



HAL
open science

Multigrain seabed sediment transport modelling for the south-west Australian Shelf

Fangjun Li, Cedric M. Griffiths, Chris P. Dyt, Pierre Weill, Ming Feng, Tristan Salles, Chris Jenkins

► **To cite this version:**

Fangjun Li, Cedric M. Griffiths, Chris P. Dyt, Pierre Weill, Ming Feng, et al.. Multigrain seabed sediment transport modelling for the south-west Australian Shelf. *Marine and Freshwater Research*, 2009, 60 (7), pp.774-785. <10.1071/MF08049>. <hal-00680638>

HAL Id: hal-00680638

<https://minesparis-psl.hal.science/hal-00680638v1>

Submitted on 5 Jun 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Multigrain seabed sediment transport modelling for the south-west Australian Shelf

F. Li^{A,D}, C. M. Griffiths^A, C. P. Dyt^A, P. Weill^A, M. Feng^B,
T. Salles^A and C. Jenkins^C

^ACSIRO Petroleum Resources, 26 Dick Perry Avenue, Kensington, WA 6151, Australia.

^BCSIRO Marine and Atmospheric Research, Underwood Avenue, Floreat, WA 6014, Australia.

^CInstitute of Arctic and Alpine Research (INSTAAR), University of Colorado at Boulder,
1560 30th Street, Campus Box 450, Boulder, CO 80309-0450, USA.

^DCorresponding author. Email: fangjun.li@dpi.wa.gov.au

Abstract. With increasing concerns about climate change and sea-level rise, there is a need for a comprehensive understanding of the sedimentary processes involved in the erosion, transport and deposition of sediment on the continental shelf. In the present paper, long-term and large-scale seabed morphological changes on the south-west Australian continental shelf were investigated by a comprehensive sediment transport model, Sedsim. The investigated area covers the continental shelf and abyssal basins of the south-western region. The regional seabed is sensitive to environmental forces and sediment supply, and most terrigenous sediment carried down by major rivers is trapped in inland lakes or estuaries. Only a small fraction of fine-grain sediment reaches the continental shelf. The simulation has also confirmed that the Leeuwin Current and high-energy waves play the most important roles in regional long-term seabed evolution. Although the numerical implementation only approximates some forcing and responses, it represents a significant step forward in understanding the nature of potential long-term seabed change as a response to possible climate change scenarios. The 50-year forecast on the seabed morphological changes provides a reference for the management of coastal and offshore resources, as well as infrastructure, in a sustainable way.

Additional keywords: climate change, continental shelf, morphological change, seabed.

Introduction

The Australian continental shelf has been of research interest for many decades. A large number of research vessel cruises have sampled seabed sediment for different reasons. Long-term and continuous satellite observation records of winds, waves and imaging of ocean temperatures have been accumulated and made available for general research. Most importantly, the development of the Bluelink system, Ocean Forecasting Australia (Oke *et al.* 2005, 2008; CMAR 2008), has significantly improved the level of our knowledge about the waters surrounding Australia. In addition, many other seabed-related data and knowledge are available in the fields of civil engineering, oceanography and geology. The aim of the present paper was to build links between the environmental forces and seabed responses, and to test our understanding of modern seabeds to answer the fundamental questions: (i) what does the sediment consist of; (ii) why is the sediment distributed in these locations; (iii) are the sediments relict or modern; and (iv) how will the type and distribution of sediments respond to reasonable assumptions of climate change?

Most seabed areas consist of both relict and modern sediment. The relict sediment was deposited during or before the previous geological cycle and has not been modified by modern environmental conditions. By contrast, modern sediment is sensitive

to the effects of waves, tides and ocean currents. The first two questions posed above, which are not trivial, could be addressed by a combination of discrete seabed sampling, mapping, interpolation, observations of environmental forces and modelling of ocean currents. However, forecasting the future trend of seabed change is not possible without a numerical sediment transport model.

Sedsim is a comprehensive process-based stratigraphic forward model initially developed under a consortium at Stanford University in the 1980s. Since the 1990s, the program has been systematically redeveloped. Sedsim has now been tested for sediment transport over long periods controlled by many of the major erosional, transport and depositional processes, including fluvial, aeolian, shallow and deep marine, coastal waves and storms, carbonate growth, slope failure, turbidity flows and deep ocean geostrophic currents (Tetzlaff and Harbaugh 1989; Koltermann and Gorelick 1992; Martinez and Harbaugh 1993; Griffiths *et al.* 2001; Li *et al.* 2003, 2005a, 2005b, 2006a, 2006b, 2007).

In Sedsim, the Navier–Stokes equations and the continuity equation are simplified and solved by using a marker-in-cell technique in two horizontal dimensions. Flow velocity and sediment load are represented at points that move with the fluid. A two-dimensional square grid is used to represent the depth of flow

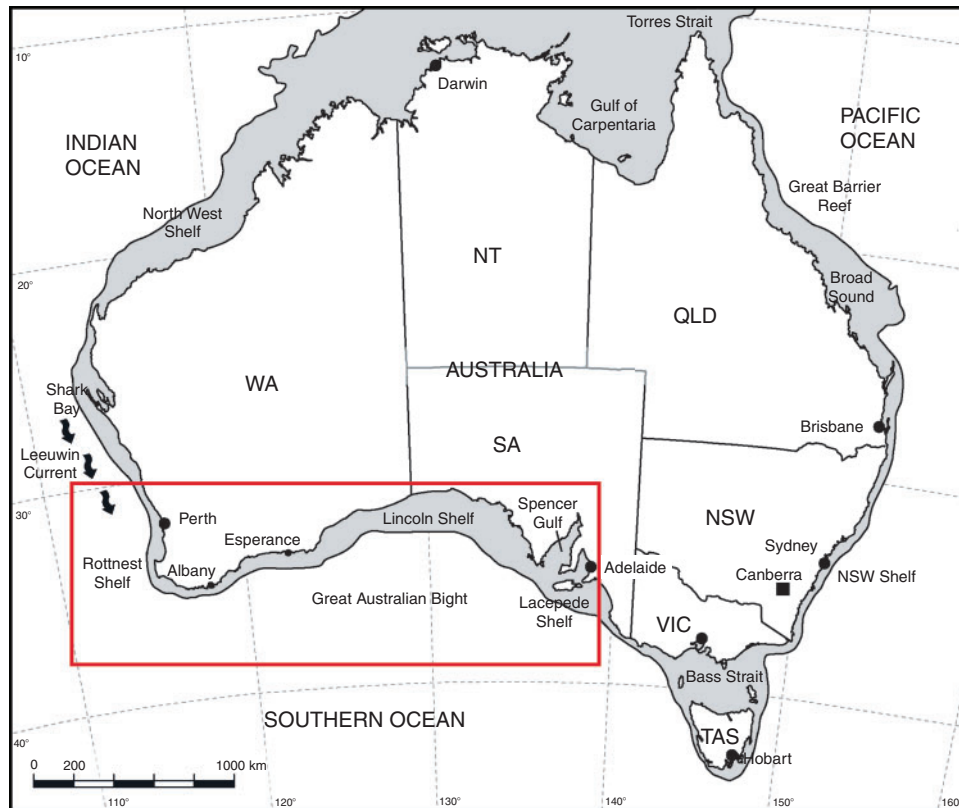


Fig. 1. Location map of the study region.

and elevation of the water–sediment interface. At each time step, each fluid element's position and velocity are recalculated. This technique combines the advantages of Eulerian and Lagrangian representations of fluid flow.

To allow for the computation of seabed morphological evolution on time scales of decades and spatial scales of hundreds of kilometres, substantial simplification schemes are essential because full-scale, direct simulation of all involved processes is not feasible. Major model assumptions include: (i) morphological seabed change has a negligible effect on deep ocean currents, tides and waves; and (ii) oscillatory water movement caused by waves and tides creates negligible long-term net sediment transport in deep water. The oscillatory water movements are only responsible for mobilising sediment and making sediment available for transportation by large-scale ocean circulation.

