National Science Challenges

SUSTAINABLE SEAS

Ko ngā moana whakauka

Guidance

Monitoring estuaries in a changing world:

Lessons for designing long-term monitoring programmes

This guidance outlines key lessons for managers to consider when designing long-term monitoring programmes for estuaries. These lessons were learned from the Manukau Marine Ecology Monitoring Programme, one of the longest, ongoing estuary monitoring programmes in Aotearoa New Zealand, and informed by research from the Sustainable Seas National Science Challenge *Tipping Points* project.

Long-term marine monitoring programmes are one of the only ways that we can:

- Define the state of the environment
- Understand the causes and magnitude of natural variability
- Provide baseline information so environmental changes related to management decisions can be detected
- Identify changes driven by manageable, human-driven stressors
- Show and track key trends to inform future management strategies

About the *Tipping Points* project

This project was the first nationwide assessment of how estuaries and harbours in Aotearoa New Zealand respond to change. The project team identified the critical factors to consider, and the recommended data required, for a robust monitoring programme to detect tipping points.

Learn more about the *Tipping Points* project: sustainableseaschallenge.co.nz/tipping-points

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About this document

This guidance outlines key lessons for managers to consider when designing long-term monitoring programmes for estuaries.

Contact: Judi Hewitt, sustainableseasNC@niwa.co.nz

Key organisations: NIWA, Auckland Council

We recommend reading this guidance alongside our other resources on estuary management:

Guidance

Monitoring for tipping points in the marine environment
sustainableseaschallenge.co.nz/monitoring-for-tipping-points-in-marine-environments

Guidance

Managing the impact of turbidity, nutrients and sea level rise on coasts and estuaries
sustainableseaschallenge.co.nz/managing-turbidity-nutrients-and-sea-level-rise-on-coasts

Summary

Impact case study: Robust, cost effective marine monitoring
sustainableseaschallenge.co.nz/ics-robust-cost-effective-marine-monitoring

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National Science Challenges
NIWA Taihoro Nukurangi
Auckland Council Te Kaunihera o Tāmaki Makaurau

Introduction

Estuaries are at the interface of land and sea and subject to many human uses and impacts. Their inherent complexity requires robust monitoring and focused management attention.

In August 2020, the Parliamentary Commissioner for the Environment (PCE) released *Managing our estuaries*, a report that calls for national standardised approaches to managing estuaries. The PCE recommended establishing a “robust monitoring system to help local government and communities make informed decisions”.

State of the environment (SOE) monitoring provides local government and communities with information on what is happening in the environment.

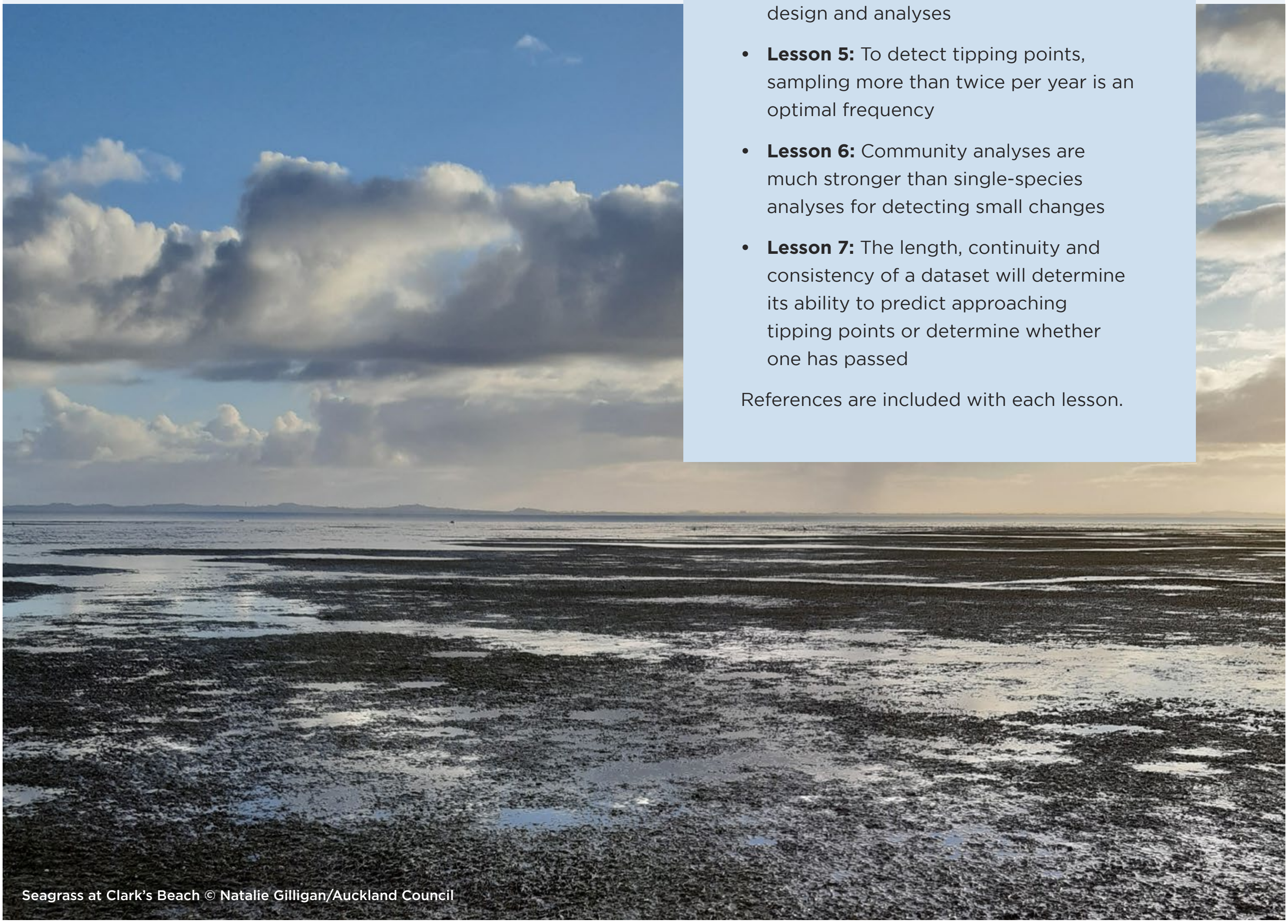
The importance of long-term data in SOE monitoring has increased with our knowledge that climate change is occurring and that sudden, abrupt changes (tipping points) are likely consequences of multiple stressors and/or cumulative effects. Long time-series are one of the only ways that we can show key trends, understand the magnitude of natural variability, and separate changes driven by manageable, anthropogenic drivers from climate change.

