Reconstruction of critical habitats within Sydney Harbour: Understanding the function of shallow embayments using ecosystem response models

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Sydney Harbour is an iconic waterway that has been highly degraded due to the cumulative impacts of foreshore reclamation, changes to freshwater inputs, industrial pollutant loads, and urban nutrient loads. The harbour is classified as a drowned river valley estuary, characterised by a deep central channel flanked by numerous shallow embayments. Early maps and paintings of the harbour dating from just after European settlement show the ends of these embayments to be fringed by low lying swamps with indistinct drainage channels. This suggests that freshwater delivery to these environments would have been dominated by groundwater seepage, and that nutrient and carbon inputs would have most likely have been largely refractory. The fringing swamps have been largely reclaimed and drainage channels replaced with urban stormwater drains, and labile nutrient and carbon inputs have increased substantially. These changes are likely to have fundamentally changed the biogeochemical and ecological function of these embayments. In this paper, we use a combination of conceptual models, biogeochemical models and experimental data to illustrate the changes in function between pre-European settlement times and the present. We argue that the rehabilitation of low lying fringing swamps adjacent to embayment ends will greatly reduce pollutant loads and enhance the ecology of the harbour.

Introduction

Estuaries are among the most productive marine ecosystems in the world, supporting a diverse array of foodwebs and commercially valuable species. This arises from the unique situation of estuaries being at the interface of freshwater runoff and coastal oceanic waters, where material (e.g. nutrients and organic matter) delivered by both freshwater and oceanic flows is processed across a wide spectrum of habitat types depending on the particular morphology of the estuary. Nutrient inputs support high rates of primary productivity in both pelagic and benthic compartments (Cloern *et al.* 2014), which in turn supports a wide variety of invertebrate, fish and bird life (Jickells 1998). Particular focus has historically been given to the productivity of phytoplankton and seagrass systems within estuaries, however in recent decades the important role of benthic microalgae (BMA) growing in soft sediment habitats has been increasingly recognised (McIntyre *et al*. 1996; Underwood & Kromkamp 1999). In many shallow Australian estuaries it has been estimated that BMA may constitute the main source of primary production supporting estuarine foodwebs.

The balance between pelagic and benthic productivity (and the food chains they support) is highly variable in time in space due to interactions among controlling factors including:

seasonal and inter-annual variability in freshwater runoff; channel morphology; and the quality and quantity of nutrients and organic matter inputs. In estuaries with smaller catchments, the nature of fringing environments is also critically important in regulating terrestrial runoff and the supply of nutrients and organic matter (OM). For example, fringing environments in many smaller estuaries along the Australian coastline are dominated by low lying swamps (e.g. saltmarsh and mangroves), where freshwater delivery is primarily via a mixture of groundwater seepage and episodic pulses of overland flow. These inputs are characterised by high concentrations of dissolved organic nutrient forms and refractory particulate OM, and tend to favour BMA productivity.

Sydney Harbour estuary is classified as a drowned river valley (Roy *et al.* 2001), characterised by a deep central channel flanked by multiple shallow embayments flanked by steep sided banks of Sydney sandstone (Figure 1). Much of scientific and public attention is focused on the ecology of sub-tidal reefs (Larkum 1986; Underwood *et al*. 1996; Byrne *et al.* 2011; Wilson *et al*. 2010) and inter-tidal rocky shores (Underwood *et al*. 2008; Matias *et al*. 2010), however a cursory inspection of harbour bathymetry shows that shallow soft sediment habitats are quantitatively important. Despite their potentially important ecological role, these habitats have primary been studied as sites of chemical contamination (Batley *et al*. 1989; Birch and Taylor 2000; McCready *et al*. 2000; Roach *et al*. 2009; Birch 2011), with relatively few studies of their ecology (Bishop 2005; Chariton *et al*. 2010; Hutchings *et al*. 2011) and even fewer describing biogeochemical processes (Chapman & Tolhurst 2007; Sutherland *et al*. 2016). They are also arguably the most impacted habitats, by the development of Sydney city, since European settlement. In this study, we use a combination of conceptual models, biogeochemical models and experimental data to illustrate the changes in function between pre-European settlement times and the present.

