Otago's Intermittently Closed Estuaries: A Preliminary Assessment

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Closed barrier bar of an intermittently closed estuary (Five Mile Lagoon, Westland). Photo: M. Schallenberg

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EXECUTIVE SUMMARY

1. This report undertook to scope the development of a state of the environment (SOE) monitoring framework for Otago's intermittently closed estuaries, which currently sit outside of other SOE programmes.

2. Forty-four intermittently closed estuaries have been identified along the Otago coast from various sources of information including satellite imagery. Two published estuarine geomorphological classification frameworks were applied to the Intermittently Closed Estuaries (ICEs) but they did not adequately discriminate between the large variety of ICEs found in Otago.

3. A new hierarchical classification framework was developed which was based on three criteria: (1) geomorphological constraint, (2) tidal marine influence when open to the sea, and (3) the presence/absence of wetlands associated with the ICE. This classification system identified ten classes of ICEs along Otago's coast.

4. Values, pressures, and threats to the ICEs are discussed. Estuaries are among the most highly valuable ecosystems globally, in terms of ecosystem services. The main threats to Otago ICEs are identified as (1) eutrophication, (2) sedimentation, and (3) modified hydrology and opening regimes. The key pressures facing Otago's ICEs are catchment development and sea level rise.

5. A summary of research findings on Otago ICEs is presented along with data that is relevant to SOE monitoring and assessments. Catchment models were used to estimate hydrological loads, sediment loads and, median nitrogen, phosphorus and suspended sediment concentrations entering 43 of the ICEs. Catchment land cover was also determined using the New Zealand Land Cover Database.

6. A method for assessing the inherent vulnerability of ICEs to anthropogenic inputs, developed for intermittently closed and open lakes/lagoons in New South Wales, is discussed.

7. Five attributes for monitoring water quality and ecosystem health are proposed. Three are already part of the National Policy Statement for Freshwater Management's National Objectives Framework (2020): (1) water column chlorophyll *a*, (2) water column total nitrogen, and (3) water column total phosphorus. Two additional attributes are recommended: (4) proportion of ICE bed affected by gross eutrophic zones and (5) proportion of the ICE bed colonised by macrophytes. The latter two attributes were developed by an expert group working for the Ministry for the Environment in 2014 but have not yet been incorporated into the National Objectives Framework.

8. Four strategies for prioritising ICEs for SOE monitoring were presented.

Prioritisation strategy	Considerations
1. Focus on covering all representative types of ICE	• Prioritises the management of the full range of types of ICEs • Employs a relevant classification scheme • Prioritises monitoring a diversity of ICEs
2. Focus on safeguarding values	• Prioritises management of the most valuable ICEs • Requires an assessment of values and ecosystem services for the ICEs

Prioritisation strategy	Considerations
3. Focus on ICEs most degraded and vulnerable to degradation	• Prioritises minimising the loss of ICE values • Requires an understanding of ICE state and/or vulnerability
4. Focus on the most cost-effective ICE interventions and restoration	• Prioritises active management and cost-effectiveness • Prioritises the feasibility of interventions

9. Knowledge gaps are discussed and seven recommendations for work needed to help move the development of an SOE monitoring framework forward are presented.

1. Estimate surface area and volume of the 44 ICEs
2. Consider setting a minimum size threshold for inclusion of ICEs into the SOE reporting framework
3. Estimate estuary opening index for ICEs of interest
4. Determine elevations of ICEs in relation to sea level, indicating susceptibility to tidal influence when ICEs are open and ocean overtopping of the barrier bars when closed
5. Analyse the artificial opening regimes of the eight ICEs and consider the protection of ecological values in consent conditions
6. Select a strategy for prioritising ICEs to include in the SOE reporting framework
7. Consider including Tokomairiro, Kaikorai and Hoopers in the ICE SOE reporting framework

CONTENTS

1. INTERMITTENTLY CLOSED ESTUARIES

Along the Otago coast, numerous drains, creeks, streams, and rivers make their ways to the sea. Where they interact with the sea, the mixing of freshwater and seawater occurs resulting in an estuarine environment. The habitats and nature of these estuarine environments vary greatly along the Otago coastline. Where rivers drain larger catchments, freshwater flows tend to be persistent and open estuaries are observed, such as the Catlins River Estuary, the Clutha Estuary, the Taieri Estuary, the Waikouaiti Estuary, and the Kakanui Estuary. In catchments where freshwater flows are intermittent or when discharge rates are low for extended periods of time, the mouths of the estuaries can become temporarily blocked by barrier bars consisting of coastal substrates such as sand and shingle deposited by marine currents, waves, and tides. Thus, the latter are intermittently closed estuaries (ICEs) – a class of estuary that includes intermittently closed and open lakes/lagoons (ICOLLs), barrier bar lagoons, Waituna-type lagoons, and hapua-type lagoons, as well as other types (Kirk & Lauder 2000; Haines et al 2006; Hume et al. 2016). The key feature that distinguishes ICEs from open estuaries is that ICEs exhibit intermittent connections to the sea whereas open estuaries remain open to the sea (Figure 1). Brackish, tidal lakes, which do not have a barrier bar at their outlet, can either be associated with open estuarine systems (such as Lakes Waihola and Waipori which are components of the open, Taieri Estuary), or with ICEs (e.g., Upper Tomahawk Lagoon). This report does not address inland, brackish, tidal lake systems, which do not have barrier bars and are, therefore, part of open estuary systems.

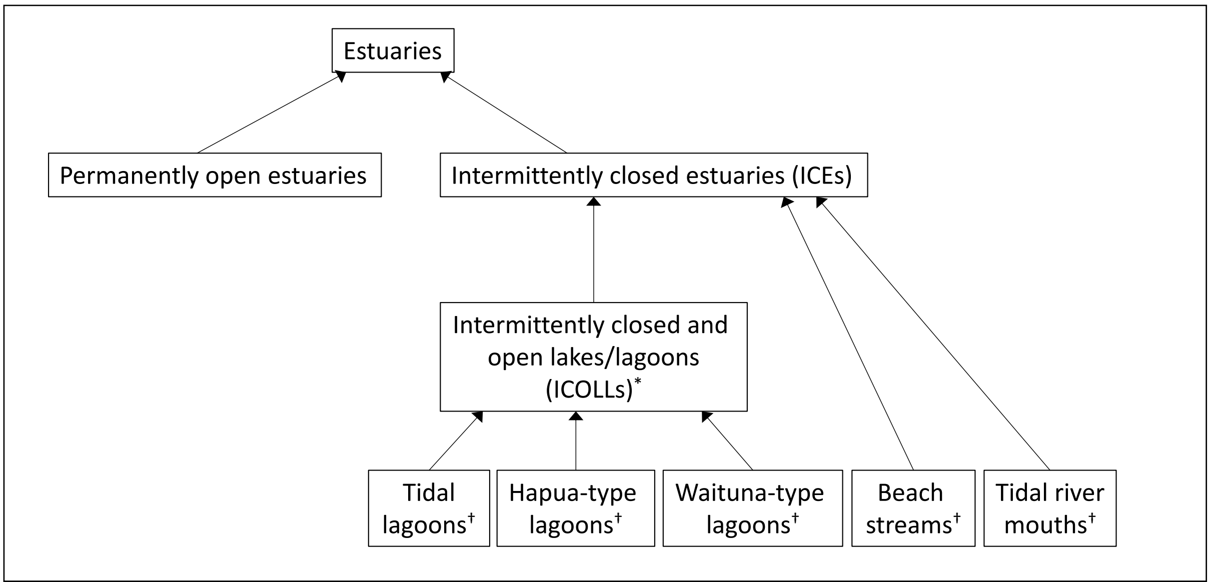

Figure 1. Taxonomy of, and relationships between, classes of estuaries, as employed in this report. Modified from the classification schemes of Kirk & Lauder (2000), Haines et al. (2006) and Hume et al. (2017). *ICOLLs is a class commonly referred to (e.g., Haines et al. 2006; Hume et al. 2016). †this taxonomy of intermittently open and closed estuaries is from Hume et al. (2016). Note that in Hume et al. (2016), hapua-type lagoons are also referred to as riverine lagoons and Waituna-type lagoons are also referred to as lacustrine lagoons.

Intermittently closed estuaries on Otago's coast

ICEs are a feature of Otago's coastline, where a variety of different types of ICEs are scattered. The Otago Regional Council (ORC) is now developing strategies to assess and monitor the extent and condition of Otago's ICEs. Open estuaries are currently being monitored while ICEs in general have not featured in the ORC's state of the environment (SOE) monitoring programmes to date, some of these systems have been the focus of studies by researchers from the University of Otago and other research organisations. The purpose of this report is to initiate the development of an SOE monitoring framework for Otago's ICEs by systematically identifying the ICEs and by summarising existing information, both empirically determined through field study as well as information inferred from remote sensing imagery and catchment models. This report also addresses pressures/threats to these systems and discusses an approach to assessing their intrinsic vulnerability to anthropogenic inputs. Finally, various approaches for prioritising ICEs for ecological monitoring and assessment are presented, knowledge gaps are discussed, and recommendations for the next steps in addressing the knowledge gaps are suggested.

Geomorphic classification

Various classification schemes for estuaries including ICEs exist (e.g., Kirk & Lauder 2000; Haines et al. 2006; Hume et al. 2016). Their applicability to the task of classifying Otago's ICEs and accounting for their diversity of habitats and conditions was assessed and found wanting. Previous classification schemes did not adequately differentiate the different types of ICEs found on the Otago Coast from the perspective of water quality, ecological values, and ecosystem functioning.

Kirk & Lauder (2000)

Kirk & Lauder (2000) identified two types of coastal lagoon systems based on a geomorphic analysis of estuaries on the South Island: (1) river mouth or Hāpua-type lagoons and (2) coastal lake or Waituna-type lagoons. Geomorphic and hydrological factors related to these types of "choked coastal lagoons" were identified, including (1) sea level and tidal ranges, (2) geological substrate supply rates and composition, (3) wave and longshore erosion and sediment transport, (4) freshwater supply and its temporal dynamics, and (5) large scale historical landforms present. Examples of hāpua included numerous small lagoons associated with the Hurunui, Rakaia, Ashburton, Opihi, Waitaki and Waiau (Southland) estuaries. Examples of Waituna-type lagoons included Waituna, Wainono, Waihora/Ellesmere and Wairewa/Forsyth lakes/lagoons.

Hume et al. (2016)

Hume et al. (2016) undertook a geomorphic classification of New Zealand's estuaries, including those that are intermittently open and closed to the sea. At the national scale, 11 broad geomorphic estuary types were discriminated, with various intermittently closed estuary types belonging to five broad geomorphic classes: (1) lacustrine or Waituna-type lagoons, (2) riverine or hāpua-type lagoons, (3) beach stream lagoons, (4) tidal river mouth lagoons, and (5) tidal lagoons (Table 1).

Hume et al. (2016) applied their classification to 18 Otago estuaries, identifying four tidal river mouth estuaries, 13 tidal lagoons, and 1 deep drowned valley. Within these, only four intermittently closed estuaries were identified into two classes: Orore and Stoney Creeks (class 4c - beach stream with pond estuaries) and Waikouaiti/Hawkesbury and Tomahawk Lagoons (class 4b - deep sand plain stream estuaries). Thus, the application of the Hume et al. (2016) classification system to 18 Otago estuaries revealed four Otago ICEs which were attributed to two classes and subclasses of estuary.

In summary, the Kirk & Lauder (2000) classification provided two classes of coastal lagoons (riverine and lacustrine), but they did not apply this classification to any Otago estuaries. The Hume et al. (2016) estuarine classification identified 11 broad estuary classes within which intermittently open estuaries were identified in 11 sub-classes of 5 broad classes of estuaries. When applied to 18 Otago estuaries, four estuaries were identified as intermittently open, and these fell within two sub-classes of one class of estuary. When considering the geomorphological diversity of Otago's ICEs as well as their potential to exhibit a wide range of water quality, ecological functions, and values, it seems that these two classification schemes may not adequately capture the diversity of these systems on the Otago coastline.

Classification of ICEs to help manage ecological health and integrity

Both classifications discussed above are based on geomorphic features of ICEs and, while geomorphology is likely to be an important feature for managing the ecological state and trends of ICEs, other associated factors may improve the classification. For example, Haines et al. (2006)

compared the attributes of over 70 intermittently closed and open lake/lagoons (ICOLLs) located in New South Wales, Australia, and developed a novel framework to classify ICOLLs for the

Table 1. Intermittently closed estuary classes from Hume et al. (2016).

Intermittently opened types			Mostly closed	Mostly open	Footprint shape change	Description
2a	Waituna-type lagoon	Coastal plain depression	Yes		Yes	Very narrow mouth (if open), very shallow, zero tidal prism, large surface area, relatively small catchment area, low freshwater input
2b	Waituna-type lagoon	Valley basin	Yes			Very narrow mouth (if open), very shallow, zero tidal prism, large surface area, relatively small catchment area, low freshwater input
3a	Hapua-type lagoon	Large		Yes	Yes	Narrow outlet, very shallow, small surface area, zero tidal prism, large catchment area and river inflow volume over tidal cycle.
3b	Hapua-type lagoon	Medium		Yes	Yes	Narrow outlet, very shallow, small surface area, zero tidal prism, large catchment area and river inflow volume over tidal cycle.
3c	Hapua-type lagoon	Small	Yes		Yes	Narrow outlet, very shallow, small surface area, zero tidal prism, large catchment area and river inflow volume over tidal cycle.
3d	Hapua-type lagoon	Intermittent		Yes	Yes	Narrow outlet, very shallow, small surface area, zero tidal prism, large catchment area and river inflow volume over tidal cycle.
4b	Beach stream	Damp sand plain stream		Yes		Flat areas where wind has removed sand down to a level where the water is permanently just below the surface or occasionally above it, stabilising the sand and preventing further surface lowering, often formed between a series of sand dunes. Damp sand plains are initially colonised by small plants such as sand carex (Carex pumila), Selliera radicans and Gunnera dentata, and then by progressively taller plants over time such as knobby club rush (Ficinia nodosa).
4c	Beach stream	Stream with pond		Yes	Yes	A riverine system that occurs where a very shallow stream flows over the beach face to the sea. This differs from a river where the larger flow cuts a subtidal channel through the beach face to the sea. Drainage to the sea occurs for most of time, except during drought conditions and/or when waves build a beach berm that bars off the outlet so flow percolates through the beachface to the sea. No tidal prism (inflow) occurs except during storm events coupled with high tides. These are generally associated with small water bodies where the dominant substrate is sand or mixed sand and gravel.
4d	Beach stream	Stream with ribbon lagoon		Yes	Yes	A riverine system that occurs where a very shallow stream flows over the beach face to the sea. This differs from a river where the larger flow cuts a subtidal channel through the beach face to the sea. Drainage to the sea occurs for most of time, except during drought conditions and/or when waves build a beach berm that bars off the outlet so flow percolates through the beachface to the sea. No tidal prism (inflow) occurs except during storm events coupled with high tides. These are generally associated with small water bodies where the dominant substrate is sand or mixed sand and gravel.
4e	Beach stream	Intermittent stream with ribbon lagoon		Yes	Yes	A riverine system that occurs where a very shallow stream flows over the beach face to the sea. This differs from a river where the larger flow cuts a subtidal channel through the beach face to the sea. Drainage to the sea occurs for most of time, except during drought conditions and/or when waves build a beach berm that bars off the outlet so flow percolates through the beachface to the sea. No tidal prism (inflow) occurs except during storm events coupled with high tides. These are generally associated with small water bodies where the dominant substrate is sand or mixed sand and gravel.
6d	Tidal river mouth	Intermittent with ribbon lagoon		Yes	Yes	Small surface area, shallow, small intertidal area, large river inflow volume over tidal cycle compared to tidal prism
7b	Tidal lagoon	Intermittently closed		Yes	Yes	Narrow mouth, sand deltas at mouth, very shallow, extensive intertidal area, large tidal prism compared to river inflow volume over tidal cycle

purpose of assessing their natural sensitivity to anthropogenic and other external inputs. These researchers developed seven ICOLL attributes: (1) waterway area, (2) waterway volume, (3) waterway shape, (4) entrance closure index, (5) evacuation factor, (6) dilution factor, and (7) assimilation factor. The first three are specific morphological attributes. The entrance closure index reflects the temporal dynamics of the opening and closing of ICEs. In their attributes 5, 6 and 7, Haines et al. (2006) considered hydrological attributes such as the freshwater hydrological load, the flushing rate, the tidal (marine) influence, and water level variations. These last three attributes are those which they deemed to reflect ICOLL sensitivity to external inputs (Table 2). In their assessment of sensitivity, Class A ICOLLs were deemed most sensitive to human and other pressures while Class D ICOLLs were more resilient and resistant to external pressures.

