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A controlling factor approach to estuary classification

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Abstract

A new approach to the classification of estuaries is described. The estuary environment classification (EEC) is based on a hierarchical view of the abiotic components that comprise the environments of estuaries. The EEC postulates that climate, oceanic, riverine and catchment factors 'control' a hierarchy of processes and broadly determine the physical and biological characteristics of estuaries. The classification differentiates estuaries at four levels of detail. Level 1 differentiates global scale variation based on differences in climatic and oceanic processes, which are discriminated by the factors: latitude, oceanic basins and large landmasses. Level 2 differentiates variation in estuary hydrodynamic processes, which are discriminated by estuary basin morphometry, river and oceanic forcing. Level 3 differentiates variation among estuaries that are due to catchment processes, which are discriminated by catchment geology and catchment land cover. The approach has been applied to all the estuaries in New Zealand using existing data sources. Estuaries were assigned class membership at each level of the classification by applying criteria in the form of decision rules to the database of assignment characteristics. GIS was then used to map the estuaries with classes being defined by colour at any level of the classification. The resulting map provides a multi-scale spatial framework that is suitable for many environmental or conservation management applications.

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1. Introduction

Environmental classifications characterize and map environmental (i.e., abiotic) variation in order to assist in understanding processes and resultant patterns at large scales. Because the broad environment constrains the development and behaviour of ecosystems, environmental classifications are also used as a surrogate for defining ecological patterns [1–3]. Classifications have been specifically promoted as spatial frameworks for environmental management [4–7]. Numerous approaches to the classification of estuaries exist including those based on geomorphology [8–10], the evolutionary stage (maturity) of estuaries [11], and/or hydrology and salinity [8,12–16] or combinations of the above [17,18]. Only a few estuary classification schemes have included consideration of habitat, water quality, ecology and catchment characteristics [19–23].

To be useful as a spatial framework for management, estuary classifications need to classify all the estuaries within the geographic domain of interest. Classifications based on hydrological or biological characteristics are dependent on collecting large and complete datasets and, therefore, may be costly to apply to large regions or whole countries. Comprehensive datasets describing the genesis or geomorphic attributes of estuaries are more easily collected, however these may not convey an understanding of processes that determine the ecological properties of estuaries as they function today. An understanding of processes is the basis for ecosystem-based management and environmental assessments. Therefore, classifications that delineate patterns based on the underlying processes can be more useful to management. A process-based approach to ecological classification of estuaries that can be comprehensively applied to a large spatial domain, using existing information, is therefore required.

Classifications based on ‘controlling factors’ are based on hierarchical considerations and have been applied to ocean, terrestrial, and river environments [4,24,25]. In this approach, broad scale abiotic factors (e.g., latitude position, topography and geology) are assumed to be the dominant controls on ecosystem characteristics at a series of hierarchically related system levels. Variation in these controlling factors is used to define classes and delineate patterns at a series of hierarchically related levels and spatial scales. This approach to classification has a number of benefits for environmental management applications. First, classification is based on a conceptual view of how ecosystems are organized, and thus codifies, in a simple way, an understanding of the processes determining spatial patterns in ecosystem character. Second, the hierarchical approach allows variation to be described and delineated at various levels of detail, enabling analysis at different levels of resolution [26,27]. Third, classes can often be assigned to the entire spatial domain using existing environmental data. In this article we present a new controlling factor and alternative approach to the classification of estuaries and trial it using a New Zealand dataset. New Zealand offers particular advantages for such a trial because the diverse climate, geology, oceanography and landforms result in a wide range of estuary types [9,28]. A key objective was to develop a method that could be used to classify all estuaries within a large geographic domain with easily obtained and generated data so that the resulting classification could be mapped. The classification is hierarchically organized and classifies whole estuaries at three levels of detail based on the effect of a number of interacting processes. Classes define groups of estuaries that should be distinctive with respect to a broad range of physical characteristics such as water temperature, chemistry and salinity, turbidity and proportion of intertidal area. Because physical characteristics are the dominant cause of biotic pattern at large spatial scales, the classes are also expected to discriminate differences in the biological characteristics of estuaries. Of course for short periods of time, a single process may determine the character of an estuary (e.g., a flood, or a spring tide inflow, or bed stirring by wind waves). However, the classification is based on differences among estuaries that arise from the long-term average effects of multiple processes. Thus, the classification averages the temporal domain in order to concentrate on variation in the spatial domain.

We start by outlining the principles of controlling factor classifications. We then suggest a conceptual model for a controlling factor classification of whole estuaries. The possibility that the scheme could be extended to further subdivide individual estuaries into component parts is discussed but has not been implemented. We propose that Level 1 can be defined within an existing controlling factor classification of global oceans [4]. We concentrate on Levels 2 and 3 of the classification in this paper.

2. Classification method

2.1. Approach

The purpose of a classification is ‘‘to obtain classes such that any member of a class can be treated as if it possessed certain properties’’ [29]. A fundamental principle of the general theory of classification is that principles involving likeness and distinctness must be used in defining classes [30]. Classifications, however, cannot represent all the detail of the classified object. Thus classification is a form of abstraction in that some of the many properties of a concrete object are selected and used to represent reality [30]. The principles involved in determining likeness and distinctness are referred to as the ‘guiding principles’ [30] and these determine how well a classification represents the detail of reality when viewed from a particular perspective.

Controlling factor classifications are guided by the principle that particular ‘factors’ are responsible for environmental processes and patterns that are observed at various spatial scales. [4,24,25]. For example, Bailey’s [4] classification of terrestrial environments is based on the assumption that at global scales, climatic processes determine biological distributions. Bailey [4] assumed that latitude and very large physiographic features such as mountain ranges control global variation in climatic processes such as precipitation and solar radiation. Categorical differentiation of these factors is used to define classes and delineate patches at the earth’s surface that are expected to be environmentally distinctive. Because thematic maps are generally available showing categorical subdivision of factors, classes may be assigned to all locations so that the classification can be mapped.

The approach is related to hierarchy theory and views environments as a series of hierarchically related ‘systems’ [31]. A hierarchical model of the processes causing environmental patterns is proposed based on a dominance in spatial scale and a dominance of process [24]. Each level of the hierarchy describes a level of organization that persists at a specific spatiotemporal scale. Hierarchies of process follow the observation that differences in upper level characteristics have immutable effects on lower level characteristics. For example, hydrodynamic processes within an estuary have an unavoidable effect on characteristics such as water chemistry, salinity and turbidity regardless of the characteristics of the freshwater catchment. Hierarchies of scale follow the observation that small-scale patches are nested within larger scale patches.

Developing a controlling factor classification comprises three major steps; defining a hierarchical model of variation in environmental characteristics, describing variation at each system level with 'categories', and finally mapping the classification. This results in a divisive or 'top–down' classification that describes characteristics at different levels of generalization and associated spatial scales [4,24,25]. The characteristics of each class at any system level are partly determined by the categories at higher system levels, reflecting the underlying hierarchical assumptions. The full classification at any level is, therefore defined by the controlling factor category at that and all preceding levels.

2.2. Conceptual model for the estuary environment classification (EEC)

The aim of EEC is to group estuaries according to their physical characteristics. The first step, therefore, is to define estuaries as single classification units. Estuaries do not have a regular form in terms of shape and size and are difficult to define because, as an interface between land and sea, they encapsulate a gradient in conditions from almost entirely riverine to almost entirely oceanic. We use a broad definition for estuaries following Day's [32] variation of Pritchard's [8] definition and define an estuary as: *a partially enclosed coastal body of water that is either permanently or periodically open to the sea in which the aquatic ecosystem is affected by the physical and chemical characteristics of both runoff from the land and inflow from the sea*. This definition includes many types of coastal water bodies described in other classifications as estuaries, drowned river valleys, lagoons, coastal lakes, fjords and tidal river mouths. A broad definition for estuaries is appropriate for management purposes because it includes the full range coastal water bodies that are subject to management.

The EEC is based on the proposition that the physical (and subsequently ecological) character of estuaries can be understood in terms of physical processes, including solar radiation, heating and cooling, precipitation, evaporation, inflows and outflows of oceanic and fresh water into the estuary basin, stratification, flushing, circulation, mixing, and sedimentation (deposition and erosion, Fig. 1). These processes are controlled by independent factors that comprise the environment of the estuary when viewed at different spatial scales. Variation in the factors, and therefore, the characteristics of estuaries, are defined at each of four levels of classification detail by factor 'categories' (Fig. 1).

