Chapter 1: General introduction

In this chapter, a general overview of the physical and biological features of sandy shores, i.e. beaches, is given with a focus on the specific habitat of this PhD thesis, namely the Belgian beaches. Its ecosystem components, food web structure and threats are discussed with a prime focus on coastal defence activities and their impact on the beach ecosystem. At the end of this chapter, the current status of the governance and policy in the Belgian coastal zone is documented to provide for a better understanding of beach and coastal spatial planning in Belgium. Finally, the aims of this PhD thesis and the thesis outline are presented.

1. Coastal zones worldwide

Being the spatial interface between the land and the ocean, coastal zones are dynamic ever-changing environments under the influence of earth's natural processes. The constant sculpture of the coastline is defined by a wide array of physical factors, e.g. temperature, salinity, tides, currents, wind, wave action, light and substrate (Levinton 1995). Tides are the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the moon and the sun and the rotation of the earth. The tidal range is defined as the vertical difference between the high tide and the succeeding low tide. It is not constant and varies globally due to tidal driving forces, geographic location, volume of water and geography of the water basin adjacent to the coast. Larger water bodies have higher tidal ranges while the geography can act as a funnel amplifying or dispersing the tide. Areas with high tidal ranges (macrotidal range > 4 m) allow waves to reach further up the shore while areas with lower tidal ranges (mesotidal range = 2 – 4 m; microtidal range < 2 m) produce deposition of sediment at a smaller elevation interval (Davies 1964). Sediment size and sorting will contribute to cross-shore beach gradient and type. With increasing grain size the beach face will steepen and the surf zone narrow. Coarse sand, cobble and boulder beaches have the steepest beach face and no surf zone (McLachlan et al. 2013). The surf zone is the most dynamic part of the beach owing to the energy released by breaking waves, which can produce onshore (wave bores), along-shore and offshore (rip currents) flows, and morphology containing single and multiple longshore and transverse bars, troughs and channels (McLachlan et al. 2013). Sand transport, driven by waves on the wet side and wind on the dry side, is highest in exposed surf zones, whereas sand storage is often greatest in well-developed dunes (Defeo et al. 2009). Given this large variety in global geomorphodynamics, a huge diversity in coastal habitats can be found from the Poles to the Equator, ranging from coastal dunes, rocky and sandy shores, mudflats, mangroves, salt marshes and tidal wetlands to estuaries, kelp forests, sea grass meadows and coral reefs.

Encompassing this broad range of habitat types, coastal ecosystems provide a wide array of goods and services (Burke et al. 2001). They store and cycle nutrients, filter pollutants from inland freshwater systems, act as sediment sinks and help to protect shorelines from erosion and storms. On the other side of shorelines, oceans play a vital role in regulating global hydrology and climate by constituting a major carbon sink and oxygen source (Beaumont et al. 2007; Beaumont et al. 2008). Coastal systems harbor unique, dynamic and fragile ecosystems with high biological productivity and genetic diversity. They are very important to the health of both marine and terrestrial environments as they are closely linked through the storage, transport and exchange of sand (Schlacher et al. 2008; Defeo et al. 2009).

However, people intensively rely on coastal regions to live as well as for trade, sea-going and recreational interests, leisure and tourism. As such, man transformed coastal ecosystems into centers of human activity. They now host the world's primary ports of commerce, serve as a major human food source for fish, shellfish and seaweed, and they provide mankind with fertilizer, pharmaceuticals, cosmetics, household products and construction materials.

1.1 Sandy shores

Sandy shores, also called beaches, cover 70 % of all continental margins (McLachlan & Brown 2006). There is no single, agreed-upon definition for a beach. One definition refers to a beach as 'accumulation of wave-washed, loose sediment that extends between the outermost breakers and the landward limit of wave and swash action' (Leatherman 1979). Another definition includes 'the area between the permanent vegetation line seaward to the point of the next geomorphic feature' (Davis 1994).

The boundaries of a beach are never rigid. They change constantly with seasonal wave activity, tidal range and reduction in sediment supply to the beach (Pilkey & Dixon 1998). Beaches may seem globally uniform continuous sandy plains from the dunes to the sea, but in reality, a variety of beach types exists. Beaches can be defined by the degree of exposure they experience, from very sheltered to very exposed. Wave-dominated beaches in all tidal ranges can also be classified based on their morphodynamic features (Masselink & Short 1993). When conditions are calm and/or the sediment is coarse, the **reflective** beach type occurs (figure 1a). Waves flow upon the beach where a major part of the incoming wave is reflected. Three beach zones appear to be generally valid on this beach type (Reilly & Bellis 1983; Greene 2002):

(1) **supralittoral** or upper beach zone: dry sand area land inwards from the mean high water level (MHW) to primary dune, only wetted by spray, during high spring tide and storms;
(2) **intertidal** or midlittoral beