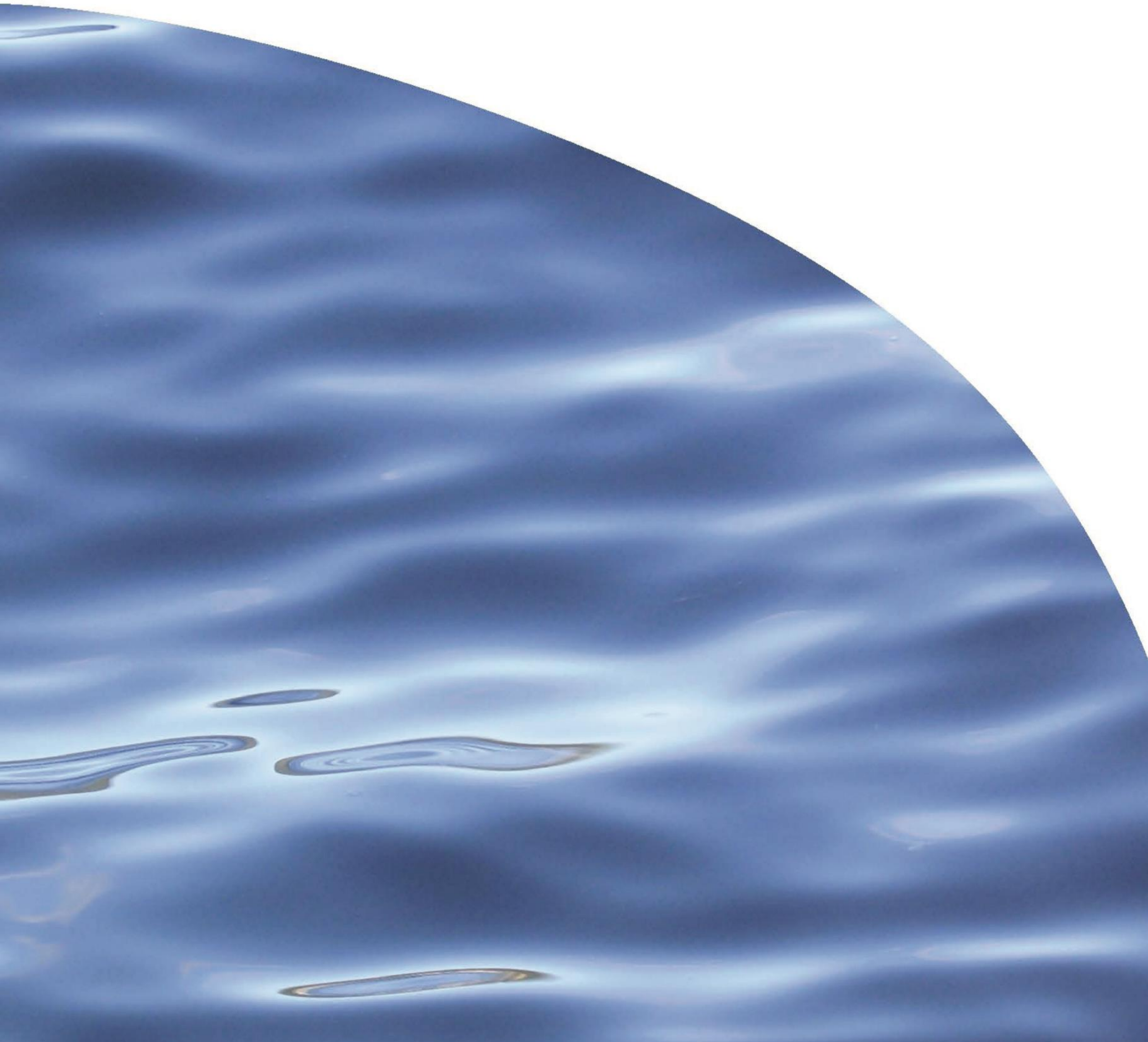
REPORT NO. 3332

TECHNICAL REPORT ON THE PROTOTYPE NEW ZEALAND RIVER ECOSYSTEM HEALTH SCORE



TECHNICAL REPORT ON THE PROTOTYPE NEW ZEALAND RIVER ECOSYSTEM HEALTH SCORE

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Prepared for Ministry for the Environment

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EXECUTIVE SUMMARY

This report describes a prototype New Zealand River Ecosystem Health Score, which was designed as a simple, easily interpretable and holistic measure of the state of biophysical condition of rivers and streams in New Zealand. It is based on the Freshwater Biophysical Ecosystem Health Framework and assesses five core components of ecosystem health: Aquatic Life, Physical Habitat, Water Quality, Water Quantity and Ecological Processes.

Each component is made up of indicators calculated from river ecosystem health data (metrics). A total of 19 metrics was used to inform the River Ecosystem Health Score. Ideally, the Score would be based on metric data from monitoring networks that represent all the rivers and streams in New Zealand. However, these data do not exist and so the prototype Score presented here has been calculated from existing datasets. The sites and data in these datasets were not designed to provide a representative picture of river ecosystem health across New Zealand. For example, small headwater systems and large rivers are dramatically underrepresented. To try and correct for the biased distribution and suitability of metric data, an assessment of data robustness was used to calculate weighted average metric, indicator and component scores. The scores were benchmarked by reference conditions observed at minimally-impacted sites and the bottom line informed by national policy or expert opinion. Grades (D to A) were assigned by the equal division of scores between 0 and 1. A ‘D’ Grade indicates that on average rivers and streams in New Zealand are in a degraded condition, whereas an ‘A’ Grade indicates that on average, rivers and streams in New Zealand are in a healthy condition.

The Score derived in this study indicates that, on average, the ecosystem health of New Zealand’s rivers and streams is impaired (B-). This means that Water Quality is comprised and contaminants are present, Physical Habitat is altered so that it can no longer support thriving native plants and animals, Water Quantity is reduced and impeding the connectivity and dispersal of biota, Ecological Processes are unable to efficiently retain, transform and absorb carbon and nutrients, and the diversity of Aquatic Life is diminished.

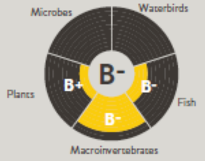
This technical report outlines the data and methods used to derive the prototype report card scores. However, this process has highlighted significant data gaps and deficiencies in New Zealand’s river and stream monitoring network design. In order to consistently and robustly assess the full biophysical condition of New Zealand’s rivers and streams in the future, and reduce reliance on expert opinion, the following actions are needed:

- Development of a representative monitoring network(s) with a priority on reference sites to establish reference benchmarks
- Development and standardisation of metrics for the assessment of Physical Habitat, Ecological Processes, and Water Quantity components
- National collation of existing metric datasets for Aquatic Life, Physical Habitat, and Ecological Processes components

METRICS

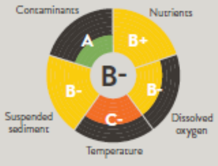
Each indicator is made up of a range of 'metrics' as shown here. Not every metric has been collected over the same amount of time or at the same places throughout New Zealand. In an ideal world, we would have the same amount of robust data for each component so we can give each component an equal weighting.

AQUATIC LIFE



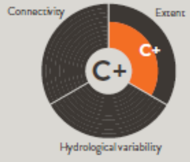
INDICATOR	METRIC	NO. OF SITES	YEAR RANGE	DATA SOURCE
Waterbirds	Diversity, Abundance	0		
Fish	Index Biological Integrity	2999	2010-2017	NZFFD
	Abundance	0		
Macroinvertebrates	MCI, % EPT richness, EPT richness	898	2013-2017	LAWA
	Abundance	0		
Plants	Periphyton biomass (Chlorophyll a)	201	2011-2018	MfE
	Weighted composite cover	0		
	% Cyanobacteria, % Native species	0		
Microbes	Bacterial Community Index	0		

WATER QUALITY



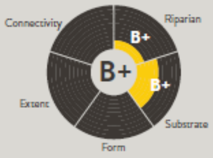
INDICATOR	METRIC	NO. OF SITES	YEAR RANGE	DATA SOURCE
Nutrients	Dissolved reactive phosphorus	928	2013-2017	LAWA
	Dissolved inorganic nitrogen	892	2013-2017	LAWA
Dissolved oxygen	Minimum dissolved oxygen	346	1990-2012	MfE
Temperature	Cox-Rutherford Index	346	1990-2012	MfE
Suspended sediment	Turbidity	925	2013-2017	LAWA
Contaminants	Ammonia toxicity	628	2013-2017	LAWA
	Nitrate toxicity	892	2013-2017	LAWA
	Heavy metals	0		

WATER QUANTITY



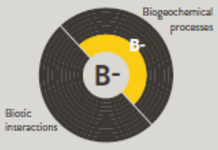
INDICATOR	METRIC	NO. OF SITES	YEAR RANGE	DATA SOURCE
Extent	Water Allocation Index	Model	2018	MfE
Hydrological variability	Mean or low flow	0		
	Flood frequency	0		
	Flood magnitude	0		
Connectivity	Floodplain	0		
	Groundwater	0		

PHYSICAL HABITAT



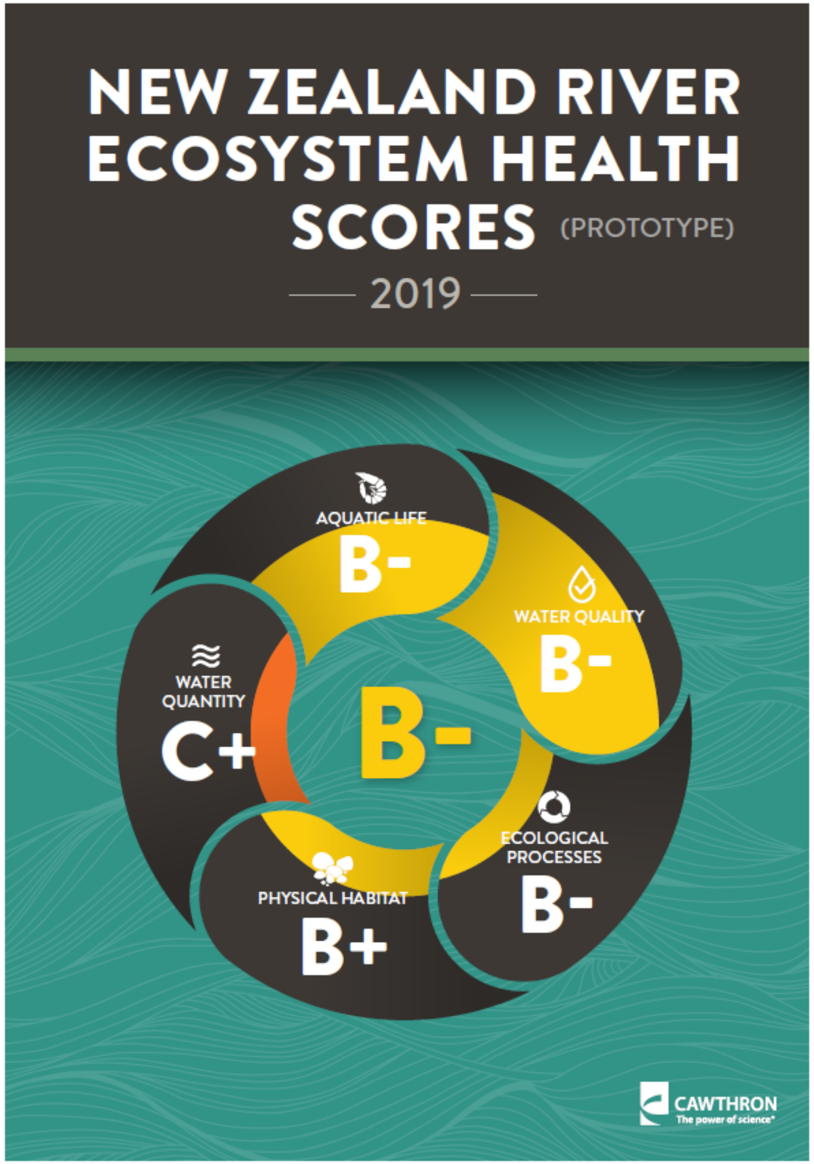
INDICATOR	METRIC	NO. OF SITES	YEAR RANGE	DATA SOURCE
Riparian	Shade	Model	2009	FENZ
Substrate	% fine sediment	673	2000-2016	MfE
Form	Natural Character Index	0		
	Bank stability	0		
Extent	Weighted usable area	0		
	Rapid habitat assessment score	0		
Connectivity	Floodplain	0		

ECOLOGICAL PROCESSES



INDICATOR	METRIC	NO. OF SITES	YEAR RANGE	DATA SOURCE
Biogeochemical processes	Gross primary productivity	156	1993-2009	Cawthron
	Ecosystem respiration	156	1993-2009	Cawthron
	Cotton decomposition	108	2008	Cawthron
Biotic interactions	Food web indices	0		

MCI= Macroinvertebrate Community Index | EPT = Stoneflies, Caddisflies, Mayflies | NZFFD = New Zealand Freshwater Fish Database
MfE = Ministry for the Environment | LAWA = Land, Air, Water Aotearoa | FENZ = Freshwater Ecosystems of New Zealand



PROJECT DESCRIPTION

- The River Ecosystem Health Score indicates that, on average, river health in New Zealand is impaired (B-).
- The River Ecosystem Health Score shows the state of biophysical condition of rivers and streams in New Zealand. It is the application of a Framework[1] that identifies five core components of ecosystem health: Aquatic Life, Physical Habitat, Water Quality, Water Quantity and Ecological Processes. Each component is made up of indicators measured using river health data.
- Ideally, the River Ecosystem Health Score would be based on data from monitoring networks that represent all of New Zealand. However, this River Ecosystem Health Score has been calculated from existing datasets that vary in their suitability to provide an unbiased picture of river health. So an assessment of data robustness is used to calculate weighted average metric, indicator and component scores[2].
- We need to improve how we measure the biophysical condition of rivers and streams to fully assess river ecosystem health.

COMPONENTS The River Ecosystem Health Score is made up of five components:

IN A HEALTHY ECOSYSTEM	IN AN UNHEALTHY ECOSYSTEM
AQUATIC LIFE Native plant and animal species thrive (such as tuna/eels), and invasive species are scarce or absent.	Introduced species of plants and animals (such as carp and didymo) are dominant and native species are reduced or absent. In more extreme cases, total community diversity declines.
WATER QUALITY Water quality supports a diverse range of plants and animals, and contaminants are scarce or absent.	Contaminants (such as heavy metals) are present and exist at levels that inhibit life and key biogeochemical processes.
ECOLOGICAL PROCESSES Carbon and nutrients are efficiently retained, transformed and absorbed into healthy aquatic food webs.	Inefficient carbon and nutrient retention, transformation and absorption causes poor water quality, algal blooms and reduced food web diversity.
PHYSICAL HABITAT The physical form of a river and its surrounding floodplain, including its riparian vegetation, allows a diverse range of plants and animals to thrive.	The physical form of a river is altered to a degree that it can no longer support the thriving of its animals and plants. This could be due to unstable river banks, loss of riparian/floodplain vegetation and physical barriers such as stop banks and dams.
WATER QUANTITY The water level and the extent of water are enough to support a diverse range of aquatic animals and plants during their full life cycle.	There is insufficient water to support a diverse range of aquatic life. Continuous low flows due to for example over-allocation, impedes the dispersal of aquatic plants and animals up- and down-stream and within floodplains.

