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ASSESSING THE HEALTH OF OTAGO'S ESTUARIES USING THE NATIONAL BENTHIC HEALTH MODELS

ASSESSING THE HEALTH OF OTAGO'S ESTUARIES USING THE NATIONAL BENTHIC HEALTH MODELS

DANA CLARK

Prepared for Otago Regional Council

CAWTHRON INSTITUTE
98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand
Ph. +64 3 548 2319 | Fax. +64 3 546 9464
www.cawthron.org.nz

REVIEWED BY:
Anna Berthelsen

APPROVED FOR RELEASE BY:
Grant Hopkins

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EXECUTIVE SUMMARY

The National Benthic Health Models (BHMs) are a new approach for assessing estuary health in New Zealand. The BHMs use information about the animals living in seafloor sediments to assign a score that indicates the health of an estuary in response to two key coastal stressors; sedimentation (Mud BHM) and heavy metal contamination (Metals BHM). This national scale approach to estuary health assessment provides consistency, enables managers to evaluate the health of their estuary in a national context and reduces the substantial costs that would be required to develop separate estuary-scale or regional-scale models. The BHM approach can also help with prioritisation of mitigation measures because each of the models is linked to a specific stressor. The BHMs use information commonly collected for estuary fine-scale monitoring, making them convenient to apply as additional sampling effort is not usually required.

The first objective of this report was to assess whether the National BHMs are suitable for application in six estuaries monitored by Otago Regional Council, based on the fit of the calculated BHM scores relative to the national dataset used to develop the models. The second objective was to use the BHMs to evaluate how estuary health has changed between 2017 and 2021. BHM scores were calculated using macrofaunal data collected during previous fine scale monitoring surveys.

Benthic Health Model suitability assessment

The National BHMs are appropriate for assessing the health of most of the monitored estuarine sites in Otago. This includes all sites in Blueskin Bay and Shag, Waikouaiti, Tokomairiro and Catlins estuaries, and some sites in Kaikorai Estuary. Poor performance of the BHMs at some Kaikorai sites is likely because the relative concentrations of metals at these sites differed from those used to develop the National BHMs. Consequently, the Metals BHM should not be used to determine the level of metal impact at Sites B, C or D in Kaikorai Estuary relative to other estuarine sites in New Zealand. Similarly, the Mud BHM is not suitable for determining sedimentation impacts at Site B relative to other sites in New Zealand. However, BHM scores can be used to track health at these sites over time. It is recommended that the fit of new site/times from Kaikorai Estuary are checked before applying the National BHMs in future.

Trends in estuary health

The BHM results indicated that sedimentation is causing moderate to very high impacts on macrofaunal communities in most of the monitored estuaries in Otago (except Blueskin Bay), relative to other estuarine sites across New Zealand. At most sites, Mud BHM scores have not substantially changed over time. However, the effects of sedimentation on macrofaunal communities appears to be getting worse with time in the middle to lower Waikouaiti Estuary, while communities appear to be recovering from sedimentation effects in the upper Tokomairiro Estuary.

The impact of metal contamination on macrofaunal communities was generally moderate to high relative to other estuarine sites across New Zealand, but indicative of good to fair health (based on an assessment of absolute health relative to sediment quality guidelines). At most sites, Metals BHM scores have not substantially changed over time. However, Metals BHM scores at the mid estuary site at Waikouaiti have steadily increased (i.e., worsened) over time and indicated high impact in 2019. Furthermore, high sediment metal concentrations have been recorded in the mid to upper parts of Kaikorai Estuary, where Metals BHM scores were found to not be a reliable assessment of health relative to other estuarine sites in New Zealand. Macrofaunal communities are likely to be impacted by metal contamination at these sites.

Recommendations

The continued use of the National BHMs to assess the health of Otago's estuaries is recommended, bearing in mind caveats relating to some sites in Kaikorai Estuary listed above. The fit of data from any new estuary monitoring sites should be checked against the models before applying the National BHMs in future.

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1. INTRODUCTION

Otago Regional Council (ORC) monitors the ecological health of six estuaries within the Otago region: Shag, Waikouaiti, Kaikorai, Tokomairiro and Catlins estuaries and Blueskin Bay (Figure 1). Most of these estuaries are tidal lagoons, except for Waikouaiti and Kaikorai estuaries, which are classified as beach stream and tidal river mouth estuaries, respectively (Hume et al. 2016). The estuary monitoring programme includes: 1) fine scale monitoring of estuarine biota and sediment quality at representative sites, 2) broad scale mapping of estuarine intertidal habitats, 3) water quality monitoring, and 4) sediment plate monitoring. Data collected within this programme enable ORC to assess the ecological health of these estuaries and identify potential drivers of change.

Figure 1. Estuaries monitored within the Otago region.

ORC engaged the Cawthron Institute (Cawthron) to assess the health of sites within these estuaries using the recently developed National Benthic Health Models (BHMs; Clark et al. 2020). The BHMs use information about the animals living in the seafloor sediments (e.g., shellfish, polychaete worms, amphipods) to assign a score that indicates the health of an estuary in response to two of New Zealand's key coastal stressors; sedimentation and heavy metal contamination. Health is defined on the basis of the range of communities observed along gradients of anthropogenic impacts, rather than requiring identification of a 'reference' condition or site. This definition identifies both acute effects and broader scale degradation in community structure. The National BHMs provide a standardised measure that enables managers to evaluate the health of their estuary in a national context.

The first objective of this report was to assess whether the National BHMs are suitable for application in these six estuaries based on the fit of the calculated BHM scores relative to the national dataset used to develop the models. The second objective was to use the BHMs to evaluate how estuary health has changed between 2017 and 2021.

2. NATIONAL BENTHIC HEALTH MODELS

2.1. Purpose of models

The National BHMs were developed in 2020, as a standardised measure of the impact of sedimentation and heavy metal contamination on benthic (seafloor) macrofaunal communities in New Zealand's estuaries (Clark et al. 2020). Benthic macrofaunal communities are commonly used to assess environmental status because they respond relatively rapidly to stressors, integrate the effects of multiple stressors over time and are composed of a diverse range of species with differing functional roles, trophic levels and sensitivities (Pearson & Rosenberg 1978; Dauer 1993; Borja et al. 2000). The BHM approach to estuary health assessment was originally developed to evaluate the impact of sedimentation and heavy metal contamination on estuaries within the Auckland Region (Anderson et al. 2002; Anderson et al. 2006; Hewitt & Ellis 2010) and has been used successfully since 2002. While the original models could only be applied in the Auckland region, the National BHMs can be applied to almost any estuary within New Zealand, provided that macrofaunal data exist at an appropriate level of taxonomic resolution. Having a national-scale tool provides consistency, enables managers to evaluate the health of their estuary in a national context and reduces the substantial costs that would be required to develop separate estuary-scale or regional-scale models. The BHM approach can also help with prioritisation of mitigation measures because each of the models is linked to a specific stressor (sedimentation or heavy metal loading). Furthermore, the BHMs use macrofaunal data commonly collected for estuary fine-scale monitoring, making them convenient to apply as additional sampling effort is not usually required.

The BHMs are underpinned by a multivariate model that characterises changes in macrofaunal community structure along an environmental gradient (Clark et al. 2020), enabling animals to 'tell the story', with respect to classifying sites along a continuum from degraded to non-degraded (Diaz et al. 2004). This multivariate approach incorporates information on all taxa and their relative abundances, meaning the BHMs have high sensitivity to detect small changes in estuary health before significant ecosystem damage occurs.