7 key lessons for designing long-term estuary monitoring programmes in a changing world

These lessons are based on the Manukau Marine Ecology Monitoring Programme and Sustainable Seas research.

- **Lesson 1:** Principles of design to be decided upon at the start of the programme
- **Lesson 2:** Undertake reviews at fixed time intervals to ensure the monitoring programme is cost-effective, yet provides quality, robust data
- **Lesson 3:** Analyses of long-term data can detect multi-year cyclic trends and patterns that short-term data cannot
- **Lesson 4:** Temporal variability can influence the ability to detect tipping points, therefore it is important to consider climate patterns in programme design and analyses
- **Lesson 5:** To detect tipping points, sampling more than twice per year is an optimal frequency
- **Lesson 6:** Community analyses are much stronger than single-species analyses for detecting small changes
- **Lesson 7:** The length, continuity and consistency of a dataset will determine its ability to predict approaching tipping points or determine whether one has passed

References are included with each lesson.



Seagrass at Clark’s Beach © Natalie Gilligan/Auckland Council

About the Manukau Marine Ecology Monitoring Programme

The programme began in 1987 and is still continued and paid for by Auckland Council today. The Manukau is the second largest harbour in Aotearoa New Zealand, with extensive sandflats covering approximately 40% of the area. The programme focuses on the benthic macrofauna of these intertidal sandflats.

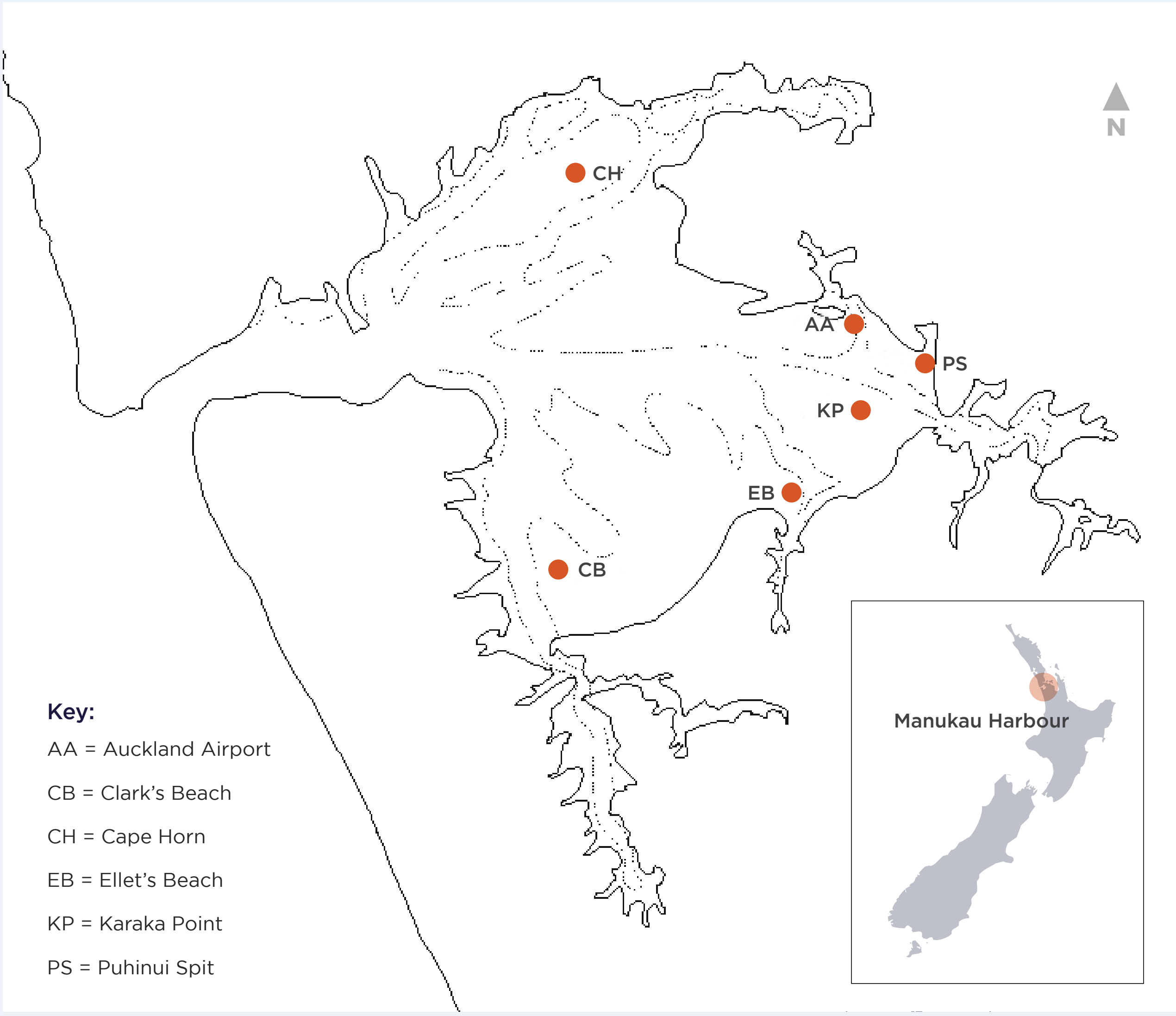
Sampling was initially conducted every 2 months at 6 sites (see map) that represented different areas of the harbour: different land uses, catchments and hydrodynamic compartments. At regular intervals the programme has been assessed for effectiveness and changes have been made to the number of sites, sampling frequency and ancillary variables measured.

