Coral Reefs (1999) 18:163–169

NOTE

P. Larcombe · K. J. Woolfe

Increased sediment supply to the Great Barrier Reef will not increase sediment accumulation at most coral reefs

Accepted: 15 January 1999

Abstract The rate of terrigenous sediment supply to the central Great Barrier Reef (GBR) coastline has probably increased in the last 200 years due to human impact on the catchments of central Queensland. This has led some researchers and environmental managers to conclude that corals within the GBR are under threat from increased turbidity and sedimentation. Using geological data and information on sedimentary processes, we show that turbidity levels and sediment accumulation rates at most coral reefs will not be increased, because these factors are not currently limited by sediment supply.

Key words Coral reefs · human impacts
sedimentation · turbidity · Great Barrier Reef

Introduction

The Great Barrier Reef (GBR) shelf hosts the largest coral reef ecosystem on Earth, and a clear understanding of human impacts upon it is important for effective management. The potential impacts of catchment-based human activity on sediments on the coastal zone and coral reefs of the Great Barrier Reef (GBR) coastline are mainly twofold: (1) increased sediment supply, and (2) increased turbidity and/or sediment accumulation. There is a clear case for increased sediment supply to the coastline over the last 200 y (eg. Belperio 1983, 1988; Moss et al. 1993; Neil and Yu 1996; Wasson 1997; see also Bird et al. 1995). While the scale of any such increase remains poorly constrained, we do not contest that an increase has occurred.

The second, and perhaps somewhat contentious issue, is that raised sediment flux to the coast is causing impacts upon coral reefs of the GBR through increasing turbidity and sedimentation. While such a case has not, to our knowledge, been presented in the formal scientific literature, it has become firmly embedded as an environmental management issue and as a focus of public debate (see Zann 1995; Brodie 1996 p.33; Wasson 1997; see also Bell and Gabric 1990, 1991 and Larcombe et al. 1996 for related issues). We evaluate these concerns, using a geological context and an assessment of current understanding of sedimentary processes on the central section of the GBR shelf. While our arguments refer mostly to the post-glacial time period (< 18 ky BP) and the Holocene highstand (about < 5.5 ky BP), similar arguments may apply (to varying extents) to any natural changes in sediment supply during the last and previous interglacials.

The interplay between coral reefs and terrigenous sediment along the inner-shelf of the GBR shelf can be discussed in terms of two principle components, sediment accumulation and suspended sediment (the latter being the main regional contributor towards turbidity). *Sediment accumulation* describes the increase in thickness of a sediment body, caused by addition of material at its upper surface. In this context, accumulation is a regional geological phenomenon, and has probably played a significant role in controlling the distribution of coral reefs within the GBR at various stages of sea level (Woolfe and Larcombe 1998; Larcombe and Woolfe 1999), primarily because accumulating sediments blanket substrates otherwise suitable for colonisation by corals. In contrast, *turbidity* is a transient oceanographic phenomenon, that is temporally and spatially variable because it is largely related to physical forces acting on the sea bed. The role of turbidity in influencing the distribution of corals is thus also spatially variable, related to regional variations in turbidity

P. Larcombe (✉) · K. J. Woolfe
Marine Geophysical Laboratory
School of Earth Sciences
James Cook University
Townsville 4811
Australia
e-mail: piers.larcombe@jcu.edu.au

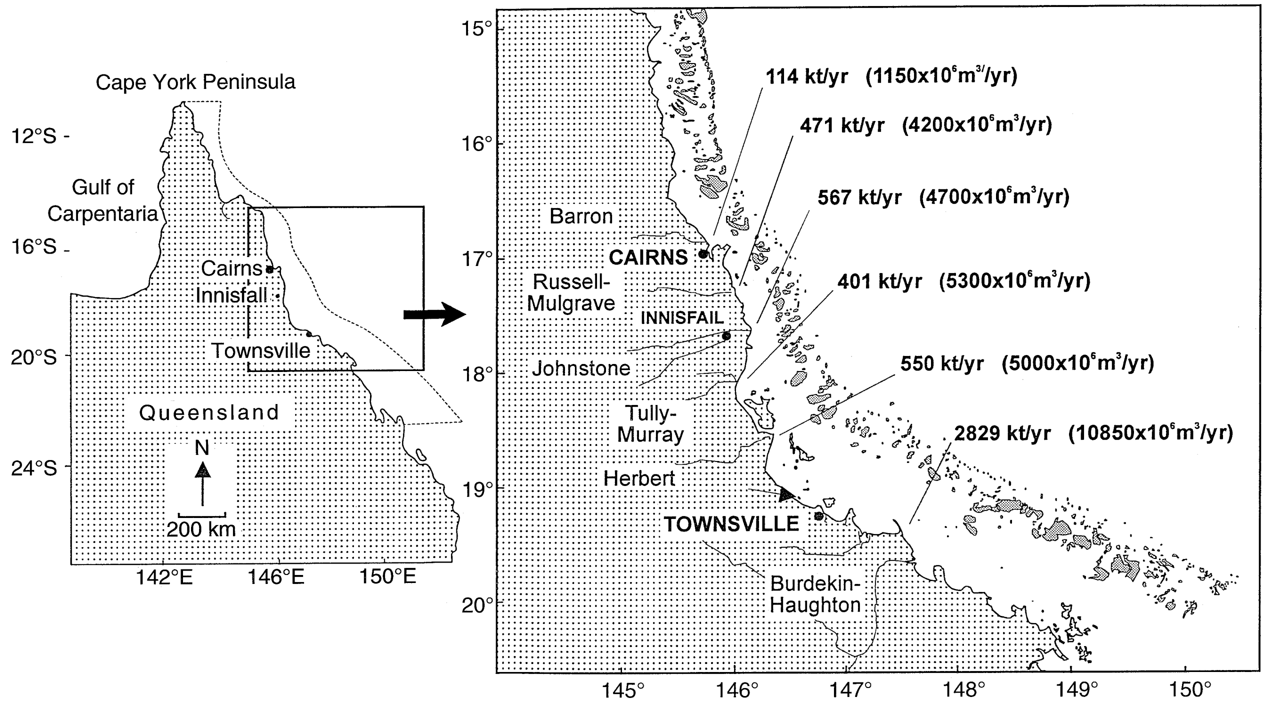

Fig. 1 Location map showing the main rivers adjacent to the central Great Barrier Reef coastline, and their estimated annual discharges of sediment (and water) (from Moss et al. 1993)

regimes, and, also on a regional scale, is probably partly controlled by the location of accumulations of muddy sediments. It is also necessary to distinguish between changes in the turbidity of rivers entering the GBR lagoon and changes in turbidity in the lagoon itself. Few coral reefs occur near river mouths, because of the high turbidity, rates of sediment accumulation, and low availability of suitable substrates generally associated with such environments (Hopley 1995).

The widely perceived impact of increased sedimentation at reef sites on the GBR is well illustrated by Furnas and Brodie (1996) who wrote: '*While many parts of many coastal reefs appear to be in a relatively 'normal' state . . . . shallow flat communities with significant branching coral reef assemblages have largely disappeared from most (though not all!) nearshore reefs over the last* 50–100 *years*'. They went on to state that:
'*In most cases, the degraded reef flat structure has been infilled with sediments. It may be hypothesised that these changes reflect increased sediment and nutrient loads in the coastal zone.*'

However, little supporting evidence exists for increased rates of sediment accumulation or elevated nutrient loads at reef sites. Further, detailed treatments of the supply of sediments (see Fig. 1), freshwater, and nutrients to the GBR lagoon (e.g. Wasson 1997) have not yet led to the establishment of links between increased sediment and/or nutrient supply, changed environmental conditions within the GBR lagoon, and impacts upon coral reefs. To our knowledge, there have been no refereed journal publications which link impacts on GBR reefs with raised turbidity and/or rates of sediment accumulation. Despite this, major reports related to environmental management (e.g. Zann 1995) and a number of articles in popular science journals and newspapers (e.g. New Scientist 1995) promulgate such ideas. In our view, such propositions remain unproven and require explanation. The arguments made in this paper consider only the characteristics of sediment accumulation and turbidity, as necessary first steps for improved appraisals of the potential for impacts from sediment-related factors. Thus, we do not address the potential impacts of changes in supply of sediment-bound contaminants to reefs in the lagoon, or of changed nutrient regimes within it.

