Advice on the use of models to support estuarine outcomes

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by

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Sedimentation run-off from rivers into coastal marine environments in Aotearoa New Zealand. Photo Credit Chris Cornelisen.

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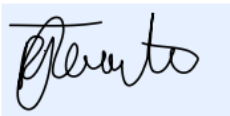

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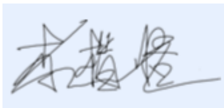

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Glossary

Bayesian Networks (Bayes Net)- A method for assessing risk by looking at how different components of a system influence each other. It is based on the probability of one component being in a certain state or condition based on what's happening to the other components it is connected to.

Cumulative effect- The resultant total change or combined impact from multiple different stressors, or from multiple additions of a single stressor.

Outcomes- These are the high-level results that are trying to be achieved by management actions. They may be set by policies or plans but should reflect local community and iwi aspirations for the estuary. Examples are improved estuarine health, restoration of mauri, collection of mahinga kai. This definition allows us to: 1) take into account differences in terminology between theNational Policy Statement for Freshwater Management (NPS-FM) and the New Zealand Coastal Policy Statement (NZCPS); and 2) integrate across activities and stressors.

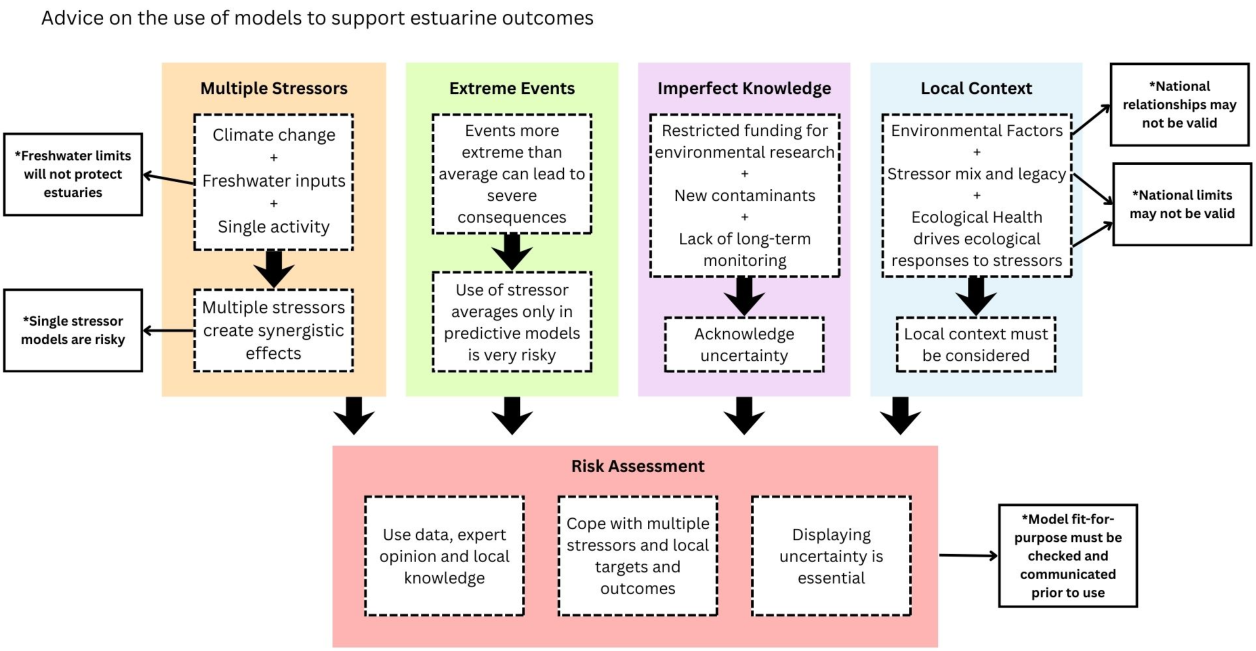
Risk- Risk is composed of the likelihood of an event occurring and the sensitivity of the environment to the event.

Stressor-driven legacies- The lasting result of a stressor remaining in the environment after the stressor has occurred, or the ecological response to that stressor remaining even when the stressor has dispersed.

Targets- Are set to support outcomes. A single outcome may be supported by more than one target, and one target may also support more than one outcome. Once targets have been set, it may become apparent that achieving a specific target may prevent another outcome from being achieved.

Tipping Point- Incremental change in the environment accompanied by a sudden large change in the network. These can occur in social, physical or ecological networks and are hard to reverse.

Graphical Abstract



Background

As the interface between the land and sea, estuaries are uniquely distinctive and dynamic environments. They are highly productive and provide numerous ecosystem services (e.g., improving water quality, supporting fisheries, protecting our coastline). The diversity of habitats contained within estuaries (e.g., crab burrows, seagrass meadows, worm mats, shellfish beds) support a wide array of species that are critical for ecosystem functioning and integrity. Unfortunately, the *Our Marine Environment 2019* report clearly identified continued national degradation of the marine environment, particularly for estuaries. Subsequent reports in 2022 and 2025 have not indicated any reversal of these trends.

While many stressors for most estuaries stem from the catchment/land side, estuaries tend to fall within the Coastal Marine Area (CMA). This can mean that the estuary being managed under regional coastal plans is disjointed from land-based management plans and the NPS-FM. For freshwater systems the implementation of the NPS-FM has used extensive modelling to inform the magnitude and scale of actions required to achieve desired outcomes. Typically, single variable/stressor models have been developed that focus on suspected key stressors for specific catchments or waterways and have not considered the estuarine receiving environment, with the outputs then used to inform wider policy direction. In many instances, national-scale models have been used (often due to limited data at smaller scales or within specific regions). While these models can be extremely useful in answering specific questions in certain circumstances, their use at scales and for purposes outside of scope, can be detrimental to achieving the outcomes desired, and may at times direct policy into areas where outcomes may in fact be perverse.

This report outlines key barriers to effective management of estuaries and provides information on the disconnect between modelling to inform freshwater management and requirements for effectively managing estuarine environments. It outlines current research and summarises it to provide guidance that regional councils can use to improve management plans both at the regional and estuary scale.

Why is managing for estuarine outcomes different? – Four key science concepts.

Scientific understanding of the differing sensitivity and functionality of freshwater systems compared to estuarine ecosystems has been long-standing. One simple illustration is consideration of sediment impacts in streams compared to an estuary (Reid et al. 2011). Contaminant residence times, impacts on biodiversity, and effects on ecosystem function are all greater in estuarine environments. Moreover, some variables commonly used in freshwaters are less meaningful for assessing estuarine state or condition. For example, in freshwaters, clarity is frequently measured as a variable important to the health of the waterway, whereas for estuaries, due to tides, total suspended sediment loads are more appropriate for assessing impacts on ecological condition. In addition, species recovery of culturally and ecologically important species if they are heavily impacted, does not come from freshwater systems but from other parts of the estuary or from the sea. As a result, the simplistic application of freshwater rules for the purposes of achieving estuarine outcomes is risky for policy makers and managers.

There are four key science concepts that need to be addressed for successful management actions in estuaries: (1) multiple stressors; (2) tipping points and delayed recovery, (3) local contexts and legacies; and (4) the effect of extreme conditions. All of these can also be important in freshwater systems, however, as estuaries are mainly depositional rather than transitional environments their effects are often more pronounced. Below we discuss their importance in estuarine management.

1. Multiple stressors

Unlike single catchment freshwater systems, estuaries often receive inputs from multiple rivers and streams, the atmosphere, the ocean and, sometimes, within-estuary activities, resulting in cumulative and interacting stressors that can vary across space and time. Even a single activity can generate more than one stressor (Figure 1). Multiple stressors concern us because of **synergism** i.e. where the combined impacts can be larger than individual ones. These have been observed worldwide, and in Aotearoa New Zealand (A-NZ) estuaries multiplicative and synergistic effects rather than simply additive effects have been observed. For example between sediment mud content and metal contaminants (Thrush et al. 2008), metals), metals and environmental gradients (Anderson 2008), and interactions between nutrients, sedimentation and metal loadings in a study of Tauranga Harbour (Ellis et al. 2017).

