

European marine aggregates resources: Origins, usage, prospecting and dredging techniques

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ABSTRACT



Marine aggregates (sand and gravel) are important mineral resources and traded commodities. Their significance is bound to increase further, due to increasing coastal zone development, stricter environmental regulation concerning land-won aggregates and increasing demand for beach replenishment material. Marine aggregate (MA) deposits can be differentiated into relict and modern deposits. The former consist of sedimentary material deposited in the past and under different environmental and sedimentary regimes than those existing presently (e.g. the gravel/sand deposits of the Pleistocene buried river valleys of the northwestern European shelves). The latter are deposits, which have been formed and controlled by the modern hydro-and sediment dynamic conditions (e.g. the linear sand banks of the southern North Sea). The present contribution reviews the current state of affairs in 9 representative European Member States concerning the prospecting and extraction (dredging) techniques as well as the levels of production and usage. The review has shown a mixed record as, in some of the studied States, marine aggregate production is an important and streamlined activity, whereas other States have not yet developed efficient marine aggregate policies and industries. It has also shown that although attempts have been lately made to coordinate the field, the industry still faces problems, which hinder its sustainable development. These include (amongst others): lack of standardisation of the relevant information, difficulties in the access to information, non-coherent regulatory regimes and limited collaboration/coordination between the marine scientific research establishments and the marine aggregate industry. These issues should be addressed as quickly as possible in order to exploit effectively this important mineral resource.

ADDITIONAL INDEX WORDS: *Marine aggregates, dredging, offshore mineral resources, relict sediments, buried palaeovalleys, mineral resource prospecting.*

INTRODUCTION

In recent years, the importance of marine aggregates (sand and gravel) as a mineral resource has increased in the EU, due both to increasing demand and stricter regulations concerning land-won aggregates in the Member States (e.g. JEWELL, 1996; PHUA *et al.*, 2004). In the last 20 years, more than 50 million m³ of sand and gravel have been extracted annually (on average) from the northern European continental shelf alone and the production may increase further to supply the material needed for the construction of the planned projects of coastal

infrastructure (PHUA *et al.*, 2004; SEAMAN, 2006; <http://www.dredging-in-germany.de>) and the replenishment of the eroding European beaches (EUROSION, 2003; HUMPHREYS *et al.*, 1996; ICES, 2006; SELBY and OOMS, 1996). Marine aggregates are of particular importance in the coastal states of northwestern Europe, with the UK, the Netherlands and Denmark collectively producing more than 80% of the European marine aggregate production (e.g. ICES, 2005; ICES, 2006).

Marine aggregates (MA) are non-metallic sediment deposits, consisting of sands, gravels and shells/shell debris, which have been formed as a result of either contemporary (modern) or past sedimentary/hydrodynamic processes (relict deposits). Two different classification schemes are in place concerning the size of marine sand and gravels. Geologists use the FOLK (1980)

grain-size classification, according to which sediments consisting of particles with sizes ranging between 0.063 and 2 mm are classified as sands and with sizes greater than 2 mm as gravels. In comparison, the MA industry classifies sediments consisting of particles with diameters ranging between 0.063 and 4 (or 5) mm as sands, and sediments with particle-sizes greater than 4 (or 5) mm as gravels. In the present contribution, the second classification is used, as most of the available data on supply and demand follow the MA industry's classification.

The nature/texture of marine aggregates is generally similar to land-won aggregates (GUBBAY, 2005; HARRISON, 2003). However, there are also differences, as marine aggregates are generally less 'contaminated' by fine-grained material (silts and clays) and have higher concentrations of undesirable salts (NaCl) and biogenic material (shells/shell debris). In addition, siliciclastic marine aggregates consist generally of "harder" material than land-won aggregates, as they have been subjected to rigorous abrasion in the energetic coastal and inner shelf marine environments (e.g. PETTIJOHN, POTTER, and SIEVER, 1972).

The composition of the MA deposits varies, depending on the original sediment source. For example, flint forms the greater part of the gravel deposits of the eastern English Channel and those offshore of the Riugen Island (Germany), being the product of erosion of the flint bands of the extensive Cretaceous Chalk outcrops found in these areas (KENNEDY and GARRISON, 1975). In comparison, marine aggregates found offshore of the Humber Estuary (UK sector of the North Sea) have more variable composition, reflecting their glacial origin (GUBBAY, 2005).

The aim of this contribution is to review the MA uses, origin, demand/supply and exploitation (prospecting/dredging) techniques in (9) coastal EU Member States (Belgium, France, Germany, the UK, the Netherlands, Poland, Spain, Denmark and Greece), representing the different European coastal areas (i.e. the Atlantic, Baltic and Mediterranean coasts).

USE OF THE MARINE AGGREGATES

Marine aggregates are used (BMAPA, 2004, 2005; CEDA, 1993): in concrete and mortar manufacture; as ingredients of asphalt and coated products; for block making; as drainage and capping material and in other fill-related uses; and as beach replenishment material. In sandy beach replenishment schemes (DEAN, 2002), material specifications (apart from project-specific grain-size requirements) are relatively simple, as the mineralogy of the material is not, generally, a significant concern. Nevertheless, replenishment material must be clean and not containing fresh biogenic material and/or contaminants such as chemical pollutants; for example, sediments from some areas of the Bristol Channel (UK) cannot be used as beach replenishment material, as they are characterised by large concentrations (exceeding in some cases 40% of the sediment weight) of waste coal (HAMILTON *et al.*, 1979; VELEGRAKIS *et al.*, 1996). Sand used in construction must comply with certain standards (DE VREE, 2003) regarding, for instance, its chloride content (Table 1).

Table 1. Chloride content limits (according to BS 882, App. C, Table 7.) in marine aggregates.

Concrete Type	Chloride Content (% weight)
Pre-stressed concrete, heat-cured concrete with embedded metal	0.01
Concrete with embedded metal made with cement BS4027	0.03
Concrete with embedded metal made with cement BS12, BS146, DS1370, BS4246, BS 6588, BS6610, or combinations with ground granulated blastfurnace slag or pulverised-fuel ash	0.05
Other concrete	no requirement

Marine gravels are also used for beach replenishment and in the construction industry. With regard to their use in the construction industry, although gravel-sized aggregates form an essential ingredient of certain concretes (see Table 2. for shell content requirements) and asphalt products, they can be replaced by good quality crushed-rock aggregates. In contrast, marine gravels are vital resources for certain beach replenishment schemes, due to their grain-size and (generally) rounded shape (e.g. ARTHURTON, 1997; BATES *et al.*, 1997).

Table 2. Shell content limits (according to BS 882 1992, Table 1.)

Grain Size/Type	Shell content (% weight)
Material with size less than 5 mm (sand)	no requirement
Shingle size up to 10 mm, graded or all-in aggregate (> 5 mm and < 10 mm)	20
Shingle sizes, graded and all-in aggregate (> 10 mm)	8

in marine aggregates.