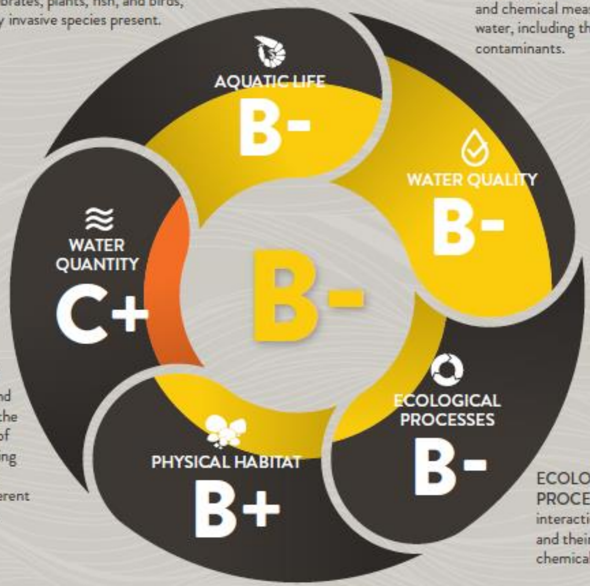
1. Clapcott J, Young R, Wilcox M, Sinner J, Storey R, Quinn J, Daughney C, Canning A 2018. Freshwater biophysical ecosystem health framework. Cawthron Report No. 3194. 89 p.

2. See the accompanying technical report for a full description of source data and analysis: Clapcott J, Goodwin E, Williams E, Harding J, MacArthur K, Schallenberg M, Young R, Death R. 2019. Technical report on the prototype New Zealand River Ecosystem Health Score. Cawthron Report No. 3332.

RIVER ECOSYSTEM HEALTH COMPONENTS AND SCORES

AQUATIC LIFE: The abundance and diversity of biota including microbes, invertebrates, plants, fish, and birds, and any invasive species present.

WATER QUALITY: The physical and chemical measures of the water, including the presence of contaminants.



WATER QUANTITY: The extent and variability in the level or flow of water, including connections between different water bodies.

ECOLOGICAL PROCESSES: The interactions among biota and their physical and chemical environment.

PHYSICAL HABITAT: The physical form, structure, and extent of the waterbody, its bed, banks and margins, riparian vegetation, and connections to the floodplain.

SCORE DESCRIPTIONS

- A HEALTHY
- B IMPAIRED HEALTH
- C HIGHLY IMPAIRED HEALTH
- D UNHEALTHY

DATA AVAILABILITY

A fully coloured section means that the data are spatially (well spread across NZ) and temporally (recent) robust and provide a complete description of each component.

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1. INTRODUCTION

In this section we introduce the Freshwater Biophysical Ecosystem Health Framework and how it can be used for reporting freshwater health in New Zealand. Application of the framework was the primary aim of this project. Specifically, the project objective was to produce a national level report card on the state of freshwater ecosystem health for New Zealand. This technical report describes the project process and findings. The report card is limited to rivers and streams and informed by existing available datasets and metrics, no new data were collected or collated. The calculation of index scores and an overall river ecosystem health score was the main outcome of the project.

1.1. Freshwater Biophysical Ecosystem Health Framework

The Freshwater Biophysical Ecosystem Health Framework (Clapcott et al. 2018) provides a consistent approach for assessing the biophysical ecosystem health of fresh waters, enabling central and local government, communities and individuals to gauge the maintenance and improvement of ecosystem health. An assessment of the biophysical components of freshwater ecosystems provides a measure of 'ecological integrity'. Ecological integrity refers to the ability of an ecosystem to support and maintain structure and function over time in the face of external stress. The use of reference state benchmarks (i.e. the condition in the absence of anthropogenic stress) ensures consistency in the assessment of the biophysical components of freshwater ecosystems.

The framework is based on a review of existing national and international frameworks developed to manage and report on the status and trends in freshwater resources. The review identified five core components of freshwater biophysical ecosystem health: Aquatic Life, Physical Habitat, Water Quality, Water Quantity, and Ecological Processes. The framework requires that each of these components be incorporated to provide an integrated and robust assessment of freshwater EH in New Zealand.

Application of the framework requires identification of indicators and their metrics for each component, reference benchmarks, a representative monitoring network, data collection, data aggregation, harmonisation and integration, as well as reporting (Figure 1). For example, a catchment or regional report may differ from a national report in spatial detail, however all five components of freshwater biophysical ecosystem health, and associated indicators, should be reported.

The Framework report is available to download from the Ministry for the Environment website: http://www.mfe.govt.nz/publications/fresh-water/freshwater-biophysical-ecosystem-health-framework.

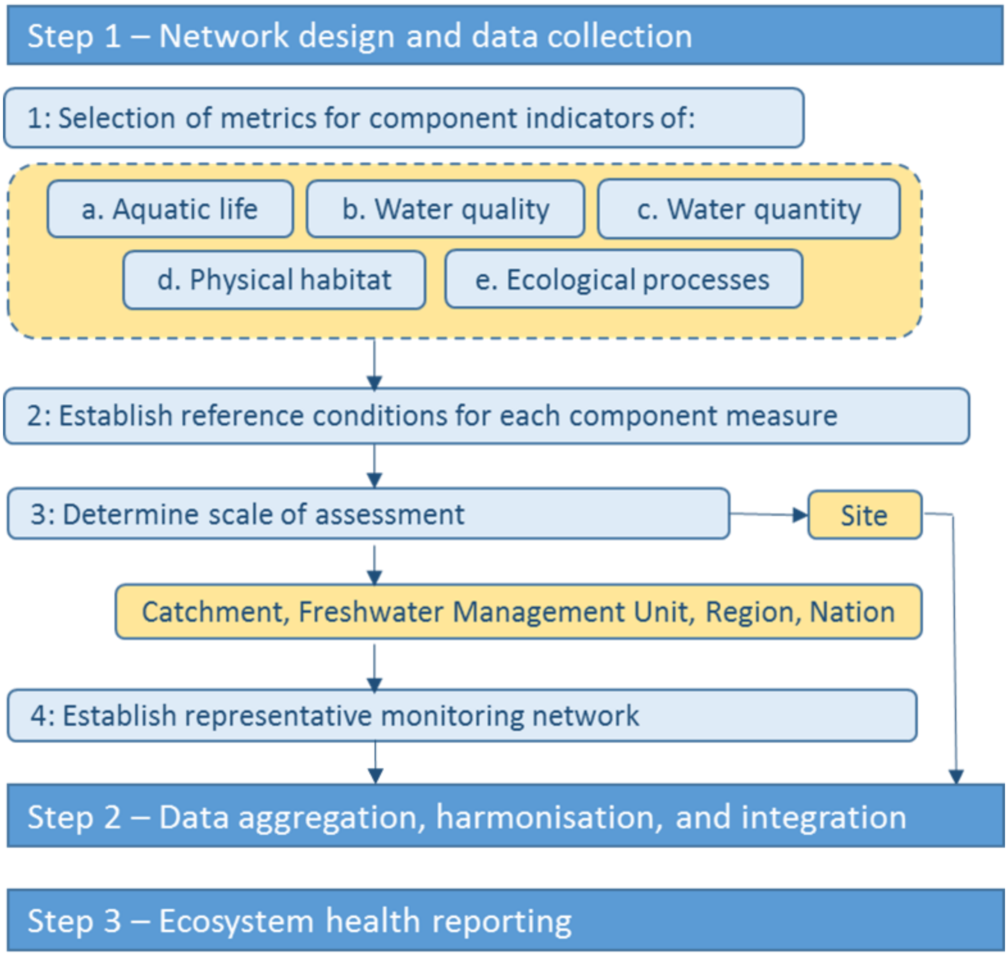

Figure 1. Flow diagram of the steps in the application of the framework for freshwater ecosystem health (from Clapcott et al. 2018).

1.2. Report cards

A report card provides a summary of information on state and/or trends. Environmental reports are informed by environmental indicator data that have been collected over a given time, to assess state, and compared to previously collected data, to elicit trends. Report cards can be a useful tool because they integrate diverse data into simple scores that can be communicated to decision-makers and the general public.

The framework supports the consistent reporting of biophysical ecosystem health across environment types and spatial scales. Four quality classes are recommended, such as 'Excellent' 'Good', 'Fair', and 'Poor', or A–D, which is consistent with the National Objectives Framework of the National Policy Statement for Freshwater Management (NPS-FM), and provides a common language for engaging communities in the adaptive management of freshwater resources.

2. METHODS

In this section we describe the datasets used to inform a national level report card on the biophysical state of New Zealand rivers and streams, including information that will allow an assessment of the suitability of datasets for future environmental reporting purposes. We further describe the methods used in the implementation of the Freshwater Biophysical Ecosystem Health Framework, including approaches to data aggregation, harmonisation and integration.

2.1. Overview

2.1.1. Metric and dataset selection

This project was restricted to existing data and therefore the selection of metrics was determined by a review of available datasets and their suitability to assess each ecosystem health (EH) component. A previous assessment of metric suitability by Clapcott et al (2018) was used to prioritise metric selection for each component (Appendix 1). Next, all known national datasets were catalogued and the largest (national coverage) and most recent available for each metric was selected for further consideration. This included both measured and modelled metrics. Measured data were selected to provide direct measurements of metrics in preference over modelled data, but modelled data were considered to fill any data gaps if they improved indicator representation.

For each EH component (See sections 2.2–2.6), we describe the chosen metric datasets including:

- where the data have come from (e.g. organisations that collect and archive the data)
- what methods were used to collect, analyse and report on samples
- where sampling sites are located
- whether these data have been published or peer-reviewed, and if so, where.

2.1.2. Data aggregation

Data aggregation was conducted to compile data to a specific spatial scale. This was one using standardised methods and the averaging of site data, although other statistics could also be used. In this project, national datasets were previously compiled from disparate sources, usually regional council (or unitary authority) state of the environment monitoring data. Data compilation sometimes involved quality control and alignment (e.g. correction for method and unit variation) but not always. We did not further assess or correct the quality or the consistency of existing national datasets.

Regional council monitoring networks are typically spatially biased towards more degraded sites reflecting in part their management priorities. Also, many river health metrics are influenced by natural bio/geographical variation. To account for this natural variation and to partially balance network bias, we adopted a stream classification system to assist with the aggregation of data. This was done to attain the best available representative national picture. For most metrics, unless stated otherwise, we used the River Environment Classification (Snelder et al. 2004) at the Climate Source Of Flow (CSOF) level of aggregation. This does not account for land cover.

All metrics were grouped by stream classes for the calculation of metric performance scores. Resulting performance scores were combined at the national level by class-weighted averaging of test site performance scores, where the weighting was a correction for the relative representation of each class. For example, if 10% of monitoring data belonged to the Cool-Wet Hill class but 30% of the national digital river network is Cool-Wet Hill then the metric score for Cool-Wet Hill class was weighted 3-fold in the calculation of the national average metric score. Over 90% of the digital river network was represented by monitoring data grouped by CSOF. How CSOF (or other relevant stream classification) was used to account for natural bio/geographical variation is further described next in data harmonisation.

2.1.3. Data harmonisation

Data harmonisation involves converting data to a common scale. This was done so that disparate metrics could be combined into indicator scores. We converted all metric values to performance scores with a range from 0–1, rendering the scores unit-less. A score of 0 indicates a degraded condition (e.g. the bottom line) whereas a score of 1 indicates minimally-impacted reference condition. A site doing better than the reference target cannot score better than 1, nor can a site that does worse than the bottom line score less than 0. This ensures that when scores are combined values beyond reference or the bottom line do not unfairly weight mean metric scores. The 0–1 scores were calculated based on an observed/expected equation, with some refinements to bound the scores between 0 and 1.

Where low values of a metric indicate a healthy stream, performance scores were calculated using Equation 1 and where high values of a metric indicate a healthy stream, the performance scores were calculated using Equation 2.

Equation 1: $$PS = \min(1, \max(0, \frac{(\mathrm{BL} - \mathrm{value})}{(\mathrm{BL} - \mathrm{ref})})$$

Equation 2: $$PS = \min(1, \max(0, \frac{(\mathrm{value} - \mathrm{BL})}{\mathrm{ref} - \mathrm{BL})}$$

Here *PS* stands for performance score (in 0–1), *value* is the measured metric value in original units, *BL* is the bottom line (lowest or highest tolerable value for that metric) and *ref* is the reference condition for that metric. Min() indicates a function that returns the lower of its two arguments, and max() a function that returns the higher of its two arguments.

For example, at a site where the Macroinvertebrate Community Index value was 90 and the reference value was 120 and the bottom-line value was 80, the performance score = (90 - 80) / (120 - 80) = 0.33. This performance score represents the proportion of the site's metric value between reference condition (score of 1.0) and bottom line (score of 0.0).

The reference condition (score = 1.0) for each metric, unless stated otherwise, was defined by the upper/lower quartile of observed values at 'reference sites' in each stream class, as recommended by Stoddard et al. (2006); this describes 'minimally disturbed condition'. 'Reference sites' were defined using the following land cover classes from the Land Cover Database v4 (LCDB4): > 85% native vegetation (forest, scrub or wetland), < 15% pastoral light, < 5% intensive agriculture, and 0% urban. These cut-offs were informed by previous research quantifying the response of freshwater metrics to land cover gradients, i.e. within these ranges there was no measureable response in freshwater metrics to land use change (Clapcott et al. 2012). Whether the upper or lower quartile value of reference sites was used depended on whether the metric increased or decreased with river health degradation (Table 1). For any stream class without reference sites sampled, the reference value was calculated as the appropriate quartile value from all reference sites sampled.

For each metric, unless stated otherwise, the bottom line as defined by national policy or expert opinion was used to inform the worst-tolerable condition (score = 0) for all stream classes (Table 1). We used class-specific reference state and bottom lines, where available, to account for natural bio/geographical variation in metrics.

Table 1. Stream classification used for data aggregation and harmonisation as well as methods used to derive reference and bottom line benchmarks for ecosystem health components in the New Zealand River Ecosystem Health Score.

Component indicator	Reference	Bottom line	Classification
Aquatic Life			
Fish	Expert opinion	Expert opinion	National
Macroinvertebrates	25th percentile	Expert opinion	REC CSOF
Plants	75th percentile	NPS-FM	Productivity class
Water Quality			
Dissolved oxygen	25th percentile	NPS-FM	National
Temperature	75th percentile	Expert opinion	National
Suspended sediment	Expert opinion	Expert opinion	Bespoke REC
Nutrients	75th percentile	Expert opinion	REC CSOF
Contaminants	75th percentile	NPS-FM	REC CSOF
Water Quantity			
Extent	Expert opinion	Expert opinion	National
Physical Habitat			
Substrate	75th percentile	Expert opinion	Bespoke REC
Riparian vegetation	FENZ model	Expert opinion	National
Ecological Processes			
Biogeochemical processes	Expert opinion	Expert opinion	River size

NPS-FM = National Policy Statement for Freshwater Management, REC = River Environment Classification, CSOF = Climate Source Of Flow, FENZ = Freshwater Ecosystems of New Zealand.