Holocene sediment accumulations and sediment availability on the shelf

Along the central GBR coast, sediment transport is predominantly northwards and can be inferred from coastal geomorphology (Hopley 1971; Belperio 1983; Woolfe et al. 1998), current-meter data (e.g. Belperio 1978), Larcombe et al. 1994; Lou and Ridd 1997; Woolfe and Larcombe 1998, and textural and mineralogical data (Beach Protection Authority 1984). This transport direction has been established throughout the mid- and late Holocene, evidenced by the clear pattern of sites of clastic sedimentation along the central GBR coastline. The main terrigenous deposits include relatively minor volumes in chenier ridges and

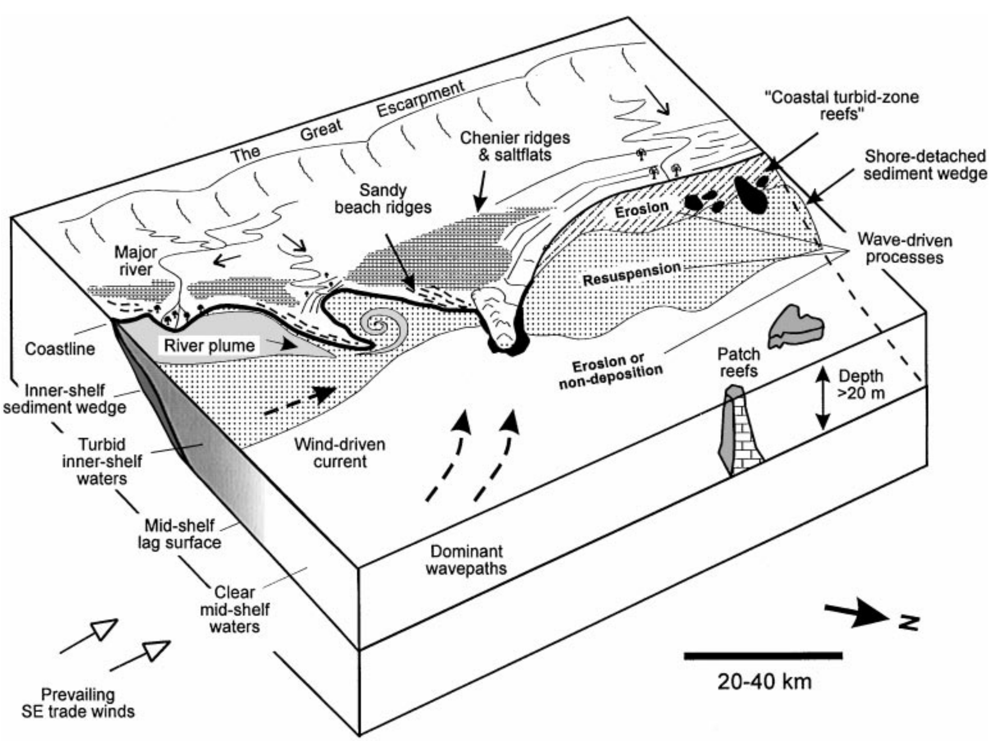

Fig. 2 Schematic view of the central GBR coastline and inner-shelf showing main sedimentary environments and mechanisms of sediment resuspension and transport. Suspended sediment concentrations maintained along the inner shelf by wave resuspension during trade-wind periods greatly exceed those present in river plumes (modified after Woolfe and Larcombe 1998)

inter-chenier plains (the latter largely comprising saltflats) and substantially greater volumes stored in large bodies of muddy intertidal and subtidal deposits. These nearshore deposits form an inner-shelf sediment wedge generally less than 5 m thick, that typically extends out to the 20 m isobath (Maxwell 1968; Belperio 1983). These marine wedges are most prominent in northward-facing embayments, which are relatively protected from the wind and swell waves induced by the prevailing SE trade winds (Belperio 1988; Woolfe et al. 1998). In such environments, the sediment wedges are shore-attached (e.g. Carter et al. 1993). In settings more open to the swell waves, the wedge is commonly shore-detached, separated from the coastline by a narrow band of erosion or non-deposition (e.g. Johnson and Searle 1984; Woolfe and Larcombe 1998). Seaward of the terrigenous wedge and within the main reef tract, the shelf is largely devoid of Holocene terrigenous sediment (Scoffin and Tudhope 1985; Harris et al. 1990). Living coral reefs are absent on the sediment wedge itself, however corals do occur in places immediately seaward of the wedge (especially as fringing reefs on islands) and locally landward of the wedge where the wedge is shore-detached (Woolfe and Larcombe 1998; Larcombe and Woolfe 1999, and Fig. 2).

In most places on the inner shelf, the thickness of the sediment wedge means that there is ample (muddy) sediment immediately available for resuspension. Sediment availability does not limit the concentration of suspended sediment (and largely, turbidity) in the water column, rather the controls are hydrodynamic in nature (e.g. Larcombe et al. 1995; Woolfe and Larcombe 1998; Larcombe and Woolfe 1999). Sediment availability probably only becomes important towards the boundary with the middle shelf, and in areas remote from riverine inputs, where surficial sediments become thin and patchy and will therefore in some circumstances limit turbidity. Consequently, in areas removed from a pro-delta, an increased rate of sediment supply to the coastline would have no detectable effects upon sediment availability, and hence turbidity, sediment transport and sediment accumulation.

