is a graphical representation of the marginal effect of a predictor variable on the response variable when the values of all other predictor variables are held constant at their respective mean values. Partial dependence plots do not perfectly represent the effects of each predictor variable, particularly if predictor variables are highly correlated or strongly interacting, but they do provide an approximation of the modelled predictor-response relationships that are useful for model interpretation (Cutler *et al.*, 2007).

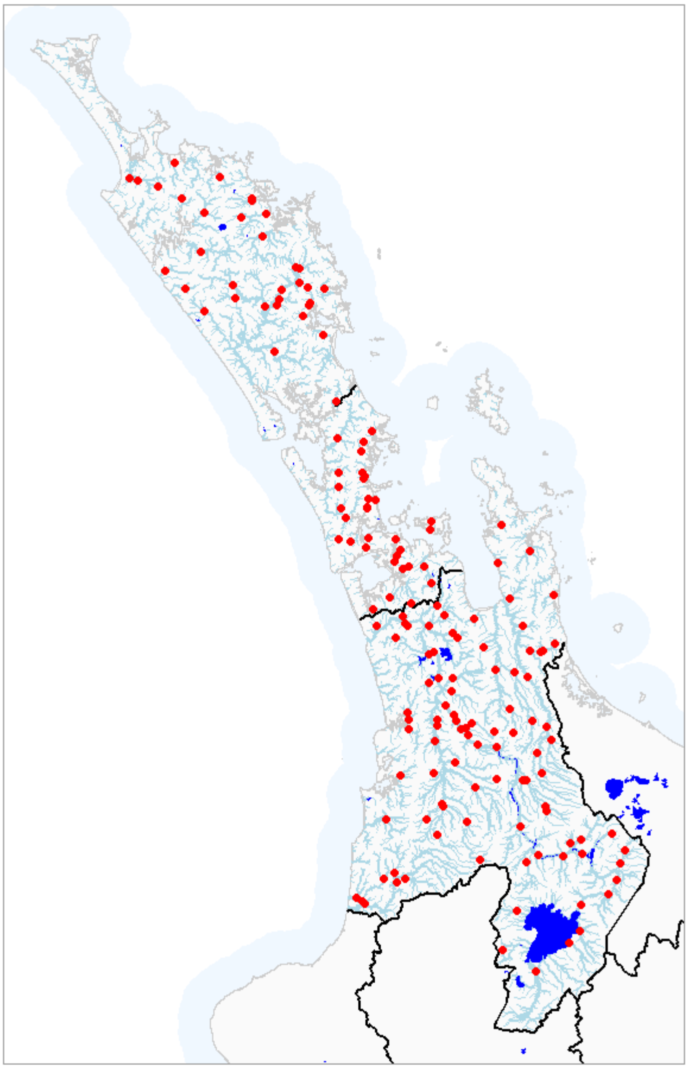

Figure 6. Locations of the 166 river water quality monitoring sites used to fit the baseline visual clarity model.

[1] The details are more complicated but have been removed for brevity. The interested reader should refer to the explanation in Whitehead, Fraser, and Snelder (2021).

The performance of the RF model of baseline visual clarity was evaluated using three measures: regression R^2, Nash-Sutcliffe efficiency (NSE), and bias (Table 2). The regression R^2 value is the coefficient of determination derived from a regression of the observations against the predictions. The R^2 value indicates the proportion of the total variance explained by the model, but is not a complete description of model performance (Piñeiro *et al.*, 2008). NSE indicates how closely the observations coincide with predictions (Nash and Sutcliffe, 1970). NSE values range from $-\infty$ to 1. An NSE of 1 corresponds to a perfect match between predictions and the observations. An NSE of 0 indicates the model is only as accurate as the mean of the observed data, and values less than 0 indicate the model predictions are less accurate than using the mean of the observed data. Bias measures the average tendency of the predicted values to be larger or smaller than the observed values. Optimal bias is zero, positive values indicate underestimation bias and negative values indicate overestimation bias (Piñeiro *et al.*, 2008). PBIAS is computed as the sum of the differences between the observations and predictions divided by the sum of the observations (Moriasi *et al.*, 2007).

The uncertainty of the RF models was quantified by the root mean square deviation (RMSD). RMSD is the mean deviation of the predicted values from their corresponding observations and is therefore a measure of the characteristic model uncertainty (Piñeiro *et al.*, 2008).

Table 2: Performance ratings for the measures of model performance used in this study. The performance ratings are from Moriasi et al. *(2015).*

Performance Rating	R^2	NSE	PBIAS
Very good	$R^2 \geq 0.70$	NSE > 0.65	|PBIAS| <15
Good	$0.60 < R^2 \leq 0.70$	0.50 < NSE ≤ 0.65	15 ≤ |PBIAS| < 20
Satisfactory	$0.30 < R^2 \leq 0.60$	0.35 < NSE ≤ 0.50	20 ≤ |PBIAS| < 30
Unsatisfactory	$R^2 < 0.30$	NSE ≤ 0.35	|PBIAS| ≥ 30

The fitted RF models were combined with a database of predictor variables for every network segment in the Auckland region and used to predict baseline median visual clarity for all segments. Because the modelled variables were $\log_{10}$ prior to model fitting, the raw model predictions were in the $\log_{10}$ or logit space. The raw model predictions were back transformed to the original units (i.e., m) by raising them to the power of 10 and correcting for re-transformation bias as described by Whitehead (2018).

2.4 Estimated baseline river sediment loads

Estimates of baseline suspended fine sediment loads were obtained from the updated version of The Sediment Load Estimator (Hicks, Semadeni-Davies, *et al.*, 2019). The Sediment Load Estimator provides national coverage and was used to inform the 2020 update to the NPS-FM. The Sediment Load Estimator is an empirical model that provides predictions of mean annual river suspended fine sediment load for every segment of DN2.4[2]. The river sediment load modelling approach was based on grid-cells with an area of 1 hectare that are described by their average slope, mean annual rainfall, land cover, and erosion terrain[3]. The sediment loads for each segment were determined by summing the sediment loads from all raster units upstream and routing these loads down the stream network, taking into account entrapment

[2] These data were accessed via MfE's Data Service (https://data.mfe.govt.nz/layer/103686-updated-suspended-sediment-yield-estimator-and-estuarine-trap-efficiency-model-results-2019/)
[3] An erosion classification developed by Manaaki Whenua / Landcare, with erosion terrain classes distinguished by slope, rock-type, soils, and dominant erosion processes.

in lakes and reservoirs. The model was calibrated to a national dataset of 273 suspended fine sediment monitoring sites located across New Zealand. Only six and 15 of these sites were located in the Northland and Auckland regions, respectively, and 54 were located in the Waikato region. The small number of sites in the Auckland and Northland region precludes fitting a model that is more specific to the Auckland region as was done for predicting baseline visual clarity.

Predictions made by the national model after the regional adjustments explained by Hicks, Semadeni-Davies, *et al.* (2019) were used. The characteristic uncertainty of these predictions were quantified by an RMSD of 0.64 in log (i.e., natural log) space.

2.5 TAS options, criteria, compliance, maximum allowable loads, and local excess load

The criteria for the suspended fine sediment attribute are defined in terms of median visual clarity (m) and vary spatially according to four suspended fine sediment classes that are defined by Table 8 in Appendix 2A of the NPS-FM, NZ Government, 2023) and are shown in Table 3 below. The streams and rivers of the Auckland region are assigned to one of three of the four suspended fine sediment classes shown in Table 3 (Figure 7).

Table 3. Criteria used to define the suspended fine sediment TASs. The criteria are defined in terms of median visual clarity (m) and are the lower limits of the respective NOF bands. The national bottom line is the bottom of the C band and is represented by the bold line in the table.

TAS (NOF band)	Suspended sediment class			
	1	2	3	4
A	≥1.78	≥0.93	≥2.95	≥1.38
B	<1.78 *x* ≥1.55	<0.93 *x* ≥0.76	<2.95 *x* ≥2.57	<1.38 *x* ≥1.17
C	<1.55 *x* ≥1.34	<0.76 *x* ≥0.61	<2.57 *x* ≥2.22	<1.17 *x* ≥0.98
D	<1.34	<0.61	<2.22	<0.98

In this study, three options for the TAS were analysed, the bottom of the C, B and A bands as defined by Table 3 and referred to hereafter as the C-band, B-band and A-band options.

For each of the three TAS options, compliance for each segment of the river network was assessed by comparing its predicted baseline visual clarity with the relevant criteria (from Table 3). Where the baseline visual clarity was greater than the criteria, the segment was assessed as compliant and vice versa.

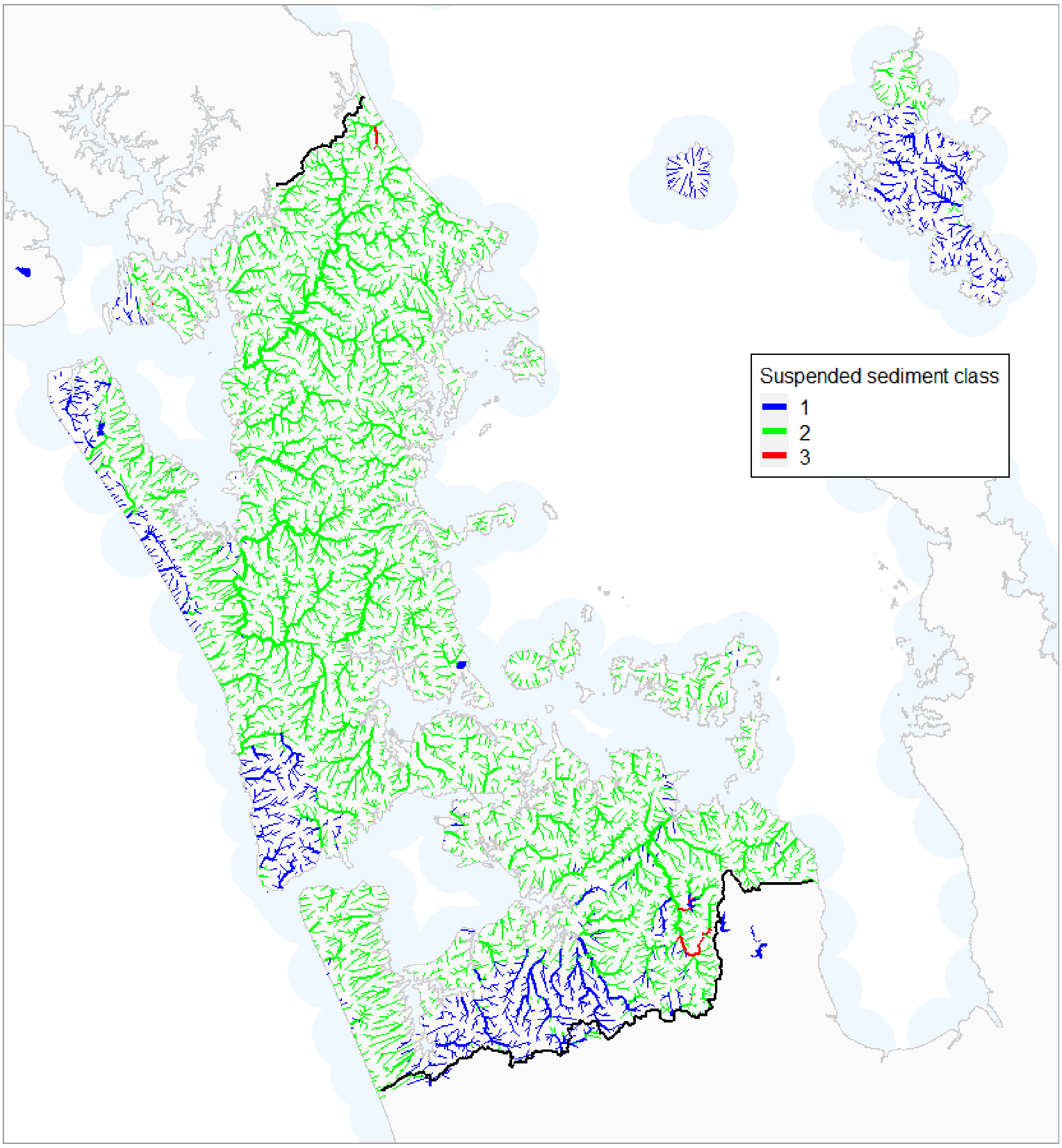

Figure 7. River segments included in the load reduction analyses categorised by their suspended sediment class. Note that this map shows all segments (i.e., including those of order 1) represented by DN2.4.

The local excess load for sediment was calculated in three steps. First, for all noncompliant segments the factor by which the baseline sediment load must be reduced to achieve the target visual clarity was calculated using the Sediment Load Reduction Factor model developed by Hicks, Haddadchi, *et al.* (2019). The Sediment Load Reduction Factor model is expressed as:

$$R = 1 - (V_t/V_B)^{1/d} \qquad \text{Equation 1}$$

where R is the sediment load reduction factor, V_t is the TAS (defined by the relevant band thresholds for visual clarity shown in Table 3), V_B is the predicted baseline median visual clarity (m). In this study, the exponent d was assigned the national mean at-site value of -0.76 derived by Hicks, Haddadchi, *et al.* (2019). Second, the local excess load for every segment was calculated as:

$$Local\ excess\ sediment\ load = \ R \times Predicted\ currrent\ sediment\ load \qquad \textit{Equation 2}$$

where the predicted baseline sediment load was obtained from the Updated Sediment Load Estimator for New Zealand (Hicks, Semadeni-Davies, *et al.,* 2019; Section 2.4). Finally, for every segment, the maximum allowable load (MAL) was evaluated as:

$$MAL = \ Predicted\ currrent\ sediment\ load - \ Local\ excess\ sediment\ load \qquad \textit{Equation 3}$$

2.6 Estimation of uncertainties

The analysis was based on three statistical models: RF models to predict baseline median visual clarity, the Sediment Load Estimator (Hicks, Semadeni-Davies, *et al.*, 2019), and the Sediment Load Reduction Factor model (Hicks, Haddadchi, *et al.*, 2019). These models were all associated with uncertainties that were quantified by their respective RMSD values. These uncertainties propagate to all the assessments produced in this study including the assessments of baseline state, compliance with a proposed target, and load reduction required.

