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Ki uta ki tai: mātāpono me te pūtaiao, ngā korero whakamahuki ma te kaitiaki – From mountains to the sea: values and science for an informed kaitiaki / guardian

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Report

Report for Sustainable Seas National Science Challenge project *Ki uta ki tai: Estuaries, thresholds and values*

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About the Sustainable Seas National Science Challenge

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

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Cover image: Waihī Estuary, Bay of Plenty (credit: Stuart Mackay, NIWA).

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Executive summary

Estuaries, located between land and sea, are diverse and productive ecosystems that provide a wide range of highly valued goods and services. The health of estuaries has been degraded by changes on land, in freshwater, in the oceans, and with the climate. It is increasingly recognised that we must alter the way we manage estuaries if we want estuarine health and values to improve. Governmental policy is seeking more integrated management of “the whole environment, from the mountains, springs and lakes, down the rivers to hāpua (lagoons), groundwater, wahapū (estuaries) and to the sea.”

Ki uta ki tai is a te ao Māori concept that more holistically encompasses and appreciates the interconnectedness of all parts of the system. The concept includes, but is not limited to, the connectivity between land, freshwater, estuaries, oceans, and climate.

Two of New Zealand’s National Science Challenges (Sustainable Seas, Our Land & Water), in partnership with the Ministry for the Environment, embarked upon a combined programme of work known as the ‘Ki uta ki tai’ project. It aimed to achieve impact by bringing knowledge streams together through shared visions, values, and processes to inform catchment-based solutions that would ultimately improve the mauri of catchments and estuaries.

The project sought to make progress towards integrated estuarine ecosystem management reflecting Ki uta ki tai concepts by:

1. elucidating pathways for meaningful and culturally appropriate partnerships with iwi, hapū, and whānau seeking to improve freshwater and estuarine management integration for better environmental and socio-cultural outcomes
2. overcoming technical challenges on the integration of freshwater/catchment modelling with estuarine ecological health assessment.

Working with mana whenua requires a willingness to engage in authentic relationships, open communication and face-to-face meetings to discuss the concerns, aspirations and priorities of localised species and spaces. Joint fieldwork and excursions to sites of interest were extremely informative and critical to the success of our project. Engaging at the local level was found to be the most appropriate and productive approach.

We developed metrics of exposure of individual estuarine sites to freshwater contaminants by (i) using rating curves to generate time-series freshwater load data, and (ii) spatially distributing those loads to sites where we had estuarine health data. We then explored drivers of change in estuarine health metrics, including exposures to suspended sediments, total nitrogen, total phosphorus, and *E. coli* (from freshwater) along with oceanic and climate-related drivers such as sea surface temperatures and El Niño strength.

Estuarine health, as indicated by estuarine macrobenthic invertebrates, responded to multiple environmental stressors and drivers—not just freshwater ones. Responses to freshwater contaminant exposures were often delayed (lagged) and were inconsistent even across sites within estuaries. However, multiple lines of evidence from intertidal and subtidal sampling across estuarine receiving environments exposed to differing freshwater sediment loadings revealed:

1. High bed sediment muddiness usually correlates with reduced benthic biodiversity.
2. In harbours with clear waters and sandy sediments, benthic diversity tends to increase with water depth, whilst in turbid and muddy harbours, it may not.
3. Seafloor photosynthesis is lowest at muddy sites with low seabed light.
4. High suspended sediment concentration (e.g., near sediment-laden river mouths) reduces seafloor photosynthesis and the proportion of daylight hours of net benthic oxygen production.

To improve the health of productive and valuable estuarine receiving bodies, we must embrace Ki uta ki tai concepts in our management practice and continue to improve appropriate interconnectivity between knowledge streams (mātauranga Māori, western science) and across disciplines (land, freshwater, estuarine, ocean). We share experiences, learnings, and key findings from the Ki uta ki tai project in this brief guidance document.

Estuarine health - the problem

Estuaries are the meeting point between freshwater and seawater. **The health of estuaries** is a complex product of changes on land, in freshwater, in our oceans, and with the climate. The accumulation of contaminants eroded from coastal catchments is just one of many reasons why **estuaries throughout Aotearoa New Zealand have become significantly degraded**.

A fundamental shift in the way we manage our estuaries is required [1-6]. Managing estuaries involves working with people who may live hundreds of kilometres apart and who do not necessarily feel themselves to be part of a catchment community, let alone connected to the estuary [1]. We must also overcome disciplinary barriers (how modellers and freshwater scientists interact with ecologists and estuarine researchers), science-policy barriers (as modelling and monitoring is sometimes not compatible with policy needs or the timeframes of plans/interventions), and barriers to the inclusion of mātauranga alongside western science in policy/plan development.

Improving estuarine management will involve designing and implementing new approaches to engagement, supported by participatory processes [1,7,8], and the **use of multiple knowledge systems** in decision-making. Collaboration and co-management will enable us to address a broader range of community aspirations and make more-informed decisions. Mātauranga Māori represents a rich repository of ancestral and contemporary knowledge of place and connections, created and maintained for centuries by iwi, hapū and whānau, as well as methodologies and practices related to those places [9-12].

Māori have unique sets of perspectives, aspirations, and objectives for freshwater and estuarine environments [13,14]. These often extend far beyond biophysical environmental states and may not be easily quantifiable using western science frameworks. For example, aspirations may involve reconnecting current or future generations to past places or cultural practices, and supporting reciprocity and kinship with the natural environment [15]. These concepts may not clearly intersect with the current 'limits and targets' themes that the government is seeking to develop to manage estuaries, highlighting a critical need to co-develop these policies with mana whenua [16].

Incorporating Treaty principles into planning processes is integral for collaboration to succeed in achieving outcomes, especially as it underpins the institutions of co-governance, co-management, and co-planning. Harmsworth et al. [17] identified that western science and modelling in support of natural resource management needs to be responsive to kaupapa Māori ways of knowing, being and doing (Figure 1). Ideally, iwi/hapū have a pivotal role in planning and decision-making—and in the environmental science and modelling—so that it is truly cross-cutting [18].

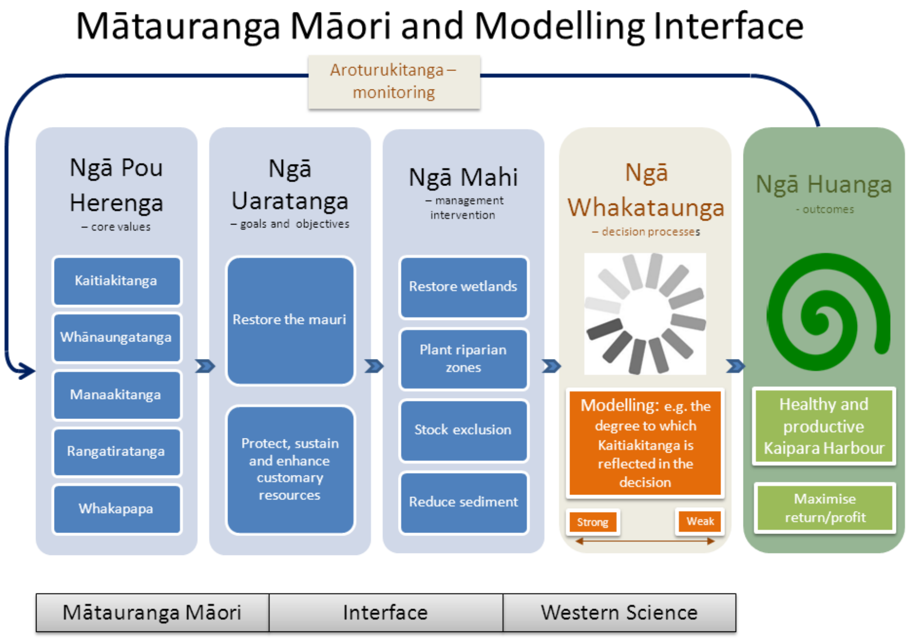

Figure 1: Mātauranga Māori and modelling interface, from Harmsworth et al. 2016, Māori research findings (2013-2016) for the Clean Water Productive Land Science Programme (C10X1006)[17].

Estuarine health - why it matters

The principle of Te Mana o te Wai prioritises the health and well-being of water bodies, the health needs of people, and the ability of people and communities to provide for their social, economic, and cultural well-being, now and in the future. It is the mauri or wellbeing of ecosystems that will support human needs and wellbeing.

Healthy estuaries are diverse and highly productive systems that are vital to Aotearoa New Zealand's socio-cultural identity and economy. The species and habitats within estuaries **provide vital functions and services that are of value to people and communities**, such as food, coastal protection, improved water quality and nutrient cycling. Understanding the many uses and values of estuaries [19], and the locations of Ecosystem Service hotspots [20,21], helps managers make decisions around things like resource use, planning and consents, catchment management, and marine protected areas.

However, **estuarine species, habitats, and ecosystem functions and services have been impacted** by multiple stressors and climate extremes.