The programme has provided useful information on monitoring design and analyses. While the monitoring was primarily of invertebrate abundance data, many of the lessons can also be applied to other data types: sediment and water quality; plant biomass and cover; and abundances and biomass of microphytobenthos and fish.

There is also a strong probability that the lessons learnt from the Manukau data will apply to other regions. This is especially likely for design criteria methods and the appropriateness of analyses. Of particular importance for estuarine monitoring networks is to determine whether the natural variability observed in the Manukau data and supported by other monitoring in the Auckland Region in two different oceans is translatable to other regions in Aotearoa New Zealand.

If long-term continuous time-series could be collected at some selected sites around Aotearoa New Zealand, the data could be used to set contexts for other less frequently monitored sites in a range of locations.

Map of the Manukau showing the positions of the 6 sites



LESSON 1: Principles of design to be decided upon at the start of the programme

- Site size needs to be representative and sample unit size (ie the depth and area) needs to consistently collect small and large species
- Spatial stratification to limit the extent to which spatial variation affects temporal differences
- Species to monitor, based on their known and different responses to important stressors
- Frequency, ie how regularly the estuary will be sampled
- Replication, ie number of samples needed to adequately describe biodiversity and detect change

Design of the Manukau Marine Ecology Monitoring Programme

Before this programme began, design principles were settled on – some are outlined below. These may prove useful when first considering the design of a programme.

- **Site size**
  The intertidal sandflats of the Manukau Harbour generally encompass 100s of metres without changing much in inundation time. Site size was set at ~1 hectare to encompass small-scale variability without changing habitat type.

- **Sample unit size**
  We conducted a small pilot study in the harbour to investigate the depth at which most macrofauna were observed (<15cm) and the area required to consistently collect both small and large species (13cm diameter rather than 5, 10 or 20cm) while not requiring too much processing time (Thrush et al 1988).

- **Stratifying the sampling**
  Spatial stratification was used to ensure that random sample points were spread over the whole site. This limits the extent to which temporal patterns are confounded by spatial variation. The size of the strata (25 x 25m (or 30 x 30m)) was set by the number of replicates and a study of the spatial patterns of macrofaunal abundances observed at each site on the first sampling occasion (Thrush 1991).

- **Species to monitor**
  26 species were selected to monitor based on their known and different responses to important stressors: contaminants; nutrients; and sedimentation/turbidity. Selecting species that respond in different ways to stressors allows analyses to determine the stressor(s) most likely to be causing any observed changes.

  For example, the polychaetes *Prionospio aucklandica* and *Boccardia syrtis* both exhibit preferences for sandy-mud sediments but one is sensitive to copper and the other to lead (Hewitt et al 2009).

- **Frequency**
  Sampling in the Manukau initially took place every 2 months. We have found that in order to detect sudden changes, sampling more than twice per year was necessary, although sampling 6 times per year was not. However, sampling 6 times per year allows greater predictability of species' natural variability.

  Abundance of macrofauna were generally considered to integrate over environmental conditions of 2 – 3 months. Selecting a sampling frequency of 2 months allowed good power to detect change within a 3-year period (18 data points) and, hopefully, to detect changes in juvenile settlement and survival.

  Initially, a within-year sampling frequency of 2- to 6-monthly is required. Reductions should be considered during the first review of the programme.

- **Replication**
  Two factors were used to determine the number of replicates needed: the number of samples needed to start approaching an asymptote of species richness; and the power to detect change (Hewitt et al 1993). The data for these analyses came from collecting 36 samples from each site on the first sampling occasion. As a result, 12 replicates per site were used thereafter.

References

Academic Publications

Hewitt JE, GB McBride, RD Pridmore and SF Thrush (1993). Patchy distributions: Optimizing sample size. Environmental Monitoring and Assessment 27:95 – 105.

Hewitt JE, MJ Anderson, C Hickey, S Kelly and SF Thrush (2009). Enhancing the ecological significance of contamination guidelines through integration with community analysis. Environmental Science and Technology 43:2118 – 2123.

Thrush SF (1991). Spatial patterns in soft-bottom communities. Trends in Ecology and Evolution 6:75 – 79.

Report

Thrush SF, RD Pridmore, JE Hewitt and DS Roper (1988). Design of an ecological monitoring programme for the Manukau Harbour. Water Quality Centre client report for Auckland Regional Authority, Hamilton.

LESSON 2: Undertake reviews at fixed time intervals to ensure the monitoring programme is cost-effective, yet provides quality, robust data

- **Review the programme at fixed time intervals and adapt as necessary**
- **Cutting sampling replication or frequency affects the ability to detect change**
- **However, reducing the number of sample sites is effective if remaining sites are continuously monitored**
- **If long-term continuous time-series could be collected at some selected sites around the country, the data could be used to set contexts for other less frequently monitored sites in a range of locations**

Reviews and adaptations

Reporting was conducted annually and after 5 years we reviewed/analysed the data to determine: how the programme could be altered to minimise costs while maintaining robustness; and what magnitudes of change could be detected with what types of analyses.