Snelder *et al.* (2020)'s approach to undertaking Monte Carlo analysis was used to estimate uncertainties in the assessments based on 100 'realisations' of the entire series of calculations in four steps. First, for a realisation (r), predictions made by all models were perturbed by a random error. Random errors were obtained by generating random normal deviates (ε_r) and applying these to predictions made using the models.

The uncertainties of all three models were quantified by RMSD values but the correlation of model errors between these models was not quantified. Therefore, the random normal deviates representing errors for each model (ε_r) were drawn from independent distributions (i.e., the errors were assumed to be uncorrelated). It is noted that correlation of the errors associated with the three models will tend to increase overall uncertainty of the analyses. Therefore, the estimated uncertainties should be regarded as 'optimistic' (i.e., the uncertainty would be higher if these error correlations were included in the analysis).

Because the RF model pertaining to river visual clarity was $\log_{10}$ transformed, the perturbed predictions for a realisation were derived as follows:

$$VC_r = \ CF \times \ 10^{[log_{10}(x) + (\varepsilon_r \times RMSD_{VC})]} \qquad \textit{Equation 4}$$

where VC_r is the predicted visual clarity for realisation *r*, *x* is the prediction returned by the RF visual clarity model, $RMSD_{VC}$ is the characteristic error of the RF visual clarity model (see Section 3.1), and CF is a factor to correct for retransformation bias (Duan, 1983).

Because the characteristic uncertainty of the predictions of the Sediment Load Estimator were quantified in log (i.e., natural log) space, the perturbed predictions for sediment load were derived as follows:

$$SY_r = \ e^{[log(x)+(\varepsilon_r \times RMSD_{SLE})]} \qquad \textit{Equation 5}$$

where VC_r is the predicted sediment yield for realisation *r* and *x* is the prediction returned by the Sediment Load Estimator and $RMSD_{SLE}$ is the characteristic error of the Sediment Load Estimator model, which Hicks, Semadeni-Davies, *et al.* (2019) reported as 0.64.

The uncertainty of the load reduction factor was derived as follows:

$$R_r = 1 - (V_t/VC_r)^{1/[d+(\varepsilon_r \times RMSD_{SLRF})]} \qquad \text{Equation 6}$$

where R_r is the predicted sediment load reduction factor for realisation *r* and $RMSD_{SLRF}$ is the characteristic measure of uncertainty of the sediment load reduction factor model. In this study, $RMSD_{SLRF}$ was taken to be the standard deviation of the at-site values of d, which Hicks, Haddadchi, *et al.* (2019) reported as 0.13 and that has the same meaning as the RMSD values for the other models.

Because the visual clarity or sediment load at any point in a catchment is spatially dependent on corresponding values at all other points in the catchment's drainage network, the values of the random normal deviates were held constant for each realisation within the river network representing a sea-draining catchment but differed randomly between sea-draining catchments.

The second step stored the perturbed predicted compliance, baseline sediment loads and sediment load reductions required. At the third step, the procedure described above (including steps 1 and 2) was repeated for each realisation using the perturbed values. At the fourth step, the distribution of values of compliance, baseline sediment loads and sediment load reductions required obtained from the 100 realisations were used to provide a best estimate and the uncertainty of the assessments. The uncertainty of the assessments of compliance was quantified by estimating the probability that each segment was compliant across the 100 realisations. Segment compliance was therefore assessed as a value between one (100% confident the segment is compliant or suitable) to zero (100% confident the segment is non-compliant). For the baseline state, local excess loads, and load reduction required assessments, the best estimate was represented by the mean value from the distribution of values. The uncertainty of these two assessments was quantified by their 90% confidence intervals. For the load reduction required assessment, the best estimates and the uncertainties were estimated from the 100 realisations for the FMUs, CRE catchments and the entire region.

2.7 Assessment of baseline state

The baseline median visual clarity calculated for SOE sites and predicted for every segment of the digital river network was graded against the Suspended fine sediment attribute bands. The primary aim of the attribute bands designated by the NPS-FM is to provide a basis for setting TASs as part of the NOF process. The attribute bands are intended to be simple shorthand for communities and decision makers to discuss options and aspirations for acceptable water quality and to define TASs. However, it is also logical to use attribute bands to provide a grading of the baseline state of water quality; either as a starting point for setting TASs or to track progress toward TASs.

A site or network segment is graded by assigning it to attribute bands (e.g., a site can be assigned to the A band for the Suspended fine sediment attribute). Grading is done by using the numeric attribute state (e.g., annual median visual clarity) as a compliance statistic. In this case, the value of the compliance statistic for a site or segment compared against the numeric ranges associated with each attribute band and a grade assigned for the site. For example, for a site in suspended fine sediment class 1, with an median visual clarity of 0.8m would be graded as “B-band”, because it lies in the range <0.93 x ≥0.76m, Table 3).

An assessment of baseline suspended fine sediment attribute NOF grade was made for all SOE sites and network segments in the Auckland region using the measured and predicted baseline visual clarity, respectively. The assessment assigned all SOE sites and network segments to a NOF grade (A, B, C or D) based on the site or segment’s suspended sediment class and the criteria in Table 3. The results were mapped to provide a basis for comparing the results of the load reduction requirements that were assessed for different nominated TAS options described in the following section.

3 Results

3.1 Modelled relationships and performance of baseline visual clarity model

The predictor variables with high importance in the RF model of baseline visual clarity reflected expected associations between visual clarity and catchment elevation, climate, land cover/use, and geology. For example, visual clarity increased with increasing catchment elevation (usElev), days with rainfall > 100 mm (usRainDays100) and annual rainfall (usRain) and decreased with increasing mean catchment temperature (usTmax). Visual clarity decreased with increasing proportion of catchment area associated with intensive agriculture (usIntensiveAg) and increased with increasing proportion of catchment area associated with native forest (usNativeForest). Visual clarity also increased with increasing catchment average phosphorous (usPhos) which may reflect geological differences (e.g., regolith of sedimentary or volcanic origin).

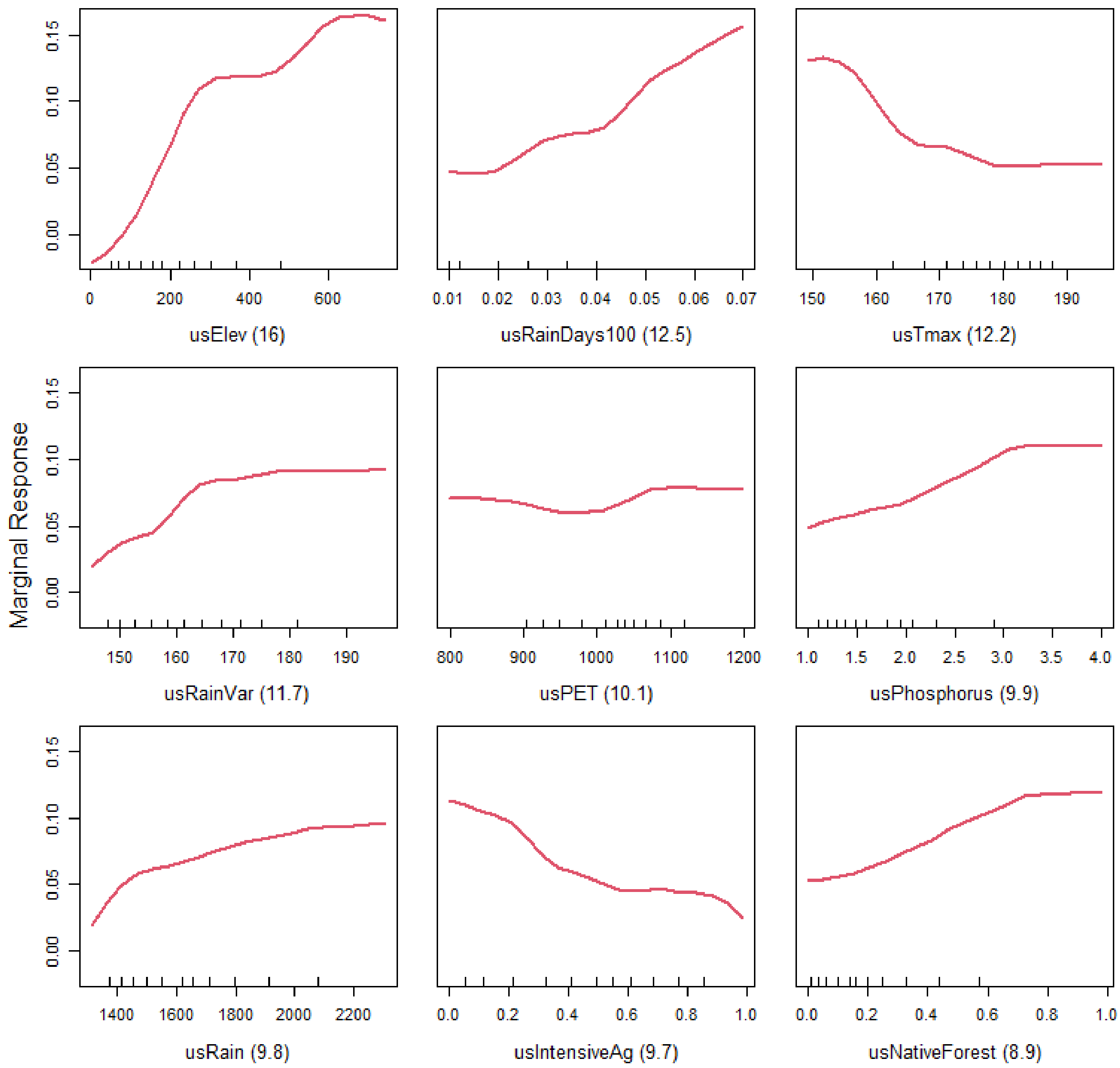

Figure 8. Partial plots for the nine most important predictor variables in random forest models of baseline median visual clarity. Each panel corresponds to a predictor, with predictor variables ordered by overall importance from most (top left) to least (bottom right) important. Y-axis represent the marginal change in log10 visual clarity with change in the predictor (x-axis). The values in parentheses on the x-axis labels are the importance scores indicating the increase in the mean squared error when the predictor is left out of the model.

The predicted baseline visual clarity varied across the Auckland region and the patterns reflected relationships with catchment elevation, climate, land cover/use and geology shown in Figure 8. For example, visual clarity was greater in high elevation areas that are dominated by native forest such as the Waitakere and Hunua Ranges. Visual clarity was lower in low elevation agriculturally dominated areas such as Waimauku and Clevedon (Figure 9).

The RF models of baseline median visual clarity had satisfactory performance (Table 4), as indicated by the criteria of Moriasi et al. (2015; Table 2).

Table 4. Performance of the RF model of baseline median visual clarity. N indicates the number of sites used to fit the model. The rating indicates the performance ratings based on lowest grade associated with the performance statistics (i.e., R^2, NSE and PBIAS) shown in Table 1.

N	R^2	NSE	PBIAS	RMSD	Rating
166	0.59	0.57	10	0.18	Satisfactory

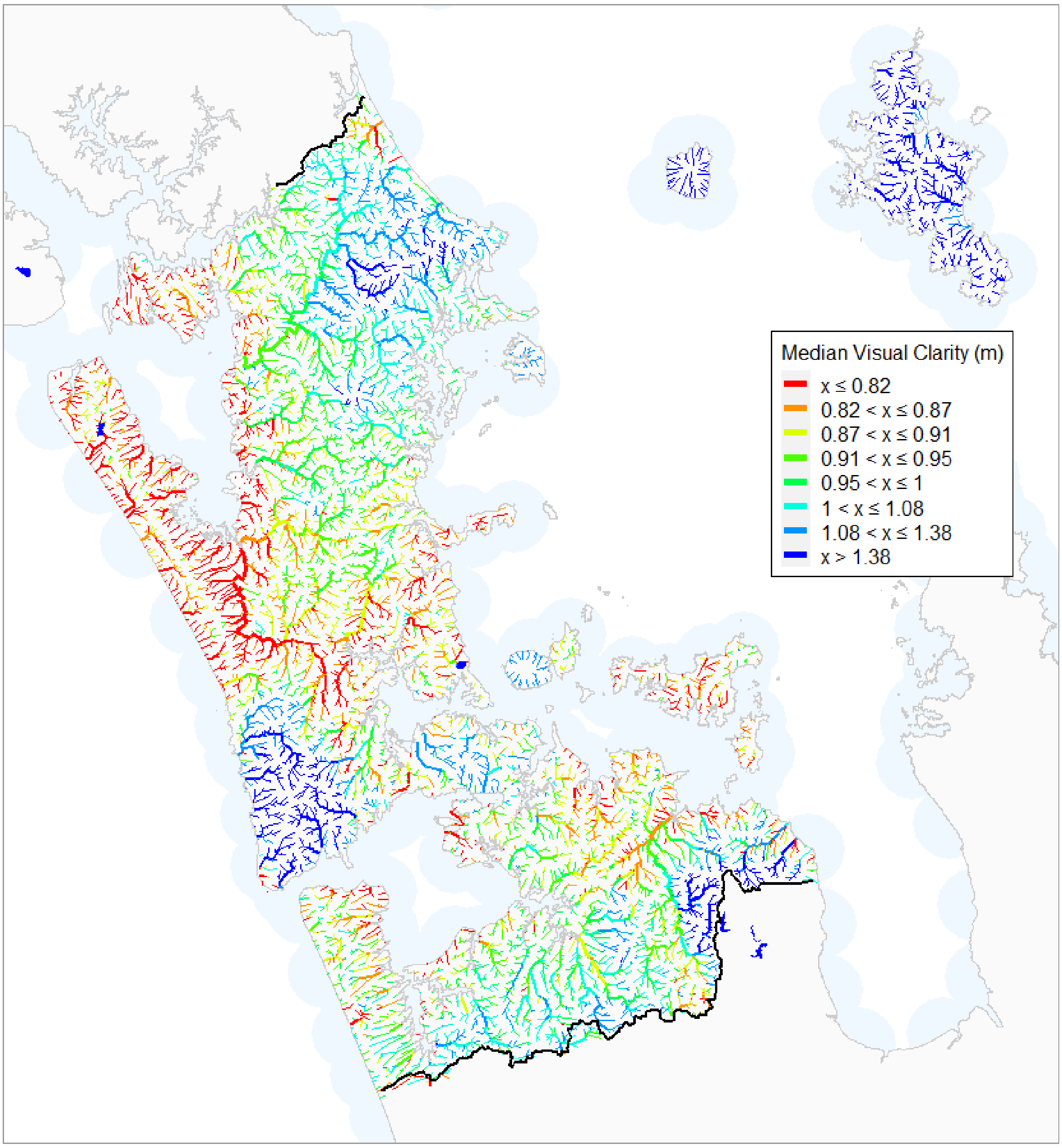

Figure 9. Predicted patterns of the baseline median visual clarity. Note that the breakpoints shown in the map legend are nominal and have no special significance (i.e., are not guidelines or standards).