2.2. Mud BHM and Metals BHM

There are two separate models: the Mud BHM and the Metals BHM. The Mud BHM assesses the impact of mud in surface sediments on macrofaunal communities, which can be used as a surrogate for sediment accumulation rates. The Metals BHM assesses the impact of copper, lead and zinc in surface sediments on macrofaunal communities, which are generally the key metals of concern in New Zealand estuaries (ARC 2004). The output from each model is a BHM score between 1 and 6, with 1 indicating least impact of the stressor(s) on macrofaunal communities, and 6 indicating most impact, relative to other estuarine sites across New Zealand. These scores allow managers to easily track the relative health of sites through time.

2.3. Using the models

Monitoring directional trends is a robust and reliable method because it is largely independent of the concept of reference conditions (Borja et al. 2012), which are difficult to define in estuaries due to their high natural variability and the scarcity of undisturbed locations (Chainho et al. 2007; Barbone et al. 2012; Berthelsen et al. 2018). For example, a directional trend approach can indicate how a site is changing over time in response to an increasing pressure, even if the site was already impacted when monitoring began. However, it is important to understand that impact using the BHMs is assessed relative to other intertidal estuarine sites across New Zealand, rather than as an absolute measure of health. This is a particularly important caveat for the Metals BHM because, although the concentrations of metals at sites used to create the Metals BHM are reflective of estuarine sites across New Zealand, higher metal concentrations are observed in estuaries globally. Thus, a high Metals BHM score indicates that a site is highly impacted by metals relative to other estuarine sites in New Zealand, but not necessarily in a global context. Recognising the difference between relative and absolute health is not as important for the Mud BHM because the stressor gradient used to develop the Mud BHM covered the full gradient of possible mud concentrations (0–98% mud content).

The BHM scores can be simplified into a five-category system that describes the level of impact caused by sedimentation or heavy metal contamination (Table 1). The boundaries between BHM groups are not based on ecological thresholds, but simply reflect a division of the stressor gradient into five equally spaced groups. For the Metals BHM, additional guidance based on existing sediment quality guidelines has been developed to indicate the absolute health (poor, fair, good) of estuarine communities in a New Zealand context (Appendix 1). Although impacts of mud on individual species and communities are relatively well known for New Zealand estuaries (e.g., Thrush et al. 2003; Thrush et al. 2004; Anderson 2008; Ellis et al. 2017), defining ecological thresholds for the Mud BHM is difficult because estuaries are naturally muddy, and the mud content varies spatially within an estuary. Thus, the target BHM score for a site in the upper reach of an estuary may differ from that in the outer reaches. Further research is required to understand where the boundary between good and poor health lies and if this varies in different contexts. Until such thresholds are developed, it is recommended that the Mud BHM health scores are examined over time and action taken if a site is progressively decreasing in ‘health’ with respect to sedimentation, rather than relying on one-off assessments of health.

Table 1. Descriptive names and boundaries for Benthic Health Model (BHM) score groups.

BHM Group	Level of impact relative to other estuarine sites in New Zealand*	BHM score
1	Very low	1.0 < 2.0
2	Low	2.0 < 3.0
3	Moderate	3.0 < 4.0
4	High	4.0 < 5.0
5	Very high	≥ 5.0

* This is a relative measure of impact rather than an absolute measure of health.

Because the BHM scores are derived from macrofaunal communities, which are influenced by many environmental (abiotic and biotic) factors, natural fluctuations in BHM scores are expected. As a general rule of thumb, BHM score changes ≤ ± 1 (the range of BHM scores within each BHM group) are considered within the realm of natural variation (Clark et al. 2020, Supplementary Material C).

The influence that estuary type has on model performance has been evaluated for tidal lagoons and shallow drowned valley estuary types, which are the most common estuary types in New Zealand (Hume et al. 2016). The BHMs responded to mud and metals in the same manner in both estuary types, indicating that these models are robust and suitable for application in many estuaries across New Zealand (Clark et al. 2020). Sites from other estuary types (i.e., tidal river mouth, deep drowned valley, coastal embayment) have also shown a good fit with the national dataset used to develop the BHMs, but the suitability of the BHMs in these estuary types has not yet been formally tested. Full details of the development and validation of the BHMs are provided in (Clark et al. 2020).

3. METHODS

3.1. Data collection

The sediment and macrofaunal data used in this report were collected between the summers of 2017–2021 following the Estuary Monitoring Protocol (Robertson et al. 2002) as part of ORC's fine scale monitoring (Table 2). Briefly, fine scale sampling sites were selected from mid-low intertidal soft sediment habitats in locations that were representative of the wider estuary or depositional zones within the estuary. Each site (30 m x 15 m) was divided into a grid of 12 plots and a macrofauna core (130 mm diameter x 150 mm depth) was collected from 10 of these plots. Macrofauna samples were sieved to 500 µm and retained macrofauna were counted and identified to the lowest practicable taxonomic resolution. Samples of the top 20 mm of sediment were collected adjacent to each macrofauna core and composited into three samples. These sediment samples were analysed for sediment grain size and heavy metals. Further details of the methods can be found in the reports listed in Table 2.

Table 2. Fine scale monitoring carried out within Otago Regional Council's priority estuaries between the summers of 2017 and 2021.

Estuary	Year	Associated reports
Shag Estuary	2017	(Robertson et al. 2017c)
	2018	Not yet published
	2019	Not yet published
Waikouaiti Estuary	2017	(Robertson et al. 2017b)
	2018	Not yet published
	2019	Not yet published
Blueskin Bay	2021	Forrest et al. (2021)
Kaikorai Estuary	2018	(Robertson & Robertson 2018a; Forrest et al. 2020a)
	2019	(Forrest et al. 2020a)
	2020	(Forrest et al. 2020a)
Tokomairiro Estuary	2018	(Robertson & Robertson 2018b; Forrest et al. 2020b)
	2019	(Forrest et al. 2020b)
	2020	(Forrest et al. 2020b)
Catlins Estuary	2017	(Robertson et al. (2017a)
	2018	Not yet published
	2019	Not yet published

3.2. Calculating Benthic Health Model scores

Macrofaunal data were standardised according to Clark et al. (2020) and replicates were averaged by site for each year of sampling. Taxa categories used for taxa that could not be assigned according to Clark et al. (2020) (10 taxa in total, total abundance across the dataset for each taxon < 5) are detailed in Appendix 2. BHM health scores were calculated following the methods of Clark et al. (2020) using PRIMER 7 (v 7.0.13) with the PERMANOVA+ add-on (Anderson et al. 2008; Clarke & Gorley 2015).

3.3. Assessing the suitability of the Benthic Health Models and comparing scores over time

The fit of the calculated BHM scores was assessed by plotting the BHM scores for each site/time against either sediment mud content (for the Mud BHM) or PC1 Metals values (for the Metals BHM) to determine whether any sites/times fell outside of the model data points. The PC1 Metals values represent the combination of copper, lead and zinc concentrations at each site/time based on a Principal Components Analysis (refer to Clark et al. 2020 for details). Mud and Metals BHM scores were then mapped and plotted at each site over time to explore changes in health over the last one to five years depending on data availability for each estuary.

4. RESULTS

4.1. Benthic Health Model suitability assessment

Most sites had a good fit with the BHM model data, indicating that the BHMs can be reliably used to assess their health. This included all sites in Blueskin Bay and Shag, Waikouaiti, Tokomairiro and Catlins estuaries, and some sites in Kaikorai Estuary. Kaikorai Site B had a poor fit with the Mud BHM in all years, and Site A (2019) and Site D (2019) were on the limits of this model (Figure 2). The level of metal impact was underestimated by the Metal BHM at Kaikorai Sites B, C and D in all years, with these sites well outside the limits of the model (Figure 3).

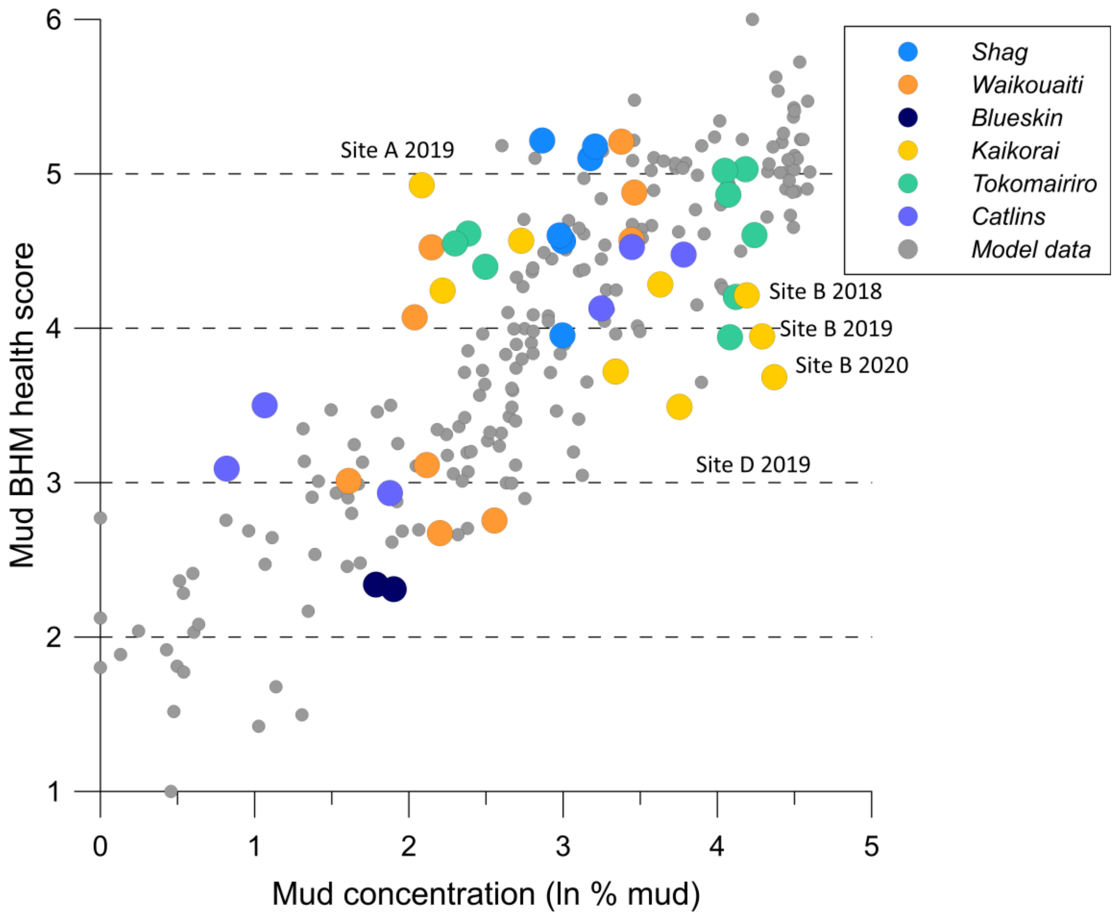

Figure 2. Comparison of Mud Benthic Health Model (BHM) scores from six Otago estuaries (coloured circles) with those from sites used to develop the model (grey circles). Names and years of site/times for which data are outlying (or close to outlying) compared to data used to develop the BHM models are indicated. BHM scores range from 1 (least impacted) to 6 (most impacted) relative to other estuarine sites across New Zealand.

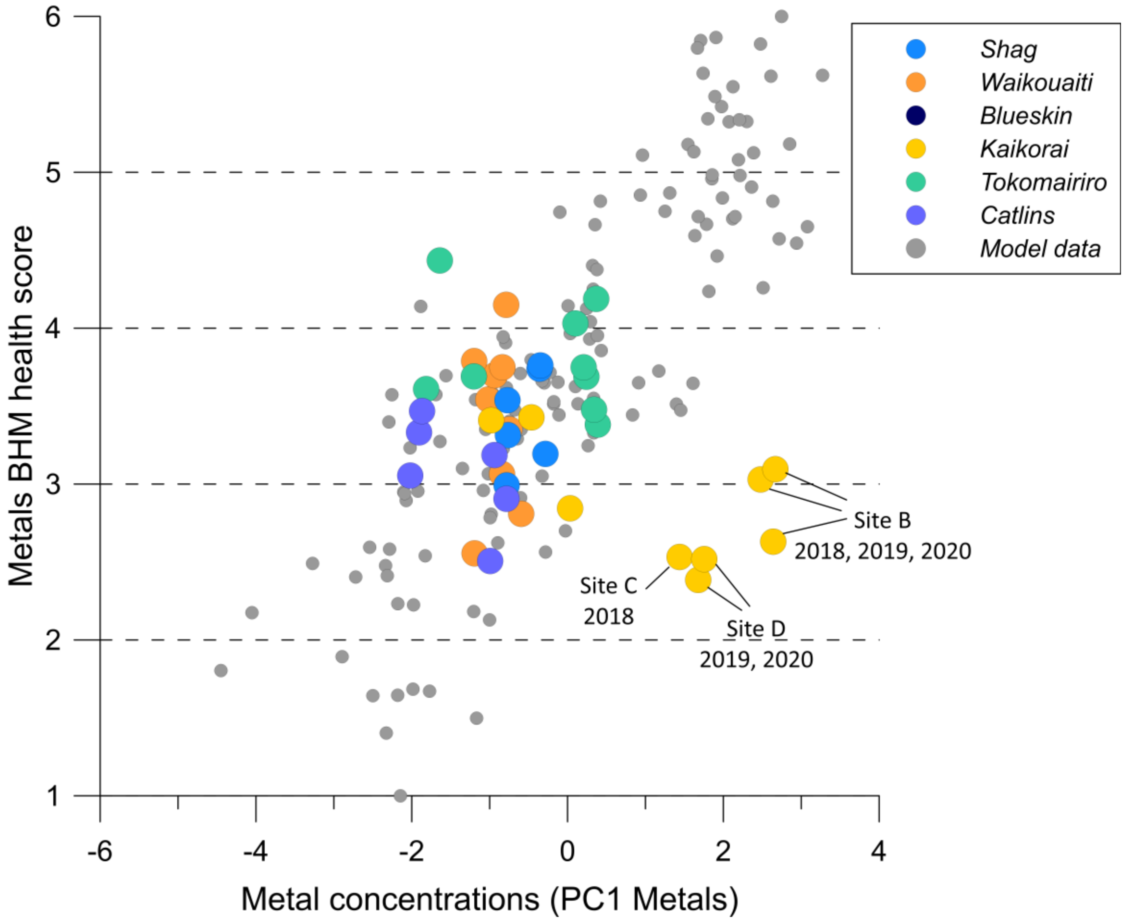

Figure 3. Comparison of Metals Benthic Health Model (BHM) scores from six Otago estuaries (coloured circles) with those from sites used to develop the model (grey circles). Names and years of site/times for which data are outlying (or close to outlying) compared to data used to develop the BHM models are indicated. BHM scores range from 1 (least impacted) to 6 (most impacted) relative to other estuarine sites across New Zealand.

4.1. Shag Estuary

Mud BHM scores indicate that the monitored sites in Shag Estuary are moderately to very highly impacted by sedimentation compared to other estuarine sites in New Zealand, with a greater impact observed at Site B, which is further from the estuary mouth (Figure 4). The Metals BHM scores indicated that the impact from metals is low to moderate at sites in this estuary compared to other sites across New Zealand and indicative of good to fair health. Mud and Metals BHM scores have not shown a substantial increase over time from 2017 to 2019.