In the first review in 1994, we investigated the effect of cutting replication and frequency of sampling (Hewitt et al 1994):

- **Replication:** Collecting 12 replicates was useful in giving us a greater ability to detect seasonality – that is, the temporal patterns were less confused by spatial variability than when fewer replicates were collected (Figure 1).
- **Frequency:** The number of trends detected, and the predictability of the time series, was greatly reduced when sampling frequency was dropped from 6 times per year to 3 times, and then 2 times per year.

  Annual sampling in winter allowed a similar number of trends to be detected, comparative to sampling twice per year. Annual sampling in summer was often affected by recruitment variability.

  Note: It might be possible to reduce frequency once there is a good baseline. In 2020, Auckland Council reduced their sampling frequency from 6 times per year to 3. This enabled sampling effort to be directed while having only minimal impact on their ability to detect change given the 30+ year record sitting behind it.

These analyses together suggested that **reducing replication or frequency would affect the robustness** of the programme. Analyses of costs demonstrated that field work was a major component and that the biggest saving would occur by removing sites. As a result, 4 sites were removed from the programme, leaving 2 sites situated in 2 of the 3 hydrodynamic compartments of the harbour.

This was not to be permanent, rather after another 5 years, all 6 sites would then be re-monitored for 2 years. This created a spatially and temporally nested monitoring programme.

In 2000, we reviewed the programme again. The analyses found that the **time series from the 2 continuously monitored sites could be used to interpret change (or lack of) in the 4 sites with the 5-year gap** (Figure 2). This strategy has continued, except when the Council has advance knowledge of changes in land management.

Other changes to the programme included:

- Adding sediment characteristics: sediment grain size, organic content and chlorophyll *a*
- Annually in October we conducted a full community analysis. This allowed the data to be converted into health indices (the AC BHMmetals, BHMmud and TBI)

References

Academic Publications

Hewitt JE and SF Thrush (2007). Effective long-term monitoring using spatially and temporally nested sampling. Environmental Monitoring and Assessment 133:295–307.

Thrush SF, RD Pridmore and JE Hewitt (1994). Impacts on soft-sediment macrofauna: The effects of spatial variation on temporal trends. Ecological Applications 4:31–41.

Report

Hewitt JE, SF Thrush, RD Pridmore and VJ Cummings (1994). Ecological monitoring programme for Manukau Harbour: Analysis and interpretation of data collected October 1987–February 1993. Auckland Regional Council Environment Technical Publication TP036.

More seagrass at Clark's Beach © Hamish Allen/Auckland Council

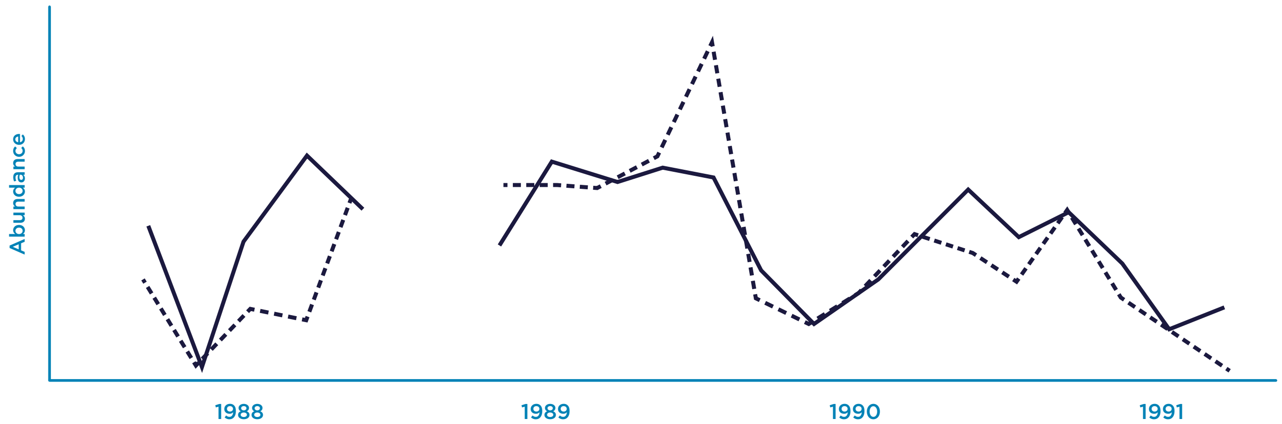


Figure 1: Solid line based on 12 replicates shows a temporal pattern of low abundances in February of each year and relatively consistent magnitudes of recruitment between years. Dashed line based on 3 randomly selected replicates shows a temporal pattern of low abundances between December and April (depending on the year) and variable recruitment levels (Thrush et al 1994).