Lagoons with large evacuation factors have poor tidal flushing potential, lagoons with large dilutions factors have short freshwater residence times (indicating high freshwater inflow rates and/or small estuary volumes), while lagoons with large assimilation factors have highly variable water levels (indicating a less stable physical environment). Using this sensitivity assessment method, eight New South Wales ICOLLs ranging in surface area from 6 to 660 ha and ranging in volume from 18 to 13,000 ML were assessed by Haines et al. (2006).

Table 2. Classification of ICOLL sensitivity based on three different indices. Table reproduced from Haines et al. (2006). A – most sensitive to human and other external pressures. D – least sensitive.

Definition of classifications representing different levels of lagoon sensitivity

	Evacuation Factor	Dilution Factor	Assimilation Factor
A	120+	24+	30+
B	80–120	16–24	20–30
C	40–80	8–16	10–20
D	0–40	0–8	0–10

Being a classification scheme that incorporates a broad range of attributes designed to assess the inherent sensitivity of ICOLLs to anthropogenic and other pressures, the Haines et al. (2006) classification scheme seems well-suited to ICOLL management, where maintaining and improving the ecological conditions of such systems is desired. By inferring the inherent sensitivity of the ICOLLs to anthropogenic pressures. However, it appears that at least two types of ICE are technically not ICOLLs (Fig. 1) and, therefore, it's unclear how appropriate the Haines et al. (2006) classification is for assessing the sensitivity of non-ICOLL ICEs such as beach stream and tidal river mouth ICEs.

A preliminary classification for Otago's ICEs

The Kirk & Lauder (2000) and Hume et al. (2016) classification schemes, which are based solely on geomorphic attributes, are probably inadequate to assess ecological conditions and don't adequately differentiate the diverse ICE values and habitats found along the Otago coast. However, the more ecological classification scheme of Haines et al. (2006) requires more input data than is currently available for many of Otago's ICEs and it doesn't cover some types of ICEs. Therefore, I propose a new approach to classifying Otago's ICEs which can be applied to all types of Otago ICEs and which accounts for three types of attributes:

1. The degree of geomorphological constraint
2. The degree of marine influence, when open to the sea
3. The presence of wetlands within the ICE

The classification of ecosystems, such as the one attempted here for Otago's ICEs, is a useful means to improve understanding of ecosystems, but classification does simplify the intrinsic complexity of ecosystems to some degree. The geomorphological constraint attribute has three levels, progressing from highly constrained to minimally constrained: (1) riverine ICE, (2) pond-like lagoon, (3) lake-like lagoon. The size threshold between pond and lake can be taken as the lower size threshold considered to be a lake, which is 1 ha (MfE 2019). The likelihood of tidal marine intrusions when open to the sea is a binary classifier related to how perched an ICE is in relation to the sea level. If the ICE is perched, then typical tides don't penetrate the ICE. Finally, the presence of wetlands is a binary classifier intended to indicate habitat complexity and biodiversity values. The presence of wetlands associated with an ICE indicates high habitat complexity and the likely importance of the ICE in relation to biodiversity values. Associated wetlands can also absorb floodwaters, thereby potentially influencing barrier bar opening dynamics.

The application of this scheme to Otago's 44 ICEs, using only satellite imagery to estimate the classifiers, resulted in 10 classes of ICEs (Figs 2 and 3). The geomorphological constraint classifier was estimated by assessing the shape of each ICE and estimating its maximum surface area from current satellite images taken from Google Earth. There is likely to be a small amount of error in estimating maximum size as some of the putative ICEs were open to the sea on the Google Earth images and the upstream limit of tidal and saline influence also had to be inferred. Whether the ICEs were likely to be tidal when open was also inferred from the Google Earth images based on the geomorphology of the mouth opening sites and the estimated distance/elevation of the outlet of the ICE in relation to the sea. ICE mouth openings located further inland and at higher elevations were inferred to indicate no tidal influence when the ICE was open. The presence of wetlands in the ICEs was also inferred from Google Earth images, accounting for the limitations on accurate ICE delimitation discussed above. For several Otago ICEs, other sources of information are available (e.g., whether artificial openings occur, physico-chemical data, observations about the state of the estuary mouth) and this information has also informed the classification.

Based on the above information, this classification identified Otago ICEs into the three hydrogeomorphic classes: river (31), pond (4) and lagoon (9). It putatively identified 13 ICEs that are likely to be tidal when open, and 27 ICEs which are not expected to be tidal. It also identified 14 ICEs with associated wetlands, and 26 without wetlands.

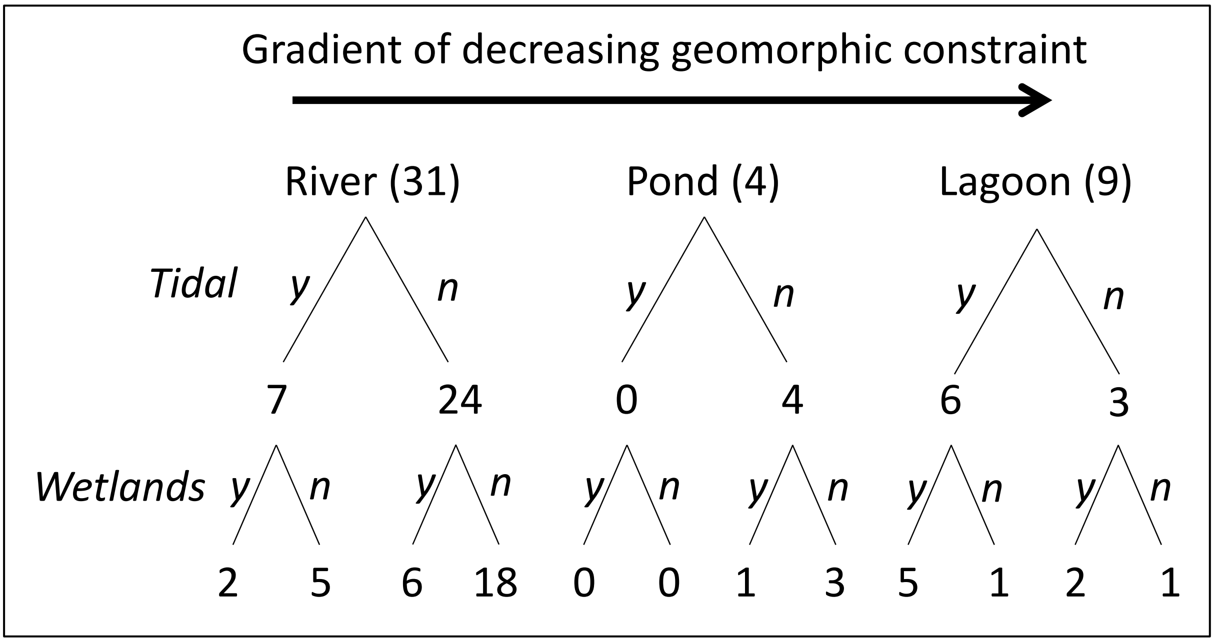

Figure 2. Proposed typology of intermittently closed estuaries of the Otago coast. Three hierarchical factors are used: (1) degree of hydrogeomorphic constraint, (2) whether the estuary is likely to be tidal when open, and (3) whether wetlands are associated with the estuary. The numbers are the number of systems on the Otago coast which fall into the various classes. "y" and "n" indicate yes and no regarding the binary classifiers (tidal influence and wetland presence). This classification putatively identified Otago's 44 intermittently closed estuaries (ICE) into the following geomorphic

classes: river (31), pond (4) and lagoon (9). It identified 13 ICEs that are likely to be tidal when open, and 27 ICEs which are not expected to be tidal. It also identified 14 ICEs with associated wetlands, and 26 without wetlands.

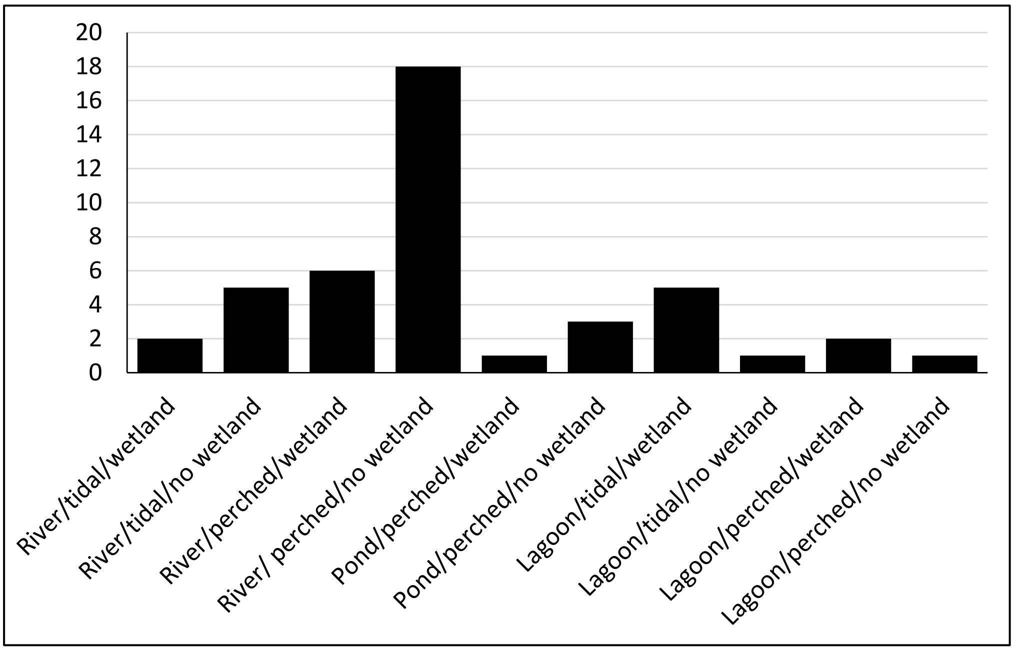

Figure 3. The numbers of different types of Otago's 44 intermittently closed estuaries, inferred from satellite imagery using the proposed 3-tier classification (1. geomorphology, 2. marine influence when open, 3. associated wetlands).

Table 3. Classification of 44 Otago intermittently closed estuaries, based on the Hume et al. (2016) scheme, using satellite imagery.

Class	**Description**	**Number in Otago**
3c	Small hapua-type lagoon	5
4b	Damp sand plain stream	19
4c	Beach stream with pond	14
7b	Tidal lagoon	6

In my observations of over almost 29 years of sand accretion dynamics at Warrington beach, it has been apparent that an ICE has been developing at the base of the sand spit, where a small creek discharging to the beach at Church Road has been developing into a small lagoon, as the sandy beach has been accreting. This highlights that the dynamic nature of coastal substrate accretion/erosion drives the development, and potentially the destruction, of ICEs. Where streams discharge across accreting beaches, eventual lagoon formation is likely. Where lagoonal ICEs exist on eroding coasts, these will disappear with time. Therefore, coastal substrate dynamics play an important role in ICE geomorphology and ontology and rates of accretion and erosion play a key role in ICE ontology.

The application of the new classification scheme to Otago ICEs should be viewed as a preliminary classification based on available data and information, which, in the case of some of the ICEs (especially many of the smaller ones), requires further information for confirmation of the attributed class. For comparison, an attempt was made to classify the 44 ICEs using the Hume et al. (2016) classification scheme, which resulted in the ICEs falling into 4 classes (Table 3).

2. VALUES

Otago's 44 ICEs span ranges of geomorphic types and degrees of marine influence, and they are also associated with a range of wetland habitats. On a per hectare basis, estuaries in general are regarded as the habitat that provides the greatest value of ecosystem services, both globally (Costanza et al. 1997) and regionally (e.g., in the Waikato region; Patterson & Cole 1999). The ecosystem services attributed to estuaries include (Costanza et al. 1997):

- Disturbance regulation
- Nutrient cycling
- Biological control
- Habitat/refugia
- Food production
- Raw materials
- Recreation
- Cultural

The total value of these ecosystem services has been estimated to be \$22,832 ha^{-1} yr^{-1} in 1994 \$US (Costanza et al. 1997). Being a subset of estuaries, ICEs are likely to have a similar, outstanding value. In their assessment of ecosystem services in the Waikato Region, Patterson & Cole (1999) estimated the direct and indirect value of Waikato estuaries to be \$863M (in 1997 NZ\$, excluding wetlands and coastal marine areas). On a per hectare basis, estuaries and wetlands were the two most valuable ecosystem types in the Waikato Region (Patterson & Cole 1999).

The above assessments of monetary value incorporate many assumptions and are, therefore, somewhat controversial. However, the calculated relative importance of estuaries and wetlands in relation to other ecosystem types is probably a robust indication of the relative value of these systems and of the need to monitor and manage these systems to prevent the decline of these values.