It is proposed that differences in 'global-scale' processes such as solar radiation, heating, cooling, evaporation, and precipitation, are the dominant causes of variation in the character of estuaries at the first level of the classification. At global scales these climatic and oceanic processes are controlled by three factors: latitude, oceanic basins and large landmasses. These factors are used to discriminate large regions (e.g., polar, temperate and tropical domains) within which estuaries share broadly similar physical (e.g., temperature, nutrient concentrations and salinity of incoming oceanic water) and ecological characteristics (e.g., primary productivity) [4].

We propose that within the regions defined at Level 1, the variation in characteristics among individual whole estuaries are dominated first by estuary-scale 'hydrodynamic' processes (Level 2) and then by 'catchment' processes (Level 3). Estuary-scale hydrodynamic processes include: mixing, circulation, stratification, flushing and sedimentation. These processes further determine physical characteristics of estuaries, such as water clarity, salinity, stratification and geomorphologic features including the proportion

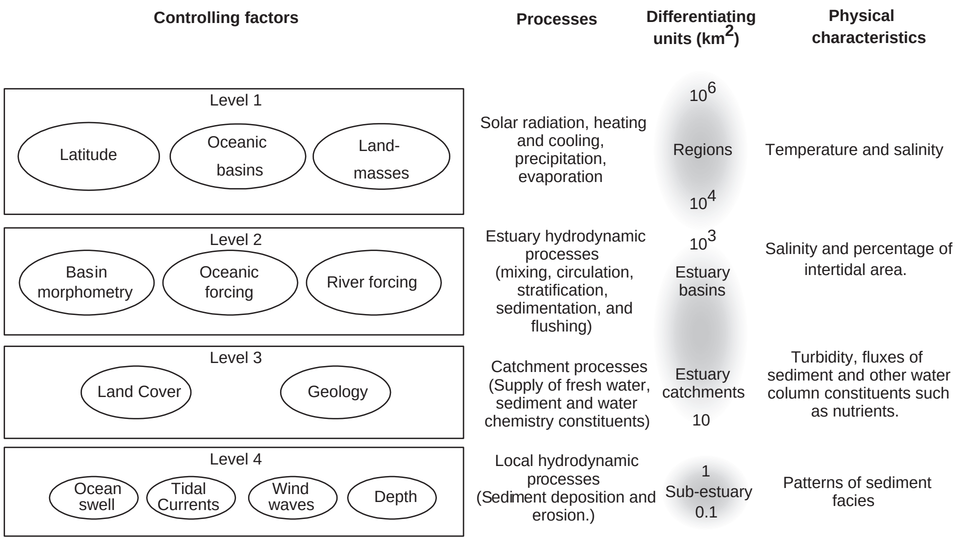


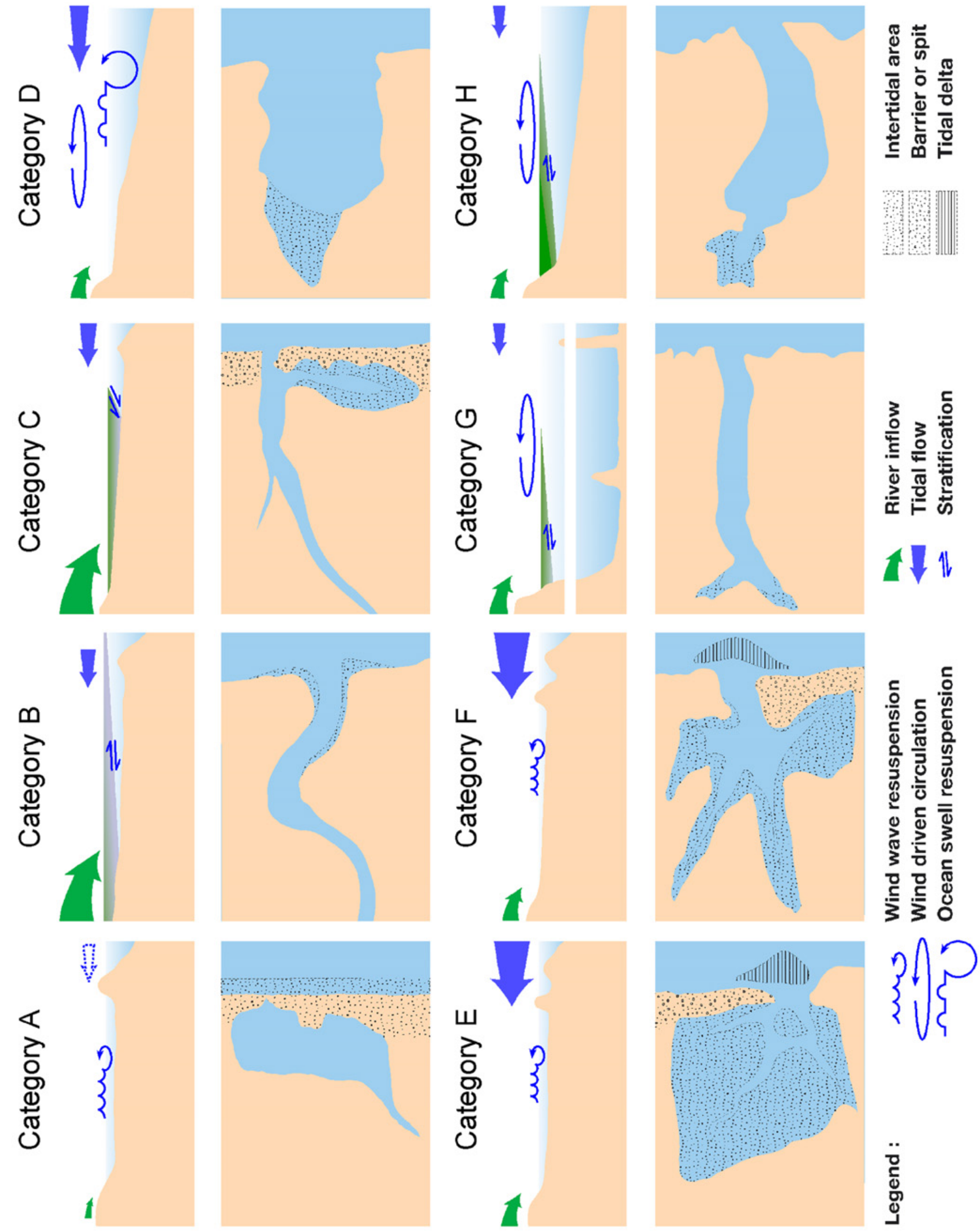
Fig. 1. Conceptual model of the hierarchically related physical processes that determine the physical and ecological characteristics of estuaries at four system levels. Each level is associated with a specific set of processes that are controlled by 'factors'.

of intertidal area. Classes at Level 2 of the classification are discriminated by the three factors that we propose are the primary controls on hydrodynamic processes, namely: oceanic forcing, river forcing and basin morphometry.

We propose that 'catchment' processes are the dominant causes of variation in the characteristics of estuaries that are within the same class at Level 2 of the classification. Classes at Level 3 of the classification further discriminate variation in freshwater inflows and fluxes of terrestrial sediment and other freshwater constituents such as nutrients. Level 3 classes are defined by two controlling factors: catchment geology and land cover. Placing these processes at Level 3 in the classification hierarchy recognizes that they are subordinate to the hydrodynamic processes level of the EEC (i.e., Level 2) in determining the characteristics of the estuary as a whole. This recognizes that characteristics such as water quality, nutrient status, substrates and habitats in estuaries are primarily dependent on the mixing, circulation, sedimentation and flushing within an estuary, and secondarily on catchment processes.

At the scale of the individual estuary, further subdivision is possible into morphological subunits (e.g., tidal arms, tidal entrances and subtidal and intertidal areas). We propose that, within morphological subunits, local hydrodynamic processes comprising sediment deposition and resuspension are the dominant causes of variation in physical characteristics. Factors that control these processes include exposure to ocean swell, tidal currents, wind waves and depth. Variation in these factors could define classes and delineate within-estuary patterns such as patterns in sediment facies, bed stresses and local deposition and erosion rates.

In the following sections we discuss the details of Levels 2 and 3 of the classification. We propose that Bailey's [4] 'Ecoregions of the Oceans', which defines regions of homogenous climate and oceanic water masses at scales of 10^4–10^6 m^2, provides an appropriate



Category A
Category B
Category C
Category D
Category E
Category F
Category G
Category H
Legend :
Wind wave resuspension
Wind driven circulation
Ocean swell resuspension
River inflow
Tidal flow
Stratification
Intertidal area
Barrier or spit
Tidal delta

subdivision of estuaries at Level 1 of the EEC. In this article we have not detailed consideration of Level 4.

