Ecosystem Modelling, a Tool for Sustainable Regional Development

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EXTENDED ABSTRACT

Governments and resource managers have generally accepted the importance of active and effective management of aquatic resources. This has lead many governments to adopt policies of sustainable ecosystem-based resource management within their jurisdictions, which has motivated the development of a diverse range of scientific tools. One of the tools being utilised is the ecosystem model Atlantis (Fulton and Smith 2004). This paper describes the development and application of Atlantis as a tool for exploring scenarios (e.g. changing climate) and evaluating management strategies for achieving conservation goals or sustainable use of natural resources (e.g. spatial zoning).

Atlantis is a whole-of-ecosystem modelling framework that allows multiple alternative submodels to be used to represent biophysical processes, relevant human activities, and adaptive management processes for regional marine ecosystems.

While Atlantis has been applied to a significant number of continental shelf and offshore regional systems, coastal applications have been restricted to two major bays in Victoria (Port Phillip Bay and Westernport Bay). Our presentation will focus on progress in applying the model to a large estuarine system (see Figure 1), where freshwater and other inputs from a largely agricultural catchment play a key role in the dynamics.

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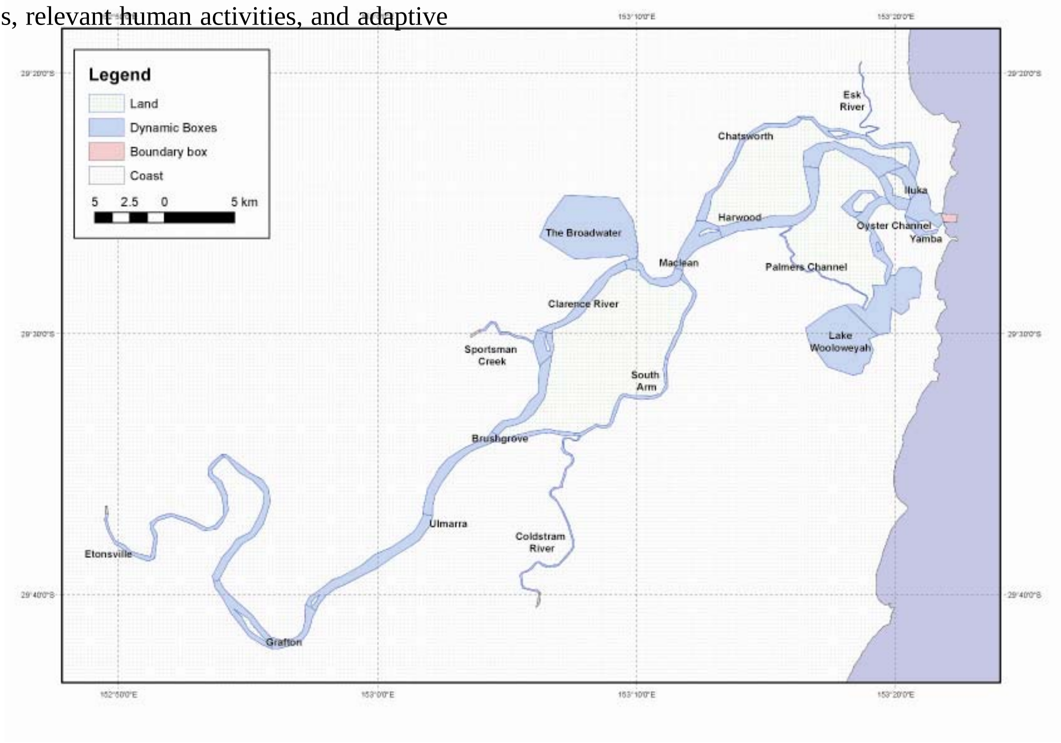


Figure 1. The polygonal box structure of the Clarence River Estuary model.

