CLUES Estuary – a tool for predicting estuary water quality

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Abstract
CLUES Estuary is a GIS-based tool for predicting nutrient concentrations in New Zealand estuaries. It incorporates predictions of nutrient loads from catchments with simple dilution models to determine the mixing between ocean- and river- water in the estuaries. The tool currently gives a single time- and space- averaged concentration as a function of mean flow and nutrient input, with the capability to include seasonal nutrient and flow differences. Future developments will enable some spatial variability to be incorporated for estuaries where spatial dilution distributions have been obtained. The tool has the potential to offer a relative comparison between different land-use scenarios (via the functionality of CLUES), and to identify estuaries likely to be highly sensitive to current nutrient loads based on their physical attributes (risk assessment).

Keywords: estuaries, water quality, nutrient loads, land-use change

1. Introduction

Estuaries are transitional water bodies between rivers and the sea and their ecological states are influenced by both catchment and oceanic processes. Changes in nutrient and sediment loads caused by land-use modification in the catchment may have significant effects in the estuaries into which catchments drain. A prediction of the resulting estuarine nutrient concentrations can provide a useful indicator as to how the estuary might respond as a result of these changes.

Estuaries have many forms. Hume et al [1] present a classification system for New Zealand estuaries that categorises estuaries into 8 classes based on physical parameters such as tidal prism, estuary volume, river flow, mouth closure index, and shape. Their classification includes a diverse range of estuaries including coastal lakes, tidal river mouths, tidal lagoons, coastal embayments, fjords and sounds. These different classes of estuaries will exhibit a range of hydrodynamic processes, including stratification, tidal exchange and mixing. For example, coastal lakes are essentially closed to the sea with no tidal exchange. Tidal lagoons may be vertically well mixed, while fjords and river mouths may be strongly stratified. Thus, the importance of each process varies between estuary classes, and may also vary between two estuaries of the same class.

While a large number of factors affect how an estuary might respond to changes in nutrient inputs (for example, depth, water clarity, extent of intertidal areas), one of the key parameters that determine to what degree concentrations of nutrients in the estuary will change is the amount of dilution occurring between the riverine and oceanic water sources.

Sophisticated computational models can be applied to simulate the flow in such systems in order to predict in-estuary nutrient concentrations, but these models require considerable input data, computational time, and modeller time. In many cases simple models can be used to capture the behaviour of an estuary sufficiently to enable assessments of the likely magnitudes of any changes in nutrient concentrations within an estuary [2].

In this project, we develop a tool to predict nutrient concentrations within a wide range of estuaries based on calculations of dilution within the estuaries. This tool is intended to be used primarily to determine the likely sensitivity of an estuary to changes in nutrient input. As will be described below, the tool is based on simple models and uses only limited input parameters for each estuary. This makes the tool applicable for regional or national comparisons between estuaries and as a screening tool, but with the expectation that more detailed and sophisticated studies be conducted where significant management decisions are to be made.

The tool consists of an estuary dilution module that is embedded within CLUES (Catchment Land Use for Environmental Sustainability model) [3, 4]. CLUES is a GIS based modelling system which assesses the effects of land use change on water quality and socio-economic indicators. While the estuary module is intended to be run inside of CLUES, it can also be used in a stand-alone approach. In this paper we describe the components of the estuary module, describe the inputs used, and illustrate its use.

2. Estuary models

2.1 Dilution factor

The dilution factor D is the ratio by which freshwater is diluted by sea water within the estuary. For example, a dilution of D = 100 means that proportion of freshwater within the estuary will be $1/D$ = 0.01. Estuaries with high dilution values would be expected to have high salinities, while estuaries with no dilution (some coastal lakes) would have a dilution of 1.

The dilution factor can be used to estimate the resulting estuarine concentration of a tracer as follows

$$C = \frac{C_R + C_O(D-1)}{D} \qquad (1)$$

where C = concentration in the estuary, C_R = concentration in the inflow, and C_O = concentration in the ocean.