Understanding the geomorphological changes and sedimentary processes that are occurring on the seabed and the shoreline is becoming increasingly important to manage coastal and offshore resources and infrastructure in a sustainable way. The present paper discusses the future state of the seabed in south-west Australia based on an extrapolation of the present-day wave, tide and current climate.

Geomorphology of the south-west Australian continental shelf

The simulation area covers the south-west Australian continental shelf and abyssal basins (Fig. 1), which includes the

Rottneest Shelf, the Perth Canyon, the Albany Canyons, the Great Australian Bight, the Lincoln Shelf, the Spencer Gulf, the Gulf St Vincent, and part of the Lapepede Shelf. The region roughly extends from 30°S to 39°S and from 110°E to 139°E.

The south-west Australian continental shelf is a narrow, high-energy open shelf on a passive margin (James *et al.* 1994). The steep continental slope is incised by Perth, Albany and Murray Canyons (Exon *et al.* 2005), leading to a 4000-m deep abyssal plain. The continental shelf and coastline have been mainly shaped by Holocene sea-level fluctuation. A rapid post-glacial transgression to a high hydrodynamic energy level with low terrigenous input has limited carbonate productivity and reworked the transgression surface (Pleistocene limestone and sandstone), developing retrograding sand dune systems. A subsequent fall in the sea level started a continuing progradation of shell beds and dunes to the present day. The seabed of the Rottneest Shelf is covered by a thin blanket (0–4 m) of relict sediment, mainly bryozoans and bivalve skeletons (cool water carbonates), on top of the Pleistocene basement (Collins 1988; James *et al.* 1992, 2001). Holocene to recent calcareous/quartzose sand dunes, Pleistocene consolidated calcarenite and sandstone, and Tertiary limestone cliffs are the main features of the south-west coastline, sometimes outcropped by Precambrian igneous rocks.

The Leeuwin Current has been influential since at least the last interglacial period. McGowran *et al.* (1997) reviewed evidence of the Leeuwin Current during the Cainozoic era and concluded that the current has been active and fluctuating since

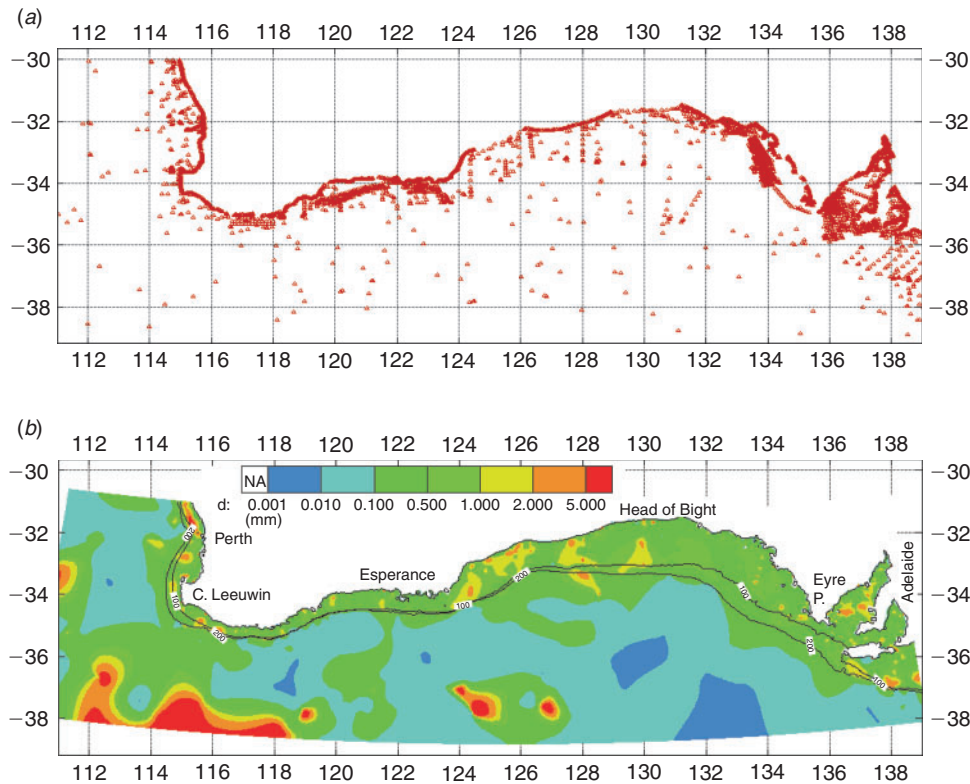


Fig. 2. Characteristics of the initial seabed sediment substrate: (a) sample locations and (b) gridded median grain sizes. The onshore (above +20.0 m Australian height datum) grain sizes are undefined and coloured white.

the later middle Eocene. The seabed of continental shelves is constantly evolving, subject to processes such as sedimentation, hydrodynamic movement, slope failure and biological activity.

Existing sediment sources

Seabed sediment

Based on the comprehensive auSEABED sediment database (Jenkins *et al.* 2003), the grain size and sediment compositions are interpolated onto the whole grid from the available samples (Fig. 2a). The map of median sediment grain size, d_{50} , shows that coarse grains (>0.5 mm) occur mainly within and around the Great Australian Bight, the Spencer Gulf, the Gulf St Vincent and part of the Lacedpede Shelf. Medium grains (0.25–0.5 mm) occupy slightly larger areas around the coarse-grained facies. Fine-grained facies (<0.01 mm) tend to occur at water depths greater than 200 m on the continental slope and abyssal basin (Fig. 2b). Gravel and exposed rock-head are frequently found in two different areas. One is the narrow shelf from Lancelin to Esperance of Western Australia, and the other is in the deep Southern Ocean south-west of Cape Leeuwin, where the water depth is more than 4000 m.

The grain sizes and sediment compositions from available observations are interpolated onto the computational grid and are broken into four representative clastic grain sizes. The four grains imported into Sedsim are: very coarse sand (3 mm),

medium to coarse sand (0.5 mm), very fine sand (0.1 mm) and silt (0.01 mm).

Sediment thickness estimations have been carried out for the Rottneest (Collins 1988) and Lacedpede Shelves (James *et al.* 1992). A reworkable sediment thickness of 0–1 m has been found for the inner shelf (0–60 m depth), and 0–4 m for the outer shelf (60–170 m depth) where wave abrasion is less efficient and carbonate production more important (bryozoan sands and muds). The thickness of loose sediment on the shoreline (beaches and dune systems) is estimated from stratigraphic information of the west coast superficial formation, ‘Safety Bay Sand’ (Australian Stratigraphic Units Database, Geoscience Australia). With a maximum thickness of 6 m, this recent unit forms most of the beaches and mobile dune systems. We make the assumption that this thickness is representative of the loose sediment stock over the studied coastline. From this information, a simple input file for the initial seabed loose sediment thickness has been built according to water depth (shoreline, inner and outer shelf) and the rock exposure parameter in the auSEABED database. For the onshore and near-shore area, with Australian height datum (AHD) from +20 m to –10 m, the loose sediment thickness is assumed to be 5 m. For the inner shelf (–10 m to –60 m AHD), the thickness is given as 1 m. For the outer shelf, –60 m and deeper, a 4-m pre-deposit is assumed between the seabed surface and the rock substrate. On top of these rough estimates, the sediment thickness is corrected to 0.1 m

Table 1. Major rivers and sediment source locations for the coastal region

Source	No.	Name of the source	Q (m ³ s ⁻¹)	C (kg m ⁻³)	Latitude (S)	Longitude (E)
WA	1	Moore River	12.68 ^A	0.052 ^A	31°21'20"	115°30'41"
	2	Swan-Canning River	19.79	0.265	31°57'49"	115°50'44"
	3	Leschenault Inlet	10.00	0.068	32°35'10"	115°46'12"
	4	Peel-Harvey Estuary	19.60	0.02	33°18'20"	115°41'37"
	5	Vasse River	0.35	0.146	33°36'51"	115°25'22"
	6	Margaret River	3.82	0.033	33°58'10"	114°59'21"
	7	Hardy Inlet	29.33	0.106	34°16'43"	115°11'31"
	8	Warren Inlet	12.68	0.069	34°36'34"	115°49'51"
	9	Walpole/Nornalup Inlet	12.59	0.071	35°00'01"	116°45'10"
	10	Irwin Inlet	5.20	0.098	34°59'23"	116°57'27"
	11	Wilson Inlet	5.20	0.098	34°58'30"	117°27'38"
	12	Oyster Harbour	6.34	0.136	34°57'21"	117°58'20"
	13	Beaufort Inlet	1.14	0.75	34°27'18"	118°52'36"
	14	Culham Inlet	4.76	0.045	33°53'38"	120°04'37"
	15	Oldfield Estuary	0.25	0.9	33°52'08"	120°47'11"
SA	16	North Spencer Gulf	3.17	0.162	32°30'39"	137°45'50"
	17	Light River	3.17	0.135	34°33'02"	138°20'26"

^AEstimated value.

if the rock exposure parameter from the auSEABED is greater than 60%.