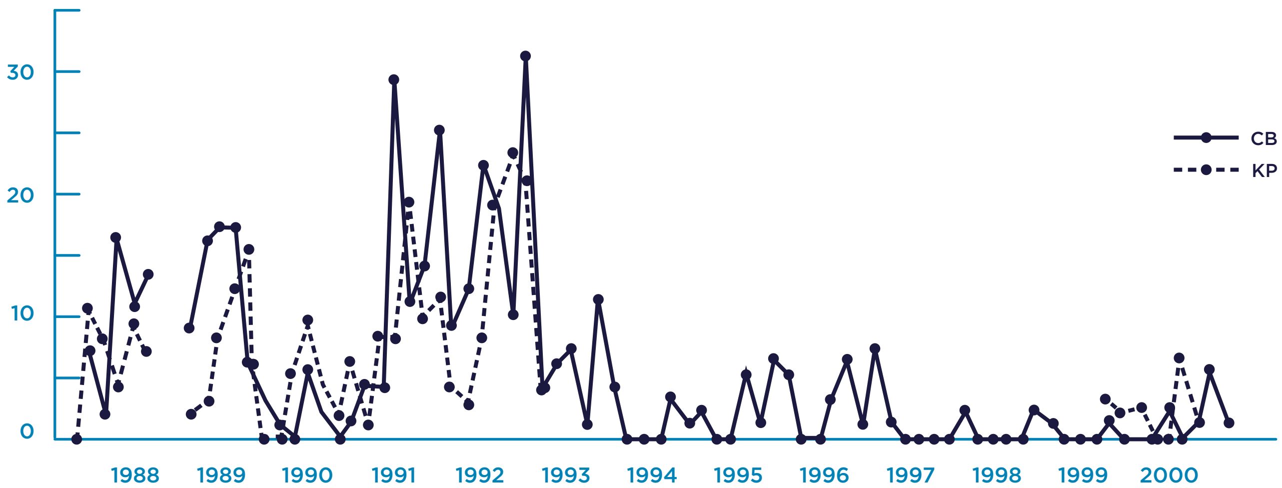


Figure 2: Difference over time detected for CB but not KP because with the interrupted sequence the abundances in 1999–2000 are similar to those in 1990–1991. However, the previous similarity in the dynamics at CB and KP suggests that KP is also undergoing a decline (Hewitt & Thrush 2007).

Puketutu Island, the Māngere coastline, and the Manukau © Natalie Gilligan/Auckland Council

LESSON 3: Analyses of long-term data can detect multi-year cyclic trends and patterns that short-term data cannot

- **Most species abundances are predictable, even though they show seasonality and multi-year cycles**
- **Multi-year cyclic patterns cause a problem for short-time series: are the trends you detect going to remain a trend or are you only seeing part of a long multi-year cycle? Temporal patterns and trend analyses from sites that have been monitored for longer time periods can be used to answer this question**
- **Incorporate temporal variability into analyses, because they are often more sensitive than ones that do not incorporate temporal variability**

Analyse to detect trends

Ecological data is often thought of as being variable, and difficult to detect changes in. Our analyses after 5 years of monitoring demonstrated that most species abundances were predictable, even though many showed seasonality and variations in recruitment between years. Similar results have since been observed for other monitoring programs of similar frequency eg Central Waitemata (Halliday & Hewitt, 2007) and Kaipara (Hailes & Carter, 2014), and is most likely to hold true across New Zealand. Trends were detected for 29% of the species/sites (Figure 3).

There are numerous statistical methods that can be used to detect gradual and step changes – most of which remove temporal autocorrelation (including seasonality). However, variation in recruitment patterns can be a signal that changes to overall abundances will be coming. After 5 years of sampling, we investigated the relative effectiveness of methods that incorporated seasonality compared to those that treated it as a nuisance. Simulations of different sized step and linear trends applied to the time series of abundances of selected species showed that a method that took account of temporal patterns (ARIMA) could detect changes as small as 9% (Figure 4) while the then-recommended BACI-type methods could only detect step changes >30% (Hewitt et al 2001).

Even after 5 years, the data revealed that many of the populations exhibited **multi-year cyclic patterns. This causes a problem for short-time series – are the trends you detect going to remain a trend or are you only seeing part of a long multi-year cycle?** It also makes surveying different estuaries in different years problematic, unless you have at least one estuary that is monitored continuously throughout the duration of the programme. The scales of variability that we have observed in data from the Manukau may be able to be used to define likely scales of variability elsewhere and thus the types of analyses needed to robustly detect changes.

In the Manukau data, 7 to 9-year cycles are common and even longer-term ones are apparent. This is similar to many other areas of the world (Gray & Christie 1983).

We found that in these situations, running batch analyses that identify trends based on p-values resulted in reports of trends long after visual inspection could identify these as a cyclic pattern. However, examination of residuals for patterns allowed us to signal whether a trend is probably part of a multi-year cycle.

Identifying trends based on p-values without visual inspection also can result in trying to force a linear pattern to a non-linear or a step change.

Again, inspection of residuals can determine whether these occur as well as, for non-linear trends, the transformation which would allow the trend magnitude to be assessed using linear regression. If there is no reason to expect a change to occur, change point detection methods are particularly useful at determining the most probable time of change for step trends and trends that start (or end) part way through the time series.

References

Academic Publications

Gray JS and H Christie (1983). Predicting long-term changes in marine benthic communities. Marine Ecology Progress Series 13:87–94.

Hewitt JE, SF Thrush and VJ Cummings (2001). Assessing environmental impacts: effects of spatial and temporal variability at the scale of likely impacts. Ecological Applications 11:1502–1516.

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Hewitt JE, SF Thrush, RD Pridmore and VJ Cummings (1994). Ecological monitoring programme for Manukau Harbour: Analysis and interpretation of data collected October 1987–February 1993. Auckland Regional Council Technical Publication 36.

Halliday J and JE Hewitt (2007). Central Waitemata Harbour Ecological Monitoring: 2000 – 2006. Auckland Regional Council Technical Publication Number 314.

Hailes SF, and KR Carter (2014). Kaipara Harbour ecological monitoring programme: Report on data collected between October 2009 and February 2014. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Document: TR2015/008.

