Exploring the impact of multiple stressors on estuarine ecosystems using a Bayesian Network model

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Contents

Tables

Figures

Executive summary

New Zealand estuaries face multiple interacting stressors at a range of scales. These include elevated sediment and nutrient inputs, urban contaminants, and climate change. There is growing evidence of the influence of multiple stressors on estuarine ecosystems, including the capacity of multiple cumulative stressors to cause sudden and non-linear shifts, or tipping points, in ecosystem function. However, there remains considerable uncertainty around how multiple stressors interact, driven in part by a lack of data required to drive mechanistic multi stressor modelling approaches. This has meant that predicting and managing their impacts, particularly regarding tipping point events, has had limited success. There is an urgent need to develop tools which can be used by managers and policy makers that are credible and defensible in the face of complexity and deep uncertainty. Bayesian networks (BNs) offer the ability to combine empirical data with expert knowledge, bridging the gap between quantitative and qualitative models to allow the effects of uncertainties on management decisions to be explored and to overcome empirical data limitations.

The primary focus of this study was to develop an expert derived Bayesian Network (BN) model to explore what is known about the impact of multiple cumulative stressors on estuarine ecosystem function. The BN model developed was used to explore potential changes in ecosystem function driven by five major estuarine stressors (suspended sediment concentrations, sediment nitrogen, mud and metal content and temperature effects of climate change). It was also used to assess the status of five selected New Zealand estuaries based on known stressor information. The trends generated in the model were validated against large experimental datasets.

The model was able to:

- Explore and summarise expert knowledge of estuarine ecosystems dynamics using a probabilistic framework which incorporated and displayed uncertainty.
- Demonstrate key relationships between ecology and biogeochemical processes and generate threshold responses to environmental stress that were accepted by experts as representing current knowledge.
- Demonstrate that the impact of individual stressors is conditional on the state of other stressors to the system, highlighting the potential limitations of single stressor management approaches.
- Highlight some areas where increased knowledge would be useful to decrease uncertainty in ecosystem responses to stressors.
- Suggest that for the case study estuaries investigated, many of the ecosystem components were sitting in the zone where poor outcomes were increasingly likely in response to further degradation. In other words, the resilience of the ecological system, its capacity to buffer against further deterioration, was likely to be limited. Of these estuaries, based on the available data, New River had already passed a tipping point and was in the worst state, whereas Tauranga appeared to be in a comparatively favourable state.

Potential limitations and considerations for using the model and interpreting the results were also discussed, including:

- The development of the model required pragmatic decisions to minimise the number of nodes and relationships, determined based on expert opinion. The models' purpose was to better understand the impact of multiple stressors on estuarine ecosystems in a general way using probability distributions to display uncertainty, not to make exact predictions of current or future states.
- The stressor data applied to each case study estuary was determined based on available data from sampling sites. The number of sampling sites at many of the estuaries was limited, and therefore may not be reflective of the entire estuary.
- We also note that while the model was designed to be able to be generally applied to a range of estuaries, much of the underlying knowledge comes from research from intertidal and shallow (<20 m) subtidal areas. Thus, the model may be less useful for exploring estuarine dynamics in systems with relatively large deep areas (e.g., sounds, fjords and outer areas of larger harbours).

1 Introduction

1.1 Background

New Zealand estuaries face multiple interacting stressors at a range of scales. There is growing evidence of the influence of multiple stressors on estuarine ecosystems, including the capacity of multiple cumulative stressors to cause sudden and non-linear shifts, or tipping points, in ecosystem function (Thrush et al. 2014, Hewitt et al. 2016, Thrush et al. 2017). There remains considerable uncertainty around how multiple stressors interact, in addition to a lack of data required to drive mechanistic multi stressor modelling approaches, which has meant that predicting their impacts, particularly in regard to tipping point events, has had limited success. There is an urgent need to develop tools which can be used by managers and policy makers that are credible and defensible in the face of complexity and deep uncertainty (Gladstone-Gallagher et al. 2019).

The complexity and uncertainty surrounding multiple stressor impacts has also contributed to a continued focus on the management of stressors in isolation. However, single stressor management has had limited capacity to address the overarching impacts of multiple stressors on estuarine ecosystems. Complexity and uncertainty surrounding multiple stressor impacts also results in ecological models being more suited to exploring the likely direction of change through developing systems understanding, rather than making accurate predictions about exactly what change will occur (Allison et al. 2018). For example, increasing model complexity may improve predictive capacity but may result in a loss in model interpretability (i.e., understanding how the explanatory variables are drivers of changes). In addition, complicated models may be less useful for large scale and complex problems such as those facing estuarine environments, where the data and knowledge to drive such predictive approaches may be incomplete. Instead, by developing models that focus on improving our understanding of the potential outcomes of interactions within estuarine ecosystems (i.e., direction of change), including the uncertainty in these relationships, management goals can be achieved in the absence of precise numeric predictions (Murray 2007).

Bayesian networks (BNs) can be used as a heuristic model to demonstrate outputs of complicated ecosystem models, or to integrate empirical data with varying degrees of certainty or which has been collected for various purposes. They can also be based, in part or solely, on expert opinion (whether ecological, physical or Mātauranga Māori). These models have a history of use in New Zealand as knowledge and decision-making tools for community and industry (Quinn et al. 2013 and Hume et al. 2008, 2009). At the same time BNs can create in-depth ecological understanding and extend theories (Gladstone-Gallagher et al. 2019). Their use around the world is increasing as their ability to bridge the gap between quantitative and qualitative models, allow the effects of uncertainties on management decisions to be explored and overcome empirical data limitations (Marcot et al. 2001, Stephenson et al. 2018, Montyniemi et al. 2013). BNs are designed to easily facilitate relationships and associated probability distributions to be updated when new data become available. In combination with other decision support tools they can play an important part of adaptive management processes (see (Landuyt et al. 2013) for a review of the pros and cons of BNs for ecosystem service modelling).

1.2 Aims and objectives

The Parliamentary Commissioner for the Environment (PCE) is composing a report investigating the characteristics and values of estuarine coastal zones, including the ecosystem services they provide and their vulnerability to anthropogenic disturbance and climate change. One aspect of particular interest to the PCE is the impact of cumulative stressors on estuarine ecosystems.

The aim of this project was to develop a BN to demonstrate how New Zealand estuarine ecosystem function could change in response to multiple interacting stressors under a variety of different management scenarios. Particular aspects of interest were benthic biodiversity, water clarity, primary productivity, denitrification, carbon stocks, large suspension feeding shellfish and fish.

PCE also wanted to use the BN to indicate how 5 selected estuaries were being impacted by stressors. These selected estuaries (henceforth called case studies) were New River Estuary, a section of Pelorus Sound, Porirua Harbour, Whaingaroa (Raglan Harbour) and Tauranga Harbour. These case studies do not form a gradient of impact, nor are they especially representative of the range of New Zealand estuaries, with three of the five being much larger and deeper than most estuaries, which are predominantly small and shallow with extensive intertidal areas.

While Ministry for the Environment & Stats NZ Environment Aotearoa (2019) recently identified 4 key stressors on marine ecosystems (sediments, nutrients, fishing and climate change), many estuaries have considerable urbanization around them with consequent potential for metal inputs from stormwaters. At the same time commercial fishing is generally limited, with customary and recreational take expected to be the predominant source of harvesting. Within estuaries, nitrogen is usually more important than phosphorus as a stressor. Therefore, the stressors (drivers) chosen to use in the BN were those related to elevated sediment, nitrogen inputs, urban contaminants (metals), and climate change.

Elevated sediment was decomposed into suspended sediment concentrations and mud content (see Table A-1 for additional details); while it would have been preferable to use sedimentation rather than mud content, this information was not available for the 5 case studies. Fishing was not included as a stressor due to the lack of information on the levels of harvesting within estuaries and uncertainty around potential impacts. Climate change focused on the effect of temperature as this was easily separable from other climate driven effects which modify the other stressors (this includes storms and increased precipitation and ocean acidification which in estuaries is strongly affected by terrestrial nutrient runoff). We note that the models' purpose was to better understand the impact of multiple stressors on estuarine ecosystems in a general way using probability distributions and not to make accurate exact predictions of current or future states. With this in mind, the ecosystem components selected were the most important identified by the workshop participants rather than including every possible stressor/response node or relationship.

2 Methods

Bayesian Networks

BNs were created using Netica software (version 6.05, Norsys Software Corporation). A BN describes joint distributions (probabilities to every possible outcome over a set of variables) by exploring conditional independence relationships and conditional probabilities, which are represented by a directed acyclical graph (DAG). A variable is conditionally independent of another if the value of the latter doesn't influence the value of the former. Conditional probability is the probability of one event occurring with some relationship to one or more other events/variables. Causal relationships (links) between the variables (nodes) are shown as arrows within the BN. Each node is composed of a conditional probability table (CPT) that defines the probability distribution of the node conditioned upon the values of the parent nodes (Marcot et al. 2001). Parent nodes are nodes from which arrows originate from, whereas child (output) nodes are those where the arrows are pointing. At the top of the BN are nodes with no parents; in this case they represent the stressors and their distributions are determined either by data or scenarios to be explored (Neuberg 2003). In the hypothetical example below, sedimentation and wave exposure are stressor nodes (Figure 2-1). The Light level node is a child node to the parent nodes Sedimentation and Wave exposure. Kelp primary production is a child node to all three other nodes, including Light levels.

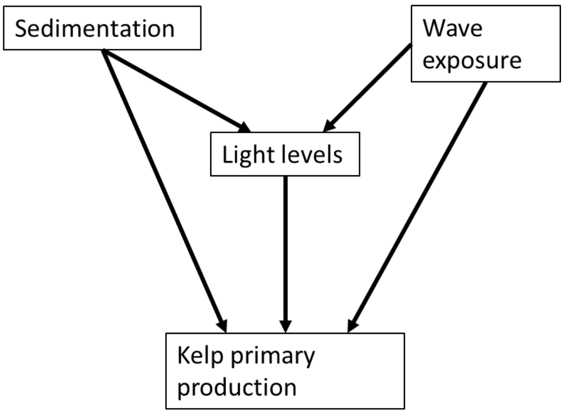

Figure 2-1: Simplified example of Bayesian Network., demonstrating unidirectional relationships between parent and child nodes, represented by a Directed Acyclical Graph (DAG).

2.1 Model development

Model structure and parameterisation was undertaken in iterative steps following best practice (Marcot et al. 2006) which are discussed in greater detail in sections 2.1.1-2.1.5. This included:

1) Develop an initial (conceptual) model structure based on literature and expert knowledge.
2) Define states based on literature and data.
3) Test this structure and define relationships with experts in a structured indirect expert elicitation process (Choy et al. 2009). Indirect approaches involve asking experts to predict the response given particular scenarios.
4) Create conditional probability relationships based on direct expert elicitation.
5) Refine model and relationships.

2.1.1 Conceptual model development

The initial conceptual model was based on a model constructed by Prof Hewitt to assess risk of tipping points in ecosystem function occurring, developed under NIWA SSIF funding and an MBIE project ("Marine Futures"). This model was adapted as per Table 2-1.

Table 2-1: Nodes used in the initial model and the final BN created for PCE. 1 = node added to allow BN to merge two effects.

	Initial	PCE BN
Stressors	Suspended sediments Sedimentation Nitrogen Metals Climate temperature	Suspended sediments Mud content Nitrogen Metals Climate change - temperature
Outputs	Water clarity change Benthic biodiversity Microphytobenthos Denitrification Large suspension feeding shellfish	Water clarity Benthic biodiversity primary productivity Denitrification Large suspension feeding shellfish Carbon stocks Fish (juveniles and adults).
Other ecosystem components	Large bioturbating deposit feeders Macrofauna Fringing vegetation Biogenic habitats Benthic nutrient and oxygen cycling Organic content	Large bioturbating deposit feeders Macrofauna Fringing vegetation Biogenic habitats Benthic nutrient cycling Macroalgae Phytoplankton Water column algae1

2.1.2 Defining states

To minimise model complexity, while ensuring that outputs were at a sufficient resolution to make robust inferences about ecosystem state (Allison et al. 2018), each node in the model was given five potential states ranging from Very low to Very High (see Figure 2-2 and Table A-1, Table A-2 for the outcome probability ranges spanned by each of these categories). Continuous variables were discretized based on literature review (including management guidelines) and analysis of empirical field datasets.

Where empirical datasets were available the state thresholds of each node were refined based on Non-Metric Multi-Dimensional Scaling analysis of macrofaunal community composition (using PRIMER V7), visually grouped by other available node states (such as mud, metals, chlorophyll). Non-Metric Multi-Dimensional Scaling is a tool which can be used to map the distribution of data across gradients based on distance or dissimilarity. In addition, percentiles were used to inform states for ecosystem functions (such as benthic primary production, denitrification) and water quality nodes: e.g., Very Low <10th percentile, Low = 10th to <30th percentile, Moderate = 30th to <70th percentile, High = 70th to 90th percentile, Very High >90th percentile. Table A-1 and Table A-2 in Appendix A give full descriptions of the states and their derivations. Datasets used to inform state thresholds included the Tipping Points dataset and publicly available regional council monitoring data (Thrush et al. 2003a, Hewitt et al. 2009, Pratt et al. 2014a).

2.1.3 Expert elicitation of model structure and relationships

The collection of the expert elicitation was undertaken during a workshop and followed the IDEA protocol ("Investigate", "Discuss", "Estimate", "Aggregate"). The IDEA protocol distils the most valuable steps from existing structured protocols and combines them into a single and practical protocol (Hanea et al. 2016). The key steps followed as part of this protocol were:

1. A diverse group of experts were recruited. A workshop was held with experts from NIWA, University of Auckland, University of Waikato, and The Parliamentary Commissioner for the Environment on 19/03/19 (attended by Prof Judi Hewitt, Dr Drew Lohrer, Dr Fabrice Stephenson, Assoc. Prof. Carolyn Lundquist, Dr. Emily Douglas, Dr Kura Paul-Burke, Dr Richard Bulmer, Prof Simon Thrush, Prof Conrad Pilditch, Stefan Gray and Maria Charry). The researchers' key fields of expertise were estuarine/marine ecology, ecosystem functioning, risk assessment and modelling.

2. Experts first *Investigated* the questions and clarified their meanings. The workshop involved further refinement to the conceptual model structure and states, and development of the relationships between nodes of the model. Relationships between nodes were defined by each participant independently, who also provided a certainty score for each relationship based on how confident they were in that relationship. This included identification of key conditional thresholds in relationships between nodes, as experts only rarely thought that linear relationships existed. For example, most experts defined the relationship between Metals and Large suspension feeding bivalves as having a threshold between Low and Moderate, where the probability of having a poor outcome (Very Low or Low state) suddenly increased from 40% to >95%. The researchers were asked to consider relationships based on the present through to the near future (i.e., within the next 20 years). The model was designed so that it could be applied across a range of scales, from the scale of individual samples, to sub estuary, estuary, and multiple estuary scale.

3. Experts received feedback on their estimates in relation to other experts.

4. Experts *Discussed* the results, resolved different interpretations of the questions, cross-examined reasoning and evidence, and provided a second and final private *Estimate*.

5. The individual estimates were *Aggregated*.

2.1.4 Creating conditional probability relationships

Post workshop, an average was generated from the individual expert's relationships, however, where the expert felt they were not able to accurately describe the relationship, these were omitted. While the strength of the relationship between parent and child nodes varied between participants, the direction of each of the relationships (e.g., increasing/decreasing relationship or hump-shaped curve) was consistent across researchers.

The conceptual model and relationships (in terms of probabilities) were then entered into Netica to create the Bayesian Network. The BN model developed included 23 nodes, 102 relationships between nodes, and 127,275 conditional probabilities (Figure 2-2). The BN was arranged so that the five stressors of interest were located at the top row of the BN (suspended sediment, mud content, nitrogen, metals, climate change), filtering through to the ecology, then the associated ecosystem functions and finally back to the ecology. As relationships between nodes in a BN are unidirectional, the second stage ecology nodes that were of particular interest (see Introduction) were added at the bottom of the model to encapsulate the feedback between species and function feedbacks (in an approximate manner).

Note that in this report we use a capital letter to indicate components (Metals or Large suspension feeding bivalves) or states (Very Low) of the model.

2.1.5 Expert checking of model output

The expert driven model was then reviewed in an iterative process with participants through subsequent meetings, and relationships were further refined as necessary.

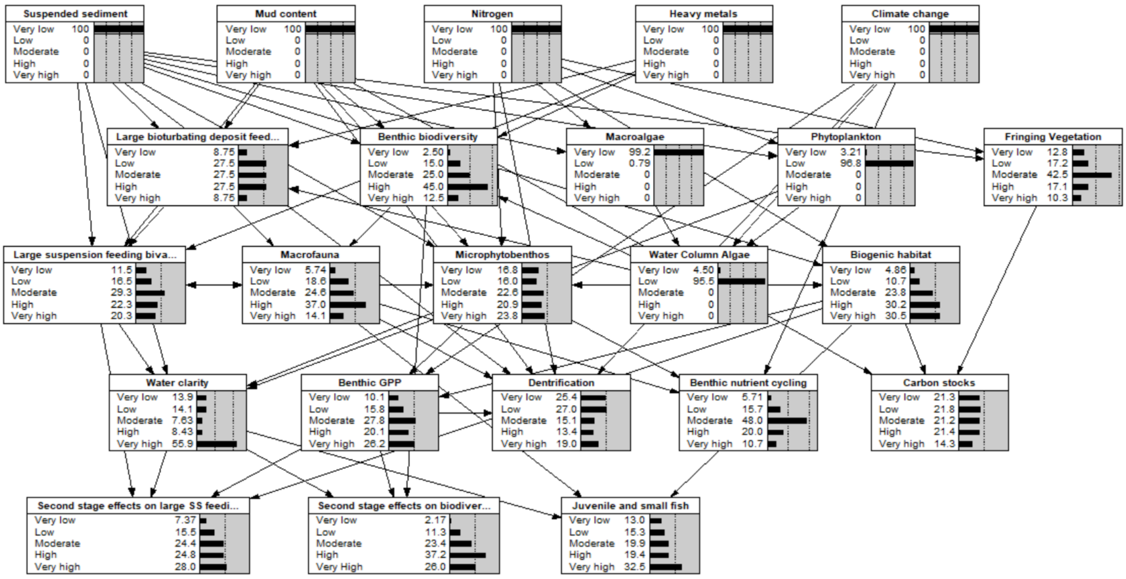

Figure 2-2: The structure of the BN model showing conditional outcomes with no stress. Second stage effects are used to understand final feedback effects on two important ecosystem components.

