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Research article

Defining wet season water quality target concentrations for ecosystem conservation using empirical light attenuation models: A case study in the Great Barrier Reef (Australia)

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ABSTRACT

Optically active water quality components (OAC) transported by flood plumes to nearshore marine environments affect light levels. The definition of minimum OAC concentrations that must be maintained to sustain sufficient light levels for conservation of light-dependant coastal ecosystems exposed to flood waters is necessary to guide management actions in adjacent catchments. In this study, a framework for defining OAC target concentrations using empirical light attenuation models is proposed and applied to the Wet Tropics region of the Great Barrier Reef (GBR) (Queensland, Australia). This framework comprises several steps: (i) light attenuation (Kd(PAR)) profiles and OAC measurements, including coloured dissolved organic matter (CDOM), chlorophyll-a (Chl-a) and suspended particulate matter (SPM) concentrations collected in flood waters; (ii) empirical light attenuation models used to define the contribution of CDOM, Chl-a and SPM to the light attenuation, and; (iii) translation of empirical models into manageable OAC target concentrations specific for wet season conditions. Results showed that (i) Kd(PAR) variability in the Wet Tropics flood waters is driven primarily by SPM and CDOM, with a lower contribution from Chl-a ($r2 = 0.5$, $p < 0.01$), (ii) the relative contributions of each OAC varies across the different water bodies existing along flood waters and strongest Kd(PAR) predictions were achieved when the in-situ data were clustered into water bodies with similar satellite-derived colour characteristics ('brownish flood waters', $r2 = 0.8$, $p < 0.01$, 'greenish flood waters', $r2 = 0.5$, $p < 0.01$), and (iii) that Kd(PAR) simulations are sensitive to the angular distribution of the light field in the clearest flood water bodies. Empirical models developed were used to translate regional light guidelines (established for the GBR) into manageable OAC target concentrations. Preliminary results suggested that a 90th percentile SPM concentration of 11.4 mg L^{-1} should be maintained during the wet season to sustain favourable light levels for Wet Tropics coral reefs and seagrass ecosystems exposed to 'brownish' flood waters. Additional data will be collected to validate the light attenuation models and the wet season target concentration which in future will be incorporated into wider catchment modelling efforts to improve coastal water quality in the Wet Tropics and the GBR.

1. Introduction

Coastal ecosystems, including seagrass meadows and coral reefs, are experiencing increasing pressure from anthropogenic activities. Seagrass habitats have declined worldwide at a rate of around 110 km^2 per year since 1980 (Waycott et al., 2009) and 27 percent of monitored reef formations worldwide were estimated to be lost in 2000 (Pockley, 2000). Declining water quality from river runoff is a significant threat to the health of coastal ecosystems through light inhibition and pollutant exposure (Cloern, 2001; Halpern et al., 2008, 2015, Romero et al., 2013; Schaffelke et al., 2017) and can also increase vulnerability to climate change stress (Halpern et al., 2008, Scheffer et al., 2015, Wooldridge, 2009, Wooldridge and Done, 2009). Conservation of nearshore marine

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environments from water quality issues requires the reduction of riverine pollutants through targeted measures on land. This can be progressed through the definition of marine water quality targets and prioritising management actions to reduce land-based sourced pollutants below accepted thresholds (Álvarez-Romero et al., , 2015; Brodie et al., 2017; Gilby et al., 2016; Saunders et al., 2017; Álvarez-Romero et al., 2015; Brodie et al., 2017; Gilby et al., 2016; Saunders et al., 2017).

Excess nutrients have been shown to affect seagrass leaf production (e.g., Connell et al., 2017; Roca et al., 2016) and can lead to significant physiological changes and reduce biodiversity in coral (Fabricius, 2005, 2011, Duprey et al., 2016). Elevated suspended sediments and sediment deposition negatively affect the reproductive cycle and early life histories of corals (Fabricius, 2005; Erftemeijer et al., 2012; Jones et al., 2015) and seagrasses are also vulnerable to elevated rates of sedimentation (Benham et al., 2016). Beside the direct impact of exposure to land-sourced pollutants (nutrients and suspended sediments), turbidity associated with elevated particulate and dissolved matter concentrations in river runoff can significantly reduce the underwater light availability for light-dependent nearshore benthic habitats exposed to flood plumes (Jerlov, 1968, 1976, Prieur and Sathyendranath, 1981). The availability of light in the water column and at the seabed determines the euphotic zone depth (Kirk, 1994) and light limitation is regarded as the primary driver of seagrass production (Collier and Waycott, 2009; Collier et al., 2014, 2016a,b) and a major threat to coral reefs (Bessell-Browne, 2017a, b).

The rate at which the photosynthetically active radiation (PAR) is attenuated with the water depth (hereafter light attenuation) is generally measured as the vertical light attenuation coefficient (Kd) in the PAR. In addition to pure water, the major drivers of light attenuation are the suspended particulate matter concentrations (SPM), coloured dissolved organic matters (CDOM), phytoplankton biomass (measured as Chl-a) or some combination of these optically active water quality components (OACs); as well as the angular distribution of the light field (e.g., Solar Zenith Angle above the sea surface, SZA) (Gordon, 1989; Kirk, 1984, 1994, 2011, Lee et al., 2005; Mobley, 1994).

There is no management action that can directly control light attenuation in flood waters per se. However, as light attenuation is linked to the OAC content of the water, it is possible to develop models able to quantitatively relate the light attenuation to OACs that can be influenced using best practice land management systems (hereafter manageable OAC concentrations) (Gallegos, 2001). Although the relative contributions of the different OACs to light attenuation in estuarine and coastal waters has been intensively studied worldwide (e.g., Kirk, 1976; Dubinsky and Berman, 1979; McMahon et al., 1992; Kostoglidis et al., 2005; Devlin et al., 2008, 2009, Foden et al., 2008; Chen and Doering, 2016), few studies have investigated the potential of using light attenuation-OAC relationships in defining manageable OAC target concentrations for light-dependent coastal ecosystems (Gallegos, 1994, 2001).

Semi-analytical light attenuation models are based on the radiative transfer theory and are amongst the most accurate models for retrieving Kd across turbid coastal to clear marine waters (Lee et al., 2005, 2013). These spectral models use in situ inherent optical properties (IOPs, including the absorption and backscattering coefficients) collected locally or inverted from local satellite reflectance, as well as the angular distribution of the light field in the water (Lee et al., 2005, 2013). However, in the dynamic coastal environment, it is challenging to develop cost-effective monitoring programs able to collect an IOP database necessary to drive semi-analytical light attenuation models over many years and climatic conditions. The dependence of IOPs on local water constituents also limits the use of published IOPs from other regions as a substitute (Dorji et al., 2016). As a result, the IOP datasets necessary to develop semi-analytical light attenuation models are often not available for many of the world's coastal areas that may have water quality issues (Chen and Doering, 2016) and empirical methods are often used to estimate the light attenuation because of their simplicity in development and accessible validation data.

This study builds on these foundations and aimed to develop a reproducible framework, modified from Gallegos (2001), to estimate minimum OAC concentrations that must be maintained to sustain sufficient light levels for conservation of marine light-dependant ecosystem (hereafter OAC target concentrations). It used simple, non-spectral, empirical light attenuation models derived from water quality parameters commonly measured in water quality programs, i.e., depth profiles of PAR, concentrations of Chl-a and SPM, CDOM absorption, Secchi Disk Depth (SDD) measurements and the SZA, derived from the time, latitude and longitude of the PAR measurements. This framework was applied to the Wet Tropics region of the Great Barrier Reef Marine Park (GBR) in Australia.

River runoff during the austral wet season is a major source of land-sourced pollutants to the GBR and high contaminant loads in river floods and associated contaminant concentrations represent the highest water quality risk to GBR marine ecosystems (Davis et al., 2016; Devlin et al., 2015; Kennedy et al., 2012; Waterhouse et al., 2017a,b). However, minimum OAC guidelines that are currently implemented to maintain coral reef and seagrass ecosystem health in the GBR focus essentially on annual conditions, while seasonal guidelines, encompassing the periods of flood conditions are still largely unknown (GBRMPA, 2010). This study therefore focused on developing OAC target concentrations for the austral wet season (December to April, hereafter wet season), when GBR coastal systems are exposed to flood plumes. It used data collected during five wet seasons (November to April), when river floods and resuspension are the main drivers of variation in light attenuation (Fabricius et al., 2014, 2016).

Empirical light attenuation models were used to define the contribution of CDOM, Chl-a and SPM to the light attenuation in and across coastal water bodies existing within the GBR during wet season conditions (hereafter flood water bodies) and to translate regional light guidelines for ecosystem conservation into OAC target concentrations that can be managed, for the period of time GBR coastal systems are at the highest risk of being exposed to deleterious concentrations of land-sourced pollutants. Preliminary OAC target concentrations were proposed and an evaluation of the applicability to the Dry Tropics region of the GBR was also investigated. Results obtained are discussed in relation to potential future application to improve land-sea management strategies in the GBR and elsewhere.

2. Case study area

The GBR (Fig. 1) is the world's largest coral reef ecosystem and contains over 2,900 coral reefs and 35,000 km^2 of seagrass meadows (McKenzie et al., 2010; Brodie and Waterhouse, 2012). Rainfall and runoff rates are highly seasonal with over two thirds occurring during the wet season in contrast to the dry season (May to November). River runoff during the wet season is a major source of land-sourced pollutants to the GBR due to agricultural and urban development of the GBR catchments and the distribution and movement of the individual pollutants varies considerably between the wet (north of Townsville) and dry tropic rivers (Brodie et al., 2012; Waterhouse et al., 2017a,b). Wet Tropic catchments have frequent storm and runoff events and frequent linkages to coastal environments, while in the Dry Tropic catchments, the major flow events may occur at intervals of years, with long lag times for the