

# Historical nutrient status in the Richmond River in the absence of monitoring data

B Logan<sup>1</sup>, K Taffs<sup>2</sup>

<sup>1</sup>UGM Environmental Services  
Email: b.logan@ugm.com.au

<sup>2</sup>Southern Cross University, Lismore, NSW  
Email: ktaffs@scu.edu.au

## Abstract

Eutrophication from nutrient over-enrichment is a serious problem for the coastal zone and the estuarine environment globally. Australian estuaries are generally oligotrophic, but assessing whether they are becoming more eutrophic over time is inhibited by a lack of long-term monitoring data. The Richmond River, Australia, provided an ideal example of estuary under anthropogenic pressure where the use of innovative palaeoecological techniques has been able to reconstruct changes in nutrient status over time. A core was extracted from a depositional area in the Richmond River, and several palaeoenvironmental techniques applied. Results of aquatic algae analysis show a strong indication that the total phosphorus levels in the Richmond River have fluctuated since 1940. Evidence also suggests that these fluctuations are most likely a function of climate. This study has successfully applied palaeolimnological techniques to the estuarine environment to produce information that can be used by environmental managers to aid decision making in relation to nutrient control for the Richmond River. This provides a case example of how this technique can be applied to assist management decisions in other Australian coastal zones.

## Introduction

Eutrophication of coastal environments from nutrient over-enrichment is a serious problem (Cloern, 2001) that results in unfavorable changes in water quality and biological populations (Gikas et al., 2006). Eutrophication reduces ecosystem functions, and has negative effects on social and economic standards of coastal environments (Smith et al., 2008). Estuarine eutrophication requires considerable attention as estuaries are heavily affected by nutrient loading from many anthropogenic sources. These include non-point sources in agricultural and residential areas, runoff from coastal urban and industrial development, as well as diffuse contributions of nutrients from the atmosphere and groundwater (Hall, 1999; Glibert, 2006; Bigler, 2007). Point sources such as ocean outfalls from sewerage treatment plants also contribute nutrients and aid the eutrophication process (Gabric & Bell, 1993; Kronvang et al., 1995).

When setting management targets for estuaries in regard to eutrophication, it is vital to have information describing variations in nutrient concentrations over time (Weckstrom, 2006; Saunders & Taffs, in press). However, a significant predicament when interpreting such changes in estuarine water quality is a lack of long-term monitoring data, with few datasets containing water quality measurements which extend back further than a few decades (e.g. Eyre, 1997). In this case, historical information stored in the stratigraphic record can be utilised, by employing a palaeoecological approach (Cooper et al., 2004).

Diatom based palaeolimnological techniques can provide information about trends in trophic status over extended time periods. This is achieved by combining advanced statistical methods with information about changing abundances of diatom species assemblages in sediment cores to perform quantitative reconstructions of water quality (Tibby & Reid, 2004). Such methods were developed and applied to lakes (Anderson, 1993; Reavie et al., 1995; Rosen, 2000) rather than the estuarine environment. However, palaeolimnological techniques have been adapted to the coastal environments, including estuaries (Miller, 1990; Cooper et al., 1993; Andren, 1999; Andren et al., 1999; Colman et al., 2002; Kaupilla et al., 2003; Vaalgaama et al., 2004; Hilgartner & Brush, 2006; Weckstrom et al., 2006; Saunders & Taffs, in press).

Comparable work in estuaries is sparse and considerably novel in Australia. Some studies developed diatom-based transfer functions for retrospective evaluation of water quality (Philibert et al., 2006; Saunders, in press; Logan & Taffs, submitted). Other research has used diatom assemblage data to qualitatively reconstruct past coastal environments in south eastern Australia (Fluin et al., 2007; Haynes et al., 2007). Other studies have highlighted the use of palaeoecological techniques as an effective management tool for setting rehabilitation targets for estuaries, in the absence of long term monitoring data (Saunders et al., 2008; Taffs et al., 2008).