Changes since European settlement

Early maps and paintings of the harbour reveal insights into the likely morphology and ecology of shallow embayments (Figure 2A). A conspicuous feature shown in these maps is the presence of low lying swamps at the embayment heads drained by small tidal creeks. Most of these bays have relatively small catchments, therefore it is likely that freshwater runoff volumes were low and dominated by groundwater seepage. Since the earliest days of the colony, approximately 22% of the total 50 km^2 area of the estuary, including bay ends (Figure 2B) and adjacent low lying swamps, were progressively reclaimed for industrial, recreational and residential uses (Birch 2007; Birch *et al.* 2009). Significant sedimentation of the bays also occurred due to catchment clearing.

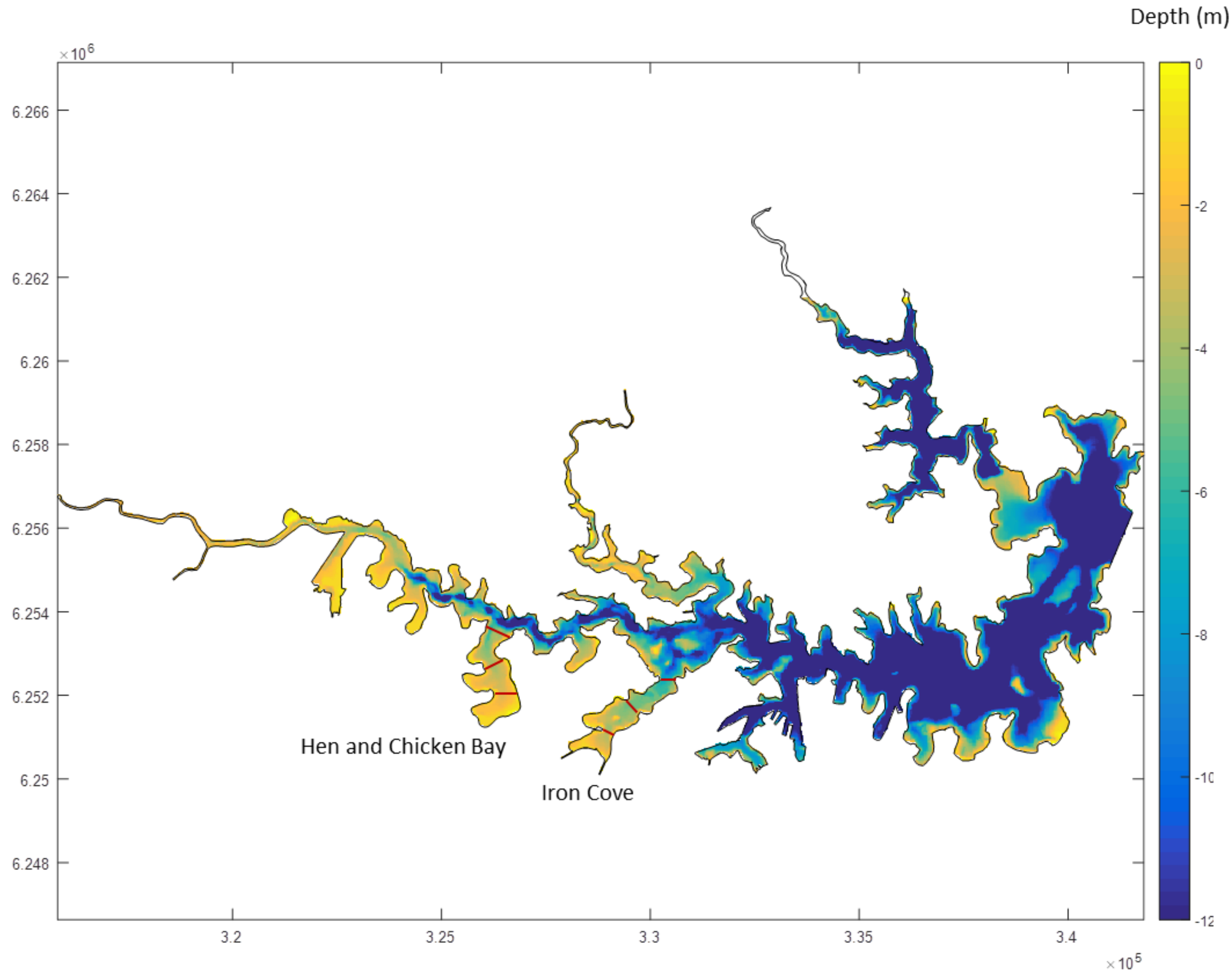

Figure 1 **Bathymetry of Sydney Harbour, showing locations of study bays. Also shown are the model box boundaries (red lines).**

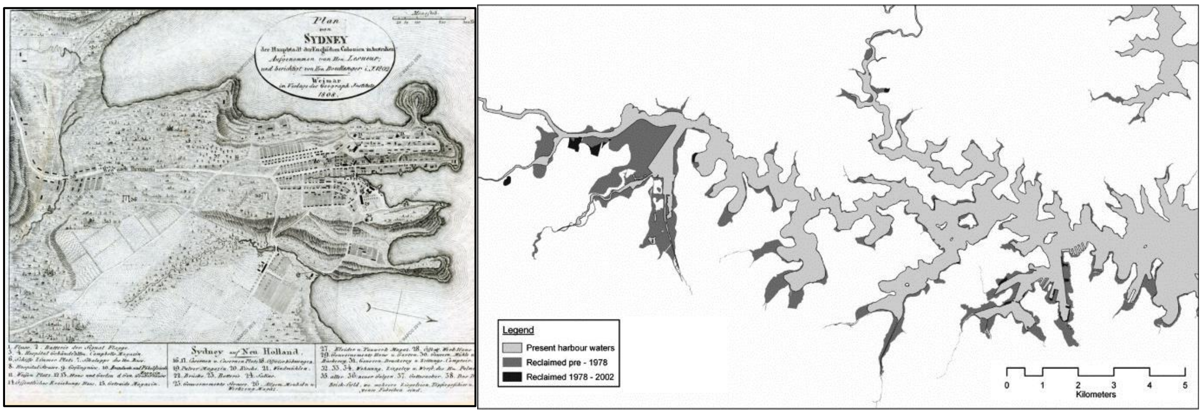

Figure 2 **A) Sydney in 1808, showing the low lying swamp environments at the head of Wooloomooloo Bay and Darling Harbour. B) The estimated areas of reclamation since European settlement (from Birch *et al.* 2009).**

At the same time, urbanistion of the bay catchments resulted in a dramatic increase in impervious surfaces and stormwater drainage channels fundamentally changing the nature of freshwater delivery to the bays (Figure 3). It is estimated that total freshwater flows to the harbour have doubled, while baseflows increased by up to five fold (CERAT). Changes to flows were coupled with a combination of industrial, urban and agricultural diffuse and point source pollution, changing the quality and quantity of nutrient and OM loads to the bays. Recent studies on the impact of stormwater on sediment biogeochemistry in Iron Cove and Hen and Chicken Bay have shown strong gradients in processes and benthic microbial communities from stormwater outlets to the central bays (Sutherland *et al.* 2016). In particular, sediment organic carbon and respiration are highly elevated adjacent to stormwater outlets and display high variability in association with runoff events.

Figure 3 Homebush Bay in 1943 showing the newly constructed stormwater channel cut through the original meandering course of Powells Creek (image from SIX Maps, NSW Department of Finance, Services and Innovation).

Modelling the impacts of urbanisation on the embayment biogeochemistry

We used a simple box model approach with a spatially resolved bathymetric grid to test the impacts of changes to freshwater delivery, nutrient supply and OM supply since European settlement. We focus on Iron Cove and Hen and Chicken Bay as major examples of Sydney Harbour embayments that were the subject of the study by Sutherland *et al.* (2016). The model uses a nutrient-phytoplankton-detritus based approach, comprising three coupled boxes for each bay operating at daily timesteps. Water exchange between boxes and across the downstream boundary is estimated as a function of freshwater inflows and tidal exchange. Water quality, light attenuation and pelagic processes are calculated for the boxes within each bay. Benthic light climate and sediment processes are solved on a 30m X 30m bathymetric grid. Model stocks and boundary conditions are presented in Table 1.