2.2 Empirical Validation of the expert driven model

Although decision making BNs are not usually validated, in this case we had some data available that we could use to create a validation. These data were collected as part of the Sustainable Seas national tipping points experiment (14 estuaries throughout the country), and the Auckland Council east coast monitoring program (8 estuaries throughout Auckland). Paired experimental data was not available for every node, however this combined dataset included a total of 372 samples, with paired data for some or all of the following nodes (or proxies): sediment mud, nitrogen and metal contents; densities of large bioturbating deposit feeders and large suspension feeding bivalves; sediment chlorophyll a content as a representation of microphytobenthos standing stock; photosynthetically active radiation on the seafloor as a representation of water clarity; benthic gross primary production, denitrification rates, benthic nutrient cycling, and number of taxa; and carbon stocks (see Table A-1 and Table A-2 further information regarding units and definitions). Suspended sediment concentrations were informed by the NIWA sediment load model and Dudley et al. (2017).

Each of the 22 estuaries were classified by the available information on their driver states and these driver states used in the BN to generate probability distributions for each of the other nodes. Empirical data on the other nodes were also classified into the corresponding states for each node and histograms of probability distributions were generated. The probability distributions generated by the BN were then compared to those generated by the pooled field data across the complete experimental dataset.

Each node was given a score out of 100 corresponding to areas of overlap between the two probability distributions. For example, if the BN CPT for an individual node was spread between Very Low (50%) and Low (50%), and the field data results were spread across Very Low (55%) and Low (45%), the score out of 100 for this would be 95/100 (minimum Very Low of 50% + minimum Low of 45%) (see Figure B-1 for further example of how scores were calculated across multiple states).

2.3 Scenario testing

A number of scenarios were used to explore the impact of multiple stressors on estuarine ecosystem function. The first set represented a hypothetical estuary exposed to progressively higher stressor levels, ranging from all Very Low states, increasing to all Low, all Moderate, all High, and all Very High.

Then a set of hypothetical scenarios were run to explore whether the response to one stressor was conditional on the state of other stressors. All stressors and nodes were considered, although we demonstrate the results only for three (Mud content; Nitrogen; and Metals) and effects on two output variables (Second stage effects on Large suspension feeding bivalves and Juvenile and small fish) for the three stressors separately, in pairwise combinations and finally altogether.

In addition, we used sample data available from the five case study estuaries, selected by PCE, to illustrate examples of estuaries exposed to a variable range of stressors. Data for each estuary was sourced from the relevant regional councils and/or publicly available datasets (Table 2-2 and Table C-1). For one estuary (Tauranga), we also ran two hypothetical scenarios. Tauranga was chosen as it contained the greatest number of samples to inform initial stressor states. One was defined based on the hypothetical impact of an increase of two states in metal concentrations (as observed in other large cities in response to land development/urbanisation), increasing the Metal state from predominantly Very Low to Moderate. The other was defined based on an upshift in multiple stressors throughout the harbour, (although not Climate change) as potentially observed as a result of accumulating suspended sediment, mud, metals and nitrogen through time consistent with New Zealand's recent history.

Table 2-2: Stressor scenarios created from the empirical data of the case study estuaries (see Table B-1). All scenarios have Moderate Climate change. Bold states represent the spread of data.

Scenario	Suspended sediment	Mud content	Nitrogen	Metals
Tauranga	Very Low = 0% **Low = 40.4%** **Moderate = 49.6%** **High = 10.0%** Very High = 0%	**Very Low = 16.7%** **Low = 40.3%** **Moderate = 39.6%** **High = 3.5%** Very High = 0%	**Very Low = 57.2%** **Low = 10.7%** **Moderate = 10.7%** **High = 12.6%** **Very High = 8.8%**	**Very Low = 94.6%** **Low = 5.4%** Moderate = 0% High = 0% Very High = 0%
Tauranga +M	Very Low = 0% **Low = 40.4%**	**Very Low = 16.7%**	**Very Low = 57.2%** **Low = 10.7%**	Very Low = 0% Low = 0%

Scenario	Suspended sediment	Mud content	Nitrogen	Metals
	Moderate = 49.6% **High = 10.0%** Very High = 0%	**Low = 40.3%** **Moderate = 39.6%** **High = 3.5%** Very High = 0%	**Moderate = 10.7%** **High = 12.6%** **Very High = 8.8%**	**Moderate = 94.6%** **High =5.40%** Very High = 0%
Tauranga +SS, Md, M, N	Very Low = 0% Low = 0% **Moderate = 40.4%** **High = 49.6%** **Very High = 10%**	Very Low = 0% **Low = 16.7%** **Moderate = 40.3%** **High = 39.6%** **Very High = 3.5%**	Very Low = 0% **Low = 57.2%** **Moderate = 10.7%** **High = 10.7%** **Very High = 21.4%**	Very Low = 0% **Low = 94.6%** **Moderate = 5.4%** High = 0% Very High = 0%
Whaingaroa (Raglan) 1- Waingaro arm	Very Low = 0% Low = 0% Moderate = 0% **High = 100%** Very High = 0%	Very Low = 0% Low = 0% **Moderate = 50%** **High = 50%** Very High = 0%	**Very Low = 50%** Low = 0% Moderate = 0% **High = 50%** Very High = 0%	Very Low = 0% **Low = 100%** Moderate = 0% High = 0% Very High = 0%
Whaingaroa (Raglan) 2 - Waitetuna arm	Very Low = 0% Low = 0% Moderate = 0% **High = 100%** Very High = 0%	Very Low = 0% Low = 0% **Moderate = 100%** High = 0% Very High = 0%	Very Low = 0% **Low = 50%** **Moderate = 50%** High = 0% Very High = 0%	Very Low = 0% **Low = 100%** Moderate = 0% High = 0% Very High = 0%
Porirua 1 - Onepoto arm	Very Low = 0% **Low = 66.7%** Moderate = 0% **High = 33.3%** Very High = 0%	Very Low = 0% **Low = 86%** Moderate = 0% **High = 14%** Very High = 0%	**Very Low = 50%** **Low = 50%** Moderate = 0% High = 0% Very High = 0%	**Very Low = 25%** **Low = 25%** Moderate = 0% **High = 50%** Very High = 0%
Porirua 2 - Pauatahanui arm	Very Low = 0% **Low = 33.3%** **Moderate = 66.7%** High = 0% Very High = 0%	**Very Low = 8.3%** **Low = 50%** **Moderate = 8.3%** **High = 33.3%** Very High = 0%	**Very Low = 100%** Low = 0% Moderate = 0% High = 0% Very High = 0%	Very Low = 0% **Low = 40%** **Moderate = 60%** High = 0% Very High = 0%
Havelock, Pelorus Sound/Te Hoiere	Very Low = 0% Low = 0%	Very Low = 0% Low = 0%	**Very Low = 25%** **Low = 25%**	**Very Low = 25%** **Low = 75%**

Scenario	Suspended sediment	Mud content	Nitrogen	Metals
	Moderate = 0% **High = 100%** Very High = 0%	**Moderate = 50%** **High = 50%** Very High = 0%	**Moderate = 25%** High = 0% **Very High = 25%**	Moderate = 0% High = 0% Very High = 0%
New River, Southland	Very Low = 0% Low = 0% Moderate = 0% **High = 100%** Very High = 0%	**Very Low = 27.9%** **Low = 29.4%** **Moderate = 25%** **High = 11.8%** **Very High = 5.9%**	Very Low = 0% Low = 0% Moderate = 0% **High = 100%** Very High = 0%	Very Low = 0% **Low = 100%** Moderate = 0% High = 0% Very High = 0%

3 Results

3.1 Conceptualizing the model outputs

The BN produces output nodes with probability distributions which are dependent on the initial stressor combinations. Even when stressors are all set to low levels, there is a small probability of a very low outcome for many of the output (child) nodes (Figure D-1). The model is not designed to accurately predict exactly when the likelihood of a low or very low outcome exceeds a critical point or threshold, but the combination of stressor magnitudes that makes this more likely, together with how certain the outcome is.

It is important to note that the conditional probability outputs of each of the nodes of the BN reflect not only the uncertainty (in the mind of the experts) as to the strength of any relationships between the state of the parent nodes and the state of the child node, but also spatiotemporal variability in potential outcomes. One way to visualise the conditional probability table (CPT) outputs for each node of the BN is to imagine randomly selecting 10 locations throughout an estuary, sub-estuary, or sampling site. The CPTs of the BN reflect the range of outcomes that may be expected over those 10 locations.

> *Example 1: At the sampling site level, if a 10 m^2 area is sampled that in theory has the same stressor states with 10 randomly placed cores to measure bivalve abundance, it is unlikely to result in 10 values all within the same output state. Instead the results are likely to cover a distribution that is skewed higher or lower based on whether stressors are towards the low or high end.*

> *Example 2: At the estuarine level, even in estuaries subject to very low stress, not all the estuarine area will support high ecology/function for all nodes. For example, in areas where mud content is increasing the effect of this will differ depending on the original sediment particle size. Areas with high quantities of shell hash will have higher diversity and different nutrient and oxygen fluxes than those with high quantities of fine sand.*

3.2 Empirical Validation of the expert driven model

Generally, the probability distributions predicted by the BN displayed a similar shape and magnitude to the field data observations, with BN generated distributions typically skewed slightly towards Very Low or Low states. This is because: (1) model background probability distributions were generated in consideration of other factors that are not in the model (e.g., harvesting and benthic disturbance, variable spatial scale, subtidal and intertidal environments, other sediment particle size information and expert uncertainty), and (2) all the field data used for validation was from sites more often located where moderate to high macrofaunal biodiversity was known to be present. The model was designed to be more generally applied across intertidal/subtidal environments and throughout estuaries.

Overall, agreement between the model and the field data ranged from 68/100 to 96/100 (Figure 3-1). Validation scores were highest for Benthic gross primary productivity and Benthic nutrient cycling, due in part to the recent research emphasis on these two components. The three components with the lowest validation values were Large bioturbating deposit feeders (68/100), Second stage effects on Large suspension feeding bivalves (71/100) and Carbon stocks (73/100).

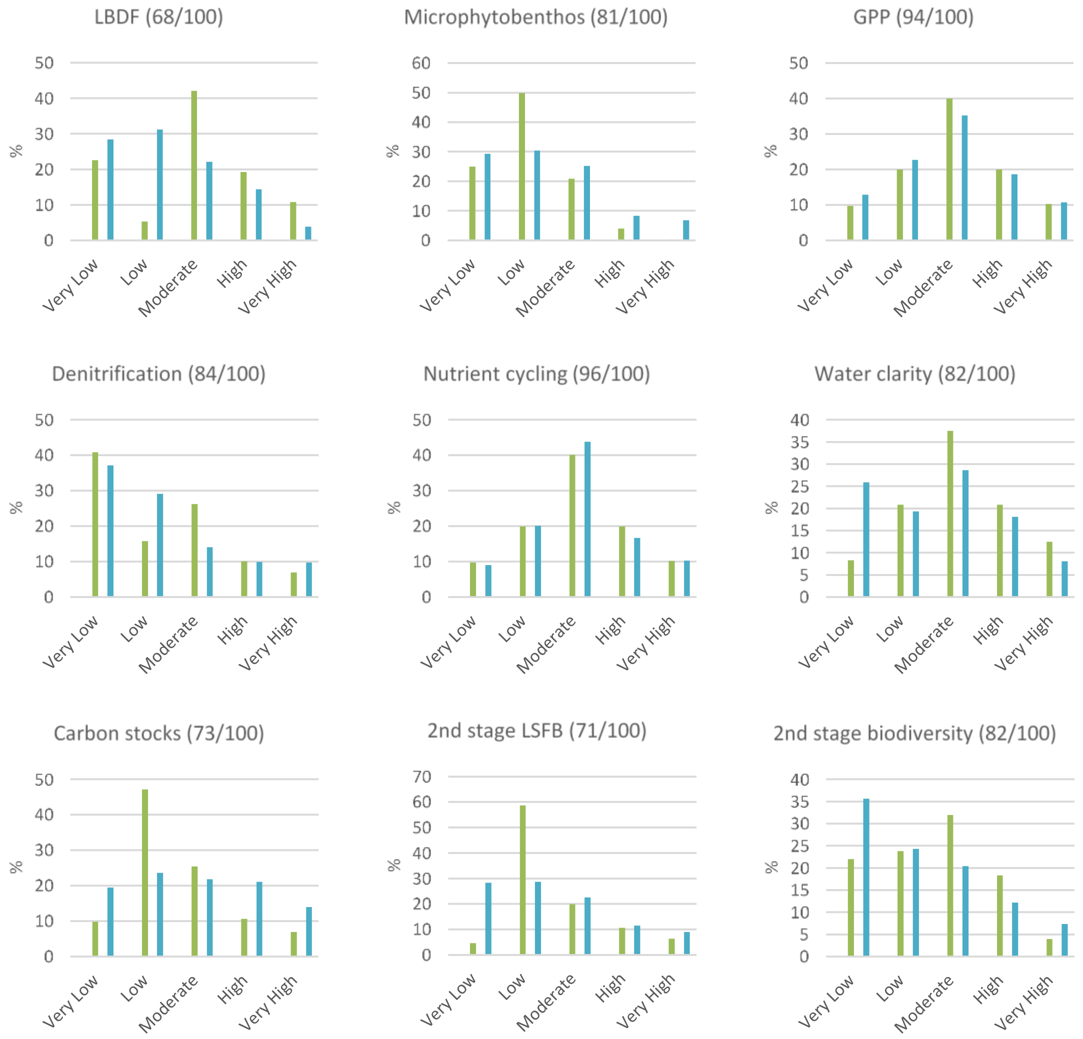

Figure 3-1: Comparison between composite field data (green) and BN output (blue). Field data were sourced from the national tipping points dataset and the Auckland Council East Coast Estuaries Monitoring. LBDF = Large bioturbating deposit feeders, LSFB = Large suspension feeding bivalves, GPP = Benthic gross primary productivity.

For Large bioturbating deposit feeders (LBDF in Figure 3-1), the expert uncertainty was generally high, although experts did generally agree that some form of hump-shaped curve was the most likely response to mud content and nitrogen. For Carbon stocks, the expert uncertainty was again generally high with experts often assigning near equal probabilities across the states. For Second stage Large suspension feeding bivalves, the ecological nodes influenced the downstream functional nodes (such as Benthic gross primary productivity, Denitrification, Benthic nutrient cycling, Carbon stocks, Water clarity), and finally to other ecological nodes contributing to increased variability in the response of downstream nodes to stress.

3.3 Scenarios

Here, we briefly summarise the BN outputs for a number of scenarios, with a primary focus on ecosystem components of particular interest: benthic biodiversity, water clarity, benthic gross primary productivity, denitrification, carbon stocks, large suspension feeding shellfish and fish (juveniles and small). More detailed results of the scenarios are available in the supplementary material that is presented in Appendix D (including graphical outputs of the model structure and CPT).

3.3.1 Increasing stress levels

This set of scenarios investigated what happened as stressors were gradually increased from all Very Low through to all Very High.

Under Very Low through to Moderate stressor scenarios, the likelihood of poor (Very Low or Low) outcomes for many of the ecosystem components was low (<40%, see Figure 3-2 and Table D-1). While changes in this likelihood occurred as stress increased from Very Low to Low to Moderate, there was a marked change for nearly all ecosystem components as the stress increased from Moderate to High (Figure 3-2), leading to a >80% likelihood of a poor ecological outcome. The corollary is that chances of good (High and Very High) outcomes decreased with increasing stress levels (see Table D-2).

A more linear response was evident for Biogenic habitat and Carbon stocks which exhibited little change with stress (Table D-1). Neither Benthic gross primary productivity nor Benthic nutrient cycling were strongly affected by increasing stress. Conversely, Nuisance Macroalgae and Phytoplankton showed a very sharp threshold occurring between Low and Moderate stress levels.

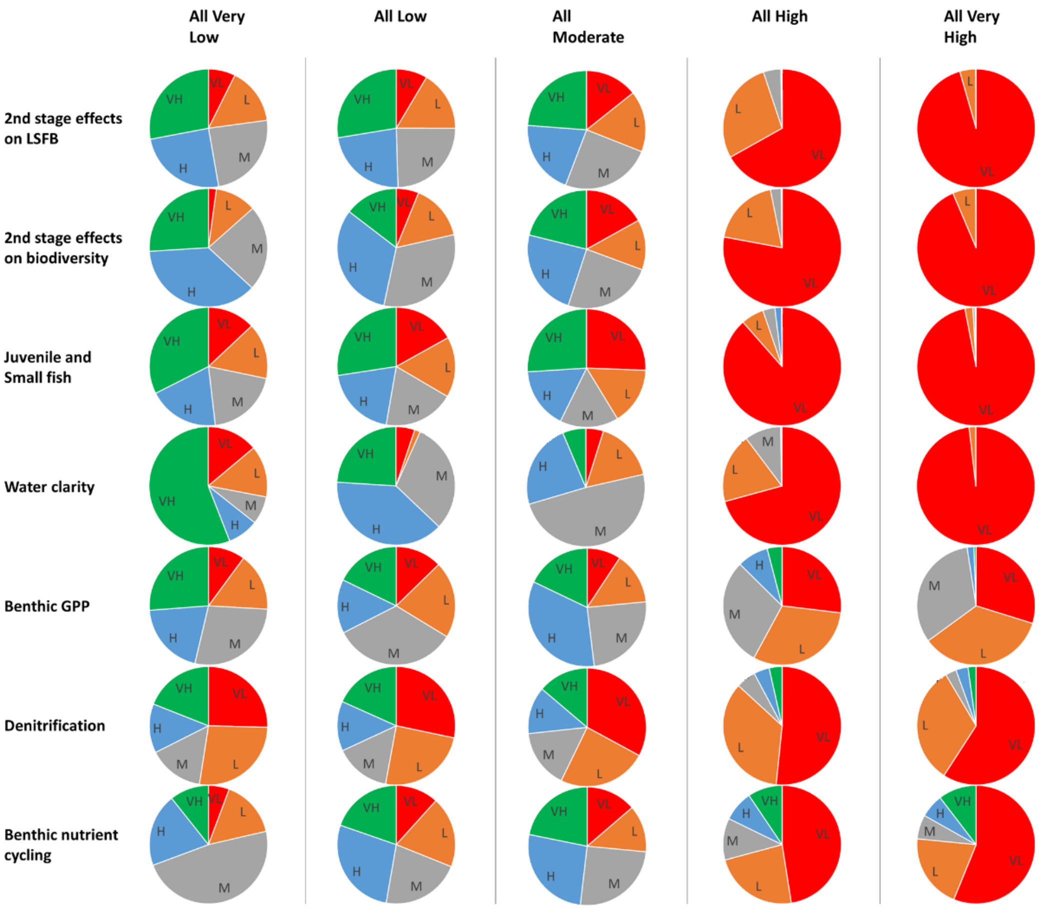

Figure 3-2: Changes in the probability of different states occurring with increasing intensity of stress in a hypothetical estuary. All stressors were modified with the exception of Climate change which was set to Moderate. Likelihood of poor outcomes are the proportion of the pie coloured red and orange. GPP = gross primary productivity.

