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Essential requirements for catchment sediments to have ongoing impacts to water clarity in the great barrier reef

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ABSTRACT

Increasing concerns over decreasing water quality and the state of coral reefs and seagrass meadows along the inshore and mid-shelf regions of the Great Barrier Reef has led to a large-scale government catchment sediment and nutrient reduction program. However the mechanistic understanding of how fine sediments washed out of catchments and transported within flood plumes leads to ongoing increases in turbidity at locations far downstream from estuaries long after flood plumes have dissipated is poorly understood. Essential criteria which need to be met in order for catchment-derived sediments to play a major role in nearshore water quality are proposed. Preliminary estimates of these essential criteria suggest that it is dynamically possible for fine sediments washed out of catchments during floods to be preferentially re-mobilised at downstream locations following the dissipation of flood plumes. However the longer-term influence of catchment-derived material on water quality is dependent upon the rate of degradation of floc particles that fall out of flood plumes and the rate of background deposition; neither of which are well quantified.

1. Background

Like many coastal environments and ecosystems, the coastal and continental shelf marine ecological communities of the Great Barrier Reef (GBR) are exposed to multiple threats. These include ocean warming and acidification, and local threats in the form of activities such as fishing, and modification of coastal catchments for urbanisation and agriculture (GBRMPA, 2014). Of these threats, it has been accepted that by far the greatest threat is global climate change, manifested through ocean warming and acidification (Pandolfi et al., 2011). Zooxanthellate corals have upper water temperature thresholds, above which thermal stress and bleaching can occur (Tchernov et al., 2011). The magnitude of this threat is demonstrated by the recent unprecedented coral bleaching event that have occurred on the GBR, and other reef systems (Ainsworth et al., 2016).

The GBR system is often categorised into three cross-shore zones: the narrow inner coastal zone (from the coast out to water depths of around 20 m), the outer fringing reefs that are located on the shelf-break or offshore edge of the continental shelf, and the lagoon that separates the coastal near-shore waters from the outer barrier reef system (Belperio, 1983; Orpin et al., 1999). Whilst coral reefs can be found in all three zones, the majority and best-known reefs are located on the offshore or eastern edge of the GBR system (Belperio, 1983). Diving tourism operations preferentially take tourists to these outer barrier reefs where possible as it is widely accepted that the combination of high underwater visibility and biodiversity on these offshore reefs leads to the best underwater experiences.

Over recent decades the water quality in the narrow nearshore coastal zone has been of increasing concern (i.e. McCulloch et al., 2003; Brodie et al., 2012). Although a lack of long-term water quality data hampers our ability to gain an adequate baseline of water quality along this coastline (Gibbs, 2013), it is now accepted that land-use changes to adjoining catchments have increased the delivery of material and contaminants from catchments into the nearshore coastal waters (Kroon et al., 2012; Brodie et al., 2012). Like in many other coastal regions of the world, changing land-use practices often result in increased delivery of fine sediments, nutrients and agricultural and other chemicals into waterways and ultimately to the coastal ocean. GBR catchments are no exception to this and it has been estimated that following large-scale land clearing and urbanisation of regional settlements since European colonisation of the catchments in the mid-1800′s, there has been a 3 to 8 fold increase in the average annual delivery of catchment loads (Kroon et al., 2012). Whilst this increase is substantial, it is small by comparison to many other catchments that have been developed. For example Douglas (1996) estimate that heavily logged Malaysian catchments can deliver over 20 times more suspended sediments than equivalent unlogged catchments. Walling (1999), citing Morgan (1986), highlight that in China cultivation has increased soil erosion rates from <0.2 kg m^{-2} year^{-1} to up to 20.0 kg m^{-2} year^{-1} (two orders of magnitude).

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The estimated increased average annual load of sediments, nutrients and pesticides into the GBR lagoon receiving waters has led to increasing concerns over the influence of these catchment loads on the water quality in inshore and mid-shelf GBR waters (Brodie et al., 2012). Increased nutrient loads has been linked to the onset of outbreaks of Crown of Thorns starfish, which after ocean warming and acidification is seen to be the next greatest threat especially to mid-shelf colonies coral colonies (De'ath et al., 2012). Ecological communities such as coral colonies and seagrass meadows can be particularly sensitive to increasing sedimentation and turbidity (i.e. Vermaat et al., 1997; Longstaff and Dennison, 1999; Weber et al., 2006). As a result, a number of studies have investigated the possible and probable impacts of increased catchment sediment loads on coral reefs and seagrass meadows along the coastline on the western or inshore side of the GBR lagoon. It is these catchment-derived fine sediments and their potential impact on seagrass meadows and coral colonies that is the focus of the thinking presented here.