One of the most recognisable indicators of estuarine degradation has been the collapse of natural shellfish populations. Pipi have declined 10-fold in some estuaries, cockles have suffered mass mortalities, and lucrative scallop fisheries have crashed nationwide. Populations have not rebounded despite harvesting bans (both rāhui and Fisheries New Zealand fisheries closures). This is devastating to mana whenua (whose identity and wellbeing has relied upon connections to such places and species for generations), to recreational and commercial fishers, and to any who appreciate the roles shellfish play in coastal ecosystems.

Estuarine health - what can be done about it?

Managing different parts of the environment discretely has the advantage of simplicity—challenges can be broken down into digestible chunks [1]. However, examining pressures in isolation, rather than collectively, can lead to profound misunderstandings of the processes at play and their likely outcomes [1].

Recent updates of the Ministry for the Environment (MfE) National Policy Statement for Freshwater Management (Clause 3.5 of NPS-FM 2022) specify that every regional council must make or change its regional policy statement to the extent needed to provide for the integrated management of effects of the use and development of land and freshwater on **receiving environments**, **including estuaries**.

MfE's Guidance on the National Objectives Framework of the NPS-FM 2022 (amended 2023) [22], states:

> *"Ki uta ki tai is the recognition and management of the interconnectedness of the whole environment, from the mountains, springs and lakes, down the rivers to hāpua (lagoons), groundwater, **wahapū (estuaries)** and to the sea. The local interpretation will vary according to tangata whenua views. Some may use different concepts with similar meaning."*

Progress towards integrated estuarine ecosystem management reflecting *Ki uta ki tai* concepts requires advancements in two key areas.

1. Pathways for meaningful and culturally appropriate participation of iwi, hapū, and whānau in planning approaches and management processes seeking to improve outcomes for freshwater and estuaries.
2. Technical challenges on the integration of freshwater/catchment modelling and estuarine ecological health assessment.

Two of New Zealand's National Science Challenges (Sustainable Seas, Our Land & Water) embarked upon a combined programme of work to be implemented in partnership with MfE. The combined initiative became known as the '*Ki uta ki tai*' project. It aimed to achieve impact by bringing knowledge streams together through shared visions, values, and processes to inform catchment-based solutions that would ultimately improve the mauri of catchments and estuaries.

Parts of our 'Ki uta ki tai' project focused on hydrological connectivity. Specifically, we endeavoured to join "land and freshwater" research/modelling from the Our Land & Water National Science Challenge with coastal and marine focused "seas" research from the Sustainable Seas National Science Challenge. However, we acknowledge that the Ki uta ki tai concept is broader than just hydrological connectivity. Integrated land-to-sea management and ecosystem-based management, which seek to balance multiple value sets and multiple interconnected pressures on ecosystems, are consistent with Ki uta ki tai concepts, but are not equivalent to them.

Lutien and Grimsdale (2020) explain *Ki uta ki tai* as follows:

> "*In te ao Māori (the Māori world) it is acknowledged that the balanced natural order of ecosystems and ecological thinking is characterised in the expression 'Ki Uta Ki Tai' which refers to the journey of wai (water) as it falls from the sky, flows over the land and out to sea. This view describes a Māori understanding of sustainable land management. Within*

this approach, all parts of the system have a relationship with each other and nothing can be separated. Wai is sacred in te ao Māori and has its own whakapapa (genealogy). Recently this relationship was culturally recognised, with the Whanganui River being granted legal personhood in 2017" [23].

We also acknowledge that Ki uta ki tai connections extend across catchment and regional boundaries. In the Murihiku catchment in Southland—which was a focus of our project due the inclusion of Koreti/New River Estuary as a case study—key connections and interactions extended far beyond the boundaries of "catchments" or "freshwater management units" (Figure 2). Compartmentalised thinking often diverges from a te ao Māori approach that considers the wider cultural landscape setting or context [24].

Ki uta ki tai connects people to place and future generations. The connections inherent in the Ki uta ki tai concept are spatial *and* temporal. The iwi and hapū in case study locations with whom we spoke lamented estuarine degradation because it has severed opportunities to engage in customary fishing practices. For example, if kaimoana are no longer able to be collected, the handing down of knowledge surrounding this practice is also at risk. This is described clearly in the Patuharakeke Hapū Environmental Management Plan (2014):

"*The decline of kaimoana species, is accompanied by a decline in traditional knowledge in regard to those species, their uses and management practices. This impacts on our duty as Kaitiaki and displaces an important role and function for our tamariki and mokopuna. Our mana as tangata whenua, is further diminished by our inability to practise manaakitanga to gather kai moana for the table both for our families and manuhiri (something we were formerly renowned for). Not only does this impact on our cultural wellbeing, but it has economic consequences, as we are unable to put kaimoana on whanau dinner tables, a practice that has always supplemented low incomes and our diet*" [24].

