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Mechanisms driving estuarine water quality: A 3D biogeochemical model for informed management

Karen Wild-Allen [a,*], Jenny Skerratt [a], Jason Whitehead [b], Farhan Rizwi [a], John Parslow [a]

[a] CSIRO Marine & Atmospheric Research & Wealth from Oceans Flagship, GPO Box 1538, Hobart, Tasmania 7000, Australia
[b] Derwent Estuary Program, GPO Box 1550, Hobart, Tasmania 7001, Australia

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A B S T R A C T

Estuaries are amongst the most productive marine ecosystems of the world but are also some of the most degraded due to coastal urban development. Sparse sampling of complex interactions between estuarine physics, sediment transport, chemistry, and biology limits understanding of the processes controlling estuarine water quality and confounds active management. We use a 3D coupled hydrodynamic, sediment and biogeochemical model to identify the key mechanisms driving fine-scale fluctuations in water quality in a temperate micro-tidal salt wedge estuary [Derwent Estuary, Tasmania]. Model results are dynamically consistent with relatively sparse monitoring data collected over a seasonal cycle and are considered to be a plausible hypothesis of sub-monitoring scale processes occurring in the estuary. The model shows enhanced mixing of nutrients across the pycnocline downstream of the salt wedge front that supports a persistent phytoplankton bloom. The length and flow regime of the estuary results in nutrient recycling and retention in the estuarine circulation driving a decline in bottom water dissolved oxygen in the mid- and upper-reaches. A budget analysis of modelled nitrogen suggests high levels of denitrification are critical to the maintenance of existing water quality. Active estuarine management focused on the improvement of bottom water dissolved oxygen for ecological health reasons must either concurrently reduce anthropogenic nitrogen loads or be sure to maintain high levels of microbial denitrification for net water quality improvement.

1. Introduction

Estuaries are amongst the most productive ecosystems of the world with the transition from fresh to salt water supporting a diverse assemblage of species. About 60% of the global population now lives along coasts and estuaries, which has resulted in widespread degradation of water quality and ecology (Wollanski, 2007). Active management is a high priority that is often hampered by limited understanding of complex multidisciplinary estuarine interactions (Davis and Koop, 2006) and multiple stressors (Cloern, 2001). In this paper we use a coupled 3D hydrodynamic, sediment and biogeochemical model to elucidate fine-scale estuarine processes in a temperate anthropogenically modified estuary for informed water quality management.

Water quality is a synthesis term for assessing the physical, chemical, biological and aesthetic characteristics of a water body against reference values to determine how 'good' the water is for specific uses. In a convoluted estuary local water quality can vary considerably over short spatial and temporal scales due to the interaction of the hydrodynamic circulation with strong gradients in salinity, suspended sediment, nutrient concentrations, dissolved oxygen and plankton concentrations. External forcing from catchment run off, synoptic weather, tidal cycles and point source discharges enhances variability and confounds the interpretation of sparse observations (Tappin, 2002). In many systems the fine-scale spatial and temporal physical, chemical and biological dynamics underpinning fluctuating water quality are poorly understood (Davis and Koop, 2006). Management of specific bays or reaches is challenging and it is difficult to prioritise intervention to target specific water quality issues or quantify resulting change.

Conceptual models help to synthesis understanding and provide a basis for first order nutrient budgets of a system (e.g. Fisher et al., 1988; Azevedo et al., 2008; Robson et al., 2008) however they necessarily overlook the detail and complexity required to address local issues. More finely resolved biogeochemical models have recently been applied in coastal and estuarine systems to enhance coastal ecosystem understanding with some success (e.g. Griffin et al., 2001; Byun et al., 2007; Arndt et al., 2009, 2010;

* Corresponding author.
E-mail address: Karen.Wild-Allen@csiro.au (K. Wild-Allen).

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Timmermann et al., 2010). Validation of model results against observations is a critical step for the successful uptake of model understanding by managers (Rykiel, 1996).

In this paper we integrate a biogeochemical model with a coupled 3D hydrodynamic (Herzfeld et al., 2005) and sediment model (Margvelashvili et al., 2005) of the Derwent Estuary and validate its performance against observations. We use the model to explore the fine-scale dynamics underpinning observed variations in local water quality and hypothesise that oscillations in the halocline downstream of the salt wedge front increase vertical exchange of nutrients across stratified layers and stimulate a persistent phytoplankton bloom in the mid estuary. The model is used as a synthesising hypothesis of cross disciplinary understanding to identify key processes controlling local water quality in the estuary for informed management.

2. Study area

The Derwent Estuary, in southeast Tasmania, (Fig. 1) is a microtidal drowned river valley (Edgar et al., 2000). It is approximately 52 km long, 1–10 km wide, 5–45 m deep and bordered by the state capital city of Hobart and a mixed catchment of urban, agriculture and forest drained by the Derwent River and numerous small rivulets (Butler, 2006). The influx of fresh water results in the formation of a salt wedge with stratified estuarine circulation modified by a small (<2 m) semi-diurnal tide (Thomson and Godfrey, 1985). Urbanisation of the catchment surrounding the Derwent Estuary has contributed to declines in estuary water and sediment quality. Historical industrial discharge from a paper mill and diffuse inputs from a zinc refinery bordering the estuary has resulted in contamination of sediments throughout the region with pulp fibre (Leeming and Nichols, 1998) and elevated metals including zinc, lead and copper (Jones et al., 2003; Green and Coughanowr, 2003). Treated sewerage effluent continues to enrich nutrient concentrations throughout the estuary (Leeming and Nichols, 1998) and appears to have increased the extent of phytoplankton blooms. Since 1999 the Derwent Estuary Program (http://www.derwentestuary.org.au) has co-ordinated initiatives to reduce water pollution and monitor estuarine health including instigation of a monitoring program and collation of water quality data (e.g. Whitehead et al., 2010).

In 2004 a high resolution 3D hydrodynamic model of the Derwent Estuary (Herzfeld et al., 2005) demonstrated that the estuary has a complex circulation that varies with fresh water influx,

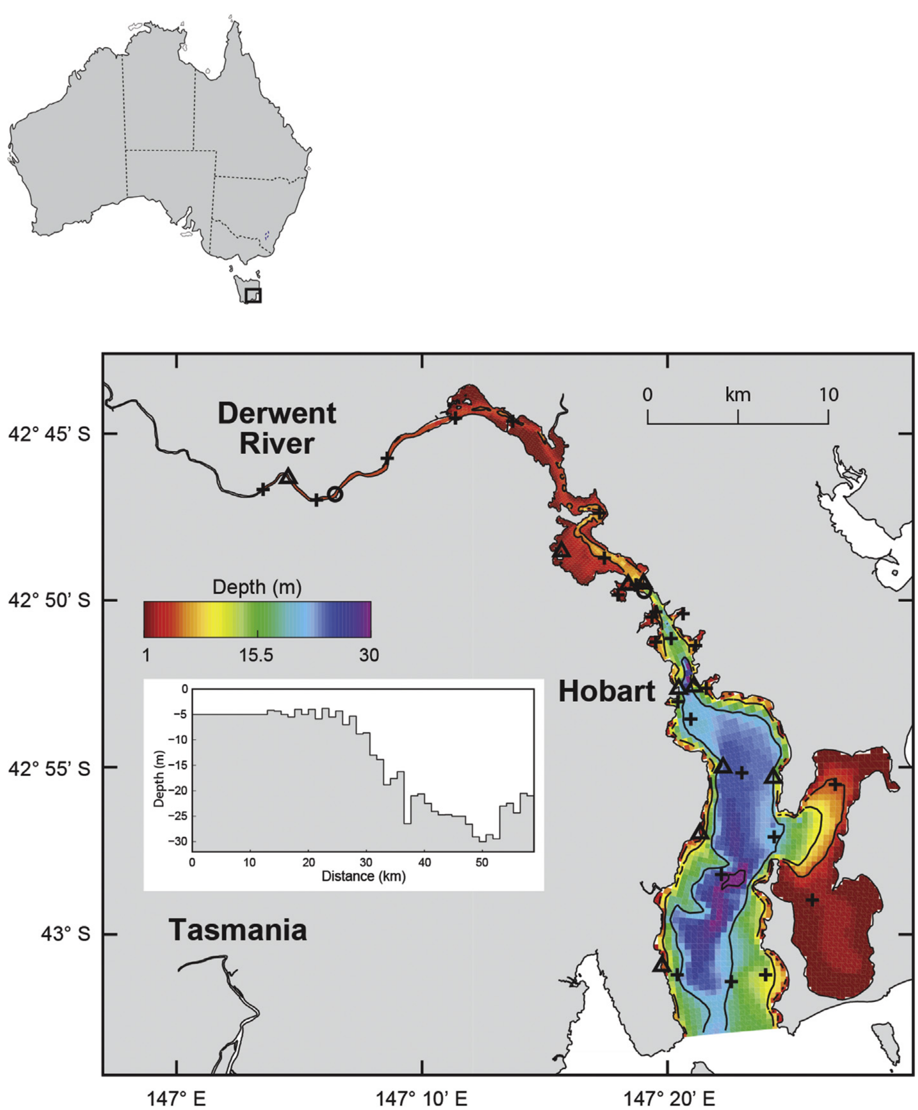

Fig. 1. Bathymetry, monthly monitoring sites (+) and wastewater (△) and industry (○) discharge locations in the Derwent Estuary, southeast Tasmania. Bathymetry cross section along the axis of the estuary inset.