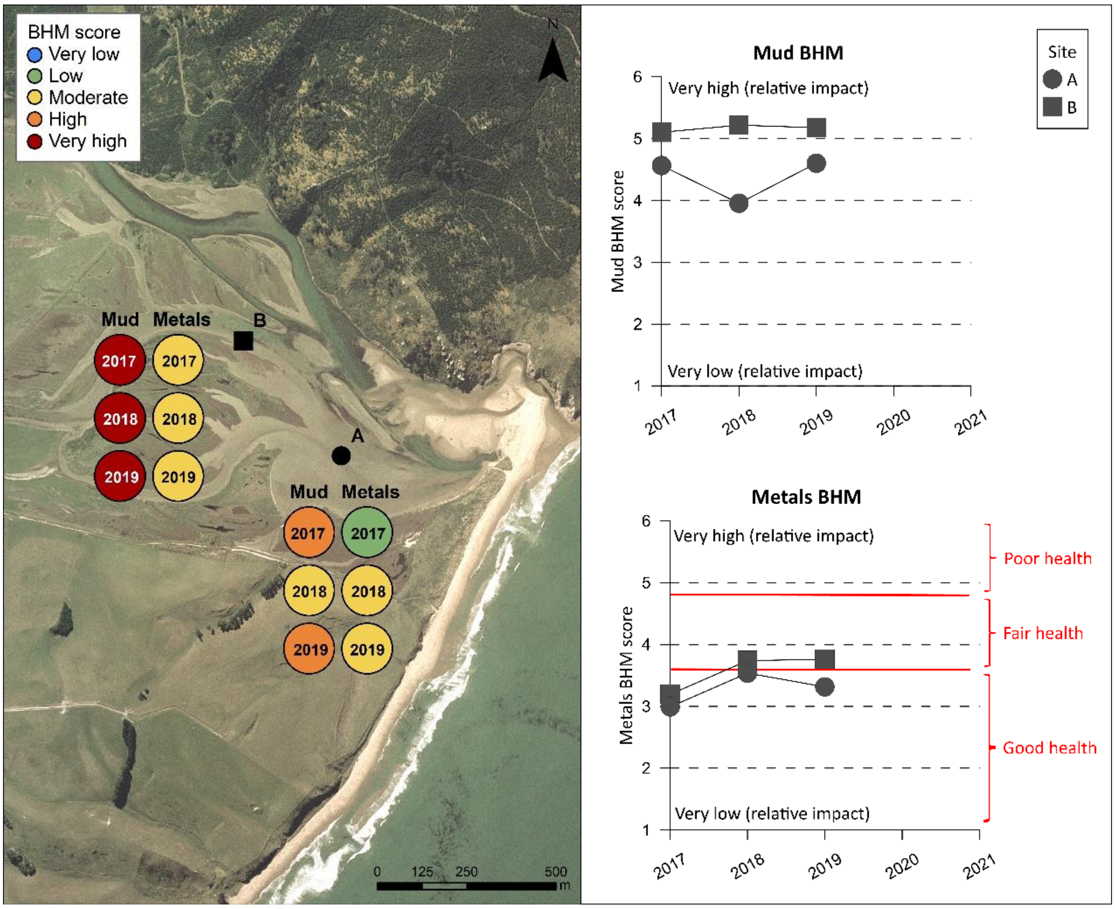

Figure 4. Shag Estuary showing sampling sites and corresponding Benthic Health Model (BHM) scores across years. Circle colours indicate the BHM score group, and the graphs provide more detail on how scores have changed through time. Indications of absolute health in a New Zealand context are provided in red for the Metals BHM (refer Appendix 1).

4.2. Waikouaiti Estuary

Mud BHM scores at monitored sites in Waikouaiti have trended upwards since 2017, suggesting increasing impact from sedimentation in this estuary, particularly in the mid to lower reaches (Figure 5). The highest impact on macrofaunal communities from sedimentation was observed in the upper estuary (Site C) where sedimentation impact was high to very high relative to other estuarine sites in New Zealand. The impact from metal contamination appears to be low to moderate at most sites compared to other estuarine sites across New Zealand and indicative of good health. However, Metals BHM scores in the middle estuary (Site B), and to a lesser degree the outer estuary (Site A), have shown an increasing trend over time. In 2019, Metals BHM scores indicated that macrofaunal communities at Sites A and B and were moderately to highly impacted by metals and in fair health.

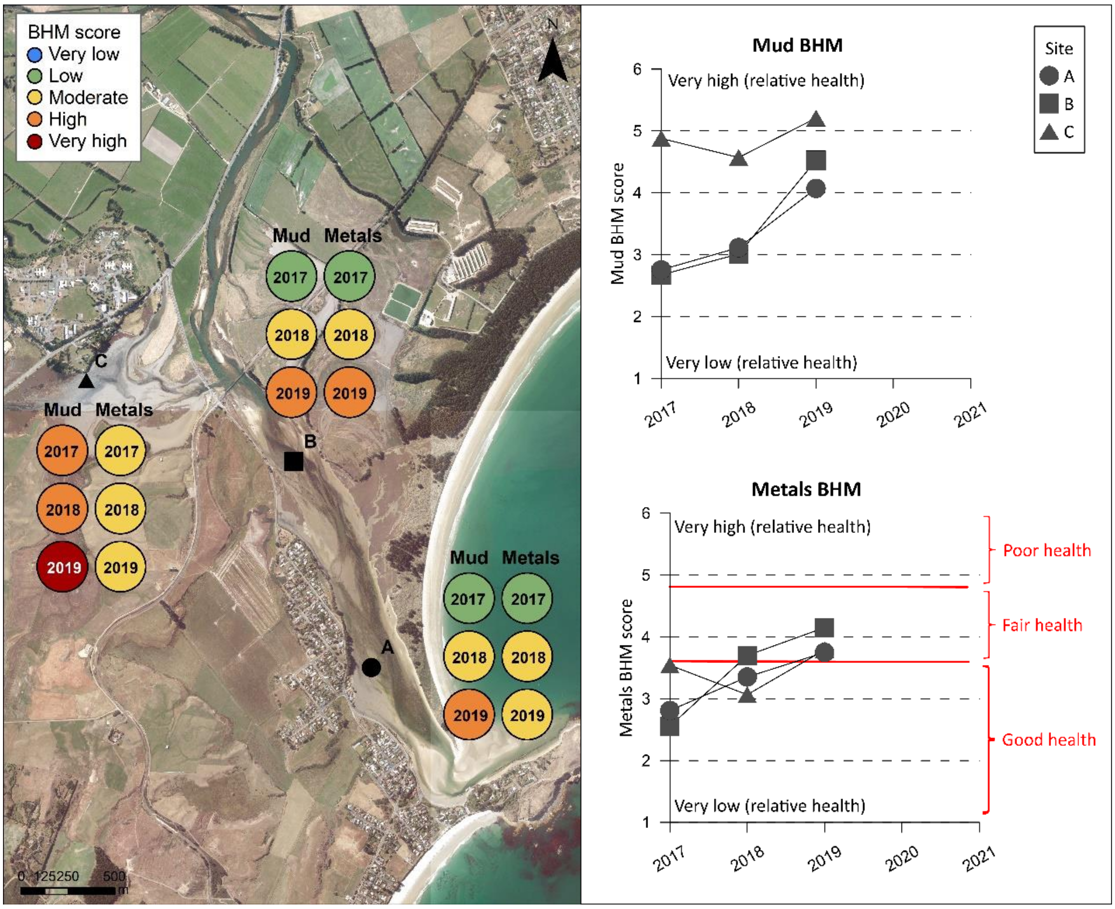

Figure 5. Waikouaiti Estuary showing sampling sites and corresponding Benthic Health Model (BHM) scores across years. Circle colours indicate the BHM score group, and the graphs provide more detail on how scores have changed through time. Indications of absolute health in a New Zealand context are provided in red for the Metals BHM (refer Appendix 1).

4.3. Blueskin Bay

The one-off sampling in 2021 at Blueskin Bay indicated low impact from sedimentation on macrofaunal communities at the three sites selected for estuary monitoring relative to other estuarine sites in New Zealand (Figure 6). The impact from metal contamination was moderate relative to other estuarine sites in New Zealand and indicative of good to fair health.

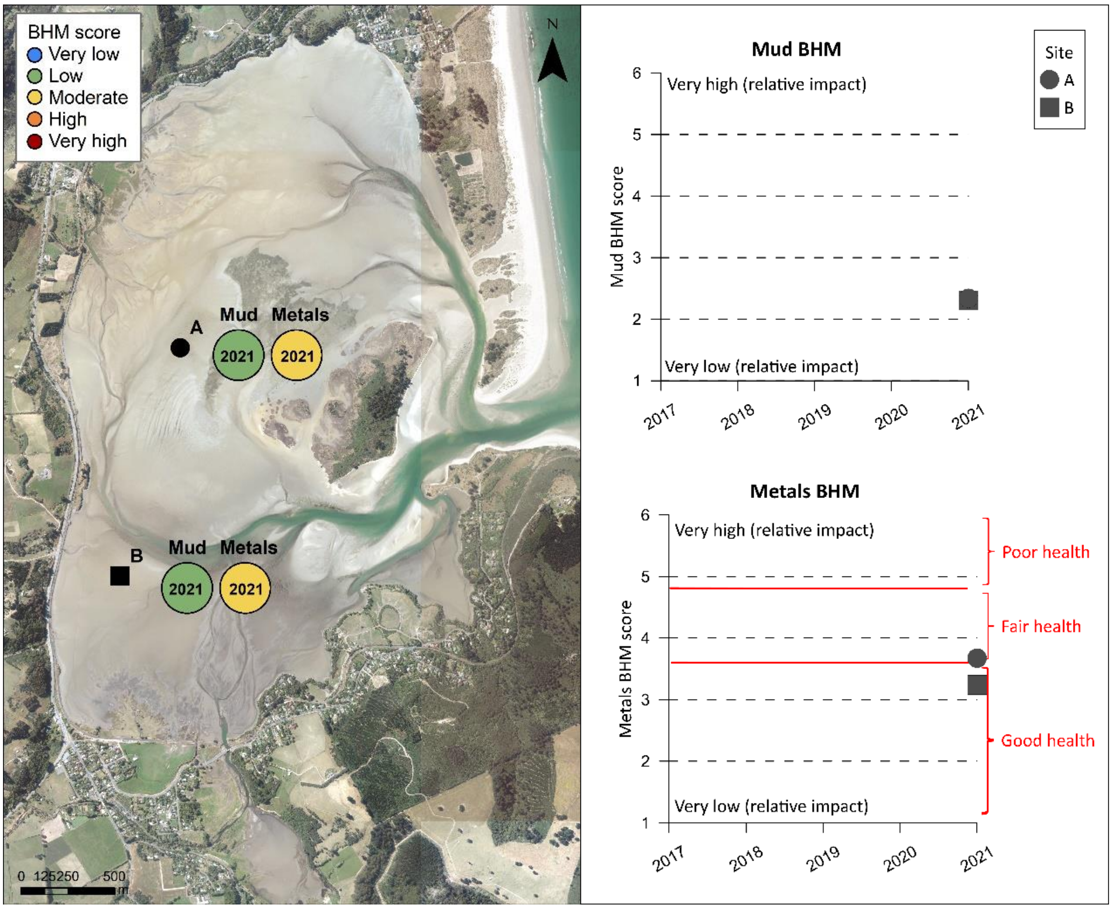

Figure 6. Blueskin Bay showing sampling sites and corresponding Benthic Health Model (BHM) scores for 2021. Circle colours indicate the BHM score group, and the graphs provide more detail on how scores have changed through time. Indications of absolute health in a New Zealand context are provided in red for the Metals BHM (refer Appendix 1).

4.4. Kaikorai Estuary

Both the Mud and Metals BHMs provided an accurate picture of estuary health at Site A and the Mud BHM is also suitable for application at Sites C and D (Figure 2). BHM scores for other sites are not shown. Mud BHM scores indicated that macrofaunal communities at these Kaikorai Estuary sites were moderately to highly impacted by sedimentation relative to other estuarine sites in New Zealand with highest impact in the lower estuary (Site A; Figure 7). Macrofaunal communities at Site A showed low to moderate impact from metal contamination relative to other sites in New Zealand and appeared to be in good health. Mud and Metals BHM scores have not substantially increased between 2018 and 2020 at these sites.

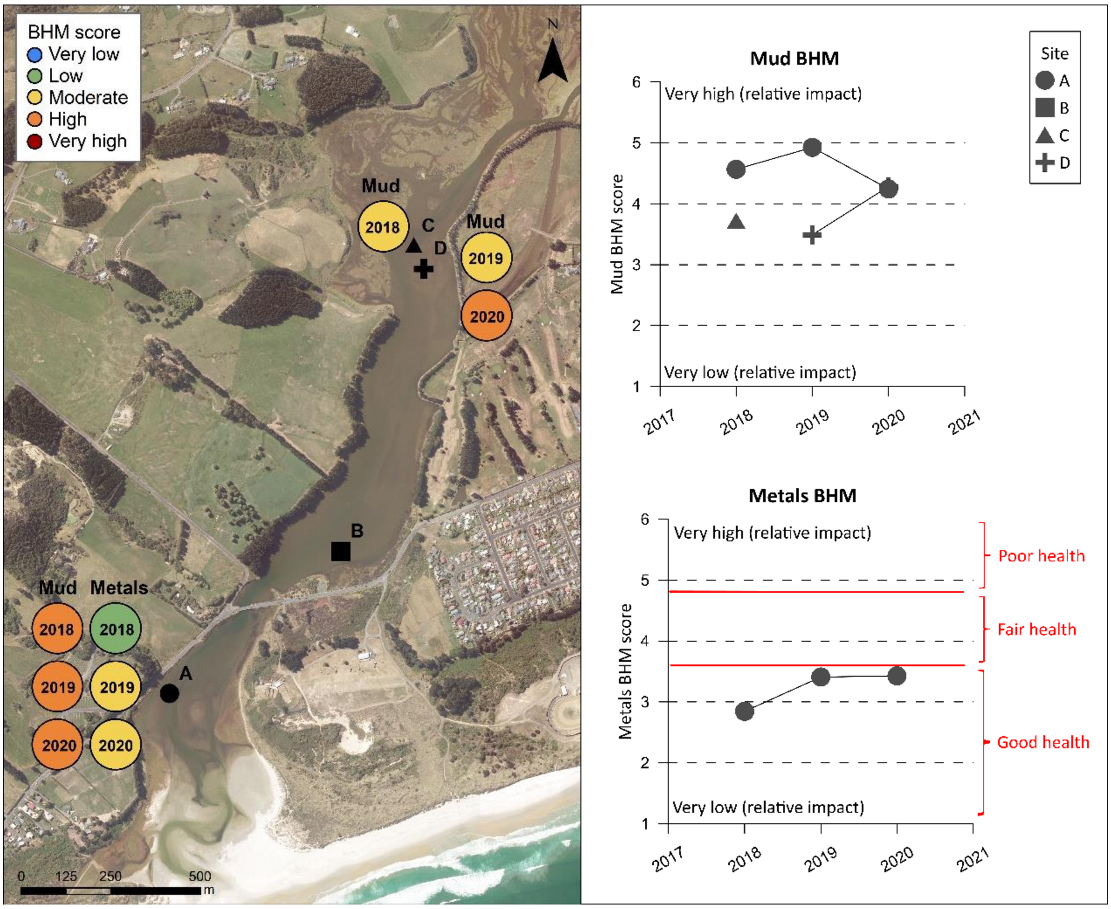

Figure 7. Kaikorai Estuary showing sampling sites and corresponding Benthic Health Model (BHM) scores across years. Circle colours indicate the BHM score group, and the graphs provide more detail on how scores have changed through time. Indications of absolute health in a New Zealand context are provided in red for the Metals BHM (refer Appendix 1). Mud BHM scores are not shown for Site B and Metals BHM scores are not shown for Sites B, C and D because they were not considered to be reliable.

4.5. Tokomairiro Estuary

Mud BHM scores in the upper Tokomairiro estuary (Site C), and to a lesser extent the mid estuary (Site B), have trended downwards over three years since 2018, suggesting decreasing impact on macrofaunal communities from sedimentation (Figure 8). These sites were initially very highly impacted by sedimentation relative to other estuarine sites across New Zealand, but now all sites in this estuary are either moderately or highly impacted. The impact of metal contamination relative to other sites across New Zealand was moderate to high and is generally indicative of fair health. Metals BHM scores have not substantially changed between 2018 and 2021.

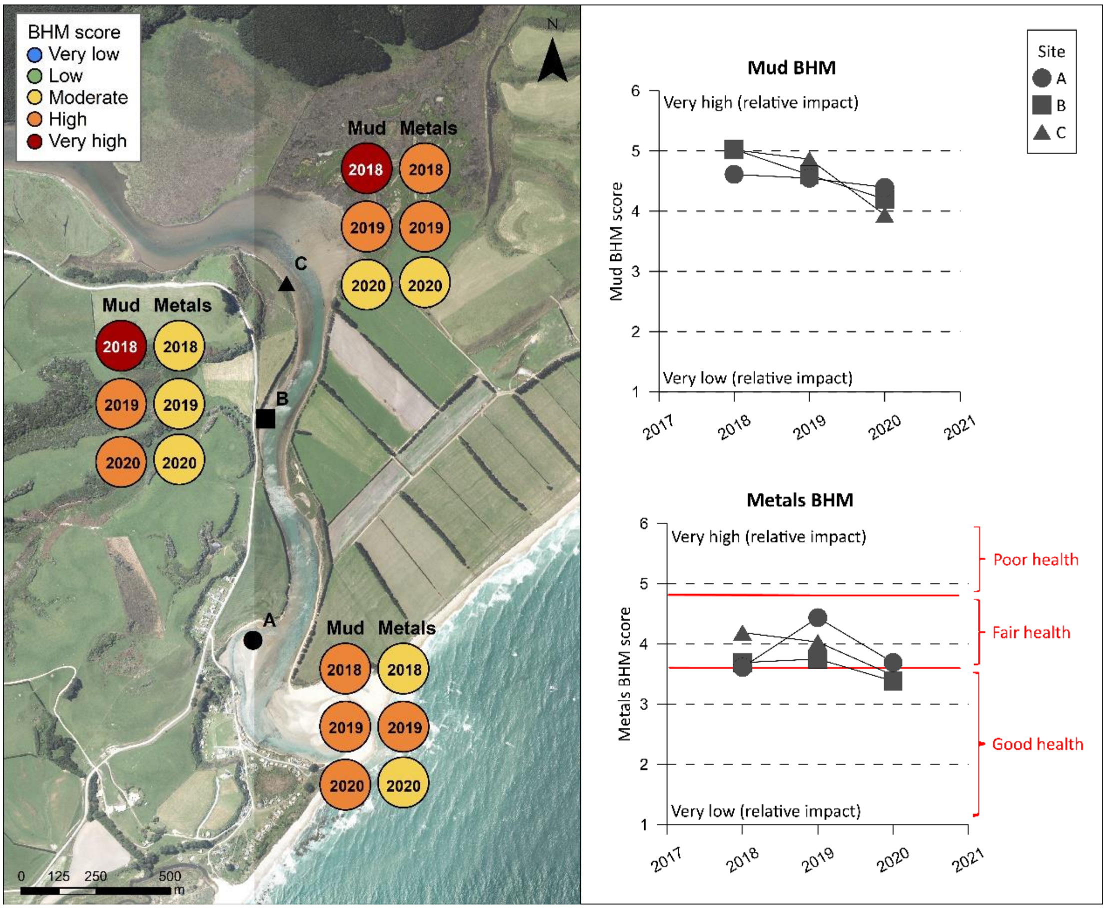

Figure 8. Tokomairiro Estuary showing sampling sites and corresponding Benthic Health Model (BHM) scores across years. Circle colours indicate the BHM score group, and the graphs provide more detail on how scores have changed through time. Indications of absolute health in a New Zealand context are provided in red for the Metals BHM (refer Appendix 1).

4.6. Catlins Estuary

Mud and Metals BHM scores indicate that the impact of sedimentation and metal contamination on macrofaunal communities at monitored sites in Catlins Estuary have remained relatively constant between 2017 and 2019 (Figure 9). There is high sedimentation impact at the upper estuary site (Site B) relative to other sites in New Zealand and low to moderate impact at the site near the estuary mouth (Site A). Metals BHM scores indicate low to moderate impact from metal contamination at these sites relative to other estuarine sites in New Zealand and suggest that macrofaunal communities are in good health.

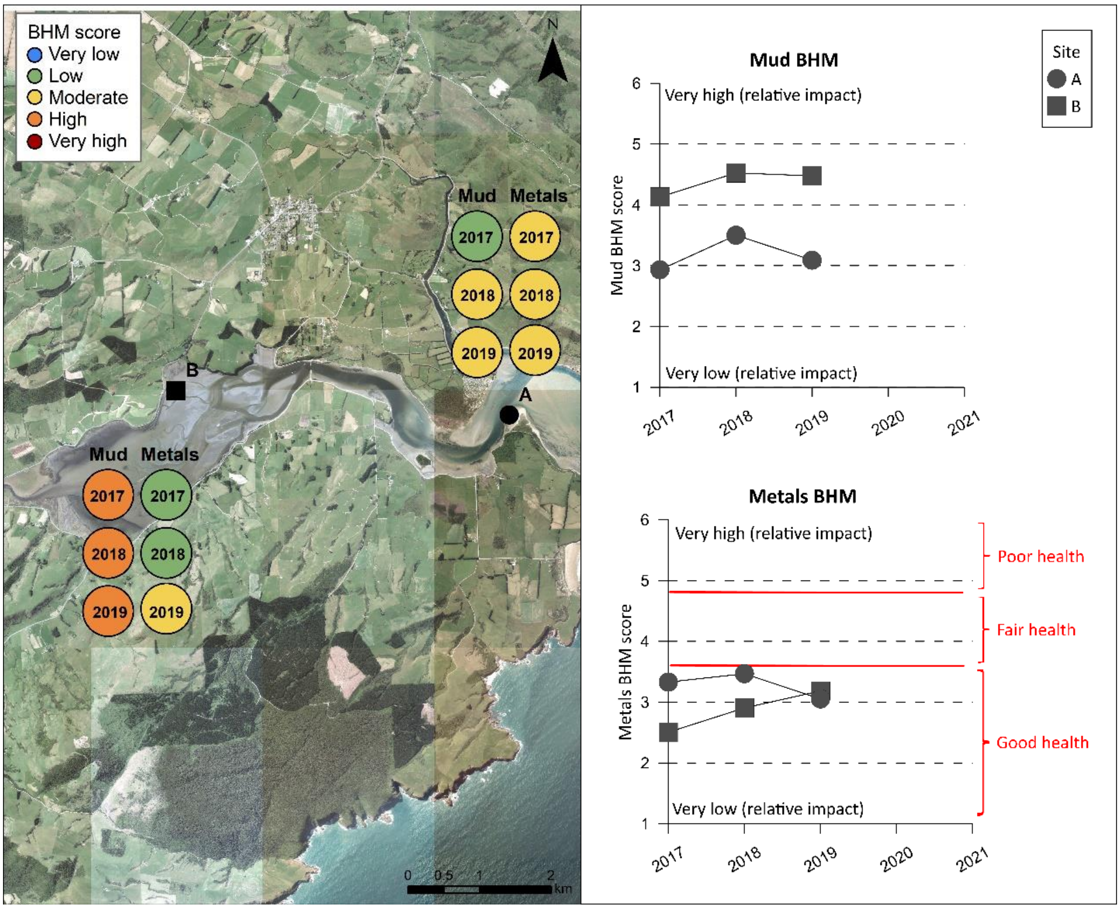

Figure 9. Catlins Estuary showing sampling sites and corresponding Benthic Health Model (BHM) scores across years. Circle colours indicate the BHM score group, and the graphs provide more detail on how scores have changed through time. Indications of absolute health in a New Zealand context are provided in red for the Metals BHM (refer Appendix 1).

5. DISCUSSION

5.1. Suitability of the Benthic Health Models

The National BHMs are appropriate for assessing the health of most of the monitored estuarine sites in Otago. This includes all sites in Blueskin Bay and Shag, Waikouaiti, Tokomairiro and Catlins estuaries, and some sites in Kaikorai Estuary. The poor fit of some Kaikorai sites suggests that the National BHMs will not always provide an accurate picture of health in this estuary, particularly in the mid to upper reaches.

Both sedimentation and metal impacts were adequately estimated at the lower Kaikorai Estuary Site A, which is more typical of the estuary sites used in the development of the National BHMs. However, the BHMs were not very good at predicting the health of Kaikorai Site B and tended to underestimate the level of impact at this site for both sedimentation and metals. Site B is located mid-estuary and has muddy, enriched sediments with relatively high trace metal concentrations, particularly zinc (Forrest et al. 2020a). The level of impact by metals was also underestimated by the Metals BHM at the upper Kaikorai Estuary sites (Site C and Site D). Although the Mud BHM scores from Sites C and D generally had a good fit with the model data, these upper estuary sites are heavily influenced by the catchment with a high volume of gravel, bark and other debris observed in the macrofauna samples (Forrest et al. 2020a). Site C is no longer sampled because it had impoverished biota (50% of cores were azoic) and was subject to strong scouring (Forrest et al. 2020a). The BHM scores at Sites C and D might reflect this scouring as they tended to provide low BHM scores relative to mud content.

The poor performance of the Metals BHM at the mid to upper Kaikorai estuary sites is likely because the relative concentrations of metals at these sites differed from sites used to develop the National BHMs. The Metals BHM relies on a high degree of correlation between copper, lead and zinc. Zinc concentrations at Kaikorai Sites B, C, and D were particularly high relative to copper and lead which could have influenced model scores. Research shows that copper has a greater impact on common New Zealand estuarine macrofauna relative to lead and zinc (Hewitt et al. 2009). Thus, the lower than expected Metals BHM scores may have arisen because species were responding more to the moderate copper levels at this site than to the high zinc levels.

Based on these results, the Metals BHM should not be used to determine the level of metal impact at Sites B, C or D in Kaikorai Estuary relative to other estuarine sites in New Zealand. Similarly, the Mud BHM is not suitable for determining sedimentation impacts at Site B relative to other sites in New Zealand. However, trends in BHM scores through time (e.g., indicating increasing or decreasing impact) are likely to be valid at these sites, as offsets at these sites are unlikely to alter the trajectory of the scores. It is recommended that the fit of new site/times from Kaikorai Estuary are checked before applying the National BHMs in future.

5.2. Trends in estuary health

The most recent (i.e., 2019–2021, depending on the estuary) sampling shows that most of the monitored sites in Otago's estuaries are moderately to highly impacted by sedimentation relative to other estuarine sites in New Zealand (Table 3). The exceptions were the upper estuary sites in Shag and Waikouaiti estuaries, which were very highly impacted by sedimentation, and Blueskin Bay, which showed only low impact from sedimentation. These findings are in keeping with recent monitoring reports, which observed unbalanced macrofaunal communities affected by elevated mud and poor oxygenation at the Shag and Waikouaiti estuary sites (Robertson et al. 2017c, 2017b) and high sediment quality with diverse and abundant macrofauna in a healthy condition at Blueskin Bay (Forrest et al. 2021).

Based on one to three years of sampling in each estuary, the effects of sedimentation on macrofaunal communities appear to be getting worse in the mid to lower Waikouaiti Estuary, while communities appear to be recovering from sedimentation effects in the upper Tokomairiro Estuary. Recent monitoring in Tokomairiro Estuary (Forrest et al. 2020b) reported no substantive changes to sediment mud content over the last three surveys, although measures from a simple macrofaunal health index (AMBI) did improve in the upper estuary between 2019 and 2020. This could indicate that the Mud BHM is a more sensitive and time integrated measure of estuary health than other measures of sedimentation (e.g., mud content) because it is based on macrofaunal changes and preserves information on all taxa and their relative abundances.

Metals BHM scores indicated that most of the monitored sites were moderately impacted by metals relative to other estuarine sites in New Zealand and in good to fair health (based on an assessment of absolute health relative to sediment quality guidelines). However, Metals BHM scores have steadily increased (i.e., worsened) at the mid-estuary site at Waikouaiti and in 2019 they indicated high impact relative to other estuarine sites in New Zealand. This trend is consistent with increasing copper, lead and zinc concentrations at this site (unpublished data, this study). The Metals BHM was not able to accurately predict metal contamination effects in the mid to upper Kaikorai Estuary, so these scores are not discussed here. However, high sediment metal concentrations have been recorded at these sites (Forrest et al. 2020a) so macrofaunal communities are likely impacted by metal contamination at these sites.

Table 3. Summary of the health of Otago's estuaries based on the most recent National Benthic Health Model (BHM) scores at each site. Colours indicate impact relative to other estuarine sites in New Zealand: very high (red), high (orange), moderate (yellow), low (green), very low (blue). Letters indicate absolute health with respect to metal contamination: good (G), fair (F), poor (P). Arrows indicate where the earliest and most recent BHM scores differed by ≥ 1. Note that an upwards pointing arrow indicates that health has worsened over time, while a downwards pointing arrow indicates that health has improved.

	Mud BHM			Metals BHM		
Estuary	Site A	Site B	Site C/D	Site A	Site B	Site C/D
Shag				G	F	
Waikouaiti	↑	↑		F	F ↑	F
Blueskin				F	G	
Kaikorai				G		
Tokomairiro			↓	F	G	G
Catlins				G	G	

5.3. Conclusions

The National BHMs are suitable for assessing the health of most of the monitored estuarine sites in Otago, except for some of the sites in Kaikorai Estuary. Mud BHM scores from surveys conducted between 2017 and 2021 indicated that in most estuaries (except Blueskin Bay) sedimentation is having a moderate to very high impact on macrofaunal communities relative to other estuarine sites in New Zealand. The impact of metal contamination on these communities was moderate to high relative to other estuarine sites across New Zealand, but these sites were in good to fair health (based on an assessment of absolute health relative to sediment quality guidelines). However, we would expect macrofaunal communities in the mid to upper parts of Kaikorai Estuary to be impacted by metal contamination, where Metals BHM scores could not be calculated.

The continued use of the National BHMs to assess the health of Otago's estuaries is recommended, with the following caveats:

- The Mud BHM should not be used to determine sedimentation impacts at Site B relative to other estuarine sites in New Zealand but can be used to track health over time.

- The Metals BHM should not be used to determine the level of metal impact at Sites B, C or D in Kaikorai Estuary relative to other estuarine sites in New Zealand but can be used to track health over time.
- The fit of new site/times from Kaikorai Estuary should be checked before applying the National BHMs in future.
- The fit of new sampling sites in any estuary should be checked before applying the National BHMs in future.

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APPENDIX 1. METALS BHM: ABSOLUTE HEALTH

The National Benthic Health Models (BHMs) provide a score between 1 (least impacted) and 6 (most impacted) that indicates the health of macrofaunal communities relative to other estuarine sites across New Zealand. The BHM scores can be simplified into a five-category health score system with boundaries between groups reflecting a division of the stressor gradient into five equally spaced groups (Table 1). While these groups are useful for tracking the health of a site through time and assessing the level of impact in a national context, they do not necessarily reflect the absolute health of estuarine communities at that site. For example, many of New Zealand’s estuaries have very little metal contamination, so simply relying on relative impact may be misleading in terms of risk to macrofaunal communities and estuarine health. Here we use existing sediment quality guidelines for metal concentrations in marine sediments (Table A1.1) to provide an indication of the absolute health of estuarine communities based on the Metals BHM scores (Table A1.2). Greater weight was given to guidelines derived from field-based species sensitivity distributions (Bjørgesæter & Gray 2008; Kwok et al. 2008), particularly those developed using New Zealand data (Hewitt et al. 2009). Other guidelines are often based on single-species, laboratory dose-response experiments with mortality as an endpoint (Calow 1998) so may not be sufficient to protect estuarine macrofaunal communities (Hewitt et al. 2009; Tremblay et al. 2017). We recommend assessing absolute health as well as relative impact when applying the Metals BHM.

Table A1.1. Existing sediment quality guidelines from various sources, along with their equivalent Metals Benthic Health Model (BHM) health score. Values for metals are in mg kg^{-1}. Darker shading indicates values that are specific to New Zealand.

Guideline	Location	Cu	Pb	Zn	PC1Met	Metals BHM	Source
Stated as low effects							
Auckland BHM Group 1/2 boundary	NZ				-0.400	3.6	a
Austrovenus EC50	NZ	11.2				3.6	b
SQG sand (0–100m)	Norway	3.0	17.0	20	-0.366	3.6	c
FEC lower (adjusted)	NZ	5.3	10.4	113	0.591	4.1	b
FEC lower	NZ	6.5	18.8	114	1.006	4.3	b
FEC upper (adjusted)	NZ	6.5	18.5	114	0.997	4.3	b
FEC upper	NZ	9.3	19.4	118	1.247	4.5	b
cHC5 (TEL)	Hong Kong	23.5	29.9	57.2	1.653	4.7	d
ERC-Green	NZ	< 19	< 30	< 124	1.931	4.8	e
TEL	Canada, USA	18.7	30.2	124	1.925	4.8	f
ERL	USA	34	46.7	150	2.629	5.2	g
T_{20}	USA	32	30	94	2.711	5.3	h
SQO Target	Netherlands	36	85	140	2.944	5.4	i
SLG-Low	Canada	16	31	120	2.929	5.4	j
DGV	NZ, Australia	65	50	200	3.232	5.6	k
ISQV-Low	Hong Kong	65	75	200	3.445	5.7	l
Stated as midrange effects							
cHC10 (PEL)	Hong Kong	33.9	34.6	78.3	2.125	5.0	d
AET	USA	390	450	410	2.669	5.3	m
PEL	Canada, USA	108	112	271	4.147	6.1	f
T_{50}	USA	94	94	245	4.524	6.3	h
SQO PEC	Netherlands	73	530	620	5.166	6.6	i
ERM	USA	270	218	410	5.318	6.7	g
Stated as extreme effects							
ERC-Red	NZ	> 34	> 50	> 150	2.664	5.3	e
T_{80}	USA	280	297	636	4.545	6.3	h
ISQV-High	Hong Kong	270	218	410	5.318	6.7	l
GV-high	NZ/Australia	270	220	410	5.323	6.7	k
SLG-Severe	Canada	110	250	820	5.492	6.8	j

EC50, concentration effective in producing 50% decline in abundance; SQG, Sediment Quality Guideline; FEC, effect concentrations; cHC5, adjusted community Hazardous Concentration 5%; TEL, Threshold Effect Level; ERC, Environmental Response Criteria; ERL, Effects Range Level; T_{20}, 20% probability of observing sediment toxicity; SQO, Sediment Quality Objective; SLG, Screening Level Guideline; DGV, Default Guideline Value; ISQV, Interim Sediment Quality Value; cHC10, adjusted community Hazardous Concentration 10%; AET, Apparent Effects Thresholds; PEL, probable effects level; T_{50}, 50% probability of observing sediment toxicity; SQO PEC, Sediment Quality Objective Maximum Permissible Concentration; ERM, effects range median; T_{80}, 80% probability of observing sediment toxicity; GV, Guideline Value.
a. calculated in his study, b. Hewitt et al. (2009), c. Bjørgesæter and Gray (2008), d. Kwok et al. (2008), e. ARC (2004), f. MacDonald et al. (1996), g. Long et al. (1995), h. Field et al. (2002), i. ANZECC (2000), j. Persaud et al. (1993); k. ANZG (2018), l. Chapman et al. (1999); m. Department of Ecology (2013).

Table A1.2. Absolute health boundaries for the National Metals Benthic Health Model (BHM).

Absolute health	BHM score	Justification
Good	< 3.6	Upper value represents the point at which the abundance of *Austrovenus stutchburyi* will have declined by 50% (EC50; Hewitt et al. 2009) and is also equivalent to the boundary between Group 1 and 2 in the Auckland-specific Metals BHM. This value also represents the sediment quality guideline for sandy sediments in less than 100 m water depth derived by Bjørgesæter and Gray (2008) using field data from the Norwegian continental shelf.
Fair	3.6 < 4.8	Encompasses the effect concentrations (FEC) guidelines derived by Hewitt et al. (2009) using field data from Auckland estuaries (BHM scores = 4.1-4.5). These values represent the point at which 5% of all taxa would have suffered a ≥ 50% decrease in abundance. This group also includes the adjusted community hazardous concentration 5% value (cHC5) derived by Kwok et al. (2008) using field data from Hong Kong (BHM score = 4.7). This value represents the highest concentration of a metal at which no benthic organisms are expected to be affected adversely.
Poor	4.8 >	Lower value represents Auckland Council's Green guideline for sediment metals (ARC 2004). This group also includes the value equivalent to Auckland Council's Red guideline for sediment metals (BHM score 5.3) and the ANZG (2018) Default Guideline Value for metals (BHM score 5.6).

APPENDIX 2. TAXA CATEGORIES USED FOR AMBIGIOUS TAXA

Table A2.1. Model taxa categories used for taxa that could not be assigned following Clark et al. (2020).

Taxon	Category assigned	Abundance across dataset
Anthozoa	Edwardsiidae [1]	4.8
Amphipoda	Amphipod other [2]	0.4
Amphipoda sp. 4	Amphipod other [3]	0.2
Austrolittorina cincta	Gastropoda unidentified	0.1
Offadesma angasi	Bivalve unidentified	0.1
Paphies subtriangulata	Bivalve unidentified	0.1
Prionospio sp.	Prionospio other [4]	1.8
Thoracophelia otagoensis	Polychaeta unidentified	0.2
Retusa striata	Gastropoda unidentified	0.1
Spionidae	Polychaeta unidentified [5]	0.1

[1] Could have been *Anthopleura hermaphroditica*
[2] Could have been Corophiidae
[3] Could have been Phoxocephalidae
[4] Always identified in conjunction with *Prionospio aucklandica* so confident of this classification
[5] Could have been *Scolelepis* or *Paraprionospio*