INTRODUCTION

Governments and resource managers have generally accepted the importance of active and effective management of aquatic resources. This has lead many governments to adopt policies of sustainable ecosystem-based resource management within their jurisdictions. A key prerequisite for the development of such management practices is an in depth understanding of ecosystem components and processes. The development of a quantitative ecosystem model provides not only the specific outputs of the model, but through its inception provides a formal framework for the development of ecosystem understanding.

The Atlantis model (Fulton and Smith 2004) is a whole of ecosystem deterministic modelling framework incorporating physical, biogeochemical, and trophic level components and processes. The model includes a deterministic sector model that emulates the effects of fisheries and other human activities on the ecosystem, a sampling model that collects data from the ecosystem and sector models and calculates indicators; and a management model that regulates the sector model. The Atlantis model is flexible enough to allow the model to be initiated using limited trophic groups and using selected sub models. This paper describes the development of a lower trophic level model which incorporates nitrogen, phytoplankton and Zooplankton (NPZ). The development of this simple model facilitated the validation of the flows for this first application of the Atlantis model to a estuary system.

The Clarence River is located on the coast of northern New South Wales and is one of the largest catchments on the east coast of Australia covering an area of 20,000 km^2, characterised by a large floodplain containing multiple river channels and two large coastal lakes. The region contains a number of towns that support a wide range of activities including grazing, cultivation, forestry, fishing, aquaculture and urban developments.

The development of land use in the catchment have resulted in a range of issues emerging along the NSW coast including;

- Impacts of land-use on water quality and other non-point source pollutants.
- Impacts of land-use on coastal habitat including fragmentation due to development, dredging and other sediment related issues, and effects of break-walls on coastal geomorphology.
- Impacts of land-use on recreational and commercial fisheries including flow rates, water quality, and acid-sulfate soils.
- Impacts of point-source contaminants including sewage treatment plants and industrial wastes.
- Impacts of shipping including dredging, spills, and introduced pests.
- Impacts on marine biota and habitats from multi-sector and multi-species commercial fisheries and recreational angling, including non-sustainable harvesting, bycatch, seafloor disturbance, and translocation of aquatic pests.
- Impacts of the incremental establishment of a system of marine reserves, fishing closures, and other conservation measures.

There is also significant potential for many of these impacts to interact and accumulate, potentially leading to entirely unforseen consequences.

The aim of this work is to develop and apply models of the ecosystem and human activities for the Clarence river estuary including

- impacts of estuarine fisheries (prawn trawling, recreational fishing);
- impacts of changing land-use (grazing, sugarcane, aquaculture, residential);
- impacts of increased freshwater extraction; and
- impacts of climate change.

We have chosen a framework that is suitable for evaluating management strategies across a range of sectors including the design and evaluation of potential monitoring programs for these systems to underpin ecosystem-based management.

This paper outlines the first stage of the model development, an NPZ model where we look at 3 scenarios, a repeat history, and low and high flood events.

1. METHODS

An NPZ model was developed exploring the relationship between dissolved inorganic and organic nitrogen, Phytoplankton zooplankton and detritus using the Atlantis modelling framework Fulton and Smith (2004).

1.1. Spatial and temporal representation

The model domain starts at the junction of the Clarence and Orara Rivers (upstream of Grafton) and extends to the mouth of the estuary including the main channel, other major channels, such as South Arm and North Arm, major lakes, such as The Broadwater and Lake Wooloweyah and tributaries of interest, such as Sportsmans Creek, Coldstream Creek and the Esk River.

This system was divided into a total of 37 polygonal boxes, each extending over the full water depth (Figure 1). A single sediment layer was also included at the base of each box. Five of the polygons were boundary boxes, where conditions were specified as forcing time-series rather than being calculated dynamically. The distribution of the remaining boxes was designed to resolve gross differences in benthic, pelagic and riparian habitats, such as might be found between large and small channels, lakes, and differing salinity and tidal regimes.

The model time-step was one day, which was considered adequate to resolve variability in river flow and biogeochemical cycling. While the semidiurnal tides were not explicitly resolved, their net impact on mixing along the estuary was represented (see discussion below). Biological processes in the model, such as primary production, were also represented as daily averages. This was consistent with the limited vertical resolution, which was not designed to resolve processes, such as diurnal vertical migration.