2.1.4. Data integration

Data integration involves combining different metric performance scores into a combined assessment (i.e. into an indicator, component and overall river ecosystem health score). We used a weighted averaging based on data suitability to integrate metric scores. Suitability scores (1, 2 or 3) for each metric dataset were assigned using expert assessment of the following dataset qualities: relevance, accuracy, timeliness and spatial coverage (Table 2). If all metrics were equal (i.e. fit for purpose, accurate, timely, and spatially representative) then weighting would not be necessary.

Table 2. Derivation of metric suitability scores based on expert assessment of data qualities.

Component	Indicator	Metric	Sites	Years	Relevance	Accuracy	Timeliness	Spatial cover	Suitability Score
Aquatic Life	Fish	Index Biological Integrity	2999	2010-2017	3	3	3	3	3.00
	Macroinvertebrates	Macroinvertebrate Community Index	898	2013-2017	3	3	3	3	3.00
		% EPT taxa richness	898	2013-2017	3	2	3	3	2.75
		EPT taxa richness	898	2013-2017	3	3	3	3	3.00
	Plants	Periphyton (chlorophyll-*a*) biomass	201	2011-2018	2	2	3	2	2.25
Water Quality	Dissolved oxygen	Minimum dissolved oxygen	346	1990-2012	2	3	1	2	2.00
	Temperature	Cox-Rutherford Index	167	1990-2012	2	3	1	2	2.00
	Suspended sediment	Turbidity	925	2013-2017	3	3	3	3	3.00
	Contaminants	Ammonia toxicity	928	2013-2017	1	3	3	3	2.50
		Nitrate toxicity	892	2013-2017	1	3	3	3	2.50
	Nutrients	Dissolved reactive phosphorus	928	2013-2017	3	3	3	3	3.00
		Dissolved inorganic nitrogen	892	2013-2017	3	3	3	3	3.00
Water Quantity	Extent	Water Allocation Index	model	2018	1	1	3	3	2.00
Physical Habitat	Substrate	Deposited fine sediment	673	2010-2016	1	2	2	1	1.50
	Riparian vegetation	Shade	model	2009	1	1	1	3	1.50
Ecological Processes	Biogeochemical processes	Gross primary productivity	156	1993-2009	1	2	1	1	1.25
		Ecosystem respiration	156	1993-2009	1	2	1	1	1.25
		Cotton decomposition	108	2008	1	2	1	1	1.25

Relevant datasets provide a direct measure of the indicator they represent (score = 3); whereas irrelevant datasets do not (score = 1). **Accurate** datasets were collected using standard methods by trained personnel and provide a good statistical estimation (score = 3). Less accurate datasets (score = 1) were collected using non-standardised methods and provide a less statistically accurate measure or modelled estimate of the indicator. **Timeliness** refers to whether datasets are up to date (score = 3), or less so (score = 1). **Spatial cover** refers to sample number and whether spatial variation across the country is well represented (score = 3) or less so (score = 1).

To calculate indicator scores based on available metric datasets, each metric performance score was multiplied by is associated suitability score. The resulting products are suitability-weighted performance scores. The sum of these products was then divided by the total of all suitability scores (Equation 3).

Equation 3: $$I = \frac{\sum_{i=1}^{n} PS_i S_i}{\sum S_i}$$

Where *I* = indicator score, *PS* is the metric performance score, *S* is the metric suitability score, little *i* counts through each metric, and *n* is the number of metrics contributing to the indicator.

For example, to calculate the macroinvertebrates indicator score:

Macroinvertebrates indicator score (0.585) = (Macroinvertebrate Community Index (0.606) * suitability score (3)) + (% EPT taxa richness (0.611) * suitability score (2.75)) + (EPT taxa richness (0.540) * suitability score (3)), divided by the sum of all suitability scores (8.75).

Suitability-weighted average scores were also used in the calculation of component scores and the overall river ecosystem health score. The suitability score for an indicator was the arithmetic mean (normal average) of its metrics' suitability scores. For example, the suitability score for the macroinvertebrates indicator was: (3 + 2.75 + 3) / 3 = 2.92. Similarly, the suitability score for a component was the arithmetic mean of its contributing indicators' suitability scores. The overall river ecosystem health score was the arithmetic mean of suitability-weighted component scores. Averaging was chosen, as opposed to the lowest score, based on a review of ecosystem health frameworks by Clapcott et al. (2018). See section 3.2.3 for further discussion.

Additionally, an 'availability' score was used to scale the report card graphic illustrating data availability, by way of the width of the coloured band. If all data were available for all metrics to make an assessment of an indicator, then the coloured band would occupy the whole width of the graphic. If only half the possible metrics were represented with data, then the width of the coloured band only occupies half of the graphic. This availability scaling score is calculated as the suitability score divided by the maximum sum possible of all contributing suitability scores (Equation 4).

Equation 4: $$A = \frac{S_i}{\sum_{i=1}^{n} S_i}$$

Where *A* = availability score and *S* = suitability score.

For example, the scaling score for macroinvertebrates (0.73) equals the sum of all existing suitability scores (8.75) divided by the maximum sum possible (12), if four metrics had been measured including a currently unmeasured macroinvertebrate abundance metric. If three metrics are required to inform an indicator scaling score the maximum suitability score would be 9, for two metrics it would be 6, and so on. Therefore, the width of band represents the completeness of the assessment.

2.1.5. The use of expert knowledge

Expert knowledge was used to inform the selection of metrics, the suitability score used in data integration described above, and to inform benchmarks where necessary. Further, expert knowledge was used to verify that resulting scores made ecological sense. Otherwise, quantitative analysis of existing datasets and published bottom lines and management guidelines were used to inform the biophysical assessment of river ecosystem health.

2.2. Aquatic life

In a healthy ecosystem, native species of flora and fauna thrive and invasive species are scarce or absent. In an unhealthy ecosystem, invasive species of flora and fauna are dominant and native species are reduced or absent. In more extreme cases, total number of species / community diversity can decline. A complete assessment of aquatic life in rivers and streams includes measures of the abundance and diversity of biota including microbes, plants, invertebrates, fish, and birds, and any invasive species present.

A catalogue of existing measured and modelled datasets showed that there were enough measured metric data available to inform fish, macroinvertebrate and plant indicators of aquatic life (Table 3). The conservation status of indigenous freshwater species was not considered applicable to this national assessment of river ecosystem health.

Table 3. Catalogue of metric datasets available for assessing aquatic life in rivers and streams. Metrics used in the River Ecosystem Health Score are in bold. NA = not available.

Indicator	Measured metric	Number of sites	Year	Source
Waterbirds	Taxa richness	NA		
	Abundance	NA		
Fish	**% Native taxa**	2999	2010-2017	NZFFD
	Index Biological Integrity	2999	2010-2017	NZFFD
	Taxa richness	2999	2010-2017	NZFFD
	Abundance	NA		
Macroinvertebrates	**MCI**	898	2013-2017	LAWA
	% EPT taxa richness	898	2013-2017	LAWA
	% EPT abundance	NA		
	EPT taxa richness	899	2013-2018	LAWA
Plants	**Periphyton (Chlorophyll-*a*) biomass**	201	2011-2018	MfE
	Weighted composite cover	NA		
	% Cyanobacteria	NA		(Wood et al. 2017)
	% Native species	NA		
Microbes	Bacterial Community Index	NA		(Lau et al. 2015)

Indicator	Modelled metric	Training data	Model diagnostics	Model source
Fish	% Native taxa	2999	AUC >0.8	(Canning 2018)
	Taxa richness	2999	AUC >0.8	(Canning 2018)
	O/E fish species	2999	AUC >0.8	(Canning 2018)
Macroinvertebrates	MCI	832	$R^2 = 0.68$	(Whitehead 2018)
Plants	Periphyton (Chlorophyll-*a*) biomass	196	$R^2 = 0.37$	(Kilroy et al. 2019)

NZFFD = New Zealand Freshwater Fish Database, LAWA = Land, Air, Water Aotearoa, MfE = Ministry for the Environment, AUC = area under curve.

2.2.1. Fish

Fish metric data were sourced from Dr Adam Canning (Fish & Game) who extracted fish taxa data from the New Zealand Freshwater Fish Database (NZFFD) to inform a predictive model of riverine fish reference assemblages (Canning 2018). The metric data were shared with Ministry for the Environment (MfE) and are available from MfE.

Data file: “IBI_2000_2017_nutrients.csv”

The extracted data used to calculate fish metrics were restricted to samples collected using electric fishing methods over a minimum 150-m stream length, as recommended by standard protocols (Joy et al. 2013), from 2000 to 2017 inclusive (Canning 2018).

The metric chosen to inform the fish indicator was:

Index Biotic Integrity (IBI) – the IBI is a multi-metric index designed to reflect the overall quality of the fish community. The method to calculate the IBI was that developed by Joy and Death (2004). It is calculated from six metrics that assess total taxonomic richness, habitat guilds (the number of native benthic riffle species, the number of native benthic pool species, the number of native pelagic pool species), tolerant species (the number of stream-degradation-intolerant species) and exotic species (proportion of alien[1] species). The six metric scores are determined using quantile regression across elevation and distance from the coast gradients to account for natural spatial variation in fish distributions. Each metric can receive a maximum score of 10 so the total IBI maximum score possible is 60 and the minimum is 0.

As sourced, the fish metric data represent the median values for 2999 sites throughout the country (Figure 2). Based on the REC classification, the fish metric data were grouped into 21 CSOF classes which represent 99.9% of the digital river network. However, the CSOF is not a meaningful classification for fish because their spatial distribution is driven primarily by distance to the coast, elevation and temperature (Joy & Death 2004). For this metric, the reference condition and bottom line (for all sites) were set at 36 and 20 respectively, informed by expert opinion and personal communication with the developer of the IBI (Dr Mike Joy, University of Wellington).

[1] Brown trout and rainbow salmon were treated as 'native' based on their sensitivity to water and habitat quality degradation (Joy & Death 2004).

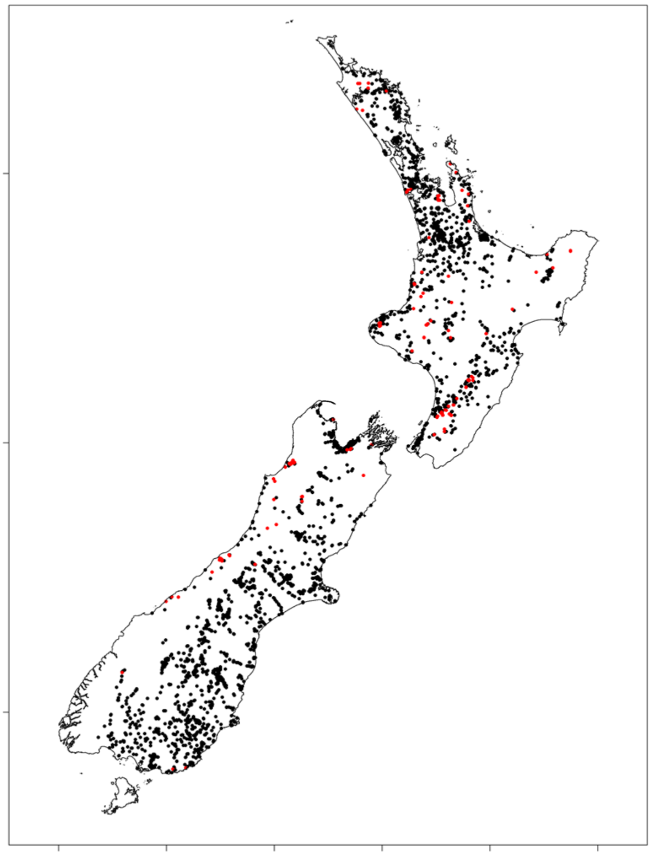

Figure 2. Distribution of fish metric sites (n = 2999) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

2.2.2. Macroinvertebrates

Macroinvertebrate metric data were sourced from Land, Air, Water Aotearoa (LAWA) who annually collate macroinvertebrate data from all 16 regional councils and unitary authorities (herein collectively referred to as regional councils). The data are published online (https://lawa.org.nz) and are available from LAWA.

Data file: "RiverMACRO_STATE_ForITE16h50m-16-Oct-2018.csv"

The three metrics chosen to inform the macroinvertebrate indicator were:

Macroinvertebrate Community Index (MCI) – the MCI is based on the tolerance or sensitivity of species (taxa) to organic pollution and nutrient enrichment. For example, most mayflies, stoneflies and caddis flies are sensitive to pollution, and typically only abundant in clean and healthy streams, whereas worms and snails are more tolerant and can be found in polluted streams. Most benthic invertebrate taxa were assigned a tolerance value ranging from 1 (very tolerant) to 10 (very sensitive). Higher MCI scores indicate better stream conditions at the sampled site. In theory MCI values can range between 0 and 200, but in practice it is rare to find MCI values greater than 150 and only extremely polluted or sandy/muddy sites score under 50.

Percentage of EPT taxa (% EPT taxa) – the invertebrate communities in healthy streams are usually dominated by three orders of insects: the mayflies, stoneflies, and caddisflies. Together, these insects are known as EPT, referring to their scientific names Ephemeroptera, Plecoptera and Trichoptera, respectively. These freshwater insects are generally intolerant of pollution, so the fewer found in a sample, the poorer the stream health. The percentage of EPT taxa is calculated by counting the total number of mayflies, stonefly and caddisfly taxa in a sample, then dividing that number by the taxa richness and multiplying by 100. A high percentage of EPT taxa indicates good stream health. However, in some New Zealand streams there are naturally few mayflies, stoneflies, or caddisflies present.

EPT taxa richness – the number, rather than the relative percentage, of EPT taxa present. In general, high EPT taxa richness is considered good.

All three metrics were calculated from sample data collected annually (at a minimum) from biomonitoring sites. The regional councils used a selection of standardised protocols, as outlined in Stark et al (2001), to collect and process macroinvertebrate samples. All protocols allow for the calculation of metrics based on the presence of taxa identified to a common taxonomic level (i.e. the MCI level). Variation in protocols used by regional councils means that it is not possible to calculate metrics based on taxa abundance. A preference for this project was to include quantitative metrics based on abundance data (e.g. % EPT abundance in particular would support calculation of an Average Score Per Metric as recommended macroinvertebrate indicator; (Collier 2008; Clapcott et al. 2017)), but as it was not broadly available we proceeded with taxa presence data.

Consistent formulae were used by regional councils to calculate % EPT richness and Taxa richness (the total number of taxa present). We used these two metrics to calculate EPT taxa richness, which equals Taxa richness * % EPT richness. A consistent formula was used by regional councils to calculate the MCI, however taxa tolerance values used in the calculation of MCI can vary slightly among regional councils and so can affect the final MCI score.

