Exposure of inner-shelf reefs to nutrient enriched runoff entering the Great Barrier Reef Lagoon: Post-European changes and the design of water quality targets

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Abstract

We used historical flood plume extent data (modelled) to quantify the typical spatial extent of the summer runoff–seawater mixing zone of the Great Barrier Reef (GBR) lagoon. Spatially explicit analysis of the variability of in situ chlorophyll \(a\) concentrations (observed) across the runoff–seawater mixing zone, then allowed us to explore regional differences in the nutrient enrichment impact of runoff events from the various river systems that drain the GBR catchment. We demonstrate the existence of a discernable north–south gradient along the length of the GBR, such that for equivalent runoff:seawater dilutions ratios, lower levels of nutrient enrichment (as indicated by chlorophyll \(a\) observations) result from the river systems that drain the relatively undisturbed northern areas of the GBR catchment, compared to more human-impacted central and south areas. We identify a strong correlation between this north–south enrichment gradient and the flood concentration of dissolved inorganic nitrogen (DIN) entrained by the various river systems. By substituting the nutrient enrichment characteristics of the human-impacted river discharges with those of the undisturbed northern rivers, we provide a means to compare the short-term enriching 'footprint' for existing runoff intrusions with those that are likely to have occurred under pre-European catchment conditions. We demonstrate that under pre-European conditions, the nutrient enriching impact from river runoff was likely to have been largely constrained within 1–2 km of the coast, whereas existing conditions support the impact of reefs some 20–30 km off the coast. By using the developed spatial relations, we show that for the heavily human-impacted river systems, reductions in the end-of-river concentrations of DIN in the order 50–80% are needed in order to restore parity with pre-European conditions. We discuss these results in regard to developing end-of-catchment water quality targets for the region.

Keywords: Terrestrial runoff; Dissolved inorganic nitrogen; Geographically weighted regression; Great Barrier Reef

1. Introduction

A characteristic feature of the annual nutrient balance for coastal waters of the GBR lagoon (Fig. 1) is the pulsed delivery of terrestrially sourced nutrients during short-duration, high intensity flood events, typically associated with tropical cyclones and monsoonal rainfall (Mitchell et al., 1997; Furnas and Mitchell, 2001). The ensuing freshwater river plumes bathe inshore and some mid-shelf reef habitats in nutrient-rich water for periods of days to weeks (Devlin et al., 2001). Post-European increases in the terrestrial nutrient load of river discharges have been cited as a possible cause of reductions in coral growth and a shift in the relative abundance and composition of corals and algae, particularly in nearshore fringing reefs (Udy et al., 1999; van Woesik et al., 1999; Fabricius et al., 2005).

Measures of phytoplankton biomass usually provide a better indicator of the nutrient status of reef waters than...
actual measured nutrient concentrations, since fast growing phytoplankton populations quickly respond to, and subsequently deplete, all available stocks of bio-available nutrients; resulting in localised ‘blooms’ in population densities (Edwards et al., 2003; Furnas et al., 2005). The photosynthetic pigment, chlorophyll a (Chl $a$), is the most commonly used measure of phytoplankton biomass, and hence is also often reported as an indicator of the eutrophication status of coastal reef waters.

A recent review of nutrient exports from Australian catchments (Harris, 2001) reveals that pristine, forested catchments export little nitrogen (N) and phosphorus (P), and what losses there are, arrive largely in the form of dissolved organic N (DON); which is presumed to be largely unavailable for phytoplankton growth (Smith and Hollibaugh, 1997). As catchments are cleared for agricultural purposes however, exports of N increase and the predominant form changes from DON to dissolved inorganic N (DIN); which is completely bio-available for phytoplankton uptake. DIN and more specifically nitrate, in river waters have proven very effective indicators of the degree of catchment development associated with fertiliser use and human population numbers (Peierls et al., 1991; Caraco and Cole, 1999). The development of the GBR catchment since European settlement (~1850) has resulted in similar trends in the end-of-catchment availability of DIN, depending on the proportion of land use dedicated to intensive cropping (fertiliser applied) and beef cattle grazing land use (Fig. 2).

Despite improved understanding of the increasing impact that human activities exert on terrestrial nutrient fluxes within the GBR catchment (Furnas, 2003; Brodie et al., 2003), little quantifiable information exists on its magnitude of influence once delivered into the coastal lagoon. Previous attempts to quantify exposure, and implicitly risk, of reefs to terrestrial material have used simple models which do not attempt to capture the current knowledge of phytoplankton dynamics in the GBR Lagoon (Devlin et al., 2003; Greiner et al., 2003, 2005). A methodology that links plankton biomass response parameters (e.g., Chl $a$), with the end-of-catchment supply of bio-available nutrients could be expected to provide a useful quantitative indicator of the extent (and degree) of terrestrial influence. For the lagoonal waters of the GBR, previous studies have shown that that the availability of DIN usually limits phytoplankton biomass (Furnas et al., 2005), and that the dilution of DIN across the runoff:seawater mixing zone follows an essentially conservative mixing process (Devlin and Brodie, 2005). It is therefore not unreasonable to envisage that the river-specific load of DIN entrained within runoff plumes may initiate a quantifiable signal in the ‘local’ phytoplankton response. This is not to say that other sources of DIN

![Fig. 1. The Great Barrier Reef and its catchments.](image)

![Fig. 2. DIN export concentrations as a function of the proportion of fertilised land use (LUF) in selected GBR catchments. Data is based on the studies of Furnas (2003), Hunter (1997), Mitchell et al. (2005), and Rodhe et al. (2005). The assumption that grazing lands contribute only one tenth of the DIN export per area compared to fertilised cropping lands is based on a number of comparison studies summarized in Brodie and Mitchell (2005).](image)
(e.g., upwelling, resuspension, nitrogen fixation; see Furnas et al., 1995) are not important, but that during the summer runoff period, the terrestrial load would be expected to dominate the inshore coastal phytoplankton response. In such a case, the intensity of a runoff-induced phytoplankton bloom would be related to the river discharge concentration of DIN and its subsequent dilution across the mixing zone. River discharges with higher concentrations of DIN could therefore be expected to support larger phytoplankton blooms at each progressive level of dilution, compared to ‘cleaner’ river discharges; thereby increasing the enriching ‘footprint’ of terrestrial runoff intrusions.

In this paper we pursue this idea by exploring regional differences in the nutrient enrichment patterns that result from summer runoff events in the numerous river systems that discharge into the GBR lagoon. Specifically we seek to quantify any discernable differences in the size of phytoplankton blooms resulting from enrichment by terrestrial runoff occurring in the relatively undisturbed northern areas of the GBR catchment and those occurring in the more human-impacted central and southern areas. To assist in this endeavour, we utilise a spatial analysis technique known as geographically weighted regression (GWR). The technique allows us to test for spatial variance in a regression relationship that equates a given ratio of runoff:seawater dilution to an in situ concentration of Chl a. Our hypothesis is that for a given runoff:seawater dilution ratio, any broad-scale differences in the in situ Chl a concentration observed between river systems, can largely be attributed to the initial concentration of bioavailable nutrients in the discharging runoff. We specifically use DIN as the most influential nutrient in driving Chl a concentrations, as phytoplankton growth in the GBR lagoon is considered to be primarily limited by nitrogen availability (Furnas et al., 2005).

We test the validity of this hypothesis using a variety of historical GBR datasets that characterise (i) the spatial extent of runoff-seawater dilution ratios (modelled), (ii) runoff-induced in situ Chl a concentrations (observed), and (iii) flood-induced river nutrient concentrations (observed). In as much as the differential enrichment responses for the various rivers systems are linked to the extent of human alteration in the adjoining catchments, this study should contribute to our understanding of the changes in the extent of exposure of inner-shelf reefs to nutrient enriched runoff that are attributable to post-European development. By providing a methodology that links a quantitative river discharge parameter (DIN concentration in event flow) with a quantitative indicator of health in the marine environment (Chl a concentration), we are also able to provide tentative estimates of the level of reduction in fluxes of a land-sourced material (DIN) that is required to achieve specified lagoonal water quality standards. We discuss these implications with respect to the process of developing rational end-of-catchment water quality targets for the region.

2. Study area

The reefs and other ecosystems of the GBR are embedded on a shallow coastal shelf that varies in width from 50 km in the north to over 200 km in the south (Fig. 1). Water depths increase across the shelf to a maximum of 100 m before the shelf break and average about 35 m. The matrix of reef structures on the outer margins of the shelf creates an incomplete barrier to the deep oceanic waters of the Coral Sea. The open water body contained between this outer barrier and the coast is commonly known as the GBR lagoon. The shallowness and width of the GBR lagoon plays an important role in the retention of imported material; distinguishing the GBR system from many other Indo-Pacific coral reefs surrounded by deeper water. The nutrients and sediments held and recycling in the inner-shelf region of the GBR lagoon are dominated by terrestrial sources (Furnas et al., 1995; Furnas, 2003). The numerous rivers systems that drain the 423,000 km² catchment adjoining the GBR lagoon provide the primary delivery mechanism for this terrestrial material (Furnas, 2003; Brodie et al., 2003).

In general, areas in the northern part of the GBR catchment remain relatively undisturbed, with limited cropping and low cattle stocking rates (Furnas, 2003; Brodie et al., 2003). As such, the dissolved nutrient and particulate matter concentrations in coastal waters of the far northern GBR are generally regarded as representative of water quality under minimally altered conditions. The central and southern regions of the GBR catchment however, are characterised by high catchment-wide cattle stocking rates and intensive cropping activities on the coastal floodplains. River discharges from these developed catchments have elevated dissolved nutrient and particulate matter concentrations, for example, DIN concentrations in flood flow for these rivers are up to 30 times that of rivers in the northern undeveloped catchments (140–1400 µg L⁻¹ compared to 14–70 µg L⁻¹) (Brodie, 2002; Furnas, 2003).

Post-European changes in vegetation cover on GBR catchments (Gilbert and Brodie, 2001; Furnas, 2003) may have led to increased runoff and this has certainly been shown to occur in grazing lands at the paddock scale (McIvor et al., 1995). It has also been suggested that this is true at the scale of the Burdekin River (McColloch, 2004); the largest river discharging into the GBR lagoon. However a reconstructed Burdekin discharge record using coral core fluorescent bands (Isdale et al., 1998) suggests that Burdekin flow has decreased in the period 1922–1980 compared to the period 1644–1921. This is attributed to long-term rainfall variation rather than changes in catchment rainfall–runoff relationships. The rivers draining the GBR catchment have limited impoundments, especially as a volume proportion of the annual runoff (Gilbert and Brodie, 2001; Furnas, 2003), and these have only a small effect on runoff.

One of the defining hydrologic characteristics of the rivers that discharge into the GBR is the sharp division
between a wet season state, lasting a short period annually (one to eight weeks) and a prolonged dry season condition. In the dry season, little or no freshwater discharge occurs and the estuaries behave as tidal inlets with a sharp division between freshwater (salinity ~0 psu) and seawater (salinity ~36 psu). In the wet season, estuaries are totally river dominated with the 'estuarine' mixing zone (where the salinities range from 0 to 36 psu) lying outside the river mouth on the continental shelf. A salt wedge exists but lies outside the river itself as the river flushes fresh throughout its depth profile to the sea.

The initial fate of the terrestrial material that is delivered to the GBR lagoon can be understood from the flood plume sampling of Devlin et al. (2001). In the initial mixing zone, water velocity is reduced and changes in pH and salinity, promote flocculation of particulate matter. Most of the river-derived particulate matter initially settles from the plume in this zone (Devlin and Brodie, 2005). A remotely sensed image (MODIS) of the 2005 summer flood event clearly demonstrates this depositional effect around the Burdekin River mouth (Fig. 3a). Representative measurements that have previously been sampled across this depositional zone (see Devlin et al., 2001; Rodhe et al., 2005) are also plotted, demonstrating that particulate concentrations (in this case phosphorus) drop to very low levels only a few kilometres from the river mouth at salinities between 5% and 10%. Dissolved fractions in the river runoff are transported far further than the particulate fractions. For example, typical plots of DIN (and DIP) in relation to salinity within the GBR lagoon in a flood plume (Fig. 3b) suggest an essentially conservative dilution process (Devlin et al., 2001; Rodhe et al., 2005). This conservative mixing behaviour for the dissolved nutrient fractions means that their range of influence may extend across hundreds of kilometres from river mouths.

3. Materials and methods

3.1. Data sources

3.1.1. Runoff:seawater dilution data

An archive of flood plume modelling simulations (see King et al., 2001, 2002) enabled us to quantify typical spatial patterns for runoff:seawater dilution rates within the inner GBR lagoon. The historical database is based on the discharge trajectories and distributions of the Burdekin, Herbert, Tully, Johnstone, Russell, Barron, Daintree, Endeavour, Jeannie and Normanby Rivers for the period 1969–1998 (King et al., 2002). The 30 years of simulations show that after leaving the river, the buoyant runoff plumes are generally advected northwards due to a combination of coriolis force and barotropic hydrodynamics (Wolanski and van Senden, 1983). The extent of cross-shelf dispersion associated with a particular flood plume event is affected by both the discharge volume and the prevailing wind conditions.

The frequency with which the inner-shelf areas of the GBR lagoon experience plume water varies greatly with location along the GBR coast (Devlin et al., 2001, 2003);
reflecting the likelihood of high intensity rainfall falling on the adjacent coast. Plumes occur in inner-shelf waters of the Wet Tropics coast (Herbert to Daintree Rivers) at least annually and often twice a year; the Dry Tropics coast, which includes the Burdekin River produces significant plumes approximately at 3–4 year intervals; the Endeavour to Normanby Rivers on the Far Northern coast produce significant plumes at approximately 2–3 year intervals. The simulated record shows that for large rainfall events, the individual river plumes often merge together and stretch over large portions of the inner-shelf areas; but rarely exceed more than 30 km from the coast.

3.1.2. Chlorophyll \(a\) and river monitoring data

We used data from a network of long-term monitoring sites to help characterise regional variations in the summer (i.e., wet season) concentration of Chl \(a\) across the lagoonal waters of the GBR (Fig. 4). Since 1992, surface concentrations of Chl \(a\) have been sampled at approximately monthly intervals from up to 90 sites (Brodie et al., in press). The individual sites form a series of regional transects that run from inshore to offshore waters. For each regional transect, maximal Chl \(a\) concentrations are typically recorded in summer (October–April inclusive); presumably related to the mixing of nutrient-rich riverine inputs with the warm lagoonal waters whilst the ‘estuarine’ mixing zone occurs away from the river mouth. The monitoring program however is not designed specifically to target maximal runoff influences, instead relying on a regular monitoring schedule.

River nutrient load monitoring has only been undertaken for a limited number of catchments within the GBR. For this study we utilised the long-term (1987–2000) monitoring results of Furnas (2003) to help characterise nutrient loads in the Normanby, Barron, Johnstone, Tully, Herbert and Burdekin Rivers.

3.2. Data selection and rationale

For the present work, we were particularly interested in extracting integrative data summaries from the large volume of raw data that would be most beneficial in eliciting regional differences in terms of the degree of nutrient enrichment per unit freshwater (river) input. In particular we were mindful of (i) developing a consistent runoff:seawater dilution topology with which to interpret the relative influence of runoff at a site (i.e., the relative degree of flood inundation), and (ii) investigating only those periods when terrestrial runoff influences are expected to dominate phytoplankton responses. It was therefore necessary to consider the differing spatial and temporal characteristics of each data source, as well as the limitations imposed by the respective monitoring (or modelling) strategies.