ORIGINS OF THE MA DEPOSITS

Exploitable MA deposits have been mostly formed in the Quaternary. On the basis of their formation period, they may be differentiated into relict and modern sedimentary bodies (e.g. McMANUS, 1975). Relict deposits are those formed in the past and under different environmental conditions i.e. in environments controlled by sedimentary regimes different than those existing presently. Typical examples are the gravel/sand deposits found within the Pleistocene buried river valleys of the northwestern European shelf (ANTOINE *et al.*, 2003; GIBBARD, 1988; VELEGRAKIS, DIX, and COLLINS, 1999), the moribund banks found at the outer shelf (at 60-140 m water depths) of the Celtic Sea (e.g. KENYON *et al.*, 1981; REYNAUD *et al.*, 1999) and the glacial (e.g. HERRMANN *et al.*, 1999) and transgressive (BELLEC, DIESING, and SCHWARZER, this volume) deposits of the southern Baltic Sea. Such deposits are not normally involved in the modern sedimentary processes, although some movement of their superficial layers may take place under particular conditions,

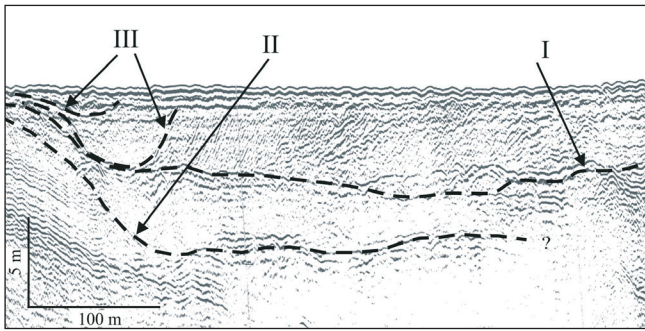


Figure 1. Seismic (boomer) section and its interpretation from a tributary paleovalley of the 'English Channel River' (Gibbard, 1988; Hamblin et al., 1992) in the central English Channel. The infilling sediments form different seismostratigraphic units, with coarse-grained sediment topping the sequence (shown from the acoustic character of the deposit, e.g. from the presence of numerous diffractions, and ground truth data). Key: I, lower bounding unconformity of the coarse-grained deposit; II, upper bedrock erosional surface; III, late channels.

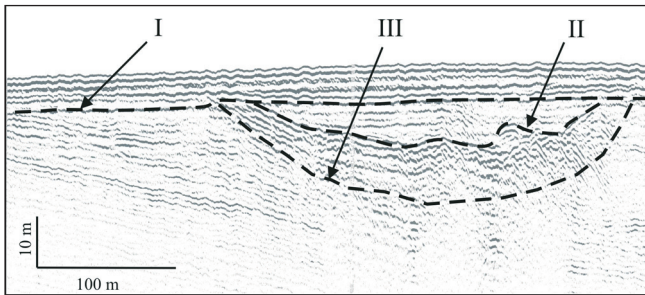


Figure 3. Seismic (boomer) section and its interpretation from a buried valley of the eastern English Channel. The infilling sediments form different seismostratigraphic units, with (mostly) fine-grained deposits topping the infilling sequence. Key: I, upper bounding unconformity of the transgressive deposit (transgressive system tract (TST)); II, upper bounding unconformity of the coarse-grained deposit of the lowstand system tract (LST) see Posamentier and Vail (1988); and III, upper bedrock erosional surface.

such as storm waves (e.g. DALRYMPLE *et al.*, 1992). Modern deposits are those, which have been formed and controlled by the modern hydro- and sediment dynamic conditions. In areas associated with high tidal and/or wave energy, as it is the case in most shallow Atlantic continental shelves, modern deposits can be characterized by significant mobility (e.g. VELEGRAKIS *et al.*, 2007; VINCENT, STOLK, and PORTER, 1998), which may result in considerable material exchanges between them and the adjacent areas.

Relict MA deposits

These deposits have been mostly formed during the Pleistocene climatic changes and sea level oscillations. During the Pleistocene sea level falls (lowstands), continental shelves around northern Europe were repeatedly exposed to sub-aerial erosion and drained by large periglacial river systems

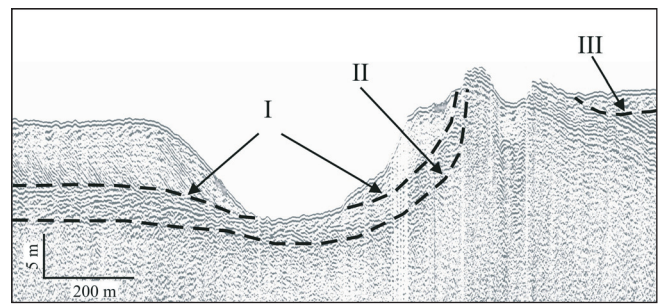


Figure 2. Seismic (boomer) section and its interpretation showing drowned river terraces in the Eastern English Channel (water depth ~30 m at the upper part of the deposit). These terraces are found along a submerged tributary of the Northern Paleovalley (the large submerged valley of the English Channel, see Hamblin et al. (1992)), which, in many areas, is devoid of sediment infilling, possibly due to an extreme flooding event during the last (Flandrian) transgression (e.g. Smith, 1985; 1989). The terrace material consists mainly of flint gravel and/or sandy gravel, indicated by the presence of acoustic diffractions on the echogram and verified by ground-truth data. Key: I, lower bounding unconformity of the coarse-grained terrace deposit; II, upper bedrock erosional surface at the terrace area; III, upper bedrock erosional surface at the interfluvium.

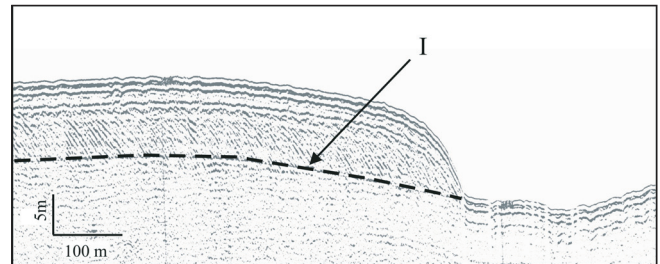


Figure 4. Seismic (boomer) section and its interpretation showing a coarse-grained drowned beach in the Eastern English Channel (water depth ~35 m at the upper part of the deposit). The material consists probably of flint gravel and/or sandy gravel, shown by the plethora of sound wave diffractions present on the image and ground truth data (core sampling). Key: I, upper bedrock erosional surface.

(e.g. ANTOINE *et al.*, 2003; GIBBARD, 1988); deposition of unconsolidated (and relatively well-sorted) coarse-grained material was taking place at the riverine thalwegs, terraces, point bars and fans (LEEDER, 1999). These deposits are of particular interest for the MA industry, since they contain large quantities of gravel and sandy gravel (Figure 1.). Although, such coarse-grained deposits are usually buried under transgressive/highstand finer-grained deposits (see below), in some cases they can also be found exposed on the present seafloor (Figure 2.).

During the early stages of the subsequent marine transgression, the lowstand fluvial environments were transformed first into estuarine and then marine environments (e.g. ALLEN and POSAMENTIER, 1993). Therefore, the last (Flandrian) transgression caused fine-grained sedimentation (i.e. muddy sands and muds) over large sections of the river palaeovalleys, which were previously characterised by coarse-grained sedimentation (e.g. FLETCHER, KNEBEL, and KRAFT, 1992). Such sedimentary se-

quences (Figure 3.) are difficult to exploit, as fine-grained sediment deposits must be excavated before reaching the coarse-grained resource (but see LOMAN (2006) for new technological developments which may address this problem).

Other relict sedimentary bodies with a good resource potential are associated with drowned beaches and barrier islands (LEEDER, 1999). These are coastal sedimentary bodies left behind during the last marine transgression, as a result of their protected position (e.g. perched in front of coastal cliffs) and/or the fast rate of the transgression (Figure 4.). These deposits are of particular interest, as they are characterised by relatively good sorting and consist of material resistant to abrasion, which makes them ideal for beach replenishment. Their texture depends on the particulars of the drowned sedimentary environment and their exploitability is controlled by the depth of their present position (BATES *et al.*, 1997).

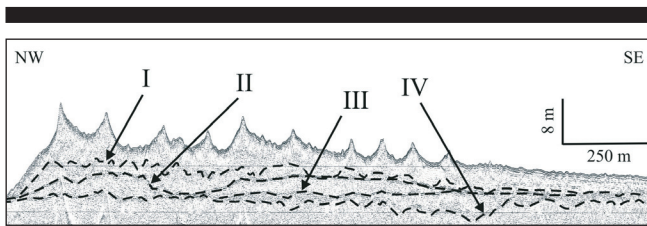


Figure 5. Seismic section and its interpretation across the Kwinte Bank (Flemish Banks, southern North Sea). Key: I, base of the modern sand bank; II, base of the transgressive coastal bar preceding the modern bank; III, base of the tidal flat deposits; and IV, base of the estuarine channels.

