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Recommendations for the sustainable exploitation of tidal sandbanks

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ABSTRACT

A basic requirement for allowing marine aggregate (sand) extraction on the Belgian Continental Shelf (which takes place on sandbanks) is that it should not result in major environmental changes. However, a tidal sandbank (Kwinte Bank, Flemish Banks), exploited intensively since the 1970's, has shown evidence of significant morphological changes with the development of a 5 m deep depression in its middle section; thus, since February 2003, sand extraction has ceased in this area in order to study the environmental impacts and the regeneration potential of the seabed. The present contribution synthesises the results of the multidisciplinary research, which has taken place in the area and, on the basis of these findings, considers the need for an efficient management framework, in both the planning and monitoring stages of the extraction. The investigation has shown that extraction has had significant impacts on the seabed sedimentary character and ecology and the local hydro-and sediment dynamic regime. Under these conditions, regeneration of the seabed is not likely in the short-term and, although modelling exercises have indicated possible recovery in the medium- and long-term, this is likely to be inhibited by the lack of appropriate sediments in the area. The results have provided the basis of the identification of a 'suite' of criteria, which can assist in the strategic planning/design of marine aggregate concession zones, the efficient management of marine aggregate extraction and the planning of effective environmental monitoring; these criteria are related to considerations on resource location, the nature/thickness of the targeted deposits, morphodynamics and sediment dynamics, biology and ecology and extraction practices. The Kwinte Bank investigation has demonstrated also the need for intensive monitoring schemes in order to identify the morphological, sedimentary and ecological impacts, related to the dredging activities. A critical part of these schemes should be the evaluation of the dredging-related effects, against the background of the natural dynamics of the seabed; thus, baseline information is crucial, as, in its absence, impact assessments are likely to remain inconclusive.

ADDITIONAL INDEX WORDS: *marine aggregate extraction; dredging; environmental impact assessment; environmental monitoring; sustainable development; mining guidelines; seabed regeneration.*

INTRODUCTION

The formulation of recommendations and guidelines, concerning 'the best practice' in marine aggregate (MA) extraction is a complex issue, as it is driven by both 'top-down' considerations (i.e. considerations related to the regulation and management of extraction activities) and 'bottom-up' constraints (i.e. constraints associated with the diagnosis and prognosis of the complex physical environmental processes). The regulation of MA exploitation is associated with different levels of legislation, consisting of international Conventions, European Directives and national laws; however, although all European Member States have to comply with the rules prescribed by ratified international Conventions and the European environmental legislation, there are also significant differences in the management and regulation of MA exploitation between them. These differences stem mainly from the different approaches adopted by the Member States in the incorporation into their national legislation of the relevant environmental European Directives (particularly the Environmental Impact Assessment (EIA), the

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Strategic Environmental Impact Assessment (SEA) and the Habitats Directives), as well as from the particularities of the Member States' administrative structures (see RADZEVICIUS *et al.,* this volume). Hence, the national regulatory framework, related to MA exploitation, is not consistent throughout Europe, with a wide variety of processes and procedures existing in terms of resource policy, data and information management and research co-ordination and dissemination.

The main issue, involved in the regulation of MA exploitation, is associated with resource sustainability, as well as with the environmental impacts of the extraction and their assessment. With respect to the assessment of the environmental impacts, there are many different interpretations on how to identify 'best practices'. This is due partly to the presence of a large array of habitats along the European coast, which have different characteristics and are associated with different environmental risks, when being disturbed. In addition, there are disparities between the different EU Member States concerning the 'know-how' necessary to address effectively the various scientific problems associated with resource prospecting and the environmental impact of MA extraction (see also VELEGRAKIS *et al.*, this volume). Many of the environmental effects of MA extraction are likely to be site-specific, but general conclusions can be drawn from the results of site-specific research. Nowadays, developing technology and an increase in the efficiency of environmental monitoring, in combination with innovative and effective research, allow an improved estimation of the effects of MA extraction.

Groups with industry-interest (e.g. the European Marine Sand and Gravel Group (EMSAGG)), the International Council for the Exploration of the Sea (ICES) and Non-Governmental Organisations (e.g. World Wildlife Fund (WWF)) are working already on initiatives related to MA extraction and the promotion of appropriate research, to address problems at a supra-national (regional) level. Within ICES, the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT) produces Annual Reports including overviews of: (a) extraction activities; (b) seabed resource mapping programmes; (c) approaches to environmental impact assessments; and (d) related environmental research developments. The group has also formulated guidelines concerning the information which has to be collated/acquired in order to assess effectively the environmental impacts of MA extraction (ICES, 2003). The OSPAR Commission has stated that the OSPAR Contracting Parties should take these guidelines into account, within their procedures, for the authorization of the extraction of marine sediments (see RADZEVICIUS *et al.,* this volume). According to the ICES guidelines (ICES, 2003), wide-ranging information is required for evaluating the physical impacts of MA extraction, i.e. information on: (1) the impacts of sediment extraction on the coastal and offshore sedimentary and hydrodynamic processes, including potential draw-down of neighbouring beaches, changes to sediment supply and transport pathways and modifications to wave and tidal regimes; (2) potential changes to the seabed morphology and sediment type; (3) exposure of different substrates; (4) changes in the behaviour of bedforms, within the extraction and adjacent areas; (5) the potential risk of the release of contaminants during aggregate dredging and exposure of potentially toxic natural substances; (6) the transport and redeposition of fine-grained sediments, which are either resuspended by the dredging activities or are released into the water column through hopper overflow or on-board aggregate processing; (7) the effects on the water quality of increases in the concentration of resuspended fine material; (8) changes in local water circulation, resulting from removal or creation of topographic features on the seabed; and (9) the time-scale for potential physical "recovery" of the seabed. In order to assess the biological impacts, ICES guidelines recommend studying: (1) changes in the benthic community structure and in any ecologically-sensitive species, or habitat that may be vulnerable to extraction operations; (2) the effects of aggregate dredging on pelagic biota; (3) the impacts on the fishery and shell fishery resources, including spawning fish, nursery areas, over-wintering grounds for ovigerous crustaceans and known routes of migration; (4) the effects on trophic relationships, e.g. between the benthos and demersal fish populations; (5) the impacts on sites designated under local, national or international regulations (see above); (6) rates and modes of recolonisation of exploited sites, taking into account initial community structure, natural temporal changes, local hydrodynamics and any predicted changes in sediment type; (7) the effects on marine flora and fauna, including seabirds and mammals; and (8) the impacts on the ecology of boulder fields/stone reefs.

The aim of the present contribution is to present and evaluate the procedures concerning some of the topics identified in the ICES guidelines and to provide recommendations on the improvement of some aspects of the environmental monitoring of MA extraction sites. Toward this objective, the results obtained from the environmental monitoring of the central part of the Kwinte Bank (Flemish Banks, southern North Sea), where a depression has formed due to intensive MA extraction, are synthesised and discussed. Physical, ecological and potential cumulative impacts are evaluated, whilst a suite of criteria is provided which can assist in limiting the environmental impacts of MA extraction. Finally, a more general methodological research framework is proposed, together with recommendations on the refinement of monitoring schemes.