It is beyond the scope of this report to delve into the various specific ecosystem services provided by estuaries, ICEs and wetlands, but these systems generally play crucial roles in:

1. processing sediment and nutrients transferred from the land to the marine environment. Estuaries can convert these contaminants through high rates of productivity and can eliminate them by trapping them in floodplains and associated wetlands or by microbially transforming them to inert substances (e.g., via denitrification)
2. acting as reservoirs of estuarine biodiversity
3. furnishing resident, transitional (migratory) or nursery habitats for highly valued plant (e.g., seagrass) and animal (e.g., eel/tuna, flounder/pātiki, cockle/tuaki) species.

The fish and shellfish species listed are key estuarine components of mahika kai and the protection and enhancement of the hydrological, water quality, and habitat values that enhance populations of these species are goals desired by many Māori and pakeha, alike. New Zealand and international studies have identified ICEs as habitats that often have distinct fish and invertebrate communities with intermittently high biomasses of invertebrates and fish biomass (Lill et al. 2011; Taddese et al. 2018; and references in these). They are important resident, corridor, and nursery areas for diadromous fish such as black flounder/patiki (Jellyman et al. 1996; Taddese et al. 2018), eels/tuna (Jellyman et al. 1996) and whitebait (Taddese et al. 2018). It has also been hypothesised that ICEs are important in structuring metapopulation dynamics of coastal invertebrate (Lill et al. 2012) and fish species (Taddese et al. 2018).

The presence of salinity and associated elevated levels of some elements in sea water results in some differences in biogeochemical processes in estuaries in contrast to freshwater systems (Caraco et al. 1989). For example, the binding of phosphorus by mineral particles in bed sediments can be reduced due to the scavenging of iron binding sites by sulphate/ide, resulting in increased availability of phosphorus in estuaries (Caraco et al. 1989). Furthermore, when ICEs are closed, tidal mixing is reduced resulting in an increased likelihood of deoxygenation of the bottom waters and concomitant release of redox-exchangeable phosphorus in the sediment (c.f., Schallenberg & Crawshaw 2017). On the other hand, substantial denitrification can occur in ICEs due to a combination of high standing stocks of nitrate, organic matter, coupled with steep oxygen gradients (Crawshaw et al. 2018, 2019). These are only a subset of the biogeochemical processes which alter physico-chemical conditions and nutrient availability in estuaries, substantially affecting the flux of nutrients from land to sea.

The above examples indicate some of the ecosystem services that estuaries and, in particular ICEs, provide. They also highlight reasons for the prudent management of these systems to safeguard and enhance the values and ecosystem services associated with these types of systems.

3. THREATS AND PRESSURES

The previous section described the substantial values and ecosystem services that ICEs provide. As these systems are situated at the bottom of catchments, activities in the catchments have the potential to influence and impact on ecological integrity, ecological health, and the values that they provide. In addition, ICEs are influenced by the marine environment and changes that occur to the marine system can also impact ICEs. Furthermore, some human activities impact directly on these systems, such as urban development and the management of their hydrological inputs and opening regimes. These pressures can manifest themselves as eutrophication, salinisation, water level perturbations, changes to freshwater flushing dynamics, and changes to the dynamics of migratory species. Below, these outcomes of anthropogenic pressures on ICEs are briefly discussed.

Eutrophication

In developed catchments, substantial amounts of nitrogen, phosphorus, and trace elements (e.g., micronutrients) can move from land to water through ground water leaching and surface runoff, and eventually to estuaries. Biogeochemical changes that occur to nutrients within ICEs can also influence microbial, primary and secondary productivity, leading to eutrophication. Thus, estuaries are often highly productive ecosystems and are often the habitat in a catchment the most likely, or the first, to exhibit symptoms of eutrophication.

Eutrophication can manifest in various ways including: loss of seagrasses, anoxia, phytoplankton and/or macroalgal proliferation, and fish kills. In ICEs, eutrophication usually manifests during a period of closure to the sea, when the flushing of nutrients and biomass is reduced or halted. Therefore, the dynamics of barrier bar opening can strongly influence the eutrophication of ICEs and the monitoring of indicators of eutrophication is recommended particularly during periods of closure to the sea (Waituna TAG 2013).

Siltation and sediment infilling

Estuaries are located at the terrestrial/marine ecotonal boundary where flowing freshwater meets the tidal influence of the sea. As such, the velocity of freshwater inflows tends to decrease, resulting in the sedimentation and trapping of suspended particulate matter within the estuarine environment. In addition, when the salinity of the water is increased by mixing with sea water, dissolved organic matter in the freshwater inflow may chemically precipitate into particulate form, augmenting the particulate load to the estuary (Sholkovitz 1976). It has been demonstrated in many parts of the New Zealand that anthropogenic activities have contributed to increased sedimentation rates in many New Zealand estuaries (Cosgrove 2011).

When ICEs are closed to the sea, turbulence from tidal currents and freshwater inflows are minimised and the "silting-out" of particulate matter from the water can be enhanced. However, turbulence from density currents associated with the tidally migrating salt wedge can resuspend sediment when ICEs are open and, furthermore, wind-induced turbulence can resuspend sediment in larger intertidal ICEs.

These processes can result in complex sedimentation dynamics in ICEs but can also help flush sediment out of estuaries.

Excessive siltation/sedimentation can negatively impact valued estuarine organisms such as seagrasses, bivalves and other benthic and filter feeding organisms. Fine sediment also carries phosphorus and many other undesirable contaminants into estuaries, enhancing eutrophication and negatively impacting the species harvested for food.

Salinisation

Salinity plays a key role in estuarine ecology and biogeochemistry. The salinity tolerances of organisms drive the community structure of estuarine ecosystems (Remane & Schlieper 1971; Attrill & Rundle 2002). The linear rate of eustatic sea level rise at Dunedin has been calculated as 1.35 mm yr^{-1}, since around the year 1900 (Denys et al. 2020). This indicates that saline influence in Otago estuaries has been increasing over the past 120 years. However, the actual saline influence on ICEs is also determined by factors such as freshwater inflow, barrier bar elevation, and barrier opening dynamics. For example, on some parts of the coast, wave exposure, longshore drift, and sediment supply will variously influence barrier bar height and, therefore, the elevation of ICEs above sea level. Some ICEs will be closer to sea level in elevation while others will be more perched and this will impact sea water penetration when the ICEs are open to the sea. Even when closed, some ICEs can receive seawater inputs due to waves overtopping the barrier bar during rough seas and/or high tides and ocean sprays.

In general, it is likely that the inland penetration of sea water as well as the average salinity at given sites within estuaries is slowly increasing. Thus, biogeochemical processes associated with the mixing of saline and freshwaters will be changing as well the distributions of freshwater, oligohaline, euryhaline and marine species within Otago’s estuaries, including ICEs. The general shift inland of zones of mixing of freshwater and seawater will shift the estuarine ecosystem inland. On the time scale of decades and centuries, this will shift estuarine species and processes inland. The potential also exists for geomorphology to change due to the migration of estuaries and coasts inland. Changing geomorphology will result in changing ecological functioning of ICEs over century and millennial time scales.

Water level perturbations

Being tidal, estuaries exhibit tidal water level fluctuations. In addition, riverine discharge variation can reflect a range of conditions, from floods to low flows. Furthermore, ICEs experience water level variations related to barrier closures and openings. Rising water levels can result in flooding of land surrounding ICEs, impinging on land uses and potentially resulting in subsequent drainage of nutrient rich waters into the ICEs. The Otago Regional Council has given consents for the manual opening of eight ICEs along the Otago coast, principally to protect assets and activities on land surround the ICEs. Water level variations can also negatively impact biota by altering environmental conditions such as light and oxygen availability on the beds of estuaries.

Galaxiids (e.g., species of whitebait such as *Galaxias maculatus*) spawn in vegetation along the terrestrial margins of estuaries and use spring tides to time their synchronous spawning. Therefore, anthropogenic manipulations of water level variations have the potential to impact the spawning of whitebait species and the life histories of other estuarine organisms that are sensitised to water levels at any of their life stages.

Freshwater flushing

When open to the sea, ICEs are subject to tidal mixing and the flushing of estuarine waters out to sea. In smaller ICEs, semidiurnal tides are the main mixing and flushing factors, whereas in very large ICEs (e.g., Lake Ellesmere/Te Waihora), the roughly fortnightly lunar cycles of the spring tides play an increasingly important role in mixing and flushing the estuary (Schallenberg et al. 2010). Together with morphology, the entrance closure index (i.e., proportion of time the barrier bar is closed) also determines the potential of ICEs to flush nutrients, algae, and contaminants out to sea. Some degree of flushing can occur when the barrier bar is closed if seepage through the barrier bar occurs. In some ICEs, the amount of seepage through the barrier bar increases as the water level of the ICE increases (Schallenberg & Robertson 2017).

The opening regime is a major factor affecting the flushing dynamics of ICEs, with each barrier bar opening providing the potential for a flushing event and, thereby an opportunity to reset the algal biomass and water column nutrient concentrations, depending on the degree of tidal flushing and freshwater input associated with the opening.

Migratory species/biological connectivity

In addition to facilitating the flushing of ICEs, barrier bar openings also facilitate the active and passive migration of numerous species into, out of, and through ICEs. Many highly valued species migrate through ICEs. For example, species that are passively exported from ICEs can include galaxiid larvae and mysid shrimp, while adult eels/tuna actively migrate out of ICEs to commence their journey to spawning grounds in the open ocean. Examples of highly valued species that can actively migrate into ICEs include eels (tuna), black flounder (pātiki), mullet, and kahawai. While artificial openings of barrier bars have often been undertaken solely for flood control (Schallenberg et al. 2010; Waituna TAG 2013), ecological values are being increasingly considered in the consenting of ICE opening regimes (Schallenberg & Robertson 2017).

4. ASSESSMENT OF STATE

Summary of existing literature

When initiating a monitoring and management programme for Otago ICEs, it's useful to determine what is already known about the current state of these systems. A review of the literature revealed that research focused on specific ICEs as well as comparative studies of multiple ICEs has been previously undertaken (Table 4). For example, the lower Tomahawk Lagoon has been the subject of at least two research programmes focused specifically on the ICOLL. Crawshaw (2018; 2019) studied the drivers of nutrient dynamics within the lagoon, including denitrification rates and the effects of benthic invertebrates and sediment characteristics on microbial nitrogen processing. Lill (2005) undertook a detailed study of the life history and population dynamics of mysid shrimps in Kaikorai Lagoon and found that only two of the four species found in the lagoon underwent a breeding cycle there, suggesting that two of the four mysid species present are adapted to completing a full life cycle in ICEs. The Tomahawk Lagoon Citizen Science project has undertaken regular water quality and biota surveys in the lagoon since 2018 (https://tomahawkcitizenscience.com/who-are-we/). These studies provide detailed information on the ecological conditions, processes, and dynamics of the lagoon.

Otago ICEs have also been the subject of comparative analyses. For example, Lill (2013) compared Otago ICEs with some of Otago's permanently open estuaries, specifically regarding invertebrate community structure and water quality. He studied 14 ICEs and 6 permanently open estuaries. In addition, his PhD included studies on the effects of ICE openings on water quality and invertebrate community structure. Of particular note is his calculation of an opening index for the 14 ICEs. The opening index was found to be a key variable related to water quality of the ICEs, whereby a higher opening index correlated negatively with average annual water temperature, total phosphorus, total nitrogen, and water column chlorophyll *a* concentrations (Lill 2013). This study also summarised previously published Australian and South African relationships between estuaries with intermittent openings vs. permanent openings and the community structure of invertebrates and fish. In many cases, the communities were statistically different in ICEs vs. permanently open estuaries, confirming the results of Lill's Otago study on estuarine hyperbenthic invertebrates (Lill 2013).

Taddese et al. (2018) undertook a comparative study of fish communities in Otago's estuaries, spanning a range of connection to the sea, from permanently open estuaries (n = 6) to ICEs (n = 6).

ICEs generally showed higher fish abundances and lower fish species richness (6 species) than permanently open estuaries (10 fish species). In addition, salinity in ICEs was generally lower than in open estuaries. Common bully was by far the most numerically abundance fish species in ICEs, whereas triplefins and mullet were the most numerically abundance fish collected in permanently open estuaries.

Table 4. Some key studies done on Otago ICEs. [1] Taddese et al. (2018), [2]Lill (2013), [3]Foote (2016), [4]McSweeney (unpubl. data), [5]Crawshaw et al. (2018; 2019), [6]Wass & Mitchell (1998).

ICE ID	ICE name	Latitude	Longitude	Fish	Invertebrates	Ecology	Other studies
				Taddese[1]	Lill[2]	Foote[3]	
1	Karoro Creek	46.39806	169.78004				
2	"North of Clutha Mouth 2	46.28646	169.93101				
3	Johnston's Creek	46.28144	169.94068				
4	Washpool Creek	46.27492	169.95604		Yes		
5	Wangaloa Creek	46.24393	170.00135				
6	Shagree Creek	46.23867	170.00815				
7	Rock Valley Creek	46.22356	170.04258		Yes		
8	Tokomairiro	46.21851	170.04625				
9	Glenledi Creek	46.19225	170.10218		Yes		
10	Bull Creek	46.17684	170.13120				
11	Sawmill Road Creek	46.06232	170.19511	Yes	Yes		
12	Reids Stream	46.00499	170.24579		Yes		
13	Otokia Creek	45.94828	170.33131	Yes	Yes		
14	Taylors Creek	45.93999	170.34478	Yes			
15	Kaikorai Lagoon	45.92388	170.39434	Yes	Yes		Sarah McSweeney (barrier openings)[4]
16	Tomahawk Lagoon	45.90536	170.54033		Yes		Crawshaw (denitrification, nutrients, invertebrates)[5]
16	Tomahawk Lagoon						Tomahawk Citizen Science Project (water quality and biodiversity)
17	Hoopers Inlet	45.86339	170.67195				
18	Jennings Creek	45.76225	170.68007				
19	Whareakeake	45.76344	170.67153		Yes		
20	Mabel Creek	45.76205	170.65502				
21	Drivers Creek	45.75586	170.64740		Yes		
22	Hawkesbury Lagoon	45.60499	170.67882		Yes	Yes	Wass (waterfowl and water quality)[6]
23	Tavora Reserve	45.53171	170.75707				
24	Stoney Creek	45.50834	170.77621		Yes	Yes	
25	Tarapuke Ck	45.41272	170.82524				
26	Back Ck	45.40236	170.83441		Yes		
27	Trotters Creek	45.39419	170.84524				
28	Moeraki	45.38822	170.85408				
29	Waiwherowhero Creek	45.33836	170.82370				
30	Ngutukaka	45.33849	170.82414				
31	Baghdad Creek	45.33789	170.82409				
32	Kuriiti Creek	45.32704	170.82416				
33	Kurinui Creek	45.32409	170.82492	Yes			
34	Kakaho Creek	45.29856	170.83268				
35	Frame Road stream	45.29283	170.83671				
36	Bowalley Creek	45.23302	170.86458				
37	Orore Creek	45.21090	170.88334		Yes		
38	Awamoa Creek	45.14268	170.93506		Yes		
39	Beach Road Stream	45.12580	170.96272				
40	Oamaru Creek	45.10203	170.97170				
41	Landon Creek	45.06474	171.01846				
42	Waikoura Creek	45.02798	171.07126				
43	Corbett Rd	45.00414	171.09764				
44	Riverstone	44.95967	171.13252				

Table 5. Summary of differences in phytoplankton and macroalgae in permanently open, intermittently open and closed coastal systems. Table is from Foote (2016).