Due to its large drainage area, medium-large discharge events for the Burdekin River dominate the runoff response within the GBR lagoon; typically causing the individual plumes from the many rivers of the Wet Tropics region to merge into a single continuous plume (King et al., 2002). It is during the sampling period surrounding these larger events that elevated Chl \(a\) responses can most confidently be associated with a terrestrial enrichment signal. Upon inspection of the flood plume database (between 1969 and 1998), it was observed that the above mention scenario is represented for runoff:seawater dilution values starting \(\sim\)75th percentile response. We thus chose the 75th percentile runoff dilution value (for each \(2 \times 2\) km pixel) as the representative runoff:seawater dilution topology from which to interpret the relative influence of runoff at each measuring site (Fig. 4). For each pixel, the 75th percentile dilution may actually result from different flood events.

Ideally, we would have been able to match the selected runoff:seawater dilution topology with the equivalent Chl \(a\) response. Unfortunately, as stated earlier, the monitoring program for Chl \(a\) is not designed specifically to target maximal (summer) runoff influences, instead relying on a regular (sometimes opportunistic) monitoring schedule. As a compromise, we undertook our comparative analyses based on the 90th percentile summer concentrations of Chl \(a\) (as characterised from the ensemble of 12 years of data). By choosing the 90th percentile summer value we endeavoured to replicate the relative spatial
profile of Chl \( a \) responses that may reasonably be expected to occur for the chosen runoff:seawater dilution topology. Analysis showed that the choice of a particular percentile was not overly important provided it was towards the more maximal range of the ensemble of Chl \( a \) responses. This makes sense, since these values are most likely to be representative of conditions in which terrestrial influences are dominating.

### 3.3. Integrative spatial analysis

To investigate regional variability in the level of phytoplankton biomass (i.e., Chl \( a \) concentration) found at particular runoff:seawater dilutions, we utilised a relatively new spatial technique known as Geographically Weighted Regression (GWR). In recent years, GWR has become popular for exploring spatial variations among relationships (Brunsdon et al., 1996; Fotheringham et al., 2002). GWR attempts to capture spatial variation by calibrating a multiple regression model that allows different relationships between variables to exist at different points in space. The basic idea is that a regression model is fitted at each point in the data, weighting all observations by a function of distance from that point. The neighbours sampled near the point have more influence on the resulting regression coefficients than observations further away. GWR produces a set of parameter estimates at each point in the defined geographic area. These parameter estimates can then be mapped using visualization tools, such as a geographic information system (GIS), to investigate local spatial variation in the regression relationships under study.

For this study, the GWR model chosen to quantify the relationship between Chl \( a \) (response variable) and runoff:seawater dilution (explanatory variable) may be expressed as

\[ \text{Chl}\ a(\theta) = \alpha(\theta) + \beta(\theta)\text{(runoff:seawater dilution)} + \epsilon \]

where \( \alpha \) and \( \beta \) are location-specific parameters (for which the spatial coordinates are provided by the vector \( \theta \) that represent the intercept and slope of the linear regression respectively, and \( \epsilon \) is a residual error term. For a specific location within the GBR lagoon, it reasonable to interpret \( \alpha \) as representing ambient background summer level of Chl \( a \) regardless of any runoff impact, whilst \( \beta \) captures the sensitivity of the Chl \( a \) response to a specific river runoff volume. Conceptually, the scaling behaviour of \( \beta \) can be envisaged as performing in a similar fashion to a nutrient concentration gradient, i.e., as \( \beta \) increases, the level of nutrient enrichment (per unit runoff input) increases. As such, for an equivalent level of runoff:seawater dilution, a larger value for \( \beta \) will support a higher concentration of in situ Chl \( a \).

For the present study, calibration of the spatial regression parameters was undertaken using an adaptively defined kernel with a bi-square function in which the bandwidth was determined by minimisation of the Akaike Information Criterion (Fotheringham et al., 2002). A Monte Carlo significance test was used to determine if the model parameters displayed significant non-stationarity across the study site (Fotheringham et al., 2002; Hope, 1968).

### 4. Results

#### 4.1. Runoff enrichment in the GBR: dilution gradients

In order to investigate the sensitivity of summer Chl \( a \) observations to the degree of runoff:seawater dilution, we initially pooled all the regional Chl \( a \) measurements into a single, spatially lumped dataset. As expected, Chl \( a \) concentrations were shown to be enhanced for locations in which the relative impact of river runoff was strongest, with progressively lower concentrations observed across the runoff:seawater dilution gradient (Fig. 5a). The result confirms that for the inner-shelf waters of the GBR lagoon, nutrient enrichment from terrestrial runoff sources does contribute to observed variations in the summer concentrations of Chl \( a \). For those sites which are largely outside the runoff–seawater mixing zone, the Chl \( a \) concentrations converged to \( \sim 0.32 \, \mu g \, L^{-1} \); which is representative of ambient summer concentrations for Chl \( a \) in the more offshore waters of the GBR lagoon (Brodie et al., in press).