2.3. Level 2—hydrodynamic processes

Level 2 of the EEC subdivides estuaries according to differences in estuary-scale hydrodynamic processes. Hydrodynamic processes are forced by the interaction of tides and ocean swell with freshwater inflow within the estuary basin, and wind acting on the surface of the estuary basin. These processes are controlled by the ocean at the estuary mouth, freshwater inflows at the headwaters and the morphometry of the estuary basin (i.e., whether it is deep, shallow or largely intertidal, broad and open, long and narrow or a complex branching network of arms). Together these forcing mechanisms produce: mixing, circulation, stratification, sedimentation, and flushing at the scale of the whole estuary. Importantly, our conceptual model assumes that the net effect of the three factors on hydrodynamic processes is independent of the size of each estuary. Thus, small estuaries have similar characteristics to larger-scaled versions.

We define eight categories at Level 2 that are based on distinctive hydrodynamic processes (Fig. 2). These categories are diagnosed by particular combinations of the three controlling factors (ocean forcing, river forcing and basin morphometry). The estuary-scale hydrodynamic processes and resultant physical character of estuaries in each category are described below.

Category A estuaries are very shallow basins (several metres depth), often elongate in shape and orientated parallel to the open coast shore. For the majority of the time there is no ocean (i.e., tidal or swell wave) forcing because the entrance to sea is for most of the time barred off. Thus, these estuaries have zero intertidal area and are poorly flushed. Episodic flood events can open an entrance for several days or weeks each year, permitting exchange with the ocean. Such entrances are generally narrow, and close when littoral drift overwhelms the ability of tides and river inputs to flush sediment from the entrance. River inputs are small and may be ephemeral. Wind generated two-dimensional circulation and mixing occurs. Because these estuaries are shallow, wave suspension of bottom sediments is an important driver of whole-estuary sedimentation processes. These estuaries are characterized by muddy substrate. No ocean swell enters the system because the entrance is closed for most of the time and, when open, the narrow and shallow entrance filters out wave energy. Category A estuaries are representative of features commonly termed coastal lakes.

Category B estuaries are elongate basins of simple shape and several to ten metres depth. The majority of the estuarine area is subtidal. The volume of river flow delivered during a tidal cycle is a significant proportion of the volume of the basin, and is greater than the tidal volume entering the basin. Thus, the estuary-scale hydrodynamic processes are dominated by river flows and these estuaries are well flushed. On shorelines with littoral

Fig. 2. Schematic drawings (conceptual models) of the 8 hydrodynamic classes of estuary showing their dominant morphometry and oceanographic properties. The relative levels of tidal versus river forcing scale according to the size of the blue and green arrows, respectively. The elevation and plan views are not to scale and the plan view is vertically exaggerated for communication purposes. The models represent average and unmodified conditions in estuaries, rather than those of impacted or degraded systems. Conceptual models are useful because they communicate simple images of major processes in real-world systems.

drift, these estuaries have small sand bodies (bars) on the ocean side of the entrance. In deeper systems a circulation pattern (estuarine) can be set up where outflowing freshwater is balanced by the inflow of seawater entrained beneath freshwater and a salt wedge develops. Seawater intrudes a considerable distance up estuary on low gradient coastal plains. Large floods can expel much of the ocean water from the estuary. Wind generated two-dimensional mixing and wave driven resuspension are minor as wind fetch and waves are small and depths are largely too great for significant bed stress to be produced. Thus sediments tend to be muddy except in areas of high tidal flows. Category B estuaries are representative of features termed tidal river mouths.

Category C estuaries occur where the mouth of a main river channel connects to shallow lagoons. While the main river channel is mostly sub-tidal, the lagoons can have significant intertidal area. The volume of river flow delivered during a tidal cycle is a significant proportion of the volume of the total basin and is greater than the tidal volume entering the basin. Thus, the estuary-scale hydrodynamic processes are dominated by river flows. However, river flows tend to bypass the lagoons. Thus in the deeper main arm a circulation pattern (estuarine) can be set up where out flowing freshwater is balanced by the inflow of seawater entrained beneath freshwater and a salt wedge develops. The main river channel is, therefore, well flushed, but seawater remains trapped in the lagoons where the flushing is comparatively poor. Wind generated two-dimensional mixing and wave resuspension of the substrate is minor in the main river channel, but greater in the lagoons because of the larger wind fetch and shallow depths. Wave resuspension produces coarser substrates in the lagoon. On shorelines with littoral drift, these estuaries have small sand bodies (bars) on the ocean side of the entrance. Category C estuaries are representative of features termed tidal river mouths.

Category D estuaries are shallow, circular to slightly elongate basins with simple shorelines and wide entrances that are open to the ocean. They are mostly sub-tidal with small intertidal areas restricted to the headwaters (sheltered areas) of the more elongate types. There is little river influence and circulation is weak and ocean forced. The entrances are wide and open to the ocean, allowing swell to enter the bay and resuspend seabed sediments. Thus, the estuary-scale hydrodynamic processes are dominated by the ocean. There are no sand bodies (tidal deltas) on the ocean side of the entrance. Wind generated two-dimensional mixing and wave driven estuary-scale sedimentation occurs. As a result the substrate is sandy, except in areas where wave resuspension of the substrate is limited by depth. Category D estuaries are representative of features termed coastal embayments.

Category E estuaries are shallow, circular to slightly elongate basins with simple shorelines and extensive intertidal area. They generally have a narrow entrance to the sea that is usually constricted by a spit or sand barrier. Sand bodies occur as ebb and flood tidal deltas at the mouth on littoral drift shores. On zero drift shores funnel-shaped entrances with no sand bodies occur. The tidal prism is a large proportion of the estuary basin volume. The volume of river flow delivered during a tidal cycle is very small compared to the total volume of the estuary. Thus, estuary-scale hydrodynamic processes are dominated by ocean forcing. Wind generated two-dimensional circulation, mixing and resuspension occur at high tide. Category E estuaries have good flushing because much of the water leaves the estuary on the outgoing tide. The combination of wave resuspension of the substrate and flushing result in Category E estuaries having generally homogeneous and sandy substrates. These estuaries are also well mixed because strong flushing, wind mixing and the shallow depths prohibit density stratification. Salinity is close to that of the sea. Ocean swell can resuspend sediment in the entrance of estuaries with wider mouths at high tide when screening from the ebb tidal delta is minimized. Category E estuaries are representative of features termed tidal lagoons or barrier-enclosed lagoons.

Category F estuaries share similarities with Category E estuaries having shallow basins and narrow mouths, usually formed by a spit of sand barrier. However Category F estuaries have complex shorelines and numerous arms leading off a main basin. As a consequence, the extensive intertidal area of Category F estuaries tends to be cut by deep channels caused by drainage from the arms. Sand bodies in the form of ebb and flood tidal deltas occur at the mouth on littoral drift shores. Funnel-shaped entrances occur on low littoral drift shores. The tidal prism makes up a large proportion of the tidal volume. River inputs over the tidal cycle are very small compared to the total volume of the estuary. Thus, estuary-scale hydrodynamic processes are dominated by the tides. Wind generated two-dimensional circulation, mixing and wave resuspension of the substrate is less pronounced than for Category E estuaries because the narrow arms means that fetch is small. As a result, the main body of these estuaries is characterized by sandy substrate, with a transition to muddy substrate in the upper portion of the arms. The planform complexity means that Category F estuaries are not as well flushed as Category E estuaries because water is trapped in the arms. Although the main body of these estuaries are reasonably well mixed, the upper reaches of narrow arms are characterized by weak stratification and salt wedges. Salinity is close to that of the sea in the main body of the estuary with a transition lower salinity in the arms. Ocean swell can resuspend sediment in the entrance of estuaries with wider mouths at high tide when screening from the ebb tidal delta is minimized. Category F estuaries are representative of features termed barrier-enclosed lagoons or drowned valleys.

Category G estuaries are very deep (up to hundreds of metres), narrow, elongate and largely subtidal basins. They are characterised by sills at the mouth and along the length of the estuary that were formed as terminal moraines of glaciers. Both river and tidal inputs over the tidal cycle are very small proportions of the total volume of the basin. Water movement is controlled primarily by thermohaline forcing, that is the circulation is maintained by the large density differences produced by the salinity contrast between freshwater and oceanic water. The resulting circulation pattern is characterized by out flowing freshwater, which is balanced by the inflow of seawater entrained beneath freshwater. Wind may modify this circulation and two-dimensional and three–dimensional wind driven circulation may become a dominant force on occasions, but it is not responsible for the mean circulation over extended periods of time. Consequently, these estuaries are characterized by poor flushing, particularly in more complex shaped (multiple arm) systems. The very deep basin and partitioning by sills means that flushing takes place in a relatively thin layer of fresh water, which moves over the top of a 'dead zone' of saline water. Substrate resuspension by ocean swell or wind waves is not an important estuary-scale hydrodynamic process because of the large depth of the basin. As a consequence, the substrate is generally fine sand or mud. Category G estuaries are representative of features termed fjords or sounds.

Category H estuaries are deep (tens of metres), narrow, elongate basins and largely subtidal. Both river and tidal inputs over the tidal cycle are very small proportions of the total volume of the basin. Water movement is controlled primarily by thermohaline forcing; that is the circulation is maintained by the large density differences produced by the salinity contrast between freshwater and oceanic water. The wind may modify the circulation and become a dominant force on occasions, but it is not responsible for the mean circulation over extended periods of time. A circulation pattern (estuarine) is set up where outflowing freshwater is balanced by the inflow of seawater entrained beneath freshwater. There is a strong longitudinal gradient (head to mouth) in hydrodynamic processes with riverine forcing and stratification dominating in the headwaters and ocean forcing and vertical mixing to depth near the entrance. The systems are characterized by poor flushing. The flushing is poorer in the more complex shaped (multiple arm systems) systems. Ocean swell and wind waves are unimportant in substrate resuspension processes because of the large depth of the basin. The substrate is generally fine sand or mud. Category H estuaries are representative of features termed sounds, drowned valleys, rias or fjords.

2.4. Level 3—catchment processes

Level 3 of the EEC subdivides estuaries according to differences in catchment processes. Processes occurring within the freshwater catchment of the estuary determine the supply of land-derived sediment and other water column constituents. Within climatically homogenous regions (i.e., the broad groups of estuaries that are defined at Level 1) two factors; the Geology, and Land Cover of the catchment, are the dominant causes of differences in these processes.

We nominally define five Geology subcategories (Hard Sedimentary, Soft Sedimentary, Weak Volcanic, Strong Volcanic and Plutonic). Catchment Geology controls groundwater flow and storage capacity and thus, is likely to be the dominant cause of variation in base flows into groups of estuaries that are defined by Level 2 of the classification. Catchment Geology is also the dominant controller of hydro-chemistry, particularly at base flow, and erosion rates. Thus, catchment geology categories provide increased discrimination of hydrology, water chemistry and sediment supply. For example, the soft-sedimentary catchment geology category is characterized by larger sediment and hydro-chemical supply rates. Estuaries with this geological category are expected to be more turbid, have greater primary productivity, and a greater proportion of habitats with soft and fine substrates than estuaries with the same Level 2 class but hard-sedimentary catchment geology.

Catchments are rarely homogenous with respect to geology and will often comprise a mixture of geological types. In addition, soft geological types have been shown to have a proportionally greater contribution to sediment [33] and hydro-chemical [34,35] fluxes. Thus, a geological category may be dominant when it comprises only a small proportion of the total watershed area. Our solution to the geological heterogeneity of catchments is to classify estuaries according to their dominant catchment geology.

We nominally define four Land Cover sub categories (Urban, Exotic Forest, Pastoral and Natural). Catchment Land Cover provides increased discrimination of various catchment processes. Catchment Land Cover controls surface interception of rainfall as well as potential evapotranspiration and therefore increase discrimination of hydrological characteristics such as low flow regimes [36]. Catchment Land Cover controls hydro-chemical processes and erosion rates and is also a surrogate measure for land use. Land Cover, therefore, provides further discrimination of fluxes of sediment and catchment derived constituents including pollutants such as pathogens, heavy metals and organic compounds into an estuary. Catchment Land Cover categories, therefore, provide increased discrimination of sediment supply regime, the type of material discharging to the estuary and water chemistry.

Catchments are rarely homogenous with respect to Land Cover and will often comprise a mixture of land cover types. It has been recognized that the effect of catchment land cover on aquatic communities and water quality is not necessarily proportional to the area of land cover categories. For example, Suren and Elliot [37] report large changes in stream invertebrate communities when the urban area exceeds 15% of catchment land area results. Similarly, Biggs [35] showed that greater than approximately 25% land cover in a pastoral use results in distinctive river water quality. Our solution to catchment land cover heterogeneity is the same as for assigning geological categories and, therefore, classifies estuaries according to their dominant catchment land cover.

3. Application to New Zealand estuaries

The previous section describes the conceptual model for our classification, the hierarchical structure of classes and a nominal scheme for subdividing each level of the hierarchy with categories. Application of the conceptual model to produce a mapped classification comprises three steps; estuary definition, development of 'assignment characteristics', and the assignment procedure. The process of mapping is distinct from the process of classification and involves assignment; choosing or recognizing the class to which individual estuaries should be allotted [38]. The 'assignment characteristics' are attributes that are used to assign each estuary to a category. In general, our assignment characteristics are metrics that reflect variation in the various controlling factors.

Our application of the EEC was carried out in a Geographic Information System (GIS), which allowed us to automate many aspects of the mapping procedure. The basic classification unit for Levels 1–3 of the classification is a single estuary and its catchment. Each estuary and its catchment were delineated in a GIS using hydrographic charts and digital topographic maps that were converted to a digital elevation model (DEM) of New Zealand based on a 30-m grid. A set of assignment characteristics was then developed for each estuary. We used outputs from a numerical model of tides, modelled annual catchment runoff, and data from hydrographic charts, to derive assignment characteristics for Level 2 of the classification. Assignment characteristics for Level 3 were derived from GIS based maps of geology and land cover. The assignment procedure applies criteria in the form of rules to the assignment characteristics to determine category membership for each estuary (Fig. 3 and Table 1). The GIS was then used to map the classified estuaries.

3.1. Estuary definition

The definition we have adopted for estuaries recognizes that an estuary is a basin within which river and ocean forcing (being both tides and waves) interact to determine properties. This provides a starting point for delineating estuaries as single 'classification units' for Levels 2 and 3 of the classification.

The process of defining each estuary involves subjectivity, which we attempted to reduce by requiring that each estuary be complied with the following criteria. First, we used digital 1:50,000 maps to identify estuary basins that are at least 0.5 km long. The high water line defined the shoreline of the estuary. The seaward boundary, or mouth, of each estuary was drawn at an inlet constriction, or where the shoreline diverges up or down coast. This

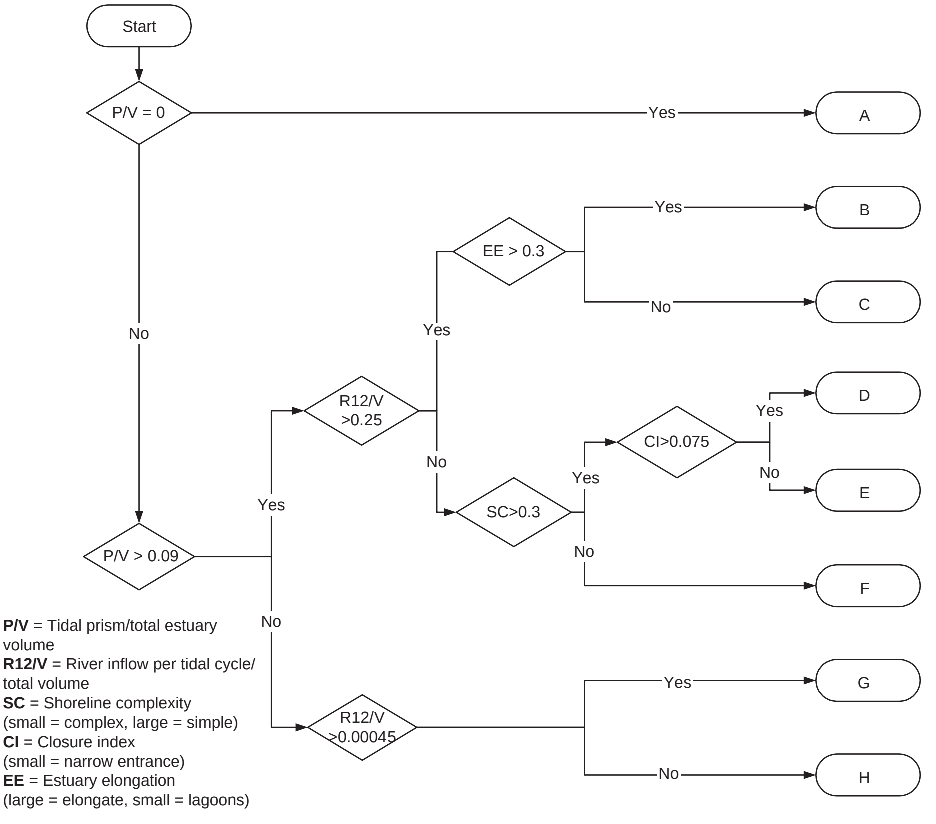


Fig. 3. Schematic diagram of the assignment procedure at the hydrodynamic processes level of the EEC showing the assignment characteristics and criteria for determining membership of each category.

Table 1
Assignment rules for mapping Level 3 of the EEC

Factor	Category	Notation	Rule
Geology	Hard sedimentary	HS	Class = the spatially dominant geology category unless combined soft sedimentary geological categories exceed 25% of catchment area, in which case class = SS
	Soft sedimentary	SS	
	Volcanic weak	VW	
	Volcanic strong	VS	
	Plutonic	Pl	
Land cover	Urban	U	Urban area exceeds 15% of total catchment area
	Pastoral	P	Pastoral area exceeds 25% of total catchment area and urban areas do not exceed 15% of total catchment area
	Exotic forest	EF	Exotic forests are the dominant land cover and pastoral and urban land categories do not exceed 25% and 15%, respectively
	Natural	N	Natural land cover categories exceed 75% of total catchment area and urban areas do not exceed 15% of total catchment area

boundary was easily defined in most situations. However, seaward boundaries were difficult to define for estuaries with funnel-shaped mouths. In these few cases the boundary was drawn to follow the general trend of the hard shore coast on either side of the mouth. The upstream limit of the estuary was easy to define in most cases because of the generally steep topography of the New Zealand coast, as the location where the coastlines met on 1:50,000 topographic maps. However, in river dominated elongate estuaries we defined the upstream boundary as the upstream limit of salinity intrusion under average tidal and river flow conditions at HW. Where there was no salinity data, we made a decision based on anecdotal evidence, the location of freshwater intakes and geomorphic information such as the location of river bars or where significant tributaries enter a system. In practice, the final class assigned to estuaries was insensitive to the precise location of the upstream limit and seaward boundary.

Once defined, each estuary basin was delineated as a polygon in a GIS database and associated with the polygon of its contributing catchment. Catchment boundaries are the land boundaries that encompass the drainage basin of the estuary above the mouth, which we derived from the DEM.

3.2. Development of assignment characteristics

3.2.1. Level 1—global scale processes

Baileys [4] 'Ecoregions of the Oceans' provide an appropriate subdivision of estuaries at the first level of our classification. Ocean ecoregions are defined by broad latitudinal zonation, oceanic basins and large landmasses. Each estuary is assigned to a Level 1 category based on the ocean ecoregion it is located within.

3.2.2. Level 2—hydrodynamic scale processes

Assignment characteristics were calculated for 443 New Zealand estuaries as follows. We used five indices (or metrics) as assignment characteristics for the Level 2 of the classification: the tidal prism to estuary volume ratio (P/V), the river inflow per tidal cycle to estuary volume ratio ($R12/V$), the shoreline complexity index (SC), the closure index (CI) and the estuary elongation index (EE). The ratios P/V and $R12/V$ are primarily measures of ocean and river forcing respectively. P/V is the ratio of the tidal prism (P is the total volume of water entering an estuary on the flood or incoming tide) to the total volume of water in the estuary at high tide (V). A large value of P/V implies that estuaries are shallow and subject to strong tidal forcing. R12 is defined as the total mean volume of water flowing into the estuary during a tidal cycle (12.4 h). Hydrodynamic processes of estuaries with a large $R12/V$ ratio are dominated by river forcing. The indices SC, CI and EE are measures of estuary planform shape that were used to discriminate differences in basin morphometry. SC varies from 1.0 (a simple circular basin) to <0.1 (very complex shoreline with multiple arms). CI is a measure of the openness of the estuary mouth and varies from ~ 0.3 (wide mouth) to <0.01 (very narrow and constricted entrance). EE is a measure of estuary elongation and varies from ~ 0.4 (very narrow elongate basins) to <0.05 (wide basins). The methods by which these indices were calculated are described below.

Total volume (V) (at high tide) was calculated for the 443 estuaries in various ways depending on the type of data available for each estuary. (1) Volumes were computed from detailed bathymetry datasets from NIWA archives created for numerical model grids

(38 estuaries). (2) Volumes were computed following on-screen digitizing soundings from the electronic versions of Royal New Zealand Navy Hydrographic charts. The unrectified TIFF files were georeferenced to the 1:50,000 shoreline (estuary polygons) in GIS, a Triangulated Irregular Network (TIN) was created for each estuary from the bathymetry dataset, and then a 'surface analysis' was undertaken to calculate estuary volume from the TINs (131 estuaries). (3) Volumes were computed as the sum of the volume of water at low tide plus the tidal prism P, where the low tide volume was calculated as the product of mean depth and surface area at low tide (274 estuaries). This latter method mostly applied to very small and shallow (mean depth generally <1 m) estuaries where there was no bathymetric data available and where the tidal prism was generally a significant proportion of the total volume. The mean depth at low water was estimated from anecdotal evidence. The surface area at low water was computed from 1:50,000 digital charts using GIS. The method used to compute the tidal prism P is described below.

Tidal prism (P) was calculated from the product of spring tidal range (T_s) and the area of the estuary at mid tide (A_m) as

$$P = T_s A_m.$$

The spring tidal range was computed using the NIWA EEZ tidal model [39] to extract tide range (M2 and S2 tidal constituents) information at the mouth of each estuary or at the closest model node to the mouth. The area of the estuary at mid tide A_m was calculated as

$$A_m = (A_{HW} + A_{LW})/2,$$

where A_{HW} (the area at high tide) and A_{LW} (the area at low tide) were computed from 1:50,000 digital topographic maps using the GIS. The estimates of P compared well with tidal prism determined by field measurements (tidal gaugings) and calculations from hydrographic charts reported for some estuaries in Hume and Herdendorf [40].

River inflow over a tidal cycle (R12) was calculated from an estimate of mean annual flow into the estuary. An annual runoff surface (mm/km^2/yr) has been estimated for the whole of New Zealand at a spatial resolution of 1 km^2 using a water-balance model, based on rainfall and potential evapotranspiration [41]. We used the GIS to sum this surface within the catchment of each estuary to estimate annual runoff because most estuaries lacked flow-measuring stations on their inflowing streams and rivers.

SC was calculated from the 1:50,000 topographic map as the length of the perimeter of the estuary shoreline, divided by the circumference of a circle that has the same area as that estuary. We used the reciprocal of this ratio so that SC is always <1.

EE was calculated as the length of the thalweg of the longest branch of the estuary basin from the mouth to the upper limit, divided by the length of the perimeter of the estuary shoreline. This ratio is always <0.5.

CI was calculated as the width of the estuary mouth, divided by the length of the perimeter of the estuary shoreline. This ratio is always <0.4.

3.2.3. Level 3—catchment scale processes

We developed assignment characteristics for the Catchment Processes level of the classification from existing digital maps of geology and land cover. We used the GIS to extract the total area in each of the geological and land cover categories described on the respective maps, for the catchment of each estuary.

The detailed geological categories appearing on the New Zealand Land Resources Inventory maps [42] were consolidated into five EEC categories. The primary aim of the catchment geology categories was to discriminate catchments on the basis of the likely amount and size grade of the sediment delivered to the estuary. The geology classes we defined for the estuary classification are very similar to those defined for the New Zealand River Environment Classification [25]. However, the geology groups defined by the river classification were selected largely on the basis of their effects on water chemistry (i.e., pH and nutrient input) and suspended sediment. For the EEC geology categories, we were primarily concerned with the erodibility of the surface rocks and the relative sand/mud proportions in the parent lithology. These are largely determined by their lithology and degree of lithification, which reflects the primary grain/crystal size. Thus, the EEC geological category consolidations had some differences from the river classification, including (i) lumping all weak volcaniclastic deposits, whether acidic or basic, (ii) recognizing a stronger volcanic group, which includes lithified/welded volcaniclastic material (e.g., ignimbrites) and lavas, (iii) including limestone in the hard sedimentary group and (iv) including marble in the plutonic and coarse-crystalline metamorphic group.

Vegetation cover was extracted from the New Zealand Land Cover Database (LCDB; www.terralink.co.nz/tech/data/lcdb/lcdb.htm), which has been compiled from satellite imagery from 1996. The GIS was used to extract the proportion of catchment area in various LCDB categories. The urban LCDB category was used as our 'Urban' category. The exotic (plantation) forest LCDB category was used as our 'Exotic Forest' category. The pasture LCDB category was used as our 'Pasture' category. The LCDB categories native forest, native grassland, and scrub were consolidated into a single 'Native' category for the EEC. The complete set of assignment characteristics were estimated for all estuaries and compiled into a single database for use by the assignment procedure.