	Chlorophyll *α*	Phytoplankton Composition	Phytoplankton Density	Macroalgae Composition	Macroalgae Biomass
Open	▪ Very low concentrations year-round	▪ Stable composition ▪ Dinoflagellates and Diatoms dominant species	▪ Lowest cell count overall	▪ Highest species diversity overall ▪ *Ulva* sp and *Macrocystis pyrifera* dominant species	▪ High variability within sample ▪ Highest biomass overall (recorded during summer)
Intermittently Open	▪ Highest summer concentration overall	▪ Most diverse composition overall ▪ Diatoms and Chlorophytes dominant	▪ Highest cell counts recorded during winter	▪ *Monostroma* sp and *Ruppia* sp dominant	▪ Biomass greatest during summer
Closed	▪ Highest concentration overall ▪ Concentration highest during summer, lowest during winter	▪ Least diverse composition overall ▪ Stable composition ▪ Dominated by Chlorophytes	▪ Highest cell count overall ▪ Highest cell count recorded during summer	▪ Lowest species diversity overall ▪ Dominated outright by *Chara* sp	▪ Biomass low overall ▪ Biomass greatest during winter

Foote (2016) studied the water quality and biological characteristics of Otago coastal water bodies along a gradient of connectivity to the sea. Her study, which examined water quality, sediment characteristics, phytoplankton, macroalgae, macrophytes, and infaunal macroinvertebrates, included two permanently open estuaries, two ICEs, and two water bodies that received no direct marine influence. While few clear points of difference emerged between ICEs and the permanently open estuaries in terms of water quality and sediment characteristics, some clearer differences were observed in phytoplankton, macroalgae and macrophytes (Table 5).

Foote (2016) found that ICEs exhibited overall the highest concentrations of water column chlorophyll *a* concentrations with the highest phytoplankton taxonomic diversity. In addition, macroalgal and macrophyte composition in ICEs differed from those of permanently open estuaries (Table 5). In terms of invertebrate infauna, ICEs had lower abundances than permanently open estuaries. Foote (2016) linked difference in macrofaunal biomass and body size to the hypothesis that open estuaries tend to be dominated by larger, *K*-selected species, whereas ICEs tend to be dominated by smaller, faster growing *r*-selected species. But relatively large differences in infaunal communities in the two replicate ICEs precluded finding strong patterns in infaunal community structure (Foote 2016).

While there are other published studies that have included one or more Otago ICE (e.g., Wass & Mitchell 1998; Desmond et al. 2013; McSweeney unpubl. data), the studies summarised above are likely to be most useful in helping to set a current baseline ecological condition for some of Otago’s 44 ICEs.

Pressures – Catchment land cover data and modelled contaminants

A key pressure on New Zealand ICEs is contaminants entering the ICEs from their catchments. Generally, urban, pasture and plantation forestry land use impact aquatic ecosystems by increasing the losses of sediment (soils) and nutrients to water bodies (Larned et al. 2018), whereas native forest tends to retain soils/sediment more effectively.

The catchments of 37 ICEs were delineated using a digital elevation model and the percentages of different land cover categories were calculated based on the Land Cover Database v. 5. Analyses of seven of the 44 ICE catchments remain to be undertaken (see Appendix 2). The distribution of catchment areas of the ICEs shows that 27 of the 37 ICEs are associated with small catchments (i.e., < 3000 ha; Fig. 4a). Analyses of land cover revealed that ICE catchments generally had a small proportion of their catchments in urban land cover, with 20 catchments having no urban areas (Fig. 4b). The most urban catchment was that of Beach Road Stream, which is a small catchment (351 ha) just south of Oamaru (32% of the catchment is urban and urban parkland cover).

In contrast, the catchments exhibited a wide range in percentage cover of high producing exotic pasture, ranging from 7% (Wangaloa Creek) to 96% (Orore Creek) (Fig. 4c and Appendix 2). This wide range in catchment development into high intensity agriculture is likely to create a wide range of eutrophication pressures of Otago's ICEs. In addition, the range of percentage catchment cover in plantation forestry spanned a range from 1% (Mable Creek and Moeraki) to 90% (Wankgaloa Creek) (Fig. 4e). However, 24 of the catchments had < 10% forestry land cover. The ranges of percentage cover of low producing pasture and native forest were more restricted, spanning from 0% to <40% in both cases (Figs 4d and 4f).

These catchment land cover data indicate that land use pressures vary widely across Otago's ICEs, suggesting a wide range of sediment and nutrient loads occurs to the ICEs.

NIWA has produced numerous catchment models which estimate hydrological flow and the flux of sediment and nutrients through catchments. The models are generalised to the national scale and are available via the NZ River Maps website (https://shiny.niwa.co.nz/nzrivermaps/). The estimates produced do not provide confidence intervals and it is, therefore, not apparent how accurate the catchment models are in predicting the sediment and nutrient loads for Otago ICEs. Nevertheless, these models may provide rough estimates of sediment and nutrient export from catchments to ICEs, which may be useful for interpreting the relative impacts of land use activities (together with climatic variation) on the health of Otago's ICEs.

To this end, the models were run for 43 of the 44 Otago ICEs (NZ River Maps does not register the catchment for Riverstone Creek). The estimate of sediment loads for the 43 ICEs are ranked in Figure 5a and are presented in Appendix 3. The sediment load estimates span a very wide range, from 5 t yr^{-1} (Washpool Creek) to 42,689 t yr^{-1} (Tokomairiro River). The models also give estimates of mean and median annual water discharges from the catchments and median annual concentrations of suspended sediment (TSS), total nitrogen (TN) and total phosphorus (TP) in the freshwater inflows to the catchments. The estimated TSS concentrations range from 1.38 mg L^{-1} (Kurinui Creek) to 5.1 mg L^{-1} (Tokomairiro River), which is less than a 5-fold range (Fig. 5b). The estimated TN concentrations range from 0.39 mg L^{-1} (Kurinui Creek) to 2.86 mg L^{-1} (Corbett Creek), which is approximately a 7-fold range (Fig. 5c). The estimated TP concentrations range from 0.009 mg L^{-1} (Kurinui Creek) to 0.113 mg L^{-1} (Landon Creek), which is approximately an 11-fold range (Fig. 5d).

In Figure 6, the relationships between these various modelled variables are examined to better understand how the models estimate these contaminant loads and concentrations. Modelled estimates of catchment area and median annual discharge are tightly correlated (Fig. 6b), indicating that flow scales strongly with catchment area. The estimated sediment load also scales moderately with catchment area (Fig. 6 a) and discharge (Fig. 6e), showing a fundamental dependence of discharge and sediment load on catchment size.

The modelled estimates of nutrient concentrations did not correlate with catchment size, but TN and TP concentrations were somewhat correlated with each other (Fig. 6d). TP and TSS concentrations were not positively correlated (Fig. 6c), which is unexpected as a large proportion of phosphorus in surface water is usually bound to particulate minerals such as metal oxyhydroxides and silicates (Stumm &

Morgan 1996). This lack of linear correlation suggests that these modelled estimates should be interpreted with a degree of caution.

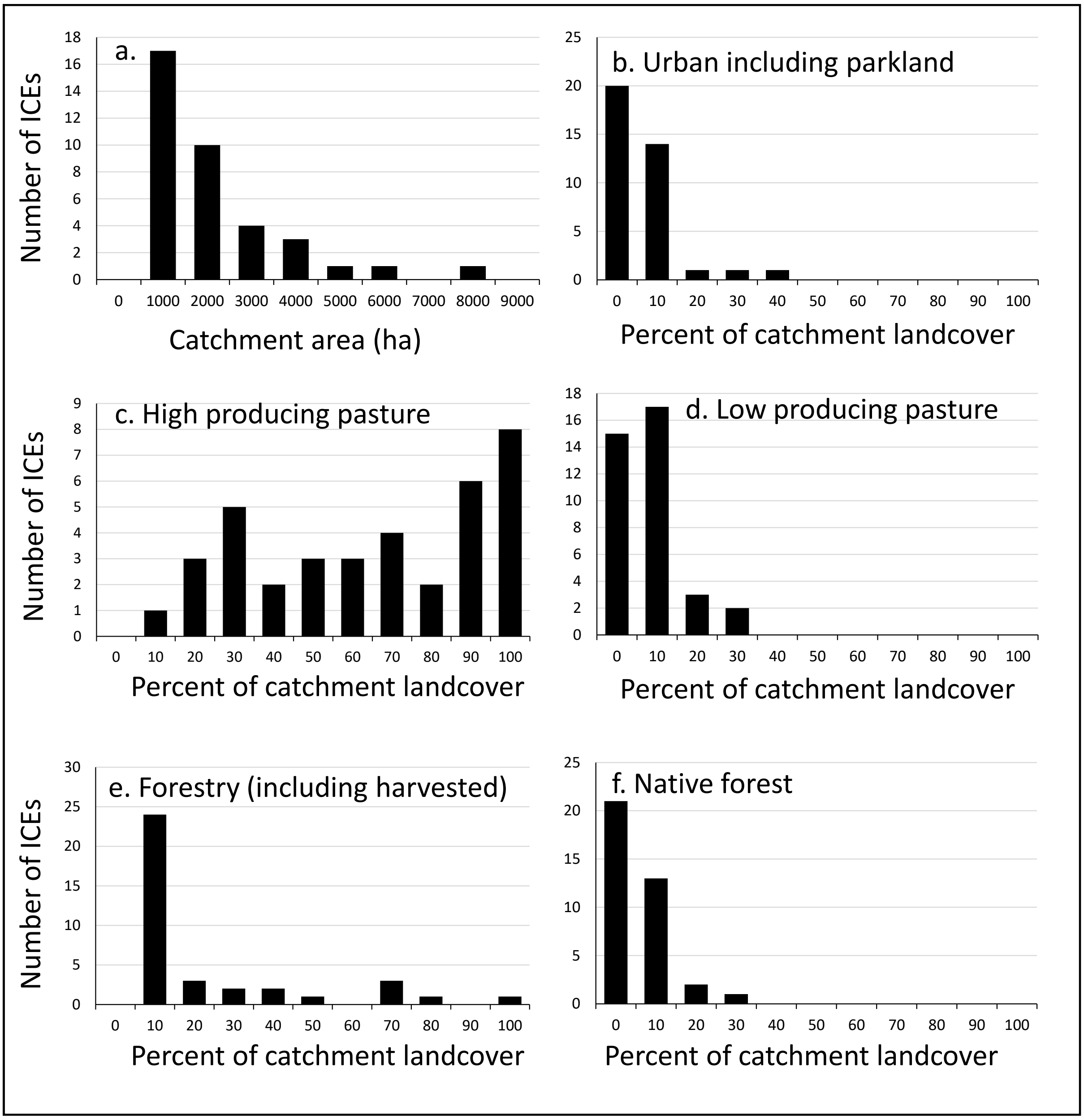

Figure 4. Frequency histograms showing land cover classes of the catchments of the 37 Otago ICEs. Data is derived from LCDB5 (K. Lloyd, Wildlands Consulting, pers. comm.).

The modelled estimates of concentrations relate to the inflows of the ICEs and do not consider the size of the receiving water body, its flushing rate, its tidal exchange, nor the proportion of time it is open to the sea. The concentrations that the contaminants will ultimately reach within the ICEs will depend on these characteristics as well as on the ability of ICEs to process and distribute the incoming contaminants.

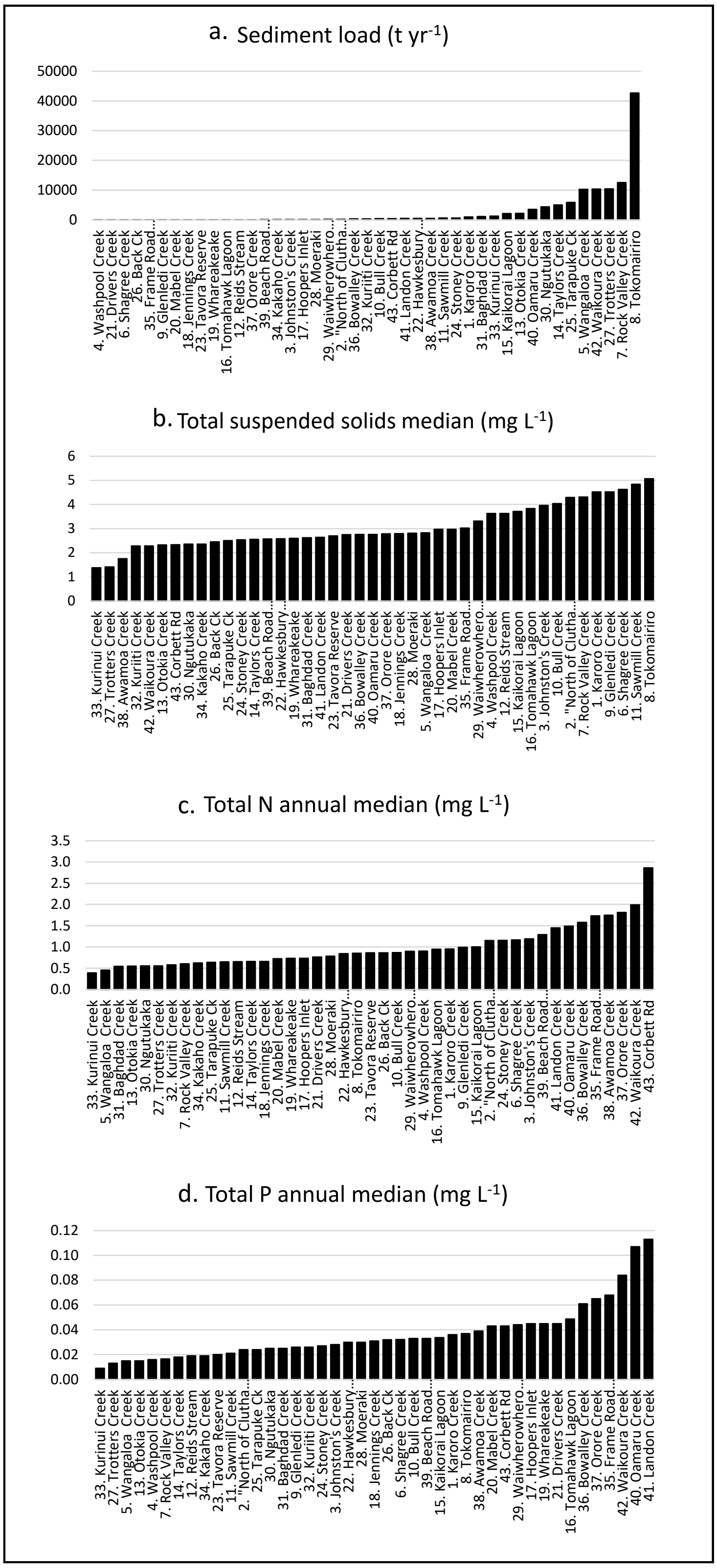

Figure 5. Estimated sediment loads, suspended sediment and nutrient concentrations of the inflows to 43 Otago ICEs. Estimates are from catchment models available in NZ River Maps (https://shiny.niwa.co.nz/nzrivermaps/).

