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The cumulative impacts of repeated heavy rainfall, flooding and altered water quality on the high-latitude coral reefs of Hervey Bay, Queensland, Australia

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ABSTRACT

Terrestrial runoff and flooding have resulted in major impacts on coral communities worldwide, but we lack detailed understanding of flood plume conditions and their ecological effects. Over the course of repeated flooding between 2010 and 2013, we measured coral cover and water quality on the high-latitude coral reefs of Hervey Bay, Queensland, Australia. In 2013, salinity, total suspended solids, total nitrogen and total phosphorus were altered for up to six months post-flooding. Submarine groundwater caused hypo-saline conditions for a further four months. Despite the greater magnitude of flooding in 2013, declines in coral abundance (~28%) from these floods were lower than the 2011 flood (~40%), which occurred immediately after a decade of severe drought. There was an overall cumulative decrease of coral by ~56% from 2010 to 2013. Our study highlights the need for local scale monitoring and research to facilitate informed management and conservation of catchments and marine environments.

1. Introduction

Flooding is a natural occurrence which can be an important source of sediment and nutrients to a variety of downstream riverine, estuarine and marine environments (Furnas, 2003). However, when catchments are modified or floodwaters become increasingly large and more frequent, the benefits of flooding can be overridden by the excessive transport of freshwater, nutrients, sediment and pollution. The effects of excessive flooding on downstream environments have been documented for many years but we are only just beginning to understand how far-reaching and long lasting the impacts can be. While many studies have shown, for example, localised negative impacts of flooding on the marine environment, such as coral reefs (Butler et al., 2013) or sea grasses (Campbell and McKenzie, 2004), the transport of sediment and nutrients may also have long lasting effects over hundreds or thousands of kilometres (Brodie et al., 2012a).

There have been many reports of flooding impacts on coral reefs (Lovell, 1989; Ayling and Ayling, 1998; Butler et al., 2013; Jones and Berkelmans, 2014). Mortality can rapidly occur when corals experience extreme hyposalinity (Jokiel et al., 1993) or heavy sedimentation (Riegl, 1995), particularly when combined with high nutrient levels (Fabricius and Wolanski, 2000; Fabricius et al., 2003). Long lasting negative impacts to corals and coral communities may arise through the energetic costs of persisting through degraded water quality that occurs during, and persists after, flooding. Hyposalinity causes physiological and osmotic stress (Fabricius, 2005; Berkelmans et al., 2012) while elevated sedimentation and turbidity reduce photosynthesis, which reduces energy reserves (Philipp and Fabricius, 2003; Erftemeijer et al., 2012). Prolonged exposure of corals to sedimentation and nutrients can result in increased morbidity and bleaching (Weber et al., 2012; D'Angelo and Wiedenmann, 2014; Pollock et al., 2014), while the need for repeated removal of sediment comes at great energetic cost (Stafford-Smith and Ormond, 1992; Weber et al., 2006).

Although the potential negative effects of flood plumes on corals are well understood, rarely are measurements made on reefs during the course of flooding to understand the spatial and temporal variation in salinity, sediment, turbidity and nutrients. Such variations may be significant. For example, during the 2011 floods in Hervey Bay, Queensland, Australia coral mortality varied with proximity to the mainland as a result of wind direction, currents and flood plume pathway, but not with proximity to the adjacent

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Mary River (Butler et al., 2013), yet exposure to this river is an important factor in the distribution of coral communities in Hervey Bay (Zann, 2012). While the adverse effects of flood transported hyposaline waters, sediment and nutrients are understood generally, much less is known of the day to day variability in flood waters conditions and how the exposure to this translates into mortality and post-flood coral health. Exposure to these stressors and pollutants can last from hours to months and levels of mortality will depend on the magnitudes and combinations of these stressors (Fabricius, 2005; Berkelmans et al., 2012). In non-flood situations, salinities from 26 to 30 ppt may cause mortality after as little as one day of exposure (Berkelmans et al., 2012). Elevated turbidity (>30 NTU) and sedimentation may take weeks to significantly impact corals (Fabricius, 2005; Weber et al., 2006), however, when sedimentation is combined with elevated nutrients, mortality may take only a matter of days (Fabricius et al., 2003; Weber et al., 2012).

Although water quality monitoring is carried out worldwide, the general aim of these programs is to capture ambient levels of water quality parameters or target the sources of altered water conditions over broad time frames. These time scales tend to be inappropriate for capturing acute short term events such as flooding, which require a more targeted, intensive sampling regime over hours, days or weeks at the onset of flooding, which itself is unpredictable. Generalised large scale monitoring, while appropriate for measuring regional conditions, is inappropriate for understanding water conditions in particular habitats at specific locations. The actual content of floodwaters and their duration in the water column are important for understanding the true exposure of an organism to these altered conditions. In eastern Australia, for example, as a result of the ephemeral nature of the river systems, floodwaters are the primary means of sediment and nutrient transport to downstream areas (Furnas, 2003; Wooldridge et al., 2006). Knowledge of the magnitude of floodwaters and the conditions within them is thought to provide great insight into the health of the catchment from which the floodwaters were derived (Wallace et al., 2009; Kroon et al., 2011; Kroon, 2012), but these data are rarely collected. Through the measurement of parameters such as suspended solids and nutrients, we can assess impacts (e.g. erosion or over-use of fertilisers) within a catchment and then specifically measure their influences through future monitoring to determine the effectiveness of catchment management (Kroon, 2012).