BACKGROUND TO THE KWINTE BANK MA EXTRACTION

The topics, included in the ICES guidelines, are discussed with reference to the Kwinte Bank (see Figure 11., VELEGRAKIS *et al.,* this volume); this is a tidal sandbank situated in the southern North Sea, on the Belgian Continental Shelf in water depths of -8 to -25 m MLLWS (mean lowest low water level, at spring tides) (Figure 1.). MA extraction commenced on the bank in the 1970's and, from 1997 until 2003, 75 % (11,620,000 m^3) of all the Belgian MA extraction was related to this sandbank. Since 2003, MA extraction activities have seized on the bank, in order to evaluate the environmental impacts and monitor changes and recovery rates (see VAN LANCKER *et al.*, this volume). As such, the Kwinte Bank provides an ideal example for the investigation of the impacts of MA extraction, within a tidally dominated environment.

Within Belgium, sediment removal from sandbanks is, for each individual extraction activity, restricted to an excavation depth of 0.50 m; as such, only the upper surface sediments are removed. This approach has been considered to cause only minimal environmental impacts, as it has long been believed that sandbank maintenance processes would counterbalance the loss of the extracted sediments (VAN LANCKER *et al.*, this

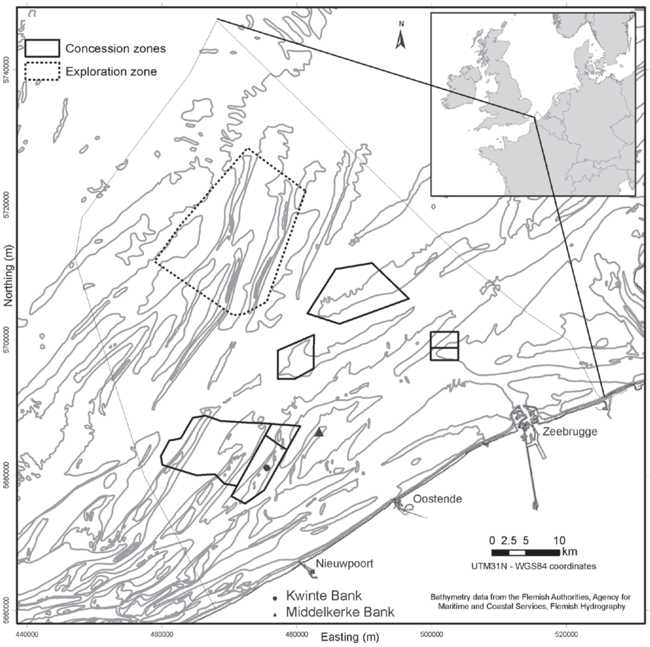

Figure 1. Concession zones on the Belgian Continental Shelf. The more offshore exploration zone for future marine aggregate extraction is indicated also.

volume). Since 1976, the exploited sandbanks have been monitored and, until recently, only limited physical environmental impacts had been reported. However, in 2000, a depression (5 m deep, 700 m wide and 1 km long) was identified along the most intensively exploited upper part (crown) of the sandbank (see Figure 3., Degrendele *et al.,* this volume). To allow regeneration of this section of the sandbank, sand extraction has been prohibited, since February 2003. Multidisciplinary research programmes, covering a 2-year period, have been set-up to address the regeneration potential, from a physical and ecological perspective; these have been based upon state-of-the-art methodology and instrumentation. The physical impact of extraction, on the seabed, has been assessed using hydro-, sediment- and morphodynamic modelling and calibrated/validated using *in-situ* measurements. The ecological impact was focussed upon the macrobenthos and included a comparison between exploited and non-exploited sandbanks. The framework for the investigations, together with the issues arising after 30-year of monitoring, are discussed in Van Lancker *et al.* (this volume).

Apart from the impacts related to the depression area of the sandbank, the long-term monitoring results did show a significant loss of the total bank's volume (Norro *et al.,* 2006). Moreover, De Moor (2002) had reported a general erosive tendency for the whole of the Flemish Bank region, including both exploited and non-exploited sandbanks, with the swales between the banks being either stable or slightly erosional. This pattern indicates that aggregate extraction may not be the only cause for the observed erosive trends; nonetheless, it emphasises the need for a more sustainable exploitation approach.

SYNTHESIS OF THE NEW RESULTS

Physical Impacts

Bellec *et al.* (this volume) and Degrendele *et al.,* (this volume) studied the geology, morphology and sedimentology of the Kwinte Bank and its central depression. Comparing bathymetric profiles obtained in 1992 and 1999, a difference of up to 6 m was observed between the deepest part of the depression (-16 m MLLWS) and the former crown (-10 m MLLWS) of the sandbank; in comparison, the western swale remained stable, at around –25 m MLLWS (Degrendele *et al.,* this volume). Following cessation of dredging activities, the depression's bathymetry remained quite stable and its morphodynamics became similar to those of the adjacent, non-exploited crown of the sandbank (Degrendele *et al.*, this volume). No clear evidence of morphological regeneration could be established, at least over a 2-year observation period. The depression could be distinguished also from its surroundings on the basis of acoustic imagery and seabed classification. Large dunes were found also in the depression, but they were characterised by locally lower heights, whereas their steep face was observed to be pointing progressively towards the NE, i.e. in the direction of the flood flow (Bellec *et al.*, this volume). Interestingly, a lot of the dunes, found within the depression, appear to have uninterrupted crests (see Figure 3., Degrendele *et al.,* this volume), suggesting early recovery of the basic bedform morphology.

Intensive sediment sampling showed that the sandbank might be divided into subareas, each with a particular sedimentary character (Bellec *et al.,* this volume). The seabed of the depression showed a wide range of fine- to medium-grained sediments, with variable shell content, whereas, the sediments in the surrounding areas of the bank were found to consist of poorly-sorted and coarse-grained, shelly sediments in the west and reasonably homogeneous, well-sorted, finer-grained sediments in the east. The observations indicated that the depression might act as a 'transport corridor' for shelly material, transported by the flood flow. Over a 2-year period, the overall sediment characteristics in the depression remained fairly consistent, suggesting very limited sediment exchanges. However, the evolution of the mean grain size of sediments, within the depression, showed trends resembling those of the more heterogeneous swale sediments; as such, these sediments are different from those anticipated for the crown of a sandbank. Within the depression, observations obtained during the ebb (flow in a SW direction), have revealed the presence of ephemeral muddy deposits; this indicates that the depression has the potential to trap also fine-grained sediments. Combined with the shelly coarser-grained material, brought in by the flood flow, this might initiate a slow regeneration of the depression.