The results presented in this study are based on a comparison of pristine and current upstream boundary conditions coupled with 'dry weather' downstream boundary conditions in order to highlight the impacts of changes to the delivery of material from the individual bay catchments. Pelagic and benthic stocks for both simulations were intialised using current conditions. Simulations were run for an eighty-day period encompassing multiple rainfall events during the initial half of the simulation period, followed by dry conditions for the remainder of the simulation. Catchment flows for the current scenario were estimated using the Source catchment model developed as part of the Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly, 2015). Pristine (pre-development) flows were estimated from the current scenario flows by distributing flows on any particular day over the subsequent eight days in order to mimic a slower delivery of runoff as groundwater seepage. For the purposes of this simulation, the total volume of freshwater flows was not changed, only the timing of delivery.

The model was calibrated using a combination of data collected as part of the NSW Monitoring Evaluation and Reporting program, and data collected as part of the Sydney Harbour Stormwater Project (Sutherland et al 2016).

Table 1 Boundary conditions adopted for the model simulations

Paramater	Upstream		Downstream
	Pristine	Current	Dry
salinity	0	0	35
TSS (mg L-1)	1	20	1
DON (mg L^{-1})	900	600	200
DIN (mg L^{-1})	150	2200	20
DIP (mg L^{-1})	15	150	20
Chl-*a* (mg L^{-1})	0.1	0.1	1
labile OM (mg L^{-1})	100	1550	150
refractory OM (mg L^{-1})	2500	50	20

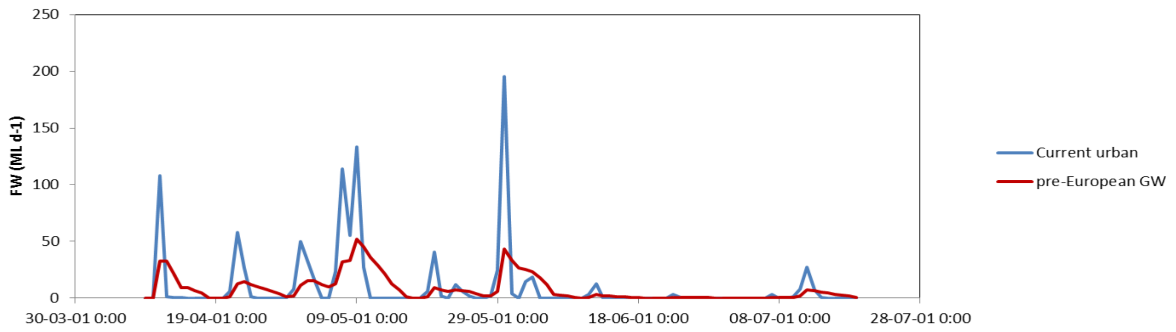

Figure 4 Freshwater flows to Iron Cove over the simulation period.

Results and discussion

The simulation of pristine catchment conditions resulted in marked different responses within both embayments (Figure 5). Although both simulations delivered the same volume of freshwater runoff, the lower concentrations of bio-available nutrients, suspended sediments, and labile organic matter in the pristine scenario resulted in a complete shift from pelagic to benthic productivity. Phytoplankton became nutrient limited due to lower concentrations in runoff coupled with competition for available nutrients by benthic microalgae (BMA). In contrast, phytoplankton bloomed following the major rainfall events, stimulated initially by the nutrient-rich stormwater runoff, and then by recycling of bio-available nutrients from the sediments. We chose to present simulations using 'dry' weather downstream boundary conditions (i.e. close to oceanic conditions), however in reality these bays are influenced by the import of material and freshwater from the main channel across their downstream boundary which would tend to exacerbate the impacts demonstrated by our study.

The reduction in labile OM in catchment runoff in the pristine scenario, coupled with the reduction in phytoplankton biomass, meant that OM supply to the sediments was greatly reduced resulting in the gradual decline in sediment OM during the course of the simulation as the system approached a new steady state. This suggests that OM content of sediments in the pristine bays would have been far lower than today. In contrast, the sediment OM pool in the current scenario simulation displayed high temporal variability in response to freshwater inflows, highlighting the impact of both catchment-derived OM and settled phytoplankton biomass as important sources of sediment enrichment. BMA productivity was not limited by either light or nutrients under pristine conditions, while under the current scenario light was limiting following runoff events due to a combination of suspended sediments and phytoplankton biomass. The net result of these factors was that sediments were a net source of bio-available nutrients in the current scenario, and a net sink under the pristine scenario (Figure 6).