3.2 Baseline state assessment

Patterns in the grade of the baseline suspended fine sediment attribute state of rivers were consistent with predicted variation in baseline visual clarity (Figure 9) and reflected reducing visual clarity in streams and rivers in association with decreasing elevation and increasing proportion of catchments occupied by agricultural and other land uses (Figure 10). By total stream and river length, 47%, 39%, 3% and 10% of the regional network were graded A, B, C and D, respectively. The grades of Auckland Council's SOE sites (points shown in Figure 10) was the same as the predicted grade for the network segment on which they were located in 61% of cases. Grades of sites that differ from that predicted for the related network segment reflects the uncertainty (only satisfactory performance, Table 4) of the RF model of visual clarity.

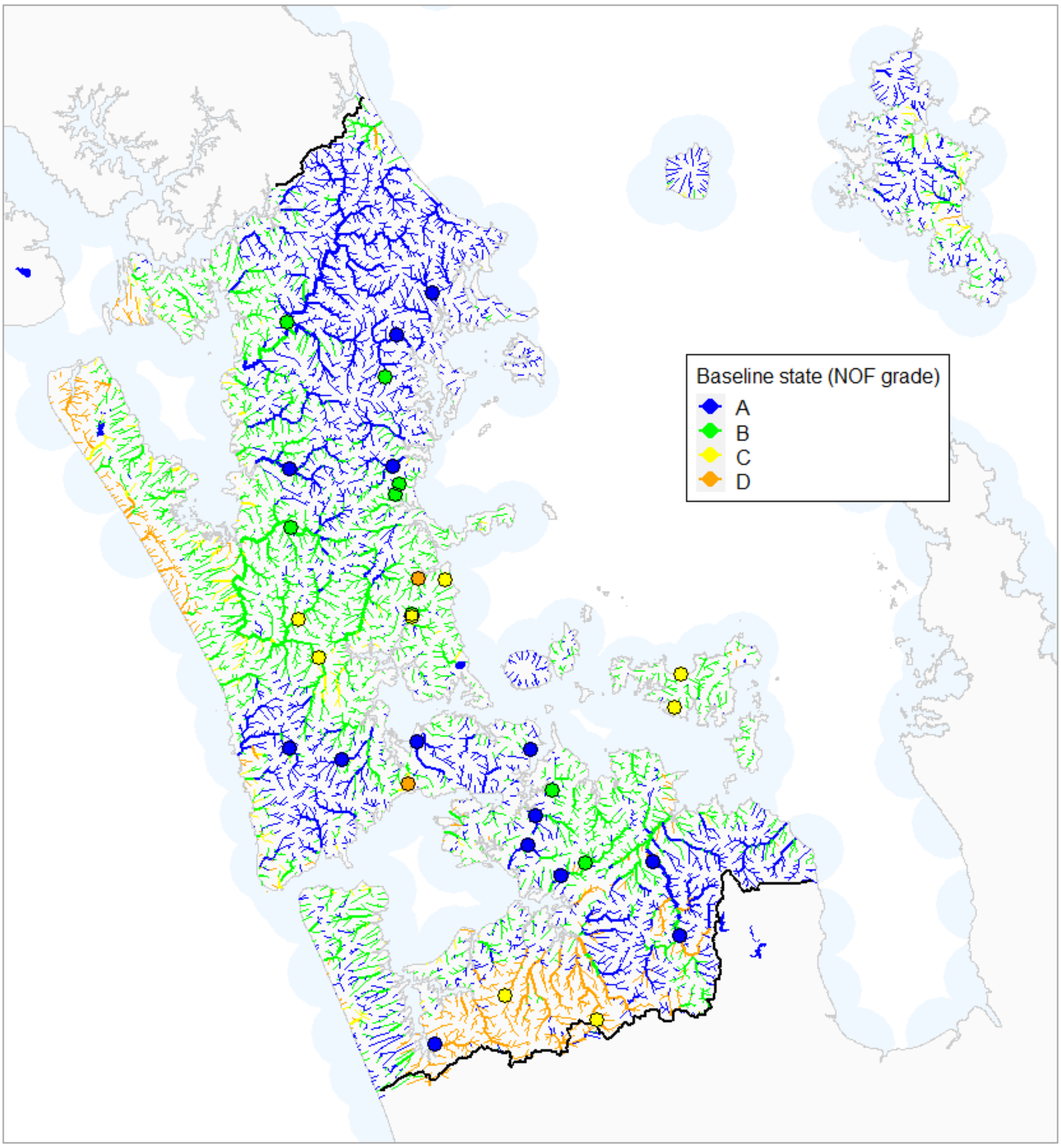

Figure 10. Baseline state of the suspended fine sediment attribute as NOF grades for all SOE sites and segments of the river network for the Auckland region. The points indicate the SOE sites and their calculated NOF grades. The lines represent the streams and rivers and the NOF grades derived from the baseline visual clarity predicted by the RF model.

3.3 Assessment of the C-band option

3.3.1 Compliance

For the C-band TAS, baseline visual clarity had a greater than 60% probability of being less than the relevant criteria (i.e., of being non-compliant) for 11% of river segments in the region (Figure 11). The location of segments having low probability of compliance was consistent with the location of segments that were predicted to be in the NOF D band (Figure 10).

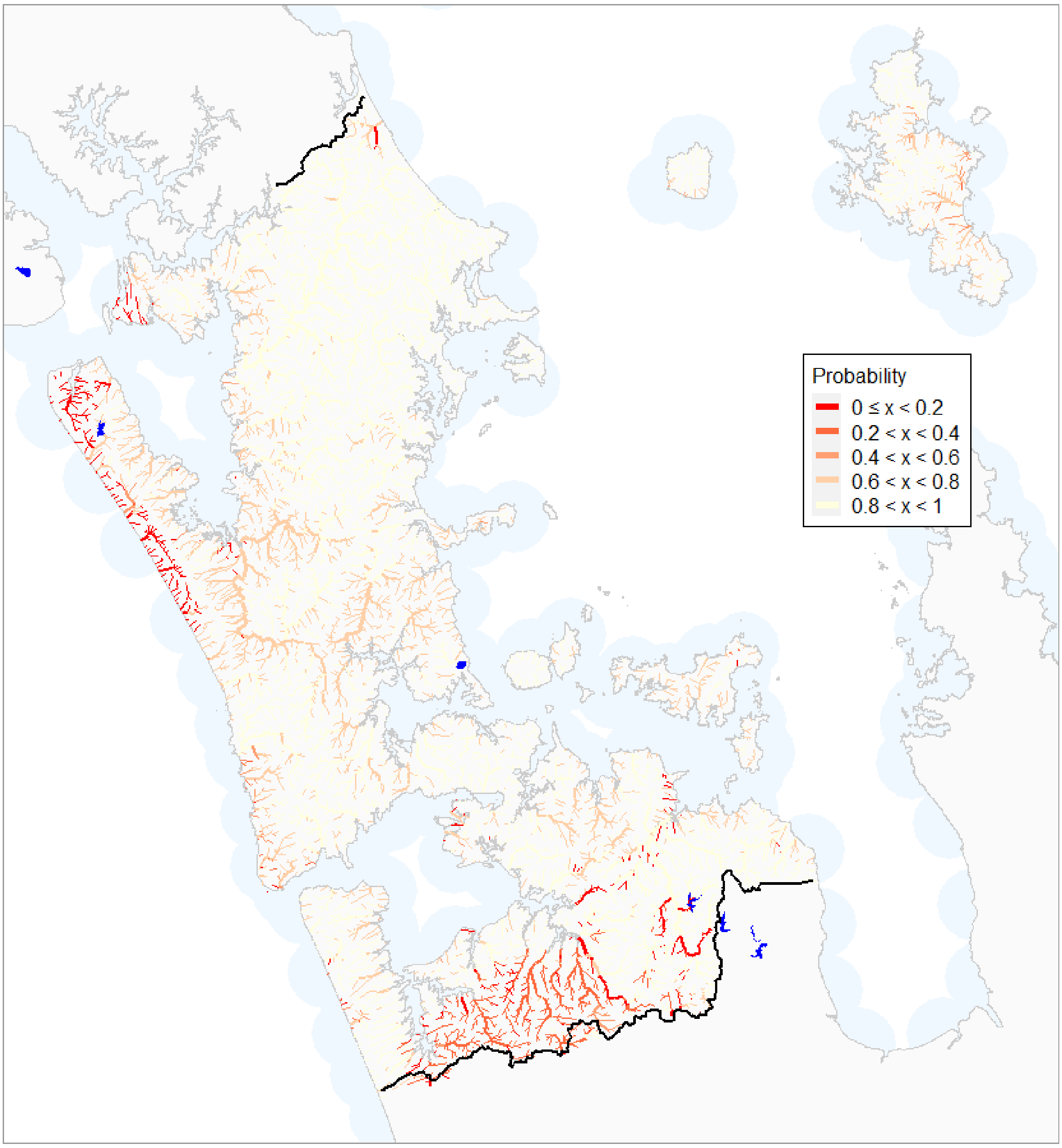

Figure 11. Probability that river segments comply with visual clarity criteria associated with the river suspended fine sediment attribute C-band.

3.3.2 Local excess loads

The local excess sediment load is the amount by which the baseline sediment load at each network segment (i.e., stream or river receiving environment) would need to be reduced to achieve the TAS. For the C-band option, local excess sediment loads for rivers exceeded 2 t km^{-2} yr^{-1} and 10 t km^{-2} yr^{-1} for 7% and 2% of segments, respectively (Figure 12). Note that the 2 t km^{-2} yr^{-1} and 10 t km^{-2} yr^{-1} are nominal breakpoints for communication purposes and correspond to the legend thresholds on Figure 12. For the C-band option, local excess sediment loads were zero for 91% of segments.

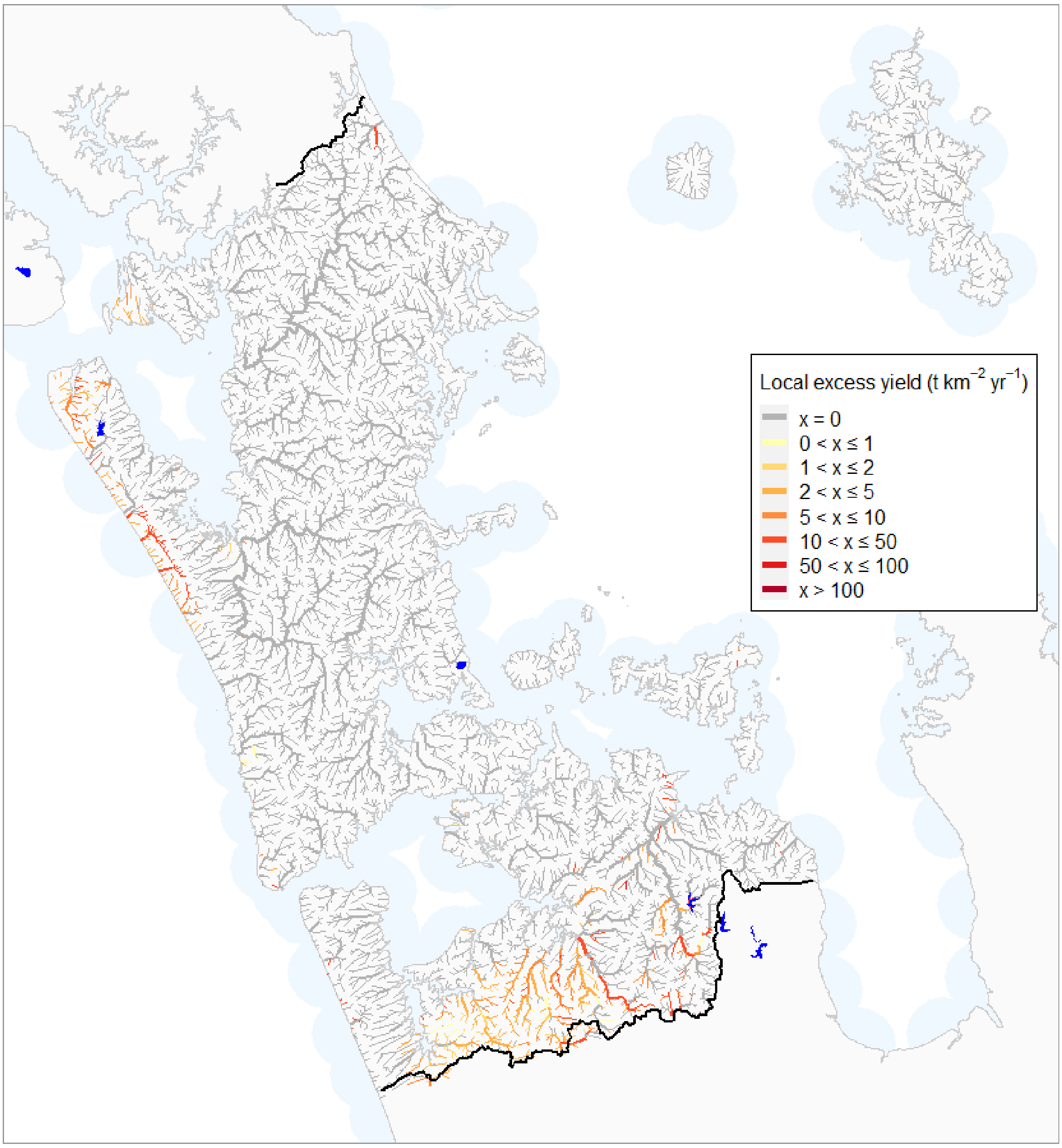

Figure 12. Local excess sediment loads for rivers for the river suspended fine sediment attribute C-band. Note that the breakpoints for the local excess loads in the map legend are nominal and have no special significance (i.e., are not guidelines or standards).