The potential for sediment transport towards the depression and, hence, for natural regeneration, has been studied on the basis of short-term hydro-sedimentary observations (Garel, this volume). Tidal cycle measurements, carried out under reduced wave activity, have shown differences between the near-bed tidal ellipses and the across-bank component of the peak (ebb and flood) flow inside the depression and those at the crown of the bank. Divergent net sand transport was predicted for the area of the depression, suggesting seabed erosion. Sediment transport pathways were investigated also on the basis of grain size trend analysis (Poulos and Ballay, this volume). Two main transport pathways were identified: (a) to the NE (flood-directed) in the central depression and along the western

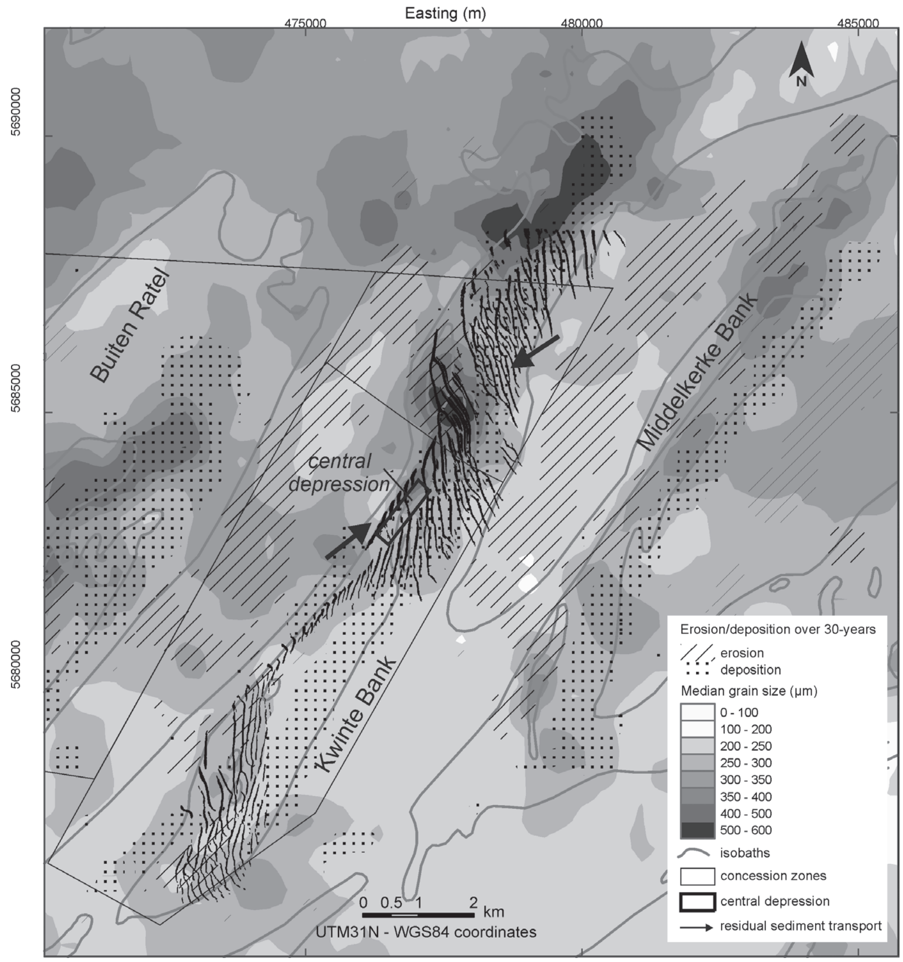

Figure 2. Concession zones and grain size (median grain size after Verfaillie, Van Lancker, and Van Meirvenne, 2006) distribution of the surficial sediments of the Kwinte Bank and surrounding areas. The crestlines of large to very large subaqueous dunes are also shown on the Figure, as well as the type of sedimentary environments and the major transport sediment pathways (for details, see text). The location of the central depression is indicated.

flank; and (b) to the SW (ebb-directed) along the gentle eastern slope of the Kwinte Bank; these results contrast to those of a previous similar study over the Kwinte Bank (Gao *et al.*, 1994), which had suggested across-bank sediment transport mainly. Generally, it appears that the central depression acts more as a transit area, than as a depocentre, for the sediments.

Process-based, 'bottom-up' modelling has been used to investigate the general seabed dynamics of tidal sandbanks (Brière *et al.,* this volume, and Van den Eynde *et al.,* this volume). Generally, there was good agreement between the derived numerical results and the obtained field measurements. Flood and ebb tidal flows were found to dominate the western and eastern flanks of the Kwinte Bank, respectively, whereas the overall residual currents were found to be mainly towards the WSW, indicating ebb-dominance for this part of the bank. In addition, distinct erosion/deposition patterns were simulated; these appeared to be similar, for different levels of dredging-induced lowering of the sandbank (Van den Eynde *et al.,* this volume). Under such conditions, no destabilisation of the sandbank was indicated. Modelling of the sediment transport under wave-current interaction was undertaken, as the crests of shallow tidal sandbanks have been shown to be particularly vulnerable to wave action; as such tidal erosion/deposition patterns may change, according to superimposed wave activity (Giardino, Van den Eynde, and Monbaliu, this volume). The modelling showed a high increase in sediment transport, but also a change in direction of the net flux of sediments (Giardino, Van den Eynde, and Monbaliu, this volume). The dominance of the ebb flow along the eastern flank can be suppressed by southerly (or SW) winds, which is the prevailing wind direction over this area. Previous studies (Van Cauwenberghe, 1971) had indicated that the sandbanks have not migrated; this might be due to the long-term 'balancing out' of the sediment transport over the bank under the influence of waves, i.e. the sediment transport under the combined action of tidal currents and (relatively low) waves along the eastern flank and the sediment transport due to tidal currents and higher waves along the more exposed western flank (Giardino, Van den Eynde, and Monbaliu, this volume).

The long-term impact of sand extraction has been modelled, using complementary approaches, which combined the benefits from numerical, 'bottom-up' modelling and idealised models

Table 1. *Evolution of the central depression, after cessation of dredging. Indications of erosion. The references can be found in this Special Issue.*

Methodology	Indications of an erosional trend
Multibeam bathymetry	The depression is 5 m deeper than the surrounding sandbank and since 2003; there is still a minor increase in depth (natural processes?). Large sand dunes are lower in height and move faster in the depression than outside of it (Degrendele et al.). The higher current speeds likely prevent deposition during the flood (Bellec et al.).
Surficial sediment sampling	Temporal grain size trends in the depression resemble more the evolution of sediments in the swale; they differ significantly from those along the crest of a sandbank (Bellec et al.). Along the axis of the depression, significant NE directed sediment transport is indicated, on the basis of grain size trend analysis (Poulos and Ballay). The presence of the depression is more a sediment transit area, than a depocentre, (Bellec et al., and Poulos and Ballay).
Hydrodynamics ADCP – S4	Due to the canalisation of the flow, there is a stronger erosional potential during flood. A divergence of net sand (bed load) transport has been calculated inside the depression, with net erosion during the tidal cycle (Garel).
Process-based model Delft 3D	Throughout a tidal cycle, erosion over the central depression was modelled (0.001 m of erosion during 10 days, in the absence of waves) (Brière et al.).
MU-SEDIM and SISYPHE models	Without atmospheric conditions and waves being taken into account, erosion occurs in the depression and on the western flank of the sandbank (Van den Eynde et al.). Giardino et al. demonstrate higher sediment transport capacities and changing residual transport directions, under the combined action of tidal currents and waves.
Biological sampling	No further impoverishment, but a species composition difference has been observed within the wide niche width of the sandbank transitional species assemblages, with lower relative polychaete and higher relative crustaceans and echinoderms abundance. Nonetheless, similar macrobenthos density and species richness exists (Bonne).