As sourced, the macroinvertebrate metric data represent the 5-year (2013–2017) median value for 911 sites. A minimum of three data points over the last five years was required for a median value to be calculated for sites that are sampled once a year. Sites that were sampled twice per year needed a minimum of six samples over the last five years. We averaged site values on the same NZReach[2] which resulted in a total of 898 sites nationally (Figure 3).

Based on the REC classification, the macroinvertebrate data were grouped into 20 CSOF classes which represent 97.3% of the digital river network. Thirty-one sites were classified as reference state based on land cover and informed the reference condition for each CSOF class as shown in Table 4. The bottom line (for all classes) of 80 for the MCI metric was informed by the National Policy for Freshwater Management (NPS-FM) 2017 and is based on the ‘Poor’ water quality class described in Stark & Maxted (2007). The bottom line of 25 for % EPT richness was based on expert opinion with precedence of use in the Waikato River Report Card (Williamson et al. 2016). The bottom line of 5 from EPT richness is based on expert opinion informed by the correlation between MCI and EPT richness.

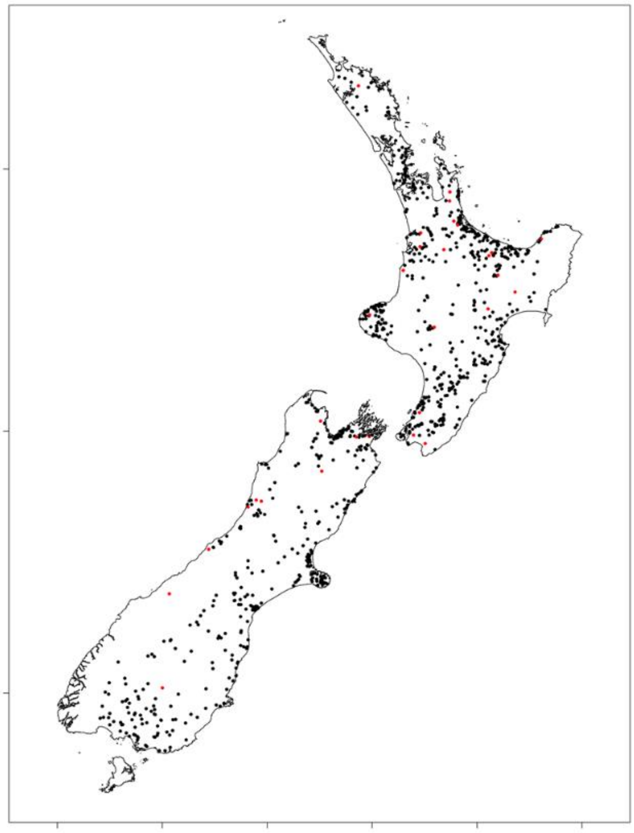

Figure 3. Distribution of macroinvertebrate metric sites (n = 898) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

[2] A unique identifier available for every stream segment (length of stream between tributary junctions) in the RECv1 digital river network

Table 4. The reference condition and bottom-line values for macroinvertebrate metrics by Climate Source Of Flow (CSOF) class.

	MCI		%EPT richness		EPT richness	
CSOF	Reference	Bottom line	Reference	Bottom line	Reference	Bottom line
CD/H	121.9	80	55.2	25	13.9	5
CD/L	127.0	80	65.2	25	15.7	5
CD/Lk	121.9	80	55.2	25	13.9	5
CD/M	121.9	80	55.2	25	13.9	5
CW/GM	121.9	80	55.2	25	13.9	5
CW/H	125.1	80	58.5	25	11.0	5
CW/L	133.1	80	58.3	25	14.5	5
CW/Lk	121.9	80	55.2	25	13.9	5
CW/M	116.9	80	55.2	25	13.9	5
CX/H	137.6	80	65.1	25	19.6	5
CX/L	120.0	80	53.3	25	11.5	5
CX/Lk	119.3	80	58.6	25	14.7	5
CX/M	121.9	80	55.2	25	13.9	5
WD/L	121.9	80	55.2	25	13.9	5
WD/Lk	121.9	80	55.2	25	13.9	5
WW/H	111.7	80	44.8	25	12.5	5
WW/L	132.1	80	57.1	25	14.4	5
WW/Lk	121.9	80	55.2	25	13.9	5
WX/H	121.9	80	55.2	25	13.9	5
WX/L	121.9	80	55.2	25	13.9	5

2.2.3. Plants

Plant metric data, specifically periphyton biomass data, were sourced from Ministry for the Environment who collated periphyton data from 6 regional councils. The data are available from MfE.

Data files: Greater Wellington "GWRCPeriphytonMonthlyData.csv", Horizons "DataForTon2.rdata", Southland "Southland_monthlyCHLa_RWQ_Fre3.csv", Bay of plenty "ChlA_09032018_WQAppended.csv", Northland "2018_Periphyton data_Ton Snelder.csv" , Canterbury "chla_DIN_DRP_all_dates.csv"

The metric chosen to inform the plant indicator was:

Periphyton (chlorophyll-*a*) biomass – the quantity of algae (mg chl-*a*/m^2) attached to the streambed provides a measure of the trophic status of waterways. Periphyton provides a food source for macroinvertebrates and different types of periphyton have different levels of chlorophyll-*a*. In general, the periphyton that macroinvertebrates prefer (e.g. diatoms) are low in chlorophyll-*a*, whereas unpalatable periphyton (e.g. filamentous green, blue-green) are high in chlorophyll-*a*. An exception is didymo

(*Didymosphenia geminate*), which can have very high biomass but low chlorophyll-*a*. High levels of periphyton can smother habitat, alter macroinvertebrate communities and produce adverse fluctuations in pH and dissolved oxygen concentrations constraining life-supporting capacity.

Ideally, additional metrics would be available to inform a plant indicator, including an assessment of the different types of plants and periphyton present as well as their spatial distribution or cover as well as abundance. We used the periphyton (chlorophyll-*a*) biomass metric because it was the most recent compilation of regional council data available and because established bottom lines are available in the NPS-FM.

The periphyton biomass metric is calculated from sample data collected monthly by regional councils at biomonitoring sites using a standard protocol (Biggs & Kilroy 2000) between 2011 and 2018. As sourced, the periphyton metric data were raw data for each monthly sample for each site in each council. The date ranges varied for each council as follows: Environment Southland (November 2014–August 2017), Greater Wellington Regional Council (August 2015–August 2017), Environment Bay of Plenty (October 2015–December 2017), Environment Canterbury (July 2011–June 2014), Horizons Regional Council (December 2008–June 2017), Northland Regional Council (July 2013–May 2018).

We used all data available to calculate the 83rd and 92nd percentile value (to represent the cover exceeded 17% and 8% of the time respectively) for each of 208 sites. We averaged sites on the same NZReach to provide a total of 201 sites which were spatially restricted to the six regions (Figure 4).

When explored by CSOF, the periphyton metric data group into 15 classes that represent 97.3% of the digital river network. However, we did not use the CSOF classification to inform reference condition and instead used the Productive and Default periphyton classes as defined in the NPS-FM 2017. Within the metric data, 193 sites were in the Productive class and 8 sites were in the Default class. There were only 7 reference sites based on land cover and they were all in the Productive class. As such, we used this data to inform the reference condition for both classes and the bottom line of 200 mg chl-*a*/m^2 for both classes as defined in the NPS-FM 2017 (Table 5).

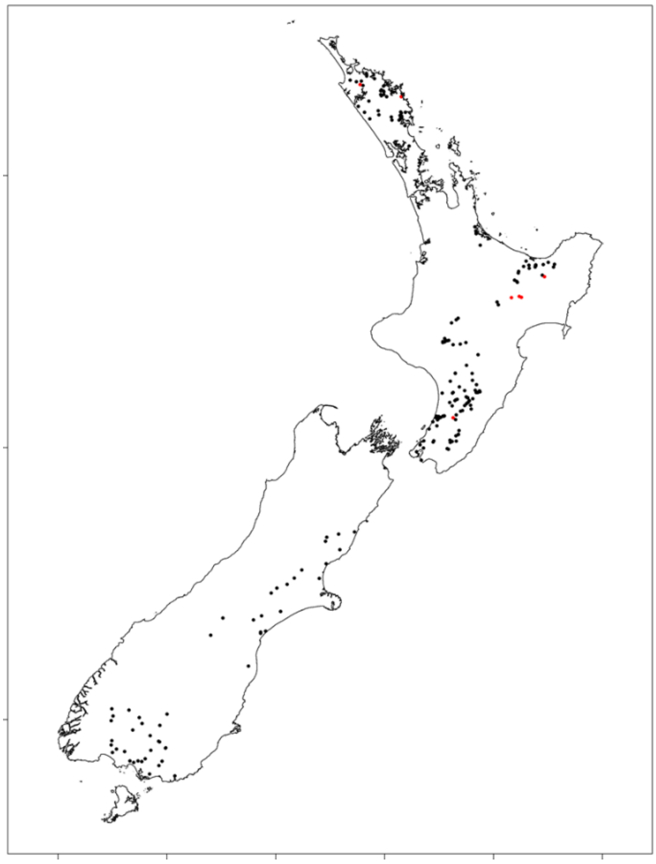

Figure 4. Distribution of periphyton metric sites (n = 201) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

Table 5. The reference condition and bottom-line values (mg chl-a/m^2) for the periphyton metric by Productivity class.

Class	Periphyton (Chlorophyll-*a*) biomass Reference	Bottom line
Productive (83rd percentile)	2.88	200
Default (92nd percentile)	4.06	200

2.3. Ecological processes

Ecological processes are the interactions among biota and their physical and chemical environment, which describe how well a system is functioning. A healthy ecosystem, with high biodiversity and connectivity can retain, transform and absorb carbon (as in leaf litter) and other nutrients (such as from land run-off/leaching). An unhealthy ecosystem is unable to retain, transform and absorb carbon and other nutrients which can cause algal blooms. A complete assessment of ecological processes includes measures of the interactions among biota and their physical and chemical environment.

A catalogue of existing measured and modelled datasets showed that there were enough measured data available to inform biogeochemical processes indicators of ecological processes (Table 6).

Table 6. Catalogue of metric datasets available for assessing ecological processes in rivers and streams. Metrics used in the River Ecosystem Health Score are in bold.

Indicator	Measured metric	Number of sites	Year	Source
Biotic interactions	Food web metric	NA		
Biogeochemical processes	**Gross primary productivity**	156	2009	Cawthron
	Ecosystem respiration	156	2009	Cawthron
	Cotton decomposition	108	2009	Cawthron
Indicator	**Modelled metric**	**Training data**	**Model diagnostics**	**Model source**
Biogeochemical processes	Gross primary productivity	156	TDE = 26%	(Clapcott et al. 2011a)
	Ecosystem respiration	156	TDE = 34%	(Clapcott et al. 2011a)
	Cotton decomposition	108	TDE = 55%	(Clapcott et al. 2011a)

NA = not available, TDE = total deviance explained.

2.3.1. Biogeochemical processes

Biogeochemical process metric data were sourced from Cawthron Institute who gathered the data for a Department of Conservation-funded project 'Quantifying relationships between human pressures and ecological integrity' (Contract number 3948 CDRP). The data were used in three publications (Clapcott et al. 2010, 2011a, 2012) and are available from the Cawthron Institute.

Data file: "FwPrFunallNational.csv"

The three metrics chosen to inform the biogeochemical processes indicator were:

Gross primary productivity (GPP) – estimates the rate (g $O_2/m^2/d$) at which organic carbon enters an ecosystem through photosynthesis (plant growth). It provides a measure of the energy available to fuel river food webs. The primary drivers of GPP in rivers are light, temperature, nutrients and physical habitat through the provision of energy and substrate and the physical limitation of metabolic processes. These primary drivers are all subject to natural temporal and spatial variability. However, what makes GPP a good indicator of river health is that it is affected by human impacts (such as nutrient additions) especially through changes to these primary drivers.

Ecosystem respiration (ER) – estimates the rate (g $O/m^2/d$) at which carbon leaves an ecosystem through combined respiration of plants and all other organisms. Like

GPP, ER is primarily driven by temperature, nutrients and physical habitat and can be strongly affected by human impacts. ER is often strongly linked to GPP in autotrophic systems (i.e. those dominated by plant growth). However, most river systems are heterotrophic (i.e. reliant on external sources of energy) and that's why it is important to measure both GPP and ER.

Cotton decomposition – the rate of organic matter decomposition is a key ecosystem process which drives carbon and nutrient flows in rivers. The cotton assay provides a standardised measure of organic matter decomposition potential, predominantly through a microbial pathway.

Ecosystem metabolism metrics (GPP and ER) were calculated from continuous dissolved oxygen data recorded for a minimum of 24 hours at each site and using a published spreadsheet model based on the single station night-time regression method (Young & Collier 2009). Data were only included when regression coefficients were greater than 0.4. Sites included those sampled as part of the DOC-funded project combined with published data collected by Cawthron Institute or calculated from continuous dissolved oxygen data collected by regional councils.

Cotton decomposition metric data was collected using standard methods (Tiegs et al. 2013) including the deployment of cotton substrates between 7 and 14 days with rates corrected for the average stream temperature during deployment (rate of decomposition per degree day, *k*dd). Sites were those sampled as part of the DOC-funded project combined with published and unpublished data (but using the same methods) collected by regional councils or Cawthron Institute. Because proposed management bands were available for organic matter decomposition in rates per day (*k*d), we converted units from *k*dd to *k*d using a regression built with data where both units were available (n = 89, R^2 = 0.98).

As sourced, the biogeochemical processes metric data represent the average site value (often based on a single value) for 156 sites for ecosystem metabolism metrics (GPP and ER) and 108 sites for cotton decomposition. Based on the REC classification, the ecosystem metabolism data grouped into 11 CSOF classes which represent 93.9% of the digital river network. Only 3 sites were defined as reference based on land cover. Cotton decomposition data grouped into 15 CSOF classes which represent 74% of the digital river network and only 2 sites were defined as reference. Despite relatively moderate to high CSOF representation, sites were geographically restricted to parts of the country (Figure 5).

Due to a lack of reference sites to inform reference conditions we used proposed management bands to determine both reference and bottom lines for all three biogeochemical processes metrics (Table 7; Young et al. 2008). Cotton decomposition and ER show non-linear responses to human impact and therefore have minimum and maximum exceedance values for bottom lines. Sites were classified by stream order (< 5 small wadable streams, ≥ 5 larger non-wadable streams) to apply proposed amendments to management bands for ecosystem metabolism metrics (Clapcott 2015).

