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Characterisation of spatial variability in water quality in the Great Barrier Reef catchments using multivariate statistical analysis

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ABSTRACT

Water quality monitoring is important to assess changes in inland and coastal water quality. The focus of this study was to improve understanding of the spatial component of spatial-temporal water quality dynamics, particularly the spatial variability in water quality and the association between this spatial variability and catchment characteristics. A dataset of nine water quality constituents collected from 32 monitoring sites over a 11-year period (2006–2016), across the Great Barrier Reef catchments (Queensland, Australia), were evaluated by multivariate techniques. Two clusters were identified, which were strongly associated with catchment characteristics. A two-step Principal Component Analysis/Factor Analysis revealed four groupings of constituents with similar spatial pattern and allowed the key catchment characteristics affecting water quality to be determined. These findings provide a more nuanced view of spatial variations in water quality compared with previous understanding and an improved basis for water quality management to protect nearshore marine ecosystem.

1. Introduction

Degradation of water quality is a global issue (Schwarzenbach et al., 2010). Human activities, such as agriculture and urbanisation, are major causes of water quality degradation (Zia et al., 2013). For example, Bricker et al. (2014) showed that the excess nutrient discharge to coastal waters in the Chesapeake Bay region of the USA over the past 200 years was linked to increased anthrophonic pressures, including discharge from sewage treatment plants, and runoff from urban and agricultural land uses.

In-stream surface water quality is important for the health of inland and coastal waters (De'ath et al., 2012; Harris, 2001; Packett et al., 2009). For instance, discharge of sediments and nutrients to marine ecosystems from inland catchments poses a threat to near-shore tropical coral reefs globally (Aronson et al., 2014; Ginsburg and Shinn, 1995). Coral reefs maintain not only environments with rich biodiversity, but they also provide economic benefits from tourism, fishing and aquaculture (Chabanet et al., 1997; Connell, 1978). The ecosystem in the Great Barrier Reef (GBR), Australia, has been deteriorating during recent decades (DeVantier et al., 2006). It is estimated that the GBR-wide coral cover has decreased by 50% since 1985, and the coral cover on inshore reefs has declined by 34% since 2005 (Brodie et al., 2013). De Valck and Rolfe (2018) estimated that failure to maintain water quality in GBR could result in substantial losses of local economic benefits associated with tourism.

While there are many reasons for the reduction in coral cover in the Great Barrier Reef, poor quality of the water discharging into the reef from the inland catchments is thought to be one major cause (Brodie et al., 2012; Hunter and Walton, 2008; McKergow et al., 2005). Suspended sediments (often derived from soil erosion) have resulted in a reduction in the light essential for organisms in marine ecosystems, including seagrass and coral. Sediments and organic rich flocculent masses can also smother marine organisms when particles settle out (Brodie et al., 2013; Haynes, 2001). Nutrients, especially nitrogen and phosphorus, have been closely linked to the observed decline in coral cover through these two mechanisms. Excessive nutrients have facilitated outbreaks of the crown-of-thorns starfish, a major coral predator (Brodie et al., 2005; Fabricius et al., 2010), and they have also been implicated in coral bleaching (Hoegh-Guldberg et al., 2007; Wooldridge and Done, 2009).

To protect aquatic environmental health and values in both rivers and bays, it is recognised that an improved water quality management strategy is essential (Lynam et al., 2010; Santhi et al., 2006; Sidle et al., 2006). This requires a sound understanding of the underlying reasons

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for water quality degradation in these rivers. However, constituent concentrations are highly variable in space and time due to hydrological variability (Allan et al., 1997), physical and bio-chemical processes (Ayers and Westcot, 1985; Letterman, 1999; Melching and Flores, 1999) and hydrological transport (Hrachowitz et al., 2016). Therefore, it is important to understand the spatial and temporal controls of water quality (Zhou et al., 2007b).

Previous studies of the Great Barrier Reef catchments using the water quality record have been conducted which either estimated the constituent loads (Kroon et al., 2012; Wallace et al., 2016), or focus on small scale or individual catchments land use effect of pollutant exports (Hunter and Walton, 2008; Packett et al., 2009; Stephen Lewis et al., 2014). Other efforts to understand variations in water quality in the Great Barrier Reef catchment have centred on modelling (Carroll et al., 2012; McCloskey et al., 2011; Waters et al., 2013). Through these earlier studies, a conceptual understanding of the role of different catchment characteristics in controlling differences in water quality between catchment is emerging. In addition, given the importance of catchment water quality to the Great Barrier Reef marine ecosystem, a detailed water quality monitoring system has been implemented by the Queensland Department of Science, Information and Innovation (DSITI). The detailed catchment scale monitoring data resulting from that monitoring system has not been systematically compared with catchment characteristics to date.

Most studies addressing the association between water quality and catchment characteristics have focused on temperate catchments in Asia, America and Europe (Ding et al., 2016; Donohue et al., 2006; Lowrance et al., 1997; Renard et al., 1997; Rice et al., 2015; Suif et al., 2016; Vrebos et al., 2017; Wu et al., 2015). Much less research has been undertaken in tropical catchments, like the Great Barrier Reef catchments. The key anthropogenic influences leading to water quality degradation in the Great Barrier Reef catchments have previously been studied at local scales. These include the relationship between sediment and particulate nutrients and erosion processes, and between non-point source dissolved nutrient and pesticide pollution from agricultural activities (Davis et al., 2016, 2017; Kroon et al., 2012; Kroon et al., 2016; Kuhnert et al., 2012; McKergow et al., 2005). These working hypotheses need continual testing as more detailed data emerge.