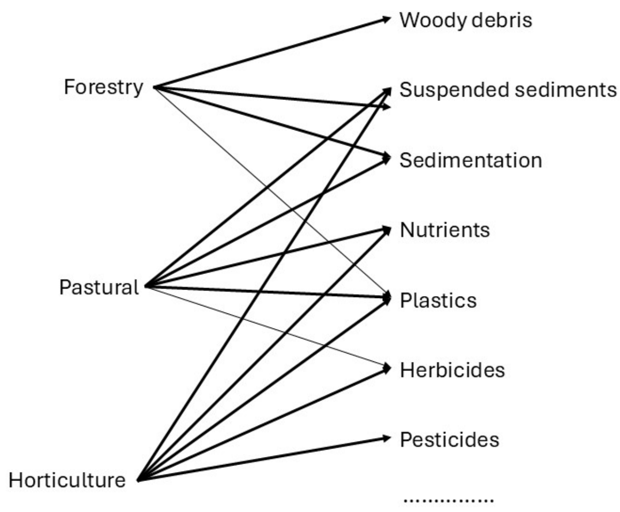


Figure 1: Single activities, as shown on left, can generate multiple stressors, as shown on right.

As sediment and nutrient loading increase, ecological processes start to break down because functional groups tend to contribute less to the overall ecosystem functioning (Thrush et al. (2017). The resulting decline in assimilative capacity, combined with increasing stress are likely to result in a nonlinear change or tipping point in ecosystem's ability to cope with nutrient load. These effects may be masked by sea level rise with the effects of nutrient pollution, sediment addition, and sea level rise being non-linear and non-additive (O'Meara et al. 2017)

Despite these peer-reviewed scientific examples, A-NZ policy work and implementation has tended to focus on single stressor attributes (e.g., MfE Manging Upstream project 2016-2018). In an attempt to understand the interactions between two of the major freshwater derived stressors, a national scale experiment was conducted in 2017 manipulating sediment nutrient concentrations along a suspended sediment gradient in intertidal areas. Distinct changes in the ecosystem networks that drive sediment nutrient processing were observed driven by changes in incident light (associated with elevated suspended sediment concentrations). The result demonstrated that as turbidity increases with sediment load, estuaries become more vulnerable to eutrophication (Thrush et al. 2021). Moreover, managing only one of these stressors would compromise the ability of people to collect kai moana.

These examples highlight the need to consider the effects of multiple stressors when setting policy to achieve estuarine outcomes.

2. Tipping Points

Increasingly, research internationally and within A-NZ has demonstrated that gradual accumulation of ecological responses to single or multiple stressors often drives ecosystem tipping points and thresholds. A critical aspect of a tipping point is that recovery is difficult and/or unpredictable. Estuaries are particularly prone to tipping points as they have a high potential for multiple stressors, they are depositional environments leading to accumulation of stressors (legacy effects) and biotic community recovery needs to either come from elsewhere in the estuary or from nearby coastal areas.

Tipping points are often referred to as "surprises" as the sudden changes were not predicted by past relationships (which generally showed no change despite increasing stress) Unfortunately these surprises can also be generated by the use of single stressor relationships and simplistic models that do not include important interacting factors.

However, ecological systems are now understood well enough to know that it is not only a result of not knowing that can lead to surprises in ecosystem response, it can also be a feature of the networks within an ecosystem. This highlights the importance of empirical testing and long-term data collection (monitoring) which provide critical information to be able to avoid tipping points.

The likelihood of tipping points emphasises that precautionary approaches should be utilised when an estuary is near to a tipping point and management actions should be focused on reducing stressors (Thrush et al. 2016). Precautionary approaches can also include:

- Maintaining adaptive capacity – an ecosystem's ability to adjust to stressors and disturbances while sustaining its core functions.
- Restoring biodiversity - recovery of an ecosystem's species diversity and ecological functions to support a healthy, resilient environment.
- Enhancing multi-functionality - improving an ecosystem's ability to provide multiple functions and services simultaneously, supporting resilience and overall ecological health.
- Integrating management strategies - coordinating multiple approaches to achieve cohesive and effective ecosystem or resource management.

3. Local contexts

Local context is critical to understanding a systems behaviour and resilience, and research on tipping points and cumulative effects demonstrates the importance of place and history in how an estuary will respond to environmental change. Examples of these are given below.

(1) Local geomorphology, land-use of the catchment and the physical setting of the estuary (hydrodynamics, oceanic exchange, residence time) affect which freshwater and terrestrial stressors affect the estuary and how stressors are moved around and through the estuary.
(2) Whether the stressors, in combination with estuary physics, result in accumulating impacts within the estuary. This is an important consideration when attempting to identify recovery timeframes, as legacy issues may not be immediately resolved through limiting freshwater loadings. Despite this many estuarine sediment transport models do not include legacy sediments (see for example DHI 2025).
(3) The past effect of stressors on the estuary health is also important. As an example of this, recent understanding has moved from thinking that 15 % mud content represents a threshold beyond which negative ecological effects will occur, to realising that there is another earlier

threshold at 3-5 % mud. As this earlier threshold is passed, estuaries become less able to remove bio-available nitrogen, making them more vulnerable to the effects of nutrient loading. Suspension-feeders (for example pipis and cockles) spend more energy feeding in environments that have higher percentages of terrigenous sediments, affecting their health and resilience to other stressors. More recent thinking is that estuaries undergo a cascade of tipping points, driven by cumulative effects.

Thus, knowing where the estuary is placed within the legacy cascade (history) and which stressors now are drivers (place) is key to management.

The effect of place also creates problems for use of any national relationships whether between stressors, stressors and environment, or stressors and ecological responses. For example, data on macrofaunal densities and sediment characteristics was collected from 19 estuaries and used to create species-specific models predicting the probability of occurrence relative to sediment mud content (Thrush et al. 2003). These were used to forecast the response of macrofaunal species to long-term changes in sediment type. However, although significant relationships were found there was considerable variability of species responses to mud between estuaries. A 2005 study examined whether the relationships held if the predictions were made from data collected from all 19 estuaries, a single estuary or a single tidal flat (Thrush et al. 2005). A major finding was that across-estuaries, relationships reflected other variables correlated with mud content within an estuary that differed across estuaries. This demonstrates the importance of site-specific factors for identifying species responses.

Additionally a body of A-NZ experimental work over the years has shown that ecological responses to stressors is highly dependent on previous ecological conditions (Gladstone-Gallagher et al. 2023a; Douglas et al. 2017; Gladstone-Gallagher et al. 2018). The ecological state of the local system together with the mix of stressors in place can also result in non-linear response dynamics (Hewitt et al. 2016; Gladstone-Gallagher et al. 2024).

Frequently there are well-known reasons why a relationship for a single estuary may differ markedly from a nationally derived one. For example, Otago Regional Council has many streams where turbidity measures are driven by tannins. The national relationship between total suspended solids and turbidity does not hold for these streams and the estuaries they drain into (Neverman & Smith 2022). This is an extreme case, but the relationship between suspended sediments and turbidity will also be affected if nutrient enhanced phytoplankton growth is the driver of turbidity. Changes in the sediment size class will also affect the relationship between total suspended solids and turbidity. Relationships between turbidity, total suspended sediments and clarity are similarly affected.

This is not simply a A-NZ issue, Serrao-Neumann et al. (2016) raised the need for marine governance to be flexible to context-specific rules.