Salinity can be used as a tracer, and provides a means by which dilution can be estimated from field data (alternatively salinity can be predicted if dilution is calculated by another method). Using C_R = 0, $C_O = S_O$ (ocean salinity) then the dilution factor can be estimated from the time and space-averaged estuary salinity S as

$$D = \frac{S_O}{S_O - S} \qquad (2)$$

2.2 Model types

Three models are used to derive a steady state, spatially and temporally averaged dilution factor for an estuary. The choice of which model is used depends on physical parameters of the estuary, as will be described later.

2.2.1 Simple tidal prism

The simple tidal prism model is a very basic approach for estimating dilution. The estuary is assumed to be fully mixed, that entrainment and therefore estuarine circulation is negligible, and that no outgoing flow returns to the estuary. In essence, this approach treats the tidal exchange as a continuous inflow and outflow. Dilution is calculated as:

$$D = \frac{Q_F T + P}{Q_F T} \qquad (3)$$

where Q_F = freshwater inflow ($m^3\ s^{-1}$), T = tidal period (generally 12.42 hr = 44712 s), and P = volume of the tidal prism (m^3).

2.2.2 Luketina tidal prism

Luketina [5] noted several flaws in the development of the simple tidal prism model, and derived a more theoretically correct model. This model allows for differences in the duration of the flood and ebb tides (the duration of the ebb tide increases as river flow increases), and also incorporates a return flow factor b, which accounts for the portion of the water entering the estuary from the ocean on the flood tide consisting of water that flowed out of the estuary on the previous ebb tide. The return flow reduces dilution within an estuary.

Luketina gives equations for salinity, which we convert to a dilution factor using Equation 2 to obtain

$$D = \frac{P(1-b) + \frac{Q_F T}{2}(1+b)}{Q_F T} \qquad (4)$$

A default value of b = 0.5 is used in this study. This parameter can be adjusted for individual estuaries if a better estimate is available.

A meaningful solution (i.e. $D \geq 1$) can only be obtained from Equation 4 if $P \geq ½\, Q_F T$. Where this does not occur, the simple tidal prism (Equation 3) is used instead.

2.2.3 ACExR

ACExR is a time-dependent box model of exchange and mixing processes originally developed for fjord-like systems [6]. For this application, the model represents the estuary as two horizontally uniform (mixed) layers. The model calculates the volume, thickness, salinity and temperature of each layer. The model is forced with wind stress, river discharge, surface heat flux, tide and boundary conditions of oceanic salinity and temperature profiles. The estuary is assumed to have a fixed total volume and tides treated as a constant inflow/outflow from the lower layer. The freshwater inflows are added to the upper layer, and the outflow from this layer consists of the inflow plus water entrained from the lower layer via the estuarine circulation process.

The original ACExR model is simplified in CLUES-estuary because the input data are generally limited. A simplified hypsography is used derived from the volume of the estuary at high and low tide, assuming that the estuary (in cross-section) is the shape of an elongated inverted triangle. The original model also has third layer of deeper water for systems with sills. For the CLUES-estuary tool, ACExR is run for a 28 day period to obtain a steady state solution for salinity, from which an estuary-averaged dilution factor is calculated.

It is simple to calculate dilution values from the tidal prism and Luketina models. However, running ACExR each time an output is required is time consuming. To reduce the computation time each time CLUES-estuary is run with different flows, a regression between inflow and dilution is pre-calculated for each estuary by running the ACExR model at a range of flows. The regression equation is used when the ACExR model is selected by CLUES-estuary.

2.3 Model inputs

Default values for tidal prism and volume for each New Zealand estuary are obtained from a New Zealand coastal classification database known as Coastal Explorer. This database is built on data from a variety of sources including 1:50,000 topographic maps, aerial photographs, RNZN hydrographic charts and various reports and publications [1]. The most important parameters from this database for this application are the estuary volume and tidal prism (or tidal range and surface area at high and low tides).

Freshwater inflows are obtained either from values in the coastal database or output from running CLUES for the catchments contributing to each estuary. User-input flow values are also permitted to test different scenarios. All estuary models use constant inflow values only.

