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Highs and lows: The effect of differently sized freshwater inflows on estuarine carbon, nitrogen, phosphorus, bacteria and chlorophyll *a* dynamics

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A B S T R A C T

Freshwater inflows play a key role in the delivery of organic carbon to estuaries. However, our understanding of the dynamics between discharge and carbon globally is limited. In this study we performed a 30-month monitoring study on the Bega and Clyde River estuaries, Australia, to understand the influence that discharge had on carbon, nitrogen, phosphorus, bacteria and chlorophyll *a* dynamics. We hypothesised that 1) discharge would be the most important factor influencing carbon and nutrient concentrations, though during low flows chlorophyll *a* would also be positively related to carbon, 2) bacteria would be related to dissolved organic carbon (DOC), and chlorophyll *a* to temperature, nitrogen and phosphorus, and 3) that concentrations of carbon, nitrogen, phosphorus, bacterial biomass and chlorophyll *a* would be significantly different between large 'flood flows', smaller 'fresh flows' and base flow conditions. We found that discharge was always the most important factor influencing carbon and nutrient concentrations, and that primary production appeared to have little influence on the variation in DOC concentration even during base flow conditions. We suggest this relationship is likely due to highly episodic discharge that occurred during the study period. Bacteria were related to DOC in the lower estuary sites, but phosphorus in the upper estuary. We suggest this is likely due to the input of bioavailable carbon in the upper estuary leading bacteria to be P limited, which changes downstream to carbon limitation as DOC becomes more refractory. Chlorophyll *a* was positively related to temperature but not nutrients, which we suggest may be due to competition with bacteria for phosphorus in the upper estuary. Carbon, nitrogen and phosphorus concentrations were different under flood, fresh and base flow conditions, though these differences sometimes varied between estuary locations for different resources. Overall, the results demonstrate that discharge plays an important structuring role for carbon, nutrient and bacteria dynamics on the Bega and Clyde Rivers, and that the differences observed between flood and fresh inflows suggest that further study into the influence of differently sized inflow events is important.

1. Introduction

Freshwater inflows play a critical role in defining estuarine functioning. Each year rivers transport, transform and store up to 1.9 pg C y^{-1}, of which around half is transported to estuaries and coasts (Cole et al., 2007). Biogeochemists have a long history of studying organic matter in aquatic ecosystems (Findlay, 2003). Despite this, as suggested by Cauwet (2002), having a precise understanding of the nature of organic carbon delivered by rivers is difficult. Part of this stems from the overwhelming complexity and dynamism of the processes involved. At the catchment scale, there are a variety of factors that influence carbon dynamics including; precipitation, land use, temperature, water regulation and dams, soil and vegetation types and geomorphology (Findlay and Sinsabaugh, 2003). When riverine carbon enters the estuary there are another set of influencing factors including; biological transformation, production of autochthonous carbon (primary production within the estuary), retention time, mixing and dilution, flocculation, adsorbtion and aggregation (Day et al., 2012).

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Essentially this means that predicting the relationship between discharge and organic carbon in a particular system is extremely difficult without long-term data that captures both temporal and spatial variability.

The majority of allochthonous carbon enters rivers, and in turn estuaries, during episodic flow events (Webster et al., 1987; Hinton et al., 1997; Raymond and Saiers, 2010; Westhorpe and Mitrovic, 2012). A number of studies have conceptualised hydrologic conditions in the rivers as 'storm flow' and 'base flow' which has been useful in demonstrating that whilst storm flow conditions only occur for short periods of time, they disproportionally account for a large portion of organic carbon exported from the catchment (Hinton et al., 1997; Buffam et al., 2001; Raymond and Saiers, 2010). Puckridge et al. (1998), whilst not specifically talking about carbon dynamics, went further separating storm flow conditions into 'flood pulses' and 'flow pulses'. Flood pulses are large flows of water that inundate floodplains and may variably occur every year or two, whereas flow pulses are smaller flow events where water does not break the banks of a channel and occur more frequently. Few studies that have approached the topic of discharge and carbon in estuaries have utilised these types of frameworks to describe conditions. Such a framework may prove a useful way of discerning the different ways that discharge influences the movement of carbon in estuaries.

Phytoplankton and bacteria both play keys roles in the carbon, nitrogen and phosphorus cycles (Lin et al., 2006). A great deal of attention has been paid to the influence of autochthonous vs. allochthonous influences on estuarine metabolism (McDowell and Asbury, 1994). It is common that carbon is more related to discharge during wet or high flow periods and related to primary production during dry or low flow periods (Ochs et al., 2010). In many systems where allochthonous inputs are small, primary production is the main source of dissolved organic carbon and in turn bacterial production is closely coupled with phytoplankton biomass or chlorophyll *a* (Cole et al., 1988). In estuaries, phytoplankton are predominantly limited by temperature and the availability of nitrogen and phosphorus (Eppley, 1972). Nutrient limitation may be relieved with freshwater inflows that bring available nitrogen and phosphorus, but conversely if inflows bring high loads of suspended sediment or coloured organic matter then primary production may be light limited (Cloern, 1987).