1.2. Physical and chemical components

Water temperatures were represented by the mean seasonal cycle, however salinity in the estuary is strongly dependent on the quantity of freshwater flowing into the system. For example, during dry periods brackish water can reach as high as Grafton, while under flood conditions freshwater extends all the way to the mouth. Salinity was therefore estimated dynamically, with freshwater carried downstream by river flow and mixing with seawater carried upstream by the tides.

Approximately 80% of the freshwater entering the Clarence system comes from the upper Clarence and Orara Rivers, which join at the western end of the model. There are long-term stream-flow datasets available from both of these tributaries (MHL662, 1995) and they have been combined to provide a 44 year time-series of daily freshwater flux (Figure 2). A similar record was used to specify the freshwater flux delivered via Sportsmans Creek.

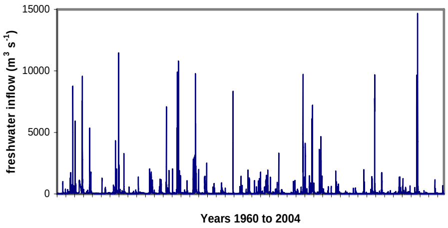


Figure 2: Combined freshwater flux from the upper Clarence (measured at Lilydale) and the Orara River (measured at the Bawden Bridge) (MHL662, 1995). The relatively high correlation (r2 = 0.70) between the two flow records allowed any data gaps in the two records to be filled (Orara flow = 0.242 x upper Clarence

Most of the other smaller tributaries have been represented by point sources draining the various sub-catchments in the region (see Figure 3). These inputs will eventually be estimated from catchment models however, for the purpose of developing this simple model, the data described above has been used for the main channel and Sportsmans Creek, and estimates made for the much smaller inputs from Coldstream Creek and the Esk River.

Each of the freshwater input sources also requires specification of nutrient and suspended sediment concentrations, and possibly even biological components such as phytoplankton and zooplankton. However, here only nutrients have been specified. Nitrate and ammonia fluxes were specified for the upmost model box of the main channel, Sportsmans Creek, ColdStream Creek and the Esk River. Flux time-series were estimated from the flow rates described above and the limited available data on nitrate and ammonia concentrations and were broadly consistent estimated annual budgets for the system (MHL971, 2000).

While the tidal component of the flow was not explicitly resolved by the daily time-step, it was critical to represent the associated upstream transport of salinity and other chemical and biological quantities. This was achieved by imposing an additional exchange between boxes that reversed direction at every time-step. Because the relatively coarse resolution of the box model already imposed an unquantified level of numerical diffusive transport, the proportionality constant was used as a tuning parameter to match the broad salinity distribution along the estuary with the limited available observations.

Figure 3. Major sub-catchments of the Clarence River Estuary.

1.3. Scenarios

A standard historical scenario has been developed based on the most realistic achievable representation of recent historical trends in the estuary. The total period of the run was 1951 to 2003 inclusive, although the first 10 years were designed to allow the model to adjust from (often highly uncertain) initial conditions towards a more dynamically balanced state.

The initial focus has been on climate related scenarios that consider the sensitivity of the system to rainfall and freshwater inputs. However, these same scenarios could alternatively represent differing policies on freshwater extraction from the system as summarised in Table 2..

Table 2: Scenarios based on freshwater inputs into the system.

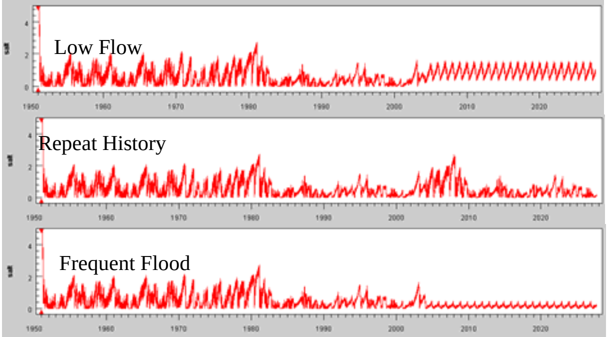
Scenario name	Scenario specification 1951-2003	Scenario specification 2003-2030	Climate scenario	Freshwater extraction scenario
Low flow	Historical flows	An historical year of anomalously low flow (2002) repeated every year	Reduced rainfall in the Clarence catchment	Dams in the catchment with large-scale diversion to other uses
Repeat history	Historical flows	Repeat of flows from the previous 27 year period (i.e. 1977-2003)	Rainfall similar to the recent past	Freshwater extraction similar to the recent past
Frequent flood	Historical flows	An historical year with a high incidence of floods (2001) repeated every year	Higher frequency of extreme rainfall events (possibly associated with increased incidence of tropical cyclones off the eastern seaboard)	

2. RESULTS

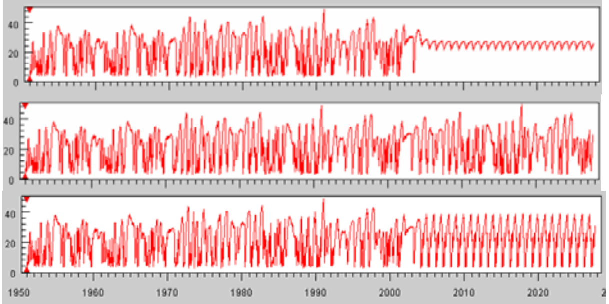
In Figure 4 the spatial distribution of key physical and biological variables are contrasted during a period of typical medium flow and the dry season, separated only by a couple of months. Under medium flow, relatively freshwater penetrates into the estuarine region (Lawrence), but then with the onset of the dry season retreats above Brushgrove as the river flow diminishes and salinities approach oceanic values inside the estuary mouth. The flushing times of the lakes are much longer than the channels and all the variables, including salinity, tend to be more stable there.

While higher flows bring more nutrients into the system, dissolved organic nitrogen generated within the system tends to get flushed out of the main channel, before rebuilding over the dry season (Fig. 4). Phytoplankton and associated chlorophyll also tend to be flushed through the main channel when flows are higher, continuing to grow until reaching the Broadwater junction where nutrients become depleted. Phytoplankton have more time to grow in the upper estuary during the dry season, but the high chlorophyll does not extend beyond Lawrence. With their relatively low growth rates, zooplankton concentrations within the channels are limited by flushing during the higher flows. This resulted in large contrasts between channels and lakes. During the dry, zooplankton took advantage of the lower flushing rates and high phytoplankton concentrations in the upper estuary.

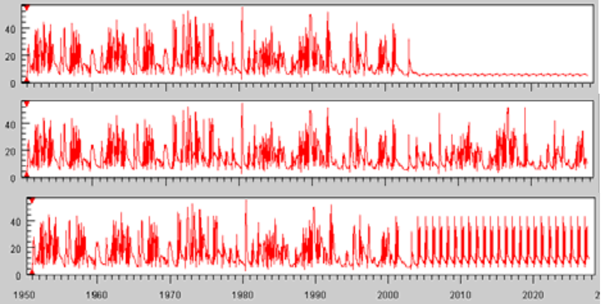
Results from the three future freshwater flow scenarios (low flow, repeat history and frequent flood) are described here in terms of time-series for the main channel of the upper estuary (Figure 5). In this region, salinities were highest under the low flow scenario, but remained within historical ranges. What is perhaps more significant is that when flows were capped, even the upper estuary was rarely fresh. The main forms of biologically available nitrogen (dissolved organic nitrogen (Figure 4), nitrate and ammonia) tended to follow the freshwater input signal and phytoplankton (and its chlorophyll surrogate) responded by increasing during periods of high flow. It is likely that turbidity levels were underestimated during flood events, so that chlorophyll levels were over estimated. The zooplankton response followed the phytoplankton, but at each higher trophic there was less variability due to their slower response times. At the level of carnivorous zooplankton,