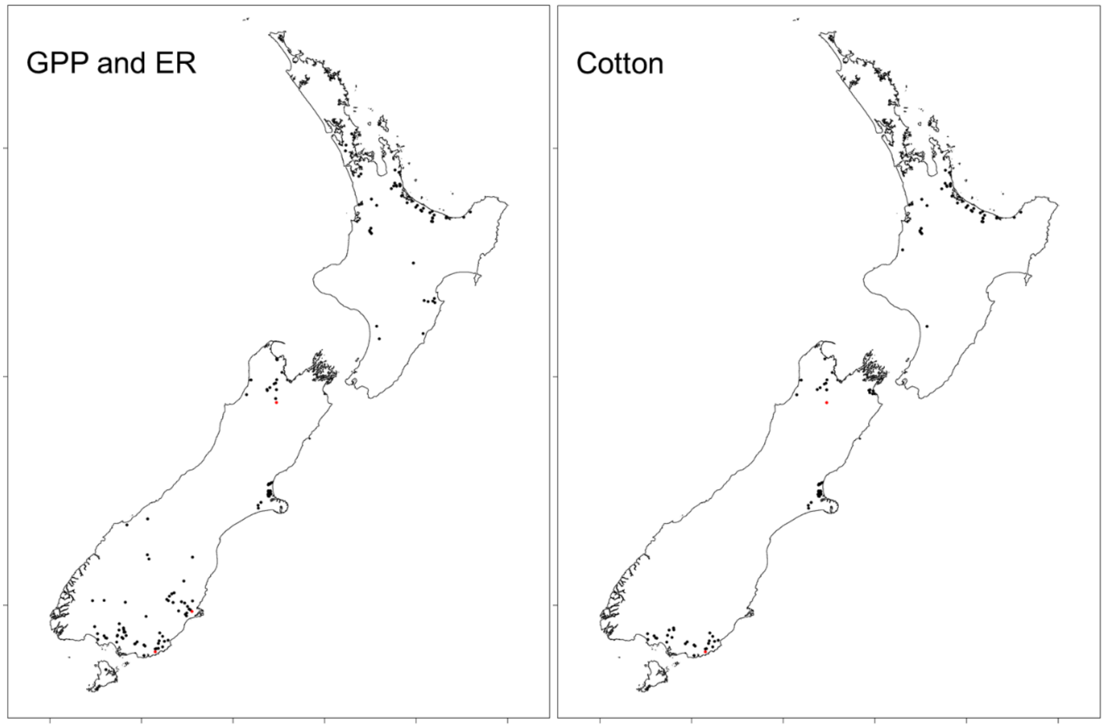

Figure 5. Distribution of biogeochemical process metric sites (n = 156 for GPP and ER, n = 108 for Cotton) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

Table 7. The reference condition and bottom-line values for the biogeochemical process metrics. Units are g $O_2/m^2/d$ for gross primary productivity (GPP) and ecosystem respiration (ER) and % cotton tensile strength loss per day for cotton decomposition.

	ER		GPP		Cotton decomposition	
Class	Reference	Bottom line	Reference	Bottom line	Reference	Bottom line
All					0.01-0.03	>0.05 or <0.005
< 5th order	1.6-5.8	≥0.8 or ≤9.5	≤3.5	7		
≥ 5th order	1.6-3.0	≥0.6 or ≤13	≤3.0	8		

2.4. Water quality

In a healthy ecosystem, water quality supports a diverse range of aquatic flora and fauna and contaminants are scarce or absent. In an unhealthy ecosystem, contaminants are present or exist at levels that inhibit aquatic life and key biogeochemical processes. A complete assessment of water quality includes physical and chemical measures of the water, including the presence of pollutants (such as excessive nutrients or heavy metals).

A catalogue of existing measured and modelled datasets showed that there were enough measured data available to inform all five indicators of water quality (Table 8).

Table 8. Catalogue of metric datasets available for assessing water quality in rivers and streams. Metrics used in the River Ecosystem Health Score are in bold.

Indicator	Measured metric	Number of sites	Year	Source
Dissolved oxygen	**Daily minimum**	347	1990-2012	MfE
	Mean	748	2006-2012	MfE
Temperature	**Cox-Rutherford Index**	167	1990-2012	MfE
	Mean	713	2006-2012	MfE
Suspended sediment	Clarity	935	2013-2017	LAWA
	Turbidity	925	2013-2017	LAWA
Nutrients	TN, TP	919, 836	2013-2017	LAWA
	DIN, DRP	892, 928	2013-2017	LAWA
Contaminants	**Ammonia toxicity**	928	2013-2017	LAWA
	Nitrate toxicity	961	2013-2017	LAWA
	Metals	NA		
Indicator	Modelled metric	Training data	Model diagnostics	Model source
Dissolved oxygen	Mean	713	PVE = 56%	(Unwin & Larned 2013)
Temperature	Mean	748	PVE = 69%	(Unwin & Larned 2013)
Suspended sediment	Clarity	587	R^2 = 0.59	Whitehead 2018
	Turbidity	878	R^2 = 0.55	Whitehead 2018
Nutrients	TN, TP	764, 740	R^2 = 0.71, 0.65	Whitehead 2018
	Nitrate, DRP	855, 877	R^2 = 0.59, 0.51	

MfE = Ministry for the Environment, LAWA = Land, Air, Water Aotearoa, NA = not available, PVE = percent variance explained.

2.4.1. Dissolved oxygen

Dissolved oxygen (DO) metric data were sourced from MfE who collated data from 12 regional councils, NIWA and Cawthron (Depree et al. 2016). The data are available from MfE.

Data file: “DO_by_site_and_date.txt”

The metric chosen to inform the DO indicator was:

Minimum dissolved oxygen – the concentration of DO (mg/l) is essential for aquatic life. Dissolved oxygen concentrations vary diurnally in response to photosynthesis of algae and other aquatic plants during daylight hours, which raises the oxygen concentrations within the water, and respiration of all river life which lowers the oxygen concentrations in the water. Also, oxygen diffusion through the water surface can either raise or lower oxygen concentrations depending on whether the water is under- or over-saturated with DO. Minimum DO concentrations usually occur early in the morning before photosynthesis begins and are best assessed using continuous data.

The minimum dissolved oxygen metric was calculated from continuous datasets with a minimum of 24 hours of 15-minute measurements occurring within the summer period (Nov-Apr inclusive). Spurious measurements were discarded (Depree et al. 2016). As sourced, the data were continuous measurements of DO recorded at 346 sites. Depree et al. (2016) note that these sites are strongly biased toward research and targeted investigation sites. However, they cover a broad spatial distribution from north to south (Figure 6). Based on the REC classification, the DO data group into 17 CSOF classes which represent 98.9% of the digital river network. Only 4 sites were classified as reference state based on land cover.

For each site, we calculated the minimum DO value observed. We did not use a classification for the DO metric with the reference condition for all streams (5.6 mg/l) informed by the 4 reference sites and the bottom line informed by the NPS-FM (4 mg/l).

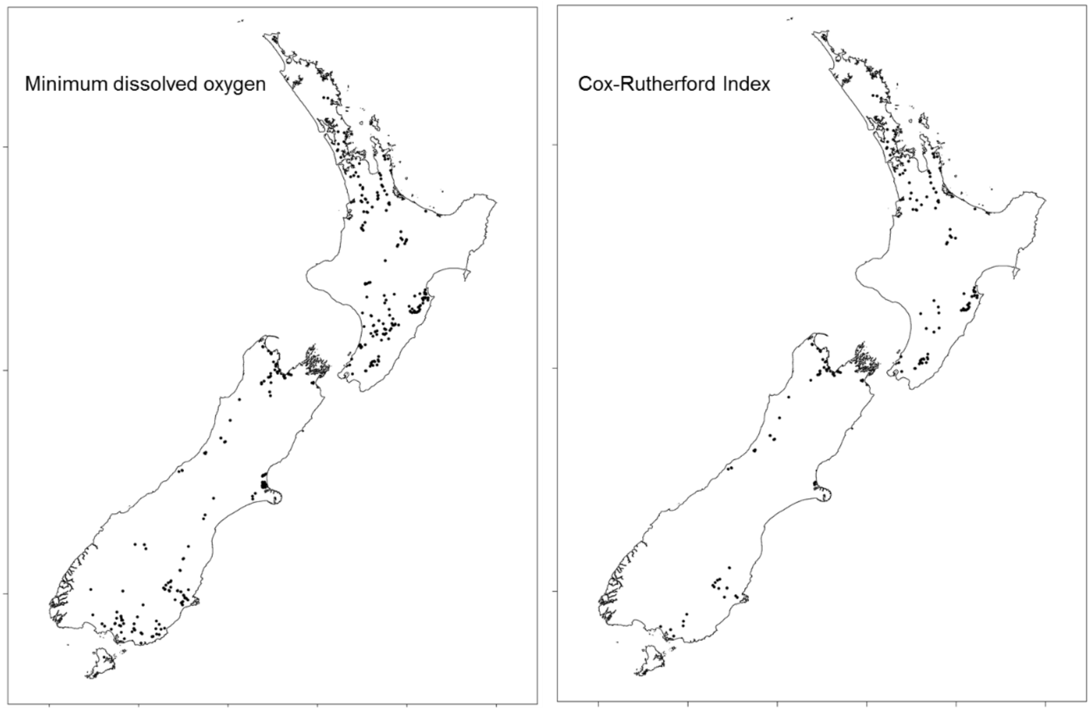

Figure 6. Distribution of dissolved oxygen and temperature metric sites (n = 346 for dissolved oxygen, n = 167 for Cox-Rutherford Index) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

2.4.2. Temperature

Continuous temperature data is recorded at the same time as DO. Temperature metric data were sourced from MfE who collated data from 12 regional councils, NIWA and Cawthron (Depree et al. 2016). The data are available from MfE.

Data file: "DO_by_site_and_date.txt"

The metric chosen to inform the temperature indicator was:

Cox-Rutherford Index (CRI) – temperature is a fundamental driver of the growth of fauna and flora as well as the distribution of biota in aquatic ecosystems. Temperature also controls the rate of biogeochemical processes. Water temperature varies diurnally and seasonally and while both minimum and maximum temperatures can affect river health, maximum temperatures most often limit biota. The CRI is the average of daily maximum and daily mean temperatures and provides a measure that permits application of (constant) temperature criteria (which are well developed for many species) to temperature regimes varying over a diel cycle in rivers.

As sourced, the temperature data included all continuous temperature measurements collated by Depree et al. (2016). While spurious measurements of DO had previously been discarded, Depree et al. (2016) did not specifically check the temperature data.

We extracted a subset of the source data where temperature had been continuously recorded for a minimum of 5 days of 15-minute measurements occurring within the summer period (November-April, inclusive). This resulted in 167 sites spread throughout the country (Figure 6). Four of the sites were in reference state condition based on land cover.

For each of the 167 sites, we calculated the 5-day CRI by identifying the five sequential days where hottest temperatures were observed. For each of those five days we calculated the maximum and mean temperature and averaged the mean and the maximum to calculate the CRI. We then averaged the 5 days of values to get the 5-day CRI.

When explored by CSOF the temperature metric data grouped into 13 classes that represent 94.4% of the digital river network. However, temperature is likely to vary naturally across the country from north to south and Davies-Colley et al. (2013) recommended the division of eastern dry climates versus maritime climates for the application of a stream temperature attribute. In the absence of an existing classification of NZReach segments that categorises maritime versus eastern dry areas, for all sites we used the reference condition informed by observed reference state (13.9 °C) at 4 sites and the bottom line informed by expert opinion based on the recommended temperature attribute table for maritime climates (24 °C) (Davies-Colley et al. 2013).

2.4.3. Suspended sediment

Suspended sediment data were sourced from LAWA who annually collate water quality data from all 16 regional councils. The data are published online (https://lawa.org.nz) and are available from LAWA.

Data file: “RiverWQ_STATE_2013-2017forITE16h17m-04Oct2018.csv”

The metric chosen to inform the suspended sediment indicator was:

Turbidity – measures the scattering of light caused by fine particles in water in nephelometric turbidity units (NTU). It is a measure of visibility in rivers. It is also used as a proxy measure of suspended sediment because turbidity can be correlated to suspended sediment on a site basis to provide an estimate of sediment load in rivers.

The turbidity data were collected by regional councils using spot measures on a monthly basis. The measurement unit (NTU) is not standardised; however, presently it is more routinely measured by regional councils than clarity (m), which provides a direct measure. As sourced, the turbidity data represented the 5-year (2013-2017) median value for 925 sites nationally (Figure 7). The median was calculated when there was at least 50% of data available over this time period.

Based on the REC classification, the turbidity data group into 21 CSOF classes which represent 99.9% of the digital river network. Sixteen sites were classified as reference state based on land cover. However, we chose to use an alternative classification system developed to better describe natural patterns in suspended sediment in rivers. The classification system is a bespoke amalgamation of REC groups by climate, source of flow and geology as described in Franklin et al. (2019). Based on the suspended sediment classification, the turbidity data grouped into all 12 classes which represent 87.3% of digital river network. Because of the low number of reference sites we used expert opinion based on a weight-of-evidence approach outlined in Franklin et al. (2019) to inform both the reference state and the bottom line for each class as shown in Table 9.

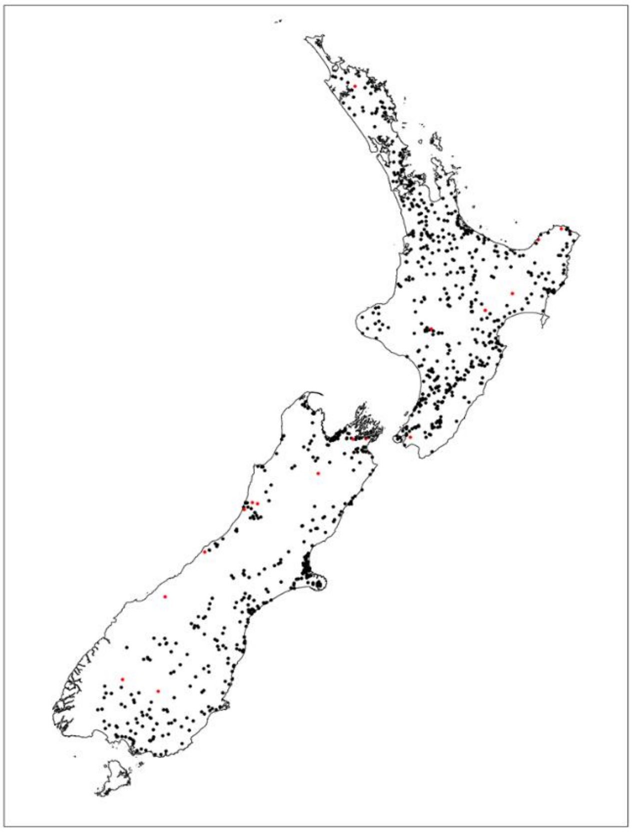

Figure 7. Distribution of suspended sediment metric sites (n = 925) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

Table 9. The reference condition and bottom-line values (NTU) for the suspended sediment metric for each suspended sediment class.

	Turbidity	
Class	Reference	Bottom line
1	1.50	3.2
2	8.80	10.5
3	0.87	2
4	2.23	4.8
5	2.20	13.1
6	1.16	8.3
7	0.67	3.3
8	4.70	6.4
9	0.77	1.6
10	0.93	1.5
11	0.60	1.6
12	1.55	3.1

2.4.4. Nutrients

Nutrient data were sourced from LAWA who annually collate water quality data from all 16 regional councils. The data are published online (https://lawa.org.nz) and are available from LAWA.