3.3.3 Critical point catchments and catchment status

The critical catchment status is the sediment load reduction that ensures the TAS can be achieved for all network segments (i.e., stream or river receiving environments) in the catchment. The critical catchment load reductions required differ from the local excess loads (Figure 12) in that they consider all receiving environments in a critical catchment. The load reduction required is expressed below as an absolute yield (i.e., t km^{-2} yr^{-1}) and as a percentage of the baseline load.

The sediment load reductions required by the C-band option for critical catchments are shown on Figure 13 and Figure 14. For the C-band option, critical point catchments that required load reductions of greater than 5 t km^{-2} yr^{-1} occupied 11% of the region and critical catchments requiring load reductions of greater than 2 t km^{-2} yr^{-1} occupied 15% of the region (Figure 13). When sediment load reductions required were expressed as a proportion of baseline loads, critical catchments that require reductions of greater than 20% or 50% occupied 12.8% and 2.4% of the region, respectively(Figure 14).

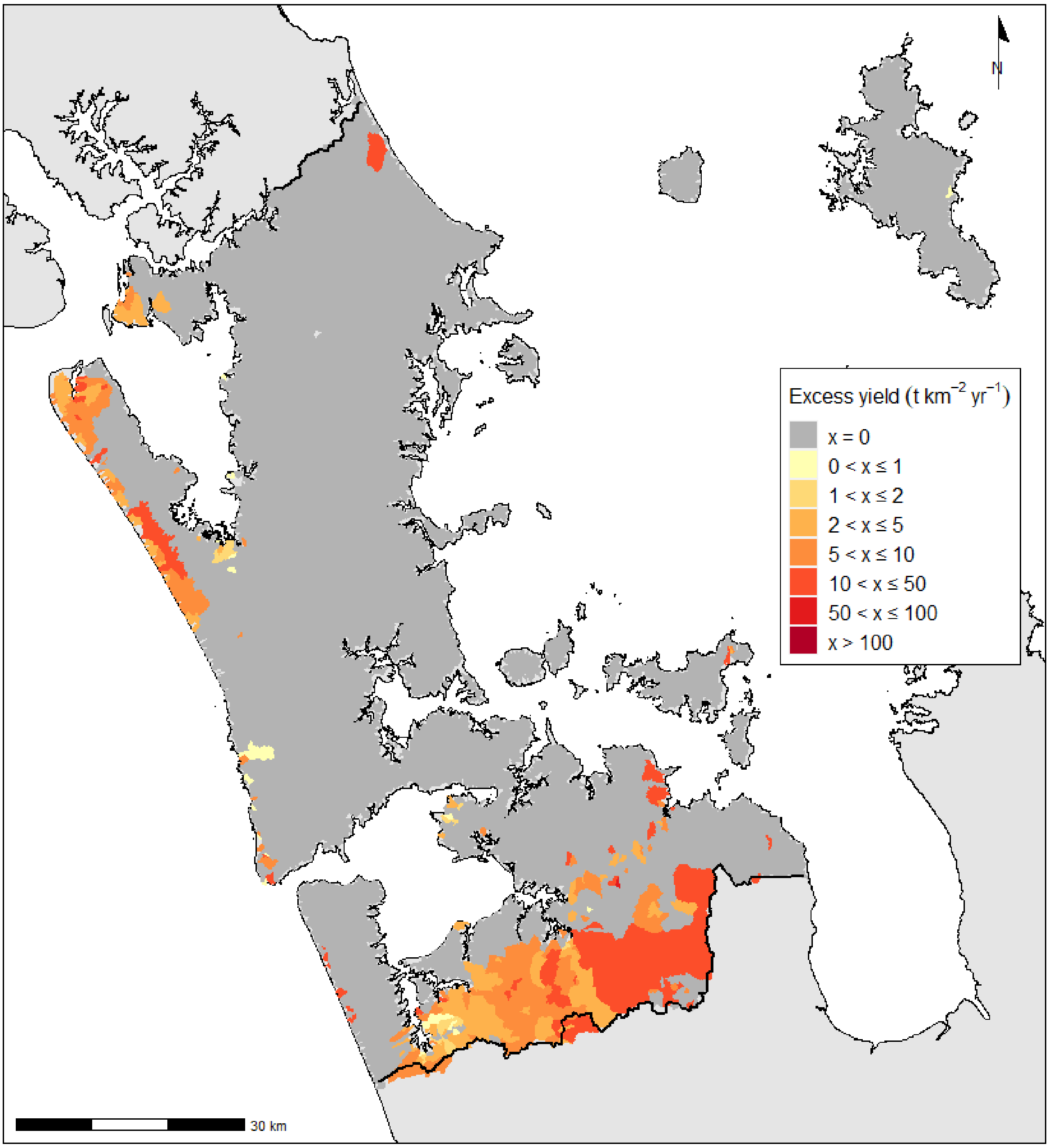

Figure 13. *The sediment load reduction required for critical catchments and the C-band TAS option, expressed as yields (t km^{-2} yr^{-1}). The critical catchment colours indicate the sediment load reductions that are required to allow all TASs to be achieved in the critical catchment (including the critical point at the bottom of the catchment).*

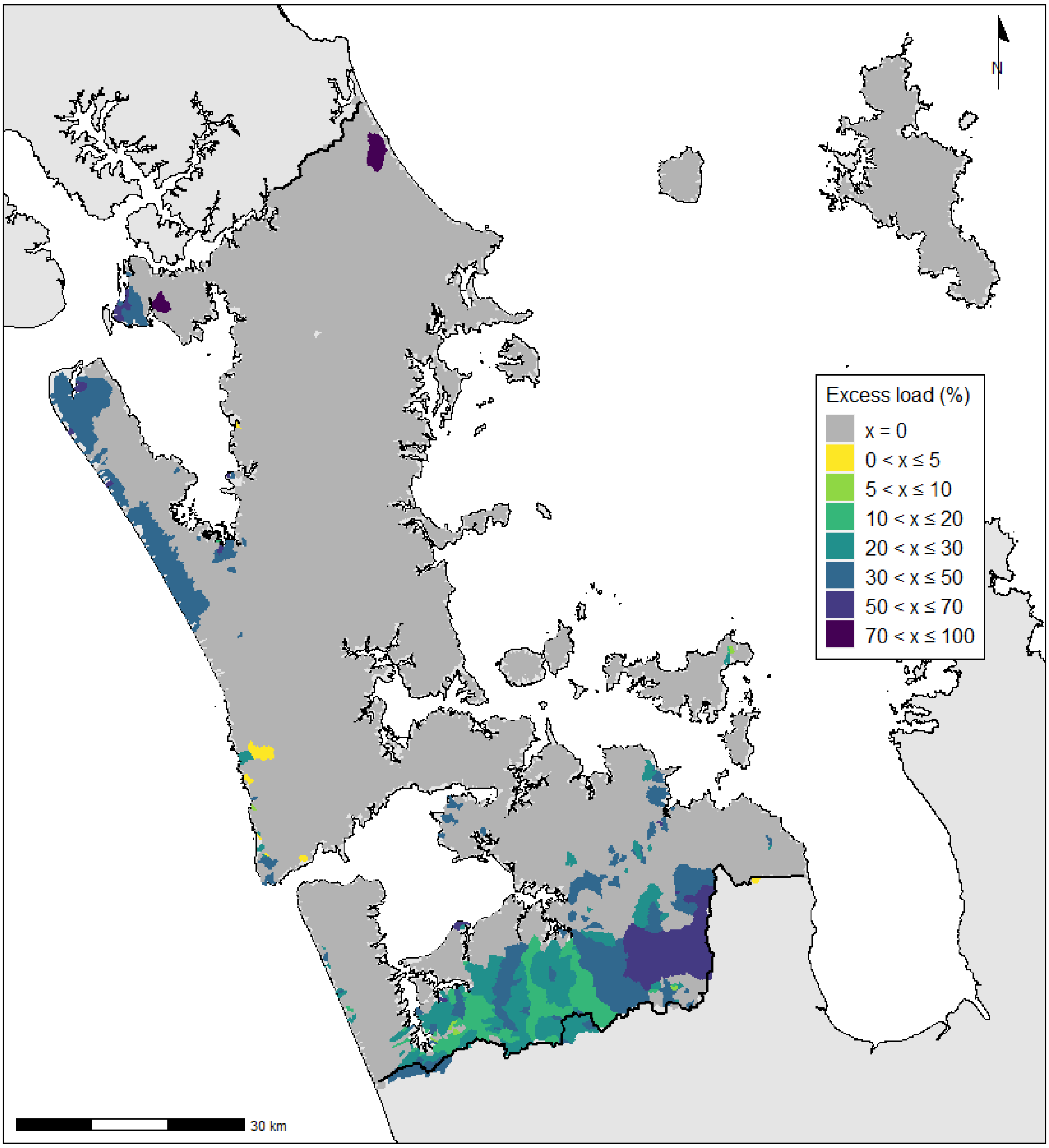

Figure 14. The sediment load reduction required for critical catchments and the C-band TAS option, expressed as a proportion of the baseline load (%). The critical catchment colours indicate the sediment load reductions that are required to allow the TAS to be achieved in all receiving environments in the critical catchment (including the critical point at the bottom of the catchment).

3.3.4 CRE, FMU and regional load reductions required

The load reductions required to achieve the C-band TAS option for each FMU and for the whole region are shown in Table 5. For the whole region, the sediment load reductions required were estimated to be 23 kilo tonnes per year (hereafter kt yr^{-1}, where kt indicates 1000 tonnes), which represents 6% of the total baseline regional load. The uncertainties for the estimated baseline load and the load reduction estimate, in terms of both absolute yields and percentage of baseline load, are expressed as the 90% confidence intervals in Table 5.

The uncertainties indicate, for example, that the 90% confidence interval for the baseline regional load extends between 291 kt yr^{-1} and 461 kt yr^{-1}. The 90% confidence interval for the regional load reduction requirement extends between 13 and 40 kt yr^{-1} of absolute yield, equating to a proportional load reduction requirement (relative to baseline) of 3% and 11% (best estimate 6%). For the C-band TAS option, the best estimates of sediment load reduction required were highest for the Manukau FMU (15%) and least for the Hauraki FMU (4%).

Table 5. Baseline load and load reduction required to achieve the C-band option for sediment for each FMU and the whole region. Note that loads are expressed in absolute terms in units of kilo tonnes (10^3 tonnes) per year (kt yr^{-1}) and as a proportion of baseline load (%). The first value in each column is the best estimate, which is the mean value over the 100 Monte Carlo realisations. The values in parentheses are the lower and upper bounds of the 90% confidence interval.

FMU	Baseline load (kt yr^{-1})	Load reduction required (kt yr^{-1})	Load reduction required (%)
Kaipara	161 (96 - 254)	9 (2 - 24)	5 (1 - 13)
Hauraki	118 (98 - 146)	5 (3 - 9)	4 (2 - 8)
Manukau	41 (32 - 54)	6 (3 - 11)	15 (7 - 25)
Region	365 (291 - 461)	23 (13 - 40)	6 (3 - 11)

The load reductions required to achieve the C-band TASs option for each CRE and for the whole region are shown in Table 6 as both absolute yields (kt yr^{-1}) and percentage of baseline load (%) and including the 90% confidence intervals. For the C-band TAS option, the best estimates of sediment load reduction required were highest for the West Coast (Kaipara FMU) CRE (27%) and least for the Mahurangi CRE (3%).

Table 6. Baseline load and load reduction required to achieve the C-band option for sediment for each CRE and whole region. Note that loads are expressed in absolute terms in units of kilo tonnes (10^3 tonnes) per year (kt yr^{-1}) and as a proportion of baseline load (%). The first value in each column is the best estimate, which is the mean value over the 100 Monte Carlo realisations. The values in parentheses are the lower and upper bounds of the 90% confidence interval.

CRE	Baseline load (kt yr^{-1})	Load reduction required (kt yr^{-1})	Load reduction required (%)
Hibiscus Coast	31 (17 - 58)	1 (0 - 3)	4 (0 - 12)
Islands	20 (17 - 23)	1 (1 - 2)	5 (3 - 10)
Kaipara	158 (92 - 250)	8 (1 - 23)	4 (1 - 13)
Mahurangi	10 (8 - 14)	0 (0 - 1)	3 (0 - 8)
Manukau Harbour	32 (23 - 43)	6 (2 - 11)	17 (7 - 30)
North East	21 (15 - 29)	1 (0 - 2)	4 (1 - 10)
Tamaki	10 (6 - 14)	1 (0 - 2)	7 (1 - 19)
Wairoa	16 (11 - 26)	1 (0 - 2)	4 (1 - 8)
Waitemata	10 (5 - 17)	1 (0 - 2)	5 (0 - 26)
West Coast (Kaipara FMU)	4 (3 - 5)	1 (1 - 2)	27 (17 - 37)
West Coast (Manukau FMU)	10 (7 - 13)	1 (0 - 1)	7 (3 - 12)
Region	365 (291 - 461)	23 (13 - 40)	6 (3 - 11)

3.4 Assessment of the B-band option

3.4.1 Compliance

For the B-band TAS, baseline visual clarity had a greater than 60% probability of being less than the relevant criteria (i.e., of being non-compliant) for 29% of river segments in the region (Figure 15). The location of segments having low probability of compliance was consistent with the location of segments that were predicted to be in the NOF C and D bands (Figure 10).