(Brière *et al.*, this volume). The latter showed that the expected long-term trend of an excavated area is recovery, resulting in a new sandbank equilibrium. Such long-term predictions contrast to those by the morphodynamic observations (Degrendele *et al.*, this volume) as well as to those indicated by the hydrodynamic observations and the short-term, 'bottom-up' modelling (see above); these do not suggest regeneration for the area of the depression. Such differences between the idealised modelling results and those by the other approaches might be due to the basic assumption of the modelling used, i.e. the presence of an infinite source of sand in the area, which, in reality, is not the case (Le Bot *et al.*, 2003, for an overview).

The impact of the different levels of the lowering of the sandbank (see above), on the coast, has been studied also

Table 2. *Evolution of the central depression, after cessation of dredging. Indications of recovery. The time-scale and the significance of the process is provided. The references can be found in this Special Issue.*

Method	Indications of recovery	Time-scale
Multibeam backscatter classification	Slight tendency for a relative increase in fine sediments, in the depression (Degrendele et al.).	3 years (Significant?)
Sediment sampling	Central depression appears to trap shelly and coarse-grained material (Bellec et al.), albeit locally. Deposition of mud, under ebb and neap tidal cycle conditions (not observed on the crest) (Bellec et al.).	Event related, Significant (Significant?)
Hydrodynamics (ADCP/S4)	Convergence of net sand transport, at the bank's crest (Garel).	Tidal cycle, Significant
Process-based model (Delft3D)	Residual transport direction from the SW (swale) towards the NE, over the sandbank crest (Brière et al.).	Two weeks, Significant
Idealised modelling	On the long-term (100 years), the system tends to a new equilibrium, displaying recovery of the depression (Brière et al.).	100 years
Biological sampling	Macrobenthic species assemblage has changed slightly, but develops well (Bonne).	3 years, Significant

within the context that intensive offshore dredging would increase a 1000-year wave height (Verwaest and Verelst, 2006). However, no significant impact could be deduced. This is considered to be due primarily to the large distance (> 12 km) of the extraction site from the coast, together with the presence of other sandbanks between the Kwinte Bank and the coast that leads to a significant dissipation of wave energy.

For environmental and resource management purposes, the physical information available from the Kwinte Bank is synthesised in Figure 2. The most economically interesting (in relation to the MA industry) grain sizes (> 300 μm) are found to the north of the Flemish Banks, although patches of coarser grain sizes occur, locally, in the remainder of the concession zones, where fine to medium sands prevail. The asymmetry of the large and very large subaqueous dunes indicates flood-dominance along the western steep flank and ebb-dominance along the gentle eastern slope of the Kwinte Bank. Modelling results, concerning areas of erosion and deposition, in the wider area, over a 30-year period (Brière *et al.*, this volume), indicate mostly erosion in the swale areas (+/- 1 m) and along the western steep flanks of the banks, together with the kink areas. In comparison, the eastern gentle flanks of the banks have been predicted to be depositional; this is also the case with the highest part of the crown of the Kwinte Bank that is situated more towards the south. According to the inferred sediment transport pathways, the sedimentary cover in the swale to the west of the Kwinte Bank could be a potential source of sediments to the depression area. However, the grain size is finer than in the depression and the thickness of the Quaternary cover in the swales is less than 2.5 m to absent (Le Bot *et al.,* 2003, for an overview). Hence, the major source of coarse sand (> grain size 300 μm), needed to rebuild this section of the bank, is located to the north of the depression.

Biological/ecological impacts

The nature and vulnerability of benthic communities to MA extraction on the Kwinte Bank, has been investigated using macrobenthic fauna sampling (Bonne, this volume). Sampling stations were located within the central depression, along its sides and outside the exploited area. In addition, the adjacent, non-exploited Middelkerke Bank (Figure 1.) was also sampled, for reference purposes. Compared to the historical data from the Kwinte Bank and the reference stations on the Middelkerke Bank, crustaceans and echinoderms have become more important over the area of the depression; this suggests a greater similarity between the depression and a swale environment. The difference in species composition in the depression can be considered within the wide niche width of the sandbank transitional species assemblages, described previously for the Kwinte Bank and the Belgian Continental Shelf (Van Hoey, Degraer, and Vincx, 2004). On this basis, sand extraction appears to have created a 'locally-different' habitat on the Kwinte Bank, with adaptation of the benthic fauna; however, the changes have not been found significant, at least on the scale of the sandbank system. It must be noted, that within the framework of the present investigation, only the macrobenthos has been considered. Vanaverbeke *et al.* (2007) have discussed elsewhere the ecological effects, based upon changes in macrobenthic, nematode and copepod communities, including also an evaluation of their short-term recovery, after the cessation of dredging. The conclusions pointed out that even without morphological changes, the increased dynamics, introduced by the creation and filling up of the dredging furrows would affect the benthos.

Erosion/recovery trends

Trends in the evolution of the depression after cessation of dredging, based on the results of the present investigation are listed in Tables 1. and 2. It appears that, in the short-term, erosion dominates, whilst recovery seems appropriate over the medium- to long-term.

DISCUSSION AND RECOMMENDATIONS

Marine environments are dynamic and complex and their knowledge base is limited; thus, many changes are not observed until it is too late for a rigorous demonstration of cause and effect (Thrush *et al.*, 1998). The same applies to the Kwinte Bank, as it was only after the formation of a 5 m deep depression along the crown of the sandbank, that an intensive research strategy was established. The results of the morphological, sedimentological and biological surveys, carried out following the cessation of dredging, have not revealed any significant recovery of the depression, at least over a 2-year observational period. The fact that such depressions develop indicates that sandbanks should not be considered as infinite resources of renewable MA deposits.

The identification of best practice in MA extraction from tidal sandbanks is linked, inherently, to the consideration of whether renewable or non-renewable sediments are being extracted; this, in turn, has implications on sustainability. Guidelines on sustainable exploitation have been described by Wellmer and Becker-Platen (2002), who addressed the sustainability of mineral resources, in general. For renewable resources, "*the rate of consumption should not exceed the rate at which they are regenerated*". Non-renewable resources imply that "*the consumption should not exceed the amount that can be replaced by functionally equivalent renewable resources, or by attaining a higher efficiency in the use of renewable or non-renewable resources*". Moreover, these investigators observed "*material and energy input into the environment should not exceed the capacity of the environment to absorb them with minimal detrimental effects*". Likewise, that "*the rate of anthropogenic input and environmental interference should be measured against the time required for natural processes to react and cope with environmental change*". Such considerations are highly relevant to the management of MA resources, at least, if extraction is envisaged within the system's natural variability. If non-renewable resources are exploited increasingly, there is a need for a more efficient use of the seabed, a search for functionally equivalent renewable resources and minimising the detrimental effects of the extraction.