Data file: "RiverWQ_STATE_2013-2017forITE16h17m-04Oct2018.csv"

The two metrics chosen to inform the nutrient indicator were:

Dissolved inorganic nitrogen (DIN) – this is combined concentration (mg/l) of nitrite (NO_2), nitrate (NO_3) and ammonia (NH_3) forms of nitrogen dissolved in the water column.

DIN promotes algal or plant growth in rivers.

Dissolved reactive phosphorus (DRP) – this is the concentration (mg/l) of dissolved (soluble) phosphorus compounds that are readily available for use by plants and algae. Dissolved reactive phosphorus concentrations are an indication of a waterbody's ability to support nuisance algal or plant growths.

As sourced, the nutrient data represent 5-year (2013–2017) median values for 892 sites for DIN and 928 sites for DRP (Figure 8). Medians were calculated when there was at least 50% of the data available over this time period, (i.e. at least 2.5 years' worth of data over a five-year period).

Based on the REC classification, the DIN metric data grouped into 21 CSOF classes which represent 99.9% of the digital river network. Sixteen sites were classified as reference state based on land cover and informed the reference condition for each CSOF class as shown Table 10. The DRP metric data also grouped into 21 CSOF classes which represent 99.9% of the digital river network. Seventeen sites were classified as reference state based on land cover and informed the reference condition for each CSOF class as shown in Table 10. The bottom line (for all classes) of 0.88 mg/l (DIN) and 0.021 mg/l (DRP) was informed by expert opinion based on a revised weight-of-evidence approach by Death et al. (2018).

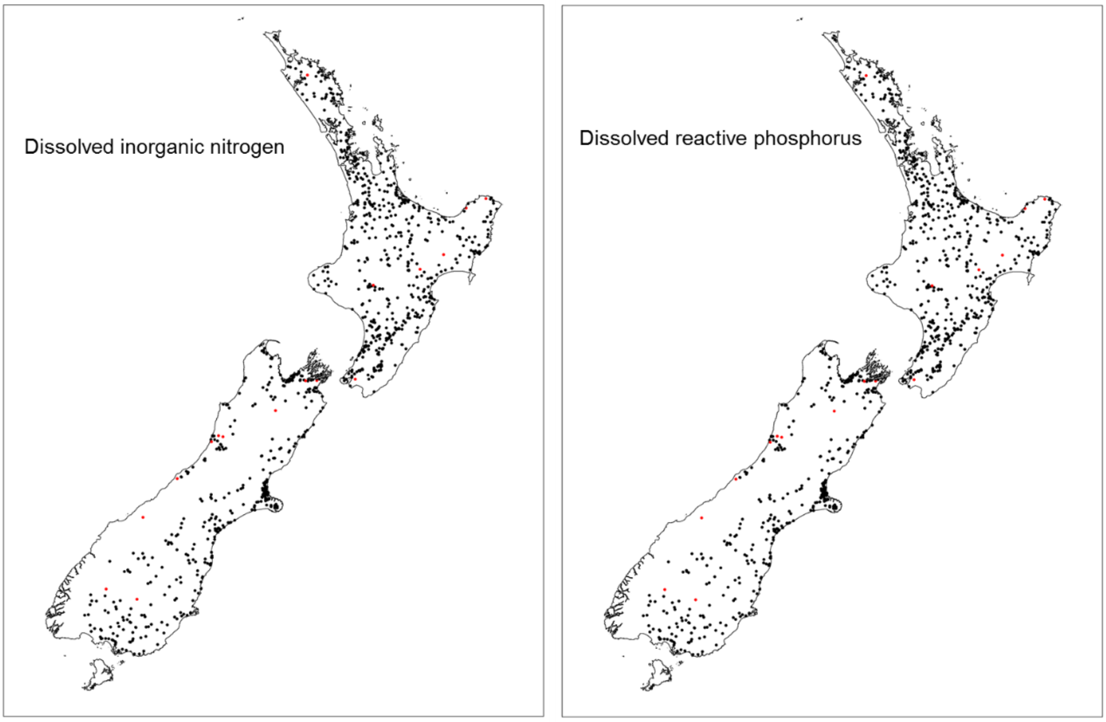

Figure 8. Distribution of nutrient metric sites (n = 892 for dissolved inorganic nitrogen, n = 928 for dissolved reactive phosphorus) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

Table 10. The reference condition and bottom-line values (mg/l) for the nutrient metrics by Climate Source Of Flow (CSOF) class.

	Dissolved inorganic nitrogen		Dissolved reactive phosphorus	
CSOF	Reference	Bottom line	Reference	Bottom line
CD/H	0.011	0.88	0.004	0.021
CD/L	0.010	0.88	0.004	0.021
CD/Lk	0.011	0.88	0.004	0.021
CD/M	0.011	0.88	0.004	0.021
CW/GM	0.011	0.88	0.004	0.021
CW/H	0.005	0.88	0.003	0.021
CW/L	0.035	0.88	0.009	0.021
CW/Lk	0.011	0.88	0.004	0.021
CW/M	0.014	0.88	0.004	0.021
CX/GM	0.011	0.88	0.004	0.021
CX/H	0.011	0.88	0.004	0.021
CX/L	0.030	0.88	0.001	0.021
CX/Lk	0.011	0.88	0.004	0.021
CX/M	0.011	0.88	0.004	0.021
WD/L	0.011	0.88	0.004	0.021
WD/Lk	0.011	0.88	0.004	0.021
WW/H	0.011	0.88	0.004	0.021
WW/L	0.016	0.88	0.008	0.021
WW/Lk	0.011	0.88	0.004	0.021
WX/H	0.011	0.88	0.004	0.021
WX/L	0.011	0.88	0.004	0.021

2.4.5. Contaminants

Contaminant data were sourced from LAWA who annually collate water quality data from all 16 regional councils. The data are published online (https://lawa.org.nz) and are available from LAWA.

Data file: “RiverWQ_STATE_2013-2017forITE16h17m-04Oct2018.csv”

The two metrics chosen to inform the contaminants indicator were:

Nitrate toxicity – nitrate-nitrogen becomes toxic at high concentrations (mg/l) which are more likely under certain temperature and pH conditions. This can cause direct harm to fish and macroinvertebrates.

Ammonium toxicity – ammoniacal nitrogen (NH_4-N), also often called ‘ammonium’, and includes two forms of nitrogen; ammonia (NH_3) and ammonium (NH_4). Ammonium enters waterways primarily through point source discharges, such as raw sewage or dairy shed effluent. Like nitrate, it is toxic to aquatic life at high concentrations (mg/l).

As sourced, the contaminant data represent 5-year (2013-2017) median values for 892 sites for nitrate and 928 sites for ammonium (Figure 9). Medians were calculated when there was at least 50% of the data available over this time-period, (i.e. at least 2.5 years' worth of data over a five-year period).

Based on the REC classification, the nitrate metric data grouped into 21 CSOF classes which represent 99.9% of the digital river network. Sixteen sites were classified as reference state based on land cover and informed the reference condition for each CSOF class as shown Table 11. The ammonium metric data also grouped into 21 CSOF classes which represent 99.9% of the digital river network. Seventeen sites were classified as reference state based on land cover and informed the reference condition for each CSOF class as shown Table 11.

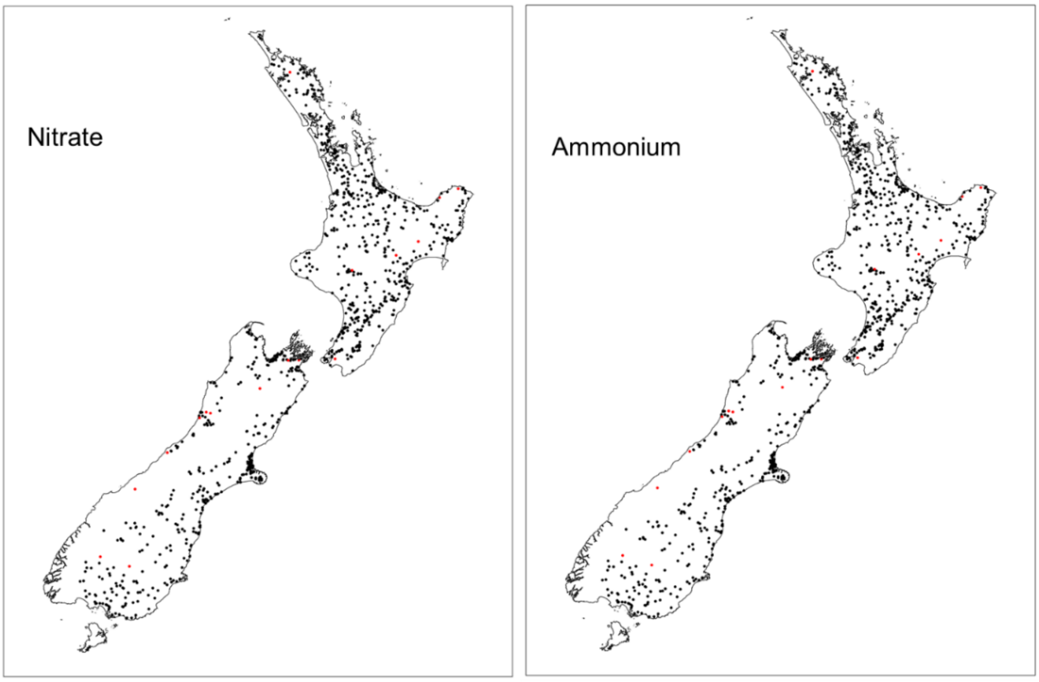

Figure 9. Distribution of contaminant metric sites (n = 892 for nitrate, n = 928 for ammonium) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

Table 11. The reference condition and bottom-line values (mg/l) for the contaminant metrics by Climate Source Of Flow (CSOF) class.

	Nitrate toxicity		Ammonium toxicity	
CSOF	Reference	Bottom line	Reference	Bottom line
CD/H	0.011	6.9	0.005	1.3
CD/L	0.010	6.9	0.005	1.3
CD/Lk	0.011	6.9	0.005	1.3
CD/M	0.011	6.9	0.005	1.3
CW/GM	0.011	6.9	0.005	1.3
CW/H	0.005	6.9	0.005	1.3
CW/L	0.035	6.9	0.005	1.3
CW/Lk	0.011	6.9	0.005	1.3
CW/M	0.014	6.9	0.002	1.3
CX/GM	0.011	6.9	0.005	1.3
CX/H	0.011	6.9	0.005	1.3
CX/L	0.030	6.9	0.005	1.3
CX/Lk	0.011	6.9	0.005	1.3
CX/M	0.011	6.9	0.005	1.3
WD/L	0.011	6.9	0.005	1.3
WD/Lk	0.011	6.9	0.005	1.3
WW/H	0.011	6.9	0.005	1.3
WW/L	0.016	6.9	0.0025	1.3
WW/Lk	0.011	6.9	0.005	1.3
WX/H	0.011	6.9	0.005	1.3
WX/L	0.011	6.9	0.005	1.3

2.5. Water quantity

In a healthy ecosystem, there is enough water as well as a flow regime (variability in rate of flow) to support a diverse range of aquatic flora and fauna during their full life cycle. In an unhealthy ecosystem, water quantity is insufficient to support a diverse range of aquatic life. Continued low flow, due to for example over-allocation, impedes the up- and down-stream dispersal by aquatic plants and animals, but also the dispersal of species on land within floodplains. A complete assessment of water quantity includes measures of the extent and variability in the level or flow of water, including connections between different water bodies.

A catalogue of existing measured and modelled datasets showed that there were no measured data available to inform indicators of water quantity (Table 12). Instead, a model of water allocation pressure was identified as a surrogate measure.

Table 12. Catalogue of metric datasets available for assessing water quantity in rivers and streams. Metrics used in the River Ecosystem Health Score are in bold.

Indicator	Metric	No. of sites	Year	Source
Extent	Wetted area, velocity	NA		
	Depth	NA		
Hydrological variability	Mean or low flow	NA		
	Flood frequency	NA		
	Flood magnitude	NA		
Connectivity	Floodplain	NA		
	Groundwater	NA		
Indicator	**Modelled metric**	**Training data**	**Model diagnostics**	**Model source**
Extent	**Water Allocation Index**	8894	multiple	(Booker et al. 2016)
Hydrological variability	Mean or low flow	485	NSE = 0.87, 0.75	(Booker et al. 2014)
	Flood frequency	485	NSE = 0.60	(Booker et al. 2014)

NA = not available, NSE = Nash-Sutcliffe efficiency.

2.5.1. Water quantity extent

Water quantity extent metric data were sourced from MfE who funded the collation of water allocation consent data to inform the Environment Aotearoa 2019 report. The data are available from MfE.

Data file: “AccumlatedFrame.RData”

The metric chosen to inform the water quantity extent indicator was:

Water Allocation Index – the total sum of accumulated upstream maximum (AccMaxRate) consented takes divided by the predicted median flow provides an estimate of the natural flow extracted from rivers. It is a best ‘estimate’ because not all consented takes are realised, in many regions permitted (unconsented) takes are greater than consented takes, and the effects of water extraction on ecosystem health are most likely to occur across a range in flows, not just median flow.

Booker et al. (2016) describe the water quantity extent metric where

> *the standardised AccMaxRate represents the proportion of the median flow that is consented upstream for each reach. For example, for a particular reach, a value of 0.1 indicates that one tenth of the median flow at that reach would be abstracted from upstream if all consents were being exercised at their maximum instantaneous rates. A value of one indicates that the median flow at that reach would be abstracted from upstream if all consents were being exercised at their maximum instantaneous rates.*

Note that it is possible for greater than the median flow to be allocated by consents, giving an AccMaxRate value greater than 1.0. The highest value seen in the dataset was approximately 15000.

As sourced, the water quantity extent data provide a standardised accumulated upstream maximum (maxrateToQ50) for each NZSegment[3]. To turn reach-scale estimates into a national indicator of water allocation, we applied the calculation of Booker (2016) to provide a weighted allocation impact assessment for all of New Zealand. A weighted allocation impact (WAI) indicator provides a broad spatial measure of the effects of allocation, with high values of WAI in indicating greater allocation. It can be interpreted as (area-weighted) proportion of nation-wide median flow allocated.

WAI = sum(wettedArea * maxrateToQ50) / totalWettedArea. We calculated wetted area as the product of predicted stream width (from Booker 2015) and shape length for any given NZReach. We used the NZReach number provided in RECv2 to translate maxrateToQ50 values from NZSegment to NZReach. This is an imperfect match.

The reference condition for the WAI is 0 or no allocation. The bottom line of 0.3 for area-weighted proportion of median flow allocated was determined by expert opinion.

2.6. Physical habitat

In a healthy ecosystem, the physical form and extent of the waterbody and its surrounding floodplain, including riparian vegetation, allows a diverse range of aquatic flora and fauna to thrive. In an unhealthy ecosystem, the physical form of the waterbody is altered to a degree that it can no longer support a diverse range of aquatic flora and fauna. This could be due to unsuitable riverbanks, loss of riparian/floodplain vegetation, and physical barriers such as stop banks and dams. A complete assessment of physical habitat includes measures of the physical form, structure, and extent of the waterbody, its bed, banks and margins, riparian vegetation, and connections to the floodplain.