3.3. Assignment procedure

The assignment procedure applies criterion in the form of decision rules to the database of assignment characteristics to determine class membership for each estuary. This produces a simple table in which each estuary is assigned to a category for each of the two classification levels. The GIS is then used to map the estuaries with classes being defined by colour at any level of the classification.

3.3.1. Level 2—hydrodynamic processes

We applied a set of 'rules' in the form of a decision tree to determine class membership at Level 2 of the classification. These rules reflect the conceptual model of the factors controlling estuary-scale hydrodynamic processes that were developed above (Figs. 1 and 2) and the description of Level 2 categories (A–H). These rules are summarized by Fig. 3 and are explained below.

The first step in the assignment process is to group estuaries on the basis of their P/V ratio. Those with no tidal inflow (i.e., water bodies closed to the sea for most of the time and $P/V = 0$) were assigned to category A. All remaining estuaries were then separated into two groups. One group comprises estuaries with $P/V < 0.09$. These tend to be relatively deep estuaries with weak tidal forcing, and are likely to be dominated by river forcing, density driven circulation and mixing and stratification. The deep estuaries were then further subdivided into two groups on the basis of $\mathrm{R12}/V$. All of these estuaries had very low freshwater input compared to their total volume, with $R12/V$ in the range 0.000045–0.002. Estuaries having a larger proportion of the estuary volume replaced by river input in a tidal cycle (i.e., $R12/V>0.00045$) were assigned to Category G. The remaining deep estuaries have very low values for $R12/V$ (i.e., <0.00045) meaning that river flow is less important as a forcing mechanism and are, therefore, assigned to Category H.

The group of estuaries with $P/V>0.09$ have a tidal prism that is at least 9% of their total volume and are relatively shallow. These estuaries were subdivided into two groups on the basis of the ratio of $R12/V$. One group of estuaries are defined by large values of $R12/V$ (i.e., >0.25). These estuaries have river inflow over a tidal cycle of more than 25% of the total estuary volume implying that estuary-scale hydrodynamic processes are strongly dominated by the river. This group was then further subdivided on the basis of EE. Estuaries with $\mathrm{EE}>0.3$ have simple, narrow and elongate basins and were assigned to Category B. Estuaries with $\mathrm{EE}<0.3$ have a more complex planform and were assigned to Category C.

The second group of shallow estuaries have small values of $R12/V$ (i.e., <0.25). These estuaries are less strongly forced by the river and estuary-scale hydrodynamic processes are dominated by tidal forcing. This group was then subdivided again on the basis of SC. A small value of SC (i.e., <0.3) implies that the estuary has a complex shore and multiple arms. The complex shape means that these estuaries are less well flushed and less likely to be stirred by waves because the fetch is small, and were assigned to Category F. A large value of SC (i.e., >0.3) implies that the estuary has a simple round shape. These remaining estuaries were further subdivided into two groups on the basis of the estuary CI. Estuaries with a wide mouth open to the ocean have a $\mathrm{CI}>0.075$ and are assigned to Category D. Estuaries with shallow circular basins and a narrow entrance, usually due to the presence of a sand spit or barrier, were assigned to Category E.

3.3.2. Level 3—catchment processes

To determine class membership at the Level 3 of the classification we applied a set of 'rules', which are summarized in Table 1. We adopted a similar rule system as used for the River Environment Classification to assign the geology and land cover categories [25]. Generally, the assigned geological category is the dominant category in terms of the proportion of catchment area. However, if the soft sedimentary category covers greater than 25% of the catchment area then a soft sedimentary category was assigned. This rule was based on the relative specific suspended sediment yields found by [33]. We accounted for the non-proportional effect of different land use types by applying an Urban category to estuaries where urban LCDB categories exceed 15% of the catchment area, and where exotic forest and pasture categories from the LCDB exceed 25% of catchment area.

4. Results

Delineation of estuaries according to our criteria resulted in the definition of about 443 New Zealand estuaries. These systems covered a large range of sizes, varying in surface area from 2 to 74,306 ha (the Kaipara Harbour), and in the size of their catchments from 25 to >2,100,000 ha. A database containing physical information for these estuaries was developed. Although this database contained about 50 metrics for each estuary, only the metrics described earlier in this paper were used in the classification.

At Level 1 of the classification, the ocean ecoregions place New Zealand in the Temperate Domain and further subdivides this domain into two divisions; the Northern Subtropical Division and the Southern Equatorward Westerlies Division. The boundary between these divisions occurs in southern portion of the North Island. This division is consistent with broad regional differences in physical characteristics and associated biological distribution. For example, there is general gradient in mean annual water temperature from 10 °C in the southern part of the country to around 18 °C in the north. Some biological distributions show latitudinal limits. For example, *Durvillaea antarctia* (bull kelp) is restricted to cooler and more southerly coastal waters and *Avicennia marina* (mangrove) is restricted to estuaries in the upper North Island.

Examples of the classification mapped at Levels 2 and 3 (i.e., the hydrodynamic and catchment processes levels), along with the Full classification, are shown in Figs. 4 and 5. Fig. 4 shows the national distribution of estuaries mapped at the Level 2. Figs. 5(A) and (B) zoom to the Auckland isthmus and southern New Zealand where there are high densities of estuaries, to show estuaries classified at Levels 2 and 3 along with the Full classification.

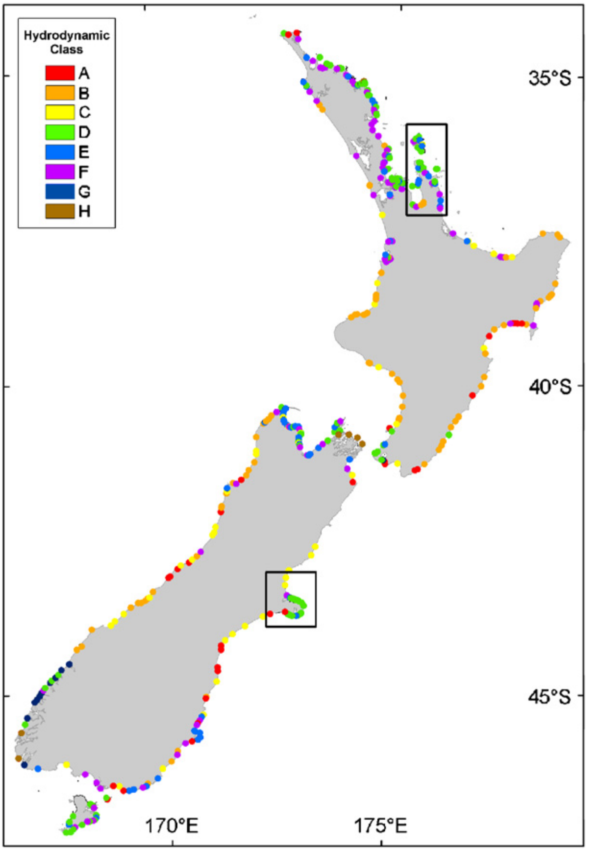


Fig. 4. The classification of New Zealand's estuaries mapped at Level 2 of the EEC (i.e., the 'hydrodynamic processes' level) showing the distribution of Level 2 estuary classes on the New Zealand coast. The box shows the areas where estuaries are mapped at higher resolution in Figs. 5(A) and (B).

From Fig. 4 it is apparent that estuaries in the eight different Level 2 classes (A–H) show a degree of clustering by geographic location. This reflects the mode of origin of the estuaries. For instance, Category A estuaries occur on shores in the eastern coastlines of the North and South Islands (Hawkes Bay and Canterbury) where littoral drift is sufficient to bar off the entrance to shallow water bodies for most of the year and form coastal lakes. Category D estuaries are restricted to rocky coasts like the east coast of the northern North Island (Northland), where littoral drift is negligible and insufficient to build barriers across embayments. Category E estuaries occur mostly on the north-eastern coasts of the North Island, in the North of the South Island (Golden Bay/Tasman Bay regions) and on the south-eastern and southern coasts of the South Island (Otago and Southland regions). Here, sea level rise flooded wide-mouthed shallow wide embayments and the wave climate and sand supplies have been favourable to build sandy spits and barriers across the openings to form narrow entrances. Category G estuaries are restricted the southwest of the South Island which is the only part of New Zealand where glaciers have cut very deep valleys that were flooded by the sea to form fjords. Thus, the classes we define here have some correspondence with classifications based on origin [9,28].