Sedimentary processes on the central GBR shelf

Waves, tides and wind-driven currents

The main energy source for sediment transport is the SE trade wind, which blows persistently along the main portion of the GBR lagoon in the ‘dry season’ (about April–Nov.). In contrast, the shorter ‘wet season’ has lighter and more variable winds, except when episodic cyclones occur. The SE winds produce swell waves on the inner shelf (period > 6 s) which are the primary agent of resuspension of bed sediments (e.g. Larcombe et al. 1995). On reaching the shoreline, these waves drive a longshore drift of sandy material to the north, and the wind forces a wind-driven northwards-flowing current. Locally, tidal action may be important in influencing turbidity, (e.g. Kleypas and Hopley 1992). Cyclones, although of high magnitude, are infrequent (Puotinen et al. 1997) and have complex wind and wave fields. Except for some localised areas where rates of coastal progradation have been high throughout the mid- and late-Holocene (e.g. the southern margin of north-facing coastal embayments), cyclones appear to have relatively little long-term sedimentary and geomorphic expression along the coast (Woolfe et al. 1998). Along much of the mainland coastline, waves and wind-driven currents associated with the SE trades appear to have reworked deposits of even the most intense cyclones.

Turbid river plumes

River flood plumes are a relatively local and short-term influence on turbidity on the inner shelf (Wolanski 1994; Taylor 1996). Away from the river mouths, river plumes on the inner shelf of the GBR have sediment concentrations of a few mg/l and may only be one or two metres thick (e.g. Taylor 1996). With northerly or offshore winds, these plumes may extend tens of kilometres offshore and may directly impinge on mid and outer-shelf reefs (Brodie 1996; Brodie and Furnas 1996) before being dispersed laterally and vertically. Despite being visually spectacular (especially by being distinguishable in colour from ambient lagoon water) the sediment load carried by such plumes is minimal. As an example, recent data from a major plume of the Barron River, Cairns (350 km north of Townsville) indicates a plume confined to the upper 2 m of the water column and containing suspended sediment concentrations (SSCs) of only 3–10 mg/l (Taylor 1996). In the event that such a plume was large, extending for 45 km along the coast and for 10 km out from the coastline, then it would contain less than 9000 tonnes of suspended sediment.

In contrast, SSCs in Cleveland Bay, off Townsville, are controlled by swell waves which stir bed sediments and may produce depth-averaged SSCs of 50 mg/l or more (Larcombe et al. 1995). With an area of 200 km^2 and an average depth of 5 m, the total mass of sediment resuspended in the bay is about 50 000 tonnes. Depth-averaged SSCs are probably twice as much during some swell wave events. Thus, the mass of sediment along the central GBR coastline held in suspension by swell waves (which affect the coast for much of the year) is likely to be several orders of magnitude greater than the suspended load introduced by even the largest individual turbid plumes. Consequently, we infer that, in terms of direct sedimentation, turbid plumes are not a significant threat to mid and outer-shelf sites.

Fundamental hydrodynamic controls upon sedimentation

The main factors which control the generation and distribution of turbidity (caused by sediment particles) on the shelf are illustrated in Fig. 3, and described briefly below.

Resuspension by waves

- the maximum shear stress at the bed is related to the maximum orbital velocity attained by water particles near the bed under waves ($U_{b\max}$), which, for any depth, is related strongly to wave period. For the central GBR, swell waves (here defined as those with wave periods > 6 s) are the major influence over most of the inner shelf (Larcombe et al. 1995).

Resuspension and transport by unidirectional current

- the shear stress generated at the bed is less for unidirectional currents than under waves for an equivalent fluid speed, so their ability to resuspend particles is less. On the inner GBR shelf, such currents will commonly augment sediment resuspension by waves, and will transport material already in suspension. However on their own, unidirectional currents (apart from strong cyclone-induced flows) will generally create relatively little turbidity and transport little sediment (Larcombe et al. 1995). In most areas of the shelf, tidal currents on the shelf are unidirectional for periods of a few hours. Wind-driven currents may persist for periods of many days.

Particle settling

- some fine-grained sediment is transported to the coast in riverine waters, maintained in suspension by turbulence. Where these flows meet saline water, they are relatively buoyant, and a surface freshwater turbid plume may extend into the inner-shelf above the saline seawater. Where fresh and saline waters mix, particles may cluster together, forming flocs, with greater settling velocities than the individual particles. This mechanism is locally and seasonally important, in estuaries and within embayments into which large rivers discharge.

Vertical mixing (turbulent diffusion)

- sediment particles in the water column are mixed vertically by turbulence and by vortices of various scales, leading to diffusion of sediment within the water column (see e.g. Dyer 1986).

A full treatment of sediment transport issues may be found elsewhere (Middleton and Southard 1984; Dyer 1986; Wright 1995; Allen 1997). In the context of the GBR, it should be noted that where sediment is already available for resuspension, the addition of extra sediment to the shelf system does not alter the concentration

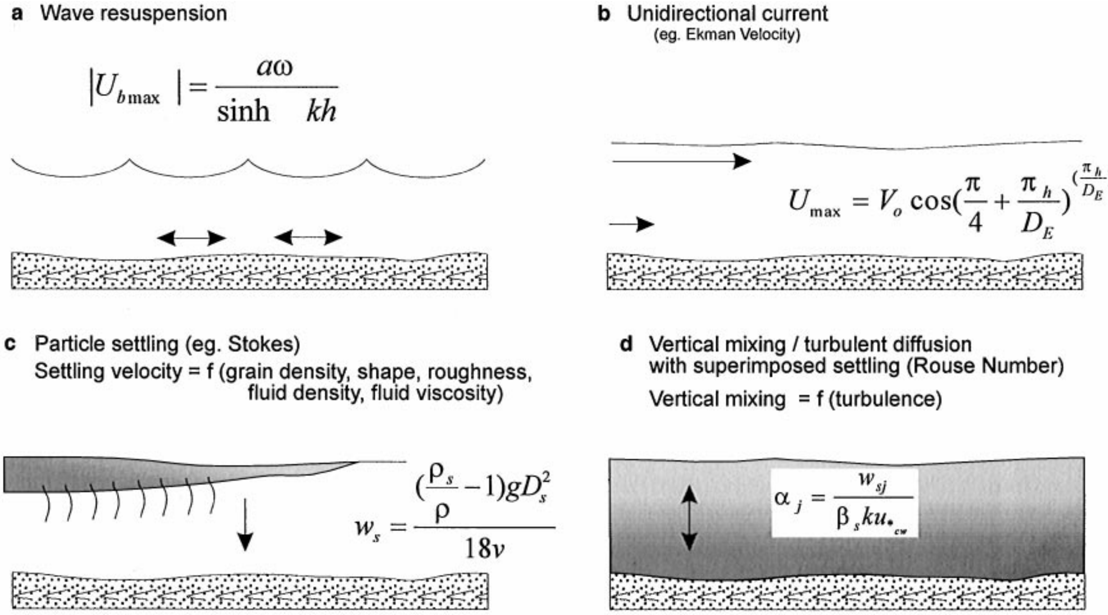

Fig. 3a–d The main factors influencing turbidity. **a** Resuspension of bed material by waves can be represented by the maximum orbital velocity at the bed ($U_{b\max}$), where a is the wave amplitude at the surface, ω the wave frequency (in radians), k the wave number and h is the depth (Wright 1995). **b** Resuspension and transport of suspended material may be strongly influenced by unidirectional currents. For wind-driven currents, a general rule-of-thumb is that the speed of the surface wind-driven current is approximately 3% of the wind speed measured 10 m above the sea surface. In moderately deep water (e.g. seaward of the GBR inner shelf) the decrease in velocity with depth h is given by the Ekman equation, where V_o is the surface current velocity and D_E is the Ekman depth (Allen 1997). **c** Stokes Law describes the rate of settling for fine-grained particles in non-turbulent waters, providing a first estimate of settling from turbid flows, but probably overestimating actual settling rates in nature because of turbulence. Downward settling velocity (w_s) of particles (e.g. from a turbid plume) is estimated using the densities of the sediment particle and the water respectively ρ_s and ρ, the particle diameter (equivalent settling diameter) D, acceleration due to gravity g and fluid viscosity v. For comparison and for coarser particles, see the empirical equations of Gibbs et al. (1971) and Hallermeier (1981). **d** The ratio of the rate of downward settling of particles to that of upward migration through eddy diffusion is given by a Rouse Number (α_j) where, w_{sj} is the downward setting velocity of a particle of size j (see Stokes equation), β_s is a constant (close to unity in unstratified flows), k is the Von Karman constant (0.4) and u^*_{cw} is the current-wave shear velocity (Dyer 1986; Wright 1995)

of sediment in the water column. The controlling parameters are those related to the physics of sediment transport. Locally, and on short time scales, a small degree of sediment transport may remove finer sediment components to leave a layer of coarser, immobile material, which then protects finer sediment beneath from further erosion. This ‘armouring’ of the sea bed may reduce sediment availability and thus turbidity. The period over which armouring is likely to be important will relate partly to the nature and rate of bioturbation. On much of the inner shelf the upper layers of the sediment body are homogenous to depths of 20–30 cm (Belperio 1978; Gagan et al. 1988; Carter et al. 1993), which indicates that the effects of bioturbation exceeds the potential rate of armouring.