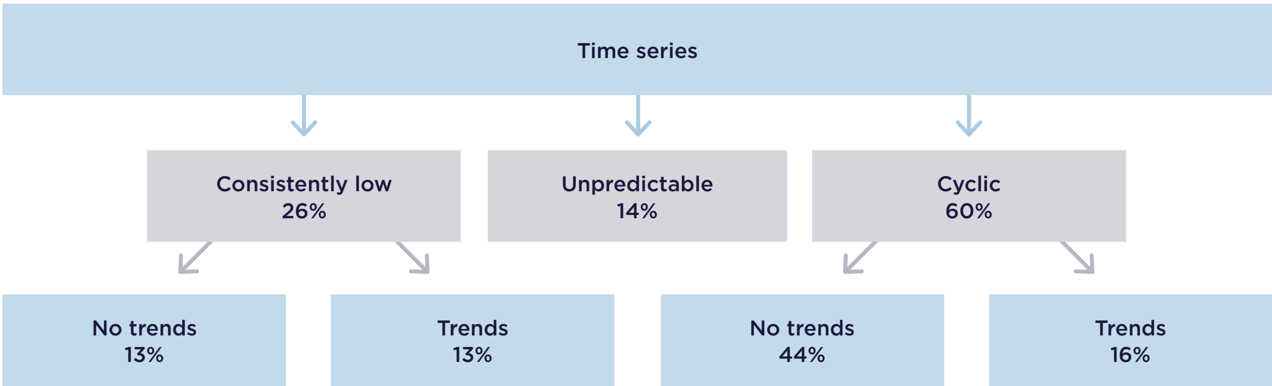

Figure 3: Types of temporal patterns observed after 5 years of sampling (Hewitt et al 1994).

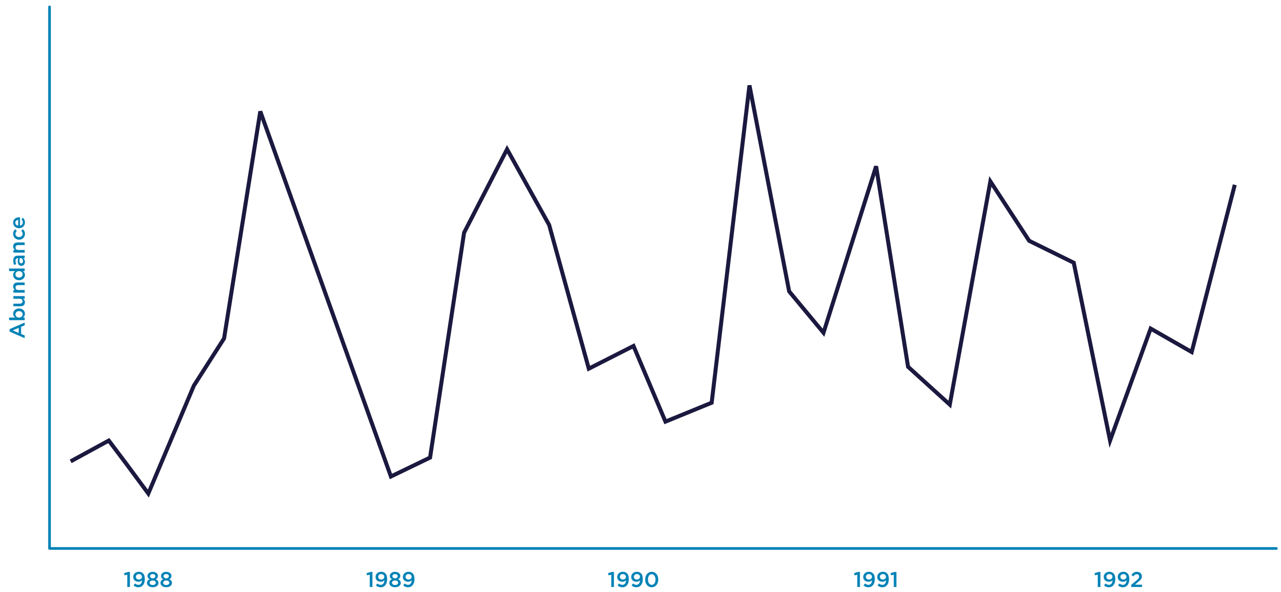

Figure 4: It looks as if an analysis would be unlikely to detect a change of 9% imposed in the middle of this time series, but we did (Hewitt et al 2001).

LESSON 4: Temporal variability can influence the ability to detect tipping points, therefore it is important to consider climate patterns in design and analyses

- Understand the strength and patterns of natural variability. This is useful when predicting risks associated with different activities, including climate change
- Incorporate Southern Oscillation indices (SOI) into analyses either to isolate trends from these patterns or to understand how likely they are to detect any change
- We are more likely to detect tipping points during La Niña, than during El Niño events

Variability caused by multi-year cycles

Analysing the multi-year cycles, we learnt how to go further than that and **incorporate SOI into our analyses**. As ENSO patterns not only affect sea temperature but also precipitation and wave/wind action, we found that including these types of variables as co-variables in our trend analysis could help us **isolate trends from these patterns** (Hewitt & Thrush 2009) and predict into unsampled times (Figure 5).

The Southern Oscillation also affects our ability to detect sudden changes (tipping points) (Hewitt et al 2021). New analyses of the macrofaunal data from sites AA and CB in the Manukau included imposing simulations of sudden changes at each point in the time sequence. We found that when the **sudden changes were imposed during El Niño events, we were much less likely to detect them than if the changes were imposed during La Niña**.

Interestingly, the previous work we had done with simulated changes (Figure 1) when much smaller changes were able to be detected, had occurred during transition from an extended La Niña period.

References

Academic Publications

Hewitt JE and SF Thrush (2009). Reconciling the influence of global climate phenomena on macrofaunal temporal dynamics at a variety of spatial scales. Global Change Biology 15:1911–1929.