Riverine nutrient loads (such as total phosphorus and total nitrogen) are obtained from CLUES. The values from CLUES are annual averages. These are converted to concentrations (g m^{-3}). Alternatively user-select values can be used.

Oceanic boundary conditions for nutrient concentrations, and salinity and temperature for the ACExR model are taken from the CARS2009 climatology [7]. Wind forcing for ACExR are obtained from the nearest of 18 meteorological stations using hourly wind speed and direction from the year 2008.

2.4 Model selection

The choice of which model to use to calculate estuary dilution is based on an assessment of the physical parameters of each estuary. The process follows the following steps:

1. If the estuary is a coastal lake and normally closed to the sea (i.e. the tidal prism P = 0), then a dilution of D = 1 is used. We assume in this case that any inflow from the ocean is negligible and ignore any losses to evaporation. The coastal lake is assumed to consist of primarily riverine water. This a worst case assumption.
2. If the estuary is deep, such as a fjord, then the estuary is likely to be stratified. The ACExR model is appropriate for such systems. A value of P/V < 0.09 [1] is used to define a deep estuary, where V is the volume at mid-tide.
3. An estuary is likely to be well mixed when the volume of freshwater entering the estuary over a tidal period is less than 10% of the tidal prism [5]. The Luketina model used if $Q_R T/P \leq 0.1$.
4. If the ratio of freshwater to tidal prism is higher than 0.1 but the estuary is shallow, then the estuary is still likely to be well mixed. The estuary is considered shallow if P/V >1. The Luketina model is used in this case.
5. If the estuary is of intermediate depth (0.09<P/V<1) but is likely to be partially mixed based on the ratio of the freshwater inflow to tidal prism ($Q_R T/P$<0.25) then the Luketina model is used. Otherwise the estuary is not likely to be well mixed and an estuarine circulation is likely. For these estuaries ACExR is used.
6. If the Luketina or ACExR models do not provide a solution for the selected estuary, then the simple tidal prism model provides a default dilution value.

This process is illustrated in diagrammatic form in Figure 2-1.

3. Application and results

3.1 Dilution factors

Dilution factors have been calculated for 443 New Zealand estuaries using annual mean flows from CLUES. A breakdown of which model provides the

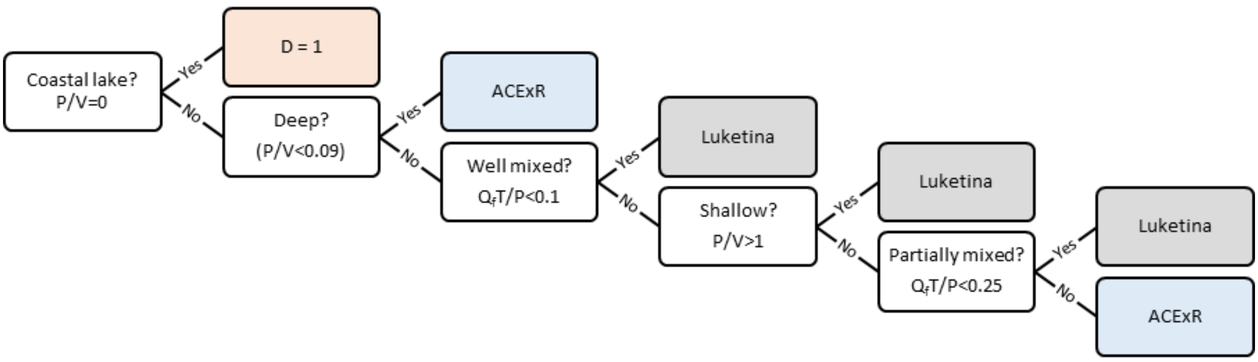

Figure 2-1 Decision tree for selecting the model to calculate the estuary dilution factor D. The choice of model is determined from the physical parameters of estuary volume V, tidal prism P and the freshwater inflow Q_f over a tidal period T. If the selected model does not provide a solution, then the simple tidal prism model (Equation 3) is used as a default.