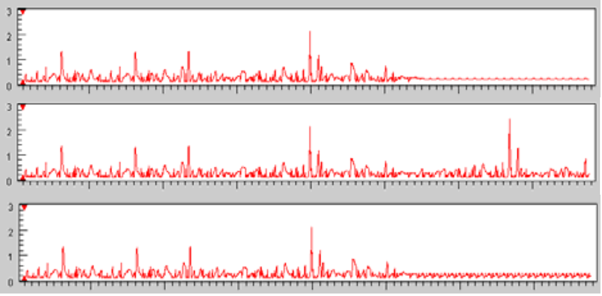
Salinty



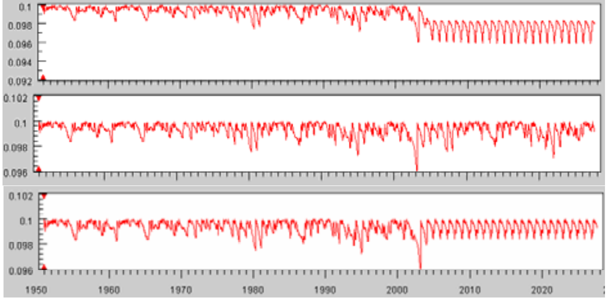
Dissolved organic nitrogen



Chlorophyll *a*



Micro-zooplankton



Carnivorous zooplankton

Figure 5. Model time-series results from a box in the main channel of the upper Clarence River Estuary Salinity is expressed in practical salinity units and other variables as biomasses in units of mg N m^{-3}