When conducted at local scales, water quality studies can inform local environmental management. For example, such studies could be used to expand on the local relevance of the Environmental Protection Policies (DERM, 2010a,b,c). These regional guidelines are derived from the framework of the Australia New Zealand Environment and Conservation Council (ANZECC) guidelines (ANZECC, 2000) which recommends refining local guidelines to ensure environmentally safe ambient levels of water quality over the long term. However, these guidelines do not account for short term pulses of poor water quality, such as flooding, even though they can cause major, potentially long term, impacts to local marine ecosystems (Preen and Marsh, 1995; Preen et al., 1995; Butler et al., 2013). Local scale water quality studies can also provide further information about the local marine environment. For example, many coastal areas of eastern Australia (e.g. Hervey Bay) have extensive groundwater dependent terrestrial habitats (see atlas: (BOM, 2015)), including extensive areas of seagrass, which are known to, at times, depend upon submarine groundwater discharge (SGD) (Johannes and Hearn, 1985), but little is known about the volume and content of the groundwater discharge itself and any potential for impacts on other local habitats, such as coral reefs. Elsewhere, SGD is considered to be a significant source of hyposaline water, nutrients (Moore, 2010) and pollutants (Costa et al., 2008; Burnett et al., 2009) to the marine environment, especially during periods of flooding (Santos et al., 2013).

In January 2011, intense flooding occurred along the east coast of Queensland, Australia (Fig. 1). In January 2013 and then again in February 2013 this same region experienced another two episodes of intense rainfall, including a severe storm from a passing tropical low pressure system (ex-cyclone Oswald). The subsequent downstream transport of sediment and freshwater from the highly modified Mary River resulted in flood plumes that travelled over seventy kilometres from the mainland into Hervey Bay (Fig. 1) and along the coast to the north (Fig. 2). This study follows on from initial work which assessed the impacts of the 2011 Mary River flood on the marginal, high-latitude coral reefs of Hervey Bay (Butler et al., 2013). Here we examine the effects of repeated flooding on the coral communities of Hervey Bay. We investigate changes in water quality over the course of the 2013 flood plumes and assess changes in hard and soft coral abundance relative to 2011 levels. Moreover, to investigate the effects of multiple flood events on the coral reefs of Hervey Bay, we compare post-flood coral abundance to pre-flooding conditions in 2010. Our study thus provides understanding of the effects of flood plume waters on water quality, on the duration and spatial variability of flood conditions and on the impacts of repeated flooding from the highly anthropogenically modified Mary River catchment on the coral reefs of Hervey Bay.

2. Materials and methods

2.1. The study area

Hervey Bay (25.3°S, 152.8°E) is situated at the northern end of the Great Sandy Straits on the southern coast of Queensland, Australia (Fig. 1). Six coral reef sites were examined for this study: 4 Mile Reef, Burkitt's Reef, Pt. Vernon West, Pt. Vernon East, Pialba and Big Woody (Fig. 1). Four Mile Reef occurs at 10 m depth and all the other reefs of this study occur in 5 m depth (Highest Astronomical Tide (HAT)) and are variously located up to 70 km from either the Burnett or Mary rivers and up to 5 km from the mainland (Table 1). All reefs are protected from prevailing oceanic swell by the presence of Fraser Island, although Burkitt's and 4 Mile reefs are more exposed to wave action due to longer fetch (70 km) (Fig. 1). Hervey Bay, the reef sites and the Mary River are described in further detail by Butler et al. (2013).

2.2. Nearshore water quality monitoring

We initiated a water quality measurement program on January 29, 2013, just after the onset of the first flood of 2013, to monitor water conditions in the flood plumes through the nearshore coral reef areas of Hervey Bay. We conducted sampling every few days during the flooding but, after water conditions cleared through April, it was reduced to monthly until August. We chose the three sampling locations, Pt. Vernon West, Pt. Vernon East and Pialba (Fig. 1) because of the existence of long-term coral monitoring data for these sites and due to easy accessibility from shore by inflatable watercraft. The timing of sampling at the reefs also complemented an existing offshore monthly water quality sampling program carried out by the Queensland state government. In the nearshore reef areas, we collected three samples between 200 and 700 m from the Hervey Bay shoreline (Fig. 1). Samples were collected approximately 100 m apart and from approximately 80 cm below the surface in waters that were ~2 to 3 m depth at mid-tide. All samples were either chilled or frozen, as required for specific tests, and then sent for analysis to a local National Association of Testing Authorities (NATA) approved laboratory (Wide Bay Water,

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