There are three major cause-effect mechanisms through which catchment loads can increase the turbidity of coastal waters in the GBR downstream from major estuaries or point sources of freshwater. The first cause-effect mechanism is when major rainfall events in the catchment deliver large volumes of sediments, nutrients and pesticides into waterways, which then discharge into the coastal ocean in the form of a turbid flood plume (i.e. Dagg et al., 2004). Major flood plumes act to immediately reduce light reaching sub-tidal ecological communities such as coral reefs and seagrass meadows that lie beneath the plume (Devlin and Schaffelke, 2009). The second major cause-effect mechanism occurs when the material transported long distances as suspended load in flood plumes falls out of the water-column and settles on the seabed. This material is then potentially available for ongoing re-suspension by subsequent wind events. Therefore in this cause-effect mechanism the impacts on turbidity or catchment-derived material can continue long after the flood plume itself has dissipated (Fabricius et al., 2014, 2016; Delandmete et al., 2016). The third cause-effect mechanism is when suspended sediments that fall out of the flood plume close to the estuary, or point where the river discharges into the coastal ocean, are later transported alongshore as a result of littoral drift and/or as bedload along the continental shelf (i.e. Lambeck and Woolfe, 2000). This material can be spread out or distributed downstream and can therefore potentially be available for ongoing re-suspension by waves and tidal currents in locations that are distant from the estuary.

Through the second and third mechanisms identified above, the ongoing re-suspension of fine sediments that are delivered to the coastal zone in the GBR region can potentially lead to routine reductions in clarity/increases in turbidity long after flood plumes have dissipated. Given that the high value ecological coral and seagrass communities that exist in the nearshore zone in the GBR are sensitive to such reductions in water clarity, it is not unreasonable to be concerned that systemic changes to water clarity may lead to ongoing unwanted impacts to these ecological communities. As such, a number of studies have investigated potential links between changes to catchment land-use and the condition of coral and seagrass communities in the nearshore zone. For example, Fabricius et al. (2014) developed statistical relationships between the mean photic depth in the GBR nearshore coastal ocean estimated from remote sensing platforms and river flows and identified that up to 74% of the variability in photic depth across the whole GBR nearshore zone could be explained by variability in freshwater discharges from major watercourses. More recently, Petus et al. (2016) developed statistical relationships between satellite sensor-derived estimates of river plumes and *in situ* measurements of seagrass meadow abundance and a proxy for coral cover. This analysis suggested that around half of the variability in seagrass abundance but <1% of coral cover abundance could be explained by the variability in river plumes. Logan et al. (2013) analysed water clarity in Cleveland Bay, which is located around 100 km downstream of the Burdekin River, the major single point source of freshwater in the GBR region (Fig. 1; Kroon et al., 2012), and found that only 14% of the variability in water clarity could be explained by variability in Burdekin River sediment loads although this analysis included effects from local winds and tides.

These statistical studies generally suggest that cause-effect linkages exist between the variability in turbidity at coastal near-shore locations tens and hundreds of kilometres downstream from major river sources and variability in catchment rainfall and land-use practices. However, such statistical studies deliberately do not explicitly model the actual dynamical or mechanistic processes of sediment or river plume transport. Furthermore, without a detailed understanding of sediment transport dynamics or pathways along the GBR coastline the contribution that newly-delivered sediments from catchments make to increasing turbidity cannot be ascertained. Orpin et al. (1999) identified that much of the nearshore coastal waters in the GBR region feature large stores of relic sediments that are available for ongoing re-suspension whenever oceanographic conditions are energetic enough to mobilise these sediments. Following this logic, Orpin et al. (1999) argued that post-European settlement increases in the delivery of sediments into the GBR lagoon should make little difference to present-day turbidity as there is already an abundance of sediments available for re-suspension. This argument is supported by a number of data sets of turbidity from a range of locations along the GBR coast that demonstrate that increases in turbidity routinely occur as a result of re-suspension of fine sediments even during periods when there has been little recent input from catchments (see for example Orpin and Ridd, 2012).

An important result from both the statistical studies and the dynamical or mechanistic studies of for example Orpin and Ridd (2012) is that there are key gaps missing in our understanding of the fate of material delivered into the GBR lagoon during major catchment flood events. In particular, the relative roles that these newer sediments discharged from catchments play in contributing to increasing turbidity at locations far away from estuaries by comparison to the existing relic sediments remains unclear. Two recent studies have helped to better fill these information gaps.

Lewis et al. (2014) analysed sediment data from the mouth of the Burdekin River and at downstream locations to the north of the Burdekin estuary. Analysis of these samples indicated that the majority of the fine sediments (defined in this work as <63 μm) discharged from the Burdekin River during major catchment flooding events are retained within around 50 km of the river mouth. With regards to the three cause-effect mechanisms identified above, the Lewis et al. (2014) result suggests that the second mechanism, whereby major loads of mineral sediments fall out of flood plumes as they traverse downstream along the coastline, mostly only occurs in the vicinity of river mouths and estuaries.

This result is consistent with the study of Bainbridge et al. (2012) who analysed samples taken from Burdekin River plumes taken following major rainfall events in 2011. A key result from this study was that as the river plume progressed along the coast, large flocs formed around fine mineral particles and these large exoploymer flocs (formed from biological organisms attaching themselves to mineral particles) were the primary cause of increased turbidity at locations many tens of kilometres downstream of the source of the plume. Bainbridge et al. (2012) also speculated that these flocs could ultimately fall out of the plume and hence be available for re-suspension long after the plume had dissipated. Therefore in terms of the three cause-effect mechanisms described above, it is clear that large river plumes do lead to short term increases in turbidity far downstream as a result of these large flocs (cause-effect mechanism 1), and the same flocs can then fall out of the water-column to potentially be available for future resuspension (cause-effect mechanism 2).

2. Scope of the thinking presented here

The Bainbridge et al. (2012) and Lewis et al. (2014) studies helped to fill critical gaps in the cause-effect mechanisms identified above.