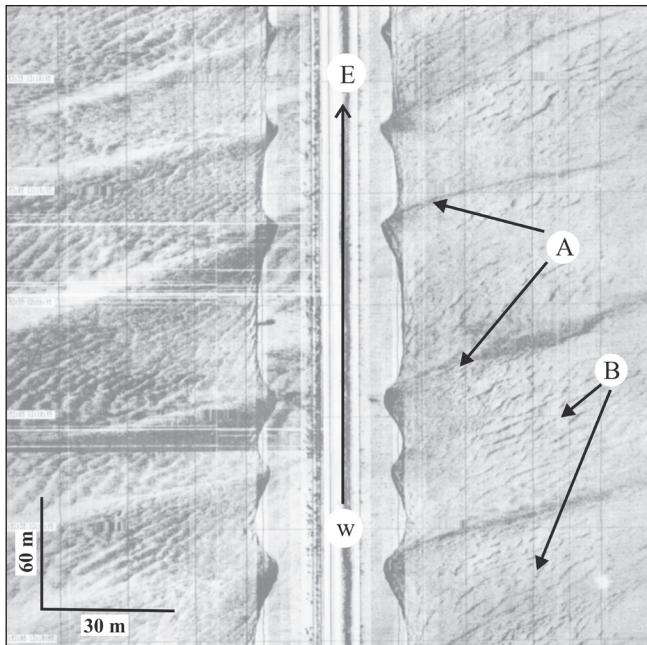


Figure 6. Side-scan sonar sonograph from the Bristol Channel (UK), showing a field of sand subaqueous dunes (Velegrakis *et al.*, 1996). Key: A, large subaqueous dunes; B, medium subaqueous dunes superimposed on the larger bedforms.

In some areas during the Pleistocene glacial episodes, ice-sheets originating from the land masses spread and extended to the shelves, depositing extensive mantles of sub-glacial till consisting of clays, sands, gravels and boulders. Although these deposits can attain substantial thicknesses (e.g. JACKSON *et al.*, 1995; JAMES, HARRISON, and CIAVOLA, 1992), they may only rarely be of economic interest due to (a) their consolidation and 'contamination' by both fine and oversize material and (b) regulatory restrictions put in place for some areas (e.g. in the Baltic Sea, see HELCOM (1998)). In some areas, however, pro-glacial till deposits, deposited by melt ice rivers from the ice front and consisting of sandy gravels and coarse gravelly sands can be of interest to the MA industry (e.g. the Cleaver Bank in the Dutch sector and the areas east of Norfolk and the Humber in the UK sector of the North Sea).

Finally, some areas of the northern European shelves are characterised by veneers of lag gravel. These deposits have been substantially reworked by the present hydrodynamic regime; they usually form thin sedimentary bodies, as it is the case in the Baltic Sea (e.g. BLAZHCHISHIN, 1976) and the English Channel (HAMBLIN *et al.*, 1992) and, thus, they have only limited economic potential.

Modern MA deposits

In terms of their dynamics, modern deposits may be broadly differentiated into: (i) sediment sinks, i.e. depositional centres that do not supply sediments to the surrounding areas and (ii) sediment stores, i.e. deposits characterised by considerable sediment exchanges with the adjacent areas. In energetic marine environments, superficial sediment deposits are likely to be mobile and, thus, can be generally classified as 'stores'. Sand stores in the continental shelf include sand sheets, sandbanks (Figure 5.), sand patches, sand ribbons and subaqueous dune fields (Figure 6.).

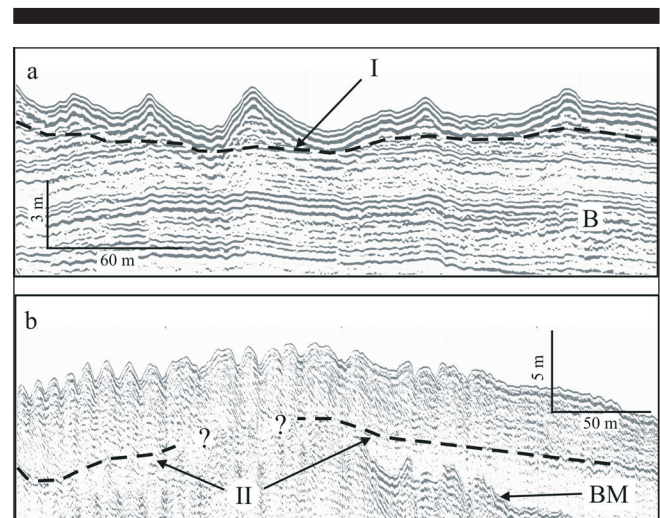


Figure 7. (a) Seismic (boomer) section showing subaqueous sand dunes in the English Channel and (b) Seismic (boomer) section showing subaqueous gravel dunes in Christchurch Bay, (southern UK). Key: I, basal unconformity of the sand bedforms; II, basal unconformity of the gravel sediments; BM, bottom multiple; B, Tertiary bedrock.

Table 3. Official MA information holders in the investigated EU Member States.

Country	Organisation/Data sets
Belgium	Fund for Sand Extraction, FPS Economy, SMEs, and Energy (www.mineco.fgov.be) (resource maps and databases of multibeam data/dredging activity) Management Unit of the North Sea Mathematical Models - MUMM, Department VI of the Royal Belgian Institute of Natural Sciences (www.mumm.ac.be/) (resource maps, licensed areas, dredging activity data, including EMS "black-box" data) Geological Survey of Belgium (www.naturalsciences.be/geology/) (geological maps and primary data sets)
France	BRGM-Bureau de Recherches Géologiques et Minières (Office of Geological and Mine Research) (www.brgm.fr) (geological maps, primary geological data) IFREMER (French Research Institute for Exploitation of the Sea) (www.ifremer.fr) (MA licenses, MA reserve maps, oceanographic databases (SISMER), subsurface data (CORIOLIS), satellite data (CERSAT)) SHOM-Service Hydrographique et Oceanographique de la Marine (Hydrographic and Oceanographic Service) (www.shom.fr) (marine data/information, including hydrographic, multibeam and geophysical data)
Poland	PGI (Polish Geological Institute) (http://www.pgi.gov.pl/) (MA licensed areas, geological maps, natural resource maps, central geological archives) and MIDAS Register (Management and Protecting of Polish Mineral Raw Materials) DGiKG (Department of Geology and Geological Concessions, Ministry of the Environment) (http://www.mos.gov.pl/dgikg/) (national proven, probable and possible mineral reserves)
Germany	BSH (Federal Maritime and Hydrographic Agency) - (http://www.bsh.de/de/index.jsp) (MA licenses, resource maps, marine environmental data and CONTIS database) BGR Federal Institution for Geosciences and Natural Resources in Hanover (http://www.bgr.bund.de/clin_029/DE/Home/homepage_node.html_nnn=true) (central authority advising the German Federal Government) State (Lander) Geological Surveys (e.g. http://www.uni-mainz.de/FB/Geo/Geologie/GeoSurv.html): Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (Office for Environment, Nature Protection and Geology) http://www.lung.mv-regierung.de/ in Mecklenburg-Vorpommern (Geological and natural resource maps, Baltic Sea Territorial Water environmental data, GIS-based geological data) Landesamt für Bergbau, Energie und Geologie (LBEG) (Office for Mining Industry, Energy and Geology (est. in 1-1-2006) in Lower Saxony (http://www.lbeg.niedersachsen.de/) (geological/natural resource maps and North Sea Territorial Water environmental data) Landesamt für Natur und Umwelt (Office for Nature and Environment) - http://www.umwelt.schleswig-holstein.de/servlet/is/155/ - in Schleswig-Holstein (geological and mineral resource data/maps, environmental databases) Behörde für Stadtentwicklung und Umwelt Geologie (Agency for Town Development and Environmental Geology) in Hamburg http://fhh.hamburg.de/stadt/Aktuell/behoerden/stadtentwicklung-umwelt/umwelt/geologie/start.html
Denmark	GEUS (Geological Survey of Denmark and Greenland) (http://www.geus.dk/) (MA extraction licenses, geological/mineral resource data and maps)
The Netherlands	TNO (Netherlands Institute of Applied Geosciences - Geological Survey) (http://www.nitg.tno.nl/eng/) (MA extraction licenses, geological/mineral resource maps and databases) Ministry of Transport, Public Works and Water management (http://www.verkeerenwaterstaat.nl/?lc=nl) and North Sea Directorate (http://www.rijkswaterstaat.nl/)
The UK	British Geological Survey http://www.bgs.ac.uk/ (geological and mineral resource maps and data bases) The Crown Estate (http://www.crownestate.co.uk/) and BMAPA (www.bmapa.org/) (information on MA extraction licenses, extraction activity database)
Spain	Instituto Español de Oceanografía (Spanish Institute of Oceanography) - IEO - http://www.ieo.es/version_eng/indexingles.htm Del Ministerio de Agricultura, Pesca y Alimentación en España (Ministry of Agriculture, Food and Fisheries) - http://www.mapa.es/ Instituto Geológico y Minero de España (Geological and Mining Institute of Spain) - http://www.igme.es/internet/default.htm Dirección General de Costas, Ministerio de Medio Ambiente (General Directorate of Coasts, Ministry of Environment) - http://www.mma.es/costas/htm/actua/infor/
Greece	IGMR Greek Geological Survey (marine geological data/maps) and HCMR (Hellenic Centre for Marine Research) (marine environmental data) Public Estates Company (MA licenses) YYN (Naval Hydrographic Office) (Hydrographic data and maps)

Sand sheets are extensive, continuous veneers of sand of variable thickness. Such deposits are commonly found over the western European shelf, mostly at relatively large (> 40-60 m) water depths (KENYON and STRIDE, 1970). Therefore, even though they may form substantial marine aggregate resources, they are probably beyond the operational capability of the majority of the vessels of the dredging industry fleet (e.g. BATES *et al.*, 1997; VISSER, 2007). Sandbanks are elongated sedimentary bodies, which may reach lengths well in excess of 30 km (COLLINS *et al.*, 1995; DYER and HUNTLEY, 1999; PATTIARATCHI and COLLINS, 1987). These sedimentary structures form huge resources of good quality, relatively well-sorted sand-sized sediments and are one of the primary targets of the MA industry (e.g. ICES, 2005; VELEGRAKIS *et al.*, 2001). Sand ribbons are flow parallel bedforms (e.g. KENYON, 1970; McLEAN, 1981) consisting of elon-

gated patches of sand resting on coarser-grained sediments and/or bedrock substrates; they form good quality MA deposits which, however, are characterised by a limited thickness and rigorous hydrodynamic regime that makes their mining difficult. Subaqueous dunes (ASHLEY *et al.*, 1990) are flow-transverse repetitive sediment structures developing on a sedimentary bed under the influence of current- and/or wave-induced flows (BELDERSON, JOHNSON, and KENYON, 1982; DALRYMPLE *et al.*, 1992). They have dune-like shapes with their crests aligned (almost) perpendicular to the prevailing flow direction and are characterised by variable sediment texture and dimensions (Figures 6. and 7.), reflecting the sediment and flow diversity of the shallow marine environments. Subaqueous dune fields can be of large economic interest, although they present certain practical problems in their exploitation (BATES *et al.*, 1997).

EUROPEAN MARINE AGGREGATE RESOURCE INFORMATION

In all investigated European Member States, MA resource information has been found to be dispersed among various organisations (Table 3.). The available information consists of both analogue and digital data sets and includes marine aggregate reserve maps and maps of areas licensed for extraction, shallow seismic and side-scan sonar records, borehole logs and vibro-core, gravity core and grab sample records. The data quantity and quality vary widely, with the most modern and uniform data bases found in the UK, the Netherlands and Denmark, where most of the information is held electronically (ICES, 2005; MEAKINS *et al.*, 1999; NIELSEN and JENSEN, 2003). Although the recent years substantial research has been undertaken to access the MA resource potential of the European shelves, there are still information gaps in all investigated EU Member States; this is true even for those states where modern surveys have been carried out. Thus, accurate estimations of the overall reserves are not available (ICES, 2006), particularly over areas exceeding 40 m water depths (e.g. BATES *et al.*, 1997).

Resource information is also not always standardised (ICES, 2005; MEAKINS *et al.*, 1999). Not only is there a wide disparity in the type/quality of data sets held by individual states, but there are discrepancies in the resource classification schemes and descriptions, in spite of the obvious benefits of data standardisation. Marine aggregate classifications appear to depend on the area, type of material and end-user. For example, the lowest

grain-size limit for in the UK varies from 2 mm to 4 mm to 5 mm, whereas in France variations occur even between regions. Classification discrepancies are of significant concern when quantitative data, such as demand or reserve estimates, are compared between different areas and/or EU Member States. Some efforts towards a consistent format/standards have been made (e.g. DE VREE, 2003), particularly by organisations in the UK, the Netherlands and Denmark; however, satisfactory standardisation has not been yet achieved. In the Mediterranean region, MA reserve information is not available in a comprehensive way, although it appears that substantial relict and modern deposits are available (e.g. VELEGRAKIS *et al.*, 2001).

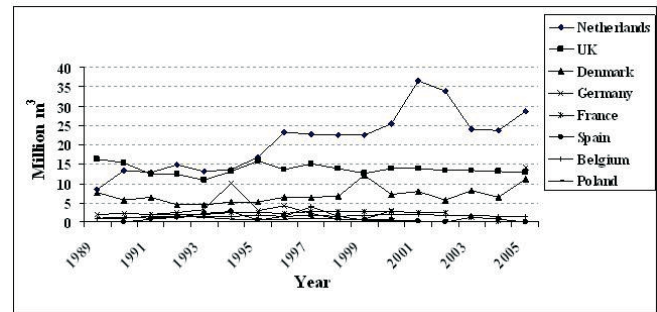


Figure 8. Marine aggregate production in 8 EU Member States in the period 1989-2005 (see also Table 4.). Data from Ices, (1995, 2000-2006) and Meakins *et al.* (1999).

Table 4. National marine aggregate extraction for the period 1989-2005. (Data from Ices, 1995; 2000-2006; Meakins *et al.* (1999) and the Belgian Fund for Sand Extraction). Note that the UK data have been estimated on the basis of a volume/weight coefficient 1/1.66 (Ices, 2005, 2006). The first value for Germany and Denmark refers to the total production volume, whereas the values in parentheses refer to production volumes from the North Sea. Key: nd, no data available.