4. Averages versus extremes

Estuaries are dynamic systems where environmental conditions can fluctuate dramatically over short timescales. Because estuaries act as transition zones between land and sea, they are exposed to episodic disturbances such as floods, storms, and extreme tides that can dominate material and energy fluxes. These infrequent but high-magnitude events often drive the greatest changes in sedimentation, salinity, and water quality, shaping the structure and function of estuarine ecosystems in ways that long-term averages fail to capture. Ignoring these extremes can potentially obscure key processes and feedbacks that determine ecosystem resilience and tipping points.

Research on sediment inputs in estuaries that result in either sedimentation or suspended sediment has highlighted that responses were not just to annual averages but to more extreme events (Thrush et al. 2004, Hewitt and Norkko 2007). This is particularly important given that most sediment enters the estuary during storm events which can result in pulses of sediment loads orders of magnitude higher than average (Hicks et al. 2000). If this sediment is deposited it quickly becomes anaerobic, resulting in the death of the resident fauna. Recovery driven by recruitment and migration is therefore slower, depending in part on the scale of the disturbance, resulting in longer lasting ecological impacts. As a result, Thrush et al. (2016) identified that the likelihood of unexpected outcomes is not only increased by ignoring known relationships to simplify models, but by basing predictions on averages, and failing to account for the impacts of extreme events. In a recent study involving cross-National Science Challenge funding, Our Land and Water attempted to include temporal variability in rainfall based on nationally developed rating curves. Correlations of the inputs provided by the models to ecological changes in three estuaries were poor and this was ascribed in part to the models being pushed past their intended temporal limits (Lohrer et al 2024). Regardless of the effect on the ecology, use of averages can make it difficult to assess the magnitude of the sedimentation. A report by DHI for Otago Regional Council (DHI 2025) noted that sediment load had to be multiplied by a factor of 3 to get results close to actual measured deposition when trying to validate the WRTDS models used for the Land and Water Plan. In general, whilst modelling approaches are being developed to better account for temporal variability many models provide estimated loads based on mean values for river and estuary systems.

Extremes of other stressors can also act as major drivers of ecological change. For example, a hypoxic threshold of 2.0 $mlO_2.l^{-1}$ (Diaz and Rosenberg 1995) is widely recognized as a critical survival limit for macrofauna and fish. Heatwaves (defined by exceedance of average values) are also being accepted as exerting severe stress particularly in intertidal regions when they coincide with midday low tides and subsequent high levels of heat stress (Helmuth et al. 2006, Wethey et al. 2011, Salmond and Wing 2023). It is also well established that larval stages of many organisms, including bivalves and fish, are particularly vulnerable to ocean acidification (Pernet and Gazeau 2025) and heatwaves (Cook et al. 2025).

More complicated extreme events can also occur. For example, nutrient pulses do not necessarily transit through the estuary and out to sea. They can be processed within the estuary, dropping out on the seafloor as organic matter which is then reprocessed over time creating within estuary sources that can combine with sources coming externally from freshwater or the sea. Monitoring is unlikely to pick up individual nutrient pulses but can capture associated accumulations in sediment organic matter and nutrients. Conversely, recent microplastic work suggests that highly toxic products from tyres washed off the roads in storms breakdown extremely quickly (Fohet et al. 2023). Thus, while toxic products might not be detected in estuarine water or sediments, the responses of organisms to them remain and can again be detected in monitoring.

Policy and management issues

Disjointed policy.

Despite their importance, estuaries often fall through policy and management gaps, sitting at the interface of planning and legislative frameworks designed primarily for either freshwater or coastal environments. In A-NZ, this may arise from the way different policy instruments, such as the Resource Management Act (RMA), New Zealand Coastal Policy Statement (NZCPS), National Policy Statement for Freshwater Management (NPS-FM), and regional planning documents, divide jurisdictional and management responsibilities. This can be further complicated by the use of national standards (separate from policies) such as the national environmental standards for commercial forestry.

The NZCPS typically manages activities within the coastal marine area, with regional and local plans needing to give effect to this higher-level instrument. However, for many estuaries, the majority of stressors arise from the land and freshwater areas, that are managed under different planning tools, therefore, the source management is not always connected to downstream receiving environment.

At the regional level, this fragmentation is often reflected in planning instruments such as Regional Policy Statements, Coastal Plans, and Land and Water Plans, which are frequently developed under separate policy drivers and timeframes. As a result, management responses to key estuarine stressors, such as sedimentation, contaminant loading, or habitat loss may be undermined by structural separation in policy intent and implementation. For example, the NPS-FM uses the words "maintain or enhance" whereas the NZ-CPS wording is "avoid significant adverse effect".

***Policy that is not implemented properly*.**

Councils are required to rewrite plans when policy statements or national rules change. However, the time period over which this occurs can be long, the freshwater and marine plans may be revised at different times and reviews of whether the relevant policies are being written into the plans and then implemented are rare. Urlich and Hanifiyani (2024) reviewed the uptake and implementation of new national regulations around forestry clear cutting and found 12 councils retained existing rules that conflicted with the regulations.

***Policies that create bias*.**

Policies can constrain the assessment of outcomes, particularly when high level models are used, such as models that consider the relative benefits of different activities and actions. Two recent documents considering the economics of forestry both remark on this. Parliamentary Commission for the Environment (2025) states that the "commercial driver relies on the artificial policy construct of an NZ ETS, which can be changed at any time" while Kaye-Blake et al (2024) notes that their predictions were largely driven by a number of factors including "the policy-driven economic strengths of forestry" and that they were constrained by "policy decisions embedded in the models". Policies can also create bias by not matching the scales at which ecological processes operate (Ellis et al. 2025).

***Legacy effects are not considered*.**

An estuary with long-term chronic stressors generated by historic issues is unlikely to respond to management actions in the same way as one without legacy effects. Considering legacy effects within an estuary would facilitate management decisions on both the likely level of degradation and recovery potential (Gladstone-Gallagher et al. 2024).

Granting consents in isolation

Consents are granted in isolation **taking into account neither the cumulative effects** of a single stressor nor of multiple stressors.

Summary- what factors make managing for good estuarine outcomes difficult?

- Stressors affecting estuaries can occur from activities within the estuary (managed under NZCPS), from the land surrounding and the freshwater inputs to the estuary (managed under NPS-FW) and from the sea- sometimes from other catchments depending on coastal circulation.
- Most activities create more than one stressor so multiple stressors are the norm, yet cumulative effects are generally not considered in granting consents with emphasis placed on the need to "consider the effects of each activity on its own merits".
- Estuarine ecosystems are a network of interacting physical, chemical and biological components, with feedbacks and indirect flows between components. "Good" outcomes will therefore depend on the states of a range of components and the maintenance, or generation, of multiple connections between them.
- The impacts of any stressor in the estuary depends on the mix of other stressors (place) and the ecological health of the estuary (history and place), yet management does not consider legacy effects.
- Species recovery if individuals die does not come from freshwater but from other parts of the estuary or from the sea.
- Whether dilution of freshwater inputs occurs is dependent on the estuarine hydrodynamics, and whether dilution is important for the outcome is dependent on stressor type.
- Responses to extreme events are generally longer-lasting than those to average events.
- Policies that are not implemented properly, are disjointed or that create biases towards specific activities.

How can science help?

Current research in A-NZ and internationally emphasizes that synergistic interactions and non-additive effects are most likely to result from multiple stressors, and that the cumulative effects are most likely to result in tipping points.

Many current stressor-ecological assessment approaches break down the issue into multiple cause and effect relationships (Clark et al. 2022), considering each stressor separately and generally the response of single ecosystem components separately (for example, a single species, a single value).

Activity, stressor and ecological response footprints do not necessarily occur in the same place, cover the same area and occur over the same time scale (Figure 2).