#### 4.2. Runoff enrichment in the GBR: regional variability

The above ‘global’ regression response derived from the pooled Chl \( a \) dataset implicitly assumes spatial stationarity...
in the relationship between summer Chl $a$ concentrations and the degree of runoff:seawater dilution. Whilst this assumption may be expected to hold true for those for sites outside the runoff–seawater mixing zone, for those sites within the mixing zone, presumably the sensitivity of the relationship will vary spatially in response to the river-specific nutrient concentration of the freshwater inputs. As a first step to investigate this variability we disaggregated the Chl $a$ response data set into three regional subsets (Far North, Wet Tropics, and Dry Tropics; see Fig. 1). The resulting regression relationships (Fig. 5b) suggest that within the runoff mixing zone of the GBR lagoon, there exists significant regional variability in the sensitivity of summer Chl $a$ observations to the degree of runoff:seawater dilution. Generally speaking, the relationships suggest that for an equivalent degree of runoff:seawater dilution, the induced concentration of Chl $a$ in the Wet Tropics will be higher than in the Far North by a factor of 2, whilst the induced concentration of Chl $a$ in the Dry Tropics will higher than in the Far North by a factor of 3–4. In terms of explained variance ($R^2$), the three separate regional regressions are each superior to the spatially lumped ‘global’ regression. In some respects, this is not unexpected since allowing parameters to vary regionally is statistically analogous to including regional factors with numerous levels (i.e., additional degrees of freedom), which precludes meaningful $R^2$ comparisons between regression models. For this study however, we are more interested in confirming the spatially varying nature of the regression parameters; and if possible to apportion the magnitude of this variance to the dissolved nutrient (DIN) characteristics of riverine inputs. For this reason, we extended the regional analysis to include ‘local’ site factors by implementing the GWR approach.

For all the performance diagnostics (Table 1), the GWR model was superior to the ‘global’ regression model. Perhaps the clearest indicator of this superiority is the improved AIC value for GWR model compared with the global model. The AIC provides a measure of how well a model fits the data after taking into consideration the complexity of the model. In general a reduction in AIC of greater than 3 can be attributed to a genuine improvement in a model (Fotheringham et al., 2002). By far the most valuable understanding gained from the GWR analysis is an appreciation of the spatial variance in the model parameters. Any variation in the $a$ (intercept) parameter between sites was shown to be spatially insignificant ($P$-value = 0.54), whilst spatial variability in the $b$ (slope) parameter was shown to be significant ($P$-value < 0.001). This result confirms our earlier indications that: (1) for areas outside the runoff–seawater mixing zone, the concentrations of Chl $a$ are essentially uniform ($\sim$0.3–0.35 $\mu$g L$^{-1}$), and (2) for areas within the mixing zone, the runoff-induced Chl $a$ response is spatially variable.

The value of $b$ (i.e., degree of Chl $a$ enhancement per unit runoff volume) varies in the south–north direction over the entire length of the mixing zone of the GBR lagoon (Fig. 6). The reducing value of $b$ from south–north is suggestive of lower concentrations of bio-available nutrients (per unit runoff volume) for river discharges in the northern areas of the GBR lagoon compared to southern areas. To investigate this finding further, we compared the south–north ‘enrichment’ gradient of $b$ with various flood concentrations of DIN for the regional river systems for which we had information. After comparing the amount of variance explained by a variety of different summary flood statistics, it was found that regional variation in the 95th percentile DIN concentrations (as based on up to 13 years of measurement) provided the most consistent explanation of the south–north variation in $b$ ($R^2 = 0.98$, Fig. 7). The surprisingly strong relationship provides some

| Table 1 | Diagnostic information for the non-spatial (global) and spatial (GWR) regression models |
|-----------------|-----------------|-----------------|-----------------|
|               | Global          | GWR             |                 |
| Effective number of parameters | 2               | 8.58            |                 |
| Residual sum of squares | 4.52            | 2.86            |                 |
| Akaike Information Criterion (AIC) | 26.76 | 18.45 |                 |
| Coefficient of determination ($R^2$) | 0.69 | 0.81 |                 |

Fig. 6. Spatial variation in the modelled nutrient enrichment parameter, $b$, across the mixing zone of the GBR lagoon.
measure of confidence to suggest that observed summer concentrations of Chl \(\text{a}\) on the inner-shelf areas of the GBR may be linked to the event flow concentrations of bio-available nutrients (such as DIN) that discharge into it.

The identification of (i) a within-lagoon, regionally varying spatial enrichment factor (i.e., \(\beta\)), and (ii) a relationship linking its regional variation with the end-of-river concentrations of DIN, provides the opportunity to tentatively extrapolate these findings in an effort to investigate: (a) the spatial patterns of Chl \(\text{a}\) concentrations resulting from specific runoff events, (b) the potential magnitude of change in Chl \(\text{a}\) response due to post-European changes in river water quality, and (c) the levels of improvement in river water quality needed to ensure specified target levels for Chl \(\text{a}\) concentration (in inshore waters) are not exceeded. We investigate the utility and limitations of these predictive capabilities below.