River input

The amount of sediment carried by rivers to the coastal area is closely related to catchment area, rainfall and vegetation. In the south-western region, 17 major river and inlet systems have been identified and evaluated in terms of their annual sediment carrying capacity (under present climate conditions) at their mouths (Table 1; Fig. 3).

Hydrodynamic forcing under present-day climate conditions

Wind climate

Wind climate data in a monthly form were provided by the Defence Oceanographic Data Centre (DODC). The data consist of mean and maximum wind speed and wind direction. The original wind data cover the time period from July 1999 to May 2005 at a resolution of 0.25°.

The wind climate of the Australian south-west is mainly controlled by the position of a high pressure ridge over the Great Australian Bight. In summer (November–March), the high pressure ridge is located over the south of the Great Australian Bight. High pressure systems generally move eastwards along the ridge, but have a favoured position south of the Great Australian Bight (~38°S). Consequently, the most frequent air stream across southern Australia during this period is from the south-east. In winter (June–September), the high pressure belt weakens and moves northward over the Bight. Frontal systems associated with depressions travelling eastwards across the ocean move north (around 30°S), highly influencing the weather over south-western Australia. The whole region is subjected to strong westerly winds, with a mean speed of 20–30 kn (12–15 m s⁻¹), and frequent storms.

Wave climate

The wave climate is extracted from both the DODC's 14-year multi-satellite data and from CSIRO Wave Analysis Model (WAM) wave hind-cast results (Hayes *et al.* 2005). The CSIRO data comprised six-hourly predictions of significant wave height, period and mean wave direction, gridded at a 0.1° spatial resolution, for the period of March 1997 to February 2002 inclusive.

The wave climate in the region is strongly related to the south-west wind regimes – west to south-west in winter and south to south-east in summer (Lemm *et al.* 1999). The south-west continental shelf is a high wave-energy environment. In winter, waves with a mean significant wave height (SWH) of up to 3 m and a mean period of approximately 9 s are observed. The maximum wave height can reach 8–9 m in the Bight. The summer values are lower, with a mean SWH of approximately 2 m, a mean period of 7–8 s, and maximum wave heights of 6 m.

Tidal currents

South-western Australia has micro-tidal, mixed and predominantly diurnal tides. The maximum tidal range along the coast from Perth to Esperance is less than 1 m and rises to 1.8 m at the Head of the Bight, and to 3.5 m at the tip of Spencer Gulf and the Gulf St Vincent. The tidal range and depth-averaged tidal current speeds for spring tides in the region were provided by the National Tidal Centre, Bureau of Meteorology. The highest tidal range and speed appears in the Spencer Gulf. Except for this area, tidal current plays a marginal role in the mobilisation of seabed sediment in this region.

Leeuwin Current and El-Niño Southern Oscillation

The dominant boundary current off south-western Australia is the Leeuwin Current, which flows along the south-west shelf, bringing warm water to the south and east. The bottom current fields simulated by the Ocean Forecasting Australia Model

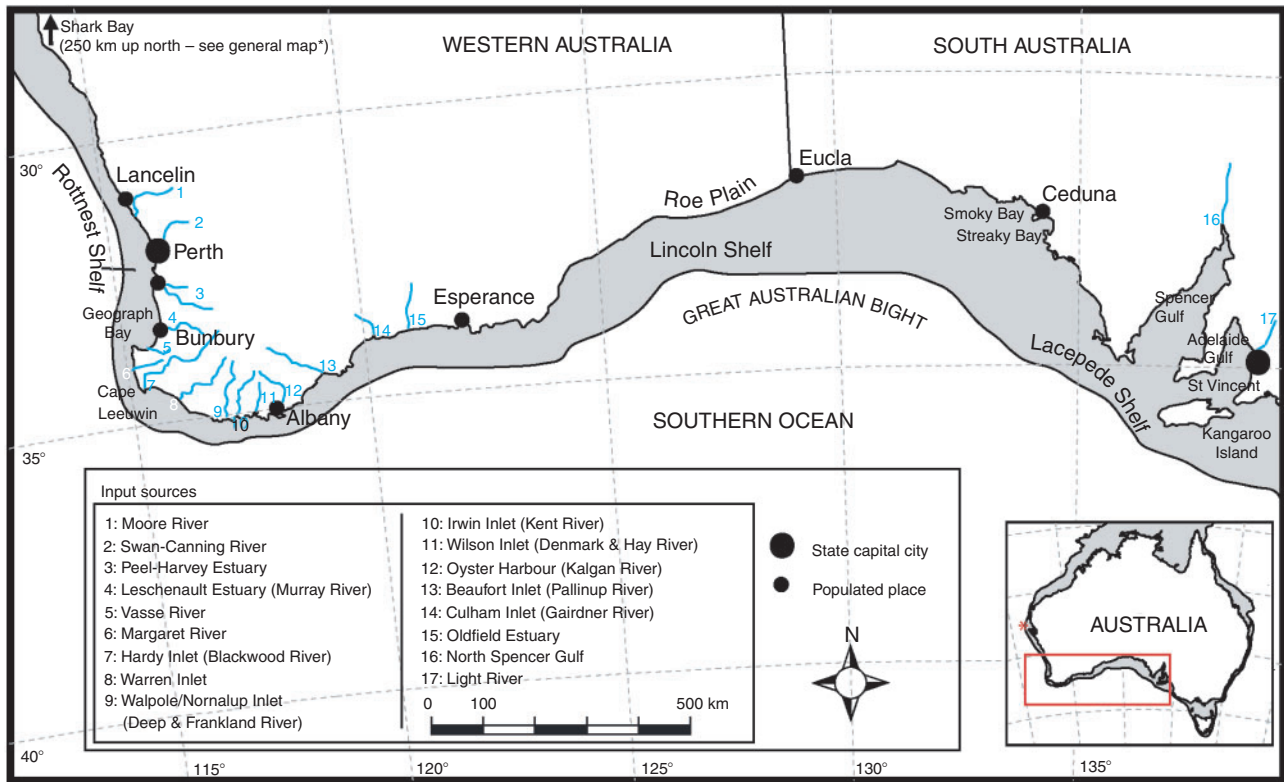


Fig. 3. Major river sediment sources in the south-western region.

(OFAM) are used as an input into the Sedsim model. The OFAM (Oke *et al.* 2005, 2008) is the global model used by Bluelink; it has 0.1° resolution around Australia. The model data provided by CSIRO Marine and Atmospheric Research is in the form of monthly averages of the OFAM output between 1991 and 2005.

The bottom current velocities show strong seasonal variation. The Leeuwin Current starts to strengthen in March–April, forming a narrow jet with a peak velocity of 0.45 m s^{-1} . During May–August, the Leeuwin Current broadens, with the 0.10-m s^{-1} southward velocities extending to almost 114°E (Fig. 4). With speeds of $0.1\text{--}0.25 \text{ m s}^{-1}$ on the shelf, the current may not be strong enough to mobilise sediment. However, it can efficiently transport particles that have been suspended by wave action.