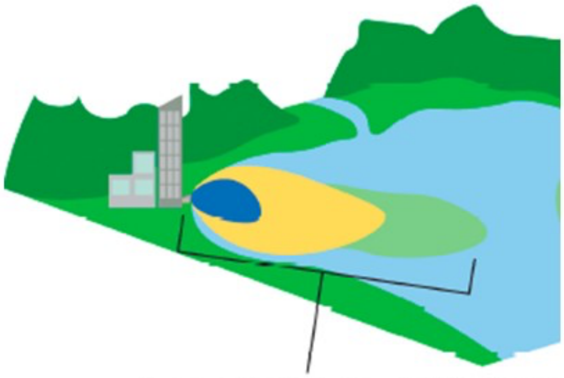


Figure 2: A common example of differences between the activity (blue), stressor (orange) and ecological response (ER, green) footprints. See Low et al. (2023) for more examples.

Recent science

New frameworks have been developed to link risks associated with cumulative effects to appropriate management actions, based on three key interconnected concepts, which are briefly summarised below.

• 'Ecological response footprints' (Low et al. 2023). This review lists problems that can occur when determining a spatial footprint of impact based solely on stressors and activities and lays out a framework to identify the "ecosystem response footprint". The framework is based on characteristics that define the spatial extent and depth of ecosystem response footprints.

•'Characteristics of marine ecosystem interaction networks' (Gladstone-Gallagher et al. 2023b). There are four important characteristics of marine ecosystem interaction networks that affect how they react to stressors. 1) simple indirect effects, 2) emergent effects as stressor magnitude increases the number of network components impacted, 3) network interactions that amplify these indirect effects, and 4) feedbacks that reinforce or stabilise against indirect effects (Figure 3). Three case studies of common coastal environmental issues demonstrate how information on these four characteristics can be used to bring together multiple lines of evidence and prioritise stressor(s) management.

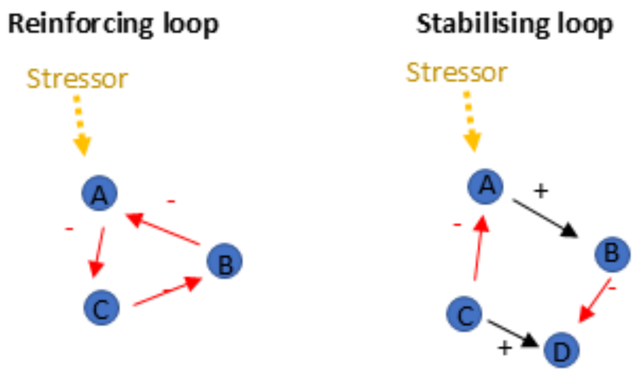


Figure 3: Example of links that either reinforce the effect of a stressor within a system or that stabilise its effect.

• 'Ecological and stressor principles' (Gladstone-Gallagher et al. 2024). Six ecological principles related to the ecological health and six stressor principles related to type, number impact, likely interactions and size of stressor footprint were determined, based largely on the previous two papers (Figure 4). The combination of these principles defines where an ecosystem is placed along sliding scales of degradation and recovery and its likely response to degradative, protective and restorative interventions. These principles can be applied even when numeric data is considered to be lacking by using a combination of expert and local knowledge. A GIS framework that allows these to be combined as layers has recently been developed (Lam-Gordillo in review).

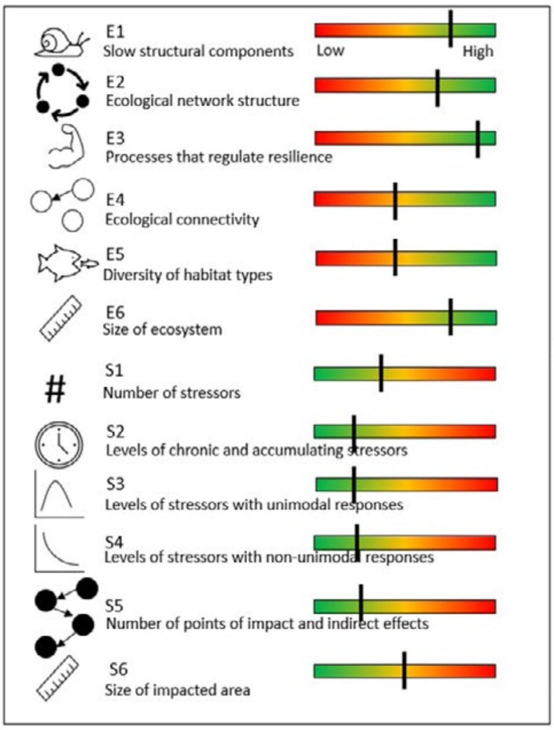
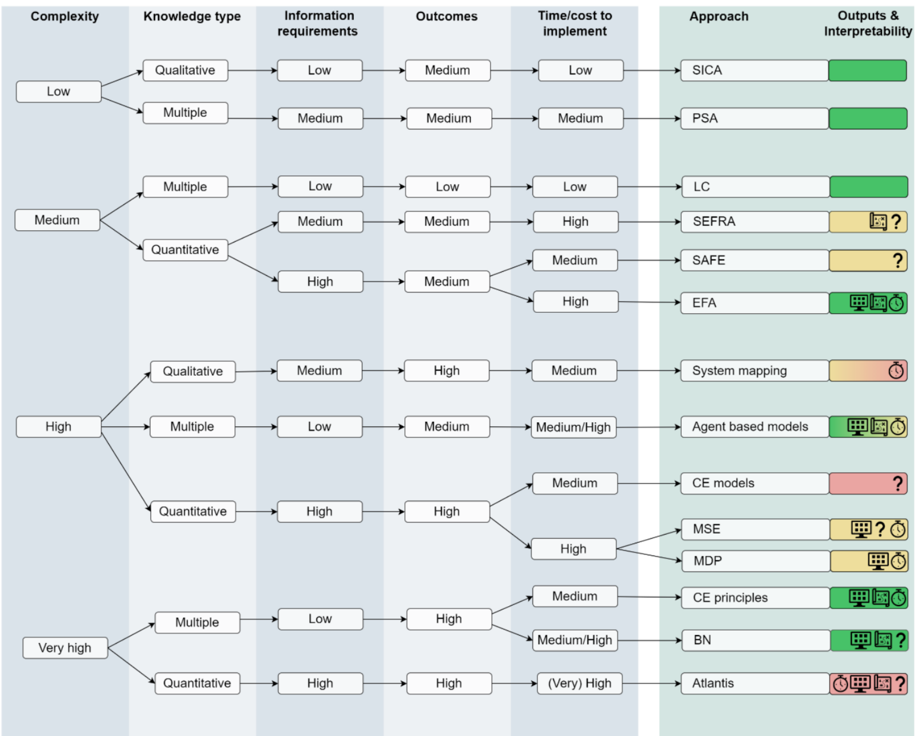


Figure 4: The 12 principles that can be used to predict the likely health of an estuarine system (green is healthy and resilient, red is degraded).

Risk assessment frameworks.

Uncertainty is often viewed as a major obstacle to management, despite relevant marine legislation and policy requiring the consideration of cumulative effects (Macpherson et al. 2023). Regardless, regional councils and central government must make decisions without perfect information, with the potential for decisions to be challenged in court. In these situations, risk assessments that explicitly deal with uncertainty are a robust tool (Clark et al. 2022). Risk is composed of the likelihood of an event occurring and the severity of any consequences of that event. As an example, for human safety, an extreme consequence, even if the likelihood of the event occurring is low, is treated as high risk and would need to be avoided. In many cases values held for estuaries may be so desired or the outcomes severe enough for the council to curtail activity (litigation, attorney general's report, flooding, road washouts). An obvious example of this is forestry harvesting, roadworks and replanting on steep slopes. Assessing the likelihood of heavy/extreme rainfall occurring during these events in a specific place is hard to predict. However, the severity of the consequences include long-lasting effects on biotic communities, smothering and death of species living within rivers and estuaries, long-term increases in estuarine turbidity and muddiness and potential challenges in funding the repair of any damage. The greater the level of uncertainty, and the bigger the potential consequences, the more important it is for stakeholders to participate in analysing risk (Table 1 in Ingles et al 2020).

Only rarely is the type and method of assessment considered and specified, despite some methods constraining the information that can be included and limiting the ability to consider a full range of actions and outcomes (Figure 5, (Clark et al. 2022, Flowers et al. 2025)). These limitations often lead to debate and uncertainty regarding the relative risks associated with different management options.



Symbols are used to distinguish additional output types, including spatial , temporal , scenario , uncertainty ?.

Figure 5: A decision tree assessing fitness for purpose of specific risk assessment methods. Colours represent whether specialist skills are required to create the models and interpret outputs ranging from easy (green) to specialist (red). See Flowers et al. (2025) for full names of abbreviated methods.

A type of model that explicitly acknowledges uncertainty, is built around a network of connecting components, and can incorporate local knowledge, stressors and outcomes is Bayesian Networks (Bayes Nets). Bayes Nets can be built at different levels of complexity, ranging from a simple wiring of stressors and outcomes with a few intermediary steps, that can be completed within a single group meeting, through models allowing for direct and indirect effects, to those containing feedback loops, outputs from single stressor models and different spatial and temporal dynamics, verified against available data. Importantly, they can include, and inform, transparent decision-making by allowing the risks to individual outcomes from different decisions or management actions to be immediately displayed to large groups. They also inform the likelihood of an outcome being achieved through interventions, as well as highlighting potential unintended consequences, if these form part of the connecting components. A recent report (Sustainable Seas 2024) demonstrates both the use of the ecological and stressor principles (Gladstone-Gallagher et al. 2024) as an initial screening method, to determine whether a more comprehensive risk assessment is required, and the use of Bayes Net models for comprehensive risk assessments as robust, evidence and science supported tools.

A Bayes Net for connecting three major stressors on A-NZ estuaries to biodiversity and shellfish has already been developed for potentially contaminated estuaries and validated by available data. Since then it has been extended for more stressors in Whangarei Harbour (Parsons et al. 2024; Bulmer et al. 2024) and for use in Hawke Bay estuaries (Bulmer 2022). Its ability to incorporate local outcomes and situations has been demonstrated for Whangateau, Kakanui and Ahuriri estuaries (Te Whanganui-a-Orotū) (Hewitt et al. 2024). The use of Bayes Nets in coastal management has also been explored (Flowers et al. 2025).

Using a flexible, stepwise framework means a Bayes Net can be made as simple or as detailed as needed for a risk assessment. At a basic level, it can give a straightforward view of likelihood and consequences. At a more detailed level, it can assess risks to ecological, social, cultural, and economic factors, while also showing the uncertainties involved. Agent-based models (ABM see Figure 5) can also provide assessments of risk to ecological, social, cultural, and economic factors – however, uncertainties are not so well treated. Both Bayes Net and agent-based models can cover scenario modelling of actions intended to aid recovery.

Communicating assumptions, uncertainty and limitations of models

Technical reports and communication materials derived from them need to be clear and begin with the spatial and temporal scale covered, the assumptions of any models, any exclusions and the reasons for them, and the uncertainty around any predictions or data produced.

Reports and communications that do not include these in the beginning statements can easily be misinterpreted. For example, a recent report (Kaye-Blake et al 2024) on the advantages and disadvantages of plantation pine forests in estuarine catchments noted that harvesting mature trees (every 25-30 years) can cause sediment and slash to run-off into estuaries. However, the predictive catchment models were based on temporal averages, as is the norm in this modelling area. This meant that the negative impacts of sediment run-off were not quantified or compared with the potential benefits, such as reduced nitrogen runoff. The timing of the vulnerability to weather events was also overlooked, although PCE (2025) records this as being 4- 6 years post pine harvesting (or 13 to 20% of the forestry cycle), assuming reforestation occurs.

Technical reports also need to include an assessment of any data used by, or created during production of, the report. In particular how closely are they related to the aims of the report. While temporal and spatial scales have already been mentioned, this aspect also includes whether extremes or averages are used, whether national rather than local relationships have been used and whether there is translation between variables, e.g., clarity rather than total suspended sediments loads.

Creating a robust adaptive plan for ecosystem-based management for estuaries.

To date for freshwater management "Acceptable State" has been proposed to be achieved by setting "limits for single stressors", that may then be translated into "limits on activities" that generate the stressors. The potential for legacy effects, tipping points and synergistic responses in estuaries, and the high value of these ecosystems require processes that acknowledge multiple stressors rather than focusing on actions that seek to limit single stressors (Selkoe et al. 2015). Hence the "limits for single stressors" approach applied in freshwater systems are unlikely to protect estuarine systems.

A robust process for developing and implementing estuary management plans needs to allow for multiple aspects described in earlier sections of this report. For A-NZ the process needs to acknowledge that many estuaries are not straight flow through systems, that deposition and frequently reoccurring secondary transport of contaminants will occur within the estuary, meaning that standards that preserve freshwater quality and health are unlikely to account for estuarine outcomes.

Therefore, a robust management plan for estuaries needs to take account:

- local stressors (past and present);
- local values and desired outcomes for the estuary;
- the ecological health of the estuary;
- the local dynamics of the estuarine system network;
- local community and iwi values and aspirations;
- future impacts of climate change; and
- long term catchment development plans and in estuary development.

Ecosystem-based management (EBM) is a natural management process for this as the principles of EBM incorporate all these aspects. EBM also includes looking outside the estuary for activities and stressors that may impact the estuary and looking forward in time to how estuarine health and human-orientated values and use of the estuary can both be improved.

EBM as defined both internationally and within A-NZ is focused on using collaborative decision making involving local communities (Serrao-Neumann et al. 2016, Hewitt et al. 2018) and weighing the cost of both management action and inaction (Selkoe et al. 2015).

Simply expressing the intention to use EBM in regional coastal plans is not sufficient to ensure appropriate area-specific management plans are developed. High level plans need to contain or refer to guidance on how to create management plans that are feasible, cost-effective and not overly data intensive. In short, estuarine management approaches should be designed in a way that is less complicated, expensive or data hungry, so that the necessary translation of policy into protection, mitigation and restorative actions can be achieved. This is critical to ensure that policy can be translated into actions without unnecessary barriers. The process should allow for the following key questions to be asked and answered. Guidance for answering each question is given in the next section.

When would the use of FW limits and single stressor models be a robust choice?

Will cumulative effects result in an adverse outcome?

When do extreme events need consideration rather than averages?

Can we treat the whole estuary as a single unit?

What type of action is needed?

When will one restricted outcome be sufficient?

Can the management plan achieve the desired outcomes?

What can be monitored to show progress towards targets and outcomes?

Local outcomes can be achieved using nuanced risk assessments, that incorporate Mātauranga Māori and local knowledge, alongside what ecologists already know more generally about how ecosystems work, respond to stress, and recover. This process will provide for local activities, targets and actions (Figure 6). If Bayes Net models are used then single stressor models and tools developed for determining freshwater inputs and limits can be incorporated, forming a bridge between freshwater and estuarine management. In addition, Bayes models can be developed using both expert knowledge as well as existing scientific data (e.g. from monitoring programs) to facilitate the development of simple less time and/or data intensive models.