Relevance of the results against sustainable MA exploitation

Physical impacts

Generally, the most severe direct physical impact of MA extraction relates to substratum removal, alteration of bottom topography and re-deposition of resuspended/jettisoned fine material (e.g. De Groot, 1996; Newell, Seiderer, and Hitchcock, 1998). Dredging-induced changes in sediment composition relate mostly to: (a) surficial grain size alterations (McCauley, Parr, and Hancock, 1977; Poiner and Kennedy, 1984); (b) an increase in the proportion of fine sands (Boyd *et al.*, 2005; Desprez, 2000; Van Dalfsen *et al.*, 2000), or silt (Van der Veer, Bergman and Beukema, 1985); and (c) an increase in gravel, through the exposure of coarser sediments (Kenny *et al.*, 1998).

Generally, depressions or pits, created by MA extraction, have been reported to be enduring seabed features, for several years. Boers (2005) has reviewed the morphological behaviour of different pits, trenches and channels, excavated in sand on the Dutch Continental Shelf. The recovery time of the depressions/pits has been shown to vary, depending on the local environmental conditions (water depth, waves, flow velocity, sediment characteristics) and pit/trench characteristics (volume, shape, orientation). Thus, the regeneration time of the depressions/pits has been found to range from months in shallow water, to decades or centuries in deep water settings; characteristic regeneration time-scales for large-scale sand extractions (> 10 million m^3), in water depths of more than 20 m, have been found to be in the order of centuries (Roos, 2004). Using process-based modelling, Van Rijn *et al.* (2005) concluded that the orientation of the pit, towards the flow, is the most important parameter. Pits or channels, lying perpendicular or oblique to the flow, enhance sedimentation, whereas those parallel to the flow promote sedimentation in the case of wide pits (Hoogewoning and Boers, 2001; Ribberink, 1989), but slight erosion in the case of narrow pits (Ribberink, 1989). If pit/depression evolution is modelled as a local topographic perturbation, the system may shift to a new equilibrium profile (Roos, 2004), with the corresponding time-scales (approx. a century) being shortest for deep and narrow pits, formed on the bank's crest.

On the Kwinte Bank, the direct impact of dredging is revealed by the presence of elongated depressions, formed within the topzones of sandbanks (Degrendele *et al.*, this volume).

Instead of homogeneous well-sorted medium to coarse sand, patches of fine and coarse sand occur next to areas of ephemeral mud deposits (Bellec *et al.*, this volume). At least, over a period of 3 years, no significant sediment infill has been observed in the depressions; this is somewhat unusual, since the crests of sandbanks are generally regarded as being dynamic, sediment pathway convergence zones (e.g. Pattiaratchi and Collins, 1987). The modelling results predict recovery of these areas, but only after a time-span of, at least, a century and on the condition that the necessary sand supply is available in the system. Nevertheless, if the extracted sediments are different from those that are transported easily within the system, restoration of the bank is more difficult to take place. There are also concerns about the effects of these depressions on the flow, as flow modification may introduce changes in the original erosion/sedimentation patterns. In some cases, such changes might lead to increased erosion in the neighbouring coasts, although no clear impacts have been described within the literature, even for extraction areas close to the coast (e.g. Brampton, Evans, and Velegrakis, 1998; Queensland, 2005).

Biological/ecological impact

Assessing ecological changes is difficult in sandbank environments. The high mobility of species, the poverty and the wide niche width of the community, together with the extent to which the community adapts to high levels of sediment reworking, makes it difficult to isolate the effect of human-induced physical disturbance. Moreover, communities in areas of high stress are characterized by higher growth rates (Jennes and Duineveld, 1985); hence, they adapt more readily to the impact of any dredging operation (Desprez, 2000). The macrobenthos at the Kwinte Bank changed, but the changes were not significant at the larger community scale indicative for the Flemish Banks; this is due to the considerable adaptability of the community with highly mobile species. The observed, relatively, small changes showed that recovery can be considered as sufficient and relatively fast. However, some of the changing biological characteristics confirmed the tendency of the excavated depression to show more similarity with the behaviour of the deeper swale areas, next to the bank. Water depth changes may indeed cause changes to benthic fauna assemblages, such as changes in the composition, species diversity and abundance (Queensland, 2005).

Potential cumulative impacts

In the increasingly anthropogenically-stressed coastal marine environment, cumulative environmental effects may be anticipated. For example, sandbanks are associated also with fishery activities, which are focussed mainly on the swales and the base of the sandbanks; in high intensity trawling zones, the seabed has been shown (by multibeam imagery) to be completely scraped (Fund for Sand Extraction, unpublished). Since these areas are very significant components of the system, forming important constituents of the sediment recirculation cells and, thus, of the sandbank maintenance mechanism (e.g. Dyer and Huntley, 1999; Pattiarachi and Collins, 1987), the cumulative impacts of fishery activities require further investigation. In addition, the modification of the seabed dynamics in relation to the installation of marine Aeolian parks (windmill farms) has not been thoroughly investigated; nevertheless, these changes could affect the dynamics of nearby MA extraction zones. Cumulative impacts may also occur, when the potential effects of sea-level rise and increased storminess are considered (e.g. Solomon *et al.,* 2007); these effects are, however, difficult to establish, since long-term datasets are required.

Criteria for sustainable exploitation

Generally, the environmental impacts of extraction are site-specific, due to variations in sediment type, mobility and bottom topography and hydrodynamic activity (Desprez, 2000); as such, the establishment of general guidelines for minimising environmental effects is a rather difficult exercise. Nonetheless, in many cases, MA extraction zones are planned in areas that are not favourable for aggregate extraction in the long-term, e.g. due to limited resource availability and/or expected environmental constraints. If criteria can be set that are clear and quantifiable, they can: (a) provide guidance to the design of MA concession zones; (b) guide decisions on the management of MA extraction; and (c) be used for effective environmental monitoring. The strictness of such criteria will depend strongly upon the view of the relevant regulatory authorities on the acceptable environmental risks.

Location criteria

One of the major criteria for selecting MA extraction sites is the potential impact on the coast. In many coastal areas, the appropriate regulatory authorities have set location criteria on the basis of the water depth, the 'closure depth' or the distance from the coast in order to limit undesirable effects of MA extraction on the neighbouring coasts as, for example, in The Netherlands and the US (e.g. Campbell *et al.*, 2003). Depending on the distance from the coast, the infill rate of dredged areas will differ as also the impact on inshore wave climate (modified refraction and diffraction) and gradients of littoral drift (Van Rijn *et al.,* 2005). It must be noted, however, that the establishment of such criteria is also constrained by economic considerations related to costs due to the increased depth of extraction and the distance from the landing facilities (e.g. Bate *et al.*, 1997).