Figure 2. Example of 'Ki uta ki tai' connections that transcends catchments and regions: Te Ara Koroka – ki uta ki tai – in the Murihiku Cultural Water Classification System (Nga Kete o te Wananga MBIE research), courtesy of Jane Kitson.

High level guidance

• Engaging with mana whenua

Improving estuarine management requires a willingness to **meet face-to-face and listen to the concerns of mana whenua**. Joint fieldwork and excursions to sites of interest are also extremely informative. Engaging at the local level is likely to be the most appropriate and productive approach.

Food safety and security is an often-identified need, with estuarine kaimoana valued for supporting households nutritionally and economically. Many of the people we spoke with at marae were involved with Jobs for Nature projects and were already actively participating in mitigations to reduce catchment contaminant loads to their local moana. The priority of the western science researchers on our team when engaging with mana whenua was to build trust and not interfere with what they were already accomplishing. Our team sought to contribute positively and demonstrate respect through patience, flexibility, regular communication, action, and follow-through. Our experiences of engaging with mana whenua in three case study estuaries—Ōtamatea (Kaipara), Waihī, and Koreti/New River—are presented in an Appendix to this report.

• Reconciling worldviews

Whilst management of estuaries is commonly considered in the context of how to reduce the risk of potential impacts from an activity on the environment, Māori have a different worldview perspective, thinking instead of how an activity can "enhance the mana" of a natural resource in the first instance (rather than being limited to reducing adverse risk). This means that the positioning, worldviews and discipline of officials from local government, officials from central government, and hapū/iwi kaitiaki will need to be considered for addressing estuarine management. The Sustainable Seas NSC has developed a set of quick guides for helping decision-makers reconcile the differences in approaches to marine management. The guides are also applicable within the context of managing estuaries and are important for informing how modelling can be used alongside locally based knowledge including mātauranga Māori [25].

The research underpinning these guidelines [26] identified that subjective factors such as worldviews, experiences, and context, along with previous learning or training, greatly shape how people perceive risk and uncertainty. All of these factors influence how people make decisions about marine management. To aid decision-making in such situations, three tools are provided:

1. **Individual Reflection**: This tool consists of questions aimed at uncovering personal influences such as worldviews, education, context, and experiences that affect decision-making.
2. **Plan Your Process**: This tool guides individuals or groups through considerations such as partnership, evidence, tools, processes, and rights balancing, helping to structure the decision-making process.
3. **Reflection on Progress**: Designed for group discussion, this tool helps measure success against various criteria, serving as a prompt for assessing progress during the decision-making process.

These tools are essential for helping decision-makers involved with estuarine management to assess risk from different points of view and deal with uncertainty. At the same time these tools prompt decision-makers to acknowledge our obligations under a Te Tiriti o Waitangi partnership.

• Expanding beyond upstream

We recommend that councils **expand beyond 'upstream' solutions** as a means of driving estuarine recovery. Because of the NPS-FW focus on limiting setting and MfE's development of a 'Managing Upstream' workstream for estuarine improvement, an emphasis of the Ki uta ki tai project was elucidating freshwater contaminant – ecological health relationships, with the goal of identifying freshwater contaminant thresholds below which desirable levels of estuarine ecological health could be achieved.

Specifically, the project was tasked, in each of the case study estuaries, to "*provide a list of suggested reductions in freshwater concentrations necessary for restoration of estuarine functionality and its mauri*". We sought to achieve this using a three-step process: (1) understanding iwi aspirations for place, (2) estuarine ecologists being able to identify freshwater contaminant thresholds or load limits for achieving or moving towards those aspirations, and (3) catchment modellers determining the necessary mitigations or changes in land use to achieve the necessary loads.

Conceptually, we know that catchment contaminants—particularly terrigenous sediment and nutrients—are key stressors that have degraded estuaries. However, **catchment contaminants are only *one part* of the stressor profile in estuaries**. Estuaries are not only affected by freshwater inputs but also by within-estuary stressors (e.g., dredging, reclamation, predator removals, overharvesting, invasive species) and by climatic and oceanic drivers (e.g., heatwaves and trends of increasing coastal sea surface temperature). Moreover, any new efforts to curb or limit freshwater contaminant inputs does not address accumulated 'legacy' sediments and nutrients that have been loaded to estuaries over decades [27]. Therefore, relationships between freshwater loads and indicators of estuarine health (even if we were able to solve the 'technical' problems satisfactorily) were always likely to be weak or idiosyncratic. **Expectations of clear and significant relationships between catchment contaminant exposures and estuarine health that could usefully inform management were unrealistic**. The project provided evidence that combinations of freshwater, climate, and ocean drivers had significant effects on indicators of estuarine health [28].

• Managing expectations

Councils and local kaitiaki should not expect immediate responses to contaminant input changes. A major impediment to identifying clear relationships between freshwater inputs and estuarine responses is the presence of time lags. **Estuarine responses are characterised by the biology responding to changes in environmental conditions**—individuals emigrate, or are unable to reproduce, or die. **These responses are unlikely to be immediately detectable**. For example, reduced shellfish reproduction in response to extremely wet weather (with copious sediment loading to the estuary) may not be observable as reduced abundance in estuarine populations until years later. Additionally, mud-tolerant species may respond positively, and mud-sensitive species negatively, to elevated inputs of terrigenous sediment. Therefore, responses of community-wide variables such as 'total abundance' may depend on the types of species present at a site and may explain the inconsistent and site-dependent relationships between contaminant loading and biological responses observed [29].

The legacy of past loadings—particularly the infilling and substantial expansion of mangroves and muddy habitats in our estuaries—**may be masking or interfering with the detection of responses to newly loaded contaminants**. There is substantial ecological theory on the topic of alternative stable states and hysteresis [30-33]. This work suggests that although elevated loading of catchment contaminants has led to estuarine degradation, we cannot expect estuaries to immediately respond to catchment contaminant reductions. This type of lag is much longer than the ecological lags described above. Although the existence of lagged responses is unequivocal, exploring the significance of lags is difficult in part because of their open-ended nature (do we test for effects of 3-month lags, 6-month lags, 12-month lags, multi-year lags?). This just increases the number of possible predictor variables and increases the number of possible significant responses, leading to an overall lack of clarity and consistency in the analysis of relationships between catchment contaminant loadings and estuary ecological responses.

Summary of project challenges (technical)

- ## The ‘modeller’ / ‘ecologist’ divide.

Catchment contaminant load models give numbers for every major stream entering every estuary in New Zealand and can be used to explore effects of changes in land use (e.g., reforestation of 10, 25, and 50% of a catchment)[34]. Information on at least four types of catchment contaminants (sediment, nitrogen, phosphorus, *E. coli*) can be produced under most scenarios. This is useful information. Similarly, many Councils around the country collect State of the Environment data in estuaries using standard protocols—high quality data that stretches back >30 years in some estuaries.

Yet, the outputs produced by modellers are often not able to be used easily by estuarine and coastal ecologists, particularly if the scales are mismatched in either space or time (or both).

<u>Spatial example</u>. Catchment contaminant load models (which can be used to explore effects of land-based mitigations, such as reforestation) stop at the edges of estuaries. Yet ecological response data (e.g., State of the Environment benthic invertebrate monitoring data) is generally collected from sites in the interior of estuaries. To overcome this,

1. Methods were developed to bridge the ‘spatial distance’ between freshwater contaminant entry points and estuarine sampling sites. In other words, the ‘**exposures’ of individual estuarine sites to catchment contaminants were estimated** [35-37].
2. Catchment contaminant input data can be averaged across the estuary and assumed to be spatially uniform. The spatial average can then be correlated with estuary-scale ecological response data, such as percent of available estuarine habitat covered by nuisance macroalgae or seagrass [38]. Note, however, it is not advisable to average estimates gathered from a handful of SOE sites (e.g., sediment accumulation rate data from buried plates or macroinvertebrate health index values) to understand whole-of-estuary health.

<u>Temporal example</u>. Readily available catchment contaminant load model outputs are time-invariant, i.e., representing long-term average ‘typical’ conditions. Yet ecological response information is often garnered from SOE monitoring; data that are collected monthly, quarterly, or annually over periods of years to decades. We want to know what is driving the trends and fluctuations apparent in the monitoring data, but we cannot do so with temporally-invariant modelled drivers. In other words, a single unchanging number cannot be used to predict fluctuations in a time-series. While dynamic catchment models for contaminant loads are available, they have not yet been developed sufficiently to use on a widespread basis nationally, they are costly, and they often struggle to represent temporal dynamics accurately. Hence dynamic catchment models were not used in this project.

To allow temporal-average load models to be used, yet provide some temporal prediction, **rating curves were used** to ‘temporally disaggregate’ the contaminant load model data, i.e., to **produce a time-series of loadings for each stream entering each study estuary** [35,39,40]. Note that this involved using the catchment contaminant load models in ways in which they were not originally intended to be used. The models may not perform particularly well when applied in these new situations.