Inter-annually, the Leeuwin Current is distinctly stronger during a La Niña year and weaker during an El Niño year. The annual average poleward geostrophic currents in normal El Niño and La Niña years are 3.4, 3.0 and 4.2 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) respectively (Feng *et al.* 2003).

Multigrain sediment transport modelling by Sedsim

Sediment entrainment and seabed mobility

High-frequency water movements caused by waves and tides are the major factors affecting local seabed sediment availability to long-term and large-scale transport, although the net sediment movement by waves and tides may be negligible, at least in deep water. The seabed mobility index, r (Eqn 1), is defined as the ratio between the value of wave- and current-combined skin-friction

Shields parameter, θ_{cws} , and the critical Shields parameter, θ_{cr} . It serves as an indicator of the level of intensity and frequency of seabed sediment available for movement

$$r = \frac{\theta_{\text{cws}}}{\theta_{\text{cr}}} = \frac{\text{combined Shields parameter}}{\text{critical Shields parameter}}. \quad (1)$$

Details about the calculation of the skin-friction Shields parameter, θ_{cws} , and the critical Shields parameter, θ_{cr} , have been discussed by Li and Amos (2001).

In fair weather conditions, the mobility index value is lower than 1.0 on most of the continental shelf, except for some isolated nearshore areas in both summer and winter seasons, shown in Fig. 5. However, in storm conditions the index is much higher, particularly in an Australian winter (Fig. 6*b*). Although the higher the mobility index value the more likelihood of sediment movement, where $r < 1$ there is still potential for sediment movement. The existing sediment on the seabed is composed of different grain sizes; thus, the median grains are stationary, but the finer fraction may be transported.

Estimated long-term, large-scale sediment transport rate by near-bottom circulation

Virtually all sediment transport occurs either as bedload or as a combination of bedload and suspended load (Soulsby 1997) (suspended load rarely occurs in isolation). The combined load is known as the total load. In practice, it is very difficult to separate bedload from suspended load. For this reason, we chose the

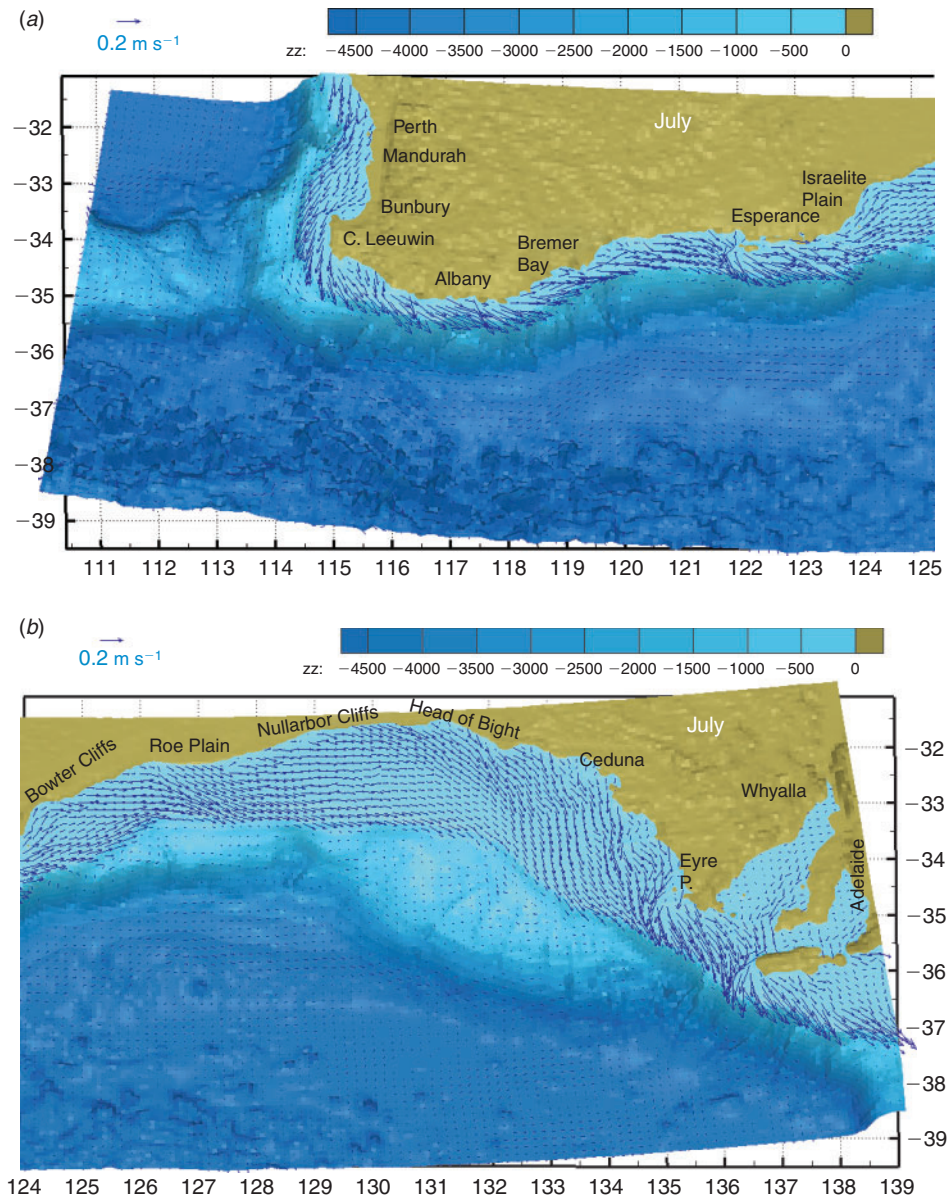


Fig. 4. Mean bottom current velocity snapshot from July. The blue arrows represent the magnitude and the direction of the currents. The Leeuwin Current is apparent and strong in winter. Data are from the Ocean Forecasting Australia Model output provided by CSIRO Marine and Atmospheric Research.

total load approach to estimate the sediment transport rate in the present study.

Li and Amos (2001) considered five equations applicable to sediment transport on a continental shelf. Of these, the Bagnold equation provides the best fit to the sediment characteristics in the south-west Australian shelf. Bagnold (1963) assumed that waves cause sediments to be stirred up, but it is the steady currents that cause net sediment transport. For combined wave-current flows, the maximum (not the instantaneous) skin-friction combined shear stress, τ_{cws} , is used to compute the net sediment transport rate from:

$$q = K \tau_{cws} u_{100} / [(\rho_s - \rho)g] \quad (2)$$

where q is the volumetric rate of sediment transport, u_{100} is the bottom current velocity at 1 m above the seabed, ρ_s and ρ are the densities of sediment and sea water, respectively, and K is the proportionality coefficient described by the empirical equation of Sternberg (1972):

$$K = M \exp[0.7(\tau_{cws} - \tau_{cr})/\tau_{cr}] \quad (3)$$

where the empirical coefficient M has a value of 0.005. The transport direction is assumed to be that of the steady current. Given the relationship of Shields parameter and bottom shear stress:

$$\theta_{cws} = \frac{\tau_{cws}}{(\rho_s - \rho)gD} \quad (4)$$

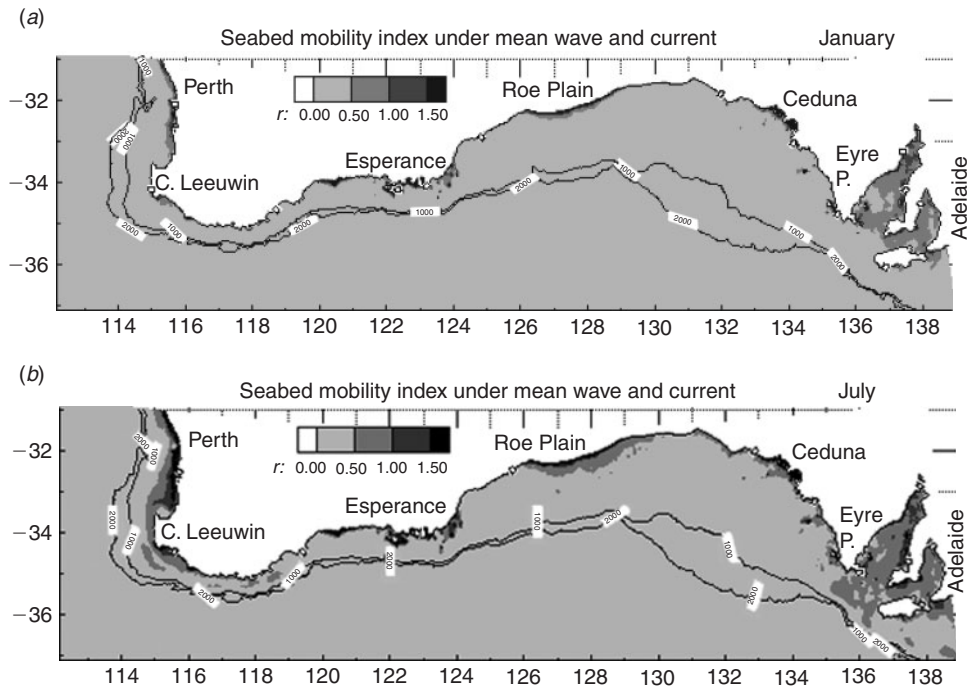


Fig. 5. Seabed mobility index, r , under monthly average wave, tide and current conditions in January and July.

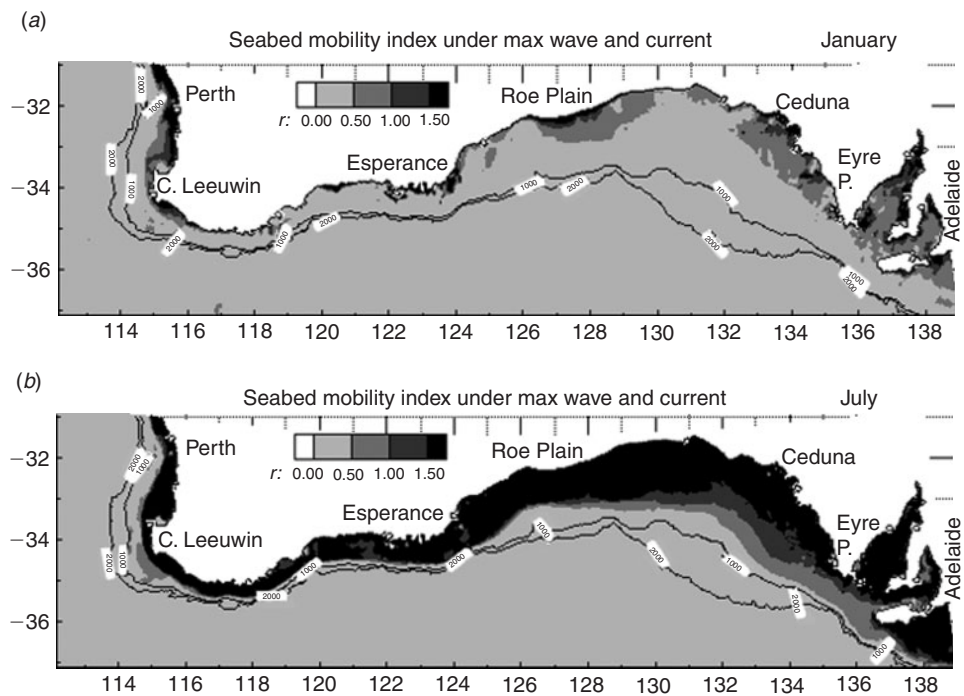


Fig. 6. Seabed mobility index, r , under monthly maximum wave, tide and current conditions in January and July.

Eqn (2) can be written as:

$$q = M \cdot u_{100} \cdot \theta_{cws} \cdot D \cdot \exp[0.7(\theta_{cws} - \theta_{cr})/\theta_{cr}] \quad (5)$$

where D is the sediment grain diameter. The bottom circulation velocity data extracted from OFAM was assumed to represent the velocity 1 m above the seabed, u_{100} .

Sediment transport prediction is at a much lower level of certainty than the modelling of waves and flows (Whitehouse *et al.* 2000). With the large uncertainties in the input data and the simplifications of the numerical modelling, seabed change predictions at any one location should be considered as indicative rather than definitive.

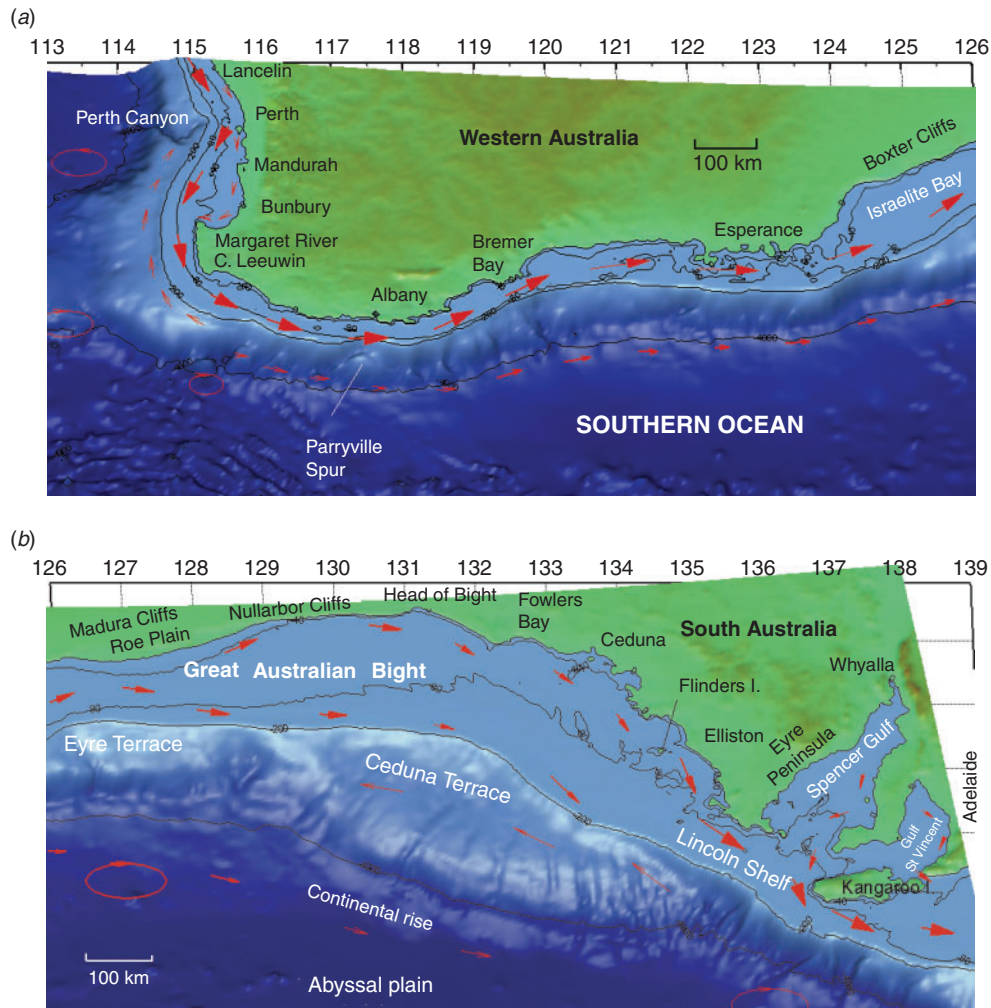


Fig. 7. Winter (May–September) bottom current circulation patterns at (a) the Rottneest Shelf and the western part of the south-western region and (b) the Lincoln Shelf and the eastern part of the south-western region.

Multigrain representation of the sediment mixture

Transport-rate measurements showed that armouring of fine sand by coarse sand gives rise to a significant reduction in the transport rate of the fine sand (de Meijer *et al.* 2002). The armouring effects are too significant to be neglected in most analyses of shelf and near-shore sediment transport (Reed *et al.* 1999), and this is particularly relevant for models that are dealing with large-scale and long-term sedimentary regimes. The armouring process can occur at relatively low stress conditions, when the coarser particles are not mobilised, but also at relatively high stress conditions, when all material can be transported.

In the present study, sediment is represented by a mixture of four grain sizes, which are coarse sand (3 mm), coarse to medium sand (0.5 mm), very fine sand (0.1 mm) and silt (0.01 mm). The total sediment transport rate (both suspended load and bedload) is estimated by a total load equation (discussed in the previous section). A transport capacity/efficiency fraction method (Tetzlaff and Harbaugh 1989; Wu *et al.* 2003) is used in the calculation of fractional sediment transport. In this method, the total load is computed using an appropriate equation, and then

the fractional transport rates are determined by distributing the total load into size groups through a transport capacity distribution function. The transport capacity distribution function is related to both hydraulic conditions and sediment properties.

Simulating the results of seabed morphological change

Simulation of the sediment erosion–transport–deposition process uses the method of Martinez and Harbaugh (1993). The regional seabed and its deposit layer are converted to a Cartesian coordinate system by Lambert projection. The research area is then represented by a 1061×341 grid with a spatial resolution of 2.4 km. The environmental factors considered in the present model are sediment-laden river flows, waves, tides, geostrophic currents, sea-level change, submarine slope failure and turbidity currents. The model predicts changes of seabed morphology, sediment grain composition and seabed mobility.

Figs 7 and 8 summarise the bottom ocean current circulation patterns in winter (May–September) and summer (October–April), respectively, based on OFAM output at 1991 to 2005. The regional continental shelf is characterised by two shelf breaks,

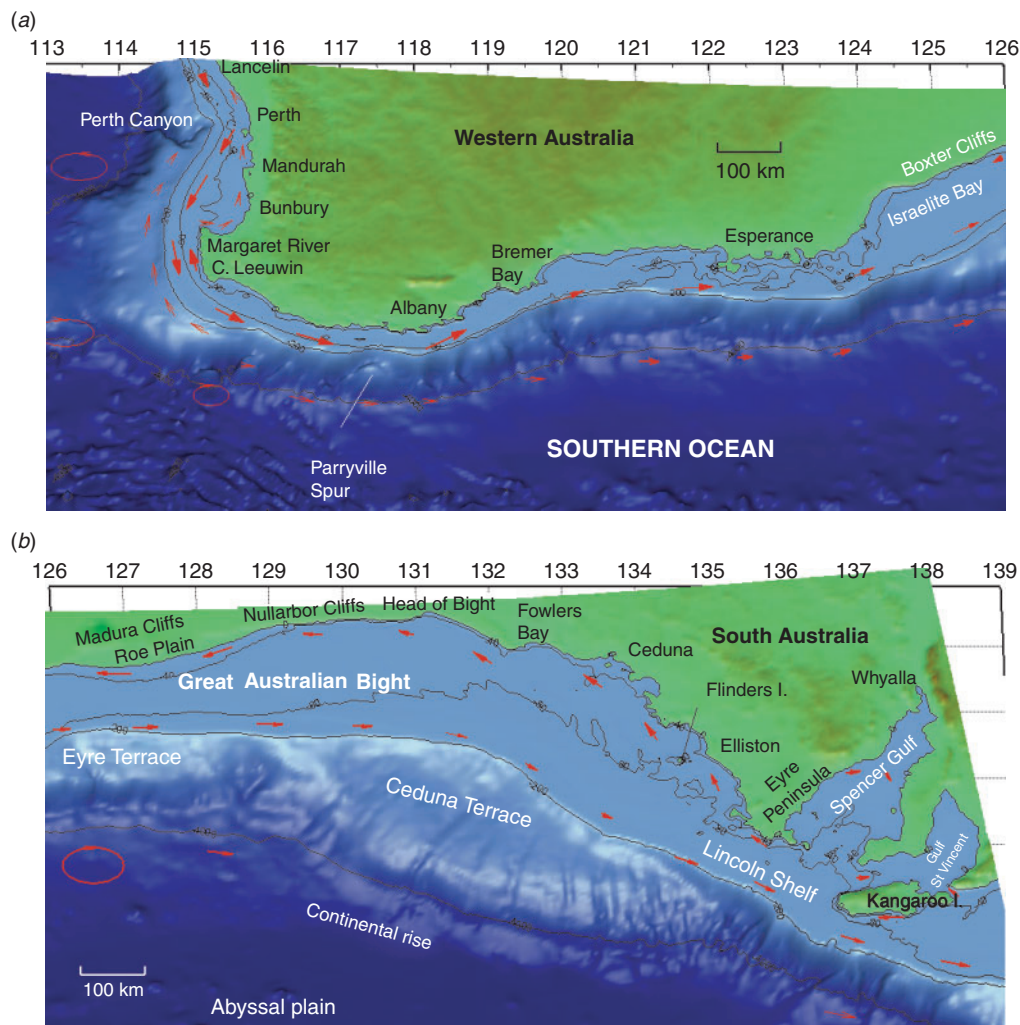


Fig. 8. Summer (October–April) bottom current circulation patterns at (a) the Rottneest Shelf and the western part of the south-western region and (b) the Lincoln Shelf and the eastern part of the south-western region.

an inner shelf break at ~ 50 m followed by a second break at ~ 200 m water depth. Under the influence of this terrace-like structure, the local ocean currents on the inner shelf are very different from the current on the outer shelf. In summer, the former, recognised as the Cape Current (Gersbach *et al.* 1999), flows northward, whereas the Leeuwin Current flows southward on the outer shelf. In winter, the Cape Current vanishes and the Leeuwin Current flows on both the inner and outer shelf. From south of Cape Leeuwin to Roe Plain, the prevailing circulation feature on the shelf is the eastward-flowing Leeuwin Current in all seasons. The current covers the entire shelf, but is strongest at the edge of the shelf. In summer, as the Leeuwin Current is weaker towards the east, the local water is partially replaced by the westward coastal current in the shallow water between Eucla and Roe Plain.

Direct discharges of sediment from fluvial sources are mainly from the Swan and Moore Rivers. Discharge is usually limited by the occurrence of estuaries impounded behind coastal ridges or semi-permanent mouth bars. Thus, most of the riverine sediment

is retained in the less turbulent estuarine environments. However, rare high-flow and large-scale coastal erosion can occasionally bring some fluvial sediment into the marine systems.

Fig. 9 shows the Sedsim predicted seabed morphological change over the next 50 years under an extension of the current climate. The model predicts a broad erosion area on the inner shelf for water depths less than 80 m. This is well-supported by existing seabed sediment samples; relict sediment could be 17 000 years old (James *et al.* 1992, 2001). Wave abrasion is strongest on the mid shelf (50–90 m), and little contemporary sediment would accumulate in this high-energy environment (James *et al.* 1994).

The most severe erosion/accretion occurs in the vicinity of the shoreline. The erosion/accretion is strongest when the shelf is narrower because it is more open to the swell and to current movement (off the Cape Leeuwin and the coast between Albany and Esperance). Most of the shoreline suffers from erosion, particularly the coast facing south-west or south (from Cape Naturaliste near Margaret River to Albany). This erosion appears

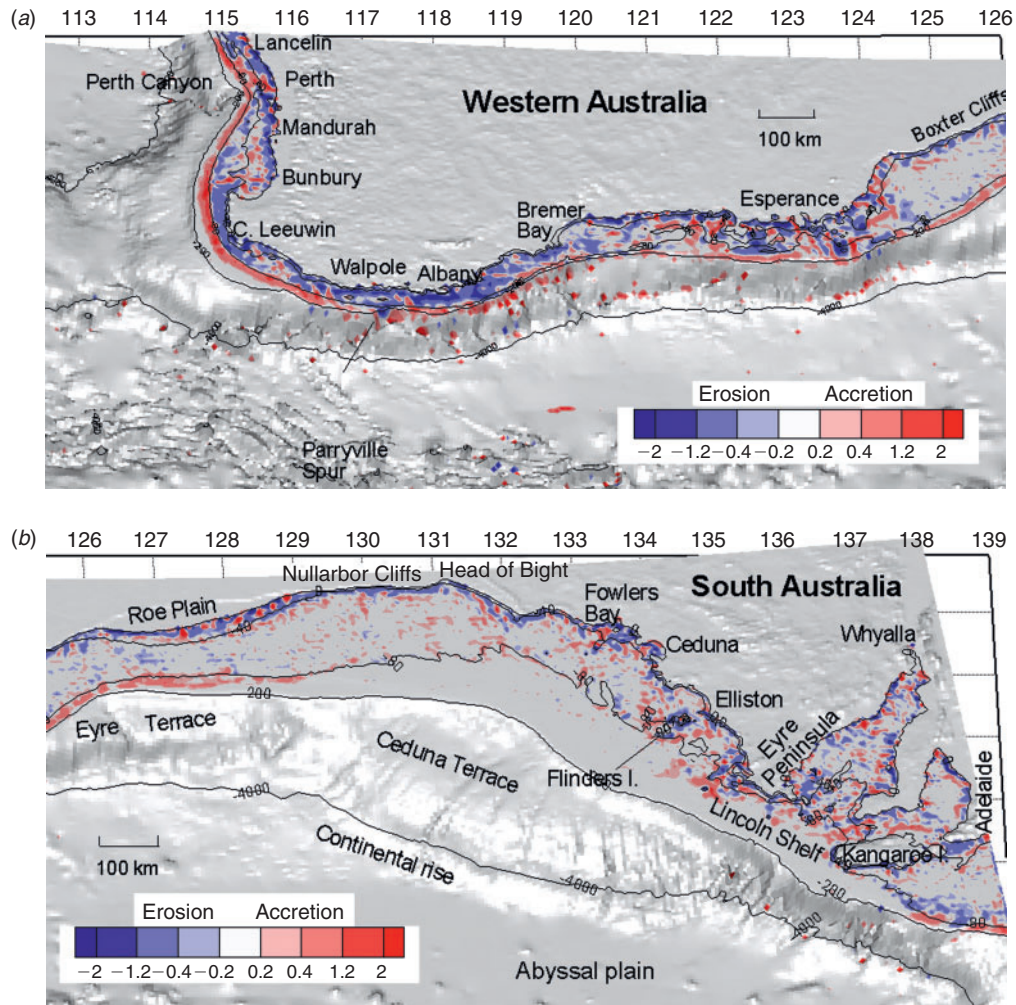


Fig. 9. Simulated seabed morphological change over the next 50 years at (a) the Rottne Shelf and the western part of the south-western region and (b) the Lincoln Shelf and the eastern part of the south-western region.

as an offshore sediment movement. The eroded material is generally redistributed by currents to water depths beyond 80 m, which is below the normal wave abrasion limit. Other areas, such as Perth beach, Rockingham beach and Geographe Bay, suffer from less erosion or even deposition with the protection from Rottne Island and Garden Island and their orientation to the wave and current direction. These sheltered environments are acting as sediment traps. Exposed areas often experience a coarsening of the sediment, and fining is observed along sheltered coastlines.

According to Collins (1988), the sediment blanket on the outer shelf is thicker than on the inner part, and a ridge of algal nodules pavement is observed on the edge of the slope. These observations are consistent with our result; even if the initial seafloor conditions, such as the sediment thickness and lithology, are not exact, the system adjusts quite well to the hydrodynamic conditions and reaches a state that is close to the observed actual morphology.

The simulation created a noticeable amount of patchy sediment accumulation at the foot of the continental shelf near Perth

Canyon, Parryville Spur, Denmark Canyon and Albany Canyon. These deposits are most likely transported down the slope by turbidity currents and slope failures, assisted by the Leeuwin Current.

A study of superficial sediments in the Great Australian Bight (GAB) (James *et al.* 2001) reveals that Holocene sedimentation can be directly related to modern oceanography on this predominantly down-welling shelf. The shelf from 50 to 100 m depth is sediment-starved because of strong wave abrasion along the southern Australian margin (Li *et al.* 1999).

The shelf in the eastern part of the simulated area is broader (GAB) and sediment movement is less intense (Figs 7b, 8b and 9b). Although the Bight is still open to the Southern Ocean long period swell, it is more sheltered than the south-west corner. Morphological changes increase from east to west. Accumulations of sediment are found down-slope. Shore erosion is widespread along the cliff coast. Sediment accumulation is predicted in the deep-water area enveloping the bottom current (Fig. 9).

The coast along the GAB consists mostly of tertiary limestone cliffs that are actively eroding. The main high mobility coastal zone is the Roe Plain, a large and low Quaternary calcarenite formation, covered by aeolian sand forming coastal dune systems. This region experiences erosion (1–2 m in 50 years) and is an important sediment supply source.

For most of the area, the amount of erosion and accretion is within 1.5 m over the next 50 years (30 mm year⁻¹). More erosion occurs at the western side of the GAB, particularly in the coastal region where there is both high mobility and in the path of the persistent Leeuwin Current.

Large-scale sediment transport follows the Leeuwin Current, southward along the continental shelf and eastward along the south coast after having circled the Cape Leeuwin. Although most of the region is situated in a high-energy environment, the actual erosion of the seabed is very often restricted by the proximity of hard relict substratum.

Conclusions

Seabed morphodynamic modelling has evolved into a useful tool to assist in the understanding of sediment transport and seabed evolution. The Sedsim model has brought together data gathered from field observations and seabed sampling and has modelled the seabed response to a complex dynamic system of environmental forces. The research program, of which this simulation forms a part, represents the first attempt to model the large-scale, long-time-frame, morphological evolution of an entire continental seabed. The south-west regional seabed is sensitive to environmental forces and sediment supplies and most of the shoreline suffers from erosion. The low fluvial sediment discharge in the south-west of Australia (at least during the period of historical record) cannot keep pace with the action of strong marine forces. The predicted maximum morphological changes on the seabed are approximately 1–2 m over the next 50 years. The Leeuwin Current and high-energy waves play the most important roles in the large-scale, long-term evolution of the south-west seabed.

Large-scale, long-term seabed modelling is a challenging task. The major problem is the very sparse and patchy nature of the observation records. To date, very few of the model predictions can be quantitatively verified with existing data. To improve the situation, more long-term seabed monitoring systems are required. The seabed model is a mathematical representation of current physical knowledge; to a large extent the same knowledge that is also used in the interpretation of field data. The fine sediment flocculation and biostabilisation are not fully considered in the current version of the Sedsim model. Therefore, the results quoted in the present study are not predictions, but rather model simulations of plausible change on the south-western seabed based on the current state of understanding. For detailed seabed changes in the coastal region involving beach erosion and offshore bar movement, the present study should be supplemented by higher resolution localised Sedsim simulations.

Acknowledgements

The authors wish to thank Martin Rutherford (Defence Oceanographic Data Centre) for meteorological data. Peter Harris and Alix Post (Geosciences

Australia) provided useful discussions on the data and model verification. Special thanks to Donna Hayes and Peter Oke (CSIRO Marine and Atmospheric Research) for the wave hindcast data and bottom current data. Also thanks to James Chittleborough (National Tidal Centre) for the tidal range and tidal current data. The National Oceans Office provided encouragement over the life of the project, and the Directors of the Wealth from Oceans Flagship, Craig Roy and Kate Wilson, have supported this work from its inception. Finally, we would like to thank the editor and three anonymous reviewers for their constructive comments and suggestions.

References

- Bagnold, R. A. (1963). *Mechanics of marine sedimentation*. In 'The Sea'. (Ed. M. N. Hill.) pp. 507–527. (Wiley-Interscience: New York.)
- CMAR (2008). 'BLUElink, Ocean Forecasting Australia.' Available at <http://www.cmar.csiro.au/bluelink> [accessed 10 March 2008].
- Collins, L. C. (1988). Sediments history of the Rottneest shelf, southwest Australia: a swell-dominated, non-tropical carbonate margin. *Sedimentary Geology* **60**, 15–49. doi:10.1016/0037-0738(88)90109-1
- de Meijer, R. J., Bosboom, J., Cloin, B., Katopodi, I., Kitou, N., *et al.* (2002). Gradation effects in sediment transport. *Coastal Engineering* **47**, 179–210. doi:10.1016/S0378-3839(02)00125-4
- Exon, N. F., Hill, P. J., Mitchell, C., and Post, A. (2005). Nature and origin of the submarine Albany canyons off southwest Australia. *Australian Journal of Earth Sciences* **52**, 101–115. doi:10.1080/08120090500100036
- Feng, M., Meyers, G., Pearce, A., and Wijffels, S. (2003). Annual and inter-annual variations of the Leeuwin Current at 32°S. *Journal of Geophysical Research* **108**(C11), 3355. doi:10.1029/2002JC001763
- Gersbach, G. H., Pattiaratchi, C. B., Ivey, G. N., and Cresswell, G. R. (1999). Upwelling on the south-west coast of Australia—source of the Capes Current? *Continental Shelf Research* **19**, 363–400. doi:10.1016/S0278-4343(98)00088-0
- Griffiths, C. M., Dyt, C., Paraschivoiu, E., and Liu, K. (2001). Sedsim in hydrocarbon exploration. In 'Geologic Modeling and Simulation: Sedimentary Systems'. (Eds D. F. Merriam and J. C. Davis.) pp. 71–117. (Springer-Verlag: New York.)
- Hayes, D., Lyne, V., Condie, S., Griffiths, B., Pigot, S., and Hallegraef, G. (2005). Collation and analysis of oceanographic datasets for national marine bio-regionalisation. Report to the Australian Government, National Oceans Office, Canberra.
- James, N. P., Bone, Y., von der Borch, C. C., and Gostin, V. A. (1992). Modern carbonate and terrigenous clastic sediments on a cool water, high energy, mid-latitude shelf: Lapepede, Southern Australia. *Sedimentology* **39**, 877–903. doi:10.1111/J.1365-3091.1992.TB02158.X
- James, N. P., Boreen, T. D., Bone, Y., and Feery, D. A. (1994). Holocene carbonate sedimentation on the west Eucla Shelf, Great Australian Bight: a shaved shelf. *Sedimentary Geology* **90**, 161–177. doi:10.1016/0037-0738(94)90037-X
- James, N. P., Bone, Y., Collins, L. B., and Kyser, T. K. (2001). Surficial sediments of the Great Australian Bight: facies dynamics and oceanography on a vast cool-water carbonate shelf. *Journal of Sedimentary Research* **71**, 549–567. doi:10.1306/102000710549
- Jenkins, C. J., Kettner, A. J., Moore, C., and Sharman, G. (2003). 'dbSEABED World Seabed Data Browser.' Available at <http://instaar.colorado.edu/~jenkinsc/dbseabed/goseabed/interactive> [accessed 6 June 2005].
- Koltermann, C. E., and Gorelick, S. M. (1992). Palaeoclimatic signature in terrestrial flood deposits. *Science* **256**, 1775–1782. doi:10.1126/SCIENCE.256.5065.1775
- Lemm, A. J., Hegge, B. J., and Masselink, G. (1999). Offshore wave climate, Perth (Western Australia), 1994–96. *Marine and Freshwater Research* **50**, 95–102. doi:10.1071/MF98081
- Li, M. Z., and Amos, C. L. (2001). SEDTRANS96: the upgraded and better calibrated sediment-transport model for continental shelves. *Computers & Geosciences* **27**, 619–645. doi:10.1016/S0098-3004(00)00120-5

- Li, Q., James, N. P., Bone, Y., and McGowran, B. (1999). Palaeoceanographic significance of recent foraminiferal biofacies on the southern shelf of Western Australia: a preliminary study. *Palaeogeography, Palaeoclimatology, Palaeoecology* **147**, 101–120. doi:10.1016/S0031-0182(98)00150-3
- Li, F., Dyt, C., and Griffiths, C. (2003). A coastal morphodynamic model for cross-shore sediment transport. In 'Coastal Engineering VI, Computer Modelling and Experimental Measurements of Seas and Coastal Regions, Cadiz, Spain, 23–25 June 2003'. (Eds C. A. Brebbia, D. Almorza and F. Lopez-Aguayo.) pp. 335–344. (WIT Press: Southampton.)
- Li, F., Dyt, C., Griffiths, C., Jenkins, C., Rutherford, M., and Chittleborough, J. (2005a). Seabed sediment transport and offshore pipeline risks in the Australian southeast. *APPEA Journal* **45**, 523–534.
- Li, F., Dyt, C., and Griffiths, C. M. (2005b). Long-term coastal sedimentation model. In 'Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference and the 10th Australasian Port and Harbour Conference, Adelaide, South Australia, 20–23 September 2005'. pp. 281–286.
- Li, F., Dyt, C., and Griffiths, C. (2006a). Multigrain coastal sedimentation model based on equilibrium sediment distribution: application to nourishment design. *Estuarine, Coastal and Shelf Science* **67**, 664–672. doi:10.1016/j.ecss.2006.01.006
- Li, F., Dyt, C., Griffiths, C., and Jenkins, C. (2006b). 'Wind-driven water circulation and its impact on seabed sediment transport in the Australian Northeast'. In 'Proceedings of the 7th Pacific/Asia Offshore Mechanics Symposium, 17–21 November 2006, Dalian, China'. The International Society of Offshore and Polar Engineers (ISOPE PACOMS).
- Li, F., Dyt, C., Griffiths, C., and McInnes, K. (2007). Predicting seabed change as a function of climate change over the next 50 years in the Australian southeast. In 'Coastline Changes: Interrelation of Climate and Geological Processes'. (Eds J. Harff, W. W. Hay and D. M. Tetzlaff.) pp. 43–64. (Geological Society of America: Boulder, CO, USA.)
- Martinez, P., and Harbaugh, J. W. (1993). 'Simulating Nearshore Environments.' (Pergamon Press: New York.)
- McGowran, B., Li, Q., and Moss, G. (1997). The Cenozoic neritic record in southern Australia: the biogeohistorical framework. In 'Cool-Water Carbonates'. (Eds N. P. James and J. Clarke.) pp. 185–203. SEPM Special Publication, vol. 56. (SEPM (Society for Sedimentary Geology): Tulsa, OK, USA.)
- Oke, P. R., Schiller, A., Griffin, D. A., and Brassington, G. B. (2005). Ensemble data assimilation for an eddy-resolving ocean model. *Quarterly Journal of the Royal Meteorological Society* **131**, 3301–3311. doi:10.1256/QJ.05.95
- Oke, P. R., Brassington, G. B., Griffin, D. A., and Schiller, A. (2008). The BlueLink Ocean Data Assimilation System (BODAS). *Ocean Modelling* **21**, 46–70. doi:10.1016/j.ocemod.2007.11.002
- Reed, C. W., Niederoda, A. W., and Swift, D. J. P. (1999). Modeling sediment entrainment and transport processes limited by bed armoring. *Marine Geology* **154**, 143–154. doi:10.1016/S0025-3227(98)00109-1
- Soulsby, R. (1997). 'Dynamics of Marine Sands.' (Thomas Telford Publications: London.)
- Sternberg, R. W. (1972). Predicting initial motion and bedload transport of sediment particles in the shallow marine environment. In 'Shelf Sediment Transport, Process and Pattern'. (Eds D. J. P. Swift, D. B. Duane and O. H. Pilkey.) pp. 61–83. (Dowden, Hutchinson & Ross: Stroudsburg.)
- Tetzlaff, D. M., and Harbaugh, J. W. (1989). 'Simulating Clastic Sedimentation, Computer Methods in Geosciences.' (Van Nostrand Reinhold: New York.)
- Whitehouse, R., Soulsby, R., Roberts, W., and Mitchener, H. (2000). 'Dynamics of Estuarine Muds.' (Thomas Telford Publications: London.)
- Wu, B., Molinas, A., and Shu, P. (2003). Fractional transport of sediment mixtures. *International Journal of Sediment Research* **18**, 232–247.

Manuscript received 25 February 2008, accepted 15 February 2009