The results of this study give an insight into the likely biogeochemical function of shallow embayments in Sydney Harbour under pre-European conditions. The much clearer water and lower nutrient statues would have greatly favoured BMA productivity over phytoplankton, resulting in highly diverse and productive benthic-based food-chains. While not included in the current model setup, it is likely that these conditions would have also been favourable to seagrass growth and expansion, suggesting a much wider range of seagrass distribution throughout the harbour than at present. Scaled up to the entire harbour upstream of the bridge, our results indicate that BMA and seagrass may have dominated primary production in the system (Figure 7). We suggest that the rehabilitation or recreation of low-lying swamp environments, as filters for stormwater drainage, would greatly improve the function and ecology of these critical harbour habitats.

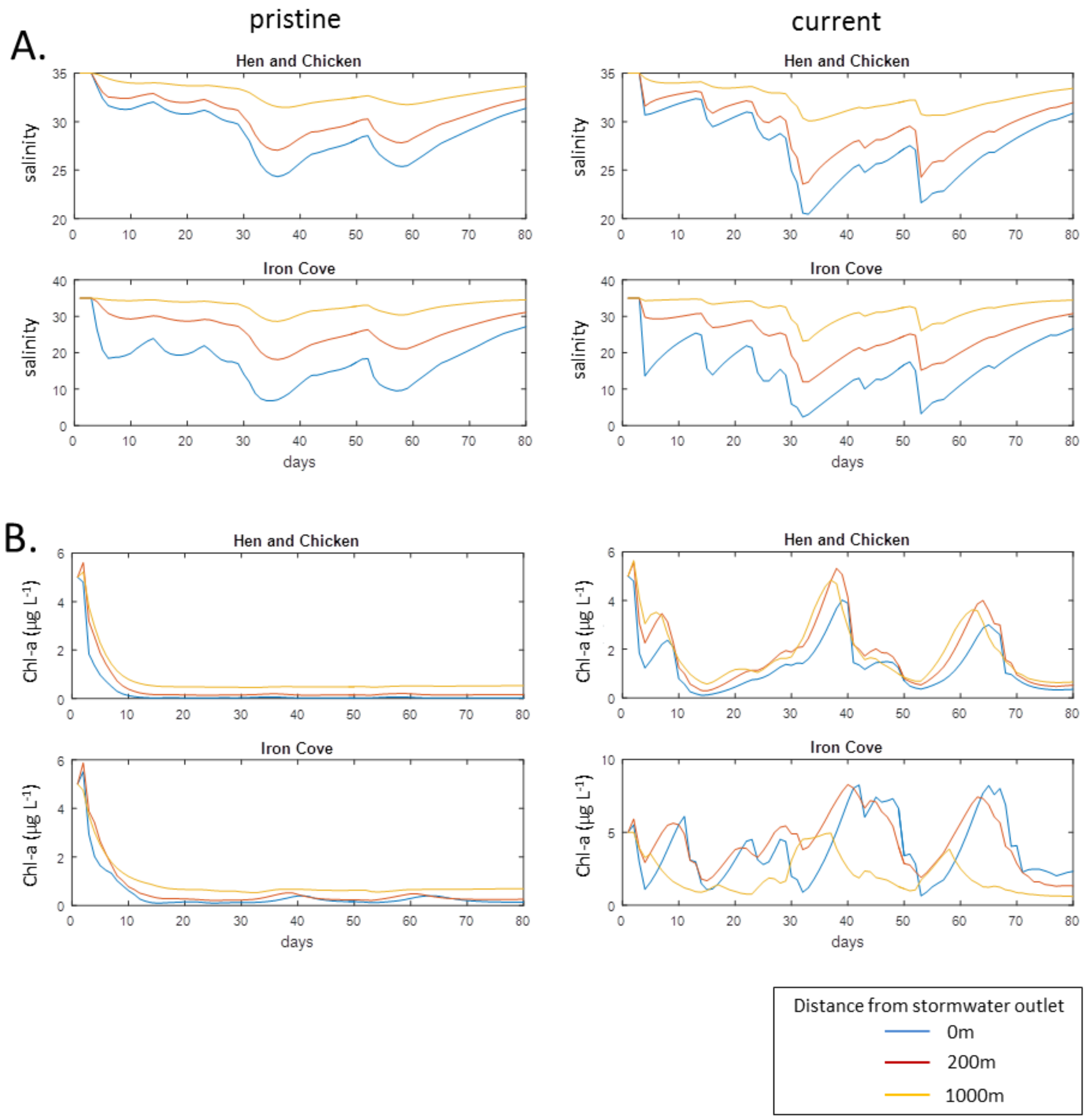

Figure 5 Model outputs for A) salinity and B) phytoplankton (converted here to units of chlorophyll-*a*)