dilution value for each estuary according to estuary type is shown in Figure 3-1. The Luketina model provides the dilution for the majority of estuaries, while ACExR is used only for estuaries likely to be strongly stratified such as fjords, some sounds, tidal river mouths, and very few tidal river lagoons, coastal embayments or lagoons. The simple tidal prism model is used for coastal lakes, although *D*=1 for these estuaries as there is no tidal prism. The other instances where the tidal prism has been used are for estuaries where the freshwater inflow is too large relative to the tidal prism to obtain a solution from the Luketina model as described previously.

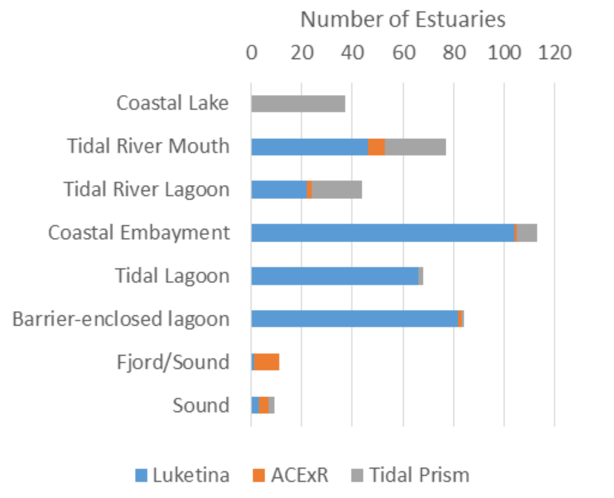

Figure 3-1 Breakdown of model providing the dilution value by estuary type. The Luketina model is used for the majority of estuaries. ACExR is mostly used for strongly stratified estuaries such as fjords, while the tidal prism is used as a default when other models do not provide a solution

Figure 3-2 shows dilution factors for the 443 New Zealand estuaries plotted against estuary volume. The data points are coloured to indicate estuary type, which is based on the classification according to [1]. There is considerable spread in dilution between estuaries of similar size and also between estuaries of the same type.

There is some indication that dilution increases with estuary size, and that certain estuary types have lower dilution. Table 1 gives the mean dilution values for each estuary type. Note that mean dilutions have been calculated from the dilution fraction (1/*D*) to reduce the tendency of high dilution values skewing the averages. Coastal lakes, tidal river lagoons and tidal river mouths generally have low dilution compared to coastal embayments, fjords and sounds. Tidal lagoons and barrier-enclosed lagoons have on average intermediate dilution values. This indicates that we might expect coastal lakes, tidal river mouths and tidal river lagoons to be much more sensitive to increased nutrient loads than coastal embayments, fjords and sounds.

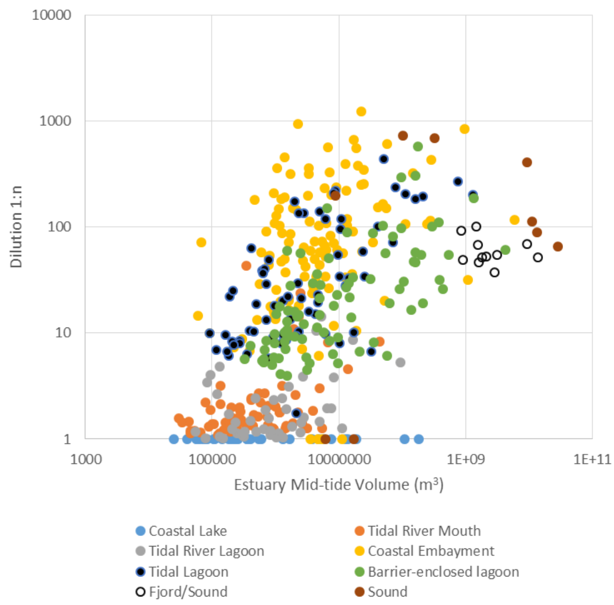

Figure 3-2 Dilution factors for 443 New Zealand Estuaries. Values are coloured by estuary type and plotted against estuary volume. Dilution is a function of both estuary type and size.