3.3.2 Stressor responses conditional on the state of other stressors

This set of scenarios investigated the relationship between multiple stressors by manipulating stressors individually over multiple different combinations of stress. The examples in Figure 3-3 focus on Second stage effects on Large suspension feeding bivalves (2^{nd} LSFB) (which include important kaimoana species such as cockles) and Juvenile and small fish. These examples clearly demonstrate the threshold response of 2^{nd} LSFB and Fish to stressor impacts, with low probability of poor outcomes (i.e., few to no bivalves/fish) under Very Low or Low cumulative pressures. At these levels of stressors, having more than one stressor makes little difference. However, once the stressors reach the Moderate category, this is no longer true. For 2^{nd} LSFB metals are a strong influence with a stronger probability of poor outcomes when nitrogen is also moderate. This occurs despite the strong threshold effect of metals. For Fish, the effect of metals is not strong and a strong cumulative effect of the three stressors combined is apparent. As our knowledge grows in regard to multiple stressor impacts it will be possible to revise these relationships further, the ability to relatively easily update priors is a key feature of BNs.

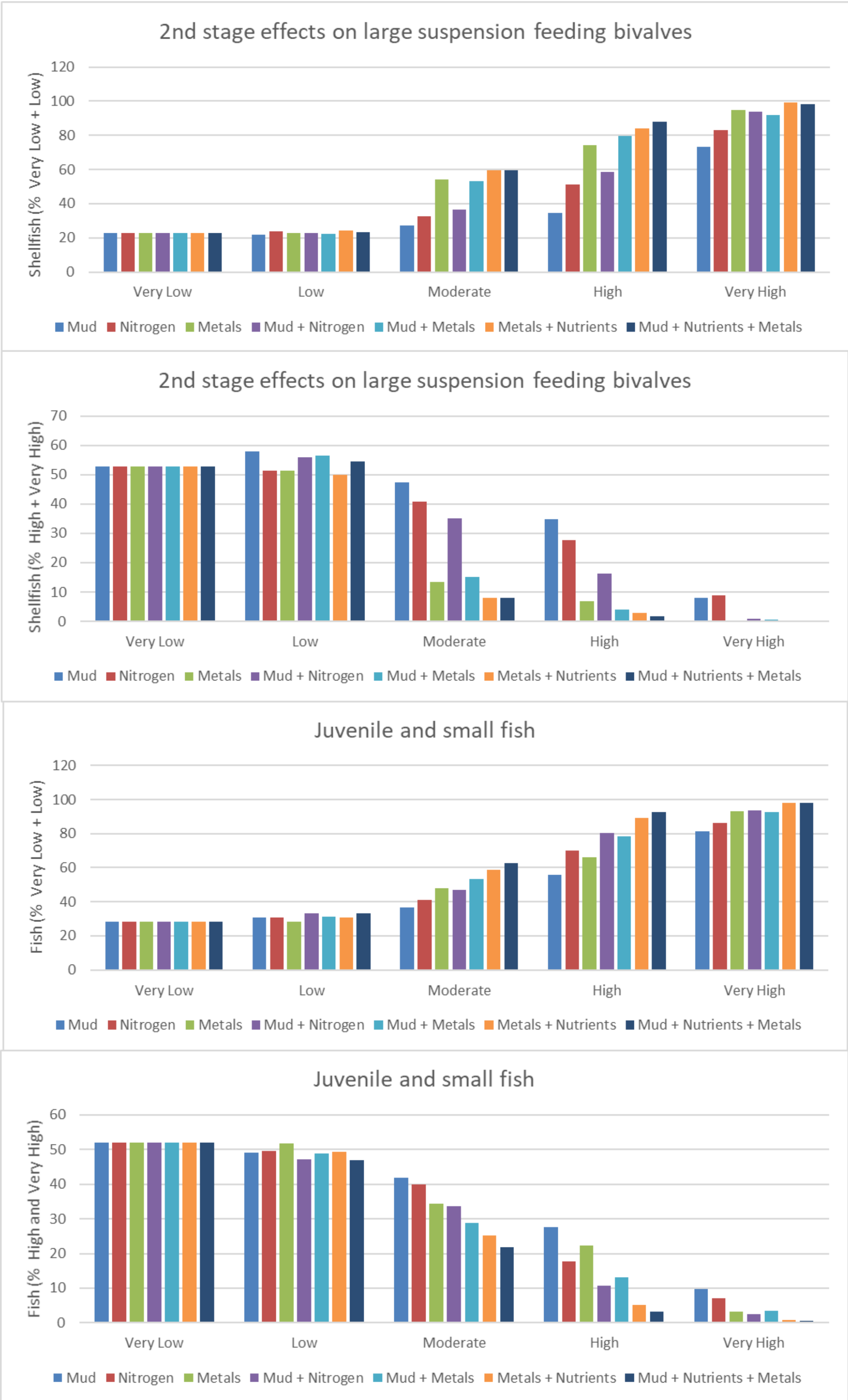

Figure 3-3: Outputs demonstrating the response to an individual stressor conditional on the state of other stressors.

3.3.3 Case study estuaries

These scenarios represent different combinations of stressors, driven by data for the five estuaries of interest to PCE. None of the estuaries are pristine, although Tauranga does not exhibit predominantly High or Very High status of any of the stressors (see Table 2-2). Given the wide range of stressor states for Whaingaro and Porirua, both of which had samples collected from two distinct arms of the harbours, the arms are treated separately below.

New River estuary and the Waingaro arm of Whaingaroa both recorded High Nitrogen status, High Suspended Sediment and Low Metals. Conversely, both arms of Porirua recorded Moderate to High Metals and Very Low Nitrogen. All but Tauranga and the Onepoto arm of Porirua recorded High Suspended sediments (Table 2-2).

Generalising across these estuaries (and more specifically the sampling sites within these estuaries), the model suggested a high likelihood of poor (Low or Very Low) outcomes for many of the ecosystem components (Figure 3-4 and Figure 3-5).

Across the five case study estuaries, the greatest likelihood of poor outcomes was at New River (Figure 3-4), consistent with the higher stressor states applied to the model for this estuary. The two Porirua arms and Tauranga displayed the lowest likelihood of poor outcomes (Figure 3-4 and Figure 3-5).

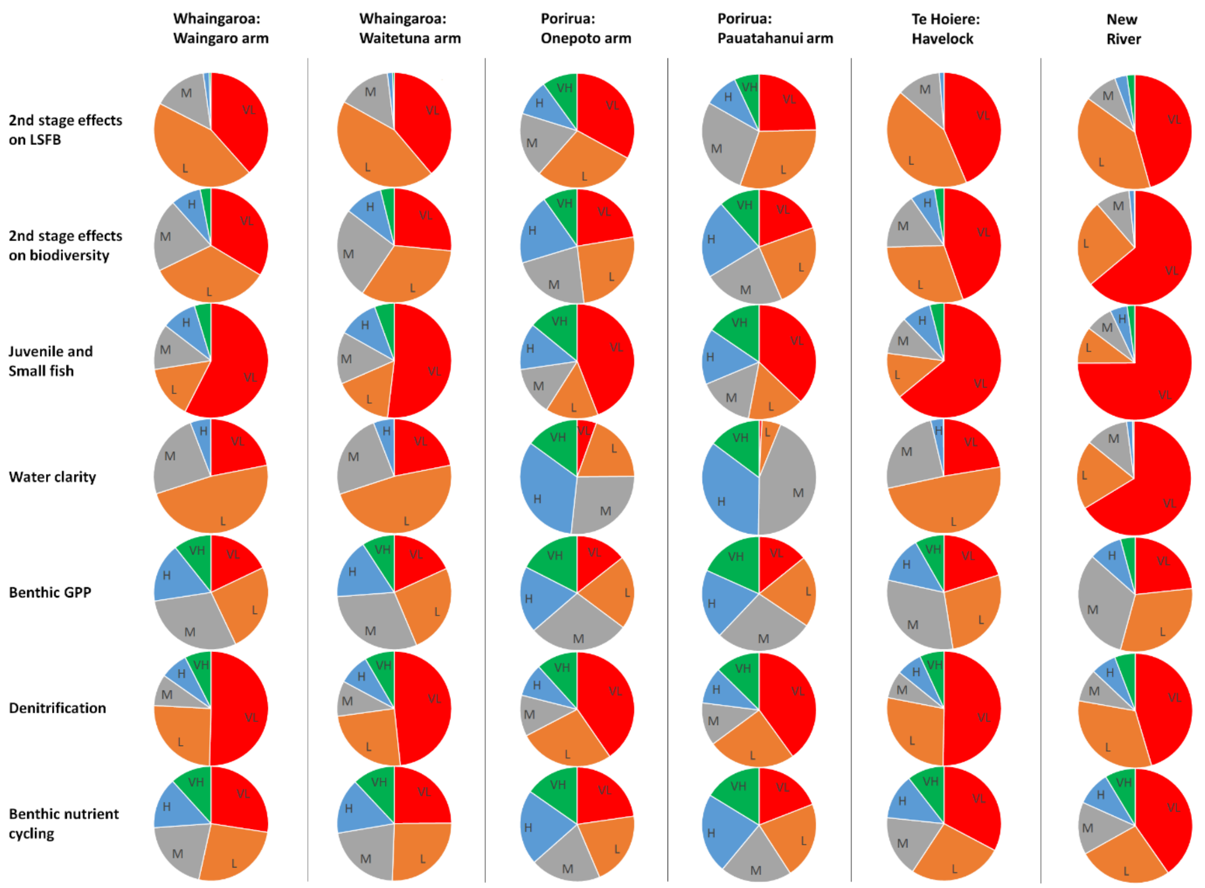

Figure 3-4: Present state of selected ecosystem components in 4 case study estuaries based on empirically derived stressor states. Likelihood of poor outcomes are the proportion of the pie coloured red and orange. GPP = gross primary productivity.

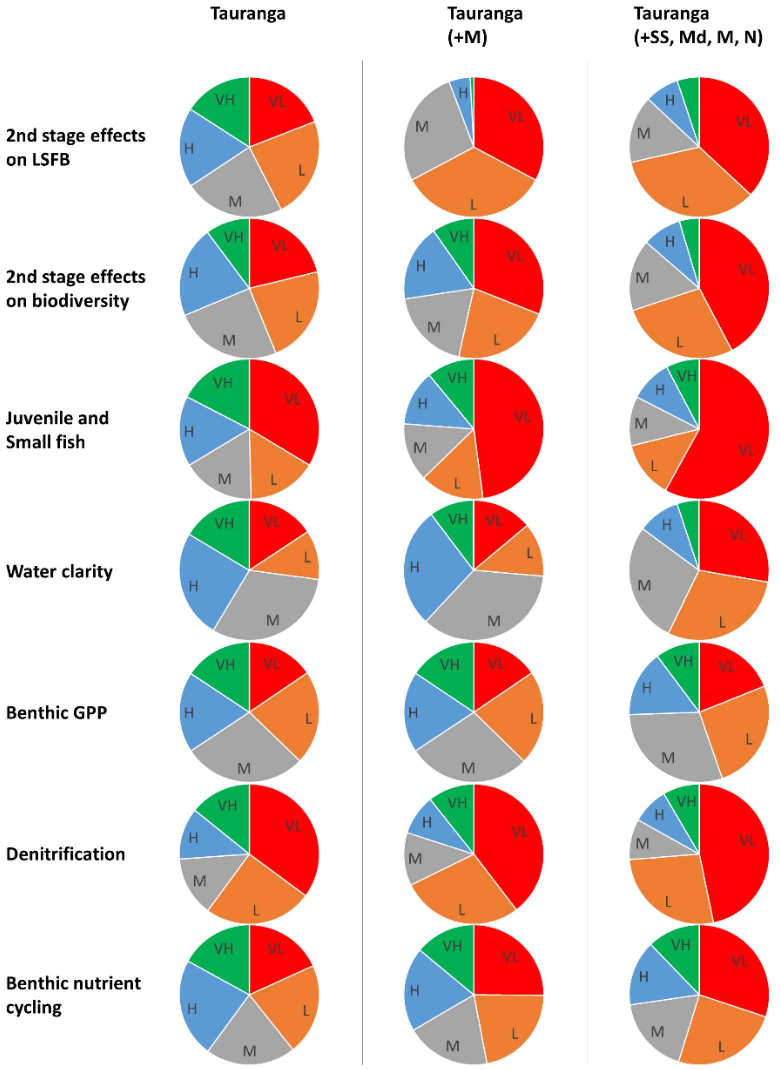

Figure 3-5: Scenarios based on Tauranga empirically derived stressor states. +M increase in metals by two states, +SS, Md, M, N increase all by one state. Likelihood of poor outcomes are the proportion of the pie coloured red and orange. GPP = gross primary productivity.

For Tauranga, two extra scenarios were run: an increase in metal concentrations from predominantly Very Low to Moderate; and an upshift by one state of Suspended sediment, Mud content, Metals and Nitrogen. Figure 3-5 shows that the likelihood of a Very Low or Low state for 2nd LSFB for the baseline scenario was 44% across the estuary. Increased estuarine metal concentrations increased the likelihood of a poor (Very Low or Low) outcome for 2nd LSFB to 67%, and by increasing all stressors by one state, the likelihood increased to 70%. Visualising these outcomes spatially, this suggests that the spatial coverage of High or Very high densities of 2nd LSFB may reduce from approximately 34% of the estuary, to only 6% and 13% respectively. Equivalently dramatic effects were observed for 2nd stage effects on Biodiversity and Juvenile and small fish. Not surprisingly, increased metals had little effect on Water clarity, but also on Benthic gross primary productivity. Benthic nutrient cycling appeared relatively unchanged by either of the hypothetical scenarios.

4 Discussion

Estuarine ecosystems incorporate a range of indirect and direct relationships including biological, physical, and chemical processes which have significant consequences for ecosystem function. These interactions can result in distinct spatial and temporal patterning throughout estuaries that can generate abrupt changes from one state to another (Thrush et al. 2012, Thrush et al. 2014, Hewitt et al. 2016, Thrush et al. 2017). This may be the result of extreme levels of stress, but may also be triggered by chronic and cumulative lower level impacts (Thrush et al. 2012). The primary focus of this study was to develop an expert derived model to explore the impact of multiple cumulative stressors on estuarine ecosystem function. The BN model produced was able to explore this dynamic using a range of scenarios informed by field data from estuaries throughout New Zealand.

4.1 Summary of findings

The model demonstrated key qualitative relationships between environmental stress and ecosystem response that satisfied experts in estuarine ecosystem functioning. This included producing thresholds where the likelihood of a poor ecological outcome increased dramatically and impacts of individual stressors which were conditional on the state of other stressors to the system. These were not only observed for the ecological nodes in the model, but also for many of the functional nodes (such as benthic primary production and nutrient cycling).

A validation process for the model was undertaken; which is frequently not able to be done for this type of BN. Validation results for all the nodes were markedly higher than random, varying from 68 to 96% concordance. Validation was highest for Benthic gross primary productivity and Benthic nutrient cycling, possibly due in part to the recent research emphasis on these two components. The three components with the lowest validation values were Large bioturbating deposit feeders, Second stage Large suspension feeding bivalves and Carbon stocks. For Large bioturbating deposit feeders and Carbon stocks, the expert certainty was generally low, suggesting that these would be useful areas for future research.

The model suggests that the case study estuaries investigated are vulnerable to the impacts of further stress, with many of the nodes sitting in the zone where a poor (Very Low or Low) outcome becomes increasingly likely in response to further degradation. In other words, the resilience of the ecological system, its capacity to buffer against further deterioration, is likely to be limited when compared to estuaries with lower stressor levels. Of these estuaries, based on the available data, New River had already passed a tipping point and was in the worst state, whereas Tauranga appeared to be in a comparatively favourable state.

4.2 Findings in relation to literature

Many species can maintain populations across a range of stress levels, but begin to rapidly tip once the stressors exceed tolerance ranges (Thrush et al. 2004). Defining when this tipping point occurs is difficult, particularly in the context of multiple stressors, as the interactive effects of stress can have unexpected effects on species tolerance ranges (Breitburg et al. 1999). The probabilistic output of the BN illustrates this concept. For example, a very low or low ecological outcome is possible even under " favourable" stressor conditions. For macrofaunal components, the relationships with stressors were defined so that the stressors constrained the likelihood of an outcome once a certain level of stress was reached, and prior to this occurring the stressor had limited impact on the model. For example, Benthic biodiversity, Large bioturbating deposit feeders and Large suspension feeding bivalves have a wide tolerance range to stressors (including Suspended sediment, Mud content, Nitrogen, Metals), before reducing in abundance at Moderate to Very High levels (Thrush et al. 2004, Hewitt et al. 2009, Green et al. 2014, Ellis et al. 2017b). Part of this response is due to differences in species responses within the broad node definitions. For example, pipis and horse mussels are very sensitive to suspended sediment, whereas cockles prefer some suspended sediment and pacific oysters and green mussels can remain feeding at even higher levels (Hewitt and Norkko 2007, Hewitt and Pilditch 2004, Hawkins et al. 1999).