A catalogue of existing measured and modelled datasets showed that there was only measured data available to inform a substrate indicator of physical habitat (Table 13). Additionally, a model of historic and contemporary riparian shade was identified as a proxy measure to inform a riparian indicator of physical habitat.

[3] A unique identifier available for every stream segment (length of stream between tributary junctions) in the RECv2 digital river network

Table 13. Catalogue of metric datasets available for assessing physical habitat in rivers and streams. Metrics used in the River Ecosystem Health Score are in bold.

Indicator	Measured metric	Number of sites	Year	Source
Substrate	**Deposited fine sediment**	342	1999-2016	MfE
Form	Natural Character Index or Habitat Quality Index	NA		
Extent	Weighted usable area	NA		
	Rapid habitat assessment score	NA		
Connectivity	Floodplain	NA		
Riparian	Shade	NA		
Indicator	Modelled metric	Training data	Model diagnostics	Model source
Substrate	Deposited fine sediment	10023	TDE = 55.7%	(Depree et al. 2018)
Riparian vegetation	**SegRipShade, SegHisShade**	NA	NA	(Leathwick et al. 2010)
Connectivity	DSDamEffect	NA	NA	(Leathwick et al. 2010)

MfE = Ministry for the Environment, NA = not available, TDE = total deviance explained.

2.6.1. Substrate

Substrate metric data were sourced from MfE who funded the collation of data from a variety of sources including regional councils, published research, the NZFFD, NIWA and Cawthron (Depree et al. 2018). The data are available from MfE.

Data file: “Deposited sediment observed data.csv”

The metric chosen to inform the river substrate indicator was:

Deposited fine sediment (% fine sediment) – fine (< 2 mm) inorganic particles that settle on the streambed describe a component of the substrate that when present in high amounts can adversely affect river health. Excessive fine sediment enters a river due to bank and landscape erosion and can reduce habitat suitability for benthic species, obstruct connectivity between surface and groundwater, and alter key biogeochemical processes. The percentage cover of fine sediment deposited on the streambed in run habitats is visually assessed.

We extracted data from the source dataset where deposited fine sediment had been measured by regional councils using either the standard ‘Instream visual assessment’ or ‘Bankside visual assessment’ methods described in Clapcott et al. (2011b). This average % cover of fine sediment on the streambed in a run habitat was calculated from either a minimum of 20 stratified views using an underwater viewer or estimated from the bank, respectively.

As sourced, deposited fine sediment data included multiple samples from 673 sites spread across five regions in the country (Figure 10). We calculated the average site value for data collected between 2010 and 2016. Ideally, sites would be measured monthly over a minimum of 3 years to inform a robust assessment of average fine sediment cover, however, in the extracted dataset, most sites were sampled on a single occasion.

Like the suspended sediment metric, we chose to use an alternative classification system developed to better describe natural patterns in deposited sediment in rivers. The classification system is a bespoke amalgamation of REC groups by climate, source of flow and geology as described in Franklin et al. (2019). Based on the deposited sediment classification, the data grouped into 10 and out of 12 classes which represent 96.8% of the digital river network. There were 16 reference sites based on land cover that were used to inform the reference condition as shown in Table 14. We used expert opinion based on a weight-of-evidence approach outlined in Franklin et al. (2019) to inform the bottom line for each class (Table 14).

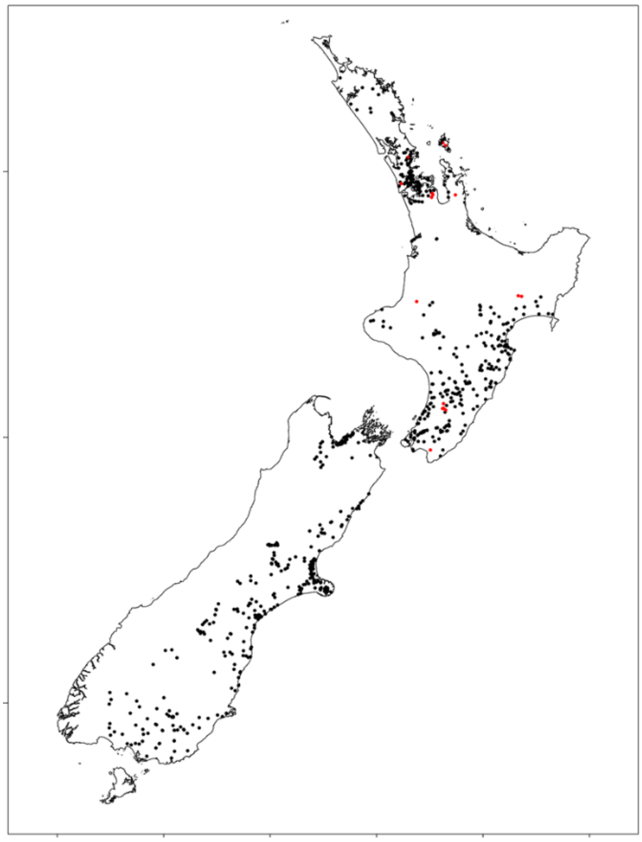

Figure 10. Distribution of deposited sediment metric sites (n = 673) throughout New Zealand. Red dots indicate reference sites as defined by land cover.

Table 14. The reference condition and bottom-line values (% fine sediment cover) for the deposited sediment metric for each deposited sediment class.

	Deposited sediment	
Class	Reference	Bottom line
1	6	97
2	1	21
3	12	60
4	6	23
5	6	92
6	1	46
7	1	56
8	6	45
9	6	61
10	9	29
11	6	89
12	2	45

2.6.2. Riparian vegetation

Riparian vegetation metric data were sourced from the Freshwater Ecosystems of New Zealand database. Data were *modelled* using Landcover Database v2 based on satellite imagery from 2001/2002 and estimates of historical land cover before human habitation (Leathwick et al. 2010). The data are available from DOC.

Data file: "fenzPred.txt"

The metric chosen to inform the riparian vegetation indicator was:

Riparian shade – the proportion of shade provided by streamside vegetation is a primary driver of stream temperature, as well as the delivery of organic matter to fuel the food web, hence it is also important for controlling biogeochemical processes in streams. Riparian shade can also be indicative of streambank stability.

As sourced, the riparian vegetation data are modelled estimates of contemporary (SegRipShade) and historical (SegHisShade) shade for every NZReach in the country. SegRipShade is the likely degree of riparian shading derived from national, satellite image-based vegetation classification, with the degree of shading then estimated from river size and expected vegetation height in each segment. Values range from 0 to 80%. SegHisShade is the estimated shade assuming complete vegetation cover as could be expected during pre-human conditions. Values range from 0 to 80%.

We calculated the riparian shade metric for each NZReach as SegRipShade/ SegHisShade and averaged all NZReach values to provide a national score that indicates the proportion of shade remaining. For example, the estimated average contemporary shade cover of 55.5% divided by the estimated average historical shade cover of 80% equals a national average of 69% riparian shade. While the reference condition for riparian shade was determined by the SegHisShade layer, the bottom line of 0 for the proportion of shade remaining was informed by expert opinion.

2.7. Overall ecosystem health score

Performance scores for each metric were integrated into indicator, component and an overall river ecosystem health score as described in Section 2.1.4. Boundaries for reporting results as grades (i.e. A to D) were derived by the division of the gradient between the reference state (1) and bottom line (0) into equal classes (consistent with the Water Framework Directive recommendations; European Commission (2011)). The middle grades were further equally divided to provide greater resolution resulting in 6 grades (Figure 11). Hypothetically, a total of 8 grades could be assigned, including A+ for scores equal to 1 and D- for scores equal to 0. However, in practice at the national level, it is not possible to get an A+ grade (i.e. all rivers and streams in reference state) or a D- grade (i.e. all rivers and streams below the bottom line). A+ and D- grades are seen for individual metrics at the site level.

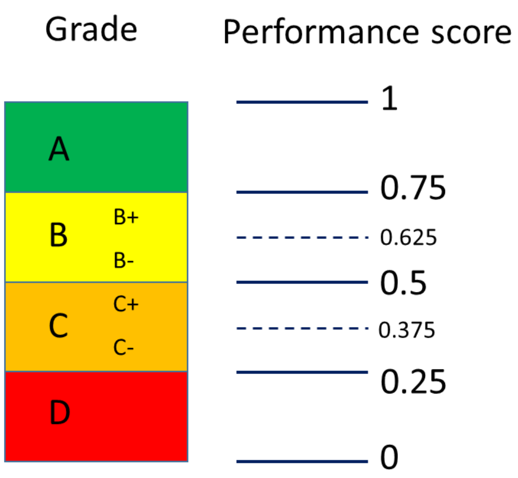

Figure 11. The process of assigning grades to performance scores.

3. RESULTS AND DISCUSSION

In this section we present the findings of the implementation of the Freshwater Biophysical Ecosystem Health Framework to produce a national report card on the biophysical state of New Zealand's rivers and streams. Scores for metrics, indicators, components and overall ecosystem health are described as well as the limitations of the analysis. Main recommendations for future assessments of river health are discussed.

3.1. River ecosystem health scores

The performance scores and suitability weightings for each metric, indicator and component are shown in Table 15. A total of 19 metrics was used in the analysis and resulting performance scores ranged from 0.352 (Cox-Rutherford Index) to 0.99 (ammonia toxicity). Between one and three metrics contributed to indicator scores and between one and five indicators contributed to component scores.

Table 15. Overall river ecosystem health, component, indicator and metric scores and data suitability weighting factors and assigned grades in the River Ecosystem Health Score. The data availability scaling factor used to inform band width in report card infographics is also provided.

Component, Indicator, Metric	Score	Suitability weighting	Grade	Availability scale
River Ecosystem Health	**0.605**		**B-**	
Aquatic Life	**0.634**	**2.72**	**B-**	**0.54**
Fish	0.520	3.00	B-	0.33
Index Biological Integrity	*0.520*	*3.00*	*B-*	
Macroinvertebrates	0.592	2.92	B-	0.73
Macroinvertebrate Community Index	*0.612*	*3.00*	*B-*	
% EPT taxa richness	*0.623*	*2.75*	*B-*	
EPT taxa richness	*0.544*	*3.00*	*B-*	
Plants	0.666	2.25	B+	0.19
Periphyton (Chlorophyll a) biomass	*0.666*	*2.25*	*B+*	
Water Quality	**0.617**	**2.40**	**B-**	**0.80**
Dissolved oxygen	0.574	2.00	B-	0.67
Minimum dissolved oxygen	*0.574*	*2.00*	*B-*	
Temperature	0.352	2.00	C+	0.67
Cox-Rutherford Index	*0.352*	*2.00*	*C+*	
Suspended sediment	0.530	3.00	B-	1.00
Turbidity	*0.530*	*3.00*	*B-*	
Nutrients	0.675	3.00	B+	1.00
Dissolved reactive phosphorus	*0.637*	*3.00*	*B-*	
Dissolved inorganic nitrogen	*0.704*	*3.00*	*B+*	
Contaminants	0.966	2.00	A	0.44
Ammonia toxicity	*0.990*	*2.00*	*A*	
Nitrate toxicity	*0.941*	*2.00*	*A*	
Water Quantity	**0.380**	**2.00**	**C+**	**0.22**
Extent	0.380	2.00	C+	0.67
Water Allocation Index	*0.380*	*2.00*	*C+*	
Physical Habitat	**0.708**	**1.50**	**B+**	**0.25**
Substrate	0.724	1.50	B+	0.50
Deposited fine sediment	*0.724*	*1.50*	*B+*	
Riparian vegetation	*0.692*	1.50	B+	0.25
Shade	*0.692*	*1.50*	*B+*	
Ecological Processes	**0.599**	**1.25**	**B-**	**0.21**
Biogeochemical processes	0.599	1.25	B-	0.42
Gross primary productivity	*0.769*	*1.25*	*A*	
Ecosystem respiration	*0.517*	*1.25*	*B-*	
Cotton decomposition	*0.512*	*1.25*	*B-*	

3.2. Limitations and recommendations for future river ecosystem health assessment and reporting

3.2.1. Dataset selection

Existing national datasets of measured metrics were selected in preference over modelled data for this analysis, but modelled data were used to fill the following data gaps:

- Water Quality – reference state for suspended sediment
- Water Quantity – water allocation index
- Physical Habitat – riparian shade, reference state for deposited sediment.

By using existing datasets, we accepted a known spatial bias in the data. We attempted to balance any geographical bias by weighting site data by class proportional representation during the data aggregation stage, although this was not applicable to all metrics. Further, it does not account for any bias in the monitoring networks due to human impact. For example, around 32% of the total land area of New Zealand is in conservation estate (assumed to be at or close to natural condition), yet for all datasets used in this analysis the proportion of sites defined as reference based on land cover ranged between 1.1% to 4.8%. Neither does it account for any bias in the monitoring network towards mid-sized, wadable rivers with permanent flow, which are targeted due to the nature of the sampling methods required for most metrics. We recommend that a fit-for-purpose monitoring network be established to measure a full suite of component indicators that could then be used to inform an integrated assessment of river ecosystem health at the national scale.

The size of the existing metric datasets ranged from 108 (Cotton decomposition) to 2999 (Fish IBI) and raises the question how many sites are needed to adequately assess New Zealand rivers and streams? A previous analysis of the representativeness of the combined regional council river monitoring networks suggested that there are currently insufficient sites to precisely assess or compare water quality and macroinvertebrate metrics across REC or FENZ environmental classes (Larned & Unwin 2012). They also highlighted a lack of sites in natural land cover classes. However, perhaps many fewer sites would be required if the aim was not to compare classes but to assess the national river network. Greater emphasis could be placed on ensuring all indicators are informed by robust data rather than ensuring all environment types are precisely described. We recommend a further investigation of data requirements for informing a robust national assessment of river health based on application of the Freshwater Biophysical Ecosystem Health Framework. This analysis suggests collecting and/or collating Water Quantity, Physical Habitat and Ecological Process indicator metrics is a priority.

No attempt was made in this project to further assess or correct the quality or the consistency of existing national datasets. As such there may be uncertainty in resulting scores resulting from data inaccuracy. Regional Councils and MfE are currently working towards improved data quality assurance through the development of National Environmental Monitoring Standards (NEMS), the Environmental Monitoring and Reporting (EMaR) project, and Land Air Water Aotearoa (LAWA) data quality assessment. In the near future, it should be possible to conduct a river ecosystem health assessment with robust national datasets, if a representative monitoring network is established.

Finally, an alternative to using existing measured data to inform a River Ecosystem Health Score would be to use modelled data. The catalogues of existing modelled datasets showed that there would be enough data available, although model performance varies greatly for each metric (e.g. equivalent R^2 values of between 0.26 and 0.87). Modelled data would facilitate correction of bias associated with land use impact and may provide a more spatially-balanced assessment. However, modelled data are based on measured data and predictions into unmeasured environmental space (i.e. reference condition) cannot be validated, although techniques exist to quantify model extrapolation (i.e. model suitability) (Booker & Whitehead 2018). We recommend an exploration of calculating scores by making greater use of modelled data to inform benchmarks and to correct for land use bias due to the current non-representative monitoring network.