Trapping and bypassing along the coastal sediment transport path

On the central GBR, the main point source of terrigenous sediment is the Burdekin River (Belperio 1983, 1988; Moss et al. 1993) and a series of embayments northwards along the coast contain sediments derived largely from this river. Modern and Holocene sedimentation rates decrease northwards in successive embayments. With the exception of true deltaic areas, sediment supply to and accumulation in the inner-shelf wedge is controlled by transport parallel to the coast (Belperio 1983; Woolfe et al. 1998) and is therefore ultimately controlled by winds, waves, and tides. Given this pattern of along-shelf sediment dispersal, an important concept is the ‘trapping efficiency’ of coastal embayments. As used here, an embayment with a trapping efficiency of 10% would trap 10% of sediment introduced into the bay itself (in the long-term) and allow transfer of the remaining 90% downdrift along the coast. Woolfe and Larcombe (1998) have compared sediment accumulation rates for the Holocene (based on core data from Cleveland Bay, near Townsville; Belperio 1978, 1983; Carter et al. 1993; Larcombe and Carter 1998) with accumulation rates inferred by modern measures of sedimentation (time-series oceanographic, turbidity and sediment trap data; Larcombe et al. 1994; 1995; Lou and Ridd 1997). They inferred that Cleveland Bay has a trapping efficiency of only 0.2%, so that the modern bay acts as a zone of sediment transfer far more than a zone of accumulation.

Higher trapping efficiencies might be expected during the mid-Holocene, which would reduce through time as embayments became progressively filled and increased quantities of sediment were transported northward along the coastal transport path. When coastal progradation had progressed to the extent that the effective delta front and pro-delta extended outside the embayment into which the (Burdekin) river disgorged, the coast would have become straightened (in hydrodynamic terms), reducing trapping and increasing sediment bypassing. Marked increases in rates of along-shelf transport, and associated decreases in rates of sediment accumulation in proximal embayments would have resulted. Finally, apart from the potential for slightly reduced wave energies on the late Holocene inner shelf, as the elevation of coral reef flats met sea level (Hopley 1984), there is no evidence to indicate that the major oceanographic forcing factors upon sedimentary conditions have changed significantly since the mid-Holocene.

Progradation of the inner-shelf sedimentary wedge

The regional coastal sediment wedge has in many places prograded seawards a short distance (< 6 km) since the mid-Holocene sea-level highstand, at rates of up to about 1 m/y (e.g. Belperio 1983; Carter et al. 1993). The mean rates of vertical accumulation (over the last 6000 y) range from 0.03–0.2 mm/y on the mid-shelf off Townsville (recalculated from core and seismic data of Ohlenbusch 1991 by Woolfe and Larcombe 1998) to a maxima of 0.5–8.0 mm/y in intertidal zones of Upstart Bay and Bowling Green Bay (Belperio 1983). Rates of sediment accumulation can also be inferred from estimates of sediment supply to the coast. Estimates of the modern (post-European settlement) annual supply of sediment to the GBR shelf from the mainland are about 13–28 Mt (Belperio 1983; Moss et al. 1993; Neil and Yu 1996). Assuming that the sediment grains have an average density of 2.7, and that they are deposited evenly over the area of the modern inner-shelf sediment wedge (about 10 000 km^2) at a porosity of 30%, the sea bed would be predicted to be accumulating vertically at a mean rate of 0.7–1.5 mm/y. With the regional sea-bed slope of about 1 : 1000, this would correspond to rates of seawards progradation of 0.7–1.5 m/y.

Regionally, and in the long term, seaward progradation of the sediment wedge (Harris et al. 1990) may ultimately pose a threat to adjacent inner-shelf reefs because turbidities would increase as the sediment wedge approaches. In some cases, reef burial might eventuate. Given a relatively stable sea level, and continuation of long-term rates of coastal progradation, the continental islands around 5 km beyond the outer edge of the modern inner shelf sediment wedge, might be impacted by significantly increased turbidities (related to the seawards advance of the inner-shelf sediment wedge) on a time period of 5000 y. However, over the next 10–50 y, average water depths on the coastal wedge would likely decrease by only 7–75 mm. Given a predicted rise in global mean sea level by 2050 of 75–450 mm (Watson et al. 1998) actual water depths are likely to increase at most sites, and, as a consequence, turbidity may be reduced.