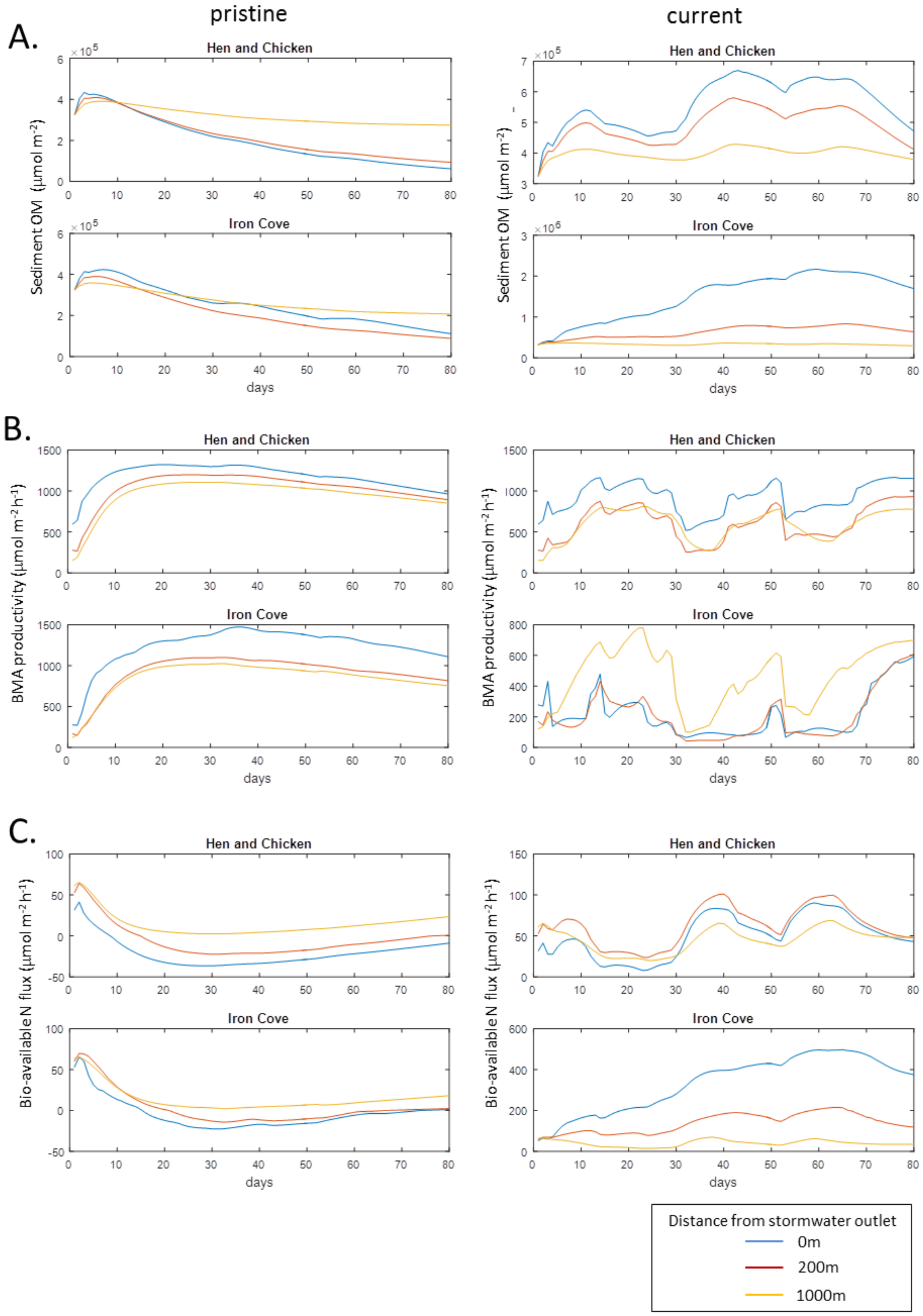

Figure 6 Model outputs for A) sediment organic matter, B) Benthic microalgae productivity; and C) Bio-available nitrogen flux from the sediments (note that positive value equals a flux of nitrogen from the sediments to the overlying water).