4.3. Runoff enrichment in the GBR: an observed event (Cyclone Violet)

To evaluate the spatial accuracy of the GWR model predictions (on an event basis), we compared observed and predicted concentrations of Chl \(\text{a}\) that resulted from the runoff event associated with Cyclone Violet. The intense tropical Cyclone Violet formed approximately 200 km offshore from Cairns in late February 1995 and moved in a south-easterly direction down the coast. Moderate south-easterly winds after the cyclone passed constrained the runoff–seawater mixing zone to within 10–15 km of the Queensland coastline. Water quality samples were collected from a total of 33 stations in the lagoonal waters adjacent to the mouths of the Herbert, Tully, Johnstone, Russell, and Barron Rivers. In situ Chl \(\text{a}\) measurements were undertaken approximately 2–3 days after the initial riverine flood inputs (Steven et al., 1996). A plot of in situ (observed) versus predicted (modelled) concentrations of Chl \(\text{a}\) in general shows good agreement (Fig. 8). A tendency towards under-prediction of Chl \(\text{a}\) across all concentrations is consistent with limitations implicit in the model for event-based predictions (see discussion for details).

4.4. Runoff enrichment in the GBR: post-European changes

To investigate the potential magnitude of change in Chl \(\text{a}\) concentration (along the GBR coast) due to post-European changes in the nutrient load of riverine discharges, we enforced the runoff enrichment characteristics of the far northern rivers to apply over the entire study area. To achieved this, we constrained the runoff enrichment parameter, \(\beta\), to the value identified for the ‘clean’ far northern rivers. Rather than comparing the differences arising from a single event, we ran the simulation for the entire 30 year archive of runoff events, and then used the ensemble of results to predict the probability that the concentration of Chl \(\text{a}\) would exceed 0.6 \(\mu\text{g L}^{-1}\) in any given year, for any location within the GBR lagoon (Fig. 9). The threshold value of 0.6 \(\mu\text{g L}^{-1}\), represents the upper limit water quality target that has been identified for concentrations of Chl \(\text{a}\) in GBR inshore coastal waters (ANZECC, 2000; Moss et al., 2005). Under the simulated pre-European conditions, the area of intensive nutrient enrichment within the runoff–seawater mixing zone was constrained to within 1–2 km of the coast (Fig. 9). Extent-
sive post-European change is evident for the predicted spatial extent of lagoonal waters that are exposed to elevated Chl $a$ concentrations under current conditions. The area of nutrient enrichment extends up to 20–30 km across the shelf, substantially increasing the number of reefs and other ecosystems potentially exposed to elevated nutrient levels during the summer runoff period.

4.5. Runoff enrichment in the GBR: impact of end-of-catchment water quality targets

We used the identified relationship between the south–north ‘enrichment’ gradient of $\beta$ and the flood concentrations of DIN in the regional river systems to investigate the degree of improvement in river water quality (i.e., % reduction in DIN concentration) that is necessary to ensure that Chl $a < 0.6 \mu g L^{-1}$ for all locations within the GBR lagoon. For this study we only consider a management scenario in which the level of reduction (%) in end-of-river DIN is assumed uniform across all river systems, and only simulate the spatial solution that corresponds to a 75th percentile ($/C24$ in 15 years) runoff event (Fig. 10). As expected, in moving across the runoff dilution gradient for a given river system, progressively lower levels of reductions (%) in DIN concentrations are required in order to achieve compliance with the threshold. For each river system, the highest levels of DIN reduction (%) are situated around the river mouth, where the runoff:seawater ratio is greatest. Visual interrogation of Fig. 10 shows that these maximum values vary for the specific river systems, ranging from a 0–10% reduction in the far northern rivers, to 70–80% in the southern rivers. Care should be taken in interpreting these results however, since the required reductions (%) in end-of-river DIN concentrations are based on the pre-existing river concentrations. For example, to achieve a 10% reduction in the end-of-river DIN concentration from a nutrient-rich river system requires a substantially larger absolute reduction in DIN (in terms of $\mu g L^{-1}$) than a 10% reduction from a nutrient-poor river system.

5. Discussion

5.1. Post-European impacts of runoff enrichment in the GBR

The potential role of post-European development in enhancing the level of sediments and nutrients entering the lagoonal waters of the Great Barrier Reef is a long-standing and controversial issue. Previous work based on coral proxy records has alluded to a 5- to 10-fold increase in the delivery of terrestrial sediments (McCulloch et al., 2003). This study however, is the first attempt at inferring the degree of post-European enhancement in the nutrient enriching ‘footprint’ of runoff entering the inner lagoon. Mirroring the south-to-north gradient of increasing human
development (Furnas, 2003; Brodie et al., 2003), our modelled enrichment parameter (Fig. 6) highlights a potential 10-fold increase in the degree of algal enhancement (=bio-nutrient availability per unit runoff input) associated with the more altered southern catchments. Whilst this level of enhancement is of similar magnitude to that reported for terrestrial sediments (McCulloch et al., 2003), the potential area of influence over which the nutrient enriching impact will be experienced is expected to be far greater. For terrestrial sediments entering the GBR lagoon, the interplay between depositional and transport processes ensures that they typically remain close (<5 km) to the coast until they ultimately settle in mangroves or north facing bays (Orpin et al., 2004). The essentially conservative mixing behaviour of many bio-available nutrients (such as DIN), ensures however, that their area of exposure increases considerably as the degree of runoff enrichment rises. Our modelling work would suggest that the nutrient enrichment area resulting from seasonal runoff events has increased by a factor of ~10–20 since European settlement (Fig. 9); substantially increasing the number of reefs and other ecosystems exposed to terrestrially sourced nutrients.