- ### The 'contaminant fate' problem

Freshwater contaminant load data is inherently "suspended" (i.e., loads of suspended sediments, total phosphorus, total nitrogen, and *E. coli*). However, many of the empirical environmental data that we collect in SOE monitoring programmes to predict estuarine health are bed-associated: e.g., sediment deposition/accumulation rate (measured using buried plates) and bed sediment muddiness (measured by grain size analysis). Council stakeholders wanted to know how estuarine muddiness and other indicators of estuarine health are responding to changes in catchment contaminant loading. They were frustrated that the **efforts to link catchment contaminant loads to estuaries did not (and could not) focus on the most familiar and best understood estuarine attributes/indicators**.

Most of the contaminant fate models that are capable of predicting sediment transport, deposition, resuspension, and final resting place (fate) are computationally complex and therefore very expensive and difficult to parameterise and run. They are also generally built on an estuary-by-estuary basis and are not generalisable. Moving forward, we will need to rely on simplified models or will need to develop wholly new approaches (e.g., machine-learning enhanced 'emulators').

Summary of project findings (technical)

Analysis of estuarine response data required us to select estuaries with sufficient quality and quantity of data. We provided MfE with a summary of estuarine response data availability in seventy-seven estuaries around Aotearoa-NZ.

<u>Understanding spatial variability</u> is necessary for determining how different parts of estuaries will respond to management activities such as the setting of freshwater load limits. We identified twelve Aotearoa-NZ estuaries with estuarine response data collected from multiple sites (>5) in a given year. These twelve estuaries covered a range of estuary types, situations, and parts of the country. Our spatial data analysis revealed:

- Ecological health is not uniform across estuaries [36].
- The exposure of individual sites to freshwater contaminants (based on optimal path distances via estuary channels) was a significant predictor of ecological health in some estuaries [36]. However, the **proximity of a site to the estuary mouth appears to be the simplest predictor of site health**, suggesting that regular flushing or cleansing by cleaner coastal waters is a key contributor to site health.

<u>Understanding the contributions of climate and oceanic drivers</u> to estuarine ecological health metrics, not just freshwater contaminant loads, is relevant to the 'managing upstream' mandate. We identified six estuaries in the Auckland and Waikato regions where macroinvertebrate time-series data had been collected at ≥ 3 sites, at least annually, for ≥ 10 years, and we assessed the role of climate and oceanic variables in driving variability in these time-series. Our analysis revealed that:

- **Climatic and oceanic drivers** (including coastal sea surface temperatures and relative El Niño/La Niña strength) **were often correlated with macroinvertebrate response**

variables. We concluded that climatic and oceanic drivers needed to be accounted for during subsequent tests of the influence of freshwater contaminants [39].
- There was evidence of **increasing coastal sea surface temperature adjacent to estuary mouths** [35]. These trends are likely to continue with climate warming.

Understanding estuarine ecological responses to temporal changes in freshwater contaminants is required to assess the effectiveness of upstream mitigations to limit catchment contaminant inputs to estuaries. Our time-series analyses of freshwater contaminant exposure and estuarine macrofaunal response data, after accounting for the effects of climate/ocean drivers, revealed:

- **responses to freshwater contaminant exposures were often delayed (lagged)** and were often **inconsistent even across sites within estuaries** [35].

- **In some cases, the direction of effects was counter to expectations** (e.g., increasing richness or abundance of macrofauna in response to increases of a known stressor like sediment) [35].

- The metrics of exposure of individual sites to freshwater contaminants developed for these analyses involved (i) temporal disaggregation of steady-state catchment model information [38] and (ii) the development of methods to spatially distribute load information from the edges of estuaries to sites in the interior [39]. Simplifying assumptions in each step may have poorly represented reality and been responsible for the weak/idiosyncratic relationships [35].

- However, there is also a sound theoretical basis for explaining the weak estuarine ecological responses to freshwater inputs, namely, **estuarine macrofauna respond to multiple environmental stressors and drivers—not just freshwater ones** (see 'Expanding Beyond Upstream' section).

Understanding climate-induced changes to freshwater contaminant loads is required to understand if mitigations to achieve estuarine targets will be effective in the future. The catchment modellers from Our Land & Water applied climate change scenarios to current land use and future mitigation scenarios to explore the consequences of climate-related increases in rainfall. This analysis suggested that:

- **Climate change will result in higher levels of erosion and sediment input to estuaries** [41], levels that have the potential to exceed the reductions (gains) made via reforestation and riparian planting.

- **Continued 'business as usual' mitigations will be increasingly ineffective in the future**.

Understanding the relative influence of different freshwater contaminants (e.g., sediment, nutrients) is critical for identifying the most effective management options. For example, is it better to focus on sediment reduction or nutrient reduction to achieve estuarine targets? Our research revealed that:

- The metrics of exposure of individual sites to **suspended sediments, total nitrogen, total phosphorus, and *E. coli* were highly correlated with one another**. This is likely reflective of the true situation in nature, namely that runoff of sediments, nutrients and faecal contaminants into estuaries is **highest during storm events when river discharges are peaking** [42].