The model generated a positive relationship between Mud content (which represented sedimentation) and Fringing vegetation and Carbon stocks. NZ loses an estimated 192 million tonnes of sediment off the land via the waterways each year (Ministry for the Environment & Stats NZ 2018). Sediment transported to estuaries contains organic matter, a proportion of which settles out on the seafloor. This results in increased sediment carbon stocks and estuarine infilling (Smith et al. 2015, Bulmer et al. 2019). Estuarine infilling provides more available habitat for fringing vegetation such as mangrove to colonise (Swales et al. 2015). Fringing vegetations is also associated with high carbon stocks both within the sediment column and within plant biomass (Bulmer et al. 2019).

In comparison, Biogenic habitat and Microphytobenthos were negatively impacted by High and Very High Suspended sediment and Nitrogen in the model. This is consistent with the reduction in subtidal seagrass, kelp forests and microphytobenthic activity observed around new Zealand and attributed to high suspended sediment/phytoplankton on benthic light availability and photosynthesis, and the documented effects of high suspended sediment on biogenic habitat structuring organism such as, such as horse mussels and sponges (Ellis et al. 2002, Lohrer et al. 2006, Chartrand et al. 2016).

Water clarity was negatively impacted by increasing Suspended sediment and Nitrogen and decreasing Macrofauna and Microphytobenthos. Large suspension feeding bivalves play an important role filtering the water column and enhancing nutrient cycling (Vaughn and Hoellein 2018) which can stimulate microphytobenthic production (Lohrer et al. 2004b, Sandwell et al. 2009, Rodil et al. 2011, Pratt et al. 2015), while microphytobenthos can provide additional structural integrity to the seafloor, reducing sediment resuspension and improving water clarity (MacIntyre et al. 1996).

Benthic gross primary productivity and Benthic nutrient cycling are positively related to microphytobenthic activity and macrofaunal abundance (MacIntyre et al. 1996, Lohrer et al. 2004b). Microphytobenthos photosynthesis to produce oxygen and consume inorganic nutrients to fuel photosynthetic processes (MacIntyre et al. 1996). Macrofauna excrete nutrients, as well as bioturbate and irrigate the sediment, and modify porewater gradients, enhancing nutrient cycling (Lohrer et al. 2004b). Benthic gross primary productivity was also weakly negatively affected by climate change, linked to increased temperatures and increased respiration/microbial activity (Pratt et al. 2014a, Bulmer et al. 2015).

Denitrification rates were associated with Benthic gross primary productivity and Macrofauna. Increased gross primary productivity is associated with increased oxic/anoxic gradients and supporting coupled nitrification/denitrification processes (Gongol and Savage 2016). Benthic macrofauna stimulate denitrification by increasing the transport of oxygen and inorganic nutrients from the water to the sediment through bioturbation and bio-irrigation (Volkenborn et al. 2010) as well as respiring, consuming organic material and excreting inorganic nutrients (Gongol and Savage 2016). Juvenile and small fish are positively associated with macrofaunal abundance/diversity (due to the provision of food (Duffy et al. 2016)), water clarity effects on predator/prey interactions) and biogenic habitat (provision of recruitment/nursery/shelter (Parsons et al. 2013, Parsons et al. 2014)).

Second stage effects on large suspension feeding bivalves and Second stage effects on Biodiversity were positively related to Large suspension feeding bivalves and Biodiversity, respectively, through positive feedbacks such as provision of recruits/structure, as well as water clarity (tolerance to suspended sediment (Hewitt and Norkko 2007)), Benthic gross primary productivity (increased supply of oxygen for survival (Lohrer et al. 2016)), and Biogenic habitat (structure for recruitment/ nursery/ shelter) (Norkko et al. 2001).

4.3 Scenarios

To demonstrate the potential utility of the model, a range of scenarios were run to explore the potential outcomes. While these are limited in number, the model has been supplied in an executable mode that is easy to use, so that new scenarios can be explored. In this mode it can be used as a communication tool to understand how effects of stressors can combine and effects flow through the ecosystem to factors of specific interest.

With respect to exploring its use in other specific estuaries, this will always be limited by the available data on the stressor's status. However, where at least some information is available environmental managers may wish to explore ramifications of different stressor combinations on estuarine ecosystems using this type of model (the conditional probability relationships linking parent/stressor and child nodes remain the same for each scenario that is run). This may facilitate consideration of elements of estuarine ecosystem function that may otherwise have been overlooked, or to help to contextualize the impact of multiple stressors on estuarine function and summarize expert thinking without requiring independent expert elicitation. For example, this may be useful for visualizing the potential limitations of single stressor management, or for improving understanding of the links between ecology and ecosystem function and how this is impacted by multiple stressors.

We demonstrated this utility using two hypothetical scenarios for Tauranga estuary. The first scenario was based on an increase in heavy metal concentrations, as observed in other cities such as Auckland associated with urban development (Hewitt et al. 2009). The second scenario was based on an increase in Suspended sediments, Mud content, Metals and Nitrogen, as observed at many estuaries throughout New Zealand over the past 20+ years (Thrush et al. 2004, Hewitt et al. 2009, Hewitt et al. 2016). In both scenarios, good outcomes for ecosystem components generally decreased, highlighting the vulnerability of the system to increasing stress. For example, the spatial distribution of High or Very High Large suspension feeding bivalves was estimated to reduce from 34% of the estuary, to only 6% and 13% respectively, i.e., a contraction of approximately 1/3 or more of the baseline densities. While macrofaunal health reduced under both hypothetical scenarios, the increase in suspended sediment, mud and nutrients also resulted in a decrease in microphytobenthic/biogenic habitat nodes and associated functional nodes such as Benthic GPP, Benthic nutrient cycling and Denitrification. This was related to factors such as a reduction in benthic photosynthetic processes due to decreased Water clarity and increased Water column algae, highlighting the cascading impacts of stress on ecosystem function.

4.4 Model caveats

1. The model was applied to estuaries and sub-estuaries of a range of different sizes, shapes, bathymetry and hydrodynamics. One of the advantages of the model is that it can be applied at a range of spatial scales, from the scale of individual samples, to sub estuary, estuary, and multiple estuary scale. However, it is important to note that

while we discuss the BN outputs broadly for each case study estuary, the data used to set the stressor levels for each scenario estuary was based on limited sampling data at the sampling scale in specific areas, which does not necessarily represent the entire estuary. This data had been collected by various agencies for a variety of reasons, not specifically for the purpose of this model and, in the case of Tauranga, agency data had been supplemented by an MBIE funded Endeavour Project. In some estuaries the spatial distribution and number of samples was relatively high (i.e., Tauranga with 69 intertidal and 45 subtidal sampling sites, or the mud data for New River with 65 sampling points) whereas at others the model was informed by less than 10 sampling points (both arms of Raglan and Porirua, Havelock).

2. The combination of limited data used to inform the model, as well as similarities in the environmental conditions at the five case study estuaries contributed to some similarity in model outputs across the five case study estuaries. Despite this, the model distinguished strongly between the New River (highest levels for most stressors) and Tauranga (lowest levels for most stressors).

3. The development of the model required pragmatic decisions to minimise the number of nodes and relationships, determined based on expert opinion (based on best practice for developing BNs, (Marcot, 2017)). The models' purpose is to better understand the impact of multiple stressors on estuarine ecosystems in a general way using probability distributions and not to make accurate exact predictions of current or future states. With this in mind, the ecosystem components selected were the most important identified by the workshop participants rather than including every possible stressor/response node or relationship.

4. The levels (states) for each ecosystem response component were determined based on expert opinion and relevant literature, in addition to percentiles of available datasets. We acknowledge that the definition of node states are a potential driver of the results as the functional form of the probability distributions and also the conditional probabilities are produced based on a combined understanding of those levels by the experts. However, the principles applied to the model hold true regardless of the state categorisations (i.e., large declines in the likelihood of high species abundance in response to high and very high stressor levels/combinations are a reflection of literature). Taking the Metal node for example, if the defined concentration of metals was increased for each state (i.e., state definitions were all shifted down so that low concentrations now are defined by the older moderate conditions, and so on), then the drop off in species abundance would simply occur earlier. The key point here being that the state definitions (which include specifics on the associated concentrations/units) determine **when** the response is generated, but the ecological response dynamics are reflections of **what** is observed/expected in the real world.

5. Prior to being constrained by stress, the potential outcomes were generated based on expert opinion in an attempt to account for the other factors that are not in the model (e.g., within species/group variability in response to stress, harvesting and benthic disturbance, species interactions, sediment characteristics other than mud content, subtidal and intertidal environments, as well as expert uncertainty). One result of this is that at Very Low and Low stressor levels, a wide range of outcomes are expected

(e.g., near equal probabilities of all states occurring for most nodes). This has the effect of diluting somewhat the changes that occur as stressors move between Very Low to Moderate. Having more background information on the spatial variability of ecosystem components within estuaries with Very Low and Low stressors levels would help overcome this.

6. In order to reduce model complexity (and increase interpretability) the model was limited temporally to the present time (and the near future to ~2040). If the model was repeated with the objective to investigate historic conditions, the conditional probability distributions for many of the nodes, under low stress scenarios, would likely to be skewed further towards the High or Very high ecological outcomes. For example, ecological communities are likely to have changed considerably through time in response to historic fishing impacts. Further, limiting the model to the near future also limits the potential impact of climate change on sea level rise and ocean acidification on estuarine ecosystems, allowing us to focus on effects of temperature. Note that other impacts of climate change, such as changes to rainfall/storm intensity, were considered by the experts to be better captured by the Suspended sediments/Mud content/Metals/Nitrogen nodes than one climate change node.

7. Much of the research on which this model relies has come from intertidal and shallow (<20m) subtidal areas due to practicalities in conducting experiments in deep subtidal areas. While this was taken into consideration by the experts in developing the relationships between nodes, it does mean that there is less certainty in applying the model to estuaries with relatively large areas of deep water (e.g., sounds and fjords). However, these types are a low proportion of the numbers of estuaries in New Zealand with approximately 38% being shallow intertidally dominated estuaries (Hume 2018). In addition, recent work in regard to the relationship between macrofauna benthic health responses to metals and mud, (Clark et al. 2019) has shown that regional and typology differences were not a significant driver of the relationships.

4.5 Potential next steps

A significant advantage of BNs is that they are relatively easy to update as more information becomes available. They can also be used to indicate where increased understanding could be beneficial (see section 3.2 and 4.1). For example, climate change temperature effects are heavily influenced by the number of extreme temperature events and presently there is little information on ecological responses to these. Given the number of days of extreme temperatures in the last summer, it is likely that we would be able to better define our conditional probabilities for this stressor in the near future.

In estuaries where additional stressors may be playing a critical role in ecosystem function (such as fishing), it may be worth creating additional models to better explore these relationships or refining the parameterisation of the model. Similarly, having more background information on the spatial variability of ecosystem components within estuaries with Very Low and Low stressors levels would be useful.

Potential next steps may include refining the model so that stressor nodes more readily link with existing field datasets and environmental data layers. This may improve the capacity of the model to represent stressor impacts and responses within estuaries. This may mean modifying stressor nodes where spatial data are either not readily available or difficult to translate into ecologically relevant relationships (for example, suspended sediment). Moving forward, applying the BN spatially may improve the value of the model, such as enabling identification of likely hotspots of ecosystem function and biodiversity within estuaries, along with areas of high resilience, vulnerability and degradation.

There are two areas for use of BNs that were not explored with this model. Firstly, BNs can be used to understand changes to values (e.g., if the relationship between mud content and walkability is known, effects on access could be incorporated). Further, the relative ease in which expert knowledge can be incorporated into BNs suggests their potential utility in generating Mātauranga based models of estuarine ecosystem dynamics (for example models informed by iwi oral histories). It may be possible to pair any such models to the current model to expand the combined scope of both approaches.

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7 Appendices

Appendix A Full description of Bayesian network nodes and relationships

Table A-1: Full description of stressor nodes, state ranges and the data used to create the states.

Node	Unit and definition	State	Expert opinion informed by:
Sediment mud content (Mud content)	% Mud (silt and clay) % by dry weight of surface (generally top 2 cm) sediment particles in a sample <63 µm in diameter.	• Very Low: <5 • Low: 5 to 20 • Moderate: 21 to 50 • High: 51 to 90 • Very High: >90	Field data, such as the Tipping Points dataset and publicly available regional council monitoring data (Hewitt et al. 2009, Thrush et al. 2012, Rodil et al. 2013).
Suspended sediment	Mean mg L^{-1}Total suspended solids (TSS) TSS is the dry-weight of all suspended particulate matter in a water sample (usually assessed by filtering the sample through a pre-weighed 0.8 or 1.2 µm pore size filter).	• Very Low: <5 • Low: 5 to <20 • Moderate: 20 to <40 • High: 40 to 70 • Very High: >70	Total suspended solid data from a nationwide summary of water quality data across New Zealand (Dudley et al. 2017) and field studies , or inferred from modelled estuarine sediment loads (retrieved from the NIWA sediment load model) (Hicks et al. 2019).
Nitrogen inputs to estuary (Nitrogen)	Total Nitrogen mg m^{-3} yr^{-1} Predicted specific nitrogen load within water column of an estuary.	• Very Low: <40 • Low: 40 to <80 • Moderate: 80 to <200 • High: 200 to 320 • Very High: >320	Estimates were derived from the GIS software CLUES-estuary (Zeldis et al. 2011), which predicts annual specific nutrient loads to estuaries. The estuary component consists of either of two flushing/mixing models a two-layer box model for deep or strongly stratified estuaries, and a modified tidal prism model used for most tidally dominated estuaries, such as the New River Estuary. The flushing/mixing models provide a time-averaged, volume-averaged prediction of total nitrogen (TN). Potential nutrient concentrations are the concentrations that would occur if there were no biological uptake or denitrification. Potential nutrient concentrations provide an indication of the loading applied to the estuary, and may be more useful than actual (measured) concentrations, which are influenced by denitrification and biological uptake. A high algae biomass, as expected in eutrophic

Node	Unit and definition	State	Expert opinion informed by:
			conditions, may take up much of the available nutrients, resulting in low measured concentrations relative to the applied loading. Potential nutrient concentrations are expected to be higher than actual concentrations.
Metal concentrations (Metal)	PC1.5 Weighted concentrations of the metals Zinc, Copper, Lead within surface sediments (generally to 10 cm depth).	• Very Low: <-0.164 • Low: -0.164 to -0.0667 • Moderate: -0.0667 to <0.0234 • High: 0.0234 to 0.1 • Very High: >0.1	Data used to inform expert opinion obtained from principal component analysis (PCA) of publicly available monitoring datasets (Hewitt et al. 2009, Rodil et al. 2013), which include metal concentrations in surface sediments and are related to Auckland Council guidelines which are increasingly used throughout the country. Values are calculated using the equation below, where *X* is metal concentration in mg/kg. The PCA 1st axis explained 94% of the variability in log Copper (Cu.500), Zinc (Zn.500), and Lead (Pb.500). PC1.5 = $0.615\times(X_{Cu}^{(500)})+0.528\times(X_{Zn}^{(500)})+0.586\times(X_{Pb}^{(500)})$
Climate change	Predicted change in air temperature (°C) through time.	• Very low: Mean temperature increase by +0.5°C; 20% decrease in frosts; 20% increase in extreme hot days • Low: Mean temperature increase by +0.7°C; 30% decrease in frosts; 40% increase in extreme hot days • Moderate: Mean temperature increase by +0.85°C, 40% decrease in frosts; 70% increase in extreme hot days • High: Mean temperature increase by +1°C; 50% decrease in frosts; 100% increase in extreme hot days • Very High: Mean temperature increase by +1.1°C; 60% decrease in frosts; 120% increase in extreme hot days	Scenarios based on IPCC 5th Assessment report and simulations run on NIWA's super computer (MfE 2018). Predictions as follows: • Mean air temperature by 2040, from +0.7°C [RCP2.6] to +1.0°C [RCP8.5]. • Minimum and maximum air temperatures, maximum increases faster than minimum. Diurnal range increases by up to 2°C by 2090 (RCP8.5). • Daily temperature extremes - frosts by 2040, a 30% [2.6] to 50% [8.5] decrease. • Daily temperature extremes hot day by 2040, a 40% [2.6] to 100% [8.5] increase. • Daily precipitation extremes dry days by 2090 [8.5], up to 10 or more dry days per year (~5% increase). • Daily precipitation extremes very wet days. More than 20% increase in 99th percentile of daily rainfall by 2090 [8.5] in South West of

Node	Unit and definition	State	Expert opinion informed by:
			South Island. A few percentage decrease in north and east of North Island. • Extreme wind speeds Up to 10% or more in parts of the country. *Note, mean precipitation is predicted to vary around the country and with season. Therefore, the climate change node is based primarily on predicted changes in temperature. To capture differences in precipitation throughout the country for individual estuaries it is instead possible to modify the suspended sediment and nutrient load nodes, which are positively related to rainfall. This node does not include other potential climate change impacts such as changes to water column temperature, pH, wave disturbance, elevated erosion, sea level rise etc.* *The model timeframe was considered now until the near future (ie to 2040) to constrain the uncertainties around climate change. Based on this timeline, in the experts view sea level rise and acidification were not a major consideration. Similarly, the experts viewed climate change induced changes to storm intensity/frequency to be a relatively minor stressor in the context.*

Table A-2: Full description of ecosystem component nodes, state ranges, the data used to create the states and the relationships with other nodes.