Whilst our results allude to potentially large post-European changes, it is important to briefly comment upon the assumptions upon which the comparison is based. The use of the northern waters as a pre-European control implicitly assume (i) that the northern catchments remain in a relatively undisturbed condition, and (ii) that the dissolved nutrient status for all river systems within the GBR catchment were roughly equivalent before the commencement of extensive human activities. In terms of the first assumption, evidence provided by Furnas (2003) suggests the likelihood of only limited alteration from pre-European conditions in the northern GBR catchments. The second assumption is more open to conjecture, since vegetation, geological and climatic (including rainfall) characteristics are likely to have varied considerably even before European settlement (Furnas, 2003). However, in terms of dissolved inorganic nitrogen (which is the principal focus of this work), previous results within the GBR catchment (as discussed by Brodie and Mitchell, 2005) show that the key determinants are the proportion of land use dedicated to intensive cropping (fertiliser applied) and beef cattle grazing use (as per Fig. 2); both of which would have been absent before pre-European settlement. Another piece of evidence is provided by data presented in Furnas (2003), which shows that the undisturbed headwater creeks and tributaries of a number of southern catchments exhibit DIN concentrations that are comparable to the undisturbed northern catchments. This occurs despite the fact that the southern catchments have considerably higher DIN concentrations in their lower reaches where farming and cattle production is more intense.

In terms of the ecological impact of post-European changes in the enriching footprint of terrestrial runoff intrusions, it is important to realise that its initial impact will be experienced as a short-term (days to weeks) pulse of high nutrient water, as opposed to a continuing diffuse source. Elevated concentrations of dissolved inorganic nitrogen have been shown to directly effect the stability of the coral-zooxanthellate symbiosis that underpins the health of coral ecosystems; commonly reported symptoms including reduced coral calcification, tissue growth and reproductive potential (see Fabricius, 2005 for a comprehensive review). However, the growing consensus in the literature (Furnas et al., 2005; Fabricius, 2005) is that the largest (continuing) impact of nutrient enriched runoff events is associated with the eventual fate of this nutrient source. After initially being diluted and dispersed in the water column, the nutrients are rapidly taken up by phytoplankton as shown in the central Queensland algal bloom (Fig. 3b), and eventually, after being recycled (once or many times) through pelagic food webs, are converted into other forms of organic matter (DOC, DON, DOP, detritus) (Alongi and McKinnon, 2005; Furnas et al., 2005). This organic matter is ultimately transformed into forms (e.g., marine snow) that may be deposited on benthic communities, such as coral reefs, and influence their structure, productivity, and health (see for example, Anthony, 2000; Fabricius and Wolanski, 2000). It is possible that ecosystem responses to this organic matter (soluble and particulate; e.g., Anthony, 2000; Fabricius and Domnisse, 2000)
is greater than the effect of the nutrients themselves (Furnas et al., 2005; Fabricius, 2005).

Within the GBR, nutrient-stimulated primary production is likely to be a major source of the organic matter that is commonly observed at inshore reef sites. A number of recent studies have documented taxonomic changes in coral reef assemblages along gradients of increasing organic enrichment in the GBR (van Woesik et al., 1999; Fabricius and De'ath, 2004; Fabricius et al., 2005). Consistently observed trends showing the reduction in coral cover and diversity, and the increase in abundance of macroalgae along gradients of riverine influence, potentially alludes to the longer-term and larger-scale impact of increasing terrestrial runoff on reef degradation.

5.2. The design of water quality targets for the GBR

In an effort to halt and reverse the increasing impacts of terrestrial nutrients, sediments and contaminants on the coastal reefs of the GBR, there is a strong management imperative to identify scientifically based end-of-catchment water quality targets that will benefit reefs that are located some distance from the river mouths (Brodie et al., 2001). The expectation of such targets is that they should lead to improved reef habitat conditions, thereby contributing to a set of circumstances that will set the ecology of degraded reefs onto a path of recovery, and thenceforth maintain a more socially desirable reef state through time: one dominated by healthy corals, comparatively less benthic algae; abundant and diverse fishes and invertebrates. Though conceptually self-evident, providing a rational framework upon which to base end-of-catchment target levels is a notoriously difficult process, in part due to the slow and cumulative (rather than acute) nature of water quality impacts, but also due to a lack of appropriate tools with which to link end-of-catchment water quality parameters with quantitative response parameters in the marine environment.

A set of targets for reduction in suspended sediment (SS) and nutrient fluxes to the GBR have previously been developed (Brodie et al., 2001). These were based on modelled estimates (NLWRA, 2001) of the increase in SS, total nitrogen (TN) and total phosphorus (TP) flux in each of the major rivers of the GBR due to catchment development (primarily agricultural development) since ca. 1850. Rivers were then prioritised for reductions in flux of 50%, 30% or zero dependent on their degree of increase over pre-development fluxes. However it was not possible at that time to give a robust connection of these proposed reduction targets to the health of GBR ecosystems. In another project connected to the development of the Reef Water Quality Protection Plan (Anon, 2003) individual rivers were prioritised in terms of their hazard to the health of the GBR (Greiner et al., 2003, 2005) from their discharge. Parts of this work were based on the earlier work of Devlin et al. (2003), who developed river pollution exposure indices for individual coral reefs of the GBR. In addition Greiner et al. (2003, 2005) used socio-economic factors to try and better quantify the hazard. However, as with all the preceding work, there was only limited success in deriving a strong connection between identified river fluxes and their potential impact on GBR ecosystems that are located at varying distances from the riverine source.