- The high correlations decreased our ability to disentangle the effects of individual stressors.
- However, **high correlations may facilitate the use of a single 'master variable'** as a means of tracking freshwater contamination (i.e., use sediment, or salinity, as a proxy for freshwater contaminant exposure more generally).

Understanding the levels of estuarine muddiness and suspended sediment concentration capable of altering biodiversity, health, function and ultimately ecosystem resilience is critical for estuarine management. However, **specific targets for muddiness and SSC will likely differ depending on environmental settings** [43]. Using multiple lines of evidence from a thoroughly and repeatedly investigated study estuary where intertidal and subtidal areas at varying distances away from a major freshwater sediment source were sampled over time, we identified the following general patterns:

- **High bed sediment muddiness usually correlates with reduced benthic biodiversity** and health. This can impact the functioning and resilience of estuarine ecosystems.
- Deeper sites tend to be muddier than shallower sites.
- Intertidal habitats near sediment entry points can remain sandy and biodiverse. In other words, **proximity to sediment source is not always the main determinant of bed sediment muddiness**.
- The level of muddiness correlated with reduced biodiversity and health may be higher in the subtidal zone, relative to the intertidal. This suggests greater tolerance to, or reduced harmfulness of, bed sediment muddiness in the subtidal zone.
- Muddiness may override the positive correlation between benthic diversity and water depth. **In harbours with clear waters and sandy sediments, benthic diversity tends to increase with water depth. In turbid and muddy harbours, it may not**.
- When overlying seawater is turbid, shallow sites have less microalgae than expected. Sediment microalgae are a critical food resource for a range of secondary consumers (microbes, meiofauna, macrofauna) that support upper trophic level vertebrates.
- Seabed light levels are lower at sites near sediment-laden river mouths. Light penetration is important for ecosystem health, e.g., needed by plants for photosynthesis and by visual predators for prey capture.
- **Seafloor primary production rates are lowest at muddy sites with low seabed light**.
- The highest primary and secondary production occurs furthest from riverine sediment sources.
- **High suspended sediment concentration reduces the proportion of daylight hours of net benthic oxygen production**. Oxygen is respired by all heterotrophic organisms (e.g., invertebrates, fish) and mediates biogeochemical processes in sediments.

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Appendix

• Summary of case studies and engaging with iwi

The Ki uta ki tai project had three case study estuaries. Māori researchers funded by the project had strong relationships and successful experiences and track records of working with iwi and hapū in each of the estuaries. We believed that these relationships and experiences would facilitate and accelerate our understanding of the aspirations of iwi and hapū associated with these estuarine spaces. We outline some of the successes and challenges we experienced in engaging with iwi in case study estuaries below.

Kaipara Harbour

Kaipara Harbour was identified as a case study estuary in part because of the Kaipara Moana Remediation project [1] and the presence of a 'business case' for large-scale Jobs for Nature investment in catchment mitigations to reverse degradation in the harbour. We believed that the groundwork for understanding iwi aspirations for the harbour was advanced and that we could quickly focus on the underpinning science to support and achieve those aspirations. We believed that this would provide an informative contrast to other estuary case studies where iwi and hapū aspirations were less well documented. In our project timeline, our first planned deliverables were for the Kaipara Harbour, as **we thought we would be able to move most quickly here**.

Ironically, our engagement with Environs / Te Uri o Hau regarding the project and Kaipara Harbour **proceeded the slowest of any of the case study estuaries**. This was likely attributable to several factors:

(1) the Māori researcher from the project tasked with leading engagement in this case study estuary had worked closely with the Integrated Kaipara Harbour Management Group (IKHMG) in the past, but the new Kaipara Moana Remediation initiative (KMR) had a different structure that the researcher may have been less familiar and involved with.

(2) Because the KMR initiative was new and ambitious, the capacity of Te Uri o Hau to engage in anything else—particularly a small project like ours—may have been limited.

(3) The project researcher tasked with leading engagement in this case study was a senior researcher at Manaaki Whenua Landcare Research and held leadership positions in both National Science Challenges. The researcher had appropriate credibility, connections, and mana. However, as a highly sought after individual with many commitments, the capacity of this researcher to contribute to the project may have been limited.

(4) Environs / Te Uri o Hau covers a large geographic area and includes 14 or more different marae. It was probably **misguided to assume we could easily understand iwi and hapū aspirations for Kaipara Moana as a whole**.