Table 1 Mean dilution factors by estuary type. The estuary categories are based on [1], while the name used for estuary type is adapted from the same source. Coastal lakes, tidal river mouths and tidal river lagoons generally have low dilution while coastal embayments, fjords and sounds have high dilution.

Category	Estuary Type	Mean Dilution
A	Coastal Lake	1
B	Tidal River Mouth	1.67
C	Tidal River Lagoon	1.61
D	Coastal Embayment	38.7
E	Tidal Lagoon	14.9
F	Barrier-enclosed Lagoon	12.6
G	Fjord/Sound	56.4
H	Sound	153

3.2 Prediction of estuary nitrate concentrations

CLUES gives predictions of total nitrogen loads (kg/yr). However, regressions can be used to estimate the fractions of total nitrogen that will in the form of NO_3-N, NH_4-N or organic-N [8]. The CLUES-estuary tool has been applied on a national basis using these to predict nitrate loads. Figure 3-3 shows the CLUES-estuary predictions of nitrate concentrations for the majority of New Zealand estuaries.

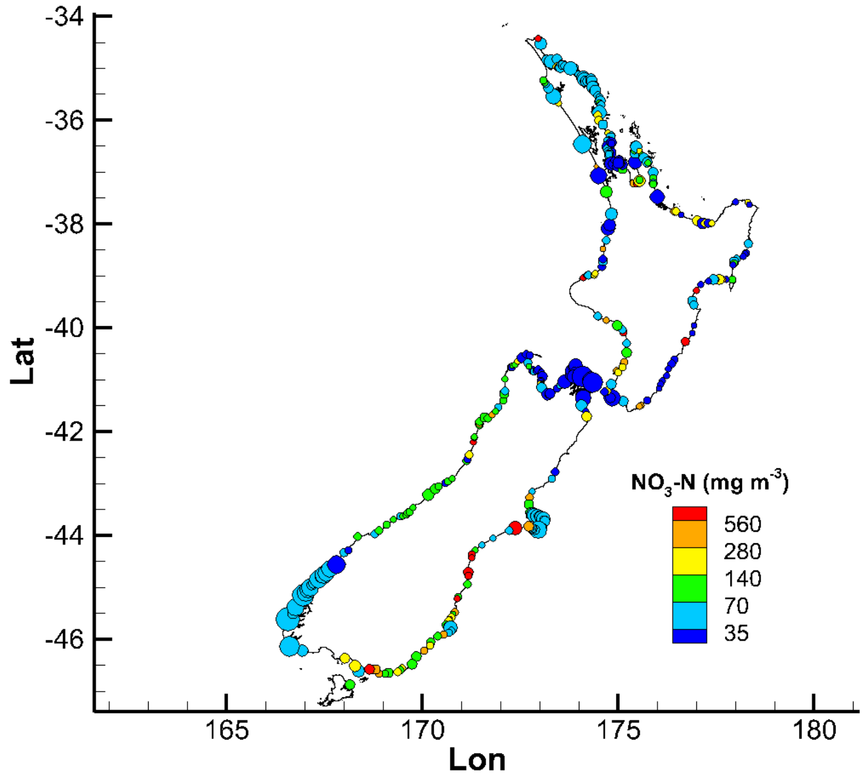

Figure 3-3 Preliminary predictions of total nitrogen concentrations for all NZ estuaries. The colour of each circle indicates the predicted total nitrogen concentration while the size is relative to estuary volume.

4. Discussion

There are important caveats associated with the nitrate predictions in Figure 3-3. Firstly, the predictions have not been validated. The number of estuaries for which nutrient monitoring is regularly undertaken is not presently known. The authors estimate that nutrient data have been collected in perhaps 50-70 estuaries throughout New Zealand. This also however illustrates the potential usefulness of the tool in that it predicts nutrient concentrations for estuaries where there are no data.