Node	Unit and definition	State	Expert opinion informed by:	Relationships
Large bioturbating deposit feeders	Number of individuals per 13 cm diameter core (generally 15 cm depth). Large deposit feeders bioturbate the sediment, transporting organic material and changing oxygen gradients throughout the sediment column, influencing carbon	• Very Low: Not present • Low: ≤1 • Moderate:1 to <2 • High:2 to 3 • Very High: >3	Field data, such as the Tipping Points dataset and publicly available regional council monitoring data (Thrush et al. 2003a, Hewitt et al. 2009, Pratt et al. 2014a).	*Suspended sediment* –Negative from Moderate to Very High (Thrush et al. 2004) *Mud content* – Positive from Very low to Low, Negative from Moderate to Very High (Thrush et al. 2003b, Ellis et al. 2017b)

Node	Unit and definition	State	Expert opinion informed by:	Relationships
	and nutrient cycling processes. Examples include *Macamona liliana* (wedge shell), *Austrohelice crassa* (mud crab), *Hemiplax hirtipes* (mud crab), *Owenia petersenae* (tube worm), *Platynereis australis* (nereid polychaete worm)			*Metals* - Negative from Moderate to Very High (Hewitt et al. 2009, Ellis et al. 2017b) *Water column algae* –Negative (Green et al. 2014)
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 source for higher trophic levels, including humans. Large suspension feeding bivalves Examples *Austrovenus stutchburyi* (cockles), *Paphies australis* (pipi), *Pectinidae* (scallops), *Atrina zealandica* (horse mussel), *Perna canaliculus* (green shell mussel).	• 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. 2003a, Hewitt et al. 2009, Pratt et al. 2014a).	*Suspended sediment* –Negative from Moderate to Very High (Ellis et al. 2002, Lohrer et al. 2006) *Mud content* – Negative from Moderate to Very High (Thrush et al. 2003b, Ellis et al. 2017b) *Metals* - Negative from Moderate to Very High (Hewitt et al. 2009, Ellis et al. 2017b) *Large bioturbating deposit feeders* - Negative from Moderate to Very High (Lohrer et al. 2013) *Water column algae* – Positive from Very Low to Moderate, Negative from Moderate to Very High (Green et al. 2014)
Benthic biodiversity	Number of species per 13cm 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. 2003a, Hewitt et al. 2009, Pratt et al. 2014a).	*Suspended sediment* – Increasingly negative from Moderate to Very High (Thrush et al. 2004) *Mud content* – Negative from Moderate to Very High (Thrush et al.

Node	Unit and definition	State	Expert opinion informed by:	Relationships
				2003b, Lohrer et al. 2004a, Ellis et al. 2017b) *Metals* - Increasingly negative from Moderate to Very High (Hewitt et al. 2009, Ellis et al. 2017b) *Water column algae* – Negative (Green et al. 2014)
Macrofauna	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
Microphytob-enthos	Chlorophyll *a* (µg g^{-1} sediment) Microphytobenthos consists of unicellular eukaryotic algae and cyanobacteria that grow within the upper several millimeters of sediments. Chlorophyll *a* is a pigment that can be measured by standard methods as a proxy for microphytobenthos abundance.	• 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).	*Suspended sediment* –Negative (Rodil et al. 2011, Pratt et al. 2014b) *Mud content* – Positive (Pratt et al. 2015) *Nitrogen* – Positive (Sandwell et al. 2009) *Water column algae* – Negative (Corzo et al. 2009, García-Robledo and Corzo 2011, Pratt et al. 2014b) *Macrofauna* – Positive (Lohrer et al. 2004b, Sandwell et al. 2009, Rodil et al. 2011, Pratt et al. 2015)
Phytoplankt-on	Chlorophyll *a* (mg l^{-1} water) Phytoplankton are microscopic algae within the water column. Chlorophyll *a* is a pigment	• Very Low:<0.001 • Low 0.001 to <0.0015 • Moderate: 0.0015 to <0.0028 • High: 0.0028 to 0.0042 chl a • Very High: >0.0042 chl a	Water column chlorophyll *a* concentrations from a nationwide summary of water quality data across New Zealand (Dudley et al. 2017).	*Suspended sediment* –Negative (Christine et al. 2003) *Nitrogen* – Positive (Anderson et al. 2002)

Node	Unit and definition	State	Expert opinion informed by:	Relationships
	that can be measured by standard methods as a proxy for phytoplankton abundance.	*Note, units updated post workshop to align with Dudley et al.2017 dataset*		
Nuisance Macroalgae	Algal cover (%) and wet weight (g) per area (m^2) Nuisance Macroalgae (e.g., *Ulva sp*/sea lettuce and *Gracilaria spp* /red algae in soft-sediment areas).	• 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 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.	Informed by outputs from a modified version of the estuary trophic index tool (Plew et al. 2019).	*Suspended sediment* –Negative (Coutinho and Zingmark 1993) *Nitrogen* – Positive (Coutinho and Zingmark 1993, Anderson et al. 2002)
Water column algae	Intermediate node which combines *Phytoplankton* and *Nuisance Macroalgae* nodes.	Intermediate node	Used to reduce the number of parent nodes feeding into child nodes throughout the model.	*Macroalgae* – Positive *Phytoplankton* - Positive
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.	Informed primarily based on mangrove data as comparably little data exists on saltmarsh (Morrisey et al. 2010).	*Suspended sediment* –Positive (Lovelock et al. 2010) *Nitrogen* – Positive (Lovelock et al. 2007)

Node	Unit and definition	State	Expert opinion informed by:	Relationships
		• Moderate: Moderate cover of fringing vegetation. Little evidence of expansion into other intertidal habitats • 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).	*Suspended sediment* –Negative (Ellis et al. 2002, Lohrer et al. 2006, Bulmer et al. 2018) *Nitrogen* – Positive (Desmond et al. 2015, Lohrer et al. 2016) *Large suspension feeding bivalves* – Positive (Anderson et al. 2019)
Juvenile and small 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).	*Macrofauna* – Positive (Duffy et al. 2016)

Node	Unit and definition	State	Expert opinion informed by:	Relationships
		• Moderate: Moderate abundance of fish present. • High: High abundance of fish present. Very High: Very High abundance of fish present.		*Biogenic habitat* – Positive (Parsons et al. 2013, Morrison et al. 2014, Parsons et al. 2014) *Water clarity* – Positive (Parsons et al. 2013)
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 (e.g., Near exit to Thames river) • 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 (e.g., Parengarenga)	Informed by secchi depth measurements from a nationwide summary of water quality data across New Zealand (Dudley et al. 2017).	*Suspended sediment* –Negative (Devlin et al. 2008) *Phytoplankton* – Negative (Devlin et al. 2008) *Microphytobenthos* – Positive (MacIntyre et al. 1996) *Large suspension feeding bivalves* – Positive (Hewitt and Norkko 2007)
Carbon stocks/ storage	% organic material in surface sediments 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.	• Very Low: <1% • Low: 1 to <2% • Moderate: 2 to <3% • High: 3 to 4% • Very High: >4%	Informed by field datasets, including the Tipping Points dataset and publicly available regional council monitoring data (Thrush et al. 2003a, Hewitt et al. 2009, Pratt et al. 2014a).	*Mud content* – Positive (Lohrer et al. 2011) *Biogenic habitat* – Positive (Bulmer and Lundquist 2016) *Fringing vegetation* – Positive (Bulmer and Lundquist 2016, Bulmer et al. 2019)
Benthic Gross Primary Production (GPP)	µmol O_2 m^{-2} hr^{-1} Benthic GPP is the gross production of oxygen by	• Very Low: Strongly net heterotrophic (benthic oxygen consumption >235 µmol m^{-2} hr^{-1} more than oxygen	States determined based on expert opinion and field data, such as the Tipping Points dataset and other benthic chamber experiments (Pratt et al. 2014a).	*Microphytobenthos* – Positive (Lohrer et al. 2011, Drylie et al. 2018)

Node	Unit and definition	State	Expert opinion informed by:	Relationships
	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).	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.		*Climate change* – Negative (Pratt et al. 2014a, Bulmer et al. 2015) *Biogenic habitat* – Positive (Drylie et al. 2018)
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. Denitrification is considered the dominant pathway for the removal of nitrogen from shallow coastal and estuarine systems.	• Very Low: Little to no net efflux of N_2 gas out of the sediment (≤0 umol N_2 µmol m^{-2} hr^{-1}) • Low: Low net efflux of N_2 gas out of the sediments (0-<37 umol N_2 µmol m^{-2} hr^{-1}) • Moderate: Moderate net efflux of N_2 gas out of the sediments (37-<100 umol N_2 µmol m^{-2} hr^{-1}) • High: High net efflux of N_2 gas out of the sediments (100-200 umol N_2 µmol m^{-2} hr^{-1}) • Very High: Very high net efflux of N_2 gas out of the sediments (>200 umol N_2 µmol m^{-2} hr^{-1})	States determined based on expert opinion and field data, such as the Tipping Points dataset (Peterson 2018).	*Benthic GPP* – Positive (Gongol and Savage 2016) *Macrofauna* – Positive (Lohrer et al. 2004b, Gongol and Savage 2016) *Suspended sediment* – Negative *Mud content* – Positive (Gongol and Savage 2016, Douglas 2018) *Nitrogen* – Positive (Nowicki 1994, Gongol and Savage 2016) *Climate change* – Positive (Nowicki 1994)

Node	Unit and definition	State	Expert opinion informed by:	Relationships
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). Calculated using field data from benthic chamber experiments, based on the difference in NH_4^+ flux from chambers exposed to the dark (where only respiration occurs) and chambers exposed to the light (where photosynthesis can occur).	• 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 based on expert opinion and field data, such as the Tipping Points dataset and other benthic chamber experiments (Pratt et al. 2014a).	*Microphytobenthos* – Positive (MacIntyre et al. 1996) *Macrofauna* – Positive (Lohrer et al. 2011, Thrush et al. 2017) *Climate change* – Positive (Bulmer et al. 2017)
Second stage effects on Large suspension feeding bivalves	Number of individuals per 13 cm diameter core Act as key species in estuarine ecosystems filtering the water column, influence seafloor/water column carbon and nitrogen cycling, and provide an important food source for higher trophic levels, including humans. Large suspension feeding bivalves Examples *Austrovenus stutchburyi* (cockles),	• 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. Bayesian Networks do not allow direct feedbacks between two nodes, relationships are required to be uni directional. By including 2nd stage ecology nodes, we are able to somewhat get around this limitation. This allows us to explore the impact of ecology on functional nodes (such as benthic gross primary production), and then the impact of functional nodes on ecology.	*Large suspension feeding* bivalves – Positive *Water clarity* – Positive (Hewitt and Norkko 2007) *Biogenic habitat* – Positive (Norkko et al. 2001) *Benthic GPP* – Positive (Lohrer et al. 2016)

Node	Unit and definition	State	Expert opinion informed by:	Relationships
	Paphies australis (pipi), *Pectinidae* (scallops), *Atrina zealandica* (horse mussel), *Perna canaliculus* (green shell mussel)			
Second stage effects on Biodiversity	Number of species per 13cm 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. Bayesian Networks do not allow direct feedbacks between two nodes, relationships are required to be uni directional. By including 2nd stage ecology nodes, we are able to somewhat get around this limitation. This allows us to explore the impact of ecology on functional nodes (such as benthic gross primary production), and then the impact of functional nodes on ecology.	*Benthic biodiversity* – Positive *Water clarity* – Positive (Hewitt and Norkko 2007) *Benthic GPP* – Positive (Lohrer et al. 2016)

Appendix B Description of deriving validation score

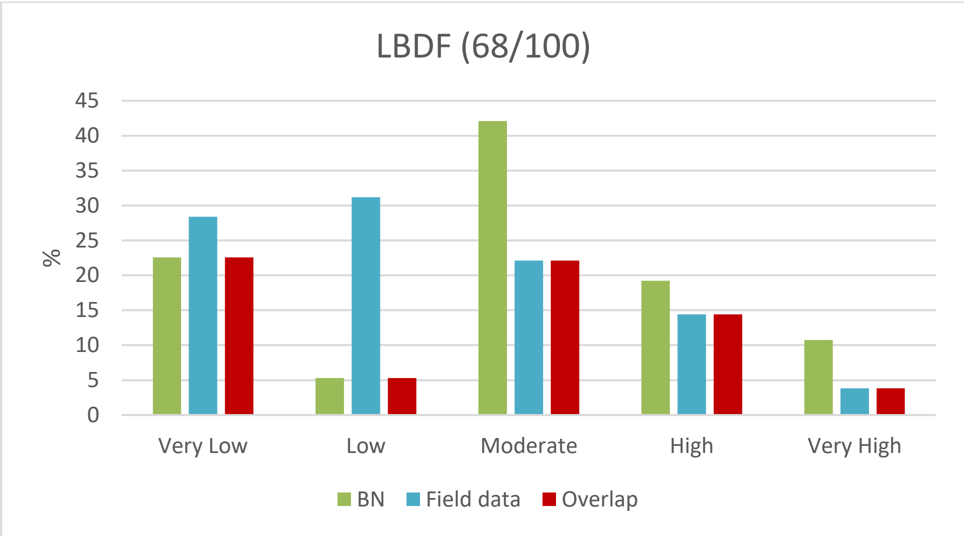

Figure B-1: Demonstration of how the BN model output was compared to field data. LBDF= Large bioturbating deposit feeders. 68/100 = sum of the areas of overlap.

Appendix C Information sources for the case study estuaries

Table C-1: Information available from the 5 case study estuaries.

	Informed by
Tauranga 1	Bay of Plenty Regional Council sediment data- 69 intertidal and 45 subtidal sites including paired sediment mud, nitrogen, and metal concentrations (Ellis et al. 2017a, Clark et al. 2018, Lawton and Conroy 2019). Suspended sediment inferred from https://statisticsnz.shinyapps.io/coastal_water_quality/
Whaingaroa (Raglan) 1 Waingaro arm	Environment Waikato REMP sediment data – 2 intertidal sites with paired sediment mud, nitrogen, and metal concentrations (3 reps per site). Suspended sediment inferred from https://statisticsnz.shinyapps.io/coastal_water_quality/
Whaingaroa (Raglan) 2 Waitetuna arm	Environment Waikato REMP sediment data – 2 intertidal sites with paired sediment mud, nitrogen, and metal concentrations (3 reps at each site). Suspended sediment inferred from https://statisticsnz.shinyapps.io/coastal_water_quality/
Porirua 1 Onepoto arm	Greater Wellington Regional Council sediment data – 3 intertidal and 4 subtidal sites with sediment mud data, paired nitrogen (2 sites) and metal concentration (4 sites) data (Robertson and Stevens 2015). Suspended sediment inferred from https://statisticsnz.shinyapps.io/coastal_water_quality/
Porirua 2 Pauatahanui arm	Greater Wellington Regional Council sediment data – 7 intertidal and 5 subtidal sites with sediment mud data, paired nitrogen (2 sites) and metal concentration (5 sites) data (Robertson and Stevens 2015). Suspended sediment inferred from https://statisticsnz.shinyapps.io/coastal_water_quality/
Havelock, Pelorus Sound/Te Hoiere	Marlborough District Council sediment mud data from 6 intertidal sites, paired nitrogen (4 sites), and metal concentration (4 sites) data. Suspended sediment inferred from Robertson (2019)
New River, Southland	Environment Southland sediment mud data from 68 sites. Remaining stressor information inferred from Robertson et al. (2017) and the NIWA sediment load and CLUES models.

Appendix D Model results for selected scenarios

Table D-1: The likelihood of scenarios resulting in Very Low or Low outcomes for each ecosystem component. The first five represent hypothetical estuaries exposed to progressively higher stressor impacts. The other scenarios are based on sample data available from five case study estuaries. Green = <40% likelihood of a Very Low or Low state, White = 40-80% likelihood of a Very Low or Low state, Red = >80% likelihood of a Very Low or Low state.

	VL	L	M	H	VH	Tauranga	Tauranga (+M)	Tauranga (+SS, Md, M, N)	Whaingaroa 1	Whaingaroa 2	Porirua 1	Porirua 2	Te Hoiere-Havelock	New River
Large bioturbating deposit feeders	36	39	34	95	100	50	62	69	67	67	65	56	74	83
Benthic biodiversity	18	27	33	98	100	48	58	74	72	63	53	49	78	90
Fringing vegetation	30	26	18	16	16	24	24	20	20	20	26	27	21	16
Large suspension feeding bivalves	28	28	32	97	100	45	72	74	87	87	66	60	89	87
Macrofauna	11	29	34	98	100	48	63	59	75	69	59	54	80	89
Microphytobenthos	33	56	24	83	98	51	51	64	62	64	49	46	71	82
Biogenic habitat	16	25	40	61	86	39	41	57	59	59	38	38	63	60
Water clarity	28	7	21	90	100	27	26	57	70	70	25	6	72	86
Benthic gross primary production	26	34	23	58	65	37	37	45	43	44	35	34	48	54
Denitrification	52	53	57	87	91	60	68	74	76	73	67	65	78	78
Benthic nutrient cycling	21	31	27	71	77	39	47	55	53	51	44	41	59	67
Carbon stocks	43	43	36	33	32	41	41	37	35	37	42	41	36	40
Second stage effects on Large suspension feeding bivalves	23	25	31	95	100	43	67	71	83	84	62	55	86	85
Second stage effects on Biodiversity	13	21	31	97	100	44	53	70	68	59	48	44	75	89
Juvenile and small fish	28	33	41	95	99	50	63	71	73	68	59	48	77	85
Nuisance Macroalgae*	100	100	27	0	1	73	73	59	59	59	100	100	54	0
Phytoplankton*	100	100	11	0	1	70	70	58	59	59	100	100	54	0
Water column algae*	100	100	17	0	1	71	71	58	58	58	100	100	54	0

**Relationships inverse to other nodes - Very Low and Low states were considered to be ecologically favourable*

Table D-2: The likelihood of scenarios resulting in Very High or High outcomes for each ecosystem component. The first five represent hypothetical estuaries exposed to progressively higher stressor impacts. The other scenarios are based on sample data available from five case study estuaries. Green = >30% likelihood of a High or Very High state, White = 10-30% likelihood of a High or Very High state, Red = <10% likelihood of a High or Very High state.