3.2.2. Missing data

Ideally, all metrics, indicators and components would contribute equally to the calculation of indicator, component and overall ecosystem health scores respectively. We used weighting factors to help correct for a lack of data suitability in terms of data relevance, accuracy, timeliness and spatial coverage. Suitability weighting factors for metrics ranged from 1.25 to 3.00 and averaged 2.25 (Table 15). Suitability of available data was lowest for the Ecological Processes and Physical Habitat components and highest for Aquatic Life and Water Quality components.

The setting of weighting factors can influence scores. For example, if the Water Quantity data had been more robust and had received a weighting of 3 instead of 2, then the overall River Ecosystem Health Score would change from 0.605 to 0.585 given the increased contribution of the low Water Quantity score. We recommend that any change in suitability weighting over time (i.e. due to inclusion of more robust datasets) should be carefully documented.

Suitability weighting factors illustrate data gaps and the lack of completeness of metric data to inform indicator and components. Further, the catalogue of existing metric data for each component and the data availability scaling factor (used to define band width in the report card) illustrate data gaps. Metric data missing from the current analysis include:

- Aquatic Life – water birds and microbial metrics, fish and macroinvertebrate abundance, plant diversity and abundance
- Ecological Processes – biotic interactions
- Water Quality – contaminant (heavy metals/emerging)
- Water Quantity – hydrological variability, extent and connectivity
- Physical Habitat – river form, habitat extent, floodplain connectivity and riparian vegetation.

For some indicators further metric development and validation is needed at the national scale. For example, for Aquatic Life, metrics that provide quantitative assessment of fish or macroinvertebrate abundance are lacking. Quantitative metrics have been developed but monitoring methods are not used consistently at the national scale to support widespread calculation of the metrics. For example, for Water Quantity, further research is required to determine how hydrological indices could be used to assess ecosystem health.

For many metrics where data were unavailable for this analysis there are regional datasets that could be collated for future analysis. For example, several regional councils measure Physical Habitat using the standardised Rapid Habitat Assessment protocol. Or, the Natural Character Index could be calculated for all of NZ using LiDAR data. Or, measurements of heavy metals could be collated from more than just the three regional councils most recently used (Gadd 2016). We recommend the collation of national datasets for missing metrics to inform future national assessments of freshwater ecosystem health.

3.2.3. Data harmonisation and integration

The setting of reference and bottom-line benchmarks is required to harmonise metric data so that it can be combined into indicator, component and overall ecosystem health scores. In this assessment, several benchmarks were in some way informed by expert opinion (Table 1):

- Aquatic Life – fish and macroinvertebrate metrics bottom lines, assignment of reference condition to periphyton classes
- Ecological Processes – selection of management guidelines from the literature
- Water Quality – nutrient and suspended sediment metrics bottom lines
- Water Quantity – water allocation index bottom line
- Physical Habitat – riparian vegetation and substrate bottom lines.

The setting of reference and bottom-line benchmarks determines the resulting metric performance scores. For one example, setting the national bottom line for the Water Allocation Index at 0.5 rather than 0.3 would change the performance score from 0.38 to 0.63. For another example, setting the national bottom line for riparian shade at 0.5 rather than 0 would change the performance score from 0.69 to 0.38. In comparison, setting the reference thresholds for DIN and DRP using Australian and New Zealand Guidelines for Fresh and Marine Water Quality default guideline values instead of 75th percentile from observed data does not result in a significant change in performance scores for DIN (0.704 versus 0.704) or DRP (0.637 versus 0.640). In this assessment, all expert decisions were based on best available knowledge and are described in the methods which should make the analysis repeatable.

To minimise reliance on expert opinion in the future, an alternative approach to setting benchmarks is to use the range in observed data. For example, in the South East Queensland Healthy Waterways Monitoring Program, the lowest observed value is used as the lower benchmark (Worst Case Scenario) and highest observed value is used as the upper benchmark (Best Case Scenario) (Healthy Land & Water 2018). This approach would work if a sites were representative of the full range of conditions present. An issue to resolve if using this approach however, is a sliding scale – should the best sites get progressively worse over time then resulting scores could indicate improvement. Likewise for non-normally distributed metrics, if the worse site got worse over time, an averaging approach would significantly downgrade resulting scores. We recommend an exploration of calculating scores based on using worst case and best case observed to harmonise metrics and limiting expert opinion to a quality assurance of resulting scores.

To integrate (combine) component scores into an overall ecosystem health score we took guidance from a review of existing ecosystem health frameworks (Clapcott et al. 2018). By far the most common way to integrate scores in existing ecosystem health frameworks is to calculate the geometric mean, i.e. simple averaging. The merits of this approach is that it acknowledges that all components are inter-related and are necessary to inform an integrated assessment. Further, component scores potentially informed by less robust metric data do not bias resulting overall scores. An alternative integration approach is to use the lowest component score to inform the overall score, For example, the one-out-all-out (OOAO) approach adopted in the Water Framework Directive is used to target rehabilitation actions. Reviews of the OOAO approach show that metrics with high uncertainty can unfairly bias overall scores, which can be viewed as over-precautionary, and instead a weight-of-evidence approach is more informative to identify multiple pressures on aquatic ecosystems (Borja & Rodriguez 2010; Carvalho et al. 2019). We recommend that future River Ecosystem Health Scores are calculated using simple averaging of component scores and the Score is always reported alongside component scores to demonstrate the relative contribution of components to overall river health.

3.2.4. Spatial scale of analysis

The Freshwater Biophysical Ecosystem Health Framework and associated River Ecosystem Health Score can be applied at any spatial scale from site to catchment to region and to the nation (Clapcott et al. 2018). This national analysis provides a score for the biophysical condition of the 425,000 kilometres of New Zealand's river and stream, including conservation estate. However, we acknowledge that this analysis was based on metric data from monitoring sites potentially biased towards certain land uses. In the absence of a representative monitoring network, we suggest it would be an informative exercise to conduct the analysis by grouping data into dominant land cover classes such as natural, urban, agriculture and exotic forests. This would demonstrate where river ecosystem health varied within New Zealand and provide a way to weight scores by land cover representation to provide a more balanced assessment at the national scale.

3.2.5. Report card presentation

The River Ecosystem Health Score card was prepared with expert input from a graphic designer and science communicator. An initial limited review of the resulting graphic by Ministry for the Environment staff indicated some difficulty with understanding the meaning of the differing widths of the coloured bars, i.e. as intended to quantify the availability and quality of data that informed each sub-score. For that reason, we recommend further exploration of alternative designs and graphics, and testing of their interpretability with a wider audience.

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Auckland Council, Bay of Plenty Regional Council, Cawthron Institute, Department of Conservation, Environment Canterbury, Environment Southland, Greater Wellington Regional Council, Hawke's Bay Regional Council, Horizons Regional Council, Manaaki Whenua Landcare Research, Marlborough District Council, Ministry for the Environment, Nelson City Council, NIWA, Northland Regional Council, Otago Regional Council, Taranaki Regional Council, Tasman District Council, Waikato Regional Council, Wellington Regional Council, West Coast Regional Council.

Kati Doehring (Cawthron Institute) and Kirsten Revell (RevellDesign) contributed significantly to the content and design of the River Ecosystem Health Score card.

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6. APPENDICES

Appendix 1. Rating of metrics to inform indicators of river ecosystem health core components from Clapcott et al. (2018).

Criteria weighting of the following factors was used to rate the suitability of metrics:

- sensitivity to anthropogenic impacts (1= no/unknown, 2 = some evidence, 3 = strong)
- standardised methods available (1 = no, 2 = in part, 3 = yes)
- current use (1= rare, 2 = moderate, 3 = common)
- ease of sampling and analysis (1 = difficult, 2 = moderate, 3 = easy)
- calibration to reference state (1 = unknown, 2 = in part, 3 = well known)
- spatial/temporal scale of measurement (1 = site/spot, 2 = reach/seasonal, 3 = (sub-)catchment/continuous)
- primary spatial/temporal scale of impact (1 = site/day, 2 = reach/week–month, 3 = (sub-)catchment/annual)

The following tables provide ratings of metrics for each ecosystem health component for an integrated assessment of wadeable river health.

Table A1. Rating of indicators of **aquatic life** in New Zealand rivers based on expert opinion. Indicators identified as compulsory attributes for assessing ecosystem health in the NPS-FM are in bold. Indicators commonly measured as part of many regional council monitoring programmes are identified with an asterisk.

Indicator	Sensitivity	Standard methods	Current use	Ease of sampling	Reference calibrated	Scale of measure	Scale of impact	Total
Waterbirds								
Taxa richness	1	1	1	1	1	1	1	7
Abundance	2	1	1	1	2	1	1	9
Native fish								
Taxa richness	1	3	2	1	1	2	3	13
Fish IBI	2	2	2	1	2	2	3	14
O/E fish species	1	2	1	1	2	2	3	12
Pest species	1	2	1	1	3	2	3	13
Invertebrates								
Taxa richness	1	3	3	2	1	1	2	13
MCI*	3	3	3	2	2	1	2	16
%EPT*	3	3	3	2	2	1	2	16
O/E species	2	2	1	2	3	1	3	14
Invertebrate IBI	3	3	1	1	2	1	2	13
SHMAK MCI	2	3	2	3	2	1	2	15
Macrophytes								
% cover	2	3	1	3	1	1	1	12
% native	2	3	1	3	3	1	2	15
MCC	2	3	1	3	1	1	1	12
Periphyton								
% cover*	2	3	3	3	1	1	2	15
Biomass (chl-*a*)*	2	3	3	2	2	1	2	15
% filamentous*	1	3	3	3	2	1	2	15
% cyanobacteria	1	2	1	3	1	1	2	11
SHMAK % cover	1	3	1	3	1	1	2	12
Microbes								
O/E species	1	1	1	3	2	1	1	10
BCI	2	1	1	3	1	1	1	10

IBI = Index of Biotic Integrity, O/E = observed to expected ratio, MCI = Macroinvertebrate Community Index, SHMAK = Stream Health Monitoring and Assessment Kit, MCC = Macrophyte Channel Clogginess, BCI = Bacteria Community Index.

Table A2. Rating of indicators of **water quality** in New Zealand rivers based on expert opinion. Indicators identified as compulsory attributes for assessing ecosystem health in the NPS-FM are in bold. Indicators commonly measured as part of many regional council monitoring programmes are identified with an asterisk.

Indicator	Sensitivity	Standard methods	Current use	Ease of sampling	Reference calibrated	Scale of measure	Scale of impact	Total
*Dissolved oxygen**								
Minimum DOɫ	2	3	2	2	1	2	2	12
Spot measure	2	2	3	3	1	1	2	13
*Temperature**								
Maximum	2	2	1	2	1	2	1	9
CRI	2	2	1	2	1	2	1	10
Spot measure	1	2	3	3	1	1	1	12
*pH**	1	2	3	3	1	1	2	13
*Susp.sediment**								
Clarity	2	2	3	3	2	1	2	15
Turbidity	2	2	3	3	1	1	2	14
Sediment load^	2	1	1	1	2	3	3	10
*Nutrients**								
Total N and P	3	3	3	3	2	1	3	18
Dissolved P	3	3	3	3	2	1	3	18
Nutrient loads^	2	1	1	2	2	3	3	11
Toxicants								
Ammonia toxicity	3	3	3	3	3	1	1	17
Nitrate toxicity	3	3	3	1	3	1	1	15
Metals	3	3	1	2	3	1	1	14

DO = dissolved oxygen, ɫ = only below discharges, CRI = Cox-Rutherford Index, ^Nutrients and sediment loads can be calculated from flow-weighted measurements or predicted using farm- or catchment-scale models, e.g. OVERSEER™ (Ledgard et al. 1999), CLUES (Woods et al. 2006).

Table A3. Rating of indicators of **water quantity** in New Zealand rivers based on expert opinion. Indicators commonly measured as part of many regional council monitoring programmes are identified with an asterisk.

Indicator	Sensitivity	Standard methods	Current use	Ease of sampling	Reference calibrated	Scale of measure	Scale of impact	Total
Extent								
Wetted area	1	2	1	3	2	1	1	10
Velocity	1	2	2	3	1	2	1	12
Depth	1	2	2	3	1	1	1	11
Hydrological variability								
Mean*	1	3	2	1	2	2	3	13
MALF*	2	3	2	1	2	2	3	14
Variability	2	3	1	1	2	2	3	13
Flood frequency	2	3	1	1	2	2	3	13
Flood magnitude	2	3	1	1	2	2	3	13
Connectivity								
Floodplain	2	1	1	1	1	2	3	11
Groundwater	1	1	1	1	1	2	3	10

MALF = Mean annual low flow.

Table A4. Rating of indicators of **habitat** in New Zealand rivers based on expert opinion. Indicators commonly measured as part of many regional council monitoring programmes are identified with an asterisk.

Indicator	Sensitivity	Standard methods	Current use	Ease of sampling	Reference calibrated	Scale of measure	Scale of impact	Total
Substrate								
% fine sediment*	2	3	2	3	2	2	3	17
Substrate stability	1	2	1	3	1	1	2	11
Interstitial space	2	1	1	3	1	1	2	11
Organic matter	1	1	1	3	1	1	1	9
Extent								
WUA	2	2	2	1	2	2	2	12
Residual pool depth	2	2	1	2	1	2	2	12
RHA*	1	3	2	3	2	1	2	14
Form								
Bank stability	2	1	1	3	1	1	1	10
Sinuosity	2	1	1	1	1	2	3	11
Gradient	1	2	1	3	1	2	2	12
Connectivity								
Floodplain connect	2	1	1	2	2	2	3	13
Riparian								
SHAP Naturalness	2	2	1	2	2	1	1	11
Shade*	2	3	2	3	2	1	1	14

RHA = Rapid Habitat Assessment, WUA = Weighted Usable Area (taxa specific), SHAP = Stream Habitat Assessment Protocols.

Table A5. Rating of indicators of **ecological processes** in New Zealand rivers based on expert opinion. Indicators commonly measured as part of many regional council monitoring programmes are identified with an asterisk.

Indicator	Sensitivity	Standard methods	Current use	Ease of sampling	Reference calibrated	Scale of measure	Scale of impact	Total
Biotic interactions								
Connectance	1	1	1	1	1	1	2	8
Rel. ascendency	1	1	1	1	1	1	2	8
Path length	1	1	1	1	1	1	2	8
Parasitism	1	1	1	1	1	1	1	7
Biogeochemical processes								
GPP	3	2	1	2	2	2	2	14
ER	2	2	1	2	2	2	2	13
Cotton strip assay*	3	3	1	3	1	1	1	13
OM processing	2	1	1	1	1	1	1	8
OM	2	2	1	2	1	1	2	11
Delta15N	2	2	1	1	1	1	1	9
Algal bioassay	2	2	1	2	1	1	1	10
Denitrification	1	1	1	1	1	1	2	8

GPP = gross primary productivity, ER = ecosystem respiration, OM = organic matter retention, Delta15N = the ratio of two stable isotopes of N (15N:14N) in primary producers or consumers.