Hewitt JE, R Bulmer, F Stephenson and SF Thrush (2021). Sampling frequency, duration and the Southern Oscillation influence the ability of long-term studies to detect sudden change. Global Change Biology 27:2213–2224.

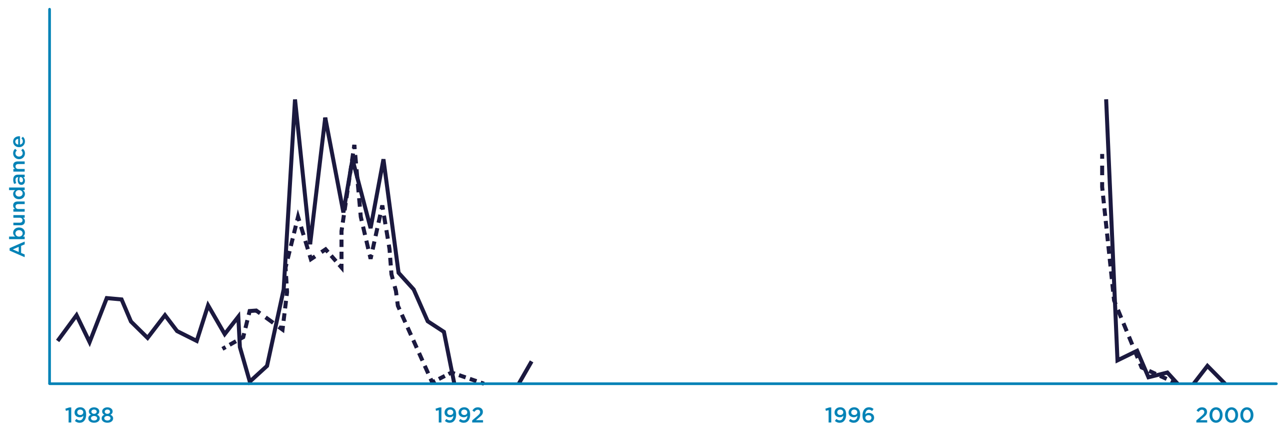

Figure 5: The solid line is the measured abundance and the dashed line is the abundance of a polychaete predicted by SOI and air temperature at one of the sites with interrupted sampling (Hewitt & Thrush 2009).

LESSON 5: To detect tipping points, sampling more than twice per year is an optimal frequency

- We can detect the arrival of tipping points
- Small management actions can have large consequences
- Small changes can be culturally or ecologically relevant

The analyses discussed in lesson 4 demonstrated that in general, **in order to detect these tipping points, sampling more than twice per year was necessary, although sampling 6 times per year was not.**

Detecting tipping points in a community: Tubeworm example

In April 2001, improvements to the wastewater treatment process for the Māngere Wastewater Treatment plant discharging to the Manukau were implemented. One of the monitoring sites was located 7km downstream from the previous oxidation pond discharge and the community at that site was dominated by a tubeworm species. This tubeworm formed a dense mat on the surface and preferred slightly enriched conditions. Abundances of the tubeworm mat were also highly variable over 5 to 7 years.

The management action coincided with a strong ENSO event and naturally low values of the tubeworm, resulting in complete disappearance of the tubeworm mat.

Both the lower nutrient concentrations and the disappearance of the tubeworm mat were demonstrated to play a role in the formation of a new macrofaunal community dominated by deposit feeders (Hewitt & Hailes 2007, Hewitt & Thrush 2010). As found elsewhere, prior to the community change (tipping point), there was a marked increase in annual variability (Figure 6).

References

Academic Publication

Hewitt JE and SF Thrush (2010). Empirical evidence of an approaching alternate state produced by intrinsic community dynamics, climatic variability and management actions. Marine Ecology Progress Series 413:267–276.

Report

Hewitt JE and SF Hailes (2007). Manukau Harbour ecological monitoring programme: report on data collected up until February 2007. Auckland Regional Council Technical Publication 334.