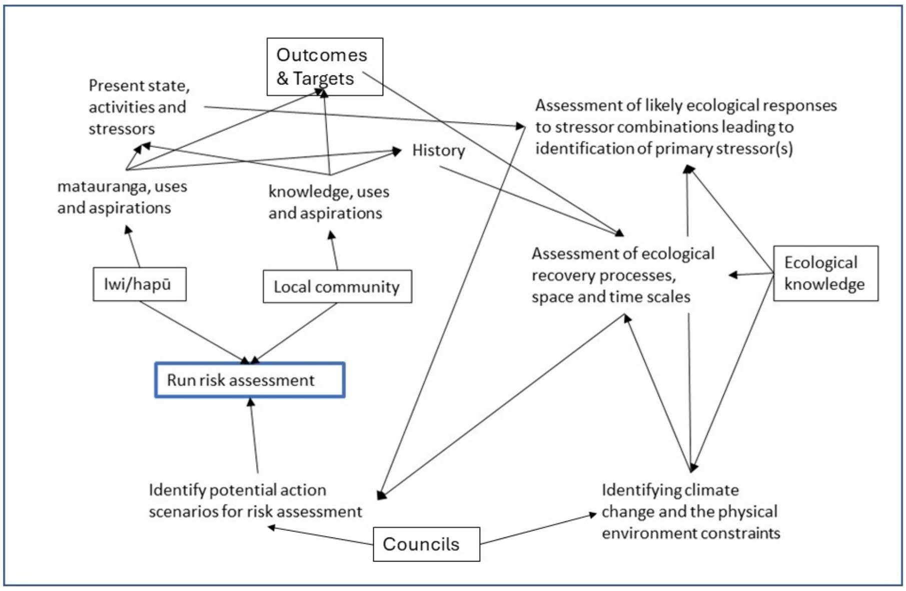


Figure 6: A process that can create local estuarine management actions.

Different areas within an estuary can be valued differently by communities and businesses. They may also experience different stressors and have different levels of ecological health. These factors highlight the need for some form of spatial planning. Spatial planning has been strongly advocated by the Environmental Defense Society (EDS) as a key tool for estuary management. However, there are a number of potential fishhooks that need to be acknowledged within the process in order to realise its full benefits. As an example, marine spatial planning as presently used has explicit geographic boundaries, is static in time, frequently does not deal with ecological responses and depends strongly on who is at the table and how the spatial area was chosen. None of these challenges are insurmountable, more that they need to be identified and resolved before progressing. For example, hard edges can be dealt with by using uncertainties and lack of temporal dynamics can be overcome by creating a series of maps and considering seasonal and annual variation in management or using ecological response footprints and uncertainties. Transparency in the process and consideration of gains and losses can be used to overcome "who is at the table". Selecting the area for the plan to cover can be made a robust process by utilising the ecological response footprint analysis in combination with risk assessments based on the spatial connectivity of ecosystem components. However, once the area is selected, uncertainty that selected area boundaries will adversely affect management outcomes can be reduced. For example, the likely effects of having a different sized area can be assessed, as can the effect of having more detailed plans and actions in some sub-areas.

Guidance and tools

When would the use of freshwater limits and single stressor models be a robust choice?

The following guidance is based around a tool (Table 1) that links specific stressors with land-based, estuary-based and coastal activities. The table identifies which stressors are generated by an activity, including whether the activity primarily generates the stressor, occurs regardless of local contexts, or may generate the stressor if the activity is not carefully managed.

Assessing the utility of freshwater limits for a specific estuary

Limits set on freshwater inputs by freshwater guidelines will contribute towards improved estuary outcomes if:

- Collectively **only** land-based activities are listed as primarily generating the stressor, and no other activities are listed as generating the stressors – even as "maybe";
- If more than one freshwater stream enters the estuary, or if stormwater inputs occur, the limits are adjusted to account for these extra inputs;
- The stressors do not create legacies within the estuary; and
- The stressors do not result in non-additive interactions (i.e one land-based stressor is not assumed to change how another stressor affects the environment), unless the stressor limits have accounted for such interactions.

However, meeting all the criteria listed above is generally unlikely, and freshwater limits need to account for oceanic sources, within-estuary sources and legacy contaminants.

Choosing between single and multiple stressor models and management

A single stressor model is fit-for-purpose if

- The activity or activities affecting the estuary generate a single stressor. In order to determine this, the present activities around or within the estuary should be assessed using the activity/stressor table (Table 1).
- There is a new activity generating a single stressor that is going to start affecting the estuary. In this case the baseline is the present ecological response footprint and ecological health and both can be altered by considering the stressor spatial footprint and magnitude. Caution is needed here however
    - as climate change also can create stressors, and
    - if the new activity includes emerging stressors with little knowledge of their long-term ecosystem consequences.
- The model is to be used to apportion management actions or prioritise further catchment work for a stressor, possibly as part of a larger Bayes Net model.

In all other circumstances, best practice would indicate that models and decision making should be based around multiple stressors. Given the very real presence of climate change impacts on our estuaries it is unlikely that making decisions based on single stressors will work to achieve the desired outcomes.

	Horticulture	Farming	Forestry	Stormwater discharge	Urban wastewater (treated/untreated human effluent and trade waste) discharge	Commercial wastewater (e.g. dairy factories, freezing works etc) discharges	Urban centres	Land-based development	Reclamations & causeways	Fish farming	Shellfish farming	Seaweed aquaculture	Bottom fishing	Mid-water fishing	Mining	Marine-based development.	Marine structures including seawalls	Ports	port and marins dredging and diposal	Shipping lanes and anchoring	Marinas	Wind energy	Wave energy	Tourism	Recreational boating	Swing moorings
Suspended sediment	Y	P	P	Y			Y	P					Y		Y	Y	Y	Y	Y	Y		Y	Y			
Sediment addition	P	P	P	Y			Y	P			M				Y	Y		Y	Y		Y					
Wood debris addition			P																							
Nutrients including organic matter	P	P	M	Y	Y		Y			P	Y															
Herbicides	P	Y		Y			Y																			
Pesticides	P			Y			Y																			
Plastics	Y	Y		Y			P	Y		Y	Y	Y	Y	Y	Y	Y		Y		M	Y			Y	Y	Y
Marine cleaning contaminants										M	M							P	Y	Y	P	M	M	M		Y
Pathogenic bacteria (entrococci, faecal coliforms) and viruses		Y		Y	P		P													M	M			Y	Y	Y
Antibiotics, drugs or hormone mimics		Y			Y		P			Y																Y
hydrocarbons and persistent organic pollutants				Y			M			M	M	M	M	M	M	M		P	Y	Y	Y			M	Y	Y
Metals				P			P	M								M		Y	Y							
Other pollutants				P		Y	P	M							Y	M		Y	Y							
Altered hydrodynamics	M	M						Y	Y	Y	Y	Y			Y		Y	P			P	Y	P			Y
Altered biological connectivity									P	Y	Y	Y	Y				P	P		Y	P	P	Y			P
Altered water temperature																										
Oxygen depletion																										
Altered salinity	M	M		Y	Y	M		M																		
Altered pH	M	M								Y	Y	Y			M											
Underwater noise								M		M	M	M	Y		P	Y	M	Y		Y	Y	Y	Y		Y	Y
Wakes										M	M	M				Y		Y		Y	Y			Y	Y	Y
Artificial light							Y	Y	Y	Y	Y	Y			M	Y	Y	Y		Y	Y	Y	M			Y
Freshwater quantity/residence time	M	M	M	Y	Y	M	Y	Y	Y																	
Sediment removal															P	Y			P							
Invasive species										F	F	F			F	F	F	P		Y	F	F	F	F		F
Species removal													P	P	Y	Y								Y		
Sediment disturbance				M						M	M		P		Y	P	M	P	P	M		Y	Y		M	
Change in habitat/sediment type									Y	M	Y		Y		Y	Y	Y	Y	P		Y	Y	Y			
Altered species behaviour (mammals, sharks, birds)								Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	P		P		Y	P	P	P	Y

Table 1: Activities and the stressors they can produce in estuaries.