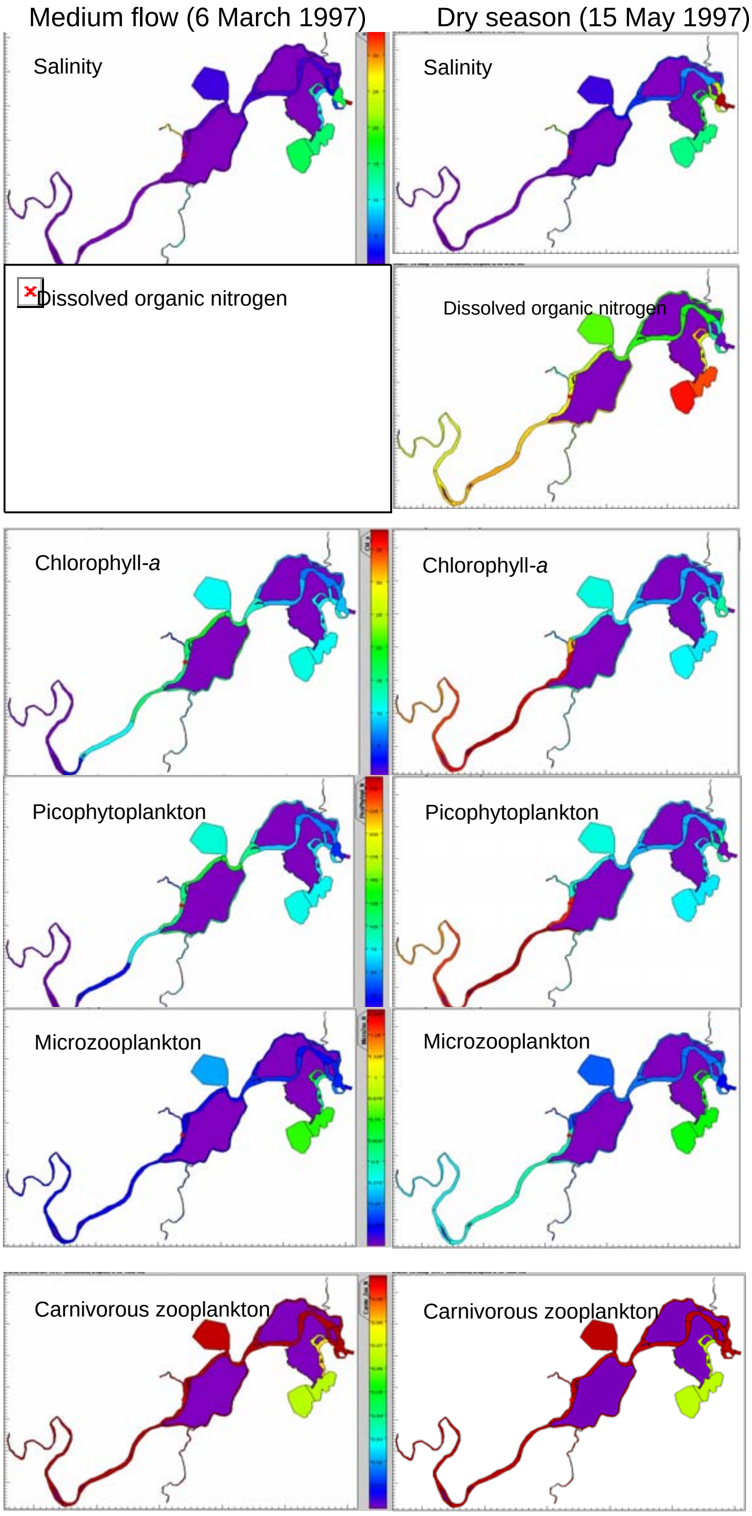


Figure 4: Snapshots of the distribution of physical and biological variables during a wet period (left) and a dry period (right) in the autumn

differences in biomasses between the three scenarios was typically only a few percent.

In the main channel of the lower estuary, salinities could approach 20 psu and remained high under the low flow scenario organic nitrogen levels were comparable to the upper estuary, but lower levels of nitrate and ammonia reflected biological uptake. However, this was compensated by lower turbidity to produce slightly higher chlorophyll and phytoplankton biomass levels downstream. Under repeated history or frequent floods, zooplankton levels are very similar to those upstream. However, under low flows carnivorous zooplankton decline by approximately 20% over the period. This may have potential implications for higher trophic groups such as prawns.

Looking at the system as a whole, the total nutrients are lower in the low flow scenario and the total phytoplankton biomass is approximately 20% lower than under the regular flood scenarios (not shown). However, the micro-zooplankton biomass is very similar in both cases. While micro-zooplankton have less food available under low flow conditions, they also experience less predation due to a 15% decline in carnivorous zooplankton under these conditions. With less phytoplankton in the system, there is also less detritus. This may be the underlying cause of the decline in carnivorous zooplankton (which also feed on labile detritus) under low flows.

3. DISCUSSION

In order to implement effective ecosystem based management it is vital that there is a clear understanding of the elements and processes that make up the ecosystem. This usually takes the form of a model describing the ecosystem elements and processes and how they influence each other. This paper has described the development of a simple NPZ ecosystem model for the Clarence river estuary. Whereas the ultimate goal is to develop a fully fledged model that will aid managers implement whole of ecosystem based management. The development process thus far has had positive outcomes;

1. illustrated, to managers and policy makers, the capabilities of the simple ecosystems model that can be developed in a short timeframe using limited resources.
2. provided a framework for the development of the flows and other physical elements of the model, which will form the bases for the development of a more sophisticated model.
3. Through examining 3 climate scenarios we have highlighted some simple relationships within the ecosystem (see below).

We are now in a position to further develop this ecosystem model as a tool to assist in ecosystem based management with all interested parties having a clear understanding of the model development process including data and resource requirements.

The preliminary conclusions of the Clarence River Estuary modelling can be summarised as follows:

- Flow rates have a significant impact nutrient cycling and productivity in the Clarence system.
- Reductions in freshwater inputs into the estuary (through changes in rainfall or freshwater extraction higher in the catchment) tend to result in a less productive system, with potential flow-on effects for higher trophic levels.
- The dynamics of the lakes are significantly different from the main channel and tend to be less sensitive to changes in freshwater inputs.
- The development of a simple model facilitates the development of a longer term work plan for a ecosystem model that is suitable for be use as a tool in ecosystem based management.

4. REFERECES

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