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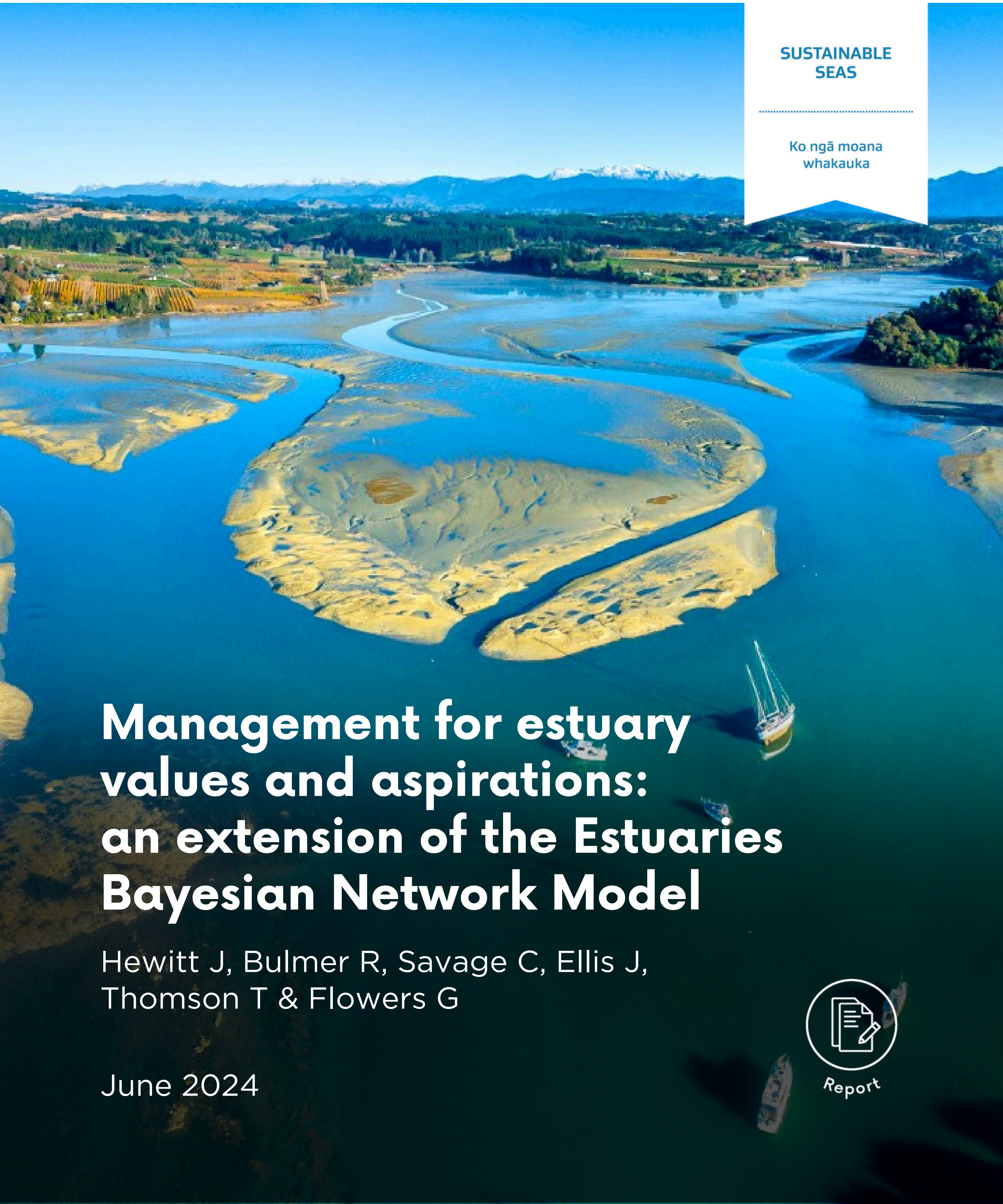

Management for estuary values and aspirations: an extension of the Estuaries Bayesian Network Model

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Report

Report for Sustainable Seas National Science Challenge synthesis activity *Improved decision-making using an ecosystem-based management (EBM) approach.*

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For more information on this project, visit: www.sustainableseaschallenge.co.nz/our-research/ecosystem-based-management

About the Sustainable Seas National Science Challenge

Our vision is for Aotearoa New Zealand to have healthy marine ecosystems that provide value for all New Zealanders. We have 75 research projects that bring together around 250 scientists, social scientists, economists, and experts in mātauranga Māori and policy from across Aotearoa New Zealand. We are one of 11 National Science Challenges, funded by the Ministry of Business, Innovation & Employment.

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Contents

Executive summary

This document reports on a project involving three estuaries where an existing Bayesian Network (BN) model was adapted using expert and community-based knowledge of key ecosystem dynamics and associated values.

Model scenarios were developed for the three case study estuaries, and results presented at workshops with local communities to help address management concerns and support participatory processes, to inform marine management decision making.

This report explains what Bayesian Network models are and what the project did and found.

Bayesian Network models can integrate different types of knowledge

Probabilistic Bayesian Network (BN) models have been identified by Sustainable Seas as key tools used to inform marine management decision-making. BNs are useful because they can integrate empirical and expert based ecological data, as well as social, cultural, and economic values.

An existing BN model was adapted to assist Ministry for the Environment (MfE) efforts to identify values and aspirations for local estuaries throughout Aotearoa and identify gaps in the current national and regional/local governance and management systems. Model scenarios were developed for three case study estuaries (Whangateau, Kakanui, Ahuriri), and results presented at workshops with local communities to help:

- address management concerns
- support participatory processes.

Overall, our experience with these three case studies highlighted the ability of local communities to appreciate the underlying concepts and be willing to use participatory tools to question the effectiveness and risks of proposed management actions.

For the existing BN to support the MfE process and local communities and management agencies in decision making, extensions were necessary. In particular, the model was extended to incorporate the effects of marine heatwaves and changes to the quantity of freshwater inflows. A method was also demonstrated whereby local communities could add components and species of local importance and include their own expert opinions.

Introduction

In 2022, the Minister for the Environment asked Ministry officials to investigate approaches for better managing estuaries, their ecosystem health, and values. He requested that officials begin by focussing on the ecosystem health of, values in, and aspirations for, three case study estuaries. By focussing on estuaries in different regions of the country and of different sizes and estuarine types, MfE anticipated that this work would identify common values and aspirations held for New Zealand estuaries. They also hoped to identify gaps in the current national and regional/local governance and management systems, i.e., resourcing, funding, and accessibility of information.

The Sustainable Seas National Science Challenge, focussed on enhancing utilisation of New Zealand's marine resources within environmental, biological and socioeconomic constraints, had been running for eight years. The project was in its synthesis stage, aiming to draw together key findings, models, and methodologies to better inform ecosystem-based management across Aotearoa New Zealand. Estuaries, while lying between terrestrial, freshwater, and marine systems (all of which had separate National Science Challenges associated with them), had become a focus of Sustainable Seas. This was principally the case because a large proportion of the population lives around and uses estuaries, so they are areas where cumulative effects arise and non-monetary values are high. This synthesis stage of the Challenge and the request from the Minister presented a valuable opportunity to use and test the guidance and methods developed by the Challenge in real estuaries and their associated communities.

Background

Phase I of Sustainable Seas had projects focussed on non-monetary valuations (Sinner et al. 2018), presenting management actions occurring in Aotearoa New Zealand that were similar to ecosystem-based management (Le Heron et al. 2018), and gaining and retaining social license to operate from iwi/hapū and local communities (Newton et al. 2020). The research from these projects all highlighted the need for:

- participatory processes in terms of engagement
- involvement in modelling
- transparency in decision making.

For example, participation in building structure (components, links, outcomes, and actions) allow group discussions of commonality and differences in decision-making and risk perceptions. From this research, a guidance document was developed that highlighted the major ingredients that would lead to a successful participatory process. The research also highlighted:

- modelling methods that worked successfully in a participatory process
- the need to understand community uses and aspirations in-place
- trade-offs that should be considered (Davies et al. 2015).

The direct and indirect effects of many individual stressors on estuarine environments have been well documented. However, most estuaries are generally affected by more than one stressor – in fact a single activity can often generate more than one stressor (Thrush et al. 2021). Multiple stressors are concerning because combined impacts can be larger than individual ones, referred to as synergisms (Crain et al. 2008). Increasing evidence suggests that synergisms can create ecological surprises – a sudden, large and unexpected change in a species, ecosystem health, or ecosystem services from which recovery is difficult and expensive, if achievable (Toth 2008, Thrush et al. 2016).

Estuaries are also highly susceptible to multiple effects of climate change, including sea-level rise, elevated temperatures, storm frequency and intensity, and variations in freshwater inputs. For these reasons, managing activities that impact on estuaries needs to be forward looking and be based on methods able to incorporate cumulative effects assessments of current and potential stressors. A major finding of Sustainable Seas was the need to focus on ecological responses to stressor footprints rather than the stressor footprints themselves as ecological response footprints are not necessarily limited to the stressors' footprints or intensities (Low et al. 2023).

As uses or cumulative effects increase so too does the level of uncertainty. In such cases, skilled facilitators and structured participatory processes can support open discussion of competing arguments, beliefs, and values about risk and to evaluate management options amongst diverse stakeholders (Ingles et al. 2018). A method for expressing uncertainty explicitly and transparently that was found particularly useful by Challenge researchers were Bayesian Network models (Clark et al. 2022). This method can integrate non-standardised empirical data with varying degrees of certainty and using different data sources.

During the Sustainable Seas Challenge, ecological research undertaken in a national experiment on combined effects of turbidity and nutrient enrichment on estuarine functioning came to the attention of the Parliamentary Commission for the Environment (PCE). Following this, PCE commissioned the development of a Bayesian Network (BN) model to explore the effect of four ubiquitous stressors (nutrients, metals, suspended sediment, and sedimentation) on biological, physical, and chemical processes with significant consequences for ecosystem functions and ultimately on the condition of an estuary. The model was based on expert opinion-derived key qualitative relationships between environmental stressors and ecosystem response, including thresholds where the likelihood of a poor ecological outcome increased dramatically (Bulmer et al. 2022).

Here, we report on the expansion of the existing BN to include water residence time and marine heatwaves as stressor nodes. Furthermore, the updated model was applied in participatory processes with communities involved in three case study estuaries to inform discussions about management options and to help identify common values and aspirations held for New Zealand estuaries.

Methods

Three case studies

In late 2022, MfE officials developed a short-list of 20 estuaries based on information from the Department of Conversation estuaries hub and State of the Environmental monitoring trends from Land, Air, Water Aotearoa (LAWA) and Regional Council reports. In consultation with members of the local and regional government Coastal Special Interest Group (C-SIG) and researchers from Sustainable Seas, three estuaries were chosen based on the following criteria:

- Sufficient available data to undertake modelling
- Sufficient community interest and engagement
- Variation in estuary size, type, and location

The three estuaries selected were Whangateau (Northland), Kakanui (Otago) and Ahuriri (Hawke's Bay).

The Omaha River forms the western arm of Whangateau Harbour has two arms with freshwater delivered by the Omaha River and several small creeks (Birdsall, Coxhead, and Waikokopu). The catchment is relatively small but the harbour is one of the larger estuaries in the district with extensive intertidal flats. Fringing vegetation is present represented by saltmarsh, mangrove and seagrass. There has been considerable urban development around the estuary. As with many Auckland estuaries it was affected by high freshwater inputs from the cyclones of 2023.

The Kakanui River and its main tributaries (Kauru River, Island Stream, and Waiareka Creek) drain a large catchment of 894 km^2 into a relatively small estuary (0.27 km^2, <230 m wide). The high volume of freshwater makes the Kakanui a 'river-dominated' estuary, with very little intertidal area. While the estuary is recorded in the past as having a deep mouth with a jetty frequently used for coastal shipping, now the mouth is very shallow with an extensive gravel bar and becomes closed on some occasions. 77% of land within the catchment is used for agriculture and much of the water is used for extensive irrigation resulting in perceived problems during drought years. An attempt to alleviate this problem by returning water through the Waiareka Creek is perceived to exacerbate problems with nutrients and promote macroalgal growth in summer.

Ahuriri Estuary (or Te Whanganui-a-Orotū), located near Napier's central business district, is surrounded by urban, industrial, and farmed land. Uplift from the 1931 Napier Earthquake and subsequent human changes within the catchment have left the estuary considerably altered. These changes included diverting the Esk and Tutakurī rivers away from the estuary, as well as draining and reclaiming land in other areas. The estuary suffered from flooding during the cyclones of 2023.

Values and aspirations summary

A series of sperate meetings was held for each case study with interested stakeholders. From these meetings, MfE collected information on the values of various groups/people and their aspirations for the estuary. They summarised these initially into categories related to Water Quality, Natural Character/Biodiversity (which included fringing vegetation, birds and fish) and Community Initiatives/Connections. For Whangateau, developers were not always perceived as meeting their obligations in terms of sediment control and high-speed recreational crafts were seen as a problem. The use of the harbour as an educational resource was also important. For Kakanui, a category called "the estuary as a provider" was also suggested and the need to be able to restore the estuary while still meeting the needs of farmers was highlighted. For Ahuriri, industry and flushing were seen as problems and the need for enhanced communication between different groups wanting to improve the estuary was frequently mentioned.

A full examination of the estuaries and the values and aspirations of groups living around them will be provided by MfE reports. The initial brief summary we provide here was taken from the MfE summary provided back to the communities living around the estuaries.

Sustainable Seas guidance and tools

The initial summary of the values and aspirations revealed that for each estuary the natural character was important for groups living around it. Restoration was highlighted, although there were frequent differences in what restoration efforts should focus on. Differences between economic values (farmers, developers, industry) and other community values (recreation, fish, birds and the estuary as a place) were apparent. There were also frequently perceived differences between what councils were doing and what locals wanted. For these reasons, our selection of Sustainable Seas guidance and tools focussed on participatory processes, enabling community participation in decision-making and increasing communication. As each estuary had stressors that locals wanted to see alleviated, we suggested the use of a scenario modelling approach centred on the PCE Estuaries BN model, which could be adapted for local issues in a participatory process.

However, we did realise that there were limitations to the Estuaries BN as it was, which required scientific input. The model could not deal with variable freshwater inputs affecting flushing and residence time, which had been highlighted as a problem for all three estuaries. We also felt that bringing in a component that would allow for marine heatwaves would be useful. As such, the Sustainable Seas research team made additions to the Estuarine BN to address these gaps, incorporating two new stressor nodes: marine heatwaves and water residence time.

The Bayesian Network was created using Netica software (version 6.05, Norsys Software Corporation). Further details on the BN model building methodology, definitions and relationships can be found in (Bulmer et al. 2022). In brief, expert opinion was used to identify potential relationships between the new components of the model and the existing estuarine BN model and refine the conceptual map of the system (Figure 1). For marine heat waves (MHWS) and water residence, a literature review was also conducted to identify empirical data and refine relationships, as well as help define their respective units and definitions) (Figure 1; Table S1 below). For each modelling scenario, data on key stressor states (suspended sediment, mud content, nitrogen content and heavy metals) collated by MfE was used to inform model outputs.

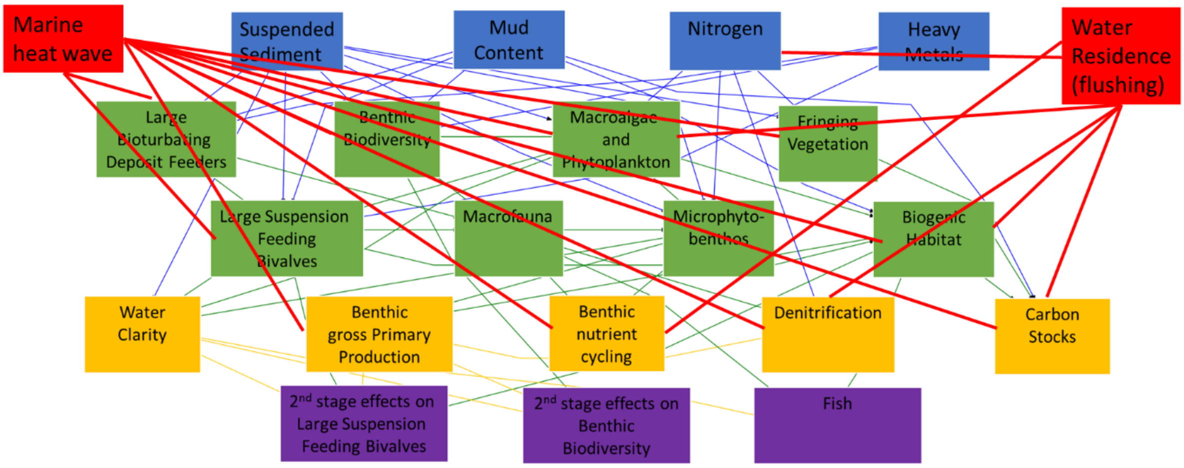

Figure 1: Conceptual map of the revised estuarine Bayes Net model, with additional stressor nodes (marine heat waves and water residence) and associated relationships coloured red. Remaining stressor components are coloured blue, ecological community nodes green, and key ecosystem function nodes orange. Second stage macrofaunal and fish components are coloured purple and are used to examine feedback effects on these important ecosystem components. All components collectively can be used to infer estuarine condition.

In addition, to assist with the participatory process at each of the regional meetings, additional elements of interest were added to the model (Bird abundance and biodiversity and Inanga (whitebait) abundance), specific to the values identified by locals, with preliminary relationships between other elements of the model identified by the project team (Figure 2). No literature review was undertaken to inform the relationships, instead these elements were added to demonstrate to communities the process of how BN models are generated and to stimulate further discussion regarding the values and aspirations of the community and associated management actions.

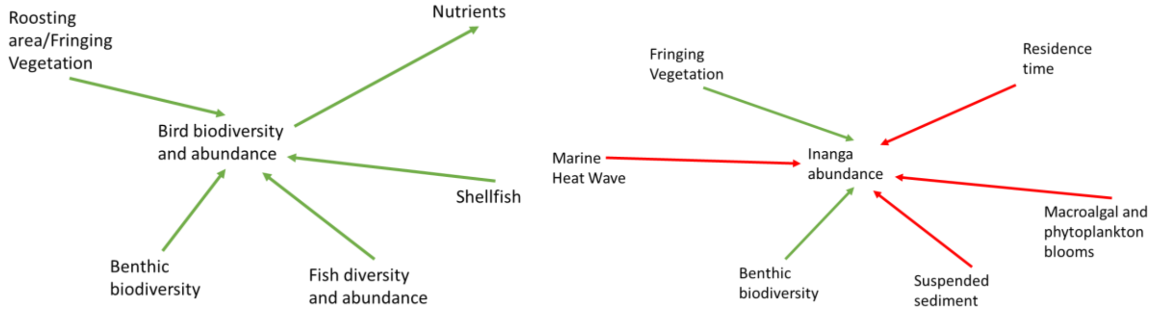

Figure 2: Conceptual map of the addition components (bird abundance and inanga abundance) showing relationship with existing components of the estuarine Bayesian Network model.

Based on the MfE summary of local values and aspirations, the following modifications and scenarios were run for each estuary:

Whangateau: Key concerns included climate change and extreme weather events (marine heatwaves a potential contributor to the historic loss of shellfish in the harbour), as well as declining bird abundance and biodiversity. Modelling scenarios included exploring:

1. present data/baseline conditions

2. how marine heatwaves may impact bird and shellfish abundance.

Kakanui: Key concerns and values included poor and variable water quantity and quality, resulting in long water residence times and macroalgal blooms, as well as poor inanga abundance. Modelling scenarios included exploring:

1. present data/baseline conditions

2. how changes in the water residence time might impact inanga and macroalgal/phytoplankton abundance

3. the impact of marine heatwave events in addition to changes in water residence time

4. the impact of water residence time/flushing.

Ahuriri: Key concerns included poor water quality and variable water quantity resulting in long water residence times in parts of the harbour, as well as declining bird abundance. Modelling scenarios included exploring:

1. present data/baseline conditions

2. the potential impact of extreme weather events (heatwaves plus increased input of sediment and nutrients to the estuary)

3. how improved catchment sediment retention may impact the estuary.

Results

Whangateau

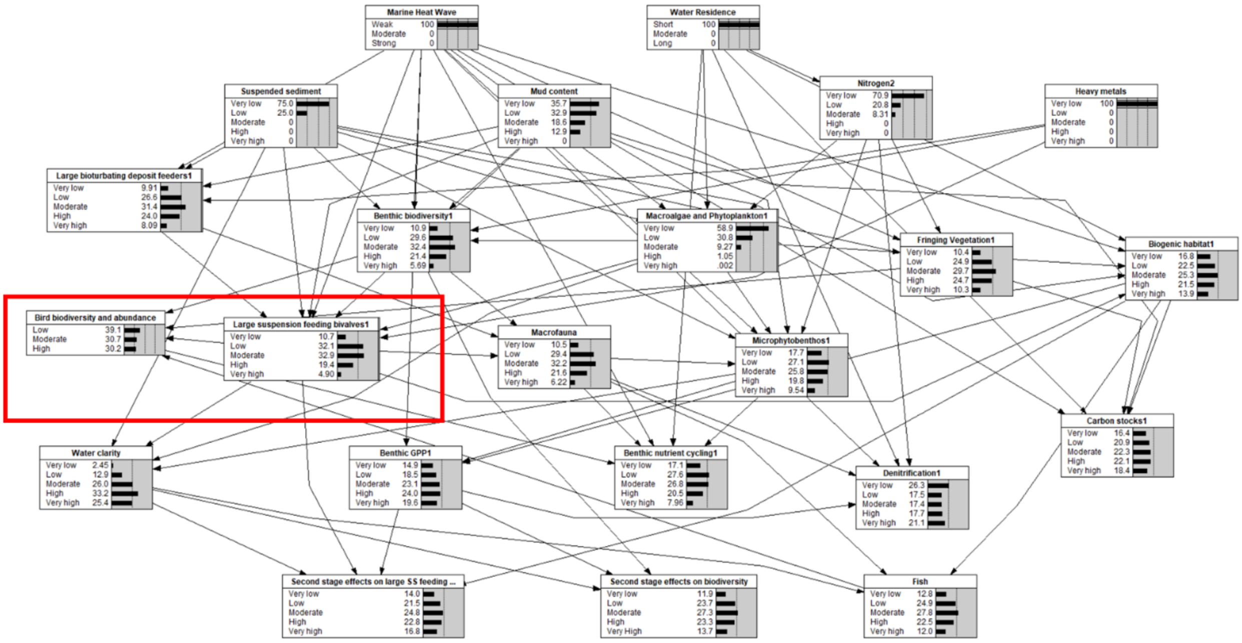

Figure 1: Whangateau Scenario 1. Baseline conditions. Bird biodiversity and abundance and large suspension feeding bivalves (shellfish) highlighted in the red box as elements of interest.

The model provides predictions for a range of ecosystem components of potential interest, informed by council datasets on the baseline status of key stressors (suspended sediment, mud, nitrogen and metals, marine heat wave and water residence) (Scenario 1; Figure 3). Focussing on bird abundance and biodiversity and large suspension feeding bivalves (shellfish), we can see that the model also makes predictions across a range of potential states (i.e. low or very low to through to high or very high). We can visualise these outputs as predicting that approximately a third of the harbour is likely to be occupied by a low density of birds, a third by moderate density of birds, and a third of the harbour by high densities of bird biodiversity and abundance. Similarly, we can infer that shellfish in the harbour are mostly to be at a moderate density, with some areas of very low and some areas of very high densities of shellfish.

Repeating the analysis with the same baseline conditions, yet under a strong marine heatwave event (Scenario 2; Figure 4), many of the components of the model were negatively affected. Focussing on birds and shellfish, the model predicted a 59% likelihood of low bird biodiversity and abundance and ~80% likelihood of low or very low shellfish abundance following a strong heatwave event.

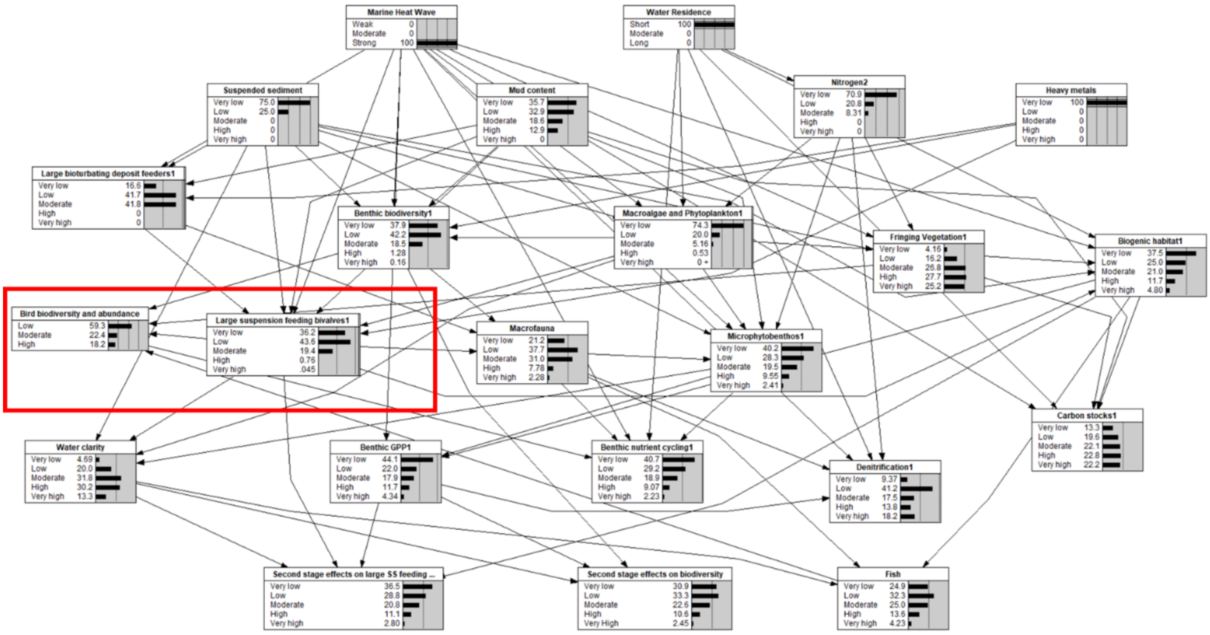

Figure 2: Whangateau Scenario 2. Baseline conditions with a strong marine heatwave event. Bird biodiversity and abundance and large suspension feeding bivalves (shellfish) highlighted in the red box as elements of interest.

Kakanui

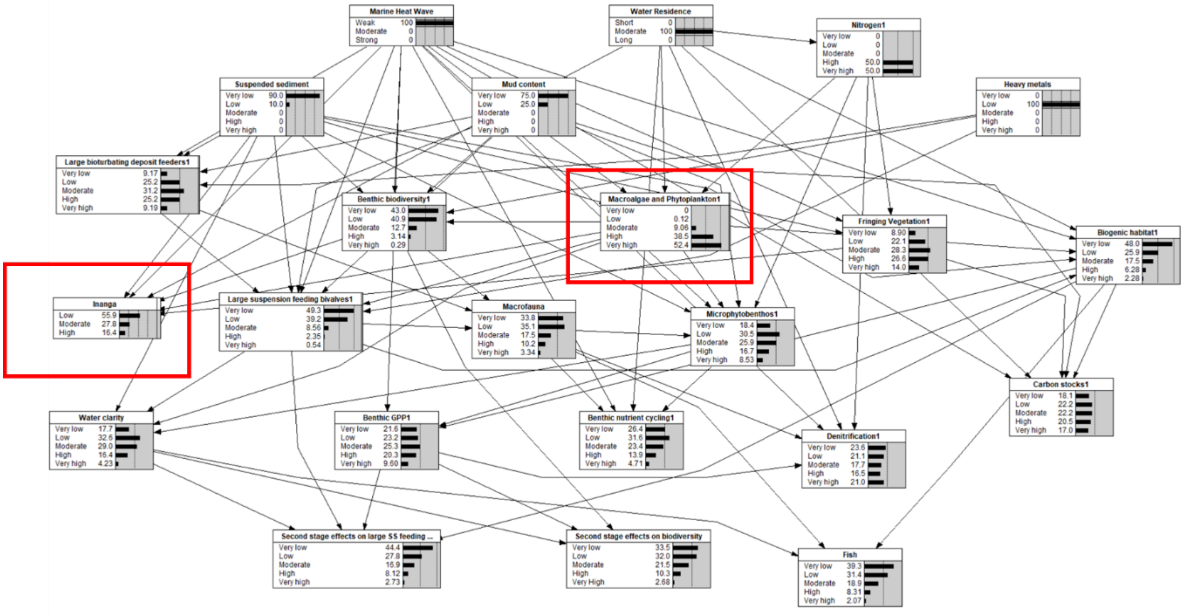

Figure 3: Kakanui Scenario 1. Baseline conditions. Inanga abundance and macroalgae and phytoplankton abundance highlighted in the red boxes as elements of interest.

For Kakanui estuary, under baseline conditions (Scenario 1; Figure 5), the model predicted that there was a greater than 50% likelihood of low inanga abundance. The model also predicted that macroalgae and phytoplankton was most likely to be high or very high.

When water residence time is increased to ‘long’ (Scenario 2; Figure 6), the model predicts that there was an 87% likelihood of low inanga abundance and a 99% likelihood of high or very high macroalgae and phytoplankton abundance. If this occurred during a strong marine heatwave event (Scenario 3; Figure 7), the model predicted that there was a 93% likelihood of low inanga abundance and an 82% likelihood of high or very high macroalgal abundance.

When the modelling is repeated with baseline conditions, yet under a scenario where water residence time was shortened (improved flushing) (Scenario 4; Figure 8), the model predicted a large improvement in inanga abundance, with the most likely state changed to high abundance (43%). However, macroalgae and phytoplankton remain elevated (77% high or very high).

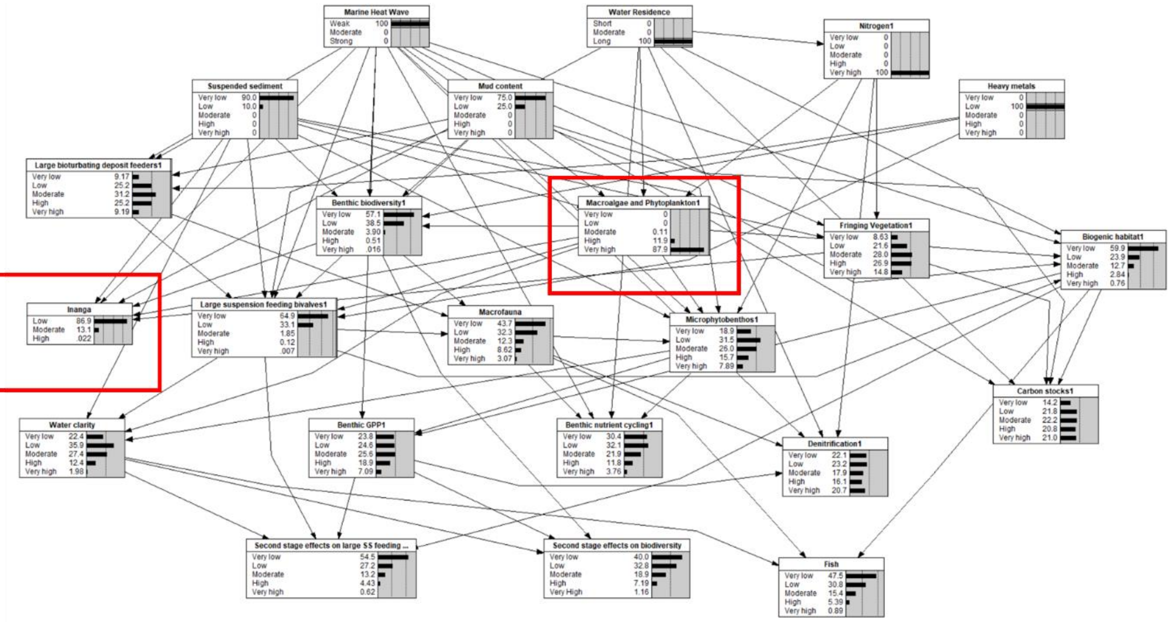

Figure 4: Kakanui Scenario 2. Baseline conditions with long water residence (low flushing). Inanga abundance and macroalgae and phytoplankton abundance highlighted in the red boxes as elements of interest.

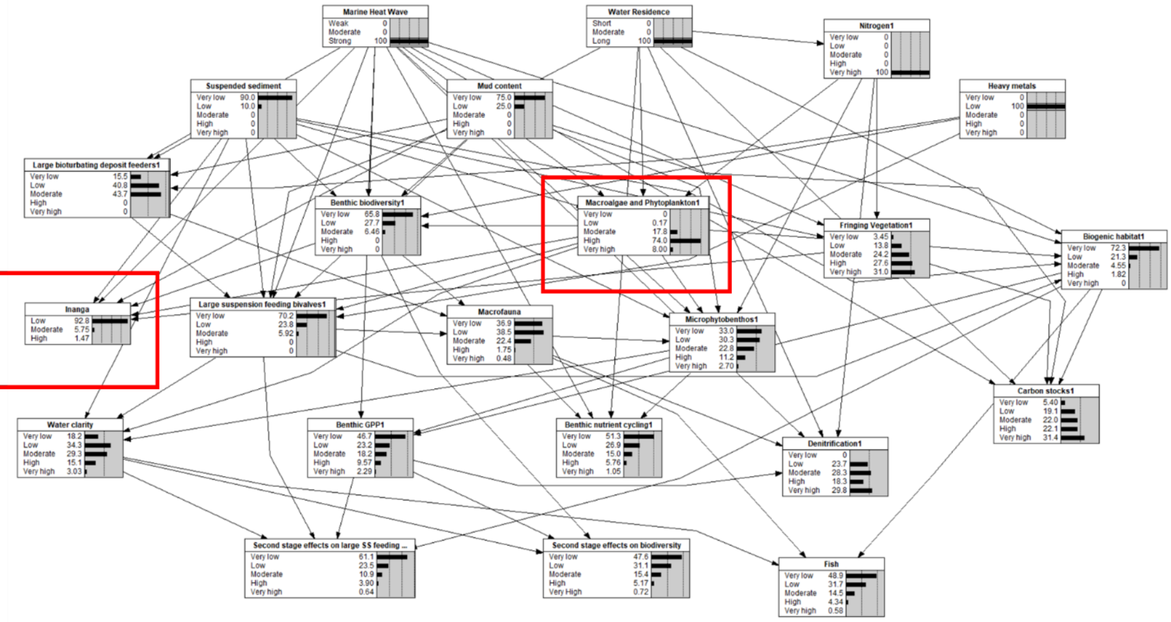

Figure 5: Kakanui Scenario 3. Baseline conditions with long water residence (low flushing) and strong marine heat wave. Inanga abundance and macroalgae and phytoplankton abundance highlighted in the red boxes as elements of interest.

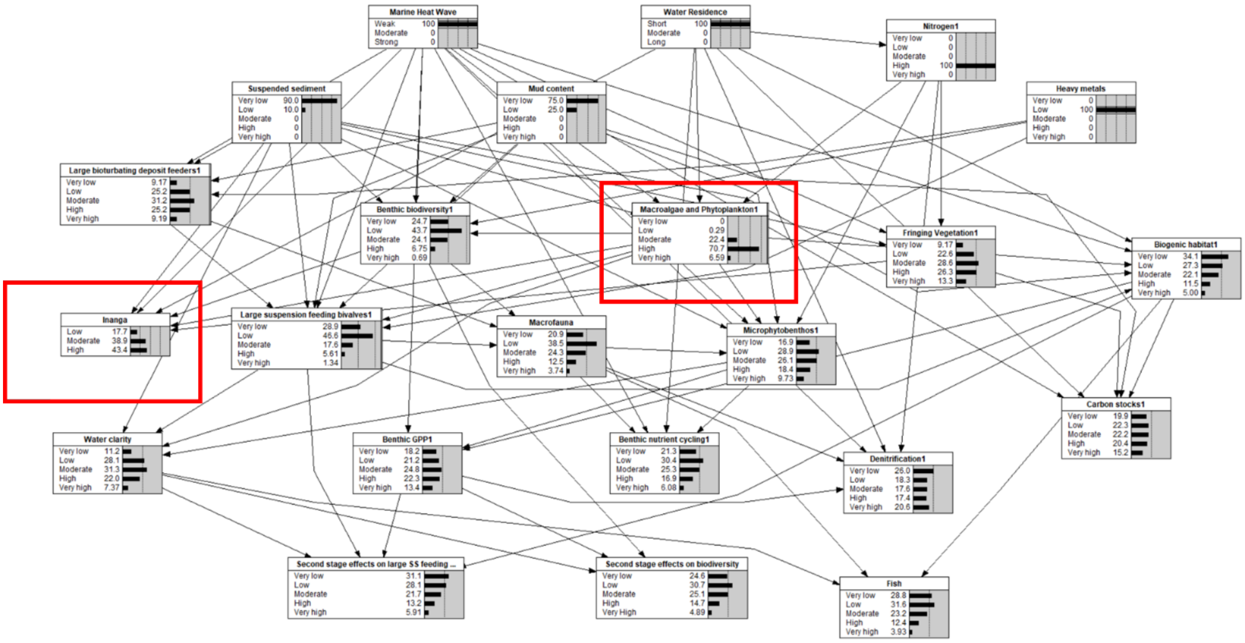

Figure 6: Kakanui Scenario 4. Baseline conditions with improve water residence (high flushing). Inanga abundance and macroalgae and phytoplankton abundance highlighted in the red boxes as elements of interest.

Ahuriri

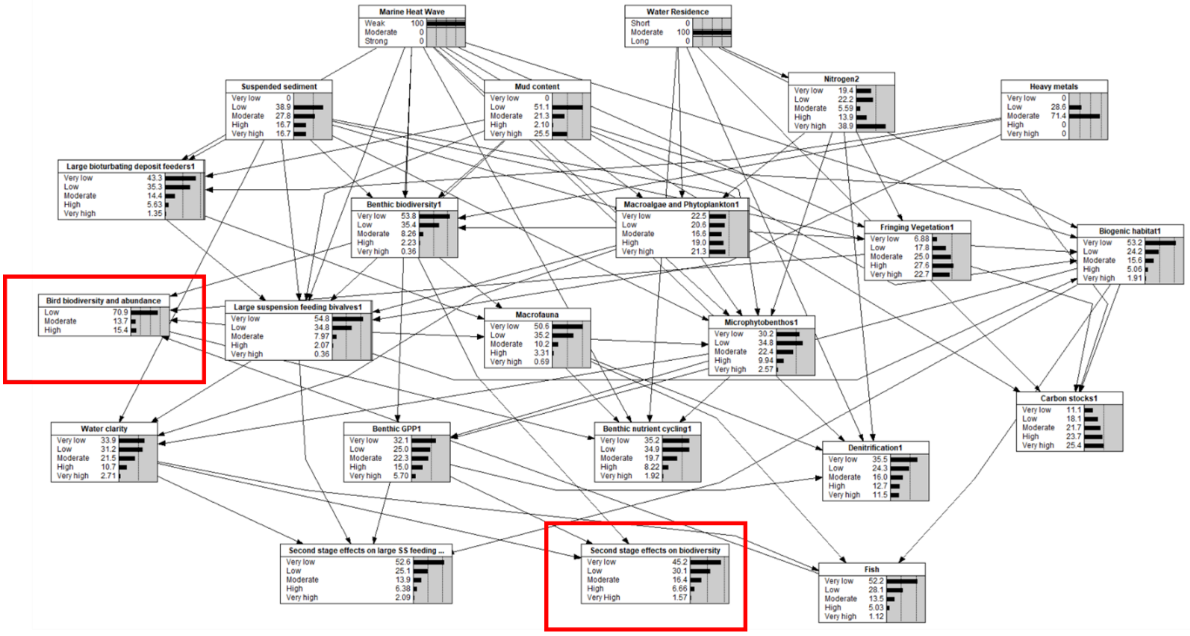

Figure 7: Ahuriri Scenario 1. Baseline conditions. Bird biodiversity and abundance and second stage effects on biodiversity highlighted in the red boxes as elements of interest.

For Ahuriri estuary under baseline conditions (Scenario 1; Figure 9), the model predicts that there was a 71% likelihood of low bird biodiversity and abundance. The model also predicts that second stage effects of biodiversity (benthic biodiversity) was most likely low (30%) or very low (45%), with only 8% likelihood of high or very high abundance.

Under an extreme weather event (where suspended sediment and mud is increased) and a strong heatwave (Scenario 2; Figure 10), the model predicted that there was a 74% likelihood of low bird abundance and an 88% likelihood of low benthic biodiversity.

When the modelling is repeated under a scenario where suspended sediment, mud, nitrogen, and metals were reduced due to improved retention of catchment sediment (Scenario 3; Figure 11), the likelihood of moderate to high bird abundance increased (43%). Similarly, the likelihood of high or very high benthic biodiversity increased (to 18%).

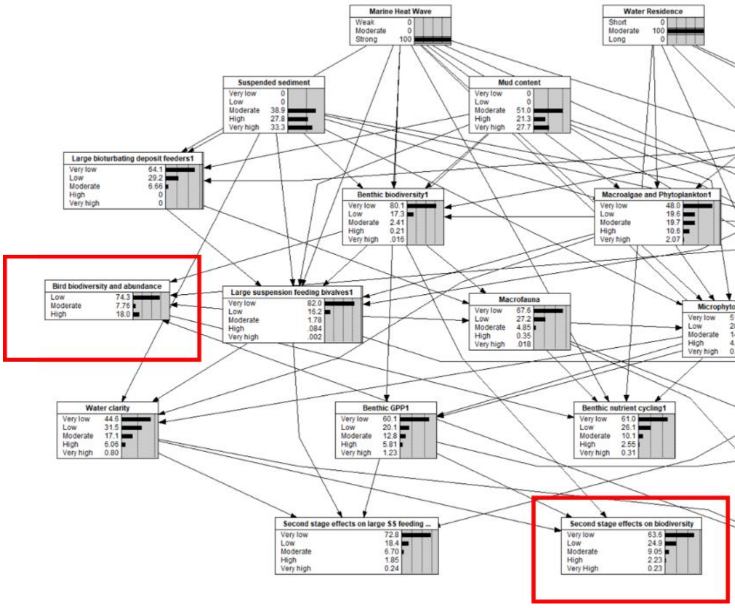

Figure 8: Ahuriri Scenario 2. Extreme weather event and strong marine heatwave. Bird biodiversity and abundance and second stage effects on biodiversity highlighted in the red boxes as elements of interest.

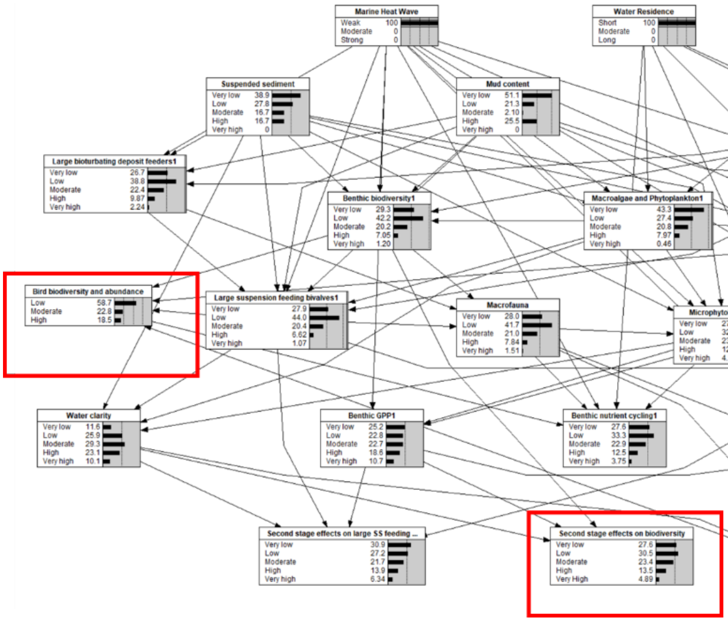

Figure 9 Ahuriri Scenario 3. Improved catchment sediment retention. bird biodiversity and abundance and second stage effects on biodiversity highlighted in the red boxes as elements of interest.

Discussion

Bayesian Network models are a probabilistic framework based on expert opinion and provide a robust and defensible tool that can be used to support decision-making, despite inherent complexity and uncertainty surrounding multiple stressor impacts. During this project, an existing Bayesian Network (BN) model was adapted using expert and community-based knowledge of key ecosystem dynamics (and associated values) to inform management decision-making. Model scenarios were developed for three case study estuaries, and results presented at workshops with local communities to help address management concerns and support participatory processes.

Key management concerns identified by the local communities for each of the case study estuaries included climate change and extreme weather events (marine heatwaves), and long residence times leading to poor water quantity and quality (e.g., macroalgal blooms), as well as impacts on birds, inanga and biodiversity. Based on this information, two new stressors (marine heatwaves and water residence time) and additional elements of interest, specific to the values identified by the locals (e.g., bird abundance and diversity, inanga abundance) were added to the existing model. A literature review was done to inform climate change nodes to enable associated scenarios to be run for each estuary (see Table S1).

Within the project, we did not have sufficient time to fully engage community members in the “bird” and “inanga” node extensions. Instead, we used these nodes as examples of the process that is undertaken to build and inform BN type models (e.g. by developing a conceptual map of the systems and informing relationships between nodes using expert/local knowledge and/or empirical data). Further development of the inanga and bird nodes could be done by community groups and council scientists and can be fine-tuned to be related to species of interest. For example, inanga were important in Kakanui estuary and have specific spawning habitat requirements. The “bird” group, however, covers a range of feeding, roosting, and reproductive modes, with different species likely to link in different ways into the BN. Some species are likely to have more influence on other components in the Bayesian Network, for example, affecting large bioturbating deposit-feeders, large suspension-feeding bivalves, and benthic biodiversity, which then have flow-on effects.

In the time since the Estuarine BN Model was first developed, methods to incorporate temporal feedback loops have become available (Chang et al. 2023). Our initial method of dealing with these was simple but effective and easily explained. Building a sequential temporal step model, while far from simple, is an elegant solution to deal with loops and flow-on effects. If this was dealt with within a participatory model building process, it would likely be easily accepted and would allow for better discussion around scenarios relating to desired outcomes with varying temporal durations.

Overall, our experience within these three case studies highlighted the ability of local communities to appreciate the underlying concepts and be willing to use participatory tools to question effectiveness of proposed management actions. This matches previous studies that have shown participatory modelling approaches to enhance cross-sector collaboration and improve social capacity to understand trade-offs associated with alternative scenarios (Davies et al. 2015) and to enable the development of common understanding of complex problems (Haag and Kaupenjohann 2001).

BN models have a further advantage over many other models in that they can be used to identify knowledge gaps. Adjustment of the model to mimic what might occur if those gaps were filled can be used to determine the extent to which the gaps affect the model and to prioritise gaps that need filling.

The process described here serves as an example of the value of engagement and collaboration between local communities, stakeholders, and management agencies in decision-making for marine management, and how tools such as BNs can support this process. Further and continued input from local communities will improve the outputs provided by decision support tools. Resources available on the Sustainable Seas website and Tohorā (an AI-powered research tool) provide further support to local communities and marine managers on what tools, guidance, and roadmaps may be available to empower decision-making that considers the values and aspirations of different groups.

Supplemental materials

TABLE S 1: FULL DESCRIPTION OF MODEL NODES, STATE RANGES AND THE DATA USED TO CREATE THE STATES.

Node	Unit and definition	State	Expert opinion informed by	Relationships
Marine heatwave (MHW)	Sea surface temperature (SST) (°C)		Field data and *in situ* temperature records, including 17 years of data from Auckland Council (Hewitt et al. 2016) and *in situ* monitoring data at Leigh and Portobello Marine Laboratories (Shears and Bowen 2017; Cook et al. 2022).	SST is strongly correlated (r = 0.80) between Leigh and Portobello marine laboratories with lag zero (Shears and Bowen 2017).
	MHW: A period when water temperatures are greater than the 90th percentile of a seasonally-varying climatology for a period of at least 5 days (Hobday et al. 2016).			Interannual variation in SST correlated with Southern Oscillation Index (SOI) (at lag zero) (Shears and Bowen 2017). Annual SST correlated with SOI (cooler temperatures during El Nino, negative SOI; warmer temperatures during positive SOI (La Nina)) (Shears and Bowen 2017).
	The Severity (S) of a heatwave describes the degree to which temperatures exceed the local climatology and is defined following the formula from Hobday et al. (2018): $S = \frac{T\text{ peak} - T\text{ clim doy}}{T\text{ 90th} - T\text{ clim doy}}$ • *T* peak is the maximum intensity of the marine heatwave (MHW) • *T* clim doy is the climatological temperature value for the day of the year (doy) • *T* 90th is the 90th percentile climatological temperature value for the day of the year (doy)	The Severity index classifies MHWs into four categories (Cook et al. 2022): • weak: $1 \leq S < 2$ • moderate: $(2 \leq S < 3)$ • strong: $(3 \leq S < 4)$ • extreme: $(S \geq 4)$	Climatology in the Cook et al. 2022 study was calculated between 1982-2010 using *in situ* temperature records from Leigh and Portobello marine labs.	MHWs occur slightly more frequently in summer (28-32%) than winter (18-22%) (Cook et al. 2022).

Water residence	Unit: d^{-1} How long a parcel of water takes to leave the body of water Calculated based on the relationship between an estuary's tidal prism and volume (Herman et al. 2007)	- Short: 0 – 3 d - Moderate: 3 – 6 d - Long: 6 – 10 d - Very long: 10+ d	Hydrographic model (Plew et al. 2018) informed by Coastal Explorer database of Hume et al. (2007) and Hume et al. (2016) for NZ estuaries. The Coastal Explorer database includes tidal prism and estuary volume needed to calculate water residence.	As the amount of river discharge goes up, the residence time goes down, regardless of whether the salinity changes or not.
	Tf = (V/Qb) where V is the mean volume of the water body and Qb the quantity of mixed water that leaves the bay on the ebb tide that did not enter the bay on the previous flood tide (m3 per tidal cycle).			
Large bioturbating deposit feeders	Number of individuals per 13 cm diameter core Large deposit feeders bioturbate the sediment, transporting organic material and changing oxygen gradients throughout the sediment column, influencing carbon and nutrient cycling processes.	- Very Low: Not present - Low: ≤1 - Moderate: 1 to <2 - High: 2 to 3 - Very High: >3	PC1.5 = $0.615 \times (X_{Cu}^{(500)}) + 0.528 \times (X_{Zn}^{(500)}) + 0.586 \times (X_{Pb}^{(500)})$ Field data, such as the Tipping Points dataset and publicly available regional council monitoring data (Thrush et al. 2003, Hewitt et al. 2009, Pratt et al. 2014). Time series data from Mahurangi Harbour in sandy and muddy sites (Hewitt et al. 2016).	*Heatwave* - Abundance of large bioturbators negative when *S* moderate to extreme (Hewitt et al. 2016). *Water residence* - Not applicable (unlikely to affect bioturbators directly; only indirectly through altered food resources and water quality).
	Examples include *Macomona liliana* (wedge shell), *Austrohelice crassa* (mud crab), *Hemiplax hirtipes* (mud crab), *Owenia petersenae* (tube worm), *Platynereis australis* (nereid polychaete worm).			
Large suspension feeding bivalves	Number of individuals per 13 cm diameter core Act as key species in estuarine ecosystems by filtering the water column, influencing seafloor/water column carbon and nitrogen cycling, and providing an important food	- Very Low: <1 - Low: 1 to <10 - Moderate: 10 to <20 - High: 20 to 40 - Very High: >40	Field data, such as the Tipping Points dataset and publicly available regional council monitoring data (Thrush et al. 2003, Hewitt et al. 2009, Pratt et al. 2014). Time series data from Mahurangi Harbour in sandy and muddy sites (Hewitt et al. 2016).	*Heatwave* - Abundance negative when *S* high in sandy sites (Hewitt et al. 2016) [interaction with %mud node]. *Heatwave* - Abundance positive when *S* moderate to high in muddy sites

	source for higher trophic levels, including humans.			(Hewitt et al. 2016) [interaction with %mud node]. *Water residence* - Not applicable (unlikely to affect suspension feeders directly; only indirectly through altered food resources and water quality).
	Examples *Austrovenus stutchburyi* (cockles), *Paphies australis* (pipi), *Pectinidae* (scallops), *Atrina zealandica* (horse mussel), *Perna canaliculus* (green shell mussel).			
Benthic biodiversity	Number of species per 13 cm diameter core	- Very Low: <10 - Low: 10 to <15 - Moderate: 15 to <20 - High: 20 to 25 - Very High: >25	Field data, such as the Tipping Points dataset and publicly available regional council monitoring data (Thrush et al. 2003, Hewitt et al. 2009, Pratt et al. 2014). Time series data from Mahurangi Harbour in sandy and muddy sites (Hewitt et al. 2016).	*Heatwave* - Taxon richness negative when *S* strong to extreme. Further the effect of elevated temperature on diversity was more pronounced at muddy site (Hewitt et al. 2016) [possible interaction with %mud node]. *Water residence* - Not applicable (unlikely to affect diversity directly; only indirectly through altered water quality).
Macrofauna	Intermediate node Intermediate node which combines *large bioturbating deposit feeders*, *Large Suspension Feeding Bivalves*, and *Benthic Biodiversity* nodes via a simple weighted sum.	Intermediate node	Intermediate node used to reduce the number of parent nodes (and their complexity of relationships) feeding into child nodes throughout the model.	*Large bioturbating deposit feeders* – Positive *Large suspension feeding bivalves* – Positive *Benthic biodiversity* – Positive *Suspended sediment* – Negative
Microphyto benthos	Chlorophyll *a* (µg g^{-1} sediment) Microphytobenthos consists of unicellular eukaryotic algae and cyanobacteria that	- Very Low: <5 - Low: 5 to <12 - Moderate:12 to <20 - High: 20 to 30 - Very High: >30	Field data, such as the Tipping Points dataset and publicly available regional council monitoring data (Thrush et al. 2012).	*Heatwave* - negative effect on MPB biomass and change in community composition at strong and extreme *S* (Cataxana et al. 2015).

	grow within the upper several millimetres of sediments. Chlorophyll *a* is a pigment that can be measured by standard methods as a proxy for microphytobenthos abundance.		Dutch Wadden Sea correlation study on multi-year temperature records and sediment chl-a concentration (de Jonge et al. 2012); microcosm experiment on elevated temperature and carbon dioxide levels on MPB (Cataxana et al. 2015).	*Heatwave* - positive effect on MPB biomass at weak *S (*de Jonge et al. 2012). *Water residence* - Not applicable (unlikely to affect MPB directly; only indirectly through changes in nutrient concentrations).
Macroalgae (nuisance) and phytoplankton	*Macroalgae:* Algal cover (%) and wet weight (g) per area (m^2) Nuisance Macroalgae (e.g., *Ulva* spp./sea lettuce and *Gracilaria* spp./red algae in soft-sediment areas).	Due to similar model dynamics and to reduce model complexity, macroalgae and phytoplankton nodes combined. State based off the higher of the two values for nuisance macroalgae or phytoplankton. *Macroalgae:* • Very Low: Algal cover <2.5% and low biomass (<25 g/m^2 wet weight) of opportunistic macroalgal blooms. • Low: Algal cover 2.5-<5% and low biomass (25 to <50 g/m^2 wet weight) of opportunistic macroalgal blooms. • Moderate: Limited macroalgal cover (5– 20%) and low biomass (50 to <200 g/m^2 wet weight) of opportunistic macroalgal blooms. • High: Persistent, high % macroalgal cover (25–50%) and/or biomass (200	Nuisance macroalgae informed by outputs from a modified version of the estuary trophic index tool (Plew et al. 2019). Laboratory experiment (Green-Gavrielidis and Thornber 2022).	*Heatwave* - positive growth at weak to moderate S but negative at severe and extreme S (e.g., for Ulva: Green-Gavrielidis and Thornber 2022). *Water residence* - negative relationship of macroalgal biomass and short water residence time (Valiela et al. 1997).

	Phytoplankton: Chlorophyll *a* (mg l^{-1} water) Phytoplankton are microscopic algae within the water column. Chlorophyll *a* is a pigment that can be measured by standard methods as a proxy for phytoplankton abundance.	to 1000 g/m^2 wet weight), often with entrainment in sediment. • Very High: Persistent very high % macroalgal cover (>75%) and/or biomass (>1000 g/m^2 wet weight), with entrainment in sediment. *Phytoplankton:* • Very Low:<0.001 • Low 0.001 to <0.0015 • Moderate: 0.0015 to <0.0028 • High: 0.0028 to 0.0042 • Very High: >0.0042	Water column chlorophyll *a* concentrations informed from a nationwide summary of water quality data across New Zealand (Dudley et al. 2017). Laboratory experiment on heatwaves and turbidity effects (Remy et al. 2017).	*Heatwave* - negative effect on phytoplankton biomass (as biovolume) (Remy et al. 2017). *Water residence* - longer water residence may favour increases in phytoplankton over macroalgae in N replete conditions due to cell division time of phytoplankton (Valiela et al 1997). *Water residence* - negative relationship with chl-a phytoplankton (rapid flushing results in low chl-a) (Gall et al, 2019); flushing also affects biodiversity of phytoplankton (Ferreira et al. 2005).
Fringing vegetation	Cover (% of estuary) of vegetation such as mangroves and saltmarsh, found in the upper intertidal areas of estuaries	• Very Low: Little to no fringing vegetation present. • Low: Low coverage of fringing vegetation. No recent changes in the extent of fringing vegetation. • Moderate: Moderate cover of fringing vegetation. Little evidence of expansion into other intertidal habitats	Informed primarily based on mangrove data as comparably little data exists on saltmarsh (Morrisey et al. 2010).	*Heatwave* - weak to moderate S will increase fringing vegetation. Warming will favour mangrove expansion in North Island, NZ. *Water residence* - no relevant studies found for direct impacts [potentially water residence may affect fringing vegetation through altered sedimentation].

		• High: High cover of fringing vegetation. Moderate loss of other intertidal habitats due to estuarine infilling/expansion of fringing vegetation. • Very High: Very high cover of fringing vegetation. Significant reduction in other intertidal habitats due to estuarine infilling/expansion of fringing vegetation.		
Biogenic habitat	Coverage (%) and composition of biogenic habitat Biogenic habitats are defined as those created by living plants (e.g., kelp forests, seagrass meadows, mangrove forests) or animals (e.g., bryozoan thickets, sponge garden, tubeworm fields) where their three-dimension structure provides shelter, protection and resources for other marine flora and fauna.	• Very Low: Little to no biogenic habitat present. • Low: Low coverage of biogenic habitat, dominated by more stress tolerant habitats such as intertidal seagrass and tubeworm mounds. • Moderate: Moderate cover of biogenic habitat, including small areas of kelp forests or shellfish beds. • High: High cover of diverse biogenic habitats. • Very High: Very high cover of biogenic habitats including very high coverage of subtidal seagrass, kelp and shellfish beds.	Informed by a national review of biogenic habitat in New Zealand (Anderson et al. 2019).	*Heatwave* - Negative effect on kelp forests (Tait et al. 2021; Thomsen et al, 2019), which is exacerbated with low water clarity (Tait et al 2021) [interaction with water clarity node]; negative for sponges (Bell et al. 2023); Positive on large suspension feeding bivalves (Hewitt et al. 2016). *Water residence* - Negative (inverse) relationship (faster water residence brings more food to bivalves, sponges etc).
Fish	Abundance of fish	• Very Low: No fish present • Low: Low abundance of fish present. Unlikely to be observed in the area.	Informed by a national review of habitats and areas of particular significance for coastal finfish fisheries (Morrison et al. 2014).	Not applicable to Heatwaves. Not applicable to Water residence other than if the estuary is closed there is no connection to the open

		• Moderate: Moderate abundance of fish present. • High: High abundance of fish present. Very High: Very High abundance of fish present.		coast for fish that move between the estuary and the coast.
Water clarity	Maximum depth (m) to which a black and white (secchi) disk can be seen through the water with the naked eye. Water clarity is a measure of visual penetration through the water column. There are many alternative ways to assess clarity or its opposite (turbidity).	• Very low: Able to routinely see <0.5 m through water column • Low: Able to see routinely 0.5 to <0.8 m through water column • Moderate: Able to routinely see 0.8 to <1.3 m through water column • High: Able to routinely see 1.3 to 2.5 m through water column • Very High: Able to routinely see >2.5 m through water column	Informed by Secchi depth measurements from a nationwide summary of water quality data across New Zealand (Dudley et al. 2017).	Not applicable to *Heatwaves.* *Water residence* - water clarity in NZ estuaries often related to total suspended solids (TSS) (Gall et al. 2019); TSS concentration is likely greater in areas with long water residence
Carbon stocks/storage	% organic material in surface sediments	• Very Low: <1% • Low: 1 to <2% • Moderate: 2 to <3% • High: 3 to 4% • Very High: >4%	Mesocosm experiment (Kauppi and Villnas 2022)	*Heatwaves* - negative C storage when *S* is moderate (increased remineralisation) but positive C storage at strong and extreme *S* (reduced remineralisation) (Kauppi and Villnas 2022).
	Sediment organic matter content (measured as the percent by weight of combustible organic material in the sediment) is a proxy for the amount of organic carbon-based matter present in the sediment.			*Water residence* - short residence time would likely lead to greater movement of organic carbon out of the estuary and lower C storage, whereas long residence time will likely lead to more settlement of SS and greater C storage in estuarine sediments.

Benthic Gross Primary Producton (GPP)	μmol O_2 m^{-2} hr^{-1} Benthic GPP is the gross production of oxygen by photosynthetically active microphytobenthic communities. Calculated in the field using benthic chambers, based on the difference in O_2 flux from chambers exposed to sunlight (where photosynthesis can occur) and dark (where only respiration occurs).	- Very Low: Strongly net heterotrophic (benthic oxygen consumption >235 μmol m^{-2} hr^{-1} more than oxygen produced). Potential for hypoxia/anoxia, shallow redox depth, etc. - Low: Weakly autotrophic (benthic oxygen production -235 to 650 μmol m^{-2} hr^{-1} more than oxygen consumed. - Moderate: Moderately autotrophic (benthic oxygen production 650 to 1900 μmol m^{-2} hr^{-1} more than oxygen consumed. - High: Highly autotrophic (benthic oxygen production >1900 to 3000 μmol m^{-2} hr^{-1} more than oxygen produced. - Very High: Very highly autotrophic (benthic oxygen production >3000 μmol m^{-2} hr^{-1} more than oxygen consumed.	States determined based on expert opinion and field data, such as the Tipping Points dataset and other benthic chamber experiments (Pratt et al. 2014a).	*Heatwaves* - Positive at S weak and moderate; negative at S strong and extreme (Vieira et al. 2013). *Water residence* - not applicable directly; indirectly residence affects sediment grain size and MPB biomass is often lower in sandy sediments compared to fine muds (de Jonge and de Jonge 1995), which in turn, can influence benthic GPP rates.
Denitrification	μmol N_2 m^{-2} hr^{-1} Denitrification is a microbially facilitated process where nitrate is reduced and ultimately produces molecular nitrogen through a series of intermediate gaseous nitrogen oxide products.	- Very Low: Little to no net efflux of N_2 gas out of the sediment (≤0 μmol N_2 m^{-2} hr^{-1}) - Low: Low net efflux of N_2 gas out of the sediments (0-<37 μmol N_2 m^{-2} hr^{-1}) - Moderate: Moderate net efflux of N_2 gas out of the sediments (37-<100 μmol N_2 m^{-2} hr^{-1})	States determined based on expert opinion and field data, such as the Tipping Points dataset (Peterson 2018).	*Heatwaves* - Positive (Gongol and Savage 2006; Gervasio et al. 2022); a doubling in denitrification rates with a 3 degree Celsius rise in temperature (Veraart et al. 2011). *Water residence* - Positive (Seitzinger et al. 2006; Dettmann 2001).

		• High: High net efflux of N_2 gas out of the sediments (100-200 µmol N_2 m^{-2} hr^{-1}) • Very High: Very high net efflux of N_2 gas out of the sediments (>200 µmol N_2 m^{-2} hr^{-1})		
Benthic nutrient cycling	µmol NH_4^+ m^{-2} hr^{-1} Sediment nutrient cycling is defined as the rate of photosynthetic uptake of NH_4^+ by microphytobenthic activity (i.e., how much ammonia released from the sediment is being intercepted and cycled by microphytobenthos rather than released to the water column).	• Very Low: Little to no photosynthetic uptake of NH_4^+ by microphytobenthic activity (<0 NH_4^+ µmol m^{-2} hr^{-1}). • Low: Low photosynthetic uptake of NH_4^+ by microphytobenthic activity (0 to <10 NH_4^+ µmol m^{-2} hr^{-1}). • Moderate: Moderate photosynthetic uptake of NH_4^+ by microphytobenthic activity (10 to <50 NH_4^+ µmol m^{-2} hr^{-1}). • High: High photosynthetic uptake of NH_4^+ by microphytobenthic activity (50 to <180 NH_4^+ µmol m^{-2} hr^{-1}). • Very High: Very high photosynthetic uptake of NH_4^+ by microphytobenthic activity (>180 NH_4^+ µmol m^{-2} hr^{-1}).	States determined by based on expert opinion and field data, such as the Tipping Points dataset and other benthic chamber experiments (Pratt et al. 2014). Mesocosm experiments (Dolbeth et al. 2021; Kauppi and Villnas 2022).	*Heatwave* - Positive; Increase in bioturbation rates and release of nutrients from sediments in heatwave conditions (Dolbeth et al. 2021); while another study found no significant change in bioturbation rates at moderate and high heatwave conditions relative to in situ (Kauppi and Villnas 2022). *Heatwave* - increase in sediment oxygen consumption (by macrofauna and microbes) at *S* moderate levels, and decrease at severe and extreme levels (halving at severe) (Kauppi & Villnas 2022). *Water residence* - inversely related to ammonia uptake by MPB (Hopkinson et al. 1999).

References

Bell, J.J., Smith, R.O., Micaroni, V., et al. 2023. Marine heat waves drive bleaching and necrosis of temperate sponges. Current Biology 33:158–163.

Bulmer, R., F. Stephenson, A. Lohrer, C. Lundquist, A. Madarasz-Smith, C. Pilditch, S. Thrush, and J. Hewitt. 2022. Informing the management of multiple stressors on estuarine ecosystems using an expert-based Bayesian Network model. Journal of Environmental Management 301:113576.

Cartaxana, P., Vieira, S., Ribeiro, L. et al. 2015. Effects of elevated tempertaure and CO2 on intertidal microphytobenthos. BMC Ecology 15:10

Chang, J., Y. Bai, J. Xue, L. Gong, F. Zeng, H. Sun, Y. Hu, H. Huang, and Y. Ma. 2023. Dynamic Bayesian networks with application in environmental modeling and management: A review. Environmental Modelling & Software 170:105835.

Clark, D. E., R. V. Gladstone-Gallagher, J. E. Hewitt, F. Stephenson, and J. I. Ellis. 2022. Risk assessment for marine ecosystem-based management (EBM). Conservation Science and Practice 4:e12636.

Cook, F., Smith, R.O., Roughan, M., Cullen, N.J., Shears, N. and Bowen, M. 2022. Marine heatwaves in shallow coastal ecosystems are coupled with the atmosphere: Insights from half a century of daily in situ temperature records. Frontiers in Climate 4:1012022.

Crain, C. M., K. Kroeker, and B. S. Halpern. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters 11:1304-1315.

Davies, K. K., K. T. Fisher, M. E. Dickson, S. F. Thrush, and R. Le Heron. 2015. Improving ecosystem service frameworks to address wicked problems. Ecology and Society 20.

de Jonge, V.N., de Boer, W.F, de Jong, D.J. And Brauer, V.S. 2012. Long-term mean annual microphytobenthos chlorophyll a variation correlates with air temperature. Marine Ecology Progress Series 468:43-56.

Dettmann, E.H. 2001. Effect of wter residence time in annual export and denitrification of nitrogen in estuaries: A model analysis. Estuaries 24:481-490.

Dolbeth, M., Babe, O., Costa, D.A., Mucha, A.P., Cardoso, P.G. and Arenas, F. 2021. Benthic estuarine communities' contribution to bioturbation under the experimental effect of marine heatwaves. Scientific Reports 11:1-11. Dudley, B., J. Zeldis, and O. Burge. 2017. New Zealand coastal water quality assessment. Prepared for Ministry for the Environment. NIWA CLIENT REPORT No: 2016093CH.

Ferreira, J.G., Wolff, W.J., Simas, T.C. and Bricker, S.B. 2005. Does biodiversity of estuarine phytoplankton depend on hydrology? Ecologial Modelling 187:513-523.

Gall, M., Swales, A., Davies-Collet, R. and Bremner, D. 2019. Predicting visual clarity and light penetration from water quality measures in New Zealand estuaries. Estuarine, Coastal and Shelf Science 219:429-443.

Gervasio, M.P., Soana, E., Granata, T., Colombo, D. and Castaldelli, G. 2022. An unexpected negative feedback between climate change and eutrophication: higher temperatures increase denitrification and buffer nitrogen loads in the Po River (Northern Italy). Environmental Research Letters 17: 084031

Graba-Landry, A., Hoey, A.S., Matley, J.K., Sheppard-Brennand, H., Poore, A.G.B., Byrne, M. and Dworjanyn, S.A.2018. Ocean warming has greater and more consistent negative effects than ocean acidification on the growth and health of subtropical macroagale. Marine Ecology Progress Series 595:55-69.

Green-Gavrielidis, L.A. And Thornber, C.S. 2022. Will climate change enhance algal blooms? The individual and interactive effects of temperature and rain on the macrolagae Ulva. Estuaries and Coasts 45:1688-1700.

Hewitt, J.E., Ellis, J.I. and Thrush, S.F. 2016. Multiple stressors, nonlinear effects and the implications of climate change impacts on marine coastal ecosystems. Global Change Biology 22:2665-2675.

Hewitt, J. E., M. J. Anderson, C. W. Hickey, S. Kelly, and S. F. Thrush. 2009. Enhancing the ecological significance of sediment contamination guidelines through integration with community analysis. Environmental Science & Technology 43:2118-2123.

Hobday A.J., Alexander L.V., Perkins, S.E., et al. 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography 141: 227-238.

Hobday , A.J., Oliver, E.C., Gupta, A.S., et al. 2018. Categorizing and naming marine heatwaves. Oceanography 31:162-173.

Hume, T.M., T. Snelder, M. Weatherhead, and R. Liefting. 2007. A controlling factor approach to estuary classification. Ocean & Coastal Management 50 (11-12): 905–929.

Hume, T., P. Gerbeaux, D. Hart, H. Kettles, and D. Neale. 2016. A classification of New Zealand's coastal hydrosystems, 120. Hamilton:Ministry of the Environment http://www.mfe.govt.nz/publications/marine/classification-of-new-zealands-coastal-hydrosystems.Haag, D., and M. Kaupenjohann. 2001. Parameters, prediction, post-normal science and the precautionary principle—a roadmap for modelling for decision-making. Ecological Modelling 144:45-60.

Kauppi L, and Villnäs A. 2022. Marine heatwaves of differing intensities lead to distinct patterns in seafloor functioning. Proceedings of the Royal Society B 289: 20221159.

Le Heron, R., P. Blackett, J. Logie, D. Hikuroa, E. Le Heron, A. Greenaway, B. Glavovic, K. Davies, W. Allen, and C. Lundquist. 2018. Participatory processes for implementation in aotearoa new zealand’s multi-use/user marine spaces?: Unacknowledged and unaddressed issues. Pages 111-130 Towards Coastal Resilience and Sustainability. Routledge.

Low, J. M. L., R. V. Gladstone-Gallagher, J. E. Hewitt, C. A. Pilditch, J. I. Ellis, and S. F. Thrush. 2023. Using Ecosystem Response Footprints to Guide Environmental Management Priorities. Ecosystem Health and Sustainability 9:0115.

Morrisey, D. J., A. Swales, S. Dittmann, M. Morrison, C. Lovelock, and C. Beard. 2010. The ecology and management of temperate mangroves. Pages 43-160 Oceanography and Marine Biology. CRC Press.

Newton, M. J., T. A. Farrelly, and J. Sinner. 2020. Discourse, agency, and social license to operate in New Zealand's marine economy. Ecology & Society 25.

Plew, D.R., Zeldis, J.R., Shankar, U. And Elliott, A.H. 2018. Using simple dilution models to predict New Zealand estuarine water quality. Estuaries and Coasts 41:1643-1659.

Plew, D., B. Dudley, U. Shankar, and J. Zeldis. 2019. Assessment of the eutrophication susceptibility of New Zealand Estuaries. Prepared for Ministry for the Environment. NIWA client report No: 2018206CH. https://www.mfe.govt.nz/sites/default/files/media/Fresh%20water/assessment-of-eutrophication-susceptibility-in-nz-estauries.pdf.

Pratt, D. R., A. M. Lohrer, C. A. Pilditch, and S. F. J. E. Thrush. 2014. Changes in Ecosystem Function Across Sedimentary Gradients in Estuaries. Ecosystems 17:182-194.

Remy, M., Hillebrand, H. And Floder, S. 2017. Stability of marine phytoplankton communities facing stress related to global change: Interactive effects of heat waves and turbidity. Journal of Experimental Marine Biology and Ecology 497:219-229.

Seitzinger, S., Harrison, J.A., Bohlke, J.K., et. Al. 2006. Denitrification across landscapes and waterscapes: A synthesis. Ecological Applications 16:2064-2090.

Shears, N. and Bowen, M.M. 2017. Half a century of coastal temperature records reveal complex warming trends in western boundary currents. Scientific Reports 7:14527.

Sinner, J., Šunde, C., Giorgetti, A., Takai, M., Stephenson, J., Awatere, S., Glavovic, B., Hewitt, J., Lewis, N. 2018. Exploring valuation frameworks and principles for sustainable seas. Cawthron Institute Report No. 3234

Tait, L., Thoral, F., Pinkerton, M.H., Thomsen, M.S. And Schiel, D.R. 2021. Loss of giant kelp, Macrocystis pyrifera, drien by marine heatwaves and exacerbated by poor water clarity in New Zealand. Frontiers in Marine Science 8:721087.

Thomsen, M.S., Mondardin, L., Alestra, T., Gerrity, S., Tait, L., South, P.M., Lilley, S.A., and Schiel, D.R, 2019. Local extinction of bull kelp (Durvillaea spp.) due to a marine heatwave. Frontiers in Marine Science 6: 84.Thrush, S., J. E. Hewitt, A. Norkko, P. E. Nicholls, G. A. Funnell, and J. Ellis. 2003. Habitat change in estuaries: predicting broad-scale responses of intertidal macrofauna to sediment mud content. Marine Ecology Progress Series 263:101-112.

Toth, F. L. 2008. Chapter Eight Dealing with Surprises in Environmental Scenarios. Developments in Integrated Environmental Assessment 2:169-193.

Thrush, S. F., J. E. Hewitt, and A. M. Lohrer. 2012. Interaction networks in coastal soft-sediments highlight the potential for change in ecological resilience. Ecological Applications 22:1213-1223.

Thrush, S. F., N. Lewis, R. Le Heron, K. T. Fisher, C. J. Lundquist, and J. Hewitt. 2016. Addressing surprise and uncertain futures in marine science, marine governance, and society. Ecology and Society.

Thrush, S., J. Hewitt, C. Pilditch, and A. Norkko. 2021. Ecology of coastal marine sediments: form, function, and change in the Anthropocene. Oxford University Press.

Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D. And Foreman, K. 1997. Macroalgal blooms in shallow estuaries: Controls and ecophysiological and ecosystem consequences. Limnology and Oceanpgraphy 42:1105-1118.

Veraart, A.J., de Klein, J.J.M. and Scheffer, M. 2011. Warming can boost denitrification disproportionately due to altered oxygen dynamics. PLoS ONE 6:e18508.

Vieira, S., Ribiero, L., Marques da Silva, J. And Cartaxana, P. 2013. Effects of short-term changes in sediment temperature on the photosynthesis of two intertidal microphytobenthos communities. Estuarine, Coastal and Shelf Science 119:112-118.