Legend P: primary, Y: present, F: faciliates, M: Minor and business/location dependent stressor on the marine ecosystem.

Will cumulative effects result in an adverse effect?

Cumulative effects arise from incremental, accumulating, and/or interacting stressors from human activities and natural events that overlap in space and/or time. The stressor regime including the number, type and impact of stressors (see principles S1 to S6 Figure 4) influence whether cumulative effects are likely to occur (Gladstone-Gallagher et al. 2024). Whilst there are no legal definitions of what constitutes an adverse effect the first four ecological principles (Gladstone-Gallagher et al. 2024; Figure 4) provide a useful basis for when an activity is likely to harm ecological health and resilience. This can be either associated with a change in condition or a sustained trend in reduced health. For estuaries, changes towards a worsening category in the national estuarine mud and metal Benthic Health Model (BHM) scores may also be used. Also both the Traits Based Index (TBI) and the Estuarine Trophic Index (ETI) have developed threshold values signaling poor status, synonymous with the framework utilised in the NPS-FM. Any of these factors can indicate an adverse ecological effect, with implications for ecological outcomes. Over time, as understanding improves, additional indicators may also be identified.

Tipping points are by their nature, significant adverse effects that occur suddenly. They occur in physical, ecological and social systems and generally exhibit 3 characteristics; self-reinforcing feedbacks, threshold behavior and persistence.

Studies on tipping points, thresholds and surprises have highlighted the circumstances that make them more likely. These include:

- no clearly observed directional change in the ecosystem despite increasing stress;
- the stressors are "stock" stressors (i.e., a small amount is necessary for the system e.g., nutrients);
- a threshold response for part of the system to a stressor has been demonstrated (e.g., paua and temperature, cockles and suspended sediments);
- the system is subject to intense and/or multiple uses and stressors; and
- the ecological system has feedbacks (e.g., Figure 3) and indirect connections.

If the estuary or management plan displays a number of these aspects, the estuary is one that is likely to undergo a tipping point with either the same level of stressor(s), increased level of one or more stressor, or introduction of a new stressor (unless it is a stock stressor at low levels).

There are also two management approaches that can contribute to a surprise.

- relying on overly simplified models such as single stressor or single species models that leave out important ecological connections.
- using models that are not framed to include local contexts and therefore miss key drivers or interactions specific to an area.

If either of these two management approaches is used while any one of the ecological circumstances outlined above are active in the managed area, the risk of adverse effects and undesirable outcomes is greatly increased. In such cases, a change in approach is required.

There are some early warning signals that a tipping point may be approaching (Hewitt & Thrush 2019):

- monitoring suggests increased temporal variability;
- spatial variability of areas of low health has decreased (ie the estuary has become more homogeneous and of low health);

- spatial variability of areas of high health has increased (ie the high health areas of the estuary have become fragmented and less connected to each other; and
- recovery after brief environmental changes (e.g., storms) seems to have slowed.

Utilising these signals requires considerable investment in monitoring and may still not give sufficient warning to prevent passing over the tipping point – once the ecological tipping point has been crossed there can be a second social tipping point in terms of use and values.

In general, it is more effective to set management plans that build ecological resilience, do not manage up to the edge of the tipping point, and proactively reduce the risk of approaching a tipping point.

When do extreme events need consideration rather than averages?

It is well established that basing management decisions on long-term averages can be highly risky for many stressors. For example:

- total suspended sediment inputs, for which the majority of the overall load occurs during episodic events.
- nutrients and oxygen concentrations;
- inputs that affect pH (e.g., Dissolved Inorganic Carbon DIC); and
- plastics.

It is likely that with emerging contaminants and climate change, understanding the effects of rarer events will become increasingly important.

But how can extreme events be defined and taken into account?

Extreme events are defined variously in the meteorological literature although the 90th percentile has been suggested both for heatwaves (Hobday et al. 2016) and precipitation (WHO: Climate crisis - extreme weather). The engineering literature instead often refers to a return period (e.g., a 100 year rainfall or wind event). All of these however rely on past data which is often limited in terms of exposure to extremes in climatic events. Climate change is now seeing many of these 'infrequent' events returning at temporal scales which would not be predicted based on past data, setting new records now on a frequent basis. As such this approach becomes untenable.

An objective way forward is to run decision-making models based on relations with average values, 10th percentile, and 90th percentile. If the decisions that would be made differ with the use of percentiles, then new models should be run using relationships with values outside (larger or smaller) those yet experienced. The results of these models are likely to indicate a threshold beyond which the risk is unacceptable.

While Levin et al. (2022) speaking about governance for extreme events state that "Transformation of infrastructures of all kinds—transformational, social and built—will need to protect the most marginalized populations especially" , a similar transformation is needed for protection of ecosystems. Understanding the consequences for ecological systems if extreme events occur, and being able to say "no" to actions that increase the consequences beyond that of the system to cope is necessary.

Can we treat the whole estuary as a single unit?

No, it is exceedingly unlikely. For a small estuary, with a single freshwater input, a short residence time, limited intertidal area and uniform usage, the estuary may be treated as a single unit with uniform management. While this might be appropriate for some values, such as shorebird foraging. it would be unlikely to account for others, such as roosting habitat or fish foraging versus juvenile nursery areas. Generally, even using freshwater limits rarely results in managing the estuary as a whole as these tend to apply to each river catchment individually. The risks inherent in applying a management action uniformly across the estuary depend on numerous factors:

- Are there freshwater inputs into the nearby coastal environment that enter the estuary from the sea?
- Is the estuary small enough that within-estuary activities and values can be considered uniform across the estuary; and
- Is the estuary environmentally and ecologically homogeneous? Estuaries with multiple arms, large depth and sediment type ranges, high biodiversity and a range of biological communities are heterogeneous.

If any of these factors occur then managing uniformly across the estuary is risky unless management is focused on preserving the most vulnerable area and enhancing the most degraded area.

Selecting the area for the management plan to cover can be made a robust process by utilising the ecological response footprint analysis in combination with risk assessments based on the spatial connectivity of ecosystem components. For example, managing a shellfish bed in part of a large estuary may be reliant on the health of a bed in another part of the estuary (source population) which is impacted by sediment. Management interventions need to account for this connectivity to achieve the environmental outcomes desired. However, once the area is selected, reviewing the impact of different sizes or planning for specific sub-areas helps minimise uncertainty about whether boundaries will affect management results.

What type of action is needed?

Whether the outcomes are related to improvement or maintenance determines to a large extent the types of action needed.

For maintenance, there are two questions.

- Are there any stressors creating legacy effects? If so then this stressor will require significant reductions over time and probably some form of mitigation or removal of the legacy.
- Is it likely that a tipping point is being approached? If so then at least one or more stressors must be stopped or reductions in the present stressor loading must occur (e.g., decreasing the amount of resuspension of sediment occurring), or the resilience of ecological system increased (e.g., increasing habitat for, or restoring specific species).

If neither of the above are occurring, then it would be appropriate to maintain the current management approach while continuing to monitor conditions.

If improvement is the goal, Gladstone-Gallagher et al. (2024) contains an assessment for whether reducing stressors will result in improvement, or whether restorative actions are required, based on present ecological health and stressor types and magnitude. This can be informed by the information on species recovery outlined in Hewitt et al. (2022).