Multivariate statistical techniques can be used to explore the underlying patterns and potentially the processes affecting multi-site, multi-parameter water quality time-series data. Studies have used multivariate techniques such as cluster analysis and principal component analysis to interpret complex environmental monitoring data (Ouyang et al., 2014; Singh et al., 2004), identify sources of spatial variability in water quality (Mitra et al., 2018; Yang et al., 2010; Zhou et al., 2007a) and assessing monitoring networks (Shrestha and Kazama, 2007; Zhang et al., 2009). For instance, Li et al. (2011) used cluster analysis to detect the key groups of sites with similar water quality responses along the Middle Route of the South to North Water Transfer Project, China. They identified three groups of sites, reflecting the water quality responses of the sites, reflecting the main drivers of water quality: natural, agricultural and industrial sources.

It is well recognised that spatial and temporal dynamics in water quality are influenced by a wide range of natural and anthropogenic factors (Alberto et al., 2001; Kuhnert et al., 2012; Pratt and Chang, 2012; Singh et al., 2004). In this paper, serving as the initial part of a large study that aims to understand both spatial and temporal responses in water quality, we concentrate on the key catchment characteristics affecting spatial variability in stream water quality. We analysed water quality monitoring data from thirty-two sites using multivariate statistical analysis, over an 11-year period (2006–2016), using the time-averaged constituents concentrations (discussed in Section 2.4, Data preparation). The aim of the present study was to characterise spatial water quality variation, and to evaluate the relationships between spatial variations in water quality and catchment characteristics (e.g., land use, catchment geological, topographic and climatic conditions). The findings from the Great Barrier Reef catchments contribute to the growing understanding and knowledge of the key factors affecting spatial variability in water quality. In particular, this study addresses the following questions. (i) How strong is the spatial pattern in the concentration of water quality constituents across the Great Barrier Reef catchments? (ii) Are there groups of constituents with similar spatial behaviour? (iii) To what degree is the pattern in water quality associated with the catchment characteristics and what are they? (iv) What is the relative importance of anthropogenic controls and natural controls on water quality, and how these controls inform the management practices to improve water quality? The evaluation of the current conceptual understanding of catchment controls on water quality will further our understanding of spatial controls (e.g., catchment land use and hydrodynamic conditions) of water quality in the Great Barrier Reef catchments, so we can better manage our riverine water quality.

2. Materials and methods

2.1. Study area

The Great Barrier Reef catchments are located in north-eastern Australia and encompass northern to southern coastal and inland Queensland. In total, the catchments have an area of 432,134 km^2 and are divided into six Natural Resource Management (NRM) regions (Carroll et al., 2012; Waters et al., 2014) (Fig. 1). According to the Köppen-Geiger climate classification, the Great Barrier Reef catchment climates range from semi-arid tropical or thru warm oceanic to wet tropical (Fig. 2a) (Peel et al., 2007), with annual rainfall ranging from around 500 mm in semi-arid tropical regions to 8000 mm in parts of the wet tropics where there are strong orographic effects near the coast (Fig. 2c) (Petheram et al., 2008). In most areas, rainfall declines from the coast to inland catchments. Generally, for inland semi-arid tropical regions, the precipitation predominantly occurs during the wet season, from November to April (Davis et al., 2016), while for the costal wet tropics, rainfall is more evenly distributed across the year. Major rainfall events are associated with tropical cyclones occurring in northern part of Great Barrier Reef catchments (Furnas, 2003; Hutchings et al., 2005). Most of the catchments drain eastwards into the Coral Sea from the Great Dividing Range, and they vary widely in topography from rugged mountains to flat river valleys and coastal plains (Fig. 2b).

Land use includes large areas of conservation lands, often covered with tropical forests; and a variety of agricultural uses including pastoral grazing, extensive rain-fed cropping and intensive rain-fed and irrigated sugar cane. Fig. 2d shows that the predominant land uses within the Great Barrier Reef catchments include grazing (~75%), nature conservation (~13%), cropping (e.g., horticulture, ~3%) and sugar cane (~1%) (Queensland Government, 2017). Denser human settlements and intensive agricultural landscapes have been developed in the coastal catchments. A detailed description of each site in terms of climate and monitored area are provided in Supplementary materials (Table S-1).

2.2. Water quality data collection

We used data from 32 water quality monitoring sites (Fig. 1) across six natural resource management regions. Water quality monitoring data was provided from the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Turner et al., 2012). The number of samples and temporal coverage vary by site (Table S-2), with largest number of samples were taken at 113006A Tully River at Euramo (e.g., 1441 samples of TSS) between 2006 and 2016 (e.g., 266 samples in 2006, Table S-3). Both intensive event-based water quality sampling during high flow events and monthly sampling during low or base flow (ambient) conditions were undertaken. During event periods, it was common that multiple samples to be collected on any given day. We