	VL	L	M	H	VH	Tauranga	Tauranga (+M)	Tauranga (+SS, Md, M, N)	Whaingaroa 1	Whaingaroa 2	Porirua 1	Porirua 2	Te Hoiere-Havelock	New River
Large bioturbating deposit feeders	36	33	31	1	0	25	13	14	13	13	16	19	11	6
Benthic biodiversity	58	44	40	0	0	28	25	12	9	12	27	31	8	1
Fringing vegetation	28	32	37	46	62	35	35	20	44	44	35	32	44	46
Large suspension feeding bivalves	43	47	42	0	0	32	1	12	0	0	17	13	0	5
Macrofauna	64	43	39	0	0	28	19	13	8	10	24	26	7	4
Microphytobenthos	45	30	24	5	1	27	26	16	16	13	30	32	13	5
Biogenic habitat	61	40	19	13	5	25	23	12	9	9	28	23	8	14
Water clarity	64	63	29	0	0	41	38	15	6	6	48	50	4	2
Benthic gross primary production	46	33	52	13	2	34	34	25	28	26	36	38	22	14
Denitrification	33	32	27	8	6	26	20	17	15	17	21	23	14	13
Benthic nutrient cycling	31	47	48	18	17	40	33	27	26	28	37	39	23	18
Carbon stocks	36	36	39	46	49	36	36	41	42	38	36	38	42	38
Second stage effects on Large suspension feeding bivalves	53	50	44	0	0	34	5	13	2	2	20	17	1	6
Second stage effects on Biodiversity	63	47	45	0	0	31	27	14	12	15	30	34	10	2
Juvenile and small fish	52	47	43	2	0	34	24	18	15	17	27	37	12	7
Nuisance Macroalgae*	0	0	4	99	99	18	18	32	0	0	0	0	25	99
Phytoplankton*	0	0	11	99	99	23	23	32	0	0	0	0	25	99
Water column algae*	0	0	19	99	99	21	21	34	6	6	0	0	28	99

**Relationships inverse to other nodes - Very Low and Low states were considered to be ecologically favourable*

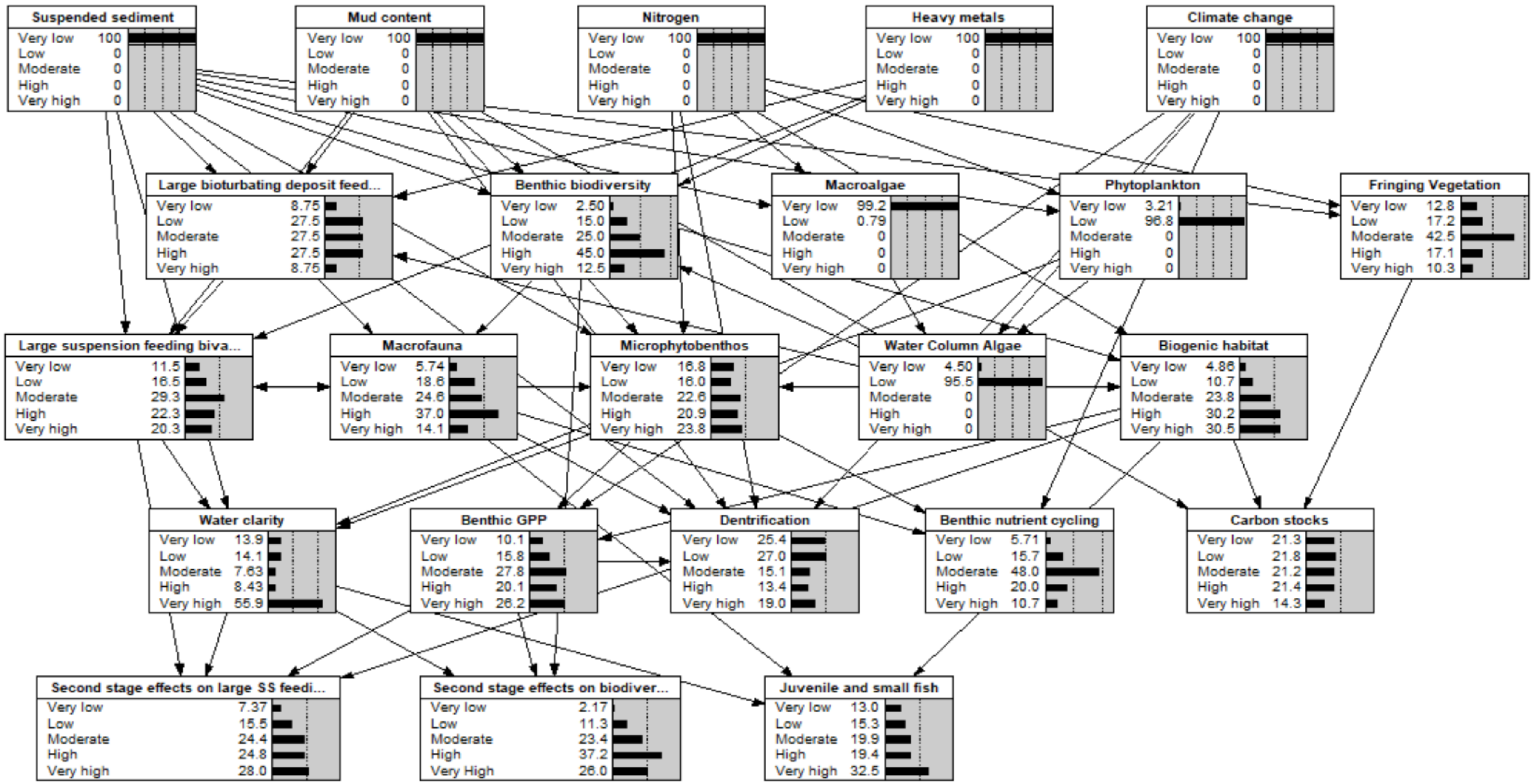

Figure D-1: BN model for all stressors set to Very Low.

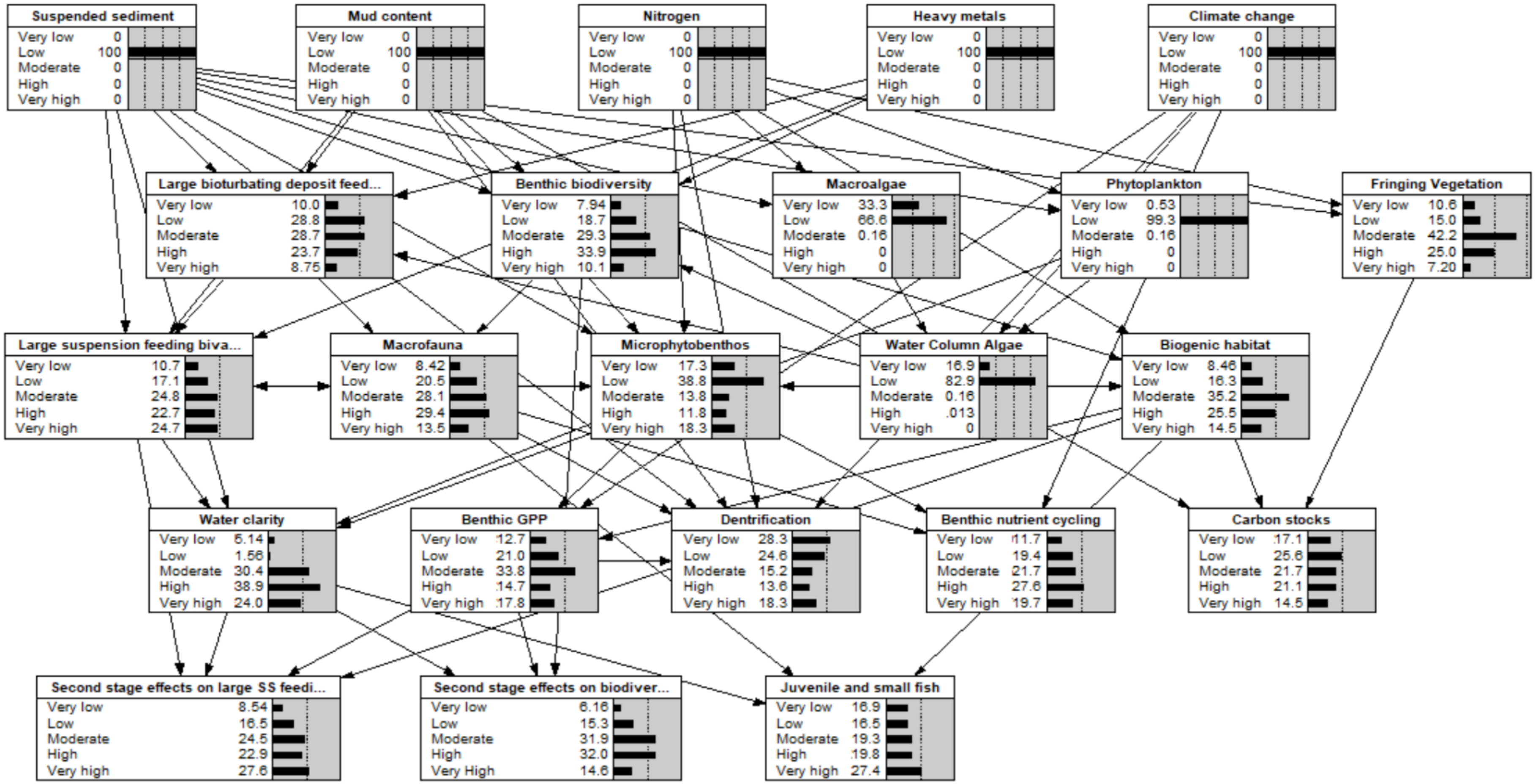

Figure D-2: BN model for all stressors set to Low.

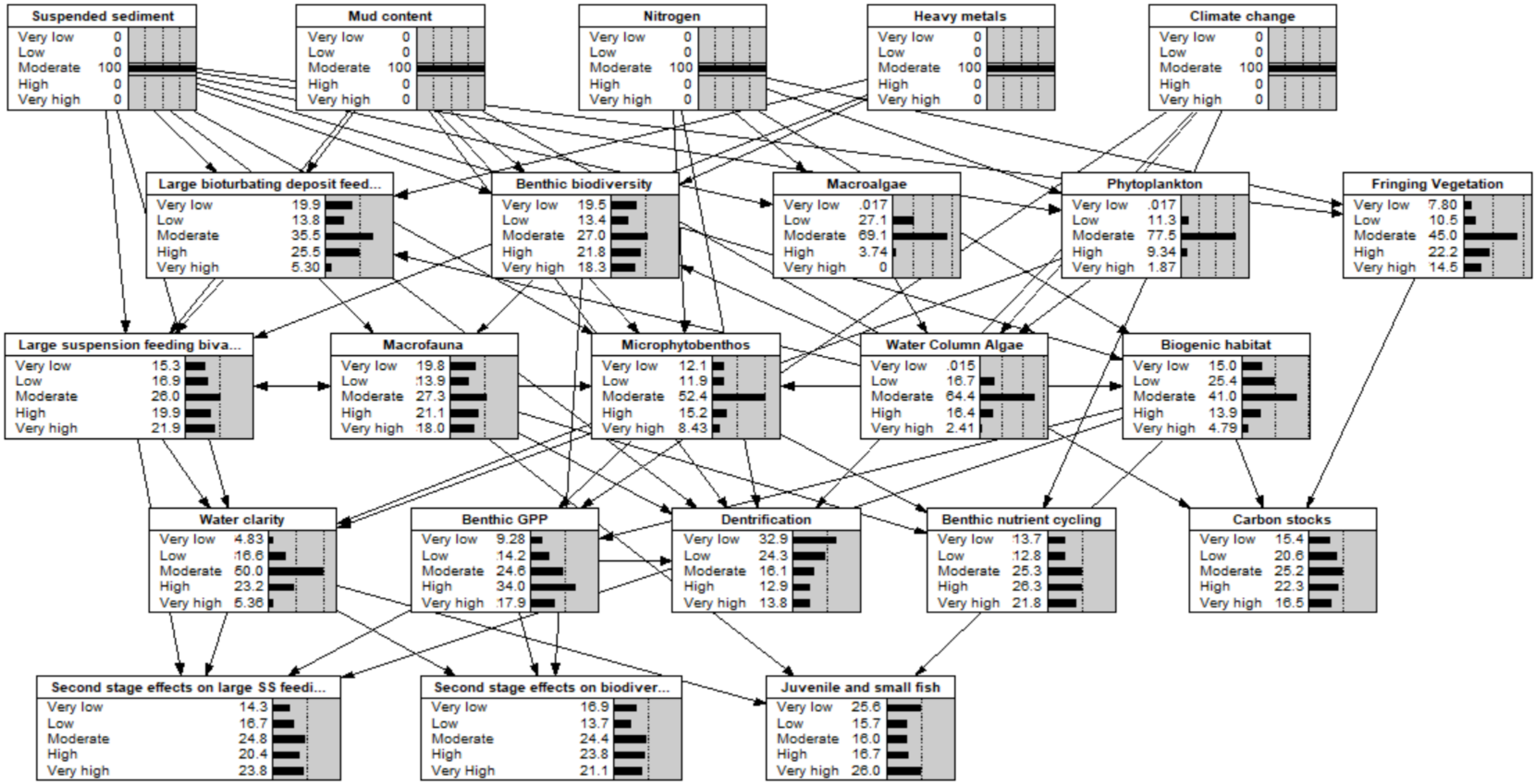

Figure D-3: BN model for all stressors set to Moderate.

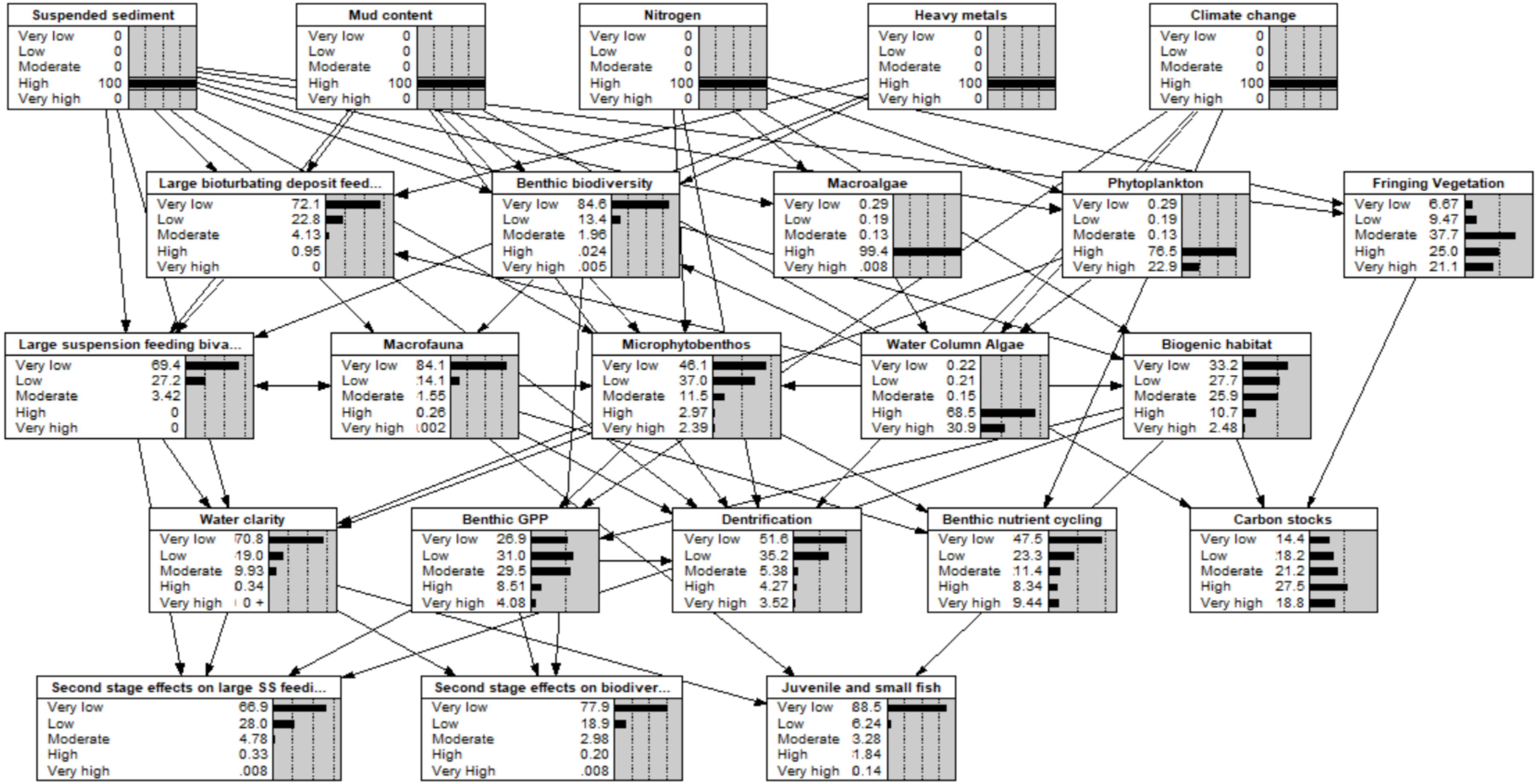

Figure D-4: BN model for all stressors set to High.