The aim of this paper is to investigate whether past nutrient levels in the Richmond River, an east Australian sub-tropical estuary on the far north coast of NSW, can be assessed using palaeolimnological techniques. The Richmond River is an example of an estuary modified by land use activities since European settlement. Thus, it provides an ideal case example to test the application of adapted palaeoecological techniques that have been utilised effectively in Northern Hemisphere estuarine systems to a Southern Hemisphere estuary. Specifically, this paper aims to reconstruct historical changes of total phosphorus concentrations in the Richmond River. This will be based on diatoms preserved in a dated sediment core, to determine if nutrient levels and associated eutrophication effects are becoming more evident over time.

## **Materials and Methods**

### ***Study Site***

The Richmond River 153.592°E, 28.877°S, is one of the largest coastal drainage systems of NSW, with a catchment area of 6878 km<sup>2</sup> (Figure 1) and a mean annual discharge of 1 920 000 ML. Over 50% of the catchment area is used for agricultural purposes (Hossain, 2004). Two major tributaries, the Wilsons River from the north, and Bungawalbin Creek from the south, merge with the main channel upstream from Woodburn, which is located ca. 40 km from the mouth. Downstream of Woodburn, the Richmond River increasingly becomes estuarine in nature, where it is joined by North Creek at its mouth prior to discharging into the sea.

The climate of coastal NNSW is humid sub-tropical, with a distinctive pattern of summer to autumn maximum in rainfall. Mean annual rainfall is 1100 mm in the western part of the catchment, increasing to 1400 mm along the coast. Daily mean temperatures in the lower part of the Richmond River catchment at Ballina vary from 27-31 °C in January, to a daily minimum of 6-12 °C in July (Hashimoto et al., 2006). This climate regime is controlled by two influences: a sub-tropical high pressure belt during the winter and spring months (June through to October) creating clear, predominately dry weather patterns; and a domination of easterly monsoonal trade winds during the summer and autumn months (November through to May). Tropical cyclones can occur between January and April, creating heavy

rainfall and flood events. Thus, the Richmond River estuary is dominated by short lived but large episodic freshwater inputs during the summer months. These inputs can flush the estuary fresh to its mouth, however, little to no flow of this magnitude occurs during the winter months, which has a significant impact on the estuary hydrology, salinity and biology (Eyre & Twigg, 1997). The majority of the annual discharge (90%) and flood events for the Richmond River occur during the summer-autumn wet season (Hossain et al., 2004). Hence, flushing times of the Richmond River can vary from 0 to 196 days in length depending of the amount of freshwater flow (Eyre, 1997; Eyre & Twigg, 1997; Eyre, 1998). The Richmond River catchment also experiences significant intra- and inter-annual variability in nutrient loads and exports (McKee et al., 2000).



Figure 1. Location map for the Richmond River. Part 'a' shows the location within Australia.; Part 'b' shows the location within the state of New South Wales; Part 'c' shows the location of five push cores extracted from the Richmond River.

The Richmond River catchment was settled by Europeans in 1840, who began introducing land uses such as grazing, agriculture and timber cutting. The development of these

industries was rapid, with population increasing to 4 000 by 1870. There was a further rise to a population of above 22 000 by 1891 due to the increasing demand for the developing dairy industry. Between 1920 and 1950 the reliance on sea and rail by this industry diminished in the Richmond River around Ballina, as local infrastructure started to support other modes of transport (Daley, 2001). In the most recent half a century, agricultural and grazing activities have increased significantly, with upwards of 75% of the upper Richmond River catchment used for agriculture. Fertiliser use in the catchment has also increased 20 fold over this time. Demographic changes have also been experienced, particularly in Ballina, with a population of over 35 000 listed in the mid 1990's. This has instigated the sub-division of agricultural land for urban development and expansion (Eyre, 1997). The Richmond River itself is located in an area that is forecast to be a focal point for increases in population growth over the next 25 years. This is expected to place increasing pressure on the estuary and associated coastal habitats (Smith et al., 2008).

The Richmond River estuary lies within a highly developed catchment area, and is currently listed as 'extensively modified' by OzCoasts (2008). Increases of vegetation clearing by the agriculture industry, and stormwater runoff from urban and industrial areas, have resulted in loss of habitat within wetland, riparian and floodplain areas. Decreasing water quality is a significant issue, with research showing dissolved and fine sediment nitrogen and phosphorus levels have increased by several orders of magnitude since European settlement (Hossain, 1998). In particular, total phosphorus loading has shown to have an association with land uses (Eyre & Pont, 2003). Hence, the Richmond River is an ideal example of an Australian estuary that has suffered from the effects of anthropogenic eutrophication.

### ***Core Collection***

The methodology used for this study was based on established methods used for similar research (Siver, 1999; Bloom et al., 2003; Reid, 2005; Woodward & Shulmeister, 2006), and was adapted to take into account the dynamic nature of an estuary. Sites of constant sedimentation for coring can be found in estuaries (Cooper et al., 2004). To ensure that a core of good integrity was selected for analysis, five push cores were extracted from a series of depositional sites in the Richmond River (Figure 1), using a 1.5m x 74mm PVC pipe and a plumb-bob. Each core was extracted from a current area of deposition within the estuary, away from the deeper main channel of flow.

### ***<sup>210</sup>Pb dating***

Ten sediment samples were dated using <sup>210</sup>Pb dating techniques at the Australian Nuclear Science and Technology Organization (ANSTO), Sydney. The total <sup>210</sup>Pb activity was determined by measuring its granddaughter <sup>210</sup>Po, which was assumed to be in secular equilibrium with <sup>210</sup>Pb. Supported <sup>210</sup>Pb was approximated by measuring <sup>226</sup>Ra activity (Harrison et al. 2002). The CIC (constant initial concentration) and CRS (constant rate of supply) models indicated a monotonic profile. The results from three Cs<sup>137</sup> analyses supported the CIC model, thus sediment ages used in this report will be based on CIC ages.

### ***Diatoms***

Twenty-seven samples from the selected core were processed for diatom analysis at differing resolutions depending upon the depth of the sample. These generally corresponded with depths at which loss-on-ignition and dating methods were also applied. Diatoms were processed according to the method of Parr et al. (2004). Slides were

inspected under an Olympus CX40 compound light microscope fitted with an Olympus DP10 digital camera. Between 300 and 400 diatoms frustules were identified and counted from each sample to determine the diatom community assemblage. Diatoms were counted across several transverses across each slide to ensure that counting was representative. Diatoms were generally identified using the photographs of Witkowski (2000) and Taffs (2005), with some input from Foged (1978) and Gell et al. (1999). Species that made up > 2% of relative abundance in at least one sample were included in reconstructions, using the diatom based TP transfer function of Logan et al (submitted a).

## Results

### <sup>210</sup>Pb dating

The unsupported <sup>210</sup>Pb activity profile in the sediment core shows a monotonic pattern of exponential decline. This indicates the core's suitability to establish a reliable geochronology for the Richmond River estuary based on a CIC model (Appleby & Oldfield, 1983) (Figure 2). Ten <sup>210</sup>Pb dates were obtained for the upper 65 cm of sediment, ranging in age from 7.31 ± 0.89 YBP (2000 AD) at the 4-5cm horizon, to 84.19 ± 4.68 YBP (1923 AD) at 64-65 cm (Table 1). <sup>137</sup>Cs activities were tested at depths of 22-24cm, 25-27cm and 32-34cm (Table 1). <sup>137</sup>Cs activity was detected at 22-24 cm layer, which may represent sediment input from the peak bomb testing period in 1963 (44 years ago). <sup>137</sup>Cs activities were not detected below 25 cm. It can be assumed these sediment layers are older than 40 ± 10 years old, which is in agreement with the CIC model.