Year	Extraction volumes (in million m ³)								
	Germany	Poland	UK	France	Netherlands	Spain	Denmark	Greece	Belgium
1989	1.97 (1.97)	0.96	16.27	nd	8.43		7.68	nd	0.96
1990	2.27 (2.27)	1.35	15.24	nd	13.36	0.08	5.74	nd	0.95
1991	2.02 (2.02)	0.99	12.23	2.00	12.77	0.66	6.40	nd	1.75
1992	2.49 (2.08)	1.58	12.41	1.90	14.80	1.32	4.38	nd	1.22
1993	3.26 (2.21)	1.35	10.78	1.90	13.02	2.19	4.32	nd	1.45
1994	10.12 (8.81)	0.74	13.13	2.50	13.55	2.75	5.17	nd	1.60
1995	2.91 (1.54)	0.81	15.72	2.50	16.83	0.42	5.31	nd	1.66
1996	4.26 (1.38)	0.85	13.61	2.30	23.15	1.48	6.32	nd	1.44
1997	2.22 (0.00)	0.96	15.00	2.60	22.75	1.67	6.40	nd	3.86
1998	0.70 (0.70)	0.69	13.80	2.60	22.51	1.41	6.66	nd	1.40
1999	0.71 (0.71)	0.74	12.60	2.60	22.40	0.49	12.04	nd	1.69
2000	2.97 (1.67)	0.82	13.89	2.60	25.42	0.41	7.12	nd	1.90
2001	nd	nd	13.71	2.43	36.45	0.30	7.86	nd	1.92
2002	nd	0.53	13.22	2.43	33.84	0.08	5.57 (3.50)	nd	1.62
2003	1.14 (0.70)	nd	13.39	nd	23.97	1.19	8.13 (6.18)	nd	1.65
2004	nd	0.85	12.98	0.34	23.59	0.79	6.46 (4.18)	nd	1.50
2005	14.00 (13.61)	nd	12.78	nd	28.76	0.05	11.05 (9.28)	nd	1.36
Average	3.64 (2.00)	0.94	13.57	2.21	20.92	0.96	6.86	nd	1.64

In view of the information gaps and classification discrepancies, the proven recoverable European MA reserves are difficult to be established with accuracy. However, such estimates exist for some of the investigated states, on the basis of detailed reconnaissance mapping (ICES, 2006). For example, Danish marine sand reserves have been estimated to be very substantial (in the order of several billions m^3), but coarse sand/gravel resources are rather limited in the North Sea (BIRKLUND and WIJSMAN, 2005). The German recoverable MA reserves of the Baltic Sea are confined (of the order of 40-50 million m^3), whereas the Polish reserves have been estimated to be close to a 100 million m^3 (HERRMANN *et al.*, 1999). Estimations for the UK have shown that the proven and potential workable marine sand reserves found within the present operational capability of dredging vessels amount to several billion m^3 (HUMPHREYS *et al.*, 1996). In contrast, coarse-grained deposits are finite, as they mostly form a thin (less than 1m thick) veneer over the seabed; only over certain areas the thickness of the gravel deposits becomes significant (Figures 1., 2. and 4.) and, thus, economically viable (e.g. ARTHURTON, 1997; BATES *et al.*, 1997).

MA PRODUCTION AND USAGE

Reliable statistics on marine aggregate production in the EU Member States are difficult to collate (e.g. ICES, 2006), due to non-standardised archiving, varying material classification, commercial confidentiality issues (MEAKINS *et al.*, 1999) and regulation discrepancies (RADZEVIČIUS *et al.*, this volume). In general, information is more complete in those countries that have increased dependence on marine aggregates and a mature MA industry; hence, limited/sparse information can be found for the Mediterranean EU States, which rely predominantly on land aggregates. Continuous production (extraction) figures (for the last 30 years) are available for the UK, the Netherlands and Belgium (CEDA, 1993; ICES reports 2000-2006), whereas France and Germany show significant information gaps (ICES, 2006; IFREMER, 2007).

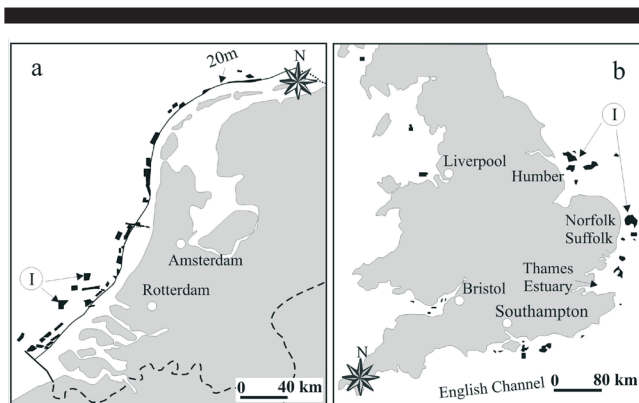


Figure 9. Licenced areas for marine aggregate extraction in (a) the Netherlands and (b) the UK. Adapted from Phua *et al.* (2004), Ices (2005) and Bmapa (2005). Key: 20 m, contour line of the 20 m water depths; and I, major dredging areas.

MA Production

In the late 1980s, MA production increased significantly in several states. The level of production has since been, more or less, stabilised (with the exception of the Netherlands), although significant interannual variations may occur in response to project-led demand (Figure 8. and Table 4.). The three main MA production countries in the EU are the Netherlands, the UK and Denmark, which collectively yield over 80% of the marine aggregates produced by the 9 studied countries (HARRISON, 2003; ICES, 2006; USCINOWICZ *et al.*, 2003).

The Netherlands

MA production (extraction) has been increasing more or less steadily since 1989 (Figure 8). The production from the North Sea licensed areas (Figure 9a.) peaked in 2001 at 36.5 million m^3 , in response to increased demand for fill and beach replenishment material during that year; in 2005, total marine sand production was ~29 million m^3 (ICES, 2006). In the Dutch sector of the North Sea, there are no exploitable gravel resources and, thus, the gravel needs of the country are covered through imports (around 2 million m^3 per year) mainly from the UK. The increased MA production is compounded by the construction of modern facilities (wharves) in the port of Rotterdam for the landing and processing of marine aggregates. This large investment shows that the Netherlands plans to shift further the production from land- to marine-based sources.

The UK

MA production has increased steadily in the past four decades (~5.7 million m^3 /year in the 60s, ~9 million m^3 /year in the 70s, ~11 million m^3 /year in the 80s and ~13 million m^3 /year in the 90s). The production peaked in 1989 at 16.9 million m^3 (to supply the large infrastructure/building projects in the London metropolitan area), to decline subsequently to 10.8 million m^3 in 1993 (GUBBAY, 2005); since then, the annual production has again been increasing to an annual average of ~13 million m^3 (Table 4.) to provide the additional material required for beach replenishment schemes and increasing exports. It is expected that the marine aggregate demand will be further increased in the near future, in order to supply the large development projects associated with the 2012 London Olympics (SEAMAN, 2006).

The highest demand for marine aggregates is in SE England; thus, MA production is concentrated in the southern North Sea and the English Channel (BMAPA, 2004). Aggregates are supplied from licensed areas offshore of the Thames Estuary, the Norfolk and Suffolk coasts and the Central and Eastern English Channel (Figure 9b.). The 3 other main MA production areas are located in the Bristol Channel, offshore of the Humber Estuary and in Liverpool Bay; these production sites supply local markets. Very limited MA extraction takes place to the north of these areas. With regard to the type of material produced (gravel or sand), there is also a differentiation according to location, with the southern coast, the Thames and the Humber licensed areas producing most of the gravel (SEAMAN, 2006).

Denmark

There has been a considerable production of marine sand (mostly for fill purposes) over the last decade (Table 4. and Figure 8.), to meet demands from the large infrastructure projects undertaken along the Danish coastal zone (e.g. HERRMANN *et al.*, 1999). With the exception of the peaks of 1999 and 2005, production volumes have remained stable at around 6-7 million m³ during the last 10 years (CEDA, 1993; ICES, 2005; 2006).

France

Marine aggregate production has remained stable (at around 2- 2.6 million m³ per year, see Table 4.) in France for several years (IFREMER, 2007). There is a significant aggregate demand in the northern Seine and Loire regions but, little MA extraction takes place despite the occurrence of substantial MA resources. At the same time, some 47 million tonnes of aggregates have been abstracted from the channel and fluvial terraces of the Rhone River alone since 1949 (ARNAUD-FASSETTA, 2003). Therefore, even though the annual aggregate demand is ~300 million tonnes, less than 1% of that is supplied from marine sources. Approximately 1 million tonnes of marine aggregates are imported annually from the UK and to much lesser extent from Belgium (IFREMER, 2007).

Germany

Marine sands and gravels are produced in several areas of the German sectors of the Baltic and (particularly) the North Seas (see SCHWARZER, DIESING, and MANSO, this volume). The produced volumes have not been great (Figure 8. and Table 4.), but they make an important contribution to regional aggregate supply. Significant quantities of the extracted material are utilised in beach replenishment schemes, whereas the remainder (approximately half of the annual production) is used in the construction industry (ICES, 2002). In 1994 and 2005, the production increased sharply due to project-led demand (ICES, 2006).

Belgium

Although the seabed of the Belgian sector of the southern North Sea contains large quantities of sand, production is concentrated mainly on the Kwinte Bank (DEGRENDELE *et al.*, this volume; HARRISON, 2003); however, sand extraction from this site has stopped in 2003 in order to study its potentially detrimental effects on the stability and biodiversity of the bank (see VAN LANCKER *et al.*, this volume). MA production has increased since the 1980s. In the recent years, with the exception of a peak during 1997 (Figure 8. and Table 4.), the annual production has remained relatively stable at 1.5-2 million m³. Most of the produced sand is used in the construction industry, whereas some small quantities are exported to France (ICES, 2006; SCHOTTE, 2003). Belgium imports yearly about 1.5 million m³ of marine sand/gravel from the UK.

Poland

Production in Poland is limited, having an average of less than 1 million m³ per year (Table 4. and Figure 8.). In 2004, the fine- and medium-grained sand extracted from the Polish sector of the Baltic Sea (~0.8 million m³) was used mostly in beach replenishment and coastal defence schemes (ICES, 2005); limited

quantities were used in the construction industry. Some material (e.g. ~0.3 million m³ in 2000), extracted from the Slupsk Bank, has been exported to Germany (USCINOWICZ *et al.*, 2003).

Spain

MA production in Spain is allowed only for beach replenishment (see RADZEVIČIUS *et al.*, this volume). The average annual production is about 1 million m³, but there are significant interannual fluctuations in response to beach replenishment needs (Table 4. and Figure 8.). Extraction takes place both in the Atlantic and in the Mediterranean inner continental shelves, but presently is concentrated offshore of the southern Spanish coastline (ICES, 2006).

Mediterranean European coast

There is not an accurate registry of MA production for Italy, the southern French coast and the other EU Mediterranean countries (e.g. Greece). In these areas, most aggregate material is still produced from land open-quarries, river channels and terraces. Published information suggests that about 690 million m³ of aggregates have been extracted in the period 1958-1981 from the Po River valley (DAL CIN, 1983; MARCHETTI, 2002), ~93 million m³ (1950-1992) from the Emilia-Romagna rivers (IDROSER, 1994), 12.7 million m³ (1966-1975) from the rivers of the Marche Region and more than 26 million m³ (1966-1981) from the Abruzzo rivers (AQUATER, 1982). Lately, MA production has attracted more attention, due to the discovery of significant reserves offshore of the coasts of Lazio (S. Capucci, pers. comm.) and Emilia Romagna (A. Lamberti, pers. comm.). With regard to Greece, MA extraction has been taking place since the 1960s, mainly from the inner continental shelf of the Greek islands (e.g. Andros, Mykonos); most of the material produced was used in the construction industry. Since the 1990s, stricter environmental regulations have resulted in the termination of most inshore MA extraction and production has since been concentrated offshore of the coasts of Trikeri (N. Evoikos Gulf) and Southern Evia. Although, there is no readily available information on annual extraction volumes, it is thought that these are of the order of hundreds of thousands of m³ rather than millions.

MA Usage

With the exception of the UK and to a lesser extent Poland and the Netherlands, marine aggregates are used in the country of production (Table 5.). Annual exports of aggregates extracted from the UK waters vary but, in some years, can be more than 20% of the UK production with the main foreign markets being the Netherlands, Belgium and France (BMAPA, 2004; ICES, 2005). Relatively small quantities of Danish marine aggregates are exported in some years to Sweden and Germany, whereas there are also intermittent Dutch and Polish MA exports to Belgium and Germany, respectively (ICES, 2005).

In the Netherlands, most of the MA production is used for fill and beach replenishment, whereas in Spain the whole production is reserved for beach replenishment (Table 5.). This is not the case in the UK, where more than 60% of the MA production can be used in the construction industry (GUBBAY, 2003, 2005; MEAKINS *et al.*, 1999). In Denmark, almost 40% of

marine sand is used in beach replenishment schemes, mainly along the west Jutland coast, whereas almost 80% of the Polish production is used for beach replenishment (ICES, 2005).

With regard to beach replenishment, most of the southern UK coast beaches consist of flint/chert gravel (shingle), whereas the remainder of the UK coastline is characterised by sandy beaches. Therefore, there will be an increasing demand for (flint) marine gravels in the southern UK to supply the beach replenishment schemes. As gravel deposits are limited (found mainly in the buried valleys/drowned beaches of the English Channel and the southern North Sea), extreme care should be taken to use them in a sustainable manner i.e. to reserve them for beach replenishment and not to use them in the construction industry, for which material of lesser quality is sufficient (e.g. ARTHURTON, 1997; BATES *et al.*, 1997).

Table 5. Different usage of marine aggregates during the last years (as a percentage of the overall production). Data extracted from Ices, 2002-2006.

Note: Data for Spain have been extracted from Ices (2006) and data for Belgium are based on an estimation and can be used only as an approximation.

Country	MA extracted (million m ³)	Construction Industry (%)	Beach replenishment (%)	Exports (%)
Belgium	1.63	93.8	6.2	0
Denmark	7.01	59.9	38.8	1.4
France	2.77	nd	nd	0
Germany	7.57	nd	nd	0
Netherlands	29.07	49.2	43.4	7.4
Poland	0.64	2.9	79.6	17.5
Spain	0.48	0	100	0
UK	13.13	66.6	4.8	28.8

Future MA demand

Prediction of the future MA demand is not an easy exercise, as it depends on forecasts of economic growth, the cyclical nature of the construction industry, national and European policies and regulation, the ability of the MA industry to penetrate markets long held by land-won aggregates and related investment (e.g. construction of dredging vessels and wharves). In addition, future demand/supply is dependent on the availability of suitable marine aggregate resources. In the Bristol Channel (UK) for example, certain MA deposits which have been dredged for over 60 years are coming to the end of their exploitation life (HARRISON, 2003); likewise, extraction from old Outer Thames Estuary licenses is in decline. However, the UK industry has found significant new reserves in the Eastern English Channel, the Irish Sea and the Bristol Channel (e.g. SEAMAN, 2006), which could last for some decades at the present rates of extraction, even though special care should be given on the availability of gravelly material which appears to be limited (ARTHURTON, 1997; BATES *et al.*, 1997; HARRISON, 2003).

Future demand figures can be distorted by large “one-off” capital development projects. For example, the UK Lincshire beach replenishment project used 8 million tonnes of marine aggregates (MEAKINS *et al.*, 1999). In the Netherlands, plans exist to use marine aggregates in major future developments, which will require large quantities of material (PHUA *et al.*, 2004).