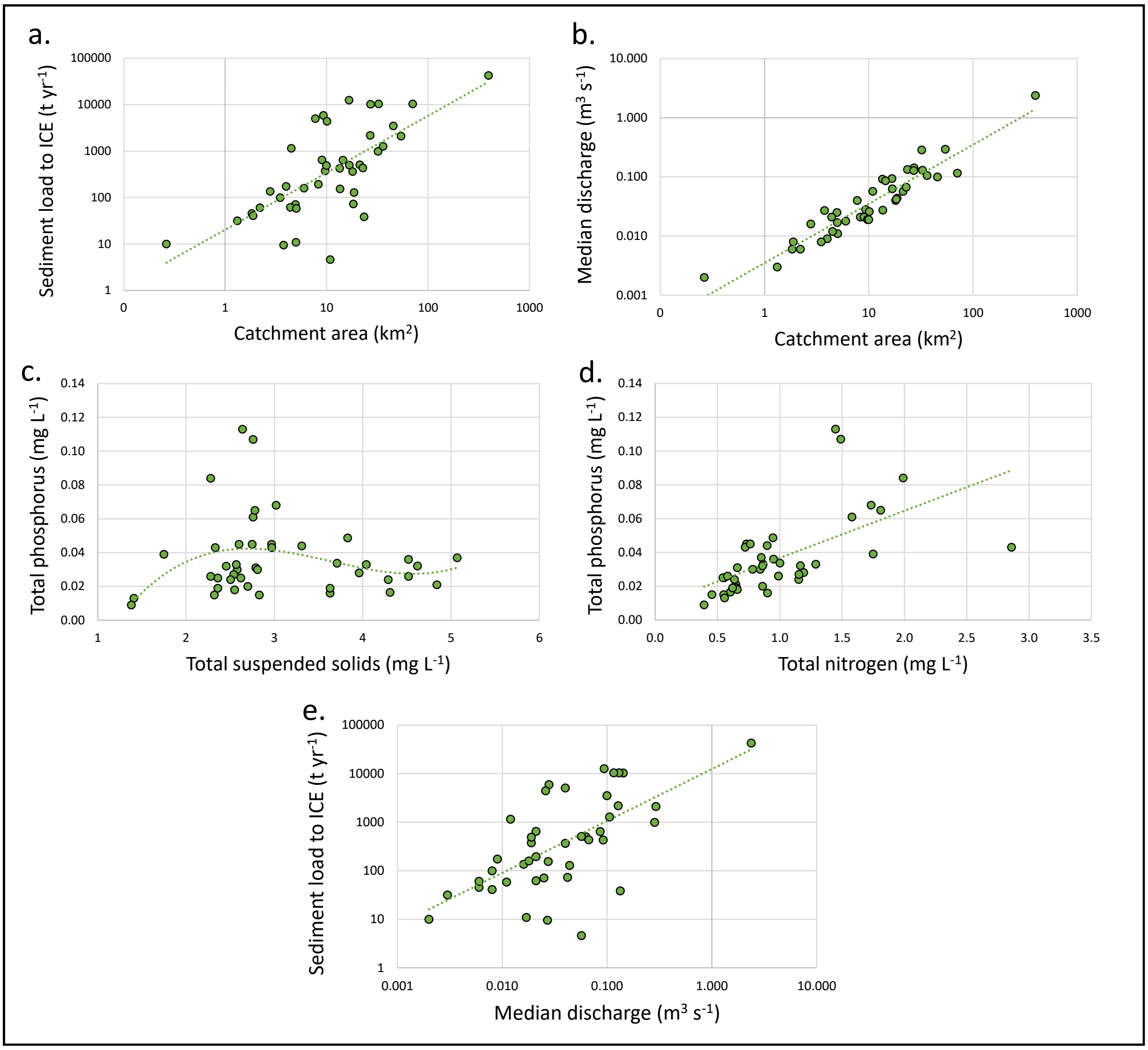

Figure 6. Relationships between catchment areas, hydrological discharges, suspended sediment loads, suspended sediment concentrations and nutrient concentrations for 43 Otago ICEs. Data are estimates based on catchment models available in NZ River Maps (https://shiny.niwa.co.nz/nzrivermaps/).

In the absence of such data, it is difficult to estimate or predict the degree of eutrophication that the ICEs are expected to exhibit.

Lill (2010) undertook monitoring of 17 ICEs along the Otago coast, which involved sampling a site near the mouth of each ICE on four occasions (once each season) between spring 2006 and winter 2007 (inclusive). Among the variables measured were chlorophyll *a*, total nitrogen, total phosphorus, and salinity. Lill also calculate an estuarine opening index (EOI) based on observations of the mouths on his sampling dates, from aerial photographs and from satellite imagery. This amounted to 7 or 8 recordings of the status of the ICE mouth (open or closed), from which he calculated the proportion of observations when the ICE was open. Using a bootstrap power analysis, Lill (2010) calculated that seven or eight observations gave a reasonably accurate estimate of the EOI. In total, Lill's data provide an empirical estimate of the nutrient enrichment and algal biomass in the water columns of the 17 ICEs across the 1-year period when the ICEs were sampled.

The EOI values show a wide range of opening regimes exist along the Otago coast (Fig. 7 a). In addition, a wide range of average salinities were recorded at the mouths of the 17 ICEs (Fig. 7b). The

EOI values were not monotonically correlated with mean salinity in the ICEs, indicating that mean salinity in these systems is not determined simply by the proportion of time the ICEs are open to the sea (Fig. 7c). Their elevation above sea level of the ICEs likely also plays an important role in determining the degree of marine influence that they experience. Open ICEs that are perched well above sea level likely receive little marine intrusion even when open, whereas ICEs that are situated near sea level likely experience strong marine influence even when they are closed (potentially due to tidal seepage or wave spill over effects). These data highlight the complexity of estimating marine influence in these systems, where mean salinity may not strongly reflect the proportion of time the ICE is connected to the sea.

The mean chlorophyll *a* concentration in the sampled Otago ICEs varied greatly, from 0.4 $\mu g\ L^{-1}$ (Tokomairiro River) to 48 $\mu g\ L^{-1}$ (Hawkesbury Lagoon) (Fig. 8a) Concentrations covaried with total nitrogen concentration in an exponential way, with an apparent threshold of approximately 1500 $\mu g\ N\ L^{-1}$ (Fig. 8b). Above this threshold, chlorophyll *a* levels tended to be $< 6\ \mu g\ L^{-1}$. A similar TN threshold for chlorophyll *a* was identified from an independent dataset of 11 brackish lakes and ICOLLs from around New Zealand (Figure 9). In these types of systems, TP concentration does not appear to be as strongly correlated with phytoplankton biomass as TN concentration is (Fig. 8c).

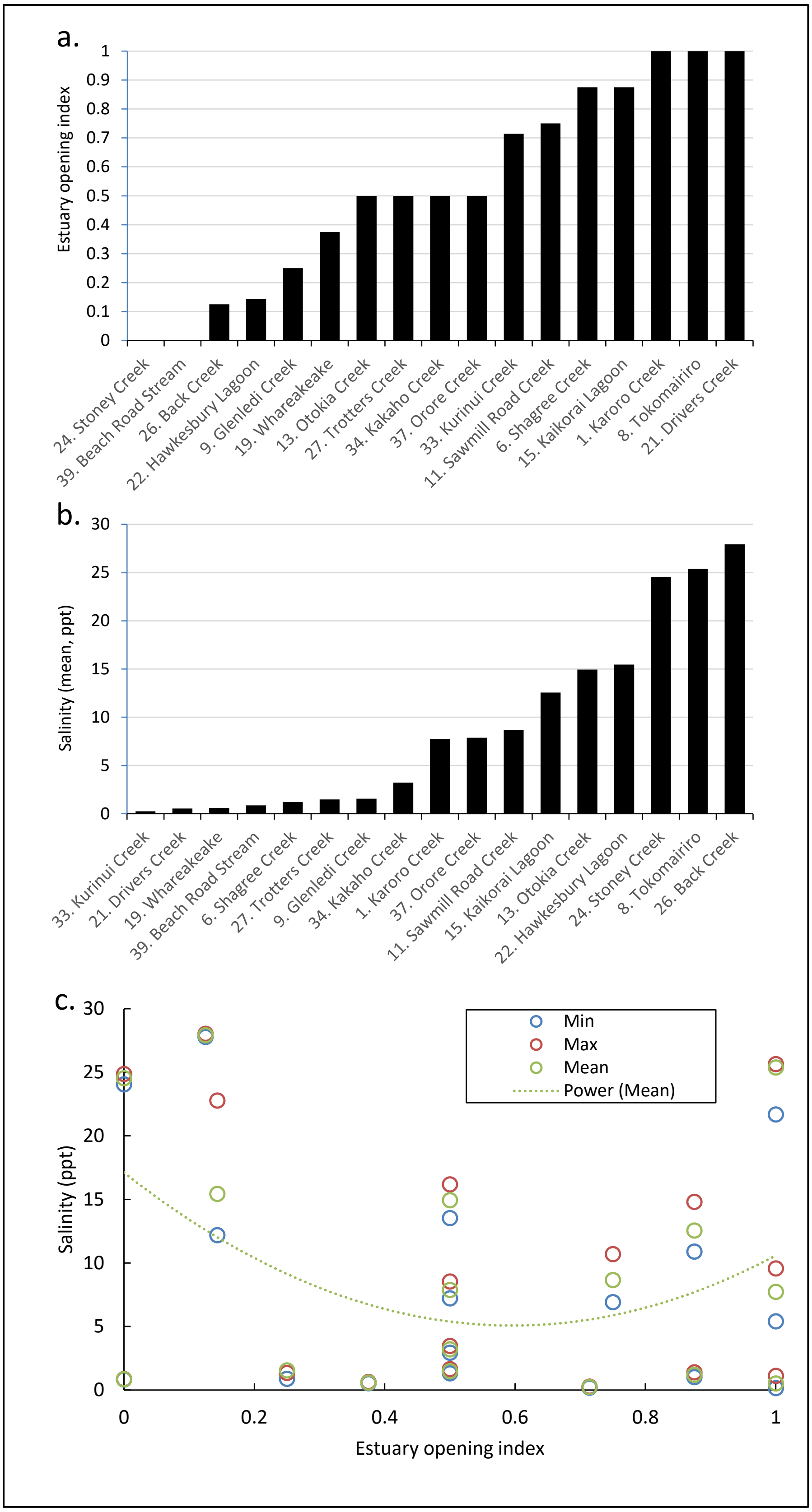

Figure 7. Salinity and estuary opening index for 17 intermittently closed estuaries along the Otago coast. See text for explanation of the opening index. The line is a second order polynomial least squares regression fit to the mean salinity data. Data are from 4 samplings of each system (Lill 2010).

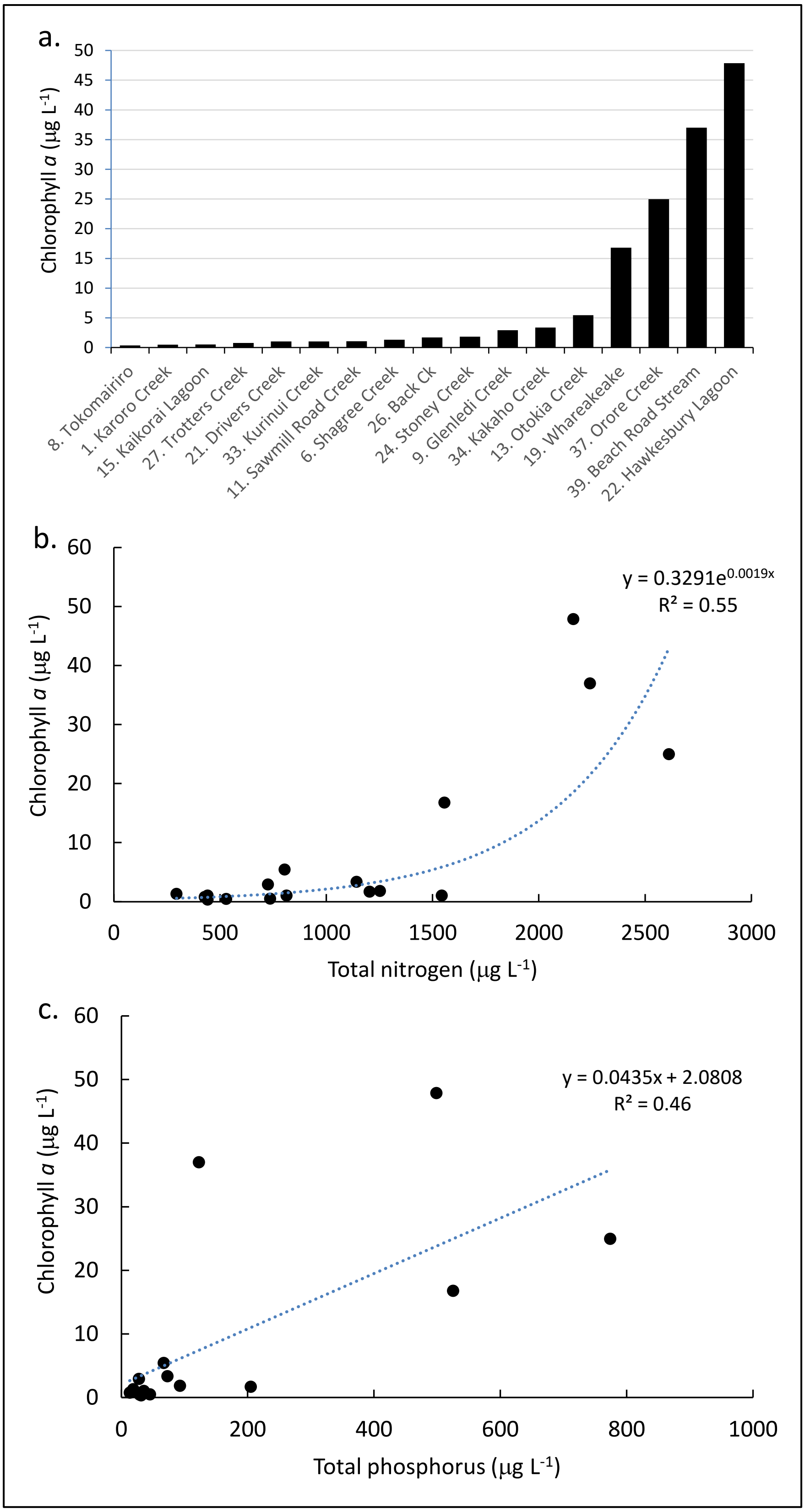

Figure 8. Eutrophication attributes for 17 intermittently closed estuaries along the Otago coast. Data are from 4 samplings of each system (Lill 2010).

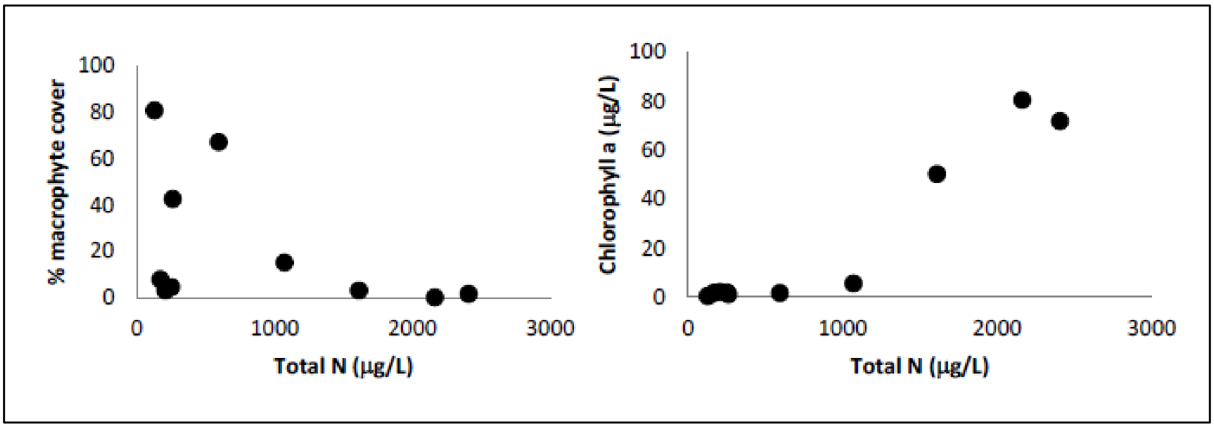

Figure 9. Relationships between total nitrogen concentrations and autotrophic biomass indicators for 11 brackish lakes and lagoons throughout New Zealand. Source: Schallenberg & Schallenberg (2012).

5. VULNERABILITY – NUTRIENTS, SEDIMENTS, AND OPENING REGIMES

The key threats to the ecological condition of New Zealand's ICEs, and its estuaries in general, are high nutrient loads, high sediment loads, and managed opening regimes (Schallenberg et al. 2010; Cosgrove 2011; Schallenberg et al. 2012; Waituna TAG, Hamill et al. 2014; Schallenberg & Robertson 2017). These pressures are to a large extent driven by catchment development (Cosgrove 2011; Larned et al. 2020).

Environment Southland undertook a detailed assessment of the link between catchment pressures and the ecological condition of Waituna Lagoon, a Southland ICOLL (Waituna TAG 2013; Schallenberg et al. 2017). The maintenance of seagrass/macrophyte cover on >30% of the bed of Waituna Lagoon was deemed to be a key goal to achieve to maintain the desired ecological condition of the lagoon. However, the actual percentage cover was highly variable from year to year and had declined to very low levels by 2011 (Robertson & Funnell 2012; Waituna TAG 2013). Multiple lines of evidence were assembled which led to the conclusion that to maintain and improve the ecological condition of the lagoon, reduction in areal nitrogen and phosphorus loads to the lagoon of approximately 50% were required (Waituna TAG 2013; Schallenberg et al. 2017). It was stated that achieving this would safeguard the macrophyte communities, thereby maintaining the ecological condition and values of the lagoon. The areal nutrient loads limits derived for Waituna Lagoon have been applied to Wainono Lagoon and Te Waihora/Lake Ellesmere in Canterbury, informing the management of these systems (Schallenberg 2013a, 2013b).

The rate of sediment infilling of Waituna Lagoon was also determined to have increased since the catchment was converted to agriculture and it was acknowledged that fine sediment loads were probably also negatively affecting the condition of the lagoon (Waituna TAG 2013). However, due to a lack of robust data and information, the scientists were unable to derive a definitive sediment load limit to safeguard the lagoon (Waituna TAG 2013).

The opening regime of Waituna Lagoon is subject to a resource consent, which allows for the barrier bar to be opened to the sea when the lagoon water level exceeds a specified elevation (Waituna TAG 2013). This modifies the natural opening regime, which would have been determined by a range of factors including lagoon water level, barrier bar elevation, coastal substrate supply and erosion, and seepage through the barrier bar. Under the consent, the lagoon may be opened to facilitate drainage of farmland around the lagoon and to protect dwellings and infrastructure. It was recognised that the managed opening of Waituna Lagoon had multiple impacts on the ecology of the lagoon and that the consent didn't allow for the consideration of many of the ecological impacts of artificial opening, such as the impacts on salinity, fish migration, contaminant retention, the fringing wetland vegetation, seagrass germination, etc. (Waituna TAG 2013). Subsequently, a study was conducted which determined that raising the trigger level would allow for better management of the ecological values of the lagoon (Schallenberg & Robertson 2017).

The Otago Regional Council artificially opens the mouths of eight ICEs and has records of 37 mouth openings (Figure 10). Like for Waituna Lagoon, these openings are to avoid the flooding of land surrounding the ICEs. And, as in the case in Waituna Lagoon, these openings will affect the ecology and water quality of these ICE systems. The consents for opening regimes potentially provide an opportunity to improve the condition of the ICEs by incorporating some ecological criteria into the consent conditions.

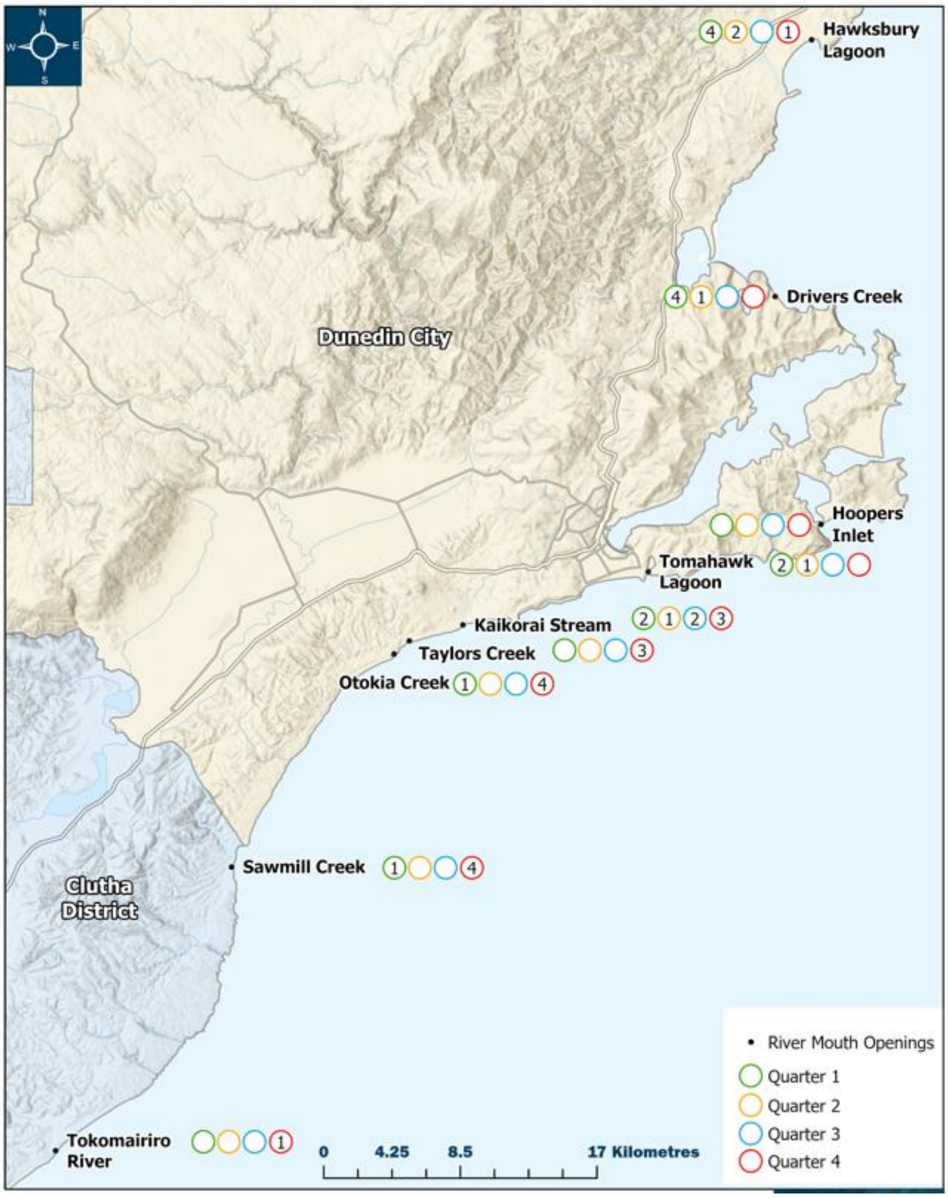

Figure 10. Artificial openings of eight intermittently closed estuaries by the Otago Regional Council. Openings are filtered by which quarter of the financial year 2021-22 (July to June) the ICEs were opened in. Map and data supplied by the ORC. Note: the number and timing of artificial openings varies from year-to-year and depends on sediments accretion rate, rainfall, and tides.

Haines et al. (2006) undertook a morphological classification and assessment of the vulnerability of New South Wales ICOLLs to anthropogenic and external inputs. Hume et al. (2016) discussed some differences between Australian and New Zealand ICOLLs that may compromise the applicability of the Haines et al. (2006) vulnerability assessment to New Zealand ICOLLS.

The vulnerability assessment comprised three indices. The assimilation factor (AF) is a measure of water level variability (in metres), which influences the capacity of biological processes to assimilate or accommodate external inputs (e.g., nutrients and sediments). The AF is positively related to the hydrological load from the catchment and the entrance closure index (which = 1 – EOI), while being inversely related to the surface area of the ICOLL. When calculated for eight New South Wales ICOLLs, the AF varied between 0.07 m and 22.8 m (Haines et al. 2006). The second index of vulnerability is the dilution factor (DF) which is a measure of the contaminant input from the catchment as a function of the volume of the ICOLL. As such, it is an estimate of the residence time or flushing rate of the contaminant of interest. The DF varied from 0.02 mg to 32.3 mg L^{-1} among the eight New South Wales ICOLLs (Haines et al. 2006). The third index is the evacuation factor (EF) which is a measure of the efficiency of tidal flushing – the ability of the ICOLL to discharge to sea and to be diluted by sea water. This dimensionless index varied between 0.02 and 0.96 among the eight Australian ICOLLs (Haines et al. 2006). As shown in Table 2, these index values were translated into four sensitivity categories by Haines et al. (2006) for the purpose of classifying the ICOLLs.

In summary, detailed studies of New Zealand ICEs have indicated that nutrient and sediment loading together with opening regimes are major factors that impact the ecological condition of New Zealand ICEs. In addition, morphological and hydrological features of ICEs can impart more or less resistance and resilience to pressures, as has been shown by the ICOLL typology of Haines et al. (2006). Thus, there is some useful information available from which to develop an environmental monitoring, management, and reporting framework for Otago ICEs. The next section of this report proposes a framework with which to do this.

6. TOWARDS A STATE OF THE ENVIRONMENT REPORTING FRAMEWORK

Ministry for the Environment policy and guidance on attribute selection

The National Policy Statement for Freshwater Management explicitly mandates "integrated management" of freshwaters from the mountains to the sea (i.e., *ki uta ki tai*), as is implied by the Māori concept of *Te Mana o Te Wai* (MfE 2020). As such, the lake trophic state attributes in the National Objectives Framework (NOF) (i.e., chlorophyll *a*, total nitrogen, and total phosphorus) also apply to "lakes and lagoons that are intermittently open to the sea". The NOF provides guidance that these attributes must be assessed for periods when the lakes and lagoons are open and when they are closed, separately. Thus, there are three attributes for intermittently open lakes/lagoons that are mandated under the NOF and for which quality bands and a national bottom line are advised. If these attributes fall below national bottom lines, regional councils are mandated to set land use limits to achieve the desired attribute states. As discussed above, total nitrogen concentration appears to be a particularly robust indicator of ICOLL trophic state and condition with respect to phytoplankton proliferation and macrophyte loss.

In 2014, and expert group was set up by the Ministry for the Environment to propose a set of NOF attributes specifically for ICOLLs and brackish lakes (Hamill et al. 2014). The expert group confirmed the applicability to ICOLLs and brackish lakes of the chlorophyll *a*, total nitrogen and total phosphorus bands and thresholds for lakes provided in the NOF. In addition, the expert group added proviso that the numerical attribute values should be calculated for both "periods when the ICOLL is open and during periods when the ICOLL is closed. Based on a rolling median of at least 12 samples for each situation (i.e., open or closed), and assuming a regular (e.g., monthly) monitoring regime."

Furthermore, the expert group proposed two new NOF attributes specifically for ICOLLs and brackish lakes: (1) the percentage cover of the bed system by gross eutrophic zones (GEZ; Table 6) and (2) the percentage cover of available habitat by aquatic macrophytes (Table 7). The gross eutrophic zone attribute is a measure of the degree of proliferation of epiphytic and benthic macroalgae (e.g., *Bachelotia* sp., *Gracilaria* sp., *Ulva* sp. *Enteromorpha* sp.) and associated sediment anoxia in the system. This macroalgal cover attribute, together with phytoplankton chlorophyll *a* attribute, improves the estimate of total nuisance primary producer biomass in these systems. The macrophyte attribute is a measure of the bed cover of submerged aquatic macrophytes (e.g., *Ruppia* sp., *Myriophyllum* sp.) in these systems. Macrophytes, especially seagrasses such as *Ruppia* sp., are considered beneficial to the ecology of these systems (Waituna TAG 2013).