Geological criteria

Selecting concession areas with most suitable sediment resources, guaranteed also in the long-term, requires an improved knowledge of the continental shelf geology, particularly in the case of sandbanks. Sandbanks are characterised by a variable and complex internal architecture, with some banks exhibiting complex internal structures, suggesting multi-phase formation (e.g. Trentesaux, Stolk, and Berne, 1999) and others showing simple structures (e.g. Collins *et al.*, 1995). These differences may be related to the antecedent morphology and type of substrate, as well as the sedimentary framework in which the sandbanks were formed. Sandbanks with a multi-phase formation are often founded on an erosional (incised) surface which is infilled by coarser material over which estuarine and shallow marine deposits with varying lithologies are draped (Trentesaux *et al.*, 1999). Only the upper part of these banks is tidally dominated, consisting of sediments, representative of the present-day hydrodynamic regime. In these cases, exploitation should be restricted to the upper body of the sandbank, both from a resource perspective (i.e. consistent quality) and an environmental impact perspective (i.e. regeneration potential). On the basis of the results of the Kwinte Bank bathymetry monitoring, the thickness of the modern tidal sedimentary cover should not be less than 5 m, as intensive dredging may otherwise uncover the underlying deposits in a relatively short time

Table 3. *Large-scale information/maps needed to support sustainable exploitation.*

Information	Function
Detailed Grain size Distribution	Target the appropriate aggregate quality Id entify potential source areas for regeneration;
Thickness/Suitability of the deposits	Ensure long-term availability and consistency in quality;
Spatial/temporal information on flow information and sediment transport and erosion/deposition patterns, supported by information on bedform dynamics and morphological changes	Indicate areas with higher dynamics Identify bedload convergence/divergence zones and the evolution of the sedimentary environments to avoid areas with poor regeneration potential (e.g. 'kink' areas and extremities of the banks) and minimise detrimental physical impacts ;
Wave Energy Distribution	Evaluate event-driven possible impacts on the extraction zones and neighbouring coasts;
Ecological Functioning	Avoid sensitive areas, or important habitats;
Other seabed uses	Minimise conflicts, optimise concurrent use.

period (Bellec *et al.,* this volume). Further, it is important that areas are selected where a sufficient unconsolidated Quaternary cover is guaranteed over larger areas, including the swales between the banks, as it appears that swale areas close to extraction sites are more erosive than others (De Moor, 2002); hence swales likely form primary sources of sediments, for bank regeneration

Morphological criteria

Less stable areas of sandbanks are best to be avoided in terms of removal of sediments, i.e. MA extraction should be avoided over 'kink' areas (if present) and bank extremities. It has been suggested (Bellec *et al.*, this volume; Deleu *et al.*, 2004; Smith, 1988) that the 'kink' areas of sandbanks are associated with higher dynamics. In some cases, these areas are somewhat lower in height (Deleu *et al.*, 2004), but the dynamics of their bedforms is often rapid and readily adjustable to the varying hydro-meteorological conditions. Moreover, modelling experiments, undertaken over a 30-year period, have shown an erosional trend for the 'kink' area of the Kwinte Bank (Brière *et al.*, this volume). In addition, flow speed and direction may change rapidly in these areas, hampering recovery.

The dynamics along the sandbank extremities are also not easily predictable. In the Flemish Bank region, bank extremities appear interesting as resource areas, with higher bedforms and coarser-grained sediments. However, sediment volumes fluctuate more here and are more susceptible to storm action than those of the middle sections of the sandbanks. On the basis of historical data, De Moor (2002) has shown that the northern extremities of the Flemish Banks are recent sedimentary accumulations, formed within the last century. This is supported by seismic evidence, which have shown that only a thin sand sheet forms these modern, tidally-controlled sandbank sections (Bellec *et al.,* this volume). In addition, due to the more dynamic bedform movement, it is difficult to distinguish natural from anthropogenic changes in these areas; consequently, negative impacts of the sediment extraction will not be timely (and easily) observed. Finally, extraction over interdune areas can have adverse environmental impacts, if the crests and troughs of the dunes represent different sedimentary environments, with the troughs usually being heterogeneous in terms of sediment composition and often richer in benthic fauna than the crests (Mackie *et al.,* 2006).

Sediment dynamics criteria

If extraction is viewed within the framework of the natural variability of the sandbank's volume, then it would be beneficial if sediment extraction involves deposits with grain sizes that can be regenerated easily, i.e. deposits with grain sizes that are readily available in the potential source areas. In addition, the extraction zones should be restricted to areas known as being depositional. Sandbanks are generally areas of sediment accumulation (e.g. Pattiarachi and Collins, 1987); nonetheless, sections of the sandbanks can be erosional, as suggested also by the results of the Kwinte Bank investigation (Van den Eynde *et al.,* this volume, and Brière *et al.*, this volume).

A difficult criterion to define relates to the sediment volumes that can be extracted, without causing any long-term impact; this requires knowledge on the natural volume fluctuations. Based upon an extensive, monitoring programme, Degrendele *et al.* (this volume) have proposed a mean natural evolution of the bank volume of +/- 0.05 m^3/m^2/year; ideally, the rate of extraction should not exceed this rate. On the basis of 12 observations, Van Lancker (1999) has identified also such variability in the erosion/sedimentation patterns of the Belgian nearshore area, but found that it is mostly 'event dependent'. As such, this rate of change can occur between successive observations, on the short-term and may be balanced out on a year's basis. Present extraction activities, on a local basis, exceed significantly this rate; inside the depression, a rate of 1.08 m^3/m^2/year has been estimated, with the rates for the surrounding area and the overall extraction zone being 0.47 m^3/m^2/year and 0.64 m^3/m^2, respectively (Degrendele *et al.*, this volume). Thus, the extraction activities in the area cannot be balanced by the natural dynamics.

Biological/ecological criteria

Sustainable management of renewable natural resources should be based upon a balance between exploitation and adverse effects on the other components of the ecosystem (Thrush *et al.*, 1998). The results of van Moorsel (1994), Kenny and Rees (1996) and Desprez (2000) have illustrated that extensive dredging may modify the sedimentary deposits slightly, but the benthic communities considerably. As such, it may be preferable to concentrate extraction within small areas of the sandbank i.e. follow an 'intensive dredging' model. Nevertheless, prolonged extraction in confined areas can also cause serious effects on seabed morphology and sediment quality

Table 4. *Overview of knowledge/data and tools/innovation needs, to support the sustainable exploitation of a particular extraction site.*

	Geology	Morphology	Sedimentology	Sediment dynamics	Biology/Ecology
Knowledge / Data need	Resource availibility *sufficient unconsolidated Quaternary cover* Good characterisation of subsoil strata (homogeneity of the subsurface layers) Resource origin	Volume calculations Fine-scale Morphometric analysis Bedforms	Spatial distribution Quality mapping << industry needs	Fine-scale hydrodynamics 2D/3D (currents + waves) Sediment transport (bedload/suspended) Sediment balance (erosion/deposition) +grain size	Identification of ecologically sensitive areas Habitat characterisation Define ecological value
	Theoretical work on sensors				
Tools / Innovation need	Very-high resolution Seismics	High frequency Acoustics	High frequency Acoustics	High frequency Acoustics/Optics/ Electro Magnetic	High frequency Acoustics
	Sensor improvement				
	+ Coring+Geotechnics	+ Video/Still	+ Sampling+Geotechnics	+ Sampling	+ Video/Sampling
		Monitoring – adequate time series – good reference framework			
	Predictive modelling – long-term				
Risk and Uncertainty Analysis					

(Desprez, 2000; Vanaverbeke *et al.,* 2007). For comparison, there exists a 'threshold scale' and a 'frequency of disturbance events' at which long-lasting ecological effects may occur, even in the case of non-anthropogenic (natural) disturbance (Kaiser and Spencer, 1996). The results obtained here for the Kwinte Bank support these suggestions.