The assignment of individual estuaries to Level 2 categories did produce some unexpected classifications. In part, this reflected our poor understanding of the key processes in some individual situations. However, there is also significant within-class

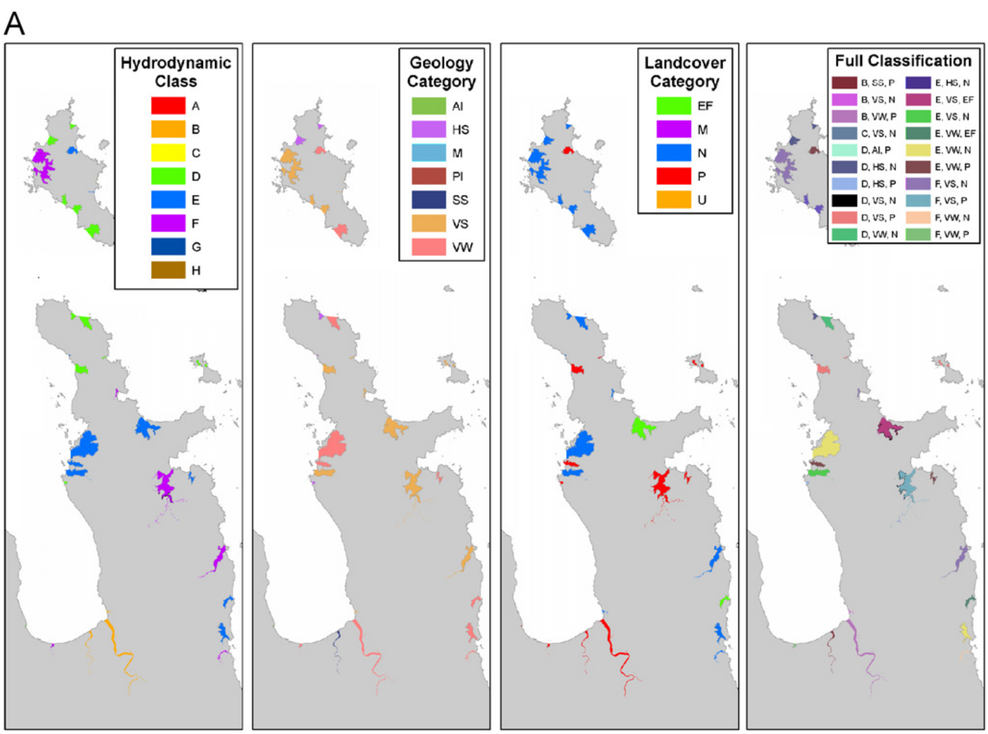


Fig. 5. Estuaries mapped at higher spatial resolution for the Coromandel Peninsula (A) and Banks Peninsula (B) showing Level 2 (hydrodynamic processes) classes and factor categories at Level 3 (i.e., geology and landcover) and the Full classification at Level 3.

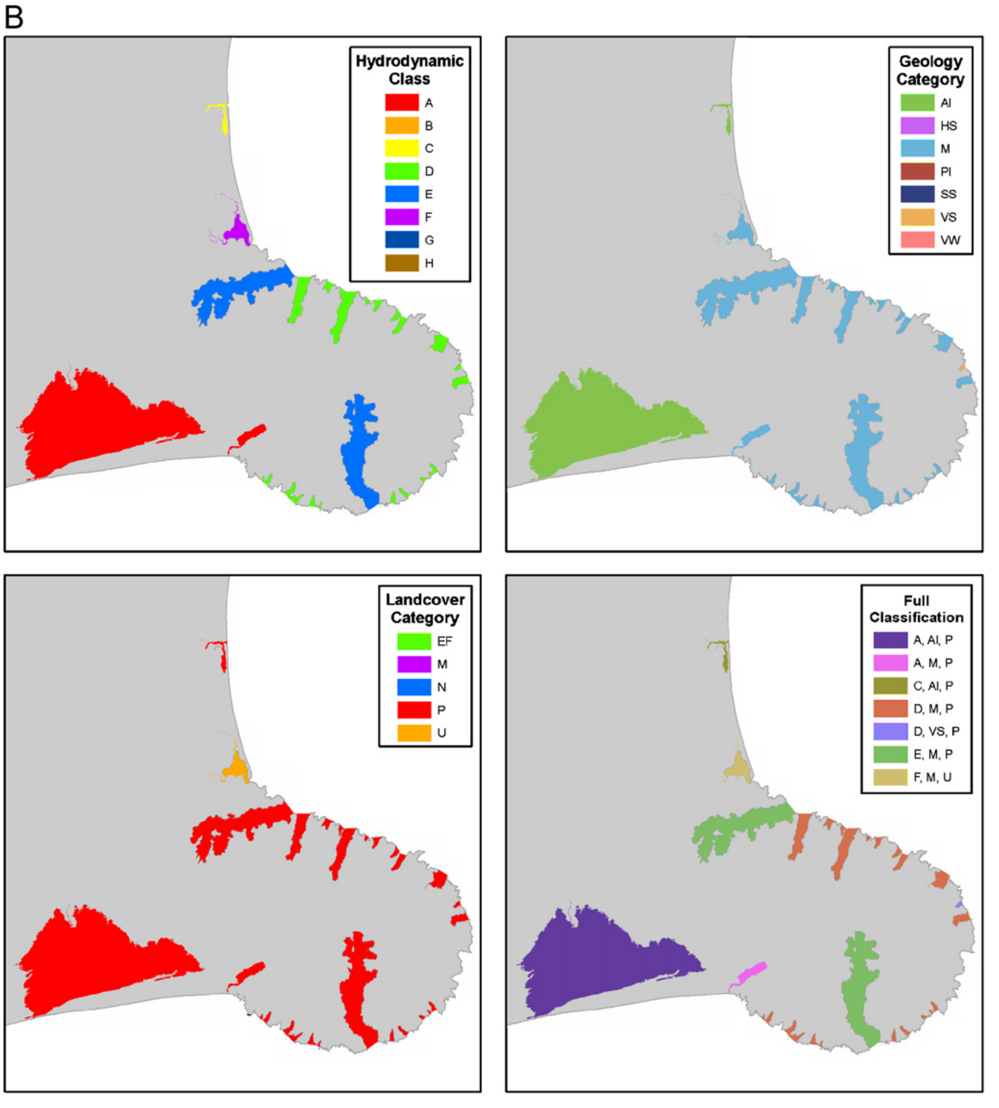


Fig. 5. (*Continued*)

variation about the mean or average type. Thus some end members of some categories have attributes that are similar to 'adjacent' categories. For instance, Categories B and C are both river mouths and dominated by river flows. The difference occurs because Category C estuaries occur on the coastline of flat coastal plains where littoral drift builds barriers across the entrance, whereas Category B estuaries lie on shores with steep uplands and zero littoral drift. It is recognized, therefore, that some estuaries are transitional cases and share some properties of both categories.

An interesting test for the EEC is provided by Maketu estuary in the Bay of Plenty. Burton and Healy [43] described how, prior to 1957, Maketu estuary had a large river flowing into it with an average flow of 47 m^3/s. It had a typical river mouth entrance configuration with a small ocean bar and no flood tidal delta (typical of our Category C river dominated situation). The river was diverted from the estuary directly to the sea via the engineered Te Temu Cut that was dredged in 1957 to prevent flooding of farmland around the shores. Only 2 m^3/s of river discharge was left flowing into the estuary. Following diversion there was rapid change in the entrance geomorphology and by 1959 the estuary had developed a substantial flood tidal delta (characteristic of our Category E and tidally dominated situation). Using the EEC assignment procedure to categorize the Maketu situation before and after river diversion confirms that hydrodynamic changes associated with diversion were enough to cause the estuary to change type and shift from an estuary with Category C characteristics to those of a Category E estuary.

Figs. 5(A) and(B) show how the classification at Level 3 (i.e., the catchment geology and landcover categories) produces further discrimination of estuary types. Note that estuaries that are classified similarly at Level 2 are often differentiated at Level 3. It is also apparent that, at Level 3, the New Zealand estuaries are very heterogeneous, even over small regions.

A full classification at any level of the EEC is denoted by the category membership at that and all subsequent levels, with categories separated by a comma (e.g., Northern Subtropical Division, B, SS, P). The shortened notations for Level 2 and 3 categories are explained in Fig. 3 and Table 1. The number of potential classes at any level in the classification is dependent on the number of categories defined at that level, multiplied by the number of classes at all higher levels. Thus, the number of potential classes rapidly increases moving down the classification. However, not all combinations will occur.