Table 6. The proposed gross eutrophic zone NOF attribute for ICOLLs and brackish lakes. From Hamill et al. (2014).

Value	Ecosystem health	
Freshwater Body Type	Intermittently Closed and Open Lakes and Lagoons (ICOLLs) and brackish lakes	
Attribute	Macroalgae - cover, biomass and sediment anoxia measured as Gross Eutrophic Zones (GEZ)[1]	
Attribute Unit	Percent cover and area in hectares [2]	
Attribute State	**Numeric Attribute State**	**Narrative Attribute State**
A	GEZ <0.5% cover	Extent of macroalgal biomass and cover is similar to natural conditions, and has little impact on surrounding ecology.
B	GEZ 0.5-5% cover	Ecological communities are slightly impacted by additional macroalgal biomass arising from elevated nutrients levels.
C	GEZ 5-15% cover	Ecological communities are moderately impacted by macroalgae and sediment anoxia. Lake primary production well above natural conditions.
National Bottom Line	GEZ 15% cover or >20ha	
D	GEZ >15% cover <u>or</u> >20ha	Extensive areas of macroalgae and sediment anoxia cause adverse impacts on aquatic macrophytes, sediment macrofauna, fish and birdlife. Internal loads likely to be substantial and high risk of ecological communities undergoing a regime shift to a degraded state.

[1] GEZ = Gross Eutrophic Zones characterised as macroalgal biomass > $500 g/m^2$ (wet weight) <u>combined with anoxic surface sediments</u>. Macroalgae includes macroscopic, loosely adhered epiphytes and periphyton.
[2] Results to be based on a survey during the period of likely maximum annual biomass.

Table 7. The proposed macrophyte cover NOF attribute for ICOLLs and brackish lakes. From Hamill et al. (2014).

Value	Ecosystem health	
Freshwater Body Type	Intermittently Closed and Open Lakes and Lagoons (ICOLLs) and brackish lakes	
Attribute	Macrophytes	
Attribute Unit	Percent cover of available habitat	
Attribute State	**Numeric Attribute State**	**Narrative Attribute State**
A	>70%	Macrophyte communities are healthy and resilient, similar to natural conditions.
B	50-70	Macrophytes and ecological communities are slightly impacted from natural conditions.
C	20-50	Ecological communities are moderately impacted from natural conditions.
National Bottom Line	20%	
D	<20%	Ecological communities significantly impacted by reduced macrophyte cover due to loss of habitat, food sources and less sediment stabilisation. Macrophytes have limited ability to buffer nutrient loads and there is a high risk of a regime shift to a persistent, degraded state.
* Results to be based on a survey during the period of likely maximum annual biomass. Available habitat to be determined based on morphological, hydrological and substrate conditions.		

Although these two additional ICOLL and brackish lake attributes were proposed as NOF attributes by the expert group, they have not been officially adopted into the NPS-FM/NOF. Nevertheless, their development by the expert group indicates that these attributes are valuable in monitoring and measuring ICOLL and brackish lake ecological condition.

The application of these attributes to Otago's 44 ICEs requires some consideration because of the very small size of many Otago ICEs. The Ministry for the Environment has defined lakes to be larger than 1 ha in surface area (MfE 2019; although threshold is not explicit in the NPS-FM/NOF), and the same threshold could be expected to apply to lagoons. Thus, the attributes discussed above may not be suitable for, or applicable to, the smaller ICEs along the Otago coast. If these smaller systems are to be assessed and monitored, then some consideration must be given to the above attributes and to the necessity of developing other attributes, or bands and bottom lines, specific to the smaller ICEs.

ICE selection

The ORC currently monitors three of the 44 ICEs under its estuary monitoring programme (Appendix 1). These are the Tokomairiro Estuary, the Kaikorai Estuary, and Hoopers Inlet. These systems are known to occasionally be isolated from the sea by a barrier bar. Thus, these estuarine systems are "lakes and lagoons that are intermittently open to the sea" and they, therefore, fall under the NPS-FM/NOF monitoring framework. As such, it may appropriate to transfer responsibility for monitoring these to a new ICE monitoring programme, which would require assessment of their attribute conditions in open and closed states, separately.

To develop a monitoring strategy for Otago's 44 ICEs, it is first necessary to understand the overarching requirements of the monitoring programme so that a prioritisation of ICEs for monitoring and assessment can be undertaken. At least four different approaches to site prioritisation could be considered in developing such a programme.

One approach is to focus on a complete representation of different ICE types within a reporting framework. For this approach, a classification scheme must first be adopted. Potential classification schemes were discussed earlier in this report. Thus, one approach would be to adopt one of the classification schemes and then to select a subset of ICEs for monitoring and assessment from the different classes. In this way, monitoring and assessment of condition and trends would cover all types of ICEs.

A second approach is to prioritise ICEs with respect to their values and ecosystem services (e.g., mahika kai, biodiversity, recreational values, etc.). To do this, an assessment of the values of the different ICEs would first have to be undertaken inform the prioritisation scheme. A monitoring and reporting strategy using this prioritisation strategy would focus on monitoring and reporting on the state and trends of Otago’s most valued ICEs.

A third approach is to prioritise ICEs with respect to the degree of anthropogenic pressures that are exerted on them and/or their vulnerability to anthropogenic pressures. To undertake such a prioritisation, it would be necessary to first assess the degree of anthropogenic pressures affecting the ICEs and/or to estimate their vulnerability to the pressures (e.g., using the method of Haines et al. 2006). If this prioritisation strategy were adopted, some consideration must also be given to monitoring some ICEs that are minimally impacted so that an understanding of the natural variability and trends in unimpacted, or minimally impacted, ICEs can also be understood and accounted for in reporting.

A fourth approach is to prioritise ICEs based on the potential for management actions to ameliorate their conditions and/or confer resilience to pressures. In this approach, an assessment of the feasibility of management actions to improve conditions and values would need to be undertaken. This approach would aim to prioritise the cost-effectiveness of management interventions on Otago’s ICEs.

The four prioritisation strategies are summarised in Table 8. It may be possible to combine strategies into a hybrid framework. Either way, an adopted prioritisation strategy should reflect the overarching purpose or goal of managing these systems, which must first be articulated by the ORC.

Table 8. Summary of different strategies for the prioritisation of monitoring and reporting investment within an Otago ICE monitoring framework. Depending on the overarching goals of the SOE reporting framework, a hybrid strategy may be most beneficial.

Prioritisation strategy	Considerations
1. Focus on covering all representative types of ICE	• Prioritises the management of the full range of types of ICEs • Employs a relevant classification scheme • Prioritises monitoring a diversity of ICEs
2. Focus on safeguarding values	• Prioritises management of the most valuable ICEs • Requires an assessment of values and ecosystem services for the ICEs
3. Focus on ICEs most degraded and vulnerable to degradation	• Prioritises minimising the loss of ICE values • Requires an understanding of ICE state and/or vulnerability
4. Focus on the most cost-effective ICE interventions and restoration	• Prioritises active management and cost-effectiveness • Prioritises the feasibility of interventions

7. KNOWLEDGE GAPS AND RECOMMENDATIONS

Coasts are dynamic environments and coastal ecosystems can be challenging to assess due to high variability and because the estuarine ecotone is mobile due to tides, sea conditions and longer- term sea level change. Furthermore, estuaries are located at the bottom of catchments where they tend to be subject to strong anthropogenic pressures due to anthropogenic activities and catchment development. Thus, the signal to noise ratio of environmental change is relatively small and careful monitoring and study are required to reduce noise so that signals of environmental degradation and recovery can be revealed.

This report identifies 44 ICEs along the Otago coast and discusses approaches for classifying them into types. It summarises some of the information available on them, which is sparse for the vast majority. As such, much of the information collated in this report was gleaned from satellite imagery and from catchment models and should be considered rough estimations of ICE pressures and conditions. ICE vulnerability to eutrophication and strategies for prioritising Otago's ICEs for inclusion in an SOE framework are also discussed.

Some key knowledge gaps were revealed in the report, and these are discussed below, along with recommendations for addressing these issues.

Should there be a size threshold for including ICEs in an SOE framework?

Most of Otago's ICEs are at the bottom of small catchments, are geomorphologically highly constrained. As such, many of Otago's ICEs are quite small – possibly too small to be of great ecological significance. Some consideration should be given as to whether a size threshold should be applied to Otago ICEs with regard to including them in an assessment and monitoring programme.

Recommendations 1 and 2:

1. ***Estimate surface area and volume of the 44 ICEs***
2. ***Consider setting a minimum size threshold for inclusion of ICEs into the SOE monitoring and reporting framework***

Marine influence

Marine influence is highly variable in New Zealand ICEs and this variability results in a wide range in ICE condition and functioning. This report assessed marine influence based on (1) a mixture of sparse salinity measurements, (2) estimates of the estuarine opening index, and (3) estimates of tidal influence determined from remote sensing imagery. The lack of robust information on the marine influence of Otago's ICEs limits the ability to classify the ICEs into types. To help improve our classification of ICEs, some further investigation of degree of marine influence on ICEs of interest should be undertaken.

Recommendations 3 and 4:

3. ***Estimate estuary opening index for ICEs of interest***
4. ***Determine elevations of ICEs in relation to sea level, indicating susceptibility to tidal influence when ICEs are closed and ocean overtopping of the barriers when open***

Opening regimes

Eight of Otago's ICEs have managed openings to the sea, which are principally carried out to benefit landowners. There is increasing interest by regulatory authorities (e.g., Environment Southland, Environment Canterbury, Greater Wellington Regional Council) in also including ecological criteria when approving consents for artificial barrier bar openings.

Recommendation 5:

5. Analyse the artificial opening regimes of the eight ICEs and consider the protection of ecological values in consent conditions

Prioritisation strategy

A strategy is required for prioritising investment into monitoring and assessment of Otago's ICEs and this report provides four different strategies for this. Hybrids of two (or more) strategies may also be useful to consider for the prioritisation of resource allocation in ICEs monitoring and management.

Recommendation 6:

6. Select a strategy for prioritising ICEs to include in the SOE monitoring and reporting framework

Dealing with ICEs that are in the estuary monitoring programme

Three ICEs are already included in the Otago estuaries SOE programme. However, the NPS-FM/NOF specifies attributes, attribute bands and bottom lines specifically for lakes and lagoons which are intermittently open to the sea. Thus, it appears that, under the current coastal SOE programme structure, the three ICEs should be assessed using NPS-FM/NOF attributes and criteria.

Recommendation 7:

7. Consider including Tokomairiro, Kaikorai and Hoopers in the ICE SOE monitoring and reporting framework

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APPENDIX 1

List of ICEs and some other coastal systems (yellow shading) in coastal Otago as identified by satellite imagery and published sources. Estuary classes are presented based on the Hume et al. (2016) estuarine classification and on the classification scheme proposed in this report.

ICE number	ICEs	Alternate name	Latitude	Longitude	Notes	Classification (Hume et al. 2017)	Classification (this report)			Artificially opened[1]	Stream/river	Estuary
							Geomorphology	Marine influence	Wetlands		water quality[2]	monitored[3]
1	Karoro Creek		46.39806	169.78004	Possibly constrained by road	4c (Beach stream with pond)	1. River	1. Perched	2. No			
	"North of Clutha Mouth 1"		46.31583	169.88445	Seepage wetland							
2	"North of Clutha Mouth 2"		46.28646	169.93101		4c (Beach stream with pond)	1. River	1. Perched	2. No			
3	Johnston's Creek		46.28144	169.94068		4c (Beach stream with pond)	2. Pond	1. Perched	2. No			
4	Washpool Creek		46.27492	169.95604		4c (Beach stream with pond)	2. Pond	1. Perched	2. No		Yes	
5	Wangaloa Creek		46.24393	170.00135	Associated wetlands	4b (Damp sand plain stream)	1. River	1. Perched	1. Yes			
6	Shagree Creek		46.23867	170.00815	Associated wetlands	4b (Damp sand plain stream)	1. River	1. Perched	1. Yes			
7	Rock Valley Creek		46.22356	170.04258	Associated wetlands	4c (Beach stream with pond)	1. River	2. Tidal	1. Yes			
8	Tokomairiro River		46.21851	170.04625		4c (Beach stream with pond)	1. River	2. Tidal	2. No	Yes		Yes
9	Glenledi Creek	Nobles Creek	46.19225	170.10218		4c (Beach stream with pond)	1. River	1. Perched	2. No			
10	Bull Creek		46.17684	170.13120		4c (Beach stream with pond)	1. River	2. Tidal	1. Yes		Yes	
11	Sawmill Road Creek		46.06232	170.19511	Upstream wetland and pond	4c (Beach stream with pond)	2. Pond	1. Perched	1. Yes	Yes		
12	Reids Stream		46.00499	170.24579	Possibly contrained by road	4c (Beach stream with pond)	1. River	2. Tidal	2. No			
13	Otokia Creek		45.94828	170.33131		4b (Damp sand plain stream)	1. River	1. Perched	2. No	Yes	Yes	
14	Taylors Creek		45.93999	170.34478		4b (Damp sand plain stream)	1. River	1. Perched	2. No	Yes		
15	Kaikorai Lagoon		45.92388	170.39434		7b (Tidal lagoon)	3. Lagoon	2. Tidal	1. Yes	Yes		Yes
	Tomahawk Creek		45.90582	170.56519	Lake upstream from ICOLL						Yes	
16	Tomahawk Lagoon		45.90536	170.54033		7b (Tidal lagoon)	3. Lagoon	2. Tidal	1. Yes			
17	Hoopers Inlet		45.86339	170.67195		7b (Tidal lagoon)	3. Lagoon	2. Tidal	1. Yes	Yes	Yes	Yes
	Papanui Inlet		45.84579	170.69938	Open estuary							Yes
18	Jennings Creek		45.76225	170.68007		4b (Damp sand plain stream)	1. River	1. Perched	2. No			
19	Whareakeake Creek		45.76344	170.67153	Associated wetlands	4b (Damp sand plain stream)	1. River	1. Perched	1. Yes			
20	Mabel Creek		45.76205	170.65502	Associated wetlands	4b (Damp sand plain stream)	1. River	1. Perched	1. Yes			
21	Drivers Creek		45.75586	170.64740		4b (Damp sand plain stream)	1. River	1. Perched	2. No	Yes		
22	Hawkesbury Lagoon		45.60499	170.67882	Hydrological alteration	7b (Tidal lagoon)	3. Lagoon (modified	2. Tidal	1. Yes	Yes		
23	"Unnamed creek"	Tavora Reserve	45.53171	170.75707		4b (Damp sand plain stream)	1. River	1. Perched	1. Yes			
	Pleasant River		45.56811	170.72572	Open estuary							
24	Stoney Creek	Anderson's Lagoon	45.50834	170.77621		7b (Tidal lagoon)	3. Lagoon	2. Tidal	1. Yes		Yes	
25	Tarapuke Creek		45.41272	170.82524	Constrained by bridges, wetlands	4b (Damp sand plain stream)	3. Lagoon	1. Perched	1. Yes			
26	Back Creek		45.40236	170.83441	Constrained by bridges	4c (Beach stream with pond)	2. Pond	1. Perched	2. No			
27	Trotters Creek		45.39419	170.84524		4b (Damp sand plain stream)	1. River	1. Perched	2. No		Yes	
28	Moeraki Creek		45.38822	170.85408		7b (Tidal lagoon)	3. Lagoon	1. Perched	2. No		Yes	
29	Waiwherowhero Creek		45.33836	170.82370		4b (Damp sand plain stream)	1. River	1. Perched	2. No			
30	Ngutukaka		45.33849	170.82414		4b (Damp sand plain stream)	1. River	1. Perched	2. No			
31	Baghdad Creek		45.33789	170.82409		4b (Damp sand plain stream)	1. River	1. Perched	2. No			
32	Kuriiti Creek		45.32704	170.82416		4b (Damp sand plain stream)	1. River	2. Tidal	2. No		Yes	
33	Kurinui Creek		45.32409	170.82492		4b (Damp sand plain stream)	1. River	2. Tidal	2. No			
34	Kakaho Creek		45.29856	170.83268	Palaeochannel	4b (Damp sand plain stream)	1. River	1. Perched	2. No			
35	"Frame Road Stream"		45.29283	170.83671	Palaeochannel	4b (Damp sand plain stream)	1. River	1. Perched	2. No			
	Wainakarua River		45.25265	170.86058	Open estuary						Yes	
36	"Bowalley Creek"		45.23302	170.86458		4c (Beach stream with pond)	3. Lagoon	2. Tidal	2. No		Yes	
37	Orore Creek		45.21090	170.88334		4c (Beach stream with pond)	3. Lagoon	1. Perched	1. Yes			
	Kakanui River		45.18806	170.89874	Open estuary						Yes	
38	Awamoa Creek		45.14268	170.93506		4b (Damp sand plain stream)	1. River	1. Perched	2. No			
39	Beach Road Stream		45.12580	170.96272		4b (Damp sand plain stream)	1. River	1. Perched	2. No			
40	Oamaru Creek		45.10203	170.97170		3c (Small hapua-type lagoon)	1. River	2. Tidal	2. No		Yes	
41	Landon Creek		45.06474	171.01846		3c (Small hapua-type lagoon)	1. River	1. Perched	2. No		Yes	
42	Waikoura Creek		45.02798	171.07126		3c (Small hapua-type lagoon)	1. River	1. Perched	2. No			
43	"Unnamed creek"	Corbett Rd	45.00414	171.09764		3c (Small hapua-type lagoon)	1. River	1. Perched	2. No			
44	Riverstone		44.95967	171.13252	Drain	3c (Small hapua-type lagoon)	1. River	1. Perched	2. No		Yes	
	"Waitaki Bridge"		44.95367	171.13562	Palaeochannel seepage wetlands							