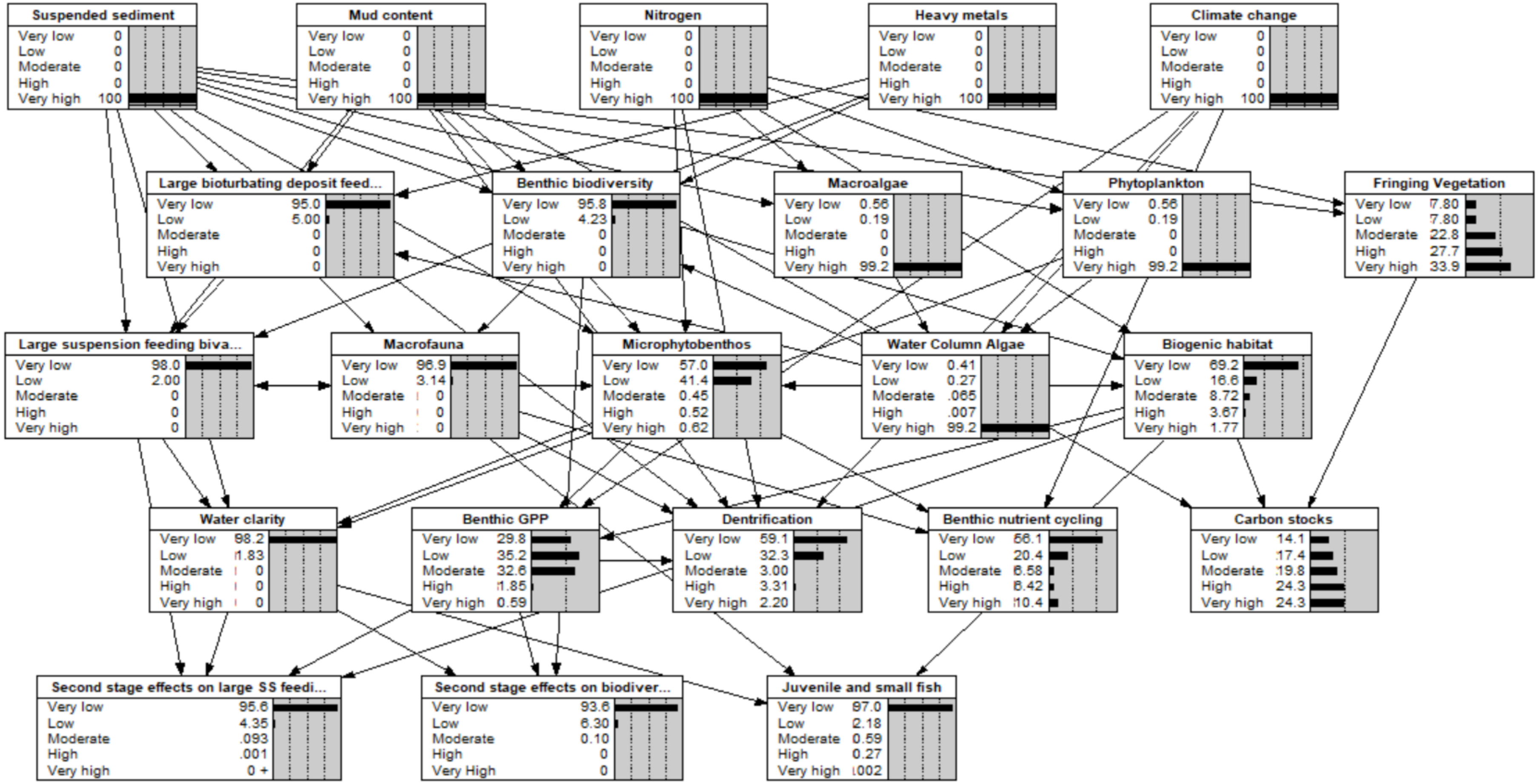

Figure D-5: BN model for all stressors set to Very High.

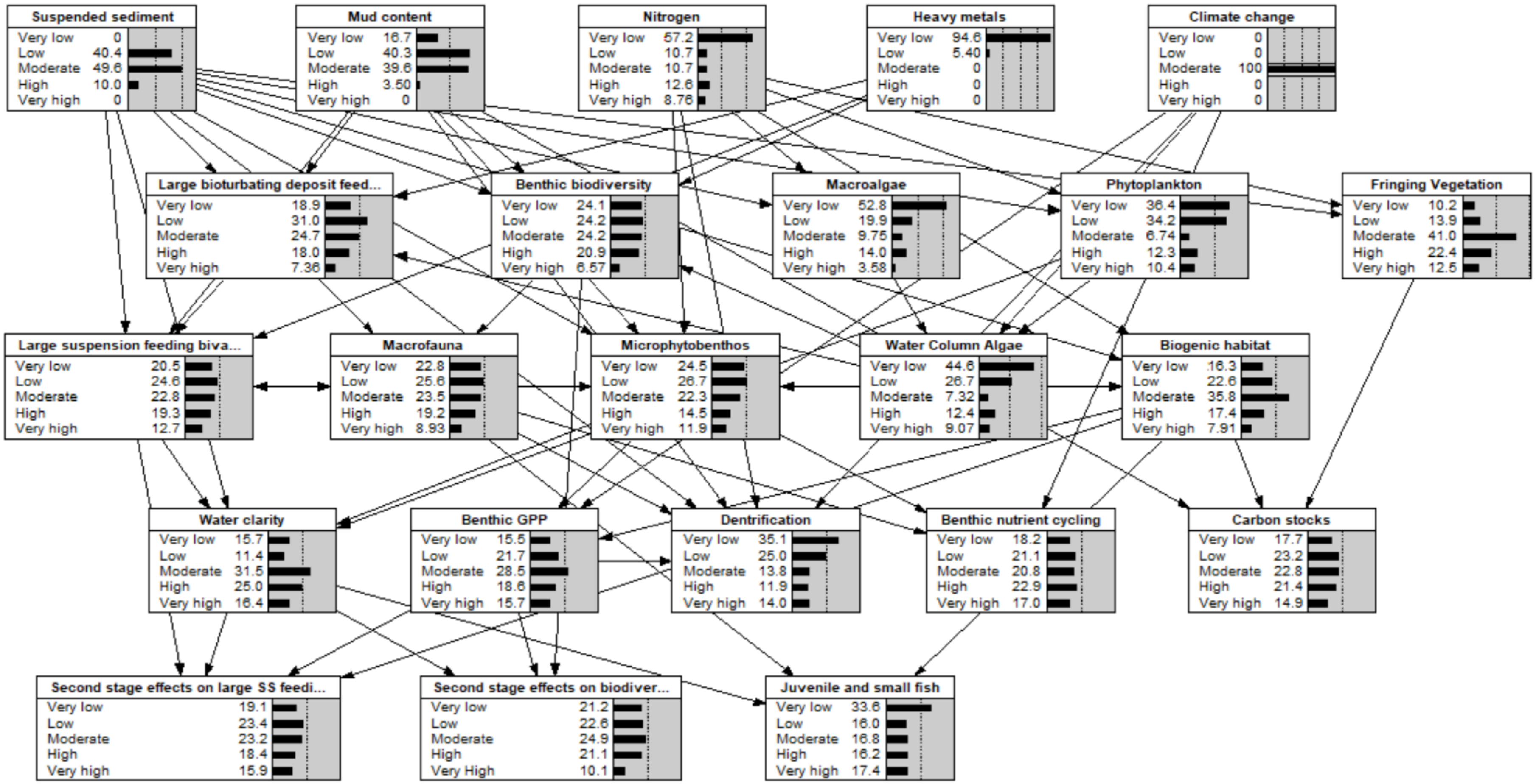

Figure D-6: BN model for Tauranga.

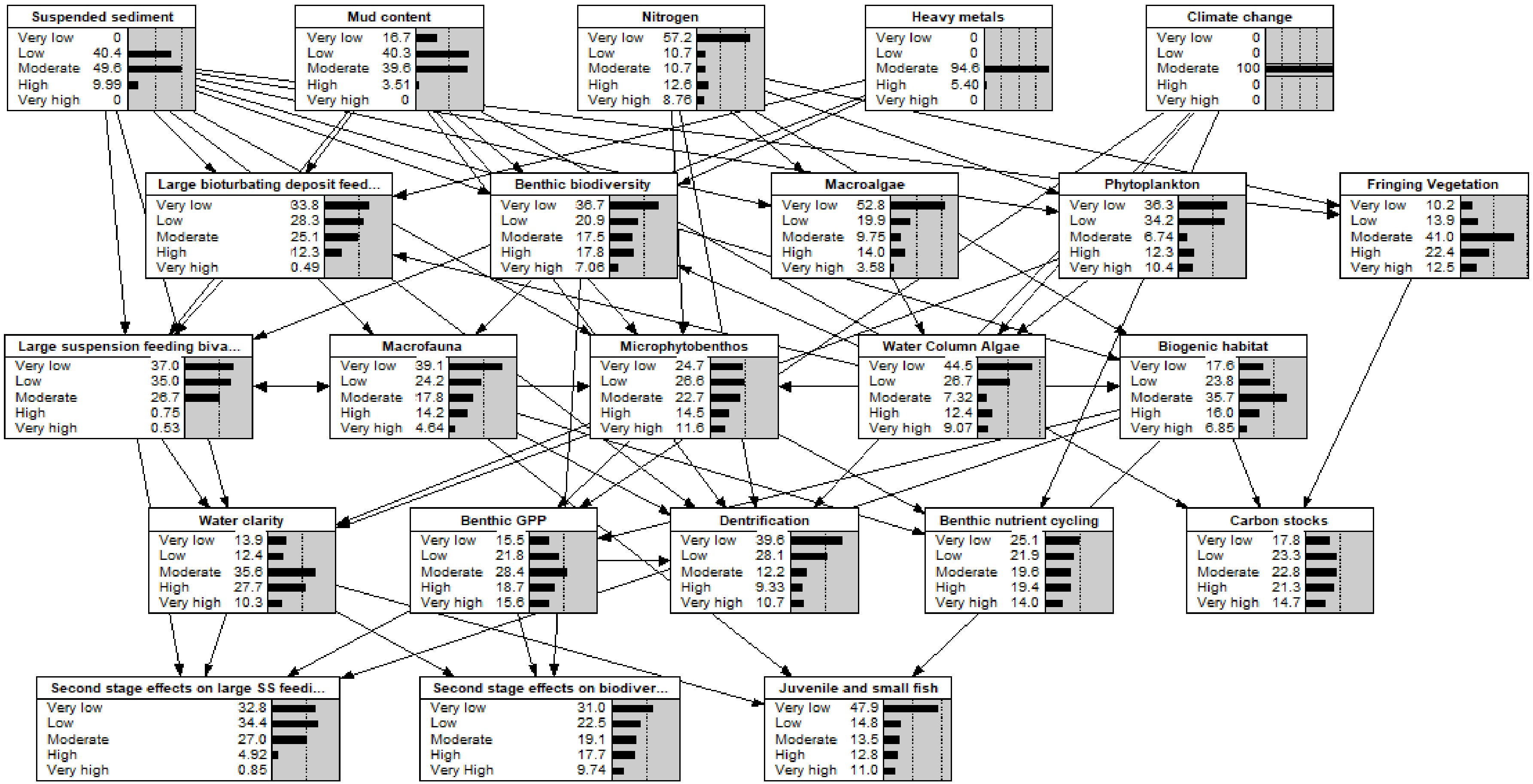

Figure D-7: BN model for Tauranga (upshift metals by two states).

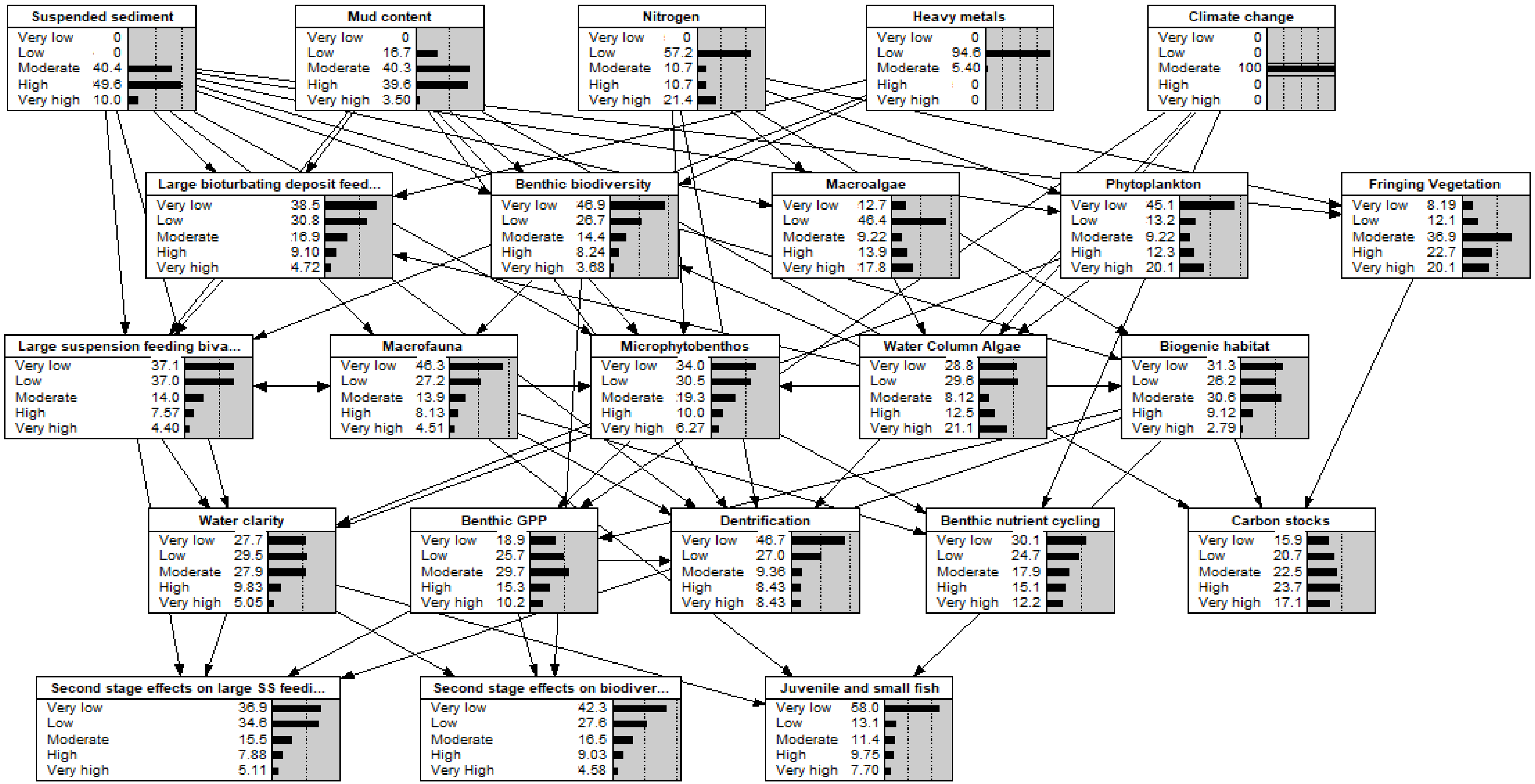

Figure D-8: BN model for Tauranga (upshift suspended sediment, mud, nitrogen, metals by one state).

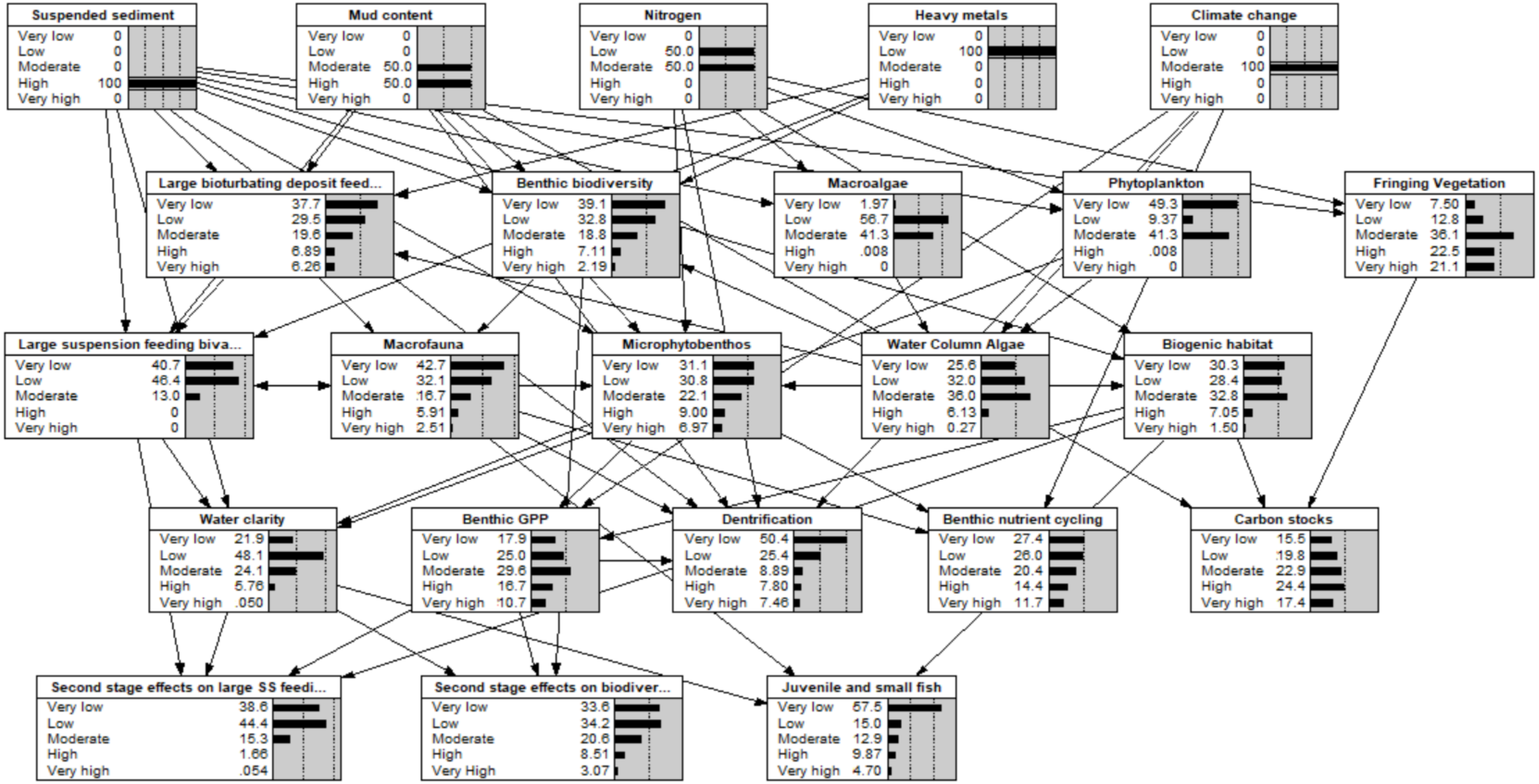

Figure D-9: BN model for Whaingaroa (Raglan) Waingaro arm.