Even allowing for the possibility that the estimates of modern rates of sediment supply to the shelf are too low, we conclude that the time scales involved in producing regional changes in sedimentation and turbidity are far greater than can reasonably be addressed by environmental management. Human impacts will be largely undetectable in the regional turbidity record. Future field studies might focus on sedimentation at the seaward feather edge of the inner-shelf terrigenous sediment edge, where sediment availability is presently a limiting factor in turbidity and sedimentation, and to those coral reefs immediately adjacent to identified point sources of sediment input.

References

Allen P (1997) Earth surface processes. Blackwell Science, Cambridge, 404 pp

Beach Protection Authority Of Queensland (1984) Mulgrave Shire Northern Beaches. Beach Protection Authority, Queensland, Brisbane, 366 pp

Bell PRF, Gabric AJ (1990) The use of field survey and satellite remote sensing in determining the extent and causes of eutrophication in the Great Barrier Reef lagoon. Proc 4*th* Pacific Conf Mar Sci Tech: 25–32

Bell PRF, Gabric A J (1991) Must GBR pollution become chronic before management reacts. Search 22: 117–119

Belperio AP (1978) An inner shelf sedimentation model for the Townsville region, Great Barrier Reef province. PhD Thesis, James Cook University, Townsville, 210 pp

Belperio AP (1983) Terrigenous sedimentation in the central Great Barrier Reef lagoon: a model from the Burdekin region. BMR J Austr Geol Geophys 8: 179–190

Belperio AP (1988) Terrigenous and carbonate sedimentation in the Great Barrier Reef province. In: Doyle LJ, Roberts HH (eds) Carbonate-clastic transitions, developments in sedimentology 42, Elsevier, pp 143–174

Bird MI, Summons RE, Gagan MK, Roksandic Z, Dowling L, Head J, Fifield LK, Cresswell RG, Johnson DP (1995) Terrestrial vegetation change inferred from n-alkane d13 C analysis in the marine environment. Geochim Cosmochim Acta 59: 2853–2857

Brodie J (1996) River flood plumes in the Great Barrier Reef lagoon. In: Larcombe P, Woolfe K, Purdon RG (eds) Great Barrier Reef: Terrigenous sediment flux and human impacts. CRC Reef Research Centre, Research Symp Procs, Townsville, pp 33–39

Brodie J, Furnas, MJ (1996) Cyclones, river flood plumes and natural water quality extremes in the central Great Barrier Reef. In: Hunter, HM, Eyles AG, Rayment GE (eds) Downstream effects of land use, a national conference on downstream effects of land use. Department of Natural Resources, Brisbane

Carter RM, Johnson DP, Hooper KG (1993) Episodic post-glacial sea-level rise and the sedimentary evolution of a tropical embayment (Cleveland Bay, Great Barrier Reef shelf, Australia). Austr J Earth Sci 40: 229–255

Dyer KR (1986) Coastal and estuarine sediment dynamics. Wiley Interscience, New York, 342 pp

Furnas MJ, Brodie J (1996) Current status of nutrient levels and other water quality parameters in the Great Barrier Reef. In: Hunter HM, Eyles AG, Rayment GE (eds) Downstream effects of land use, a national conference on downstream effects of land use. Department of Natural Resources, Brisbane

Gagan MK, Johnson DP, Carter RM (1988) The cyclone Winifred storm bed, Central Great Barrier Reef, Australia. J. Sed Petrol 58: 845–856

Gibbs RJ, Matthews MD, Link DA (1971) The relationship between grain size and settling velocity. J Sed Petrol 41: 7–18

Hallermeier RJ (1981) Terminal settling velocity of commonly occurring sand grains. Sedimentology 28: 859–865

Harris PT, Davies PJ, Marshall JF (1990) Late Quaternary sedimentation on the Great Barrier Reef continental shelf and slope east of Townsville, Australia. Mar Geol 94: 55–77

Hopley D (1971) The origin and significance of North Queensland island spits. Z Geomorphol 15: 371–389

Hopley D (1984) The Holocene 'high energy window' on the Central Great Barrier Reef. In: Marshall JF, Davies PJ (eds) Coastal geomorphology in Australia. Academic Press Australia, pp 135–150

Hopley D (1995) Continental shelf reef systems. In: Carter RWG, Woodroffe CD (eds) Coastal evolution, Late Quaternary shoreline morphodynamics. Cambridge University Press, pp 303–340