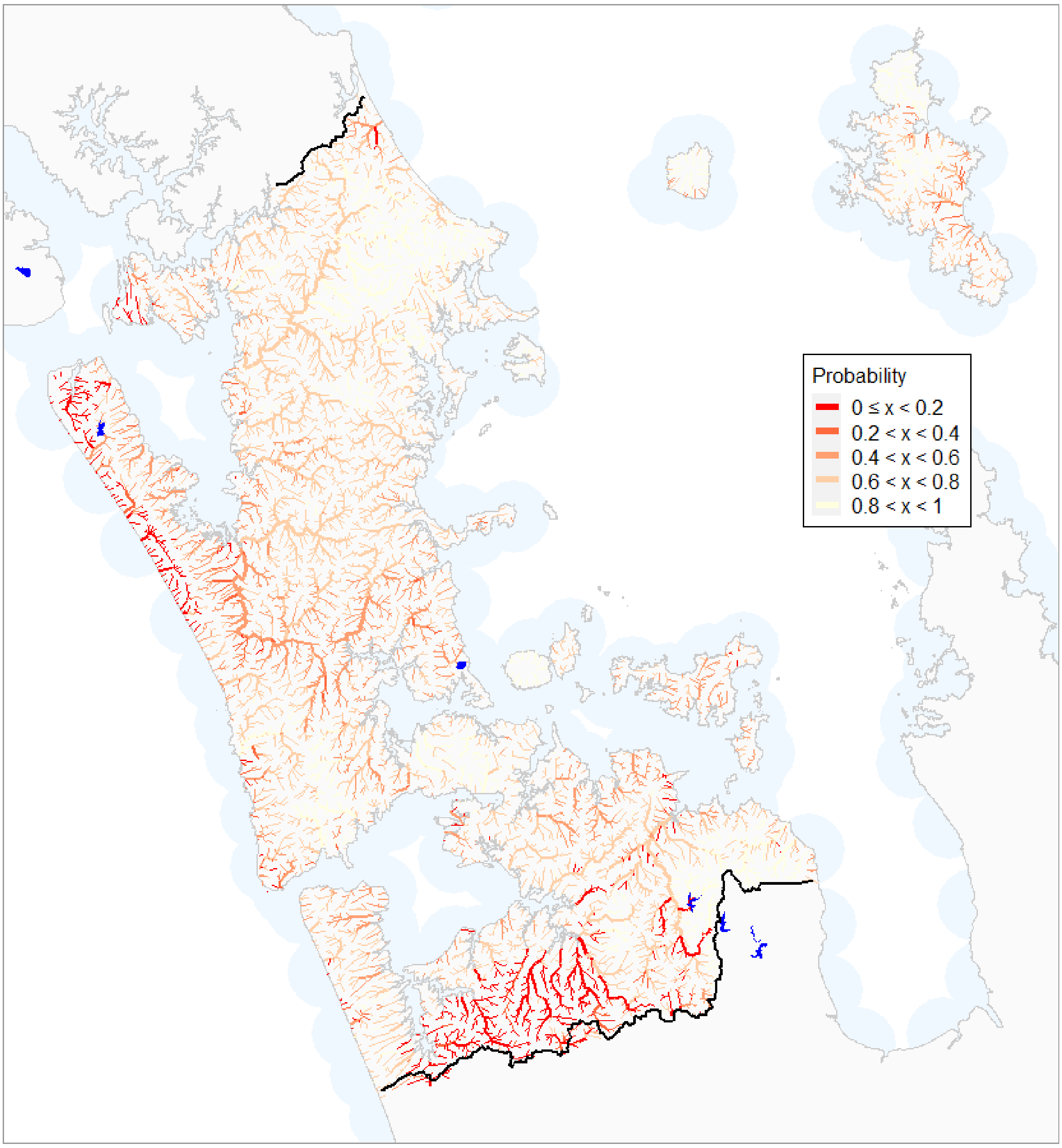

Figure 15. Probability that river segments comply with visual clarity criteria associated with the river suspended fine sediment attribute B-band.

3.4.2 Local excess loads

The local excess sediment load is the amount by which the baseline sediment load at each network segment (i.e., stream or river receiving environment) would need to be reduced to achieve the TAS. For the B-band option, local excess sediment loads for rivers exceeded 2 t km^{-2} yr^{-1} and 10 t km^{-2} yr^{-1} for 10% and 4% of segments, respectively, and local excess sediment loads were zero for 89% of segments (Figure 16). .

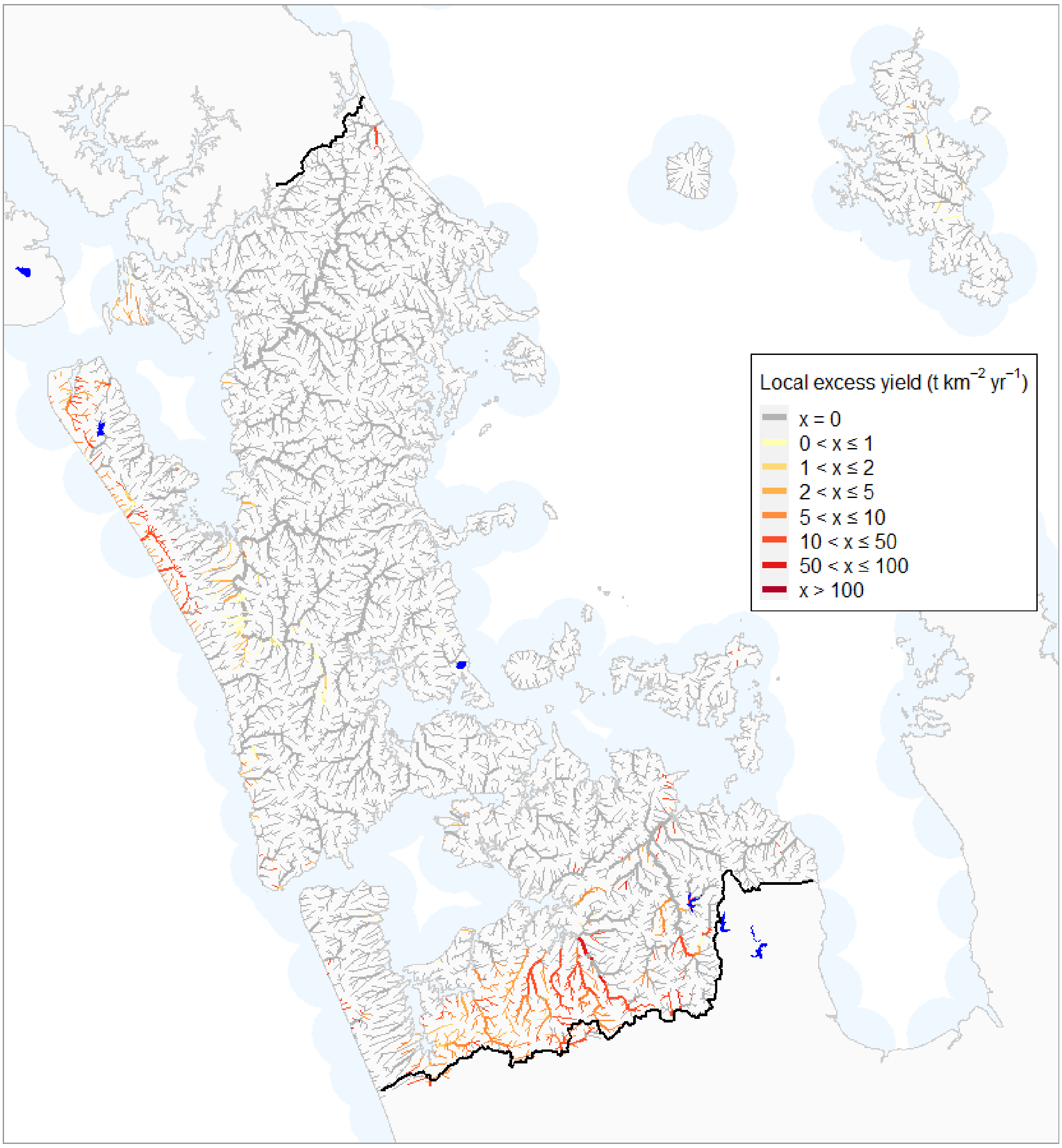

Figure 16. Local excess sediment loads for rivers for the river suspended fine sediment attribute B-band. Note that the breakpoints for the local excess loads in the map legend are nominal and have no special significance (i.e., are not guidelines or standards).

3.4.3 Critical point catchments and catchment status

The sediment load reductions required by the B-band option for critical catchments are shown on Figure 17 and Figure 18. Critical point catchments that required load reductions of greater than 5 t km^{-2} yr^{-1} occupied 10% of the region and critical catchments with load reductions of greater than 2 t km^{-2} yr^{-1} occupied 13% of the region (Figure 17). When sediment load reductions required were expressed as a proportion of baseline loads, critical catchments that require reductions of greater than 20% occupied 12% of the region and greater than 50% occupied 2% of the region (Figure 18).

It is noted that the patterns shown on Figure 17 and Figure 18 are not exactly coincident. For example, the large critical catchment with an excess yield in the zero to two range in the Kumeū area that is shown on Figure 17 does not appear on Figure 18. This is because the critical catchment excess load as a proportion of baseline loads is calculated as the mean of the ratio of excess load to baseline load over all realizations whereas the excess load as a yield is the mean of the excess yield over all realizations. These small differences reflect how the inherent uncertainty of the models affects the reported load reductions.

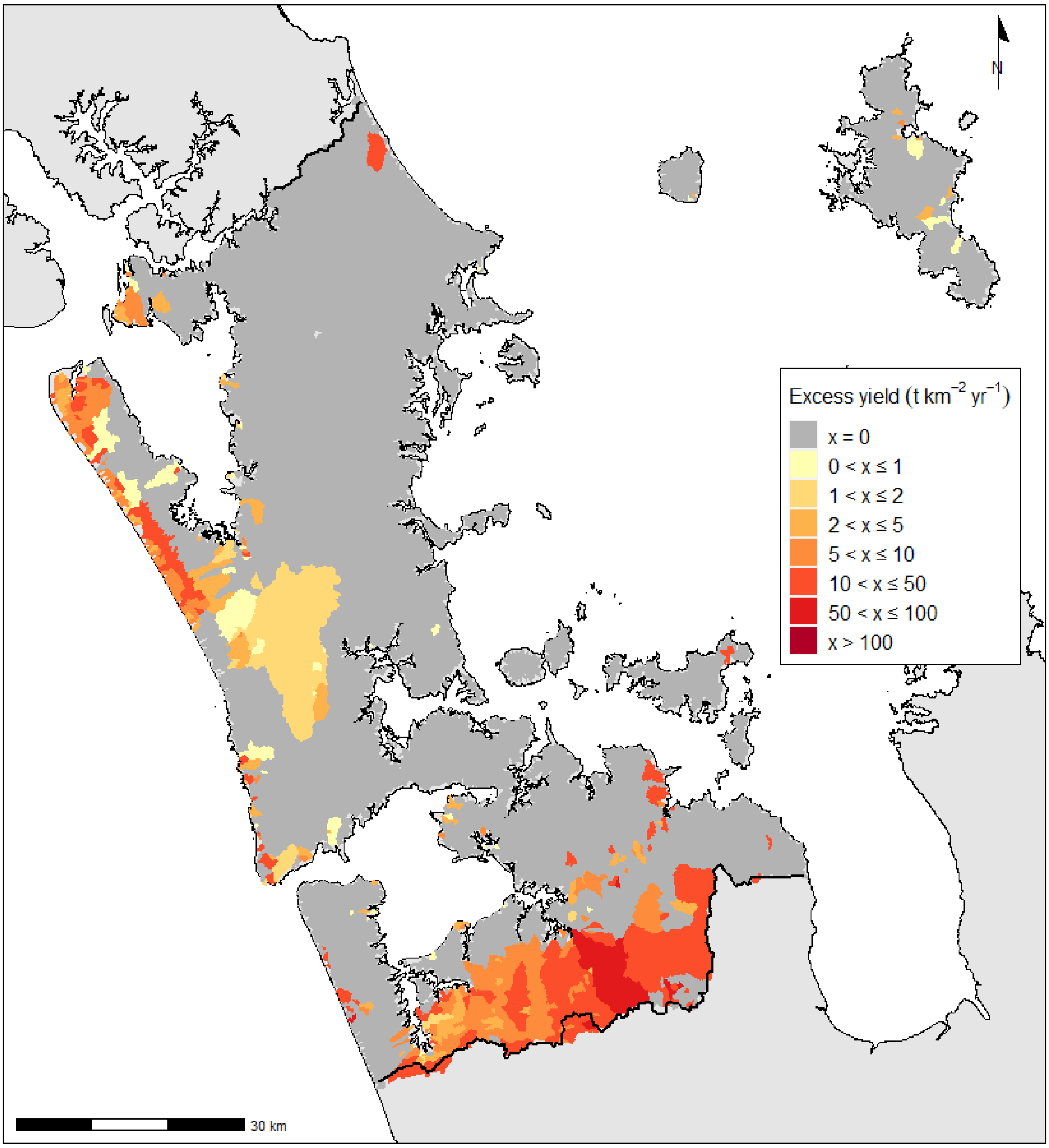

Figure 17*. The sediment load reduction required for critical catchments and the B-band TAS option, expressed as yields (t km^{-2} yr^{-1}). The critical catchment colours indicate the sediment load reductions that are required to allow all TASs to be achieved in the critical catchment (including the critical point at the bottom of the catchment).*