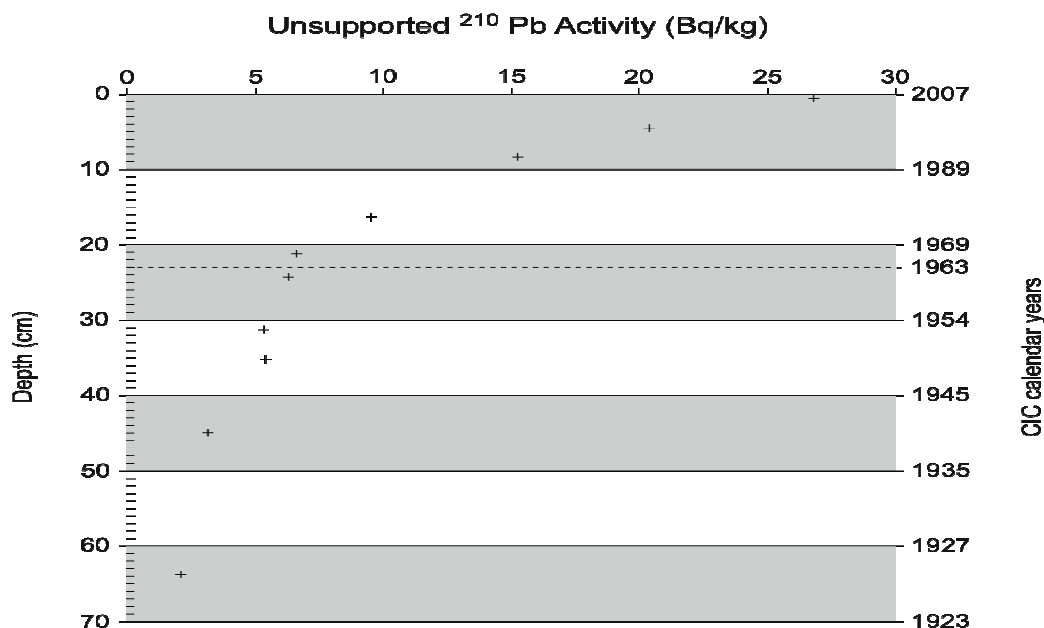


Figure 2. Unsupported <sup>210</sup>Pb activity for the RR3 core, plotted against sediment depth and calendar years.

Table 1. <sup>210</sup>Pb activity and <sup>137</sup>Cs activity, with approximate inferred age and year for specific depths in the RR3 core.

Depth (cm)	<sup>210</sup> Pb		CIC age	Calendar Year
	Total <sup>210</sup> Pb	Unsupported <sup>210</sup> Pb		
0 - 1	29.52 ± 0.76	2.82 ± 0.27	0.74 ± 0.74	2007

4 - 5	21.44 ± 0.57	1.38 ± 0.20	20.40 ± 0.61	7.31 ± 0.89	2000
8 - 9	17.85 ± 0.67	2.68 ± 0.29	15.23 ± 0.73	14.98 ± 1.14	1992
16 - 17	10.62 ± 0.54	1.14 ± 0.15	9.51 ± 0.56	31.73 ± 1.81	1975
21 - 22	8.00 ± 0.33	1.44 ± 0.17	6.64 ± 0.38	41.76 ± 2.24	1965
24 - 25	6.49 ± 0.27	0.28 ± 0.08	6.31 ± 0.29	47.67 ± 2.50	1959
31 - 32	6.37 ± 0.29	1.15 ± 0.17	5.31 ± 0.34	54.23 ± 2.60	1953
35 - 36	6.87 ± 0.33	1.53 ± 0.20	5.43 ± 0.39	58.04 ± 2.74	1949
45 - 46	5.23 ± 0.36	2.00 ± 0.23	3.24 ± 0.43	67.56 ± 3.30	1939
64 - 65	4.46 ± 0.38	2.32 ± 0.27	2.14 ± 0.47	84.19 ± 4.68	1923

Depth (cm)	<sup>137</sup> Cs		Expected age	Calendar Year
	Uncorrected <sup>137</sup> Cs	Corrected <sup>137</sup> Cs		
22 - 24	3.84 ± 1.21	0.32 ± 0.10	44	1963
25 - 27	< 2.94	< 0.24	40 ± 10	-
32 - 34	< 1.14	< 0.09	-	-

