CSIRO PUBLISHING

Marine and Freshwater Research, 2009, **60**, 1196–1200 www.publish.csiro.au/journals/mfr

Catchment management and health of coastal ecosystems: synthesis and future research

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Abstract. Globally, many coastal ecosystems are threatened by a decline in water quality from land-based runoff. However, dynamic and complex biophysical and socioeconomic interdependencies often hamper the reversal of this decline in water quality. This Special Issue illustrates an integrated approach to address deteriorating water quality from land-based runoff in the Tully basin to the Great Barrier Reef (GBR), Australia. Nitrate was identified as the key pollutant, and was mainly derived from sugarcane and banana farms. To achieve GBR water quality targets for chlorophyll *a*, the dissolved inorganic nitrogen (DIN) load needs to be reduced by at least 80%. Modelling shows that financially beneficial changes to management of sugarcane results in a 50% reduction in DIN load. However, larger reductions would come at a significant cost. An adaptive approach is proposed as a framework to assess (i) the efficacy of implementing the recommended management practices, and (ii) progress against set targets. Quantification of linkages between catchment management and coastal ecosystem health will help inform management strategies based on ecosystem performance measures. Verification of the efficacy of existing and exploration of innovative management strategies, as well as spatial and temporal prioritisation of their implementation, remain critical to achieve coastal ecosystem rehabilitation, including water quality improvement.

Additional keywords: Great Barrier Reef, integrated assessment, water quality.

Introduction

Coastal ecosystems around the world are threatened by a decline in water quality from land-based runoff (Rabalais *et al*. 2009). This decline is related to coastal human settlement, particularly land-clearing, urban and agricultural runoff, and industrial and sewage discharge (Smith and Schindler 2009), along with removal of the ecosystem's filtering and buffering capacity (Lotze *et al*. 2006; Verhoeven *et al*. 2006). The effects of declines in water quality worldwide range from sedimentation (Lotze *et al*. 2006), eutrophication (Smith and Schindler 2009) and large scale hypoxia (Zillén *et al*. 2008; Rabalais *et al*. 2009) to reductions in marine biodiversity (Fabricius 2005; Fabricius *et al*. 2005; Waycott *et al*. 2009) and fisheries catches (Caddy 2000; Lotze *et al*. 2006). However, rehabilitation of coastal ecosystems, including reversing the decline of water quality, has proven to be challenging because of dynamic and complex biophysical and socioeconomic interdependencies (Hughes *et al*. 2005; see also Parker *et al*. 2001).

Evidence of coastal ecosystem degradation in the Great Barrier Reef (GBR), Australia, has been linked with land-based runoff of suspended sediment, nutrients and pesticides from agricultural sources (Furnas 2003; Fabricius 2005; Fabricius *et al*. 2005). To reverse this decline in water quality entering the GBR lagoon, the Australian and Queensland Governments jointly launched the Reef Water Quality Protection Plan (the Reef Plan) in 2003 (Baker 2003; State of Queensland and Commonwealth of Australia 2003). However, as in other coastal systems around the world, the dynamic and complex biophysical and socioeconomic environment of the GBR (e.g. Olsson *et al*. 2008) appears to hamper this reversal in water quality decline (Brodie *et al*. 2008). Through integration of research across biophysical, socioeconomic and institutional disciplines, the papers in this Special Issue provide a substantial advance towards achieving water quality improvement for coastal ecosystems. While focusing on the Tully basin in the GBR (fig. 1 in Kroon 2009), the approaches and implications presented in this Special Issue extend to research and management of all coastal ecosystems where human activities alter water quality and ecological processes against a background of population growth and climate change.

Main findings

Key pollutants and critical sources

To establish pollutant load targets for end-of-catchment to achieve water quality improvement in the GBR lagoon, the key pollutants and critical sources for the Tully basin were identified through water quality monitoring and modelling. Nitrate and diuron were the key pollutants, with the critical sources being fertilised land uses for nitrate and sugarcane farms for diuron (Armour *et al*. 2009; Bainbridge *et al*. 2009*a*; Mitchell *et al*. 2009). The prioritisation of pollutants was based on comparing runoff between fertilised land uses and natural forest

 10.1071/MF09228 1323-1650/09/111196

(Armour *et al*. 2009; Bainbridge *et al*. 2009*a*; Mitchell *et al*. 2009), evidence of transport to receiving waters (Devlin and Schaffelke 2009), and exceedences of ecological protection trigger values (Bainbridge *et al*. 2009*a*; Devlin and Schaffelke 2009). Verification of the pollutant prioritisation is required using a formal ecological risk assessment, given that concentrations of total suspended sediment, chlorophyll *a* (Chl *a*, a proxy for nutrient availability), particulate nitrogen and particulate phosphorus are also exceeding ecological protection trigger values in flood plumes (Devlin and Schaffelke 2009).

To establish management action targets for water quality improvement in the Tully basin, marine ecosystem targets were linked to end-of-river pollutant load targets and to farm-level management practice targets (Brodie *et al*. 2009). This demonstrated that to achieve current GBR water quality targets for Chl *a*, end-of-river DIN loads would have to be reduced by at least 80% (Brodie *et al*. 2009; see also Wooldridge *et al*. 2006). Larger reductions in nitrate loads may even be required, because by not accounting for flood flows correctly, current estimates of the annual average discharge may be 15% too low and annual loads of nitrogen 47% too low (Wallace *et al*. 2009). Catchment modelling showed that almost 85% of the total DIN loads are derived from sugarcane and horticulture farms (Armour *et al*. 2009), making these land uses the prime target for nitrate reduction strategies. Moreover, management for water quality improvement in neighbouring basins is also required to reduce exposure of Tully's receiving waters to nitrate (Maughan and Brodie 2009). To enable scientifically robust target setting for pollutants across the GBR, development of quantitative models that link marine ecosystem targets to end-of-river pollutant load targets to catchment action targets is required (Brodie *et al*. 2009).

Changes in land uses and land management

To examine the economic and environmental effects of changes in land use and land management for water quality improvement in the Tully basin, the cost-effectiveness of changes in management practices to achieve pollutant load targets was estimated. Catchment modelling estimated that current end-of-river DIN loads can be reduced by up to 66% by decreasing N fertiliser applications in sugarcane, using increasingly experimental management practices that must still be validated (Armour *et al*. 2009). Up to 50% reduction in the end-of-river DIN load can be achieved using available management practices at no additional cost (and possibly even financial benefit) to the regional sugarcane industry, whereas larger reductions (i.e. −80% end-of-river DIN load target) come at a significant cost because land needs to be taken out of production (Roebeling *et al*. 2009). Implementation of recommended practices in sugarcane farming is further supported because they are likely to result in a greater reduction of nitrogen surplus than current practices under predicted climate change scenarios (Webster *et al*. 2009). To examine additional options for reducing DIN loads, priority areas were identified for riparian rehabilitation to enhance nitrate removal in groundwater (Rassam and Pagendam 2009). In addition to spatial prioritisation of implementing effective management practices (Roebeling *et al*. 2009; Rassam and Pagendam 2009), temporal prioritisation is required to address the most urgent threats to GBR ecosystem health first.

Planning frameworks and processes

To support the development and implementation of recommended management actions in the Tully basin, the planning frameworks and processes for water quality management were evaluated in light of current decentralised approaches to complex environmental management issues (Corburn 2003; Lane and Robinson 2009). Community participation in water quality planning demonstrated that all participants valued the aquatic ecosystem values of the waters in and downstream from the Tully basin, which provided the basis for setting the most stringent water quality targets (Bohnet and Kinjun 2009). Integrating this community knowledge with scientific and other types of knowledge into the planning framework elucidated three main challenges around knowledge integration and translation: uncertainty and bias in different types of knowledge, timing of knowledge contributions, and responsibilities at local, regional and national scales (Kroon *et al*. 2009). These challenges could be addressed by a developed and tested protocol of an adaptive approach to water quality management that includes (i) documenting uncertainties and performance expectations, (ii) negotiating feedback, and (iii) anticipating iterative and transformative responses to future scenarios (Eberhard *et al*. 2009). Verification of the efficacy of this protocol is required, given its potential application as a structured approach to the dynamic and complex institutional environment of water quality management of the GBR.

Future research

Linking catchment management and coastal ecosystem health

The development of quantitative modelling frameworks which link land use and practices in catchments to end-of-river flows and loads, then to water quality in coastal waters, and ultimately to coastal ecosystem health enables the setting of water quality targets that will sustain coastal ecosystem health (Lancelot *et al*. 2007; Wulff *et al*. 2007; see also Pirrone *et al*. 2005). Such quantitative linkages of catchment pollutant fluxes and coastal ecosystem response are critical to assess the relative benefits and risks arising from reductions in loads of different pollutants and/or in different catchments (Lancelot *et al*. 2007; Wulff *et al*. 2007). In the GBR, it is currently unknown whether set targets and associated implementation efforts will achieve the necessary water quality improvement or are prioritised effectively in a spatially and temporally explicit manner to protect and restore the GBR ecosystem. The development of a transparent modelling framework for target setting will enable the evaluation of set targets, including those in the updated Reef Plan (Reef Water Quality Protection Plan Secretariat 2009). In the GBR, this is particularly crucial if current efforts in land management change appear not to be sufficient (Brodie *et al*. 2009), and biophysical and socioeconomic trade-offs between ecosystem health and catchment management may have to be made (Kragt *et al*. 2009; Thomas *et al*. 2009).