Within northwestern Europe, only the UK and the Netherlands have produced official estimates of the future demand for marine sand and gravel. For the English part of the UK, the Department of Environment (DOE) (now DEFRA) has estimated that the total aggregate demand in the period 1995-2015 will be up to 7000 million tonnes (HUMPHREYS *et al.*, 1996; MEAKINS *et al.*, 1999). This demand is not spread evenly; in southeastern England, where outcrops of hard rock suitable for use (after mining and crushing) in the construction industry are not available, land-won and marine sand and gravel are vital for the construction industry (BATES *et al.*, 1997; GUBBAY, 2005). Future annual total aggregate demand for the Netherlands (until 2020) has been estimated as 20 million tonnes of gravel, 23 million tonnes of sand for concrete and 53 million m³ of fill sand (MEAKINS *et al.*, 1999); 7 out of the 20 million tonnes of gravel will be derived from Dutch land-based sources, whereas it is thought that the remainder will be supplied from recycling and imports. In 1997, the Ministry of Transport, Public Works and Water Management updated their future demand figures for MA extraction from Dutch waters. These updates suggest that for the period 1996-2030 the average annual extraction should be in the order of 30-33 mil-

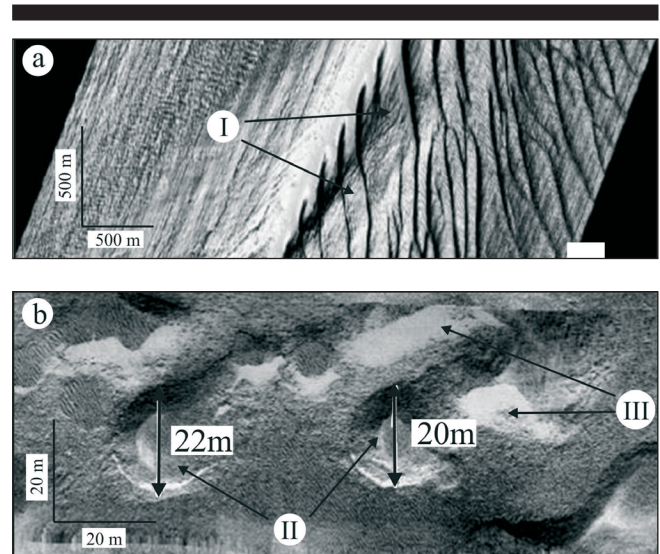


Figure 10. (a) Multibeam image of trailing suction dredging marks from the Kwinte Bank, (Flemish Banks, southern North Sea), adapted from data of The Fund for Sand Extraction, Belgium; and (b) side scan sonar image from the dredging area of Tromper Wiek (German Sector of the Baltic Sea), showing the presence of several anchor dredging pits on the gravelly seabed. Key: I, dredging marks from trailing suction dredger (Figure 10a); II, anchor dredging pits (Figure 10b); III, surficial sand deposits (light areas) on the gravelly (dark) background, formed from the spillage of the sand-size fraction of the dredged material after its screening on the dredging vessel (Figure 10b).

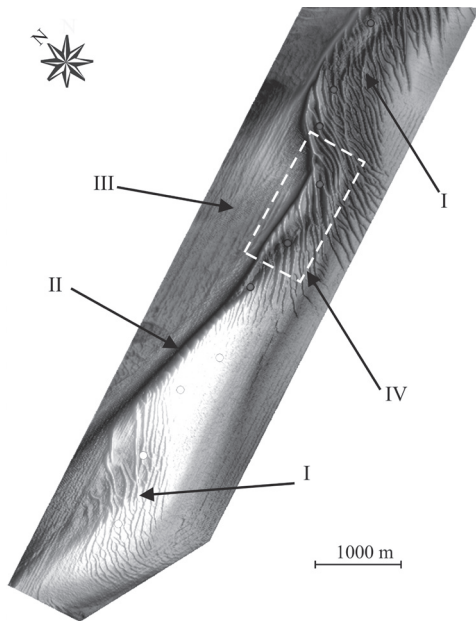


Figure 11. Multibeam image of the Kwinte Bank (Flemish Banks, southern North Sea), adapted from data of The Fund for Sand Extraction, Belgium. Key: I, large subaqueous dunes; II, bank crest; III, poorly-sorted swale sediments; and IV, dredged area.

lion m^3 of sand (MEAKINS *et al.*, 1999). These figures do not take into account additional demand for one-off projects.

It has been estimated that large quantities of marine aggregates (between 6 and 14 million m^3 of sand) will be required for beach replenishment to compensate for sand loss in eroding areas of the Dutch coastline, particularly if the effects of sea level rise are considered (RON2, 2004; HARTE *et al.*, 2003; VAN DALFSEN and ESSINK, 1997). Future annual marine aggregate demand for construction (excluding large infrastructure projects) has been estimated as between 9.3 and 29 million m^3 (PHUA *et al.*, 2004). As, however, large land reclamation projects have been planned for the near future, Dutch MA extraction may increase very substantially. The most important of these projects are: the enlargement of the Rotterdam Harbour, which will require up to 300 million m^3 of sand and the Westerschelde (Western Scheldt) Container Terminal (WCT), which will require up to 20 million m^3 (DHV MILIEU & INFRASTRUCTUUR, 2003).

MA PRODUCTION TECHNIQUES

MA production incorporates 3 main phases: (i) identification of the potential deposit; (ii) evaluation (prospecting) of the deposit and (iii) aggregate mining (extraction). The first phase (identification of a potential deposit, Phase 1) is often linked to other marine research projects such as general geological mapping of the seabed (e.g. HAMBLIN *et al.*, 1992; JACKSON *et*

Table 6. Main differences between multibeam echosounders and side scan sonars (After Van Lancker, 2003).

Very-high resolution multibeam system	Very-high resolution digital side-scan sonar system
<ul style="list-style-type: none"> • Highly accurate water depth measurements • Integrated sensors for motion correction or positioning • Provision of (depth- and angle-corrected) backscatter data, expressed in numerical values (dB), allowing quantitative evaluations • Transducers rigidly mounted onto the survey vessel hull or poles, eliminating most casting shadows • Better in deeper waters as swath width depends on water depth • Very-high resolution imagery, but extensive processing time • Sound velocity measurements over the vertical are needed • Expensive system/need for additional sensors • Various corrections required (e.g. systematic errors, tidal effects, heave, vessel lift/squat, antenna motion and internal time delays), particularly in shallow water. Sensor calibration needed. 	<ul style="list-style-type: none"> • Very-high resolution, multi-parameter image obtained in real time • Most systems have no additional sensors for water depth, motion correction or positioning • Backscatter is function of the relief and intrinsic nature of the seafloor and depends on gain settings; thus, only qualitative evaluations are possible • Superior for target detection due to the low grazing angle which produces distinctive shadows behind objects • More efficient bandwidth sampling • Better in shallow waters due to the low grazing angle and swath widths which are independent of water depth • Generally, higher resolution images • Quick processing, but thorough interpretation requires skilled personnel • No calibration required • Cost-friendly system that can easily be deployed from vessels of opportunity

al., 1995) and/or habitat mapping. If an area appears promising, a prospecting license will be obtained according to the procedures in place in each state (see also RADZEVICIUS *et al.*, this volume) to prospect/evaluate the potential of the deposit in detail (Phase 2). Finally, if the deposit is found to be economically viable, an extraction license is obtained and mining (dredging) commences (Phase 3).

Prospecting techniques

The evaluation of sand and gravel deposits (Phase 2) requires the use of specialized equipment, such as: (a) acoustic (seismic) sources, powerful enough to penetrate the medium- and coarse grained sediments and, at the same time, having sufficient resolution to map accurately the internal architecture of the sedimentary deposit and (b) coring equipment able to penetrate at least 2 to 3 m into a medium- and/or coarse-grained sedimentary sequence. Reviews of seabed mapping techniques already exist (e.g. KENNY *et al.*, 2003). Nevertheless, it is useful to summarise particular techniques used in the marine aggregate prospecting and which are based on the:

- collection of indirect (remotely-sensed) information on the geomorphology/geology of the seabed, using acoustic sources (e.g. single and/or multibeam echosounders, side-scan sonar, continuous seismic profiling equipment) and
- collection of (direct) ground-truth data, using superficial (grab) and sub-bottom (gravity and vibro-core) sediment samplers.

Information from both the direct and indirect methods is combined, as the scope of the prospecting is not only to identify the spatial (horizontal and vertical) extent of the MA deposit, but also to evaluate its quality (i.e. its texture, mineralogy, shell and salt content etc).