5. Discussion and conclusions

The EEC is an *a priori* classification that is developed from knowledge of how estuaries function and are organized in space. The controlling factors approach is based on an underlying model of physical processes and codifies basic ideas about the causes of differences in the physical characteristics of estuaries. Because physical conditions drive many aspects of estuary ecosystems, we expect that EEC classes will also broadly discriminate biological characteristics of estuaries.

The EEC is a particularly suitable classification alternative for management applications for a number of reasons. First, because the EEC is based on ‘controlling factors’ and processes, it helps to elucidate causes of variation in properties between estuaries. This helps to convey some understanding of variation at broad scales and also of why estuaries have different levels of sensitivity to human-induced changes. For a manager the conceptual models (Fig. 2) and their associated descriptions of the physical properties provide context for managing expectation and explaining to communities why different estuaries need to be managed in different ways. For instance, in a shallow estuary with poor flushing (Category A) which is large in area and has a muddy substrate, we would expect the water to be turbid when winds generate waves and stir the bed. Here the community should have a low expectation for water clarity and management options limited to introducing aquatic plants to bind the substrate. In contrast, for a shallow largely intertidal estuary that exchanges much of its water with the ocean on each tide and is also narrow there is less fetch for winds to generate waves (Category F), and we would have a much higher expectation for water clarity.

A second benefit of the EEC is that it can be developed from existing data. This allows all estuaries within a spatial domain of interest (e.g., an entire country) to be classified in a consistent and cost-effective manner. The resulting mapped classification provides a 'spatial framework' [7,44], which has application in many large scale environmental and conservation planning and assessment activities. A specific benefit of spatial frameworks that are based on hierarchical classifications is the ability to vary the classification level and differentiate characteristics at different levels of detail. This enables the 'grain' [31,45] of investigations to be altered to best suit the purposes of an analysis or management activity.

The controlling factors approach to classification has the advantage that classes are geographically independent that is, the criteria for class membership are independent of geographic location. Thus, classes group similar estuarine environments that occur at different geographic locations. This provides a basis for transferring results of process related studies, extrapolating data from one place to another and stratifying sampling effort for resource assessment. In New Zealand for instance, the classification was used to select estuaries throughout New Zealand for studies of the abundance and distribution of juvenile fish [46]. The study objectives required that the sampling take place in a selection of estuary types (different hydrodynamic classes) over large latitudinal scales and on the eastern and western coasts of New Zealand. Subsequent analysis of the data was aided by using geographically dependant (estuary specific) physical environmental variables (e.g., water depth, tidal flow, catchment water and sediment runoff) from the database along with other ecological data collected during the fish surveys.

In many conservation management applications the objective is to identify and then protect representative types in terms of ecological and habitat 'potential'. Because the EEC is based on the processes that drive ecosystem characteristics, it provides an objective method of doing this. In New Zealand the protection and enhancement of marine biodiversity is enhanced through the selection of Marine Protected Areas (MPAs) and is guided by the MPA Policy and Implementation Plan and the Department of Conservation and the Ministry of Fisheries [47]. Improved metrics and classifications including the EEC are being used to facilitate the identification, protection and restoration of representative examples of marine ecosystems and assess the adequacy of current MPAs. We argue that a process-based approach to classification has significant advantages for management applications, over methods that are based on biotic datasets or previous classifications that were based on the 'mode of origin'. For a start, biological datasets for estuaries are not often spatially complete compared to physical datasets, nor can they be generated in the same way from models that physical datasets can be. Biologically based classifications have the disadvantage that biological distributions may be affected by both natural and human induced disturbance. Thus, these classifications may reflect transient patterns and do not accurately reflect ecosystem potential. The mode of origin does not necessarily differentiate estuaries according to how they function today because the river, tide and wave forces that combined to form different estuarine types do not necessarily combine and scale (both in time and space) in the same way in todays oceanographic systems. In addition, mode of origin classifications are not hierarchical, whereas the EEC subdivides estuaries at three (or potentially four) levels of classification detail.

The EEC is a deviation from controlling factor approaches to landscape classification. Landscape classifications [24,25] assume that a single factor is the cause of variation at each classification level. We argue, however, that the characteristics of estuaries, at all four levels of classification detail, emerge from an interaction between a number of factors. For example at Level 2, our conceptual model proposes that differences in the hydrodynamic processes of estuaries result from the interaction of forcing from rivers and the tide within the estuary basin and the effect of basin shape on wind-driven circulation, mixing and sedimentation.

Our assignment rules are the most subjective aspect of the classification and reflect expert judgements. However, once defined, these rules are consistently applied, making assignment objective and consistent. The classification procedure and use of a GIS allowed us to rerun the classification to test new rules or data very easily and as they become available.

The classification does have limitations with respect to its application to large estuaries. Large estuaries tend to be investigated and managed on account of their large size. For instance, large estuaries can lie in the region of more than one management authority and quite detailed information may be needed on individual arms for resource management purposes. In this case it may be more appropriate to apply the classification to individual components of the large estuary. On the other hand, if a more general comparison of the key features of estuaries at a national or global scale is required, then classifying the large estuaries as a single type may be quite appropriate.

A practical example of how the EEC may be applied in a management application is in the assessment of susceptibility, significance and vulnerability. Susceptibility relates to how an estuary will respond when it is subjected to impacts or perturbation [48]. The EEC's underlying process hierarchy permits estuaries to be ranked according to their susceptibility to a particular impact. For example, estuaries with poor flushing and whose catchments are dominated by soft rocks will be the most susceptible to effects of land use change in their catchments that disturb soils and increase erosion. The significance of an estuary is the present and future value attributed to it by society. A key component of significance of an estuary is the rarity of the type of the environment it supports. By comprehensively classifying all the estuaries of New Zealand, the EEC provides useful input to defining the significant estuaries. Estuary classes that are rare, regionally or nationally, will be highly valued because they contain a scarce set of characteristics. Finally, vulnerability is a combination of susceptibility and significance [46]. Thus, combining rankings of susceptibility and significance of estuaries helps stratify their vulnerability and would assist in selecting justifiable environmental protection standards or determination of conservation status.

In practice this involves using the variables in the EEC database and classification engine to generate a classification to answer a specific question. For a catchment manager in a Regional Council the question might be "Which of the most (vulnerability) pristine estuaries (significance) in my region is most likely to be impacted by sediment runoff (susceptibility)?". The classification procedure is to apply criteria in the form of decision rules (algorithms) that incorporate scales and threshold. For instance a simple definition of a pristine estuary might be built into a rule that specifies that a pristine estuary is defined by 90–100% of a catchment being in native vegetation. The potential of delivery of sediment to the estuary would be based on variables and an algorithm that incorporates mean catchment flow, frequency of floods, and proportion of soft rocks (mudstone) in the catchment. The flushing ability of the estuary would be based on the hydrodynamic category or variable such as % intertidal area. Algorithms or varying sophistication can be built. Once the rules are built, the classification is run drawing on information in the database. GIS is then used to map the estuaries with classes being defined by colour that in this example would rank estuaries according to their vulnerability to sediment runoff. The output is visual and coloured maps (e.g., Figs. 4 and 5) form an excellent reference for discussion between catchment managers and council or the community about which estuaries will be most impacted by conversion of catchment to forest or urban areas or which estuaries will be most impacted when runoff increases with climate change. Used in this manner the classification provides the manager with a tool to prioritize (rank) estuaries for runoff controls and expenditure on water quality monitoring. In another application, biosecurity managers might use the classification to map the location of those estuaries where certain invasive species are likely to take hold, providing that enough is known about the conditions (variables) in which the invasive species flourish and develop good algorithms. The classification tool is particularly powerful for generating a regional or national picture when many estuaries are being considered at once, because the database permits ranking of little known systems and uniform comparisons between systems for which there are lots of information (e.g., numerical models, survey and monitoring data) versus those in remote areas where the only data is that in the EEC database. While assumptions have to be made and surrogates used for some variables and other variables may have to be weighted, the ease with which the classification can be rerun to generate new maps means that useful sensitivity testing can be undertaken and answers to new questions can be generated as the issues and scenarios are debated. Finally, we emphasize that as an *a priori* classification, the results remain a 'hypothesis' about differences and similarities among estuaries until tested. Complete testing of such a classification is unlikely to be performed as a single study. This means that the conceptual model becomes part of the assumptions that underlie any assessment that uses the EEC as a spatial framework. Users of the classification need to carefully consider the validity of these assumptions in the context of their particular assessment.

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