Johnson DP, Searle DE (1984) Post-glacial seismic stratigraphy, central Great Barrier Reef, Australia. Sedimentology 31: 335–352

Kleypas JA, Hopley D (1992) Reef development across a broad continental shelf, southern Great Barrier Reef, Australia. Proc 7th Int Coral Reef Symp: 1129–1141

Larcombe P, Carter RM (1998) Sequence architecture during the Holocene transgression: an example from the Great Barrier Reef Shelf, Australia. Sed Geol 117: 97–111

Larcombe P, Woolfe KJ (1999) Terrigenous sediments as influences upon Holocene nearshore coral reefs, central Great Barrier Reef, Australia. Aust J Earth Sci 46

Larcombe P, Ridd PV, Wilson B, Prytz A (1994) Sediment data collection. In: Benson LJ, Goldsworthy PM, Butler IR, Oliver J (eds) Townsville Port Authority capital dredging works 1993: environmental monitoring program. Townsville Port Authority, pp 149–164

Larcombe P, Ridd PV, Prytz A, Wilson B (1995) Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14: 163–171

Larcombe P, Woolfe K, Purdon RG (eds)(1996) Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts. 2nd Edn, CRC Reef Research Centre, Current Research. Townsville, 174 pp

Lou J, Ridd PV (1997) Modelling of suspended sediment transport in coastal areas under waves and currents. Est Coast Shelf Sci 45: 1–16

Maxwell WGH (1968) Atlas of the Great Barrier Reef. Elsevier, Amsterdam, 258 pp

Middleton GV, Southard JB (1984) Mechanics of sediment movement. 2nd edn, SEPM short course 3, 401 pp

Moss AJ, Rayment GE, Reilly N, Best EK (1993). A preliminary assessment of sediment and nutrient exports from Queensland coastal catchments. Environment Tech Rep 5, Queensland Depart of Environment and Heritage, 33 pp

Neil DT, Yu B (1996) Simple climate-driven models for estimating sediment input into the Great Barrier Reef lagoon. In: Larcombe P, Woolfe K, Purdon RG (eds) Great Barrier Reef: terrigenous sediment flux and human impacts. CRC Reef Research Centre, Research Symp Proc, Townsville, pp 122–127

New Scientist (1995) Old photos chart destruction of Australia's reef. 4th March, p 7

Ohlenbusch R (1991) Post–glacial sequence stratigraphy and sedimentary development of the continental shelf off Townsville, central Great Barrier Reef province. Honours Thesis, James Cook University, Townsville, 94 pp

Puotinen ML, Done TJ, Skelly WC (1997) An atlas of tropical cyclones in the Great Barrier Reef Region (1969–1997). Tech Rep 19, CRC Reef Research Centre, Townsville, 201 pp

Scoffin TP, Tudhope AW (1985) Sedimentary environments of the central region of the Great Barrier Reef of Australia. Coral Reefs 4: 81–93

Taylor J (1996) Sediment input to the Great Barrier Reef lagoon via river discharge: the Barron River. In: Larcombe P, Woolfe K, Purdon RG (eds) Great Barrier Reef: terrigenous sediment flux and human impacts. CRC Reef Research Centre, Research Symp Proc, Townsville, pp 152–154

Wasson RJ (1997) Run-off from the land to the rivers and the sea. Proc Great Barrier Reef Conf, Townsville, November 1996, pp 23–41

Watson RT, Zinyowa MC, Moss RH (1998) (eds) The regional impacts of climate change: an assessment of vulnerability. Special Report by IPCC Working Group II

Wolanski E (1994) Physical oceanographic processes of the Great Barrier Reef. CRC Press, Boca Raton, 194 pp

Woolfe KJ, Larcombe P (1998) Terrigenous sediment accumulation as a regional control upon the distribution of reef carbonates. In: Camoin GF, Davies PJ (eds) Reefs and carbonate platforms in the Pacific and Indian Oceans. IAS Spec Pub 25: 295–310

Woolfe KJ, Larcombe P, Orpin AR, Purdon RG, Michaelsen P, McIntyre CM, Amjad N (1998) Controls upon inner-shelf sedimentation, Cape York Peninsula, in the region of 12° S. Aust J Earth Sci 45: 611–622

Wright LD (1995) Morphodynamics of inner continental shelves. CRC Press, 241 pp

Zann LP (1995) (ed) Our sea, our future, major findings of the State of the Marine Environment Report for Australia. Ocean Rescue 2000 program, Department of the Environment, Sport and Territories, Canberra, 112 pp