The project team nevertheless persevered and eventually met with Environs personnel at the Maungaturoto office in Northland. Trust was established and plans were made for a visit to the **Ōtamatea Marae, located in one of the inland arms of the Kaipara Harbour in the Northland Region**. In January 2024—after the Ki uta ki tai project funding had ended—a team of marine ecologists and Māori researchers from NIWA stayed overnight at the marae to learn about the harbour and the concerns of the local kaitiaki. We jointly undertook fieldwork in the estuary the following day to collect sediment and shellfish for contaminant testing at sites identified by the kaitiaki.

Many of the people we spoke with at the marae were involved with Jobs for Nature and were working on riparian planting projects. **They already understood and were actively participating in mitigations to reduce catchment contaminant loads to the harbour**. They have observed the decline in estuarine water clarity themselves, noting they were no longer able to see the bottoms of creeks from overbridges as they could when they were young. They mentioned the lack of scallops in the harbour now, a species sensitive to suspended fine sediments. They noted the appearance of thick, muddy deposits in the harbour after Cyclone Gabrielle and the February 2023 flooding. However, **their primary concern was the point source discharge of organic and lipid-rich waste from a nearby dairy factory**, rather than the more diffuse catchment contaminants [2]. They had serious concerns about food security and safety, noting that the local arm of the harbour was used to support households nutritionally and economically.

Koreti / New River Estuary

The effects of increasing catchment contaminant inputs to New River Estuary—particularly increased nitrogen loadings associated with dairy intensification over the last 20 years—are well documented [3,4]. Widespread occurrence of nuisance macroalgae (and associated muddiness and biodiversity loss) has been one of the most overtly obvious indicators of degradation in this estuary.

Bands or targets for nitrogen inputs to the estuary have been proposed by researchers and Environment Southland as a means of reducing the biomass and extent of nuisance macroalgae [5]. However, during site visits to the estuary by modellers and ecologists, the Māori researcher for this case study pointed out that reductions in nuisance algae cover on an estuary-wide basis may not reduce the nuisance macroalgae in the specific places that matter to iwi, e.g., former kaimoana collecting spots that are now completely overrun. As has been expressed above, the loss of connections to places and the inability to share knowledge involving cultural practices across generations is a major concern.

Also, **despite New River estuary being a prime example of eutrophication and effects of excess nutrient loading from catchments, the concerns of the iwi for the estuary extend far beyond this**. For example, a large proportion of the upper estuary was reclaimed for farmland and the Invercargill airport. The documented leaching of toxic chemicals into the harbour from the municipal rubbish dump is a human and ecological health concern. The municipal sewage treatment plant discharges into the harbour with the potential to affect food safety. The estuary, now highly infilled, used to be navigable to large ships that could sail all the way to Invercargill city. Limiting inputs of new sediments through upstream mitigations is unlikely to rapidly or markedly affect legacy sediments and contaminants already present in the harbour. This suggests that **major upstream *and* within-estuary mitigations—and outside the box thinking—are needed**.

Waihī Estuary

Waihī estuary is a small estuary in the Bay of Plenty that receives a proportionally large volume of freshwater discharge from a primarily agriculture catchment with orchards and cows. The estuary has lost ~80 hectares of seagrass since 1940, with only remnant patches remaining, with nuisance macroalgae now covering tens of hectares.

In this estuary, a collective of five iwi (Ngāti Whakahemo, Ngāti Whakaue ki Maketū, Ngāti Mākino, Ngāti Pikiao, Tapuika) are working with Bay of Plenty Regional Council and collaborating with researchers from a range of institutions on the Te Wahapū o Waihī project. At the time our project started, iwi were already leading and executing a range of upstream and in-estuary mitigations aimed at revitalising the estuary. The Māori researcher for this case study estuary (Ngāti Whakahemo, Ngāti Awa) was already working with researchers from NIWA, Manaaki Whenua Landcare Research, and Cawthron on various National Science Challenge and government-funded projects.

The key priority for engagement in our specific case was to build trust and not overstep. **There is a temptation for project leaders to want to link to, and benefit by association with, success stories** such as the iwi-led Te Wahapū o Waihī project. However, the leadership, wishes, and aspirations of the iwi must be respected, and we should never seek to take credit for their successes. Our team sought to contribute and **demonstrate respect through patience, flexibility, communication, action, and follow-through**.

Our engagement involved a formal welcome from Ngāti Whakahemo at Pukehina marae followed by conversations about concerns and possible solutions for the estuary. Joint habitat mapping fieldwork was conducted with Ngāti Whakahemo in the estuary in March 2023. Draft habitat maps were delivered in June 2023. A final report with methods, maps and interpretation was delivered in December 2023 [6]. Our communication has continued and the relationship we have built together will last beyond the life of the project.

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