Acoustic sources

The acoustic devices used in MA prospecting are differentiated into those that provide information on the seabed geomorphology (bathymetry) and superficial sedimentology of the resource and those that provide information on its thickness and internal architecture (sub-bottom profilers). Depending on the research vessel used and the logistics of the prospecting survey, such equipment can be used either concurrently or sequentially.

Superficial mapping of the MA deposits

The ‘work horse’ of seabed geomorphological mapping is the side-scan sonar. It provides information (sonographs) on the distribution of the acoustic characteristics of the seabed, on the basis of the intensity of the seabed backscatter of the transmitted acoustic energy front. As the backscatter intensity is controlled by the acoustic reflection coefficient (C_R), which is different for each particular sedimentary material, sedimentary facies (and/or areas of exposed bedrock) can be demarcated on the seabed (Figures 6. and 10b.), provided that the backscatter intensity patterns will be calibrated by sufficient ground truth data (superficial sediment samples). In addition, as bedrock outcrops, sedimentary bedforms and other morphological features produce “acoustic shadows” behind them (Figure 6.), the position, dimensions and symmetry (in the case of sedimentary bedforms) of these features can be estimated from the dimensions of the acoustic shadow and its position relative to the side-scan sonar “fish”. However, corrections should be made on the different distortions apparent on the sonographs (e.g. VOULGARIS and COLLINS, 1991), which are nowadays performed by algorithms incorporated within the data acquisition systems of the digital side-scan sonars. The resolution of the sonographs depends on the frequency of the transmitted pulse being commonly between 100 and 500 kHz in the new dual frequency high resolution systems used for the mapping of the marine aggregate deposits.

Multibeam echo-sounders provide both bathymetric and backscatter data of the seabed (DAVIES *et al.*, 2001). Accurate water depth information concerning the MA deposit is essential for its efficient exploitation, whereas the acoustic backscatter of the transmitted pulses can provide information on the nature of the seabed. Although the multibeam echo-sounders are extremely powerful water depth measuring and imaging devices (Figures 10a. and 11.), they have both advantages and disadvantages concerning the mapping of the acoustic character of the seabed in relation to the side-scan sonar systems (Table 6.).

Thickness and internal architecture of the MA deposit

The MA deposit thickness and architecture are studied using continuous reflection profiling and seismostratigraphic techniques (e.g. MCQUILLIN and ARDUS, 1977; POSAMENTIER and VAIL, 1988). MA deposit surveying requires high resolution

acoustic sources (e.g. sparkers, boomers, chirp and 3.5-2.5 kHz systems), which produce sequences of relatively high frequency acoustic pulses that after their reflection from the seabed and sub-bottom reflectors return to hydrophone strings towed behind the survey vessel to be recorded and provide images of the internal architecture of the deposit (see Figures 1., 2., 3., 4., 5. and 7.). As the frequency and energy of the transmitted acoustic waves control the resolution and penetration, it is important to use the right acoustic source for optimal results. As a general rule, medium- and coarse-grained deposit surveying requires acoustic sources with frequencies equal and/or less than 2.5 kHz, commonly at 500-2000 Hz depending on the texture of the deposit. It should be noted that, as the exploitable MA deposits are located at relatively shallow areas (10-40 m water depths) there are certain difficulties in the interpretation of the acoustic (seismic) records, related to the masking of primary reflections by multiples (see for example Figure 7b.).

Ground-truth data

The remotely-sensed acoustic information requires ‘calibration/validation’ from ground truth data. These data are either superficial sediment samples collected using Van Veen, Hammon and/or large hydraulic grabs (for the calibration of the side-scan sonar and multibeam images) or sediment cores (for the calibration of sub-bottom profiling data). The preferred coring equipment is the vibro-core, as it can achieve satisfactory penetration into the medium- and coarse-grained sediments of the MA deposits. The ground truth data not only calibrate/validate the acoustic data allowing volume estimations but, they provide also information on the quality of the MA deposit (e.g. on its grain-size, mineralogy and carbonate, organic matter and chloride content) through the analysis of the recovered sediment samples.

The prospecting data can also be used to provide essential information on the mobility/morphodynamics of the MA deposit (BRAMPTON *et al.*, 1998) and to map its habitats, which are essential components of the required environmental impact assessment of the exploitation of the deposit (RADZEVICĪUS *et al.*, this volume; VIVIAN, 2003). It must be noted, however, that both the collection and the interpretation of the relevant information require careful analysis and skilled personnel, otherwise serious errors may arise in the evaluation and subsequent exploitation of the deposits (VELEGRAKIS, GAO, and COLLINS, 1994).

Extraction

The type of dredging vessel is usually determined by the existing regulatory regime, economic considerations, contractor requirements and site conditions. Nowadays, dredging vessels operate around the clock, 365 days a year. In the UK, the construction cost of a modern trailing suction vessel is around £15-20 million (22-30 million €). A modern large dredger can extract and load some 5,000 tonnes of marine sand and gravel from 40-60 m water depths in 3 hours, with overall operational cycles usually between 12 and 36 hours, depending upon the port of discharge (BATES *et al.*, 1997).

Two main types of dredging vessels are used for marine sand and gravel extraction: (i) trailer suction dredgers and (ii) an-

chor suction dredgers (see for example IHC, 2007). The former can operate under relatively rough sea conditions, extracting sediments through their suction 'pipes' while steaming over the deposit; they operate very much like moving 'vacuum cleaners', resulting in the development of suction furrows (up to 1 m deep) on the sedimentary bed (see Figure 10a.). The aggregates are emptied by opening bottom hatches or by pumps. Because of their high production rates, these dredgers carry out most land reclamation projects and are also suitable for harbour maintenance dredging and pipe trenching. The latter extract sediments while anchored and the suction method employed results in the development of suction pits (Figure 10b.). These vessels can operate in relatively deep waters, but they are sensitive to strong currents and rough weather conditions; moreover, they are not suitable for channel/harbour construction projects, as they produce confined excavations. This method is now prohibited in some EU Member States (e.g. Belgium), as it is considered to have large environmental impacts.

Dredging activities are subject to environmental impact assessments and should be controlled by the competent regulatory authorities (see RADZEVICĪUS *et al.*, this volume). In several (but not all as it should) EU Member States, dredging vessels are required to be equipped with Electronic Monitoring Systems ("black boxes"), which allow the monitoring of their activities and their compliance with the licensing terms.

SUMMARY AND CONCLUSIONS

Marine aggregates are a mineral resource of increasing importance for the EU Member States. Additional resources are needed to meet future demand, which is bound to increase substantially due to both increasing coastal zone development and the need to battle accelerating coastal erosion effectively. However, in order to develop an effective and sustainable European strategy, several problems facing the industry should be addressed. These include (amongst others): lack of standardisation of the relevant information, difficulties related to the access to information and the presence of barriers between the scientific research establishments and the marine aggregate industry.

This review has shown that there are serious standardization issues as well as important information gaps that hinder the sustainable development of the industry. With the exception of few Member States, the situation is rather discouraging, particularly in the Mediterranean countries. In some cases, it has shown to be very difficult to access the relevant information (e.g. production volumes, resource estimates), as this is scattered between several organizations. It is important that these issues should be addressed as quickly as possible, possibly through European-wide initiatives.

Although the technology and 'know-how' are available, it appears that these are seldom employed in the discovering and evaluation of new marine aggregate resources. Hence, multibeam echosounding techniques are used rarely and the same is true for the modern techniques in the acquisition and interpretation of the remainder of the acoustic data. These problems appear to be related to an apparent lack of coordina-

tion between the scientific research establishments and the MA industry, which is endemic in most EU Member States. A closer collaboration between them would not only have substantial benefits for both, but it would also prove to be cost-effective.

Finally, it should be kept in mind that marine aggregates are finite, being a non-renewable resource. Therefore, they should be used in a sustainable manner and effective policies/administrative frameworks should be developed to address future shortages, particularly with regard to certain types of material (e.g. gravel).

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