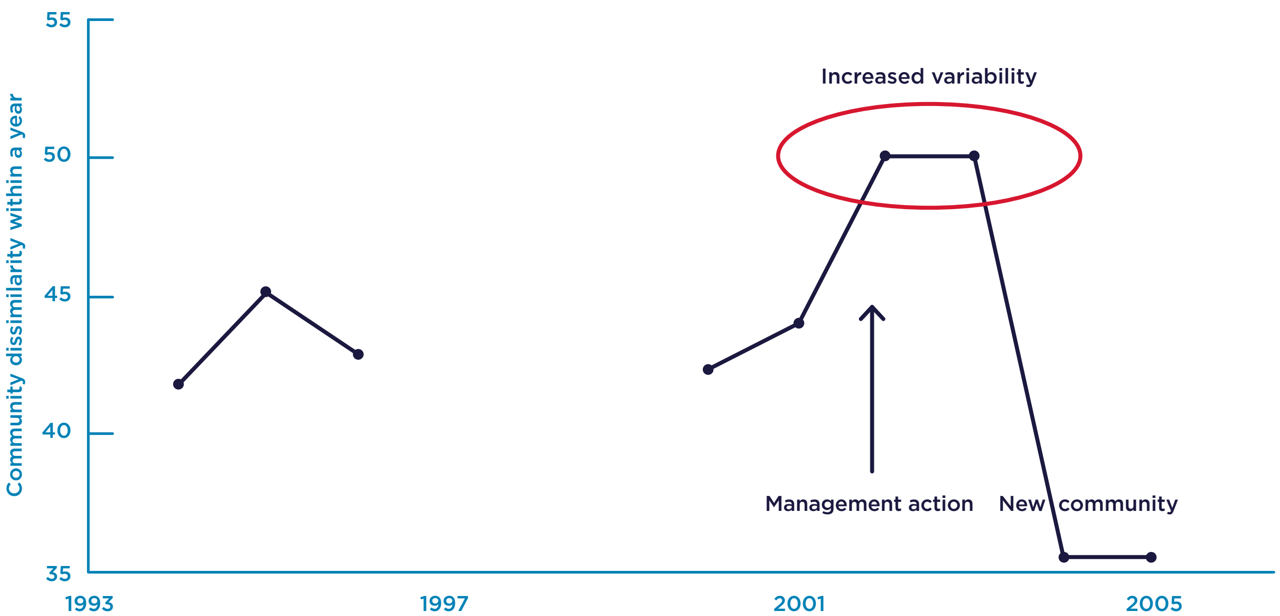

Figure 6: Prior to the tipping point, there was a marked increase (see red circle) in annual variability (Hewitt & Thrush 2010).

LESSON 6: Community analyses are much stronger than single-species analyses at detecting small changes

- Sites in areas of high biodiversity will often be more sensitive to change
- The more species exhibiting changes and the more we know about them, the easier it is to assign causality, ie to know which stressors they are responding to
- Small changes accumulate over time and through species interactions, creating large changes in biodiversity and community type

Changes, ecological relevance and causes

Detecting a change is fine, but as time goes on and more data is collected, more data points means a greater likelihood of detecting a small change.

Small changes may not be ecologically relevant – or are they? A change of ~1% per year in a species abundance (or mud content) sounds small, but over 20 years that is a change of 20% – not so small!

Small changes are particularly important if the species is of cultural or economic importance, or if it is key to ecosystem service or function. Even if this is not the case, small changes are important if many species are all showing changes. These could be increases for some and decreases for others but together they result in a different community. **That is why community analyses are so much stronger than single species ones** and is one reason why sites in areas of high biodiversity will often be more able to detect change.

As different species generally respond to stressors in different ways, one way of determining causation is by looking at which species have increasing trends, which have decreasing, and which aren't changing at all.

For example, summarising trends at a site by subtracting the number of species that show a trend in the direction expected if nutrients were increasing from those that show a trend in the opposite direction will indicate if nutrients may be becoming a problem.

In the Manukau, all the trend analyses are summarised to show whether sites show more trends than expected consistent with increases in nutrients, sediments, and metals (Table 1). Note that it should include sediment characteristics and health indices.

References

Academic Publication

Hewitt JE, Anderson MJ and SF Thrush (2005). Assessing and monitoring ecological community health in marine systems. Ecological Applications 15:942-953.

Report

Greenfield BL, McCartain LD and JE Hewitt (2019). Manukau Harbour intertidal ecology monitoring 1987 to February 2018. Prepared by NIWA for Auckland Council. Auckland Council Technical Report, TR2019/025.

Site	Nutrients	Stormwater contaminants	BHM$_{metals}$	Mud content	BHM$_{mud}$	TBI
AA		Y – copper		Y	Y	
CB	Y	Y – zinc	Y			
CH						
EB	Y					
KP						
PS						

Table 1: Presence of trends of concern at each site in the Manukau (Greenfield et al 2019).

LESSON 7: The length, continuity and consistency of a dataset will determine its ability to detect tipping points

- The longer a dataset, the more use it is for determining effects – but only if it is consistent and some sites are continuously monitored
- Having some sites continuously monitored in your network gives you more ability to detect changes in the other sites you monitor
- Data from one site can be used to provide the context for data collected from another site – or even another harbour
- Knowing whether changes are occurring at one site, in one area, in one or multiple harbours, can determine whether management responses may be necessary

Using long term data to predict effects and determine how widespread an effect is

In lesson 4, we highlighted that knowledge of likely natural variability is very useful when predicting risks associated with different activities.

Associated with understanding the natural variability is **using long-term data from one site to provide the context for data collected from another site – or even another harbour**. In this case it is the signal of the time series, the drivers and the relative magnitude of cycles rather than expecting the other sites/harbour(s) to exhibit the same magnitude of recruitment and survival at the same times of the year.

We have been able to link to other available data (eg turbidity, salinity, pH, wind, rain, temperature and SOI) to predict potential effects of climate change. For example, analysis of time series data from the Mahurangi suggests that increasing temperature, if associated with lower rainfall in negative southern oscillation index years, will drive lower densities of a functionally important shellfish (Hewitt et al 2016). Within-stream/river concentrations or loads are increasingly being able to be linked to changes in biodiversity, macrofauna communities and microphytobenthic biomass.

Looking at whether changes are occurring at one site, in one area, in one or multiple harbours, is useful to determine whether management responses may be necessary. For example, observing decreases in the abundance of nutshells observed in all east coast estuaries and harbours but not the west coast ones, suggests that this is driven by large-scale climate patterns affecting the regional species pool. Finding that tidal creek sites are not as healthy as exposed harbour sites but are changing little while the harbour sites have declining trends tells us that the impacts are now reaching further out into the harbour (Drylie, 2021)

References

Academic publication

Hewitt JE, JI Ellis and SF Thrush (2016). Multiple stressors, nonlinear effects and the implications of climate change impacts on marine coastal ecosystems. Global Change Biology 22:2665–2675.

Report

Drylie TP (2021). Marine ecology state and trends in Tāmaki Makaurau/Auckland to 2019. State of the environment reporting. Auckland Council Technical Report TR2021/09

Māngere bridge and estuary © denizunlusu/iStock

While these lessons are specifically drawn from estuarine monitoring, the majority of them are applicable for any marine monitoring programs. Only the last bullet point of lesson 4 and the specific sampling frequency mentioned in lesson 5 would not apply.