Another key deciding factor in whether restorative actions, such as removal and transplants, are required is “how long people are prepared to wait for natural recovery?” and the spatial extent over which they want improvements to occur. Models such as Bayes Nets can be explored to determine the likely time and spatial scales over which changes resulting from management actions can move through estuary components. For example, moving from remedial action in land-use in a catchment (slow at large spatial scales) to reduced suspended load into estuaries (slow if streams include depositional areas), and then reduced sedimentation and resuspension within the estuary (slow to very slow dependent on area).

When will one restricted outcome be sufficient?

Possible outcomes (see glossary for definition) from management actions in environmental systems generally form a network of connections framed by the ecological network that underlies them. Thus focusing on a single restrictive outcome (such as lowering nitrogen) presents the problem that it is not obvious whether achieving it will reduce the management options available that otherwise might lead to other positive outcomes and targets being achieved.

Having more than one outcome and having them underpinned by **ecologically informed targets** (Selkoe et al. 2015) gives more options for actions and successes.

While targets can be set in the absence of outcomes, developing high-level outcomes first (such as increased recreational use or kai moana) creates a strategy and, frequently, increases agreement between interested stakeholders.

Robust outcomes should:

1. have been selected by a diverse group;
2. explicitly declare winners and losers if the achievement of an outcome does not benefit everyone; and
3. explicitly lay out the certainty of achieving the outcomes and the expected timeframe for this.

These points require an emphasis on participatory processes and the recording of what parties were represented, what parties weren't and why.

Robust targets should :

1. lead to at least one, but preferably several, desired outcomes, for example decreased suspended sediment load may lead to increased number of swimmers (recreational use) as well as better nutrient processing (increased resilience) and increased number of pipis (kai moana);
2. explicitly lay out the certainty of achieving the targets and the time taken for this to occur and record acceptance of these;
3. be based on considerations of the present health of the estuary, the health history and use of the estuary, and the present stressors on the estuary (both those within and those exerted externally);
4. have incorporated climate change; and
5. have stated measurements of progress towards them

Setting these targets requires some form of risk assessment, linking management actions, activities, stressors, targets and outcomes. For most estuaries and outcomes, a comprehensive Bayes net model would be useful and could be used to clarify whether:

- achieving a specific target has an adverse effect on any outcomes;
- achieving a target will significantly advance an outcome and how certain that advancement may be;
- multiple decisions could result in an undesirable or limited outcome(s); and
- what types of management actions (or other levers) will increase the certainty of achieving targets and outcomes- and whether some will impede achievement.

Can the management plan achieve the desired outcomes?

Predictive assessments are typically used to determine whether a management plan or specific actions are likely to meet the desired outcomes. These assessments typically rely on some form of models. There are a number of considerations that can support the decision about which model to use and what reliance can be placed on its output. A model may be used simply to predict data to be used within another model, for example using a catchment model to predict sediment and nutrient inputs that will then be used within an economic model of benefits of an activity. At the other extreme, it may be a model that is integrating data and knowledge, or even a number of other models, to predict effects of management actions on desired outcomes, e.g., a Bayes Net model or one of the end to end data-driven models such as Atlantis.

The starting point typically relies on identifying the model outputs which may include outcomes, predicted data or values. This is followed by listing the drivers (i.e., the management actions) and a description of how these are linked to the outputs. At this stage it should be explicitly stated whether the outputs are directly related to the outcomes, values or data. If they do not, then the model should be revised and if it cannot be then the modeling process should not proceed, and use of a different model investigated.

The next stage is listing what is in the model, what isn't and why this is excluded. If the reason for exclusion is that the model cannot deal with those things, then the modelling process should not proceed, and use of a different model investigated.

In the third stage, the scale of the model needs to be specified. Models generally have three aspects of scale that need to be explicitly stated before development/use. These include:

1) the spatial resolution of any predictions relative to the management actions and the desired outcomes (or how the data is to used in the case of using the model to produce data to be used elsewhere).
2) the temporal scale that the model is producing predictions over; and
3) when nationally derived relationships/models are being used, specifying the environmental conditions that these are derived over and checking whether they include the local context.

Apart from the above, there are likely to be other model assumptions, including those associated with the model type which also need to be explicitly described.

What can be monitored to show progress towards targets and outcomes?

When outcomes may take years to show progress, monitoring the management actions themselves can be a useful initial step to establish progress. For example, how many metres of riparian fencing have been put in place can be a useful short-term measurable target, while determining whether the suspended load from a stream is decreasing may take considerably longer. This is important and can build or maintain community interest (Low et al. 2025) but does not necessarily mean that future targets or outcomes will be met.

Progress towards outcomes is a complex linkage over time between management actions, targets and outcomes and, frequently, intermediate measures are necessary.

If Bayes Net or Agent-based models have been used to link management actions to targets through to outcomes, intermediary components between the actions and targets can be monitored (the middle boxes between the inputs and the outcomes). These components need to be as closely linked to the targets as possible, that is, there should be fewer components between them and the target they represent. It is more useful to monitor a variable (component) that is directly and closely linked to the target than it is to monitor one that is directly and closely linked to the management action

Progress variables are also best to be the same type of variable and variability should be understood. For example if the target is increased number of swimmers, then measuring water clarity (and bacteria/viruses) on the outgoing tide is sensible. If the target is increased number of places where shellfish can be gathered, then measuring densities and size classes of post-settlement juvenile shellfish is more appropriate than measuring suspended sediment or mud content. If the target is reduction in muddy areas then an action might be to remove mud or deposit sand and measuring sediment deposition would be appropriate.

Summary - Essential considerations

Stressors and activities

Since stressors can interact to create impacts on the estuarine ecosystem, managers need to identify and clearly describe the activities impacting the estuary and the stressors they generate. However, in the end, the primary focus should be on the stressors rather than the activities, as a single activity will often produce more than one stressor.

Multiple stressors are particularly a concern because of;

- **synergism** i.e. where the combined impacts can be larger than simply adding individual ones, and;
- the increased risk of tipping points occurring.

It is difficult to predict when a tipping point is approaching. Utilising early warning signals for tipping points requires considerable investment in monitoring and empirical understanding and may still not give sufficient warning to prevent passing a threshold. In general it is more effective to set management plans that do not manage up to the edge of the tipping point and that proactively reduce the risk of approaching a tipping point.

Given the very real presence of climate change impacts on our estuaries it is unlikely that making decisions based on single stressors will ever be robust and therefore a multiple stressors approach is required.

Activity, stressor and ecological response footprints do not necessarily occur in the same place, cover the same area and occur over the same time scale, and this is important in defining management areas.

Knowing where the estuary is placed within the legacy cascade (history represented as health) and which stressors are present drivers (place) are key to management.

Models and communication

History and place are important considerations for estuarine management, and therefore the use of nationally derived relationships needs to be carefully considered.

The nature of feedbacks and indirect flows mean that any models need to carefully consider the implications of which components the model contains, and equally which are not.

Basing management decisions on the use of temporal averages has a high level of risk, as more extreme events have larger consequences.

Technical reports and communication materials derived from them need to be clear and begin with the spatial and temporal scale covered, the model assumptions, the uncertainty, and what isn't being included and why.

Management

Risk assessments that explicitly deal with uncertainty are generally the most robust tools, in a world with imperfect information.

Six ecological principles related to ecological health and six stressor principles can define where an ecosystem is placed along sliding scales of degradation and its likely response to degradative, protective and restorative interventions. These principles can be applied even when numeric data is considered to be lacking by using a combination of expert, local knowledge and Mātauranga Māori.

When information is limited, using risk assessment models to assess likely consequences of management actions is better than delaying action until more data is collected.

Limits set on freshwater inputs by freshwater guidelines will protect an estuary only in the rare circumstances when:

- The **only** stressors to the estuary occur from land-based activities and are delivered through freshwater streams and rivers;
- If there are multiple inputs or stressors, the limits allow for these effects; and
- The stressors do not create legacies within the estuary.

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