### Diatoms

Diatoms were well preserved to a depth of 40 cm in sediment core RR3. Below 40 cm depth diatom preservation was non-existent. The mean number of diatom taxa per samples was > 40 species. In total, 156 diatom taxa were identified in sediment core RR3. Of these, 39 occurred at a relative abundance > 2 % in at least one sample. These species were used for environmental reconstructions. There were fifteen common taxa (Figure 3) occurring with a relative abundance > 4 % in at least two samples, with seven of these being present in every sample. *Cyclotella bodanica*, *Nitzschia granulata* and *Planorbulina mediterranensis* encountered at a relative abundance > 20% in at least two samples, having minimum/maximum relative abundances of 6.84%/35.00%, 1.98%/30.59% and 4.73%/24.12%, respectively.

Changes in taxonomic composition of the diatom assemblages occurred throughout the RR3 core. Co-occurring low relative abundances of *C. bodanica* and *N. granulata* observed at depths of 5-6 cm and 24-26 cm were accompanied by increases in the abundance of the less common *Navicula arenaria* and *Nitzschia compressa*. There was a mean of 5.1 centric taxa per sample. This was generally representative of dominance by *C. bodanica* and *C. striata*. Two planktonic freshwater taxa were also present, *Actinocyclus normanii* and *Aulacoseira italica*, suggesting possible allochthonous inputs.

### Total Phosphorus Reconstruction

Diatom-inferred Total Phosphorus (DI-TP) concentrations were created using the total phosphorus (TP) transfer function of Logan & Taffs (submitted a). DI-TP (Figure 3) indicated that nutrient levels have fluctuated in the Richmond River since 1920. Peaks occurred at depths of 8-9cm (1994 AD), 10-11 cm (1992 AD), 34-35 cm (1950 AD) and 36-37 cm (1945 AD). Conversely, lower DI-TP inferences coincided with the decreases in *C. bodanica* and greater influence of less common pennate species. DI-TP indicated no clear trend of TP levels increasing significantly over time. The DI-TP peaks at 34-35 cm and 36-37 cm may have a degree of unreliability due to possible poor preservation of specific species that have lower TP optima than *C. bodanica* and *N. granulata*, the two species that dominate relative abundances at these depths.