The strength of the present modelling approach is that with an economy of effort we have correlated a quantitative river discharge parameter (DIN concentration in event flow) with a quantitative response parameter in the marine environment (chlorophyll $a$ concentrations as an indicator of phytoplankton biomass). Recommended reductions in fluxes of a land-sourced material (DIN) can thus be linked to a measurable response indicator in the GBR lagoon. Facilitating the link between changes in end-of-catchment and reef water conditions is important since it provides an integrative framework with which to prioritise management sites on a geographic and industry-type basis. Given the large size of the GBR catchment ($420,000 \text{ km}^2$), this is crucial, since it is not financially or logistically possible to implement management actions over its entire area at the same time.

Underpinning the utility of the present model is that it targets a specific form of nutrient (DIN), known to be completely bio-available, rather than total nitrogen as used in older targets (Brodie et al., 2001). Total nitrogen targets have a number of problems because they cannot be easily linked to a source. Much of the DIN in rivers draining to the GBR comes from fertiliser use (on sugarcane and horticultural crops) and sewage discharges while particulate nitrogen (PN) is a result of soil erosion associated with beef grazing (Brodie and Mitchell, 2005). Only a part of the TN flux is bio-available – all of the DIN, some of the PN (after mineralisation) and a little of the DON. TN flux is thus a crude measure of potential ecosystem effect threat while DIN has the potential to be far more precise, and thus of far greater importance from a management perspective.

Despite its obvious conceptual appeal, to suggest that the simple spatial modelling approach outlined in this paper is a panacea for the future design of water quality targets would be to ignore some of its limitations. In particular, despite the good agreement for the Cyclone Violet runoff event (Fig. 8), in general, care needs to be taken when interpreting the GWR model predictions on an event basis. The problem arises from the fact that it is not designed to reproduce the phytoplankton behaviour during the early stages of a flood plume discharge, when dissolved inorganic nutrients are not usually taken up due to light limitation caused by high plume turbidity (Devlin et al., 2001; Dagg et al., 2004; Devlin and Brodie, 2005). Concentrations of suspended matter generally need to be reduced below $10 \text{ mg L}^{-1}$ before sufficient light it available to support rapid phytoplankton growth (Turner et al., 1990). Therefore, depending on the river-specific load of particulate material that is discharged into the GBR lagoon, an interval of time ($\sim$days) will need to transpire (during which particulate sedimentation occurs) before gradients
of phytoplankton biomass coincide with the gradient of dissolved inorganic nutrient availability (viz Fig. 3b). Because the Chl-a data on which the GWR model is based where not collected during periods when plume turbidity was limiting phytoplankton growth, this initial plume effect is not captured. Rather, the GWR model predictions of Chl-a concentrations are more likely to reflect a more moderate runoff mixing state in which the biomass of phytoplankton is largely responding to the availability of dissolved inorganic nutrients. Presumably for the Cyclone Violet runoff event, (i) the low suspended sediment load of Wet Tropics rivers (Brodie and Mitchell, 2005), and (ii) the delayed interval (2–3 days) between the initiation of the runoff event and the measurement of Chl-a concentrations assisted in the good agreement between the observed and predicted response.

Other important processes such as desorption of nutrients from fluvial particles (Brodie and Mitchell, 1992) and remineralisation of dissolved organic material from under the plume (for example via nitrification, Alongi and McKinnon, 2005) are also, at best, only implicitly incorporated in the model predictions. Clearly, the modeling approach outlined in this paper will not, and was not designed to reproduce in situ responses based on ‘local’ space-time variability. Rather the approach and choice of data summaries were designed, and show reasonable capacity, at reproducing ‘regional’ space-time nutrient dynamics associated with terrestrial inputs. In particular, the ability to discriminate differential river impacts across large regional areas is noteworthy.

6. Conclusions

Previous work has shown that human development of the GBR catchment, particularly conversion to intensive (fertiliser applied) land uses, has significantly increased the dissolved nutrient status of riverine discharges into the GBR lagoon. In this paper, we developed a modelling methodology that allowed us to infer the impact of these changes in terms of their affect on the size of the nutrient enrichment zone associated with terrestrial runoff events. We showed that the nutrient enrichment ‘footprint’ associated with the summer runoff–seawater mixing zone has increased by a factor of ∼10–20 since European settlement, substantially increasing the number of reefs and other ecosystems exposed to terrestrial nutrient sources. For the most disturbed southern river systems, it was predicted that reductions in end-of-river concentrations of bio-available nutrients in the order 50–80% would be required in order to restore the predicted pre-European water quality regime. Though not expected to reproduce all small-scale variability, the identified spatial relationship between DIN concentration in river event flow and chlorophyll a concentrations (i.e., phytoplankton biomass) in the lagoonal waters of the GBR, can be expected to assist in the difficult process of setting end-of-catchment water quality targets that ensure the continuing ecological integrity of coastal reef ecosystems.

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