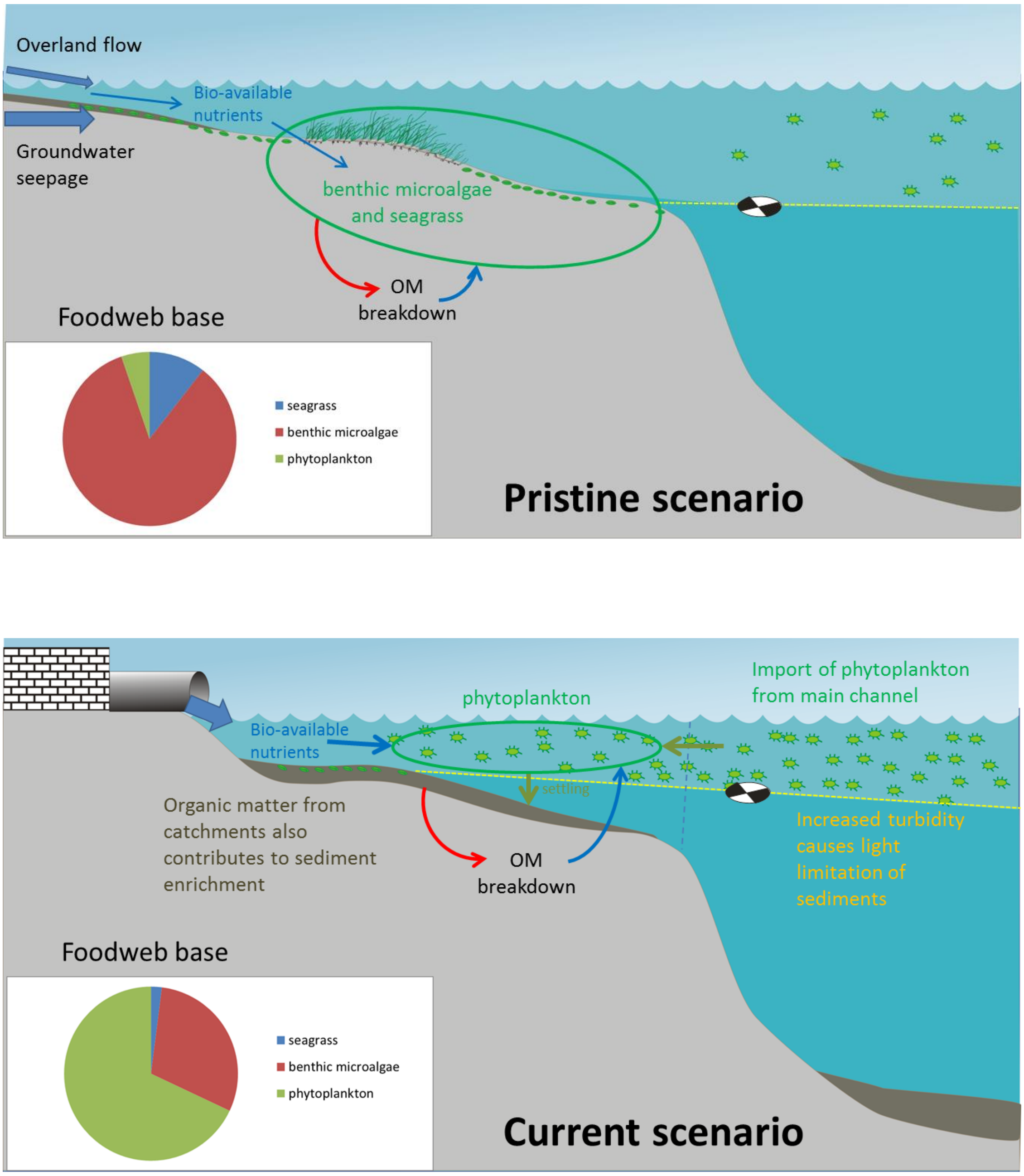

Figure 7 **Conceptual models of biogeochemical function in Sydney Harbour embayments under pristine and current conditions. Also shown is an estimation of primary productivity contributions for the harbour upstream of the bridge.**

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