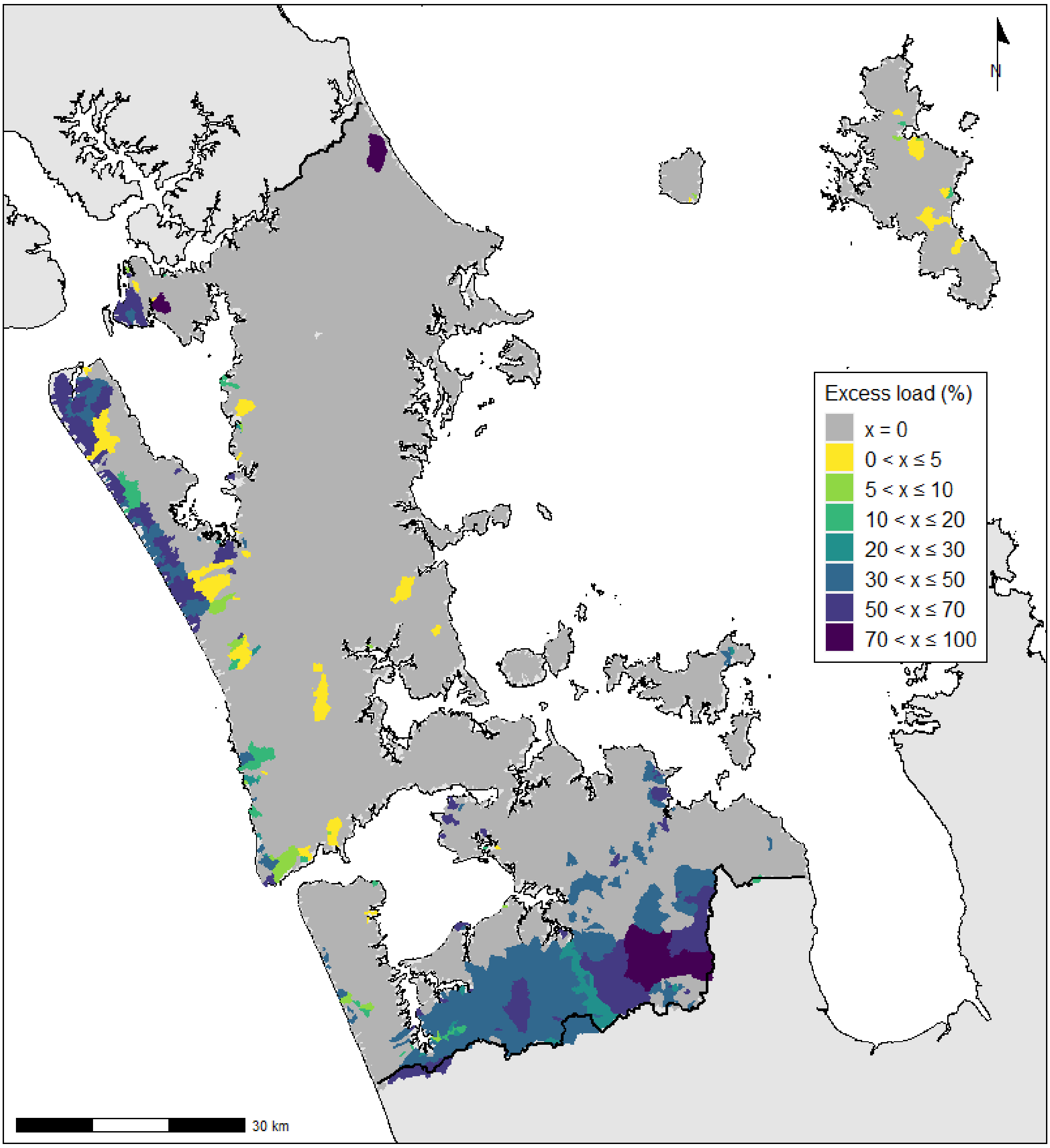

Figure 18. The sediment load reduction required for critical catchments and the B-band TAS option, expressed as a proportion of the baseline load (%). The critical catchment colours indicate the sediment load reductions that are required to allow the TAS to be achieved in all receiving environments in the critical catchment (including the critical point at the bottom of the catchment).

3.4.4 CRE, FMU and regional load reductions required

The load reductions required to achieve the B-band TAS option for each FMU and for the whole region are shown in Table 7. For the whole region, the sediment load reductions required were estimated to be 39 kt yr^{-1}, which represents 11% of the total baseline regional load. The uncertainties shown in Table 7 indicate, for example, that the 90% confidence interval for the required regional load reduction extends between 26 kt yr^{-1} and 59 kt yr^{-1}. The 90% confidence interval for the regional load reduction requirement extends between 7% and 16% (best estimate 11%). For the B-band TAS option, the best estimates of sediment load reduction required were highest for the Manukau FMU (22%) and least for the Hauraki FMU (9%).

Table 7. Baseline load and load reduction required to achieve the B-band option for sediment for each FMU and the whole region. Note that loads are expressed in absolute terms in units of kilo tonnes (10^3 tonnes) per year (kt yr^{-1}) and as a proportion of baseline load (%). The first value in each column is the best estimate, which is the mean value over the 100 Monte Carlo realisations. The values in parentheses are the lower and upper bounds of the 90% confidence interval.

FMU	Baseline load (kt yr^{-1})	Load reduction required (kt yr^{-1})	Load reduction required (%)
Kaipara FMU	154 (103 - 238)	16 (6 - 40)	10 (4 - 23)
Hauraki FMU	118 (96 - 143)	10 (6 - 16)	9 (6 - 13)
Manukau FMU	40 (33 - 51)	9 (6 - 15)	22 (15 - 32)
Region	354 (295 - 426)	39 (26 - 59)	11 (7 - 16)

The load reductions required to achieve the B-band TASs option for each CRE and for the whole region are shown in Table 8 as both absolute yields (kt yr^{-1}) and percentage of baseline load (%) and including the 90% confidence intervals. For the B-band TAS option, the best estimates of sediment load reduction required were highest for the West Coast (Kaipara FMU) CRE (35%) and least for the Mahurangi and North East CREs (6%).

Table 8. Baseline load and load reduction required to achieve the B-band option for sediment for each CRE and whole region. Note that loads are expressed in absolute terms in units of kilo tonnes (10^3 tonnes) per year (kt yr^{-1}) and as a proportion of baseline load (%). The first value in each column is the best estimate, which is the mean value over the 100 Monte Carlo realisations. The values in parentheses are the lower and upper bounds of the 90% confidence interval.

CRE	Baseline load (kt yr^{-1})	Load reduction required (kt yr^{-1})	Load reduction required (%)
Hibiscus Coast	32 (18 - 52)	3 (1 - 8)	9 (2 - 23)
Islands	19 (17 - 23)	2 (1 - 3)	9 (6 - 14)
Kaipara	150 (99 - 233)	14 (4 - 40)	9 (3 - 23)
Mahurangi	9 (7 - 13)	1 (0 - 2)	6 (2 - 17)
Manukau Harbour	31 (23 - 42)	8 (4 - 14)	24 (15 - 37)
North East	21 (14 - 28)	1 (0 - 3)	6 (2 - 15)
Tamaki	11 (7 - 16)	1 (0 - 4)	14 (4 - 36)
Wairoa	15 (10 - 24)	1 (0 - 3)	8 (3 - 21)
Waitemata	10 (5 - 18)	1 (0 - 3)	12 (1 - 33)
West Coast (Kaipara FMU)	4 (3 - 5)	1 (1 - 2)	35 (20 - 48)
West Coast (Manukau FMU)	10 (7 - 13)	1 (1 - 2)	13 (7 - 22)
Region	354 (295 - 426)	39 (26 - 59)	11 (7 - 16)

3.5 Assessment of the A-band option

3.5.1 Compliance

For the A-band TAS, baseline visual clarity had a greater than 60% probability of being less than the relevant criteria (i.e., of being non-compliant) for 70% of river segments in the region (Figure 19). The location of segments having low probability of compliance was consistent with the location of segments that were predicted to be in the NOF B, C and D bands (Figure 10).

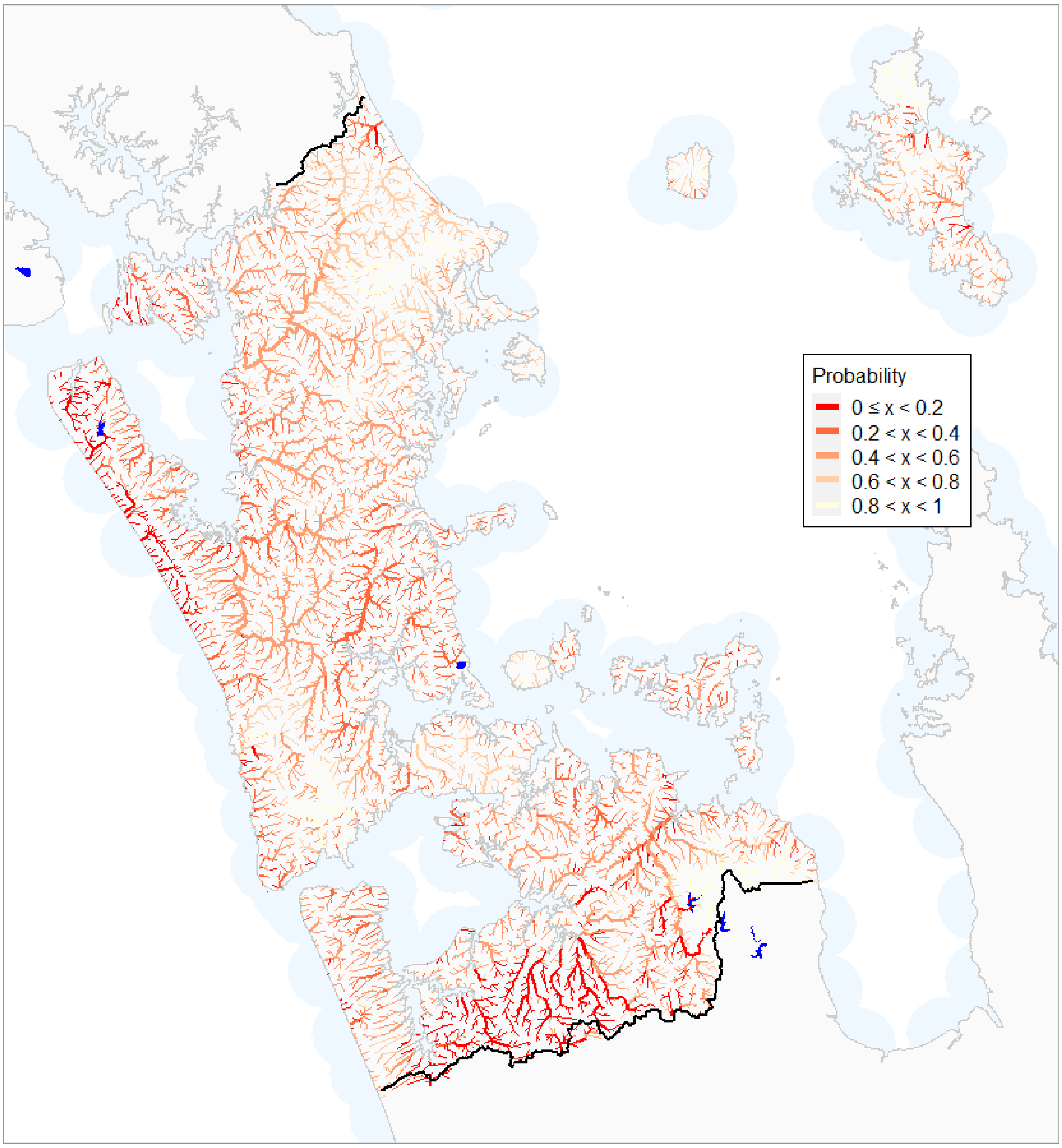

Figure 19. Probability that river segments comply with visual clarity criteria associated with the river suspended fine sediment attribute A-band.

3.5.2 Local excess loads

The local excess sediment load is the amount by which the baseline sediment load at each network segment (i.e., stream or river receiving environment) would need to be reduced to achieve the TAS. For the A-band option, local excess sediment loads for rivers exceeded 2 t km^{-2} yr^{-1} and 10 t km^{-2} yr^{-1} for 18% and 8% of segments, respectively (Figure 20). For the A-band option, local excess sediment loads were zero for 76% of segments.