Criteria related to the extraction activity itself

Van Rijn *et al.* (2005) regard the orientation of the pit in relation to the flow, as the most important parameter controlling the rates of infill (see above). From navigational safety and practical perspectives, it appears logical that extraction should take place along the direction of the main current (e.g. Bate *et al.,* 1997). However, the present investigation (Degrendele *et al.,* this volume) has shown that the depression is located slightly obliquely to the crest and parallel to the flow; this has caused an opening of the depression, towards the northwestern swale (see Figure 3., Degrendele *et al.,* this volume) with the flood flow becoming 'channelised' (Garel, this volume). Such a situation should be avoided, as it enhances erosion. Other crucial criteria relate to the amount extracted on each dredging visit and the number of extractions over a given time-span (Schrijvers *et al.*, 2007). Thresholds on these issues cannot be set on the basis of the available information, but they may be established in the future, with data becoming increasingly available on environmental impacts and dredging activities. Other issues relate to minimising the overflow, or fine material screening; however, these have been found less important on the Belgian Continental Shelf (Schrijvers *et al.*, 2007).

Example of the application of some of the criteria to other extraction zones

Applying the above mentioned criteria to the concession zones in the Flemish Banks region, leads to the selection of the eastern part of the Buiten Ratel sandbank (Figure 2.) as being most suitable: water depths are still around 10-15 m MLLWS; the distance to the coast remains around 12 km; the sedimentary deposits have a sufficient thickness (> 5m) to support long-term extraction; the sediments are characterised by grain sizes in excess of 300 μm; the area is depositional; and the overall surface area with suitable sediments is large. Bedforms over this area reach up to 4-6 m in height; their asymmetry confirms the modelling results, which suggest that this area forms a bedload convergence zone and, thus, is a depositional sedimentary environment. Moreover, the grain sizes in the swale, lying to the east, are similar to those found on the bank, hence suitable for the regeneration of the areas of extraction. The present extraction zone, which is located on the steep, western flank of the bank, does not comply with most of the above criteria. At this location, the sediment grain size is somewhat less than 300 μm and, this area has been suggested to be an erosional sedimentary environment with the adjacent swale to the west, consisting mostly of gravel (Van Lancker *et al.,* 2007b, for resource maps). Therefore, the present extraction zone is regarded unsuitable and with low regeneration potential, as regeneration is likely to be hampered by a lack of suitable material sources. Consequently, comparable problems to those described for the Kwinte Bank are likely to occur in the future, i.e. formation of a depression on the western flank of the Buiten Ratel Bank, which will not be easily restored and will affect the local ecology, which is likely to be similar to that identified for the Kwinte Bank.

Need for an improved management framework

If it is further confirmed that non-renewable sediment resources are being exploited increasingly, there is a need for an improved resource evaluation and a more efficient and targeted use of the seabed. These requirements call for a strategic management framework (e.g. a plan according to the SEA Directive, see Radzevicius *et al.,* this volume), incorporating detailed resource and environmental information, at large and small scales (Table 3.). The basis of this framework should always be high quality geological maps, incorporating the surficial extent of the resource and its availability within depth. For sandbanks, in particular, detailed knowledge of their internal architecture is crucial for the accurate estimation of the resource reserves. Moreover, the hydrodynamics and sediment dynamics of these areas should be diagnosed in order to assess (predict) the morphodynamic evolution and the physical impacts of aggregate extraction. In addition, ecological information should be acquired in order to identify vulnerable species and habitats. Finally, although data availability will vary significantly, according to location and distance from the coast, the information detail needs to be sufficiently high, to ensure a realistic initial evaluation of any potential impacts.

Multicriteria resource maps, as presented in Figure 2., can assist in the selection of optimal locations for MA extraction, within the (often predefined) concession zones. These maps can integrate information on: (a) detailed sediment grain size distribution; (b) thickness of the targeted sediment deposit; (c) bedform distribution, shape/size, asymmetry and dynamics; and (d) areas of diagnosed/predicted erosion and deposition. Similarly, seabed mobility studies (e.g. Velegrakis *et al.*, 2007) can be used as an input to the decision-making process. Erosion/deposition rates can also be modelled, or derived from historical charts and maps. In the latter case, historical changes in sediment volume and sandbank elevation can be established providing erosional/depositional rates and regional patterns of sand movement (Brampton, Evans, and Velegrakis, 1998; Gao and Collins, 1995).

Detailed spatial and temporal information on ecological functioning is difficult to acquire and integrate, but is important within the context of the protection of sensitive or valuable habitats, communities or species. For soft-substratum areas of the shelf, there is likely a strong link between the nature and dynamics of the physical and biological environment; as such, recent developments in modelling tools may enable the mapping of ecologically important zones on the basis of abiotic parameters alone (e.g. Van Lancker and Foster-Smith*,* 2007). This approach has been demonstrated for the Belgian Continental Shelf, where the nature of macrobenthic communities was predicted successfully, on the basis of the median grain size and fine material (silt-clay) percentage in the sediment (Degraer *et al.*, in press). Biological/ecological valuation criteria (e.g. Derous *et al.*, 2007) can be applied then, to obtain maps establishing the ecological value of shelf environments (Derous *et al.*, in press). Such ecological maps, together with resource maps (Van Lancker *et al.,* 2007b) and the results of more detailed, targeted research can provide an ideal basis for any spatial planning initiative (e.g. Maes *et al.*, 2007). The data can be used to establish quantitative parameters, which can serve as inputs to decision-support systems, guiding the planning and management of future extraction activities (e.g. Calewaert *et al.,* 2007; Schrijvers *et al.*, 2007). In Table 4., the knowledge/data needs and the tools and innovation, required to establish the necessary framework for an improved sustainable management of MA deposits are summarised.

Details on the morpho-sedimentary and biological environment are, nowadays, increasingly derived from very high-resolution acoustic surveys (for an overview of seabed mapping techniques in environmental monitoring and management, see Boyd *et al.* (2006) and Mesh Project (2007)). Nevertheless, targeted ground-truthing of the remote-sensed information will remain an important component, in order to: (a) calibrate the acoustic imagery and improve automated seabed classifications; and (b) establish quantitative relationships between the physical and biological environment to be used in diagnostic and predictive modelling. Hydro-sediment dynamic observations (at least over a tidal cycle), using high frequency acoustical (e.g. acoustic doppler velocimeters and current profilers, acoustic backscatter sensors), optical (e.g. optical backscatter sensors) or electromagnetic devices, together with detailed information on sediment grain size and bedform dynamics, should be considered against the outputs of morphodynamic modelling. Moreover, the results should be evaluated against extraction data to distinguish between natural and anthropogenic seabed dynamics. The significance of any impacts can be further assessed using long-term predictive modelling tools (for an overview, see Idier *et al.*, this volume).

The scientific framework of such an investigation can be managed ideally in a GIS environment, allowing simplified integrations of spatially diverse data sets. However, the availability of relevant data in an appropriate spatial and temporal resolution and the inherent uncertainties in the diagnosis and prediction of the dynamics of the marine environment remain a continuous challenge.

The management of MA activities is a complex exercise, requiring robust cost-benefit analyses and holistic, science-based practical approaches, as well as effective transfer of knowledge between scientists, managers and policy-makers. The communication and fine-tuning of the various management needs should be considered within appropriate frames of reference (e.g. Van Koningsveld and Mulder, 2004), which contain key elements such as the formulation of: (a) strategic objectives, expressing the long-term management vision and policy; and (b) operational objectives, describing how the strategic objectives will be achieved.

Environmental monitoring

Environmental monitoring of the extraction sites should be able to document whether unacceptable impacts are evident or conditions that will lead to the development of such impacts are already in place (for an overview of monitoring guidelines/practices, see Fredette *et al.* (1990) and Posford Duvivier Environment and Hill (2001)) As such, monitoring schemes should provide clearly interpretable information on whether a threshold of an adverse condition has been, or is likely to be reached. On this basis, decisions can be made on the continuation, modification or closure of MA extraction sites. ICES (2003) has put forward a number of questions that should be answered in a successful monitoring programme: *(a) what are the environmental concerns that the monitoring programme seeks to address?; (b) what measurements are necessary to identify the significance of a particular effect?; (c) what are the most appropriate locations at which to take samples or observations for assessment and what is their natural variation?; (d) how many measurements are required to produce a statistically sound programme?; and (e) what is the appropriate frequency and duration of monitoring?*

Answering these questions requires the acquisition/analysis of quantitative information at various spatial and temporal scales (e.g. Collins and Balson, 2007). The present investigation has demonstrated that intensive, concentrated monitoring is required to detect in detail the morphological, sedimentary and ecological dredging-related impacts. A critical part of the assessment is the evaluation of these effects, against the background of the natural dynamics of the seabed. This approach requires systematic monitoring of the wider areas of the extraction sites, albeit at a lower spatial resolution. However, robust monitoring programmes may become very 'labour intensive'; the Belgian experience has shown that, even in the case of relatively high temporal resolution surveying (e.g. 4-5 times/year), it is difficult to establish statistically significant trends in sediment volumes/morphology (Norro *et al.,* 2006). Baseline information is crucial, as, in its absence, impact assessments are likely to remain inconclusive (Van Lancker *et al.,* this volume). It must be noted also that the establishment of practical and efficient monitoring practices require rigorous quality control (e.g. through regular reporting and publishing in peer-reviewed journals) and continuous fine-tuning.

Extensive or intensive dredging?

An important issue in MA extraction is related to whether extraction should be procured extensively, i.e. with a high spatial spread of the extraction activities, or intensively, i.e. focussed on relatively small areas of the seabed. Ideally, the former option would imply reduced severity of the environmental impacts and increased potential for site recovery from a physical and biological viewpoint; however, these benefits should be considered against the increased requirements for information gathering and environmental monitoring. In comparison, the Kwinte Bank investigation has shown that focussing on small areas of the seabed may result in the development of enduring morphological features, which are also related to long-term changes in the sedimentary and ecological properties.

It must be noted that the intensive dredging of the Kwinte Bank has involved, mostly, dredging vessels with an average capacity of less than 5,000 m^3, reflecting the availability of the vessels presently in service and the economics of MA exploitation, which constrain the extraction site's water depth and distance from the coastline (e.g. Bate *et al.*, 1997; Posford Duvivier, 2000). In response, both to the increasing general demand (driven by large beach nourishment or land reclamation projects) and stricter regulations on the exploitation of land-won aggregates (e.g. Radzevicius *et al.,* this volume, and Velegrakis *et al.*, this volume) future resource developments are envisaged to occur in deeper waters (e.g. Bate *et al.*, 1997). Anticipating these needs, dredging vessel capacities have recently increased substantially (in some cases up to 46,000 m^3 (www.jandenul.com)). However, deeper offshore sedimentary environments (including the offshore sandbanks) are much less dynamic and, as such, their recovery potential is reduced. Therefore, strategies and practices involving the exploitation of deeper water resources should be formulated carefully.

CONCLUSIONS

The Kwinte Bank investigation has shown that the MA extraction, focussing on the upper part (crown) of the bank, has had significant environmental impacts, the most important being the formation of a substantial depression. Within the depression, the sedimentary character of the seabed was found to differ from that of the remainder of the bank's crown and its characteristics resembled more to those of the adjacent swale. Bedforms and their dynamics showed also evidence of change. Following cessation of extraction activities in 2003, the bank morphology remained remarkably stable, with no significant additional effects being observed either on the bank itself or on the adjacent coast. The formation of the depression led to changes in the hydrodynamic and sediment dynamic regimes, which appear to hamper the regeneration of the depression, at least in the short-term. In comparison, predictive modelling of the medium- to long-term evolution of the bank showed a slow recovery of the bank's morphology. However, as the sources of appropriate material, necessary for the infill of the depression, are limited in the area and with the general erosive trend of the Flemish Banks, it is unlikely that natural regeneration processes will counterbalance the effects of the extraction. Finally, sand extraction appears to have created a 'locally-different' habitat on the Kwinte Bank, with adaptation of the benthic fauna; nevertheless, the change has not been found significant, at least on the scale of the sandbank system.

As non-renewable sediment resources are likely to be targeted increasingly for extraction, efficient and sustainable resource use is required. Such an approach relies upon detailed field information and appropriate mapping and modelling approaches within a long-term perspective. The Kwinte Bank investigation, although site-specific, may assist in the formulation of general guidelines for minimising environmental effects. It is suggested that the setting of clear and quantifiable criteria is a necessary prerequisite in the planning/design of MA concession zones, the efficient management of MA extraction and the planning of effective environmental monitoring schemes. Such criteria are related to considerations on: (a) resource location (i.e. water depth and distance from the coast); (b) the nature and thickness of the targeted sedimentary deposits; (c) bank morphodynamics; (d) sediment dynamics at regional and extraction site spatial scales; (e) biology and ecology; and (f) extraction practices.

The Kwinte Bank investigation has demonstrated that intensive, concentrated monitoring is required to identify the morphological, sedimentary and ecological impacts related to the dredging activities. A critical part of the assessment is the evaluation of these effects, against the background of the natural dynamics of the seabed; thus, baseline information is crucial, as, in its absence, impact assessments are likely to remain inconclusive. Finally, the jury is still out on whether MA extraction activities should follow an extensive (i.e. widespread) or an intensive (i.e. concentrated in small areas) model, as both of these models has pros and cons.

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