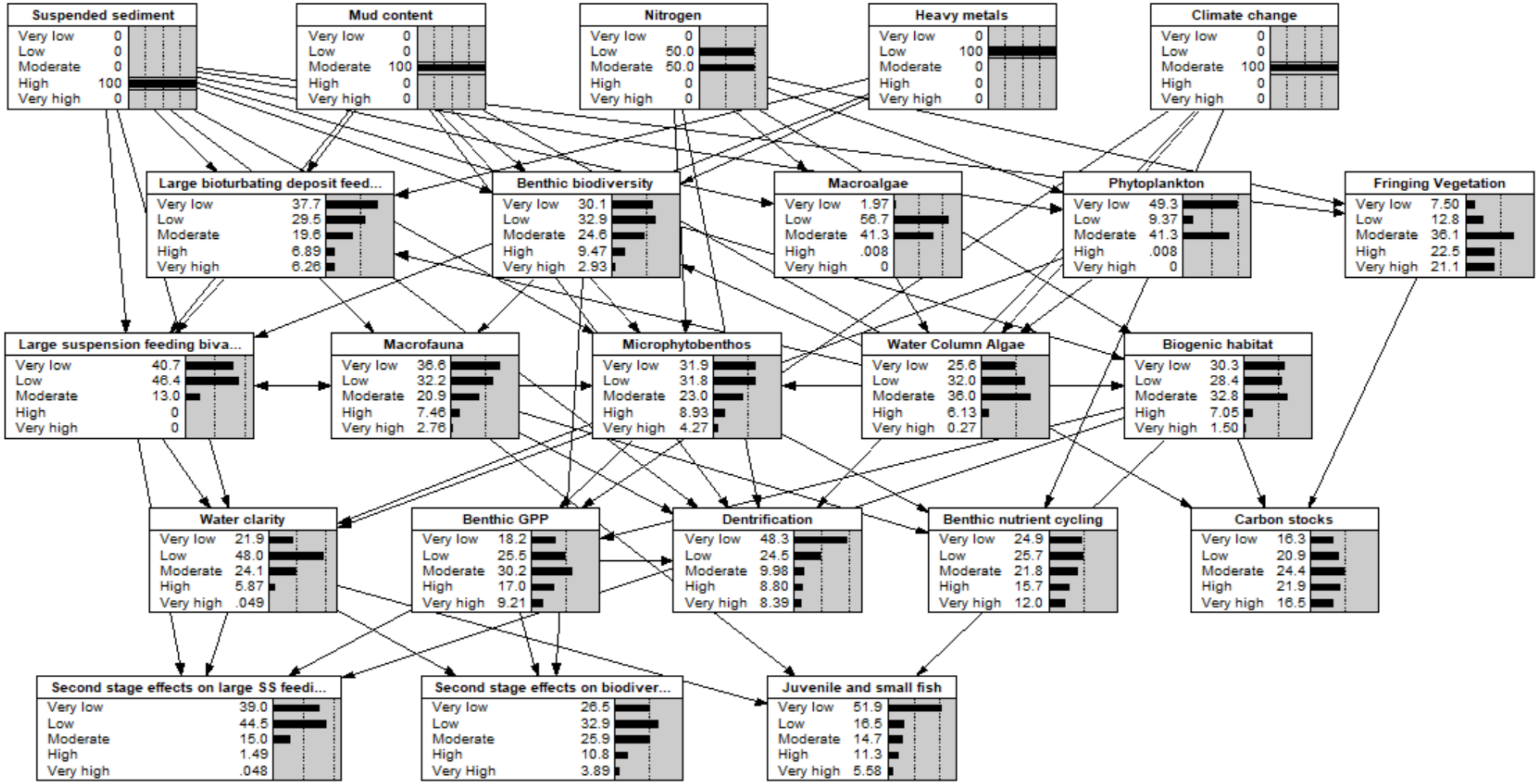

Figure D-10: BN model for Whaingaroa (Raglan) Waitetuna arm.

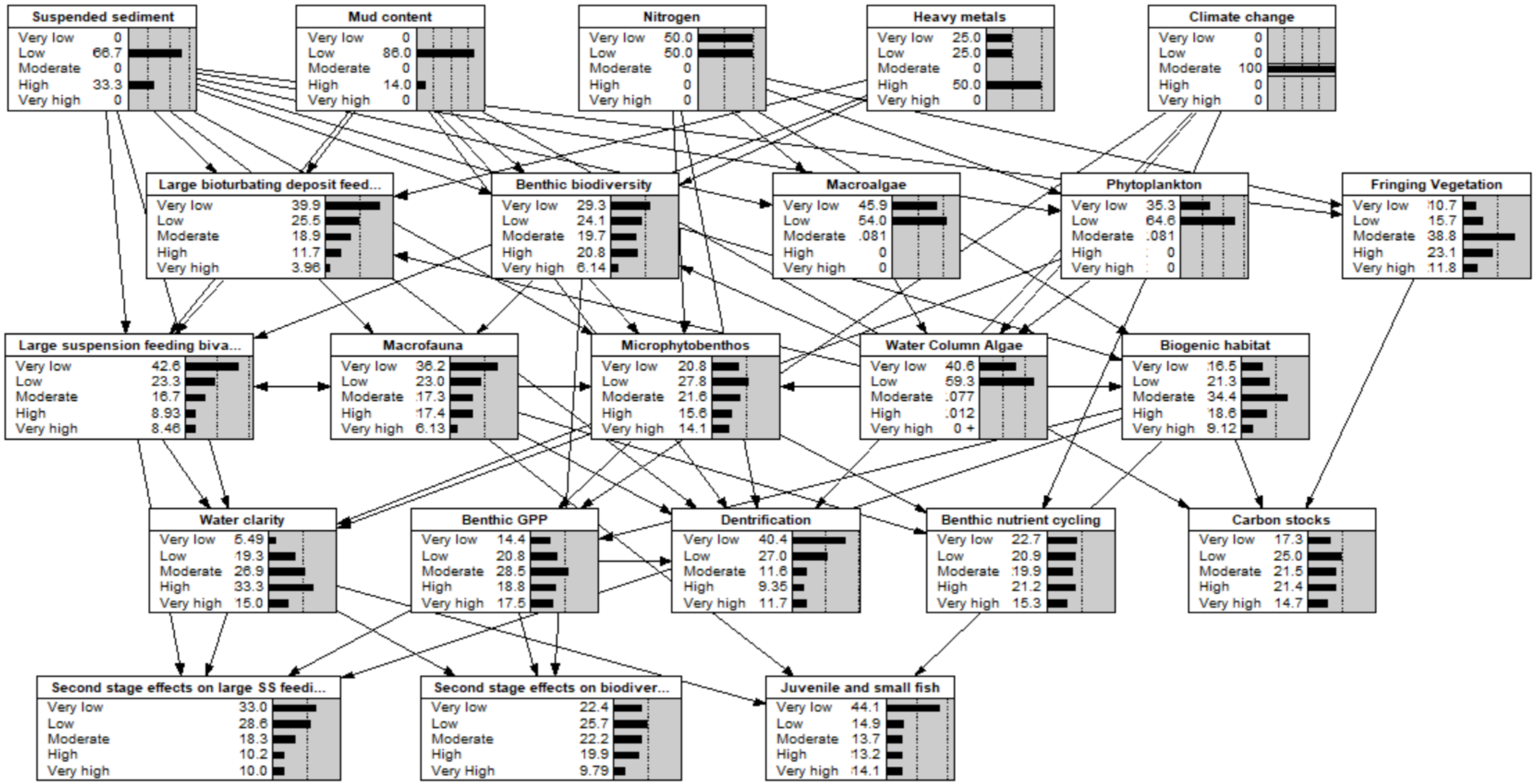

Figure D-11: BN model for Porirua (Onepoto arm).

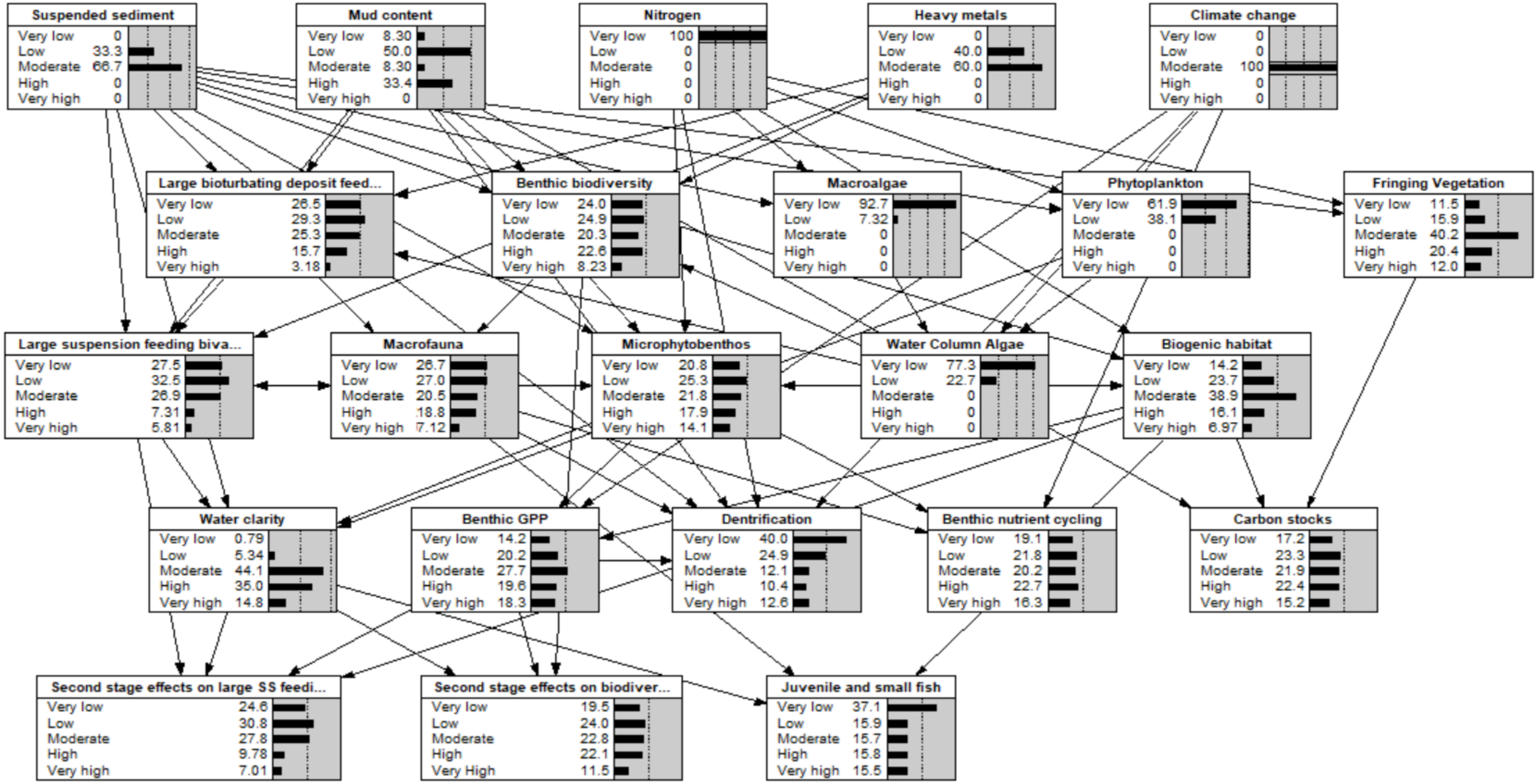

Figure D-12: BN model for Porirua (Pauatahanui arm).

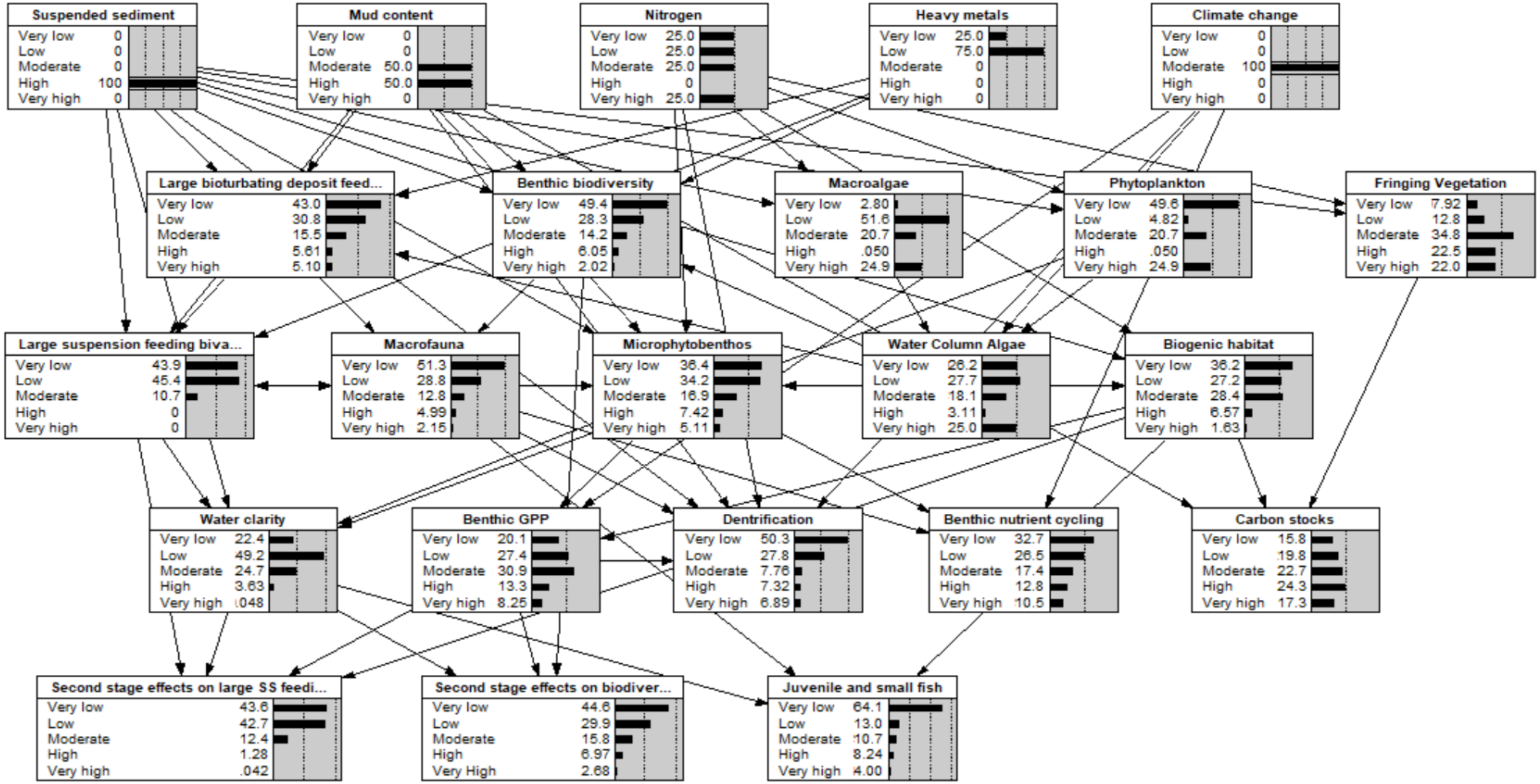

Figure D-13: BN model for Havelock, Pelorus Sound/Te Hoiere.

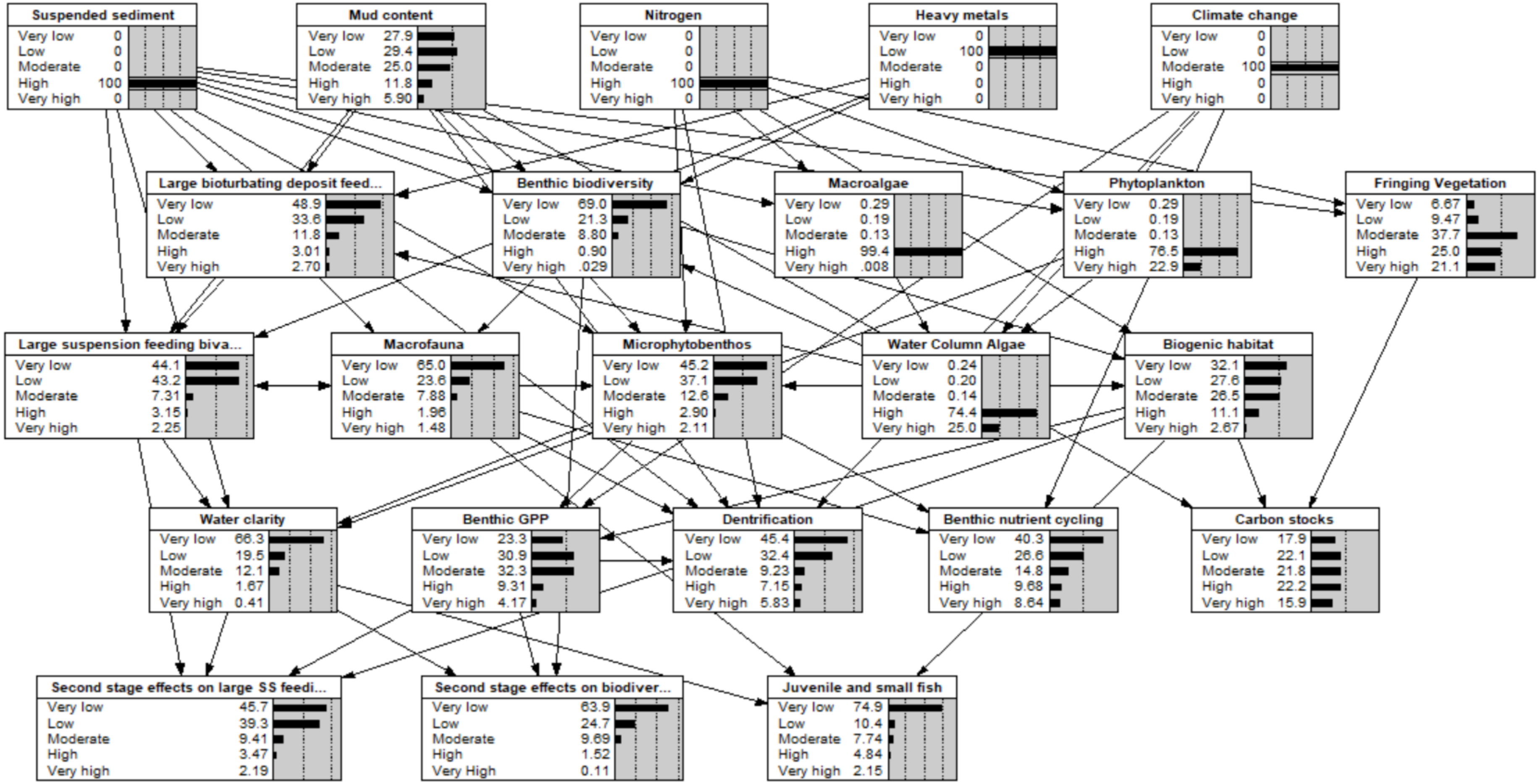

Figure D-14: BN model for New River.