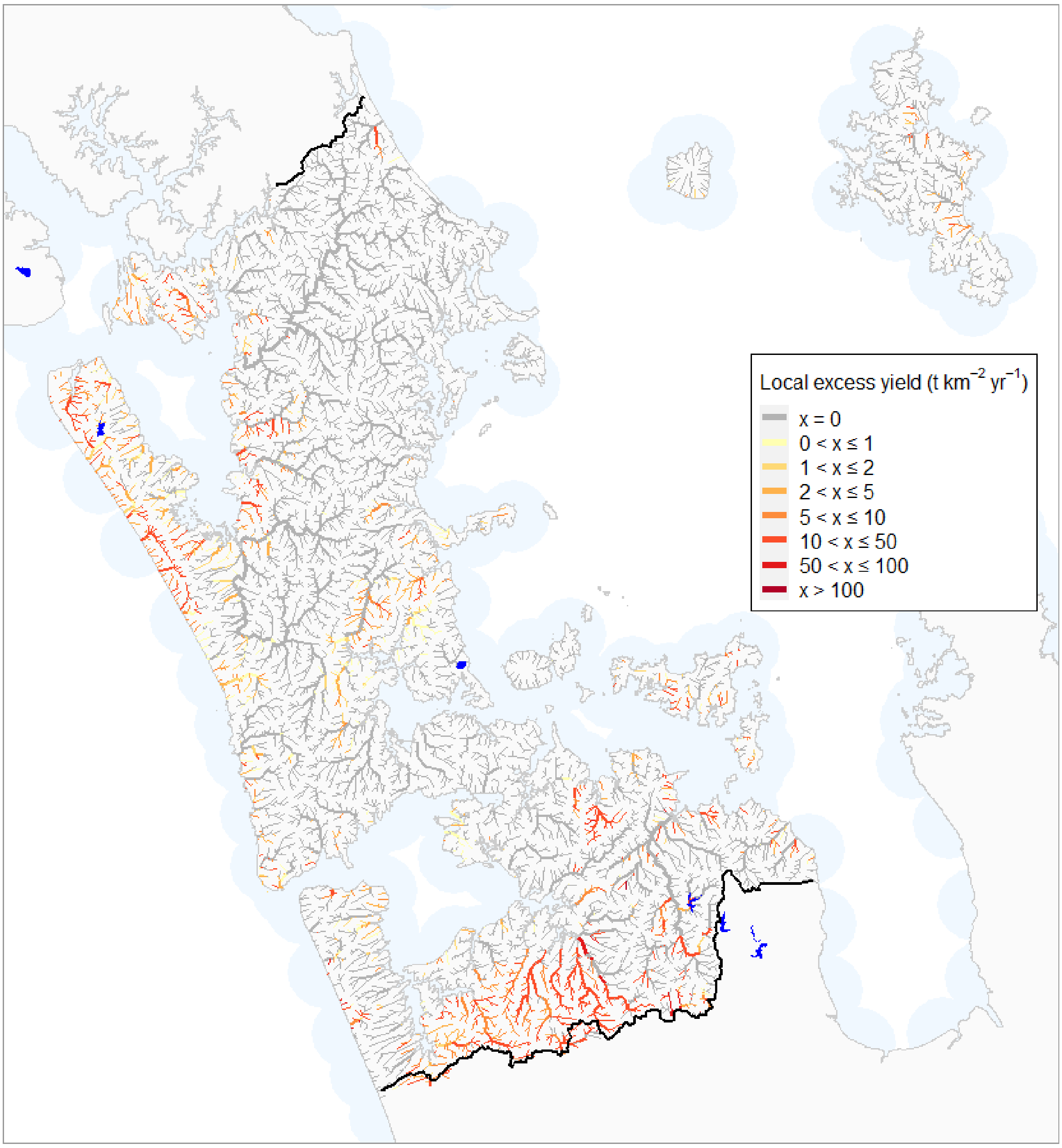

Figure 20. Local excess sediment loads for rivers for the river suspended fine sediment attribute A-band. Note that the breakpoints for the local excess loads in the map legend are nominal and have no special significance (i.e., are not guidelines or standards).

3.5.3 Critical point catchments and catchment status

The sediment load reductions required by the A-band option for critical catchments are shown on Figure 21 and Figure 22. For the A-band option, critical point catchments that required load reductions of greater than 5 t km^{-2} yr^{-1} occupied 23% of the region and critical catchments with load reductions of greater than 2 t km^{-2} yr^{-1} occupied 30% of the region (Figure 21). When sediment load reductions required were expressed as a proportion of baseline loads, critical catchments that require reductions of greater than 20% occupied 17% of the region and greater than 50% occupied 11% of the region (Figure 22).

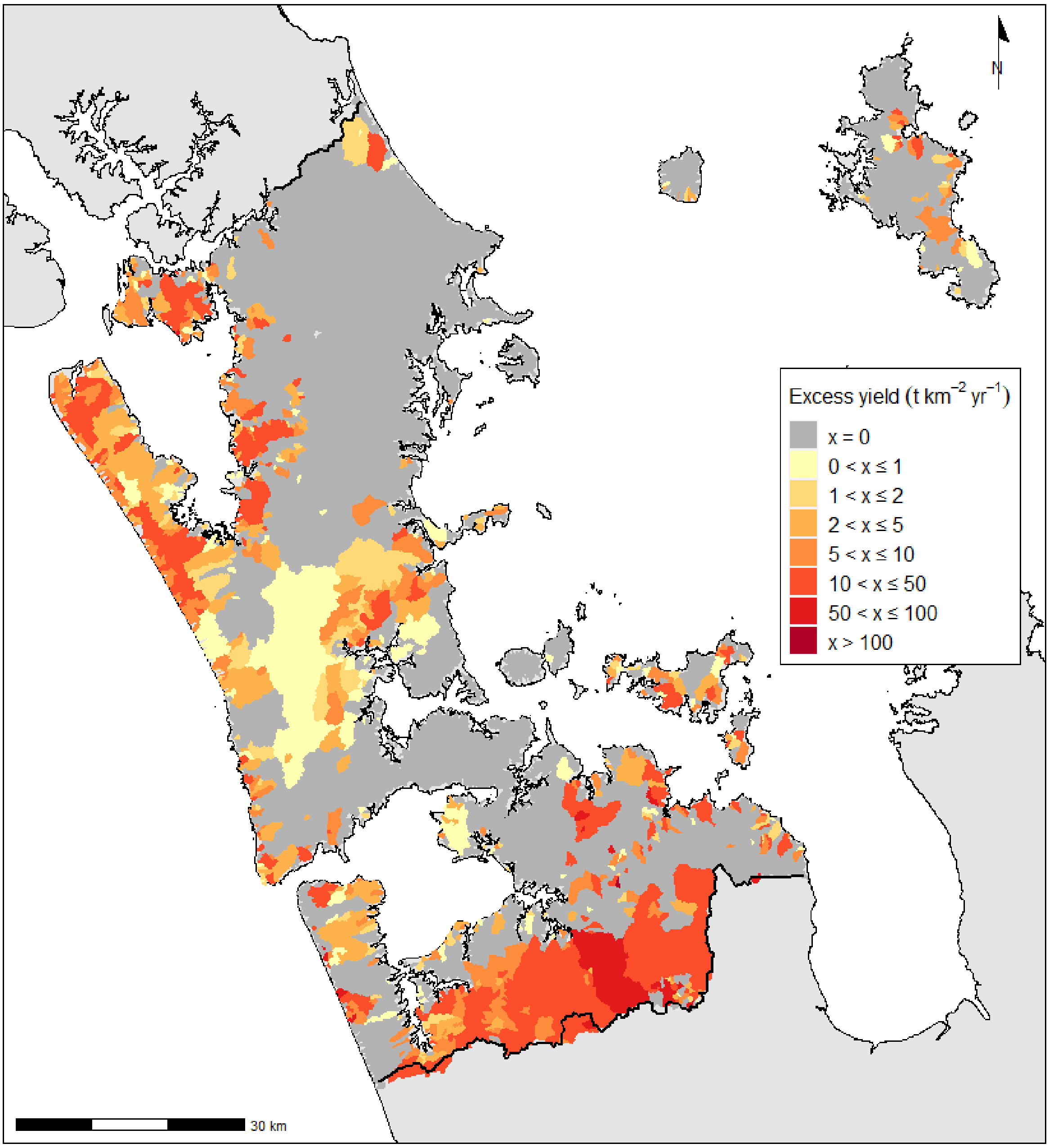

Figure 21. The sediment load reduction required for critical catchments and the A-band TAS option, expressed as yields (t km^{-2} yr^{-1}). The critical catchment colours indicate the sediment load reductions that are required to allow all TASs to be achieved in the critical catchment (including the critical point at the bottom of the catchment).

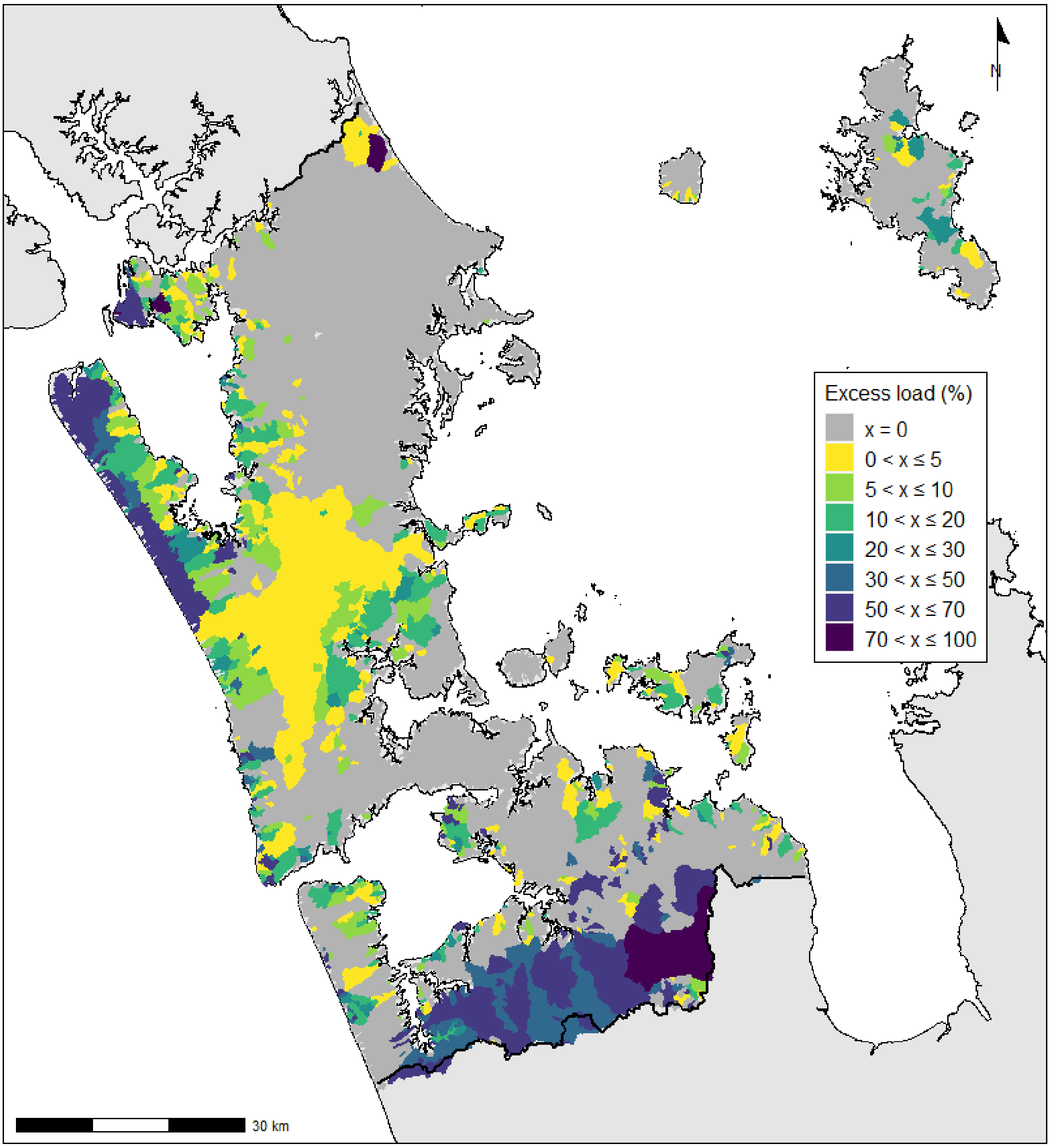

Figure 22. The sediment load reduction required for critical catchments and the A-band TAS option, expressed as a proportion of the baseline load (%). The critical catchment colours indicate the sediment load reductions that are required to allow the TAS to be achieved in all receiving environments in the critical catchment (including the critical point at the bottom of the catchment).

3.5.4 CRE, FMU and regional load reductions required

The load reductions required to achieve the A-band TAS option for each FMU and for the whole region are shown in Table 9. For the whole region, the sediment load reductions required were estimated to be 68 kt yr^{-1}, which represents 19% of the total baseline regional load. The uncertainties shown in Table 9 indicate, for example, that the 90% confidence interval for the baseline regional load reduction required extends between 43 kt yr^{-1} and 105 kt yr^{-1}. The 90% confidence interval for the regional load reduction requirement extends between 12% and 28% (best estimate 19%). For the A-band TAS option, the best estimates of sediment load reduction required were highest for the Manukau FMU (30%) and least for the Hauraki FMU (15%).

Table 9. Baseline load and load reduction required to achieve the A-band option for sediment for each FMU and the whole region. Note that loads are expressed in absolute terms in units of kilo tonnes (10^3 tonnes) per year (kt yr^{-1}) and as a proportion of baseline load (%). The first value in each column is the best estimate, which is the mean value over the 100 Monte Carlo realisations. The values in parentheses are the lower and upper bounds of the 90% confidence interval.

FMU	Baseline load (kt yr^{-1})	Load reduction required (kt yr^{-1})	Load reduction required (%)
Kaipara	157 (108 - 220)	29 (10 - 66)	19 (7 - 40)
Hauraki	117 (98 - 146)	18 (11 - 26)	15 (10 - 22)
Manukau	42 (33 - 53)	12 (8 - 18)	30 (22 - 40)
Region	361 (302 - 427)	68 (43 - 105)	19 (12 - 28)

The load reductions required to achieve the A-band TASs option for each CRE and for the whole region are shown in Table 10 as both absolute yields (kt yr^{-1}) and percentage of baseline load (%) and including the 90% confidence intervals. For the A-band TAS option, the best estimates of sediment load reduction required were highest for the West Coast (Kaipara FMU) CRE (45%) and least for the North East CRE (11%).

Table 10. Baseline load and load reduction required to achieve the A-band option for sediment for each CRE and whole region. Note that loads are expressed in absolute terms in units of kilo tonnes (10^3 tonnes) per year (kt yr^{-1}) and as a proportion of baseline load (%). The first value in each column is the best estimate, which is the mean value over the 100 Monte Carlo realisations. The values in parentheses are the lower and upper bounds of the 90% confidence interval.