When allochthonous inputs are high, bacteria may become uncoupled from phytoplankton or chlorophyll *a* (Hoch and Kirchman, 1993; Ning et al., 2005). Bacteria are most regularly limited by DOC (Malone, 1977) but may also be limited by nitrogen and phosphorus and may compete with phytoplankton for nutrients (Thingstad et al., 1998). Bacteria can quickly metabolise available DOC acting as a significant carbon sink, as well as a potential link for organic matter subsidising food webs (Findlay et al., 1992). Estuaries are commonly net heterotrophic, indicating the importance of allochthonous carbon to bacterial metabolism (Fouilland and Mostajir, 2010). Understanding how discharge affects these processes has far reaching ecological implications.

Much of our knowledge about estuarine carbon, nitrogen and phosphorus dynamics derives from North American and European systems (Tank et al., 2010 and references therein). The last decade has seen increasing studies occurring outside of these regions (for example Thottathil et al., 2008; Vargas et al., 2011). In Australia the study of organic carbon in estuaries has been fairly limited (Eyre and Twigg, 1997; Ford et al., 2005; Petrone et al., 2009; Abrantes and Sheaves, 2010; Petrone, 2010; Petrone et al., 2011). Thus, there is a need to pay greater attention to Australian catchments, in particular as temperate and sub-tropical systems in Australia exhibit particularly episodic discharge and precipitation (Finlayson and McMahon, 1988).

The purpose of our study was to investigate the influence that freshwater inflows have on organic carbon and nutrient dynamics and how these dynamics change between flood, fresh and base flow conditions. We hypothesised that 1) carbon, nitrogen and phosphorus concentrations can be explained through a combination of discharge, and for DOC, chlorophyll *a* during base flows, 2) that bacteria are related to DOC concentrations and phytoplankton to temperature as well as nitrogen and phosphorus and 3) that carbon, nutrient and bacteria concentrations are highest during flood flows and chlorophyll *a* concentrations highest during fresh flows. This work was carried out on the Bega and Clyde River estuaries, which were chosen as they are situated in a region of Australia where carbon dynamics have not previously been reported. Our study took place over a 30 month period, encompassing a range of monitoring stations spanning the length of each estuary. Sampling occurred on a monthly basis, with increased frequency during and after high flow events in order to capture the full range of flow variability.

2. Materials and methods

2.1. Study sites

The Bega River estuary, NSW, Australia, (−36° 42′ 43.64″, +149° 54′ 8.76″) is a shallow, wave-dominated estuary (Fig. 1). The estuarine volume, 6371 ML, is relatively small compared to its catchment of 1941 km^2 (Roy et al., 2001). The catchment is split into two sub-catchments, the Brogo River, regulated by Brogo Dam and Bega River which has two smaller dams, Cochrane and Candello. The upper sections of the catchment consist of mainly forested areas, whilst the middle catchment is mostly cleared for agriculture, dominated by the dairy industry (Brierley et al., 1999; Tozer et al., 2010). The freshwater tidal section has been mostly cleared for agriculture and irrigated farmland, however the rest of the estuary is largely unmodified. Broad scale land clearing since colonisation has drastically altered the river and estuary via the transportation of sandy top soils into the river channel (Brooks and Brierley, 1997). Mean annual rainfall is 605 mm (1994–2014) and was above average between 2010 and 2012 with a mean of 862 mm per year.

The Clyde River estuary, NSW, Australia, (−35° 33′ 11.44″, +150° 11′ 12.11″) is a tidally dominated estuary (Fig. 1). Its estuary volume, 50,737 ML is relatively large compared to its catchment size, 1791 km^2 (Roy et al., 2001). The river is unregulated, with no significant structures or water extraction. The catchment is almost entirely forested, with some forestry activities in the upper catchment. The lower sections of the estuary have a small urban settlement as well as oyster and other fisheries activities (Tozer et al., 2010). Average rainfall is 889 mm (1991–2014) and was above average between 2010 and 2012 with a mean of 1027 mm.

On each estuary five monitoring stations were sampled encompassing the length of the estuary (Fig. 1). Salinity ranged from 0 (at station 1) to 35 (at station 5) on the practical salinity scale.

2.2. Discharge and flow classification

Discharge information was obtained from one gauging station on the Clyde River and two gauging stations on the Bega and Brogo Rivers, which were combined to give a single value for the Bega River. Discharge (m^3 s^{-1}) data presented here was calculated as a daily average flow rate. On the Bega River these gauging stations were located approximately 5 km upstream of the tidal zone and on the Clyde River the gauging station is located approximately 11 km upstream of the tidal zone. There are no tributaries located between the gauging stations and tidal zone. In order to distinguish