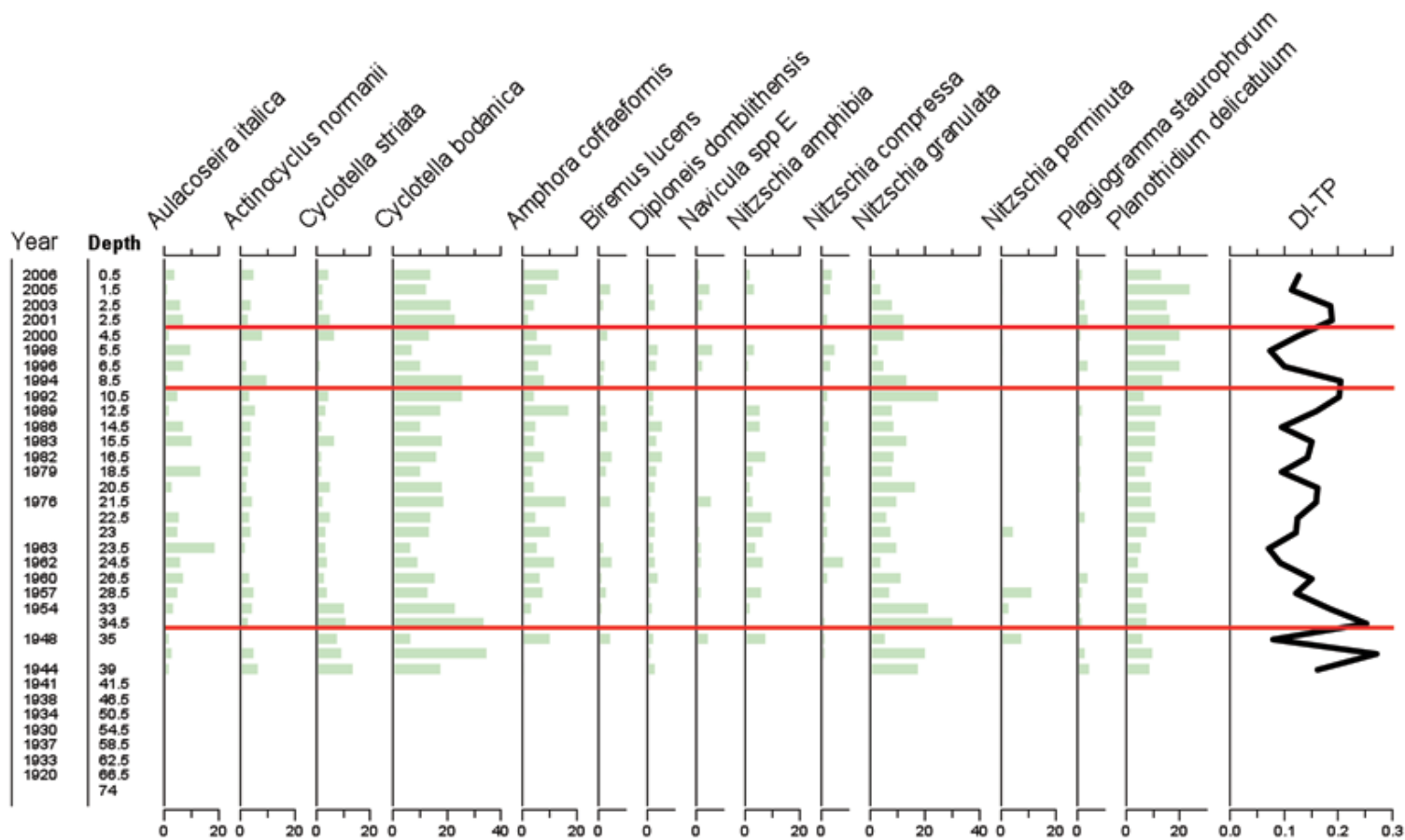


Figure 3. The fifteen common diatom taxa, and their relative abundances by percentage, plotted against depth in centimetres, and years AD inferred from  $^{210}\text{Pb}$  age. Diatom inferred total phosphorus is represented by the DI-TP chart. No diatom preservation was recorded below 40 cm. Lines through graph indicate peaks in DI-TP and *Cyclotella bodanica* sp abundance.

## Discussion

### *Coring*

The retrieval of an intact sediment core, of sufficient integrity, was given paramount consideration during the field work methodology used in this study. Careful selection of less dynamic depositional sites for coring was made, generally in areas removed from the higher energy areas of the Richmond River estuary. The results of the  $^{210}\text{Pb}$  suggest that the extraction of a useful sediment cores was successful. The site from which RR3 was extracted differed from the four others in that it received water on the flood tide only, was located at the mouth of Emigrant Creek, a tributary to the Richmond River, and was protected from most water movement by a fringe of *Avicennia* mangroves (Hashimoto et al., 2006). This site was also away from the deeper, fast flowing sections of the estuary, which were closer to sites from which the RR4 and RR5 cores were extracted (Logan et al, submitted b).

The results of  $^{210}\text{Pb}$  dating analyses indicate that the RR3 core was of good integrity. The monotonic profile of unsupported  $^{210}\text{Pb}$  showed decay with depth, which was evident from the CIC model. This was supported by  $^{137}\text{Cs}$  results. This suggests that the sediment sequence was relatively undisturbed despite being located in very close proximity to a tidally influenced section of the estuary. It has been recognized previously that sites of stable, continuous sedimentation can be found within estuaries (Cooper et al., 2004). This study also highlighted that this can be achieved when an appropriate approach is employed.

### *Diatoms*

The reconstruction of water quality conditions that pre-date European settlement was not possible due to zero diatom preservation below a depth of 40 cm. However, the diatom assemblages identified between the surface sediment sample and 40 cm did provide significant palaeoenvironmental information. No apparent trend for large increases in total phosphorus concentrations since ~1940 AD can be inferred from the diatom assemblages. This is particularly important, with no long term nutrient monitoring data existing for the Richmond River. This is also consistent with Eyre (1997), who found that phosphorus concentrations in the Richmond River have remained quite constant, despite large increases in agricultural activities in the Richmond River estuary floodplain over the past five to six decades.

The diatom stratigraphy observed here in combination with the transfer function of Logan & Taffs (submitted a) suggests that nutrient concentrations in the Richmond River since 1945 have been in a state of flux, and are controlled by climate more than anthropogenic activities. The two lowest DI-TP values were recorded at depths of 5-6 cm (0.074) and 35-36 cm (0.079), however samples from these depths were not used for  $^{210}\text{Pb}$  dating, so comparison to annual rainfall for specific years was not possible due to insufficient resolution. The third lowest DI-TP (0.091) at a depth of 24-26 cm corresponds to around 1960 AD. Annual rainfall for the year 1960 was 1185 mm, well below the recorded average of 1817 mm (BOM, 2009). The highest DI-TP (0.205) value was recorded at a depth of 8-9 cm, which corresponds to around 1990 AD based on  $^{210}\text{Pb}$  dating results. Annual rainfall for the year 1990 was 1859 mm, which lies above the annual average for the period between 1960 and 2007 AD of 1817 mm (BOM, 2009). Unsurprisingly this

suggests fluctuating nutrient levels in the Richmond River have a positive relationship with increases and decreases in precipitation.

Previous work by Eyre (1997) on the relationship between nutrient levels and rainfall for the Richmond River catchment provides support for inferences based on the diatom data. This study indicated that this estuary may receive up to 90% of nutrient loading during episodic events. Hence, non point source nutrient contributions from terrestrial runoff are a cause for elevated nutrient concentrations in times of higher rainfall. These increases and decreases are reflected in the diatom sedimentary record. This is shown by the increased presence of *Cyclotella bodanica*, shown previously to be a nutrient tolerant species (Cooper & Brush, 1993; Whitmore et al., 1996; Koster et al., 2005; Weckström, 2006). A majority of the DI-TP peaks in the diatom reconstruction are also accompanied by larger (> 0.65) c:p ratio's. Using the same core, Logan et al. (submitted b) showed that the average number of taxa per assemblage was > 40, while the number of centric taxa present in each assemblage was 5.1 species, with a maximum of six centric species in any one sample. *C. bodanica* was the most dominant of these centric taxa in all cases, providing support for the view that increases in nutrients in the Richmond River are accompanied by increased abundances and dominance of this species. Furthermore, increases in the abundance of *Navicula arenaria*, not dominant in this core but shown previously to have preference for unpolluted environments (Admiraal & Peletier, 1979), are experienced when the relative abundances of *C. bodanica* are at some of their lowest in the core.

## **Conclusion**

This is the first study to use the sedimentary diatom record to reconstruct historical estuarine TP concentrations in sub-tropical Australia. Given the lack of long term data in relation to estuarine water quality in Australia, this paper used a somewhat novel approach, by applying previously under-utilised palaeolimnological techniques to retrospectively assess total phosphorus concentrations in the Richmond River. Results of the diatom based environmental reconstruction indicate that the Richmond River's nutrient status in relation to total phosphorus has a tendency to fluctuate, and that this is more likely a function of climate. Previous research has identified this site to be highly episodic in terms of its freshwater flow, and this may be exhibiting some control over TP concentrations and subsequent primary production. No clear trend for recent increases in total phosphorus could be established, although the lack of core of sufficient length to predate European settlement in the Richmond River catchment may have had an impact on this.

Although palaeoecological estuarine research is still relatively novel in Australia, this study has demonstrated the usefulness of palaeolimnological techniques for such work. This information can be especially useful when there is a lack of monitoring data, which is the case for the Richmond River estuary. The results of this research, which indicate that nutrient levels in the Richmond River are not increasing over time, but are closely linked to climate, can provide environmental managers involved at the local level with information on which future management decisions regarding nutrient control can be based. When cores extracted for similar use can be dated to encapsulate sediments that pre-date European settlement, the inferences made can be used to provide benchmarks against which current water quality status can be assessed.

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