CRE	Baseline load (kt yr^{-1})	Load reduction required (kt yr^{-1})	Load reduction required (%)
Hibiscus Coast	30 (18 - 49)	5 (1 - 12)	16 (3 - 38)
Islands	20 (17 - 23)	3 (2 - 4)	14 (10 - 19)
Kaipara	154 (105 - 216)	28 (9 - 64)	18 (7 - 39)
Mahurangi	10 (7 - 13)	1 (0 - 3)	13 (5 - 28)
Manukau Harbour	32 (24 - 41)	10 (7 - 16)	33 (21 - 47)
North East	21 (16 - 27)	2 (1 - 5)	11 (5 - 22)
Tamaki	10 (6 - 16)	2 (1 - 6)	23 (5 - 43)
Wairoa	16 (10 - 25)	2 (1 - 5)	15 (6 - 28)
Waitemata	10 (5 - 16)	2 (0 - 6)	21 (3 - 51)
West Coast (Kaipara FMU)	4 (3 - 5)	2 (1 - 2)	45 (32 - 56)
West Coast (Manukau FMU)	10 (7 - 14)	2 (1 - 3)	19 (10 - 33)
Region	361 (302 - 427)	68 (43 - 105)	19 (12 - 28)

3.6 Comparison between scenarios

Comparisons of the sediment load reductions required for the FMUs and CREs to achieve the three TAS options are shown in Figure 23 and Figure 24, respectively. Across all FMUs and CREs, load reductions required were always largest for the A-band TAS and least for the C-band TAS. This is because the A-, B- and C-band TASs represent increasing levels of environmental quality and therefore increasingly stringent criteria.

In some FMUs and CREs, the difference in load reductions required between the options were small (points plotted close to each other in Figure 23 and Figure 24). In addition, within each FMU and CRE the error bars showing the 90% confidence intervals of the load reductions required to achieve the A-, B- and C-band TASs were generally strongly overlapping. The overlapping error bars indicate that the differences between TASs in the load reductions required are not statistically significant. This is because the models have considerable uncertainty and the visual clarity and load estimates that separate the three TAS options are similar, relative to this uncertainty.

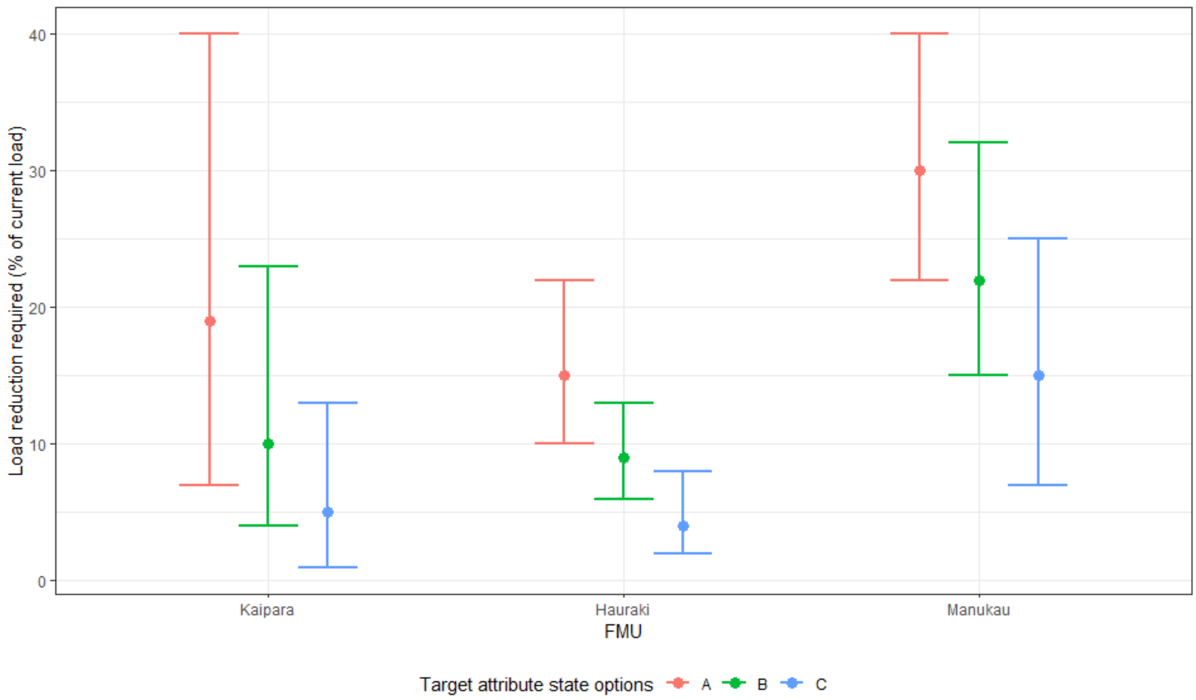

Figure 23. Comparison of the best estimates of sediment load reductions required for each Freshwater Management Units (FMU) for the three TAS options. The loads are expressed as a proportion of baseline load (%). The error bars are the 5th and 95th confidence limits (i.e., the range is the 90% confidence interval). See Figure 4 for the location of each FMU.

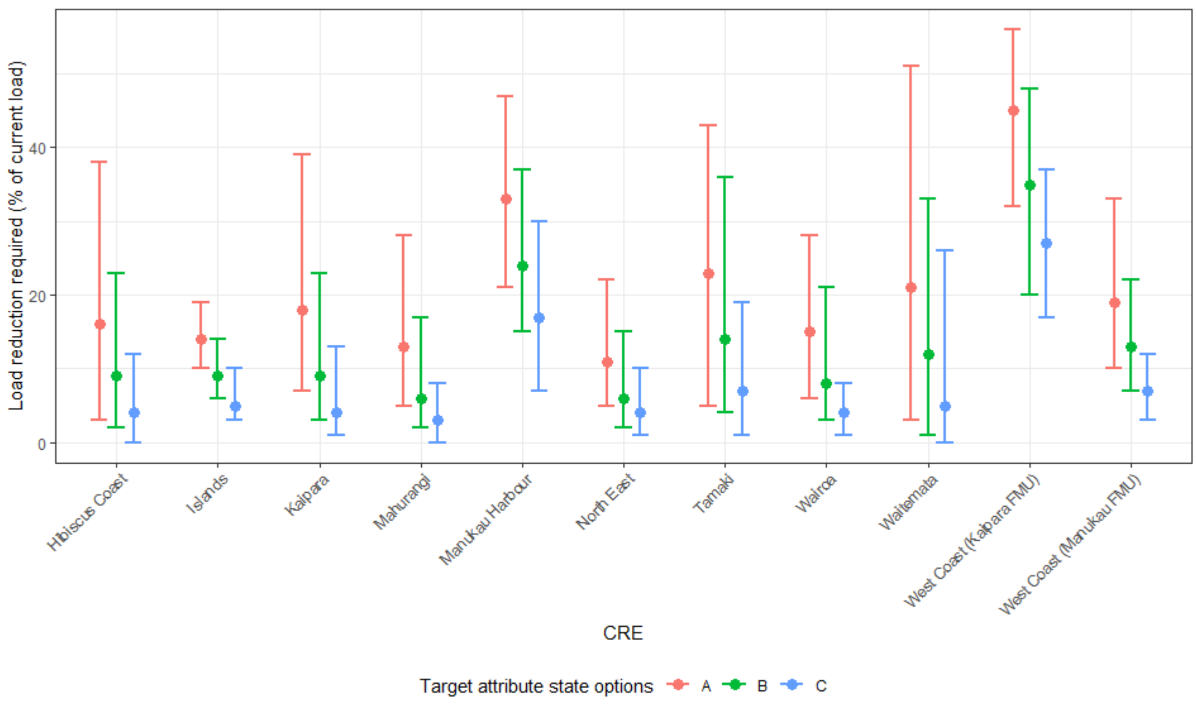

Figure 24. Comparison of the best estimates of sediment load reductions required for each Stormwater Consolidated Receiving Environment catchment (CRE) for the three TAS options. The loads are expressed as a proportion of baseline load (%). The error bars are the 5th and 95th confidence limits (i.e., the range is the 90% confidence interval). See Figure 5 for the location of each CRE.

4 Discussion and summary

4.1 Load reductions required

This study assessed baseline sediment loads in streams and rivers of the Auckland region and the reductions of those loads needed to achieve options for three \ TASs. The options for TASs are defined in terms of three NPS-FM attribute band thresholds (A, B or C) for all regional stream and river receiving environments.

Suspended sediment load reductions required for each of the TASs were quantified for all individual river segments in the study area. The load reductions that were assessed for the C-band TAS represent the national bottom line and, therefore, the minimum that AC's implementation of the NPS-FM would need to include to achieve acceptable sediment loads in the streams and rivers of the region. The model results indicate that a regional sediment load reduction of 6% (90% confidence interval 3% - 11%) is required to achieve at least the national bottom line for rivers (i.e., the C-band TAS, Table 11) in the Auckland region. This does not include consideration of sediment objectives for downstream estuary receiving environments, which may be greater than the load reductions estimated in this report to achieve visual clarity TASs in the Region's streams and rivers.

Table 11. The sediment load reductions required the region for the three TAS options. The load reductions are expressed as yields and proportions of the baseline load. The values shown in parentheses are the 5th and 95th confidence limits for the reported values (i.e., the range is the 90% confidence interval).

TAS option	Sediment reduction (kilo t yr^{-1})	Sediment reduction (%)
C-band	23 (13 - 40)	6 (3 - 11)
B-band	39 (26 - 59)	11 (7 - 16)
A-band	68 (43 - 105)	19 (12 - 28)

4.2 Uncertainties

Uncertainty is an unavoidable aspect of this study because it is based on simplifications of reality and because it has been informed by limited data. The study estimated the statistical uncertainty of the sediment load reduction estimates that are associated with three key components of the analyses: the spatial models of river visual clarity, the relative reduction in sediment load required and the absolute sediment loads (see Sections 3.1 and). The statistical uncertainty of these spatial models is associated with their inability to perfectly predict the visual clarity and loads observed at water quality monitoring sites; the error associated with these predictions is quantified by the model RMSD values (Table 4 and).

The errors (i.e., statistical uncertainties) associated with each of the models were combined using Monte Carlo analyses to provide estimates of the uncertainty for all the assessed load reduction requirements. In this study, a lower limit of the 90% confidence interval that is greater than zero, indicates a 95% level of confidence that a load reduction is required. We can therefore have high confidence (i.e., ≥ 95%) that sediment load reductions are required for all

TAS options for the region as a whole (e.g., Table 5) for all FMUs (Figure 23) and for most CREs (Figure 24).

The uncertainty of the load reductions presented in this study are associated with the statistical uncertainty of the spatial models. These are not a complete description of the uncertainty of the load reduction assessment for at least three reasons. First, because the visual clarity statistics (e.g., site median values) are calculated from monthly data, they are subject to sample error and are therefore imprecise estimates of the population statistic they are representing. Second, there is also uncertainty associated with the sediment load estimates at the sites that Hicks, Semadeni-Davies, *et al.* (2019) used to fit the Sediment Load Estimator model and that Hicks, Haddadchi, *et al.* (2019) used to fit the Sediment Load Reduction Factor model. Therefore, in assessing the uncertainties of both these spatial models, the imprecision of the relevant values at each water quality site was ignored. The uncertainty of the spatial models is therefore only measuring the ability to predict the imprecise "observed" values rather than the unknown population statistic or load. This means the uncertainty estimates are themselves uncertain and should be regarded as indicative.

The second reason that uncertainty of the load reductions presented in this study are themselves uncertain is that there are uncertainties associated with the assumptions used in the load reduction calculations that are not represented in the uncertainties reported above. Important assumptions used in the calculations are that the relationship between sediment loads and visual clarity remain constant when loads are changed. These assumptions are very likely simplifications of reality. However, we lack the scientific understanding and data needed to significantly improve the representation of these relationships or to quantify the associated uncertainty.

There is another component of uncertainty associated with environmental criteria. For example, most criteria are based on finding the stressor value for which the mean response exceeds a threshold value. This means that 50% of cases will exceed the threshold response value at the identified criteria value (see Snelder *et al.*, 2022 for more details). Generally, the exceedance of a criteria is treated as an unacceptably high risk of an adverse effect and appropriate action is taken, despite this uncertainty. This was the approach taken by this study. It has been assumed that the exceedance of a criteria represents an unacceptably high risk that the objective will not be achieved and that the appropriate management response is to increase the baseline visual clarity (i.e., reduce the sediment load), despite the uncertainty.

4.3 Representation of load reduction requirements

In this study sediment load reduction requirements for critical catchments, FMUs, and the region, are reported as both yields and as percentages of baseline loads. Both representations of load reduction requirements need to be interpreted carefully. A yield (e.g., in t km^{-2} yr^{-1}) has relevance because it has the same units as sediment loss rate estimates that are commonly estimated for specific land uses such as agriculture or urban earthworks. However, when load reductions are expressed in this study as yields, the denominator is always the area of the *entire* upstream catchment. If the catchment includes areas of land that cannot have sediment management measures applied to it (e.g., parks and/or other conservation land where sediment mitigations cannot be implemented such as the Waitakere or Hunua ranges), the required average load reduction from land where mitigations can be applied would need to be higher than the reported value to compensate for the inability to make reductions from other areas.

The percentage load reduction required provides an indication of the reduction from the 2017 baseline situation. Where the catchment includes areas of land that cannot have sediment management measures applied, the same caveat regarding the interpretation of load reductions as yields applies to these percentage values.

4.4 Informing decision-making on limits

The NPS-FM requires regional councils to set limits on resource use to achieve environmental outcomes (i.e., TASs). This report helps inform AC's process of setting limits to achieve freshwater outcomes by assessing the approximate magnitude of sediment load reductions needed to achieve several options for TASs for streams and rivers of the Auckland region, with a quantified level of confidence associated with each option. This study does not consider sediment objectives for downstream estuary receiving environments. Sediment load reductions required to meet any (yet to be identified) sediment-related outcomes in estuaries could be greater than the load reductions estimated in this report to achieve TASs in the region's streams and rivers. In addition, this study does not consider what kinds of limits on resource use might be used to achieve the load reductions, how such limits might be implemented, over what timeframes and with what implications for other values. The NPS-FM requires regional councils to have regard to these and other things when making decisions on setting limits. This report shows that these decisions will ultimately need to be made in the face of uncertainty about the magnitude of load reductions needed.

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