The model predictions do not account for any in-estuary processes, such as uptake by plants or denitrification of nutrients. They consequently give a representation of the 'potential' nutrient concentration, which should not necessarily be expected to reflect measured concentrations. However, it can be argued that potential nutrient concentrations are the most important to know, because they reflect the nutrient levels being supplied to primary producers, prior to uptake.

From preliminary observation (Figure 3-3), there are a number of estuaries where predicted nitrogen concentrations appear higher than might be anticipated. These could be caused either by errors in CLUES inputs, or in Coastal Explorer which can be examined on a case-by-case basis.

Once satisfactory confidence in input parameters is reached, we believe that CLUES-estuary has high potential to act as a valuable screening tool to signify estuaries where further ecological assessment should be made or where monitoring should be focussed.

The CLUES-estuary tool gives a time- and space-averaged prediction based on predicted mean annual flows and annual nitrogen loads. Field monitoring data give a snapshot of conditions at the time and location the samples were collected, which can impose an aliased view of the true average. Thus, sufficient, carefully collected field data will be required to obtain a meaningful average that can be used for comparison.

Currently CLUES gives only annual nutrient loads and flows. Work is underway to seasonalise CLUES predictions. This will enable more accurate predictions of periods of concern such as summer periods when algal growth is likely to be nutrient limited, making it more imperative to get good estimates of potential concentrations. The underlying estuary models are not suitable for dynamic (flow varying) simulations. However, it is possible to manually change inflows and nutrient inputs to test different scenarios.

Many estuaries including some coastal lakes and lagoons have mouths that intermittently open and close to the sea. Others may have openings that vary in width over time. Currently the only mechanism for considering the influence of these processes is via manually altering the tidal prism when running the estuary module.

Nutrient concentrations will vary throughout an estuary, particularly with distance from the mouth. Furthermore, all inflows are combined into a single freshwater source. In reality, the location where a river enters an estuary may have important implications for nutrient concentrations. Consequently parts of an estuary may be more susceptible to changes in nutrient concentrations. A major limitation of the estuary models currently incorporated in CLUES-estuary is that they return only a single value representing the entire estuary. There are a small number of estuaries where either sufficient data have been gathered, or for which hydrodynamic models have been developed, to enable calculation of spatially varying dilution factors. While the number of estuaries that have had dynamic models developed is small, they do tend to be ‘important’ systems (e.g., Kaipara Harbour). These will eventually be incorporated into CLUES-estuary by subdividing estuaries into segments with functions relating inflow to the concentrations of tracers from various sources. The intent is to replace the simple estuary models with more accurate predictions as these become available.

While its predictions of nutrient concentrations are not spatially resolved within-estuary, it is notable that CLUES estuary provides ‘added value’ beyond its calculations of average nutrient concentrations. For example, its graphical interface provides useful ‘data organising and display’ functionality by displaying all river terminal reach loadings and nutrient species breakdowns for each estuary in the database. Where such loadings enter a highly indented segment of an estuary (with potentially low flushing), they may flag that area as requiring further investigation.

Comparable approaches have been used to develop predictors of ecosystem state in New South Wales, Australia [2] using a suite of empirical models. The CLUES-estuary tool is a step in developing a similar tool for New Zealand estuaries that can applied to a wide range of estuary types.

5. Conclusion

A tool for predicting the effect of catchment land-use change on estuary nutrient concentrations has been developed. This tool currently gives predictions for most estuaries in New Zealand, although further validation work is required. Nutrient loads and flows into the estuary are predicted by a GIS-based model, and simple dilution models used to determine the mixing between ocean- and river- water in the estuaries. The tool gives a single time- and space- averaged concentration as a function of mean flow and nutrient input, however future developments will enable some spatial variability to be incorporated for estuaries where spatial dilution distributions have been obtained. While the tool is not expected to give predictions of a high accuracy, it has potential to offer a relative comparison (screening) between different land-use scenarios (via the functionality of CLUES), and to identify estuaries likely to be highly sensitive to current nutrient loads based on their physical attributes.

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