The linkages between water quality from land runoff and coastal ecosystem responses are generally complex and dynamic (Rabalais *et al*. 2009; Smith and Schindler 2009). The response of coastal ecosystems to changing water quality may be delayed in time (Bainbridge *et al*. 2009*b*), interact with other variables such as temperature (e.g. Schlöder and D'Croz 2004; Wooldridge and Done 2009), or may be overridden by other variables, in case of reduced coral growth due to ocean acidification (De'ath *et al.* 2009). Hence, the level of risk associated with using water quality targets as surrogates for ecological outcomes may be high. To address this, an ecological risk assessment of water quality pollutants, which objectively ranks the risk of individual contaminants (e.g. Jones *et al.* 2005), is a critical first step to ensure the right pollutants are targeted for management. Furthermore, such a risk assessment will need to be conducted within the context of other potential threats to warrant that resources for restoring coastal ecosystem health, including improving water quality in land-based runoff, are effectively targeted.

Innovative strategies for catchment management

Improvements in diffuse pollution in coastal catchments are generally advanced through changing management practices within current land uses, using voluntary approaches rather than compulsory compliance mechanisms (Gourley and Ridley 2005; Heinz 2008; Reef Water Quality Protection Plan Secretariat 2009). Recommended practices are usually implemented at the local or regional scale of individual farms or industries (Gourley and Ridley 2005), and less so at the larger ecosystem-scale to restore filtering and buffering capacity (Verhoeven *et al.* 2006). The recent purchase of large sugarcane areas north of the Everglades for water storage (Stokstad 2008) provides an example of large-scale rehabilitation of ecosystem function. Such ecosystem-level rehabilitation will be particularly important when current land management practices may not achieve set water quality targets (e.g. Brodie *et al.* 2009), or when pollutant loads may have increased due to removal of wetlands and the installation of land drainage systems (e.g. dissolved organic nitrogen in Tully basin; Wallace *et al.* 2009). Hence, the verification of the efficacy of recommended land management practices, the development of new management practices, and the assessment of current and potential land use change on water quality remain essential requirements to promote desirable regime changes in coastal ecosystems. This includes the spatial *and* temporal prioritisation of land use and land management change to achieve water quality improvement for coastal ecosystem rehabilitation.

Monitoring frameworks to assess coastal ecosystem health

To ensure that water quality management interventions are effective and efficient, changes in land use and land management under both voluntary and regulatory frameworks need to be evaluated against changes in water quality and coastal ecosystem health. The ability to detect such changes, particularly within policy timeframes that are generally shorter than ecosystem response times (Bainbridge *et al.* 2009*b*), would be enhanced by an adaptive approach to monitoring (Eberhard *et al.* 2009; Lindenmayer and Likens 2009). Such an approach is characterised by (i) well defined and tractable questions, (ii) rigorous statistical design of the program, and (iii) valid conceptual models.

In the GBR, a robust design needs to underpin a catchment-to-reef monitoring program to enable the detection and evaluation of changes in water quality by 2013 (Reef Water Quality Protection Plan Secretariat 2009). This design needs to take into account time lags in response times, inter-annual variability in flows, and uncertainty with pollutant load calculations (Bainbridge *et al.* 2009*b*), as well as the concurrent implementation of voluntary and regulatory policy approaches (Reef Water Quality Protection Plan Secretariat 2009). Moreover, the institutional environment for GBR water quality management is a complex and dynamic one, with involvement of local, regional, state and national stakeholders (State of Queensland and Commonwealth of Australia 2003; Reef Water Quality Protection Plan Secretariat 2009) without a formal structure for knowledge integration and translation at or across these different scales (Kroon *et al.* 2009). Although not guaranteeing success, the implementation of an adaptive approach to water quality management (e.g. Mee 2005; Boesch 2006), enabling structured feedback of new findings and recommendations into complex and dynamic environments, will offer the best chance of detecting and evaluating change against set targets within the timeframe required (Eberhard *et al.* 2009).

Conclusions

The papers in this Special Issue focus on aspects of integrated research and management to improve water quality in the Tully basin within the GBR. However, decline in water quality in coastal catchments is a global issue, and the integrated approach to environmental management presented here can be applied more widely. First, quantitatively linking coastal ecosystem health with catchment management, including the prioritisation of water quality pollutants in light of other threats, underpins efforts to set viable targets for management. Second, setting priorities in space and time for implementing catchment management strategies provides the highest likelihood for achieving these targets. Finally, monitoring water quality and ecosystem outcomes against set targets is essential to evaluating and refining management strategies. Such an adaptive approach to environmental management complements those already underway in catchment-to-coast ecosystems elsewhere in the world (e.g. Chesapeake Bay and coastal Louisiana, USA) (Boesch 2006), Europe (Mee 2005), see also Pirrone *et al.* (2005), and a meta-analysis of shared themes, outcomes, and promising research directions is timely.

Acknowledgements

The authors were supported by CSIRO's Water for a Healthy Country Flagship Program. Comments by Andrew Boulton, Iain Gordon and Scott Wilkinson improved this manuscript.

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Manuscript received 9 September 2009, accepted 23 September 2009