[1] Opened by resource concent (ORC unpublished data).
[2] Some water quality data is available.
[3] The estuary is part of the ORC estuarine state of the environment monitoring programme.

APPENDIX 2

The percentage of catchment land cover classes for catchments of 44 Otago ICEs.

ICE ID	ICE name	Latitude	Longitude	Catchment area	Built-up Area (settlement)	Estuarine Open Water	Exotic Forest	Forest - Harvested	Gorse and/or Broom	Herbaceous Freshwater Vegetation	Herbaceous Saline Vegetation	High Producing Exotic Grassland	Indigenous Forest	Lake or Pond	Low Producing Grassland	Mixed Exotic Shrubland	Orchard, Vineyard or Other Perennial Crop	Short-rotation Cropland	Urban Parkland /Open Space	Urban including parkland
				ha	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
1	Karoro Creek	46.39806	169.78004	3223	0	0	3	0	2	0	0	74	16	0	0	0	0	0	0	0
2	"North of Clutha Mouth 2"	46.28646	169.93101																	
3	Johnston's Creek	46.28144	169.94068																	
4	Washpool Creek	46.27492	169.95604	994	0	0	69	0	8	0	0	19	0	0	3	0	0	0	0	0
5	Wangaloa Creek	46.24393	170.00135	2722	0	0	90	0	1	1	0	7	0	0	0	0	0	0	0	0
6	Shagree Creek	46.23867	170.00815	583	0	0	52	13	8	2	1	21	0	0	2	0	0	0	0	0
7	Rock Valley Creek	46.22356	170.04258	1672	0	0	59	2	6	0	0	27	2	0	1	0	0	0	0	0
8	Tokomairiro	46.21851	170.04625																	
9	Glenledi Creek	46.19225	170.10218	2354	0	0	15	1	5	0	0	61	9	0	0	0	0	0	0	0
10	Bull Creek	46.17684	170.13120	1355	0	0	2	0	11	0	0	52	26	0	0	0	0	0	0	0
11	Sawmill Road Creek	46.06232	170.19511	1451	1	0	18	5	1	2	0	35	3	0	0	1	0	0	0	1
12	Reids Stream	46.00499	170.24579	495	0	0	73	0	0	0	0	25	0	0	0	0	0	0	0	0
13	Otokia Creek	45.94828	170.33131	2696	1	0	32	5	5	0	0	16	10	0	15	0	0	0	0	1
14	Taylors Creek	45.93999	170.34478	775	2	0	5	0	9	0	0	26	3	0	26	0	0	0	0	3
15	Kaikorai Lagoon	45.92388	170.39434	5497	20	1	8	0	6	0	1	48	1	0	0	1	0	0	2	22
16	Tomahawk Lagoon	45.90536	170.54033	441	10	0	7	0	2	0	0	67	0	7	0	0	0	0	1	11
17	Hoopers Inlet	45.86339	170.67195	992	0	2	5	0	0	0	3	58	0	0	15	2	0	0	0	0
18	Jennings Creek	45.76225	170.68007	184	0	0	2	0	0	4	0	89	3	0	0	1	0	0	0	0
19	Whareakeake	45.76344	170.67153	221	0	0	2	0	0	1	0	91	0	0	0	6	0	0	0	0
20	Mabel Creek	45.76205	170.65502	189	0	0	1	0	0	0	0	93	0	0	0	3	0	0	0	0
21	Drivers Creek	45.75586	170.64740	377	3	0	4	0	1	0	0	83	0	0	0	0	0	0	0	3
22	Hawkesbury Lagoon	45.60499	170.67882	1681	6	3	3	0	0	0	0	80	0	0	0	0	0	0	4	10
23	unnamed	45.53171	170.75707																	
24	Stoney Creek	45.50834	170.77621	901	0	0	4	0	0	0	0	90	2	2	2	0	0	0	0	0
25	Tarapuke Ck	45.41272	170.82524	933	0	0	22	15	4	0	1	57	0	0	0	0	0	0	0	0
26	Back Ck	45.40236	170.83441	499	0	0	10	0	0	0	0	77	0	0	0	0	0	0	0	0
27	Trotters Creek	45.39419	170.84524	3268	0	0	19	2	4	0	0	16	0	0	26	0	0	0	0	0
28	Moeraki	45.38822	170.85408	600	0	0	1	0	0	0	0	92	0	2	1	0	0	0	0	0
29	Waiwherowhero Creek	45.33836	170.82370																	
30	Ngutukaka	45.33849	170.82414	1455	0	0	17	0	4	0	0	50	0	0	0	0	0	0	0	0
31	Baghdad Creek	45.33789	170.82409																	
32	Kuriiti Creek	45.32704	170.82416	970	4	0	18	1	5	0	0	43	0	0	0	0	0	0	0	4
33	Kurinui Creek	45.32409	170.82492	3617	1	0	2	2	4	0	0	25	2	0	12	0	0	0	0	1
34	Kakaho Creek	45.29856	170.83268	1872	0	0	42	1	3	0	0	39	0	0	0	0	0	0	0	0
35	Frame Road stream	45.29283	170.83671	132	0	0	4	0	0	0	0	92	0	0	0	0	0	0	0	0
36	Bowalley Creek	45.23302	170.86458	1808	0	0	2	0	0	0	0	95	0	0	0	0	0	0	0	0
37	Orore Creek	45.21090	170.88334	1842	0	0	2	0	0	0	0	96	0	0	0	0	0	2	0	0
38	Awamoa Creek	45.14268	170.93506	2130	5	0	2	0	0	0	0	63	0	0	0	0	0	29	0	5
39	Beach Road Stream	45.12580	170.96272	351	19	0	4	0	1	0	0	60	0	0	0	0	0	0	13	32
40	Oamaru Creek	45.10203	170.97170	4615	5	0	2	0	1	0	0	89	0	0	0	0	0	1	1	6
41	Landon Creek	45.06474	171.01846	1003	0	0	5	2	3	0	0	89	0	0	0	0	0	0	0	0
42	Waikoura Creek	45.02798	171.07126	7057	0	0	4	1	0	0	0	85	0	0	0	0	0	9	0	0
43	Corbett Rd	45.00414	171.09764																	
44	Riverstone	44.95967	171.13252	1462	0	0	2	0	0	0	0	95	0	0	0	0	0	2	0	0

APPENDIX 3.

Estimates of discharge, sediment loads and nutrient and sediment concentrations from the NZ River Maps website.

ICE ID	ICE name	Latitude	Longitude	TSS Load	Median flow	Mean flow	TN median	TP median	TSS median	Catchment area
				Tonnes/yr	cumec	cumec	mg/L	mg/L	mg/L	km2
1	Karoro Creek	46.39806	169.78004	989	0.285	0.498	0.950	0.036	4.520	32.2
2	"North of Clutha Mouth 2"	46.28646	169.93101	194	0.021	0.038	1.153	0.024	4.290	8.3
3	Johnston's Creek	46.28144	169.94068	136	0.016	0.027	1.192	0.028	3.960	2.8
4	Washpool Creek	46.27492	169.95604	5	0.057	0.101	0.902	0.016	3.630	10.9
5	Wangaloa Creek	46.24393	170.00135	10259	0.143	0.246	0.456	0.015	2.830	27.2
6	Shagree Creek	46.23867	170.00815	10	0.002	0.003	1.166	0.032	4.620	0.3
7	Rock Valley Creek	46.22356	170.04258	12585	0.094	0.150	0.604	0.017	4.310	16.7
8	Tokomairiro	46.21851	170.04625	42689	2.380	4.080	0.852	0.037	5.070	396.0
9	Glenledi Creek	46.19225	170.10218	38	0.134	0.237	0.990	0.026	4.520	23.5
10	Bull Creek	46.17684	170.13120	428	0.092	0.150	0.867	0.033	4.040	13.5
11	Sawmill Road Creek	46.06232	170.19511	641	0.086	0.144	0.648	0.021	4.840	14.5
12	Reids Stream	46.00499	170.24579	71	0.025	0.045	0.654	0.019	3.630	5.0
13	Otokia Creek	45.94828	170.33131	2178	0.128	0.226	0.551	0.015	2.320	27.0
14	Taylors Creek	45.93999	170.34478	5045	0.040	0.065	0.660	0.018	2.550	7.8
15	Kaikorai Lagoon	45.92388	170.39434	2106	0.293	0.473	1.002	0.034	3.710	54.3
16	Tomahawk Lagoon	45.90536	170.54033	62	0.021	0.036	0.947	0.049	3.830	4.4
17	Hoopers Inlet	45.86339	170.67195	154	0.028	0.063	0.735	0.045	2.968	13.6
18	Jennings Creek	45.76225	170.68007	46	0.006	0.014	0.660	0.031	2.790	1.8
19	Whareakeake	45.76344	170.67153	60	0.006	0.016	0.734	0.045	2.600	2.2
20	Mabel Creek	45.76205	170.65502	41	0.008	0.017	0.724	0.043	2.970	1.9
21	Drivers Creek	45.75586	170.64740	10	0.027	0.044	0.765	0.045	2.750	3.8
22	Hawkesbury Lagoon	45.60499	170.67882	501	0.063	0.133	0.844	0.030	2.580	16.8
23	Tavora Reserve	45.53171	170.75707	58	0.011	0.034	8.620	0.020	2.700	5.0
24	Stoney Creek	45.50834	170.77621	645	0.021	0.063	1.155	0.027	2.540	9.0
25	Tarapuke Ck	45.41272	170.82524	5912	0.028	0.060	0.637	0.024	2.504	9.3
26	Back Ck	45.40236	170.83441	11	0.017	0.039	0.862	0.032	2.455	5.0
27	Trotters Creek	45.39419	170.84524	10393	0.130	0.260	0.557	0.013	1.410	32.7
28	Moeraki	45.38822	170.85408	159	0.018	0.044	0.784	0.030	2.810	6.0
29	Waiwherowhero Creek	45.33836	170.82370	174	0.009	0.023	0.899	0.044	3.310	4.0
30	Ngutukaka	45.33849	170.82414	4418	0.026	0.057	0.556	0.025	2.360	10.1
31	Baghdad Creek	45.33789	170.82409	1147	0.012	0.028	0.545	0.025	2.620	4.5
32	Kuriiti Creek	45.32704	170.82416	377	0.019	0.056	0.581	0.026	2.280	9.7
33	Kurinui Creek	45.32409	170.82492	1273	0.106	0.240	0.393	0.009	1.380	36.2
34	Kakaho Creek	45.29856	170.83268	128	0.044	0.112	0.622	0.019	2.360	18.7
35	Frame Road stream	45.29283	170.83671	32	0.003	0.009	1.734	0.068	3.020	1.3
36	Bowalley Creek	45.23302	170.86458	365	0.040	0.105	1.580	0.061	2.760	18.1
37	Orore Creek	45.21090	170.88334	73	0.042	0.115	1.810	0.065	2.780	18.4
38	Awamoa Creek	45.14268	170.93506	508	0.057	0.131	1.750	0.039	1.750	21.3
39	Beach Road Stream	45.12580	170.96272	100	0.008	0.022	1.290	0.033	2.570	3.5
40	Oamaru Creek	45.10203	170.97170	3504	0.100	0.277	1.490	0.107	2.760	45.5
41	Landon Creek	45.06474	171.01846	491	0.019	0.056	1.448	0.113	2.640	10.0
42	Waikoura Creek	45.02798	171.07126	10372	0.116	0.370	1.990	0.084	2.280	70.6
43	Corbett Rd	45.00414	171.09764	433	0.067	0.168	2.860	0.043	2.330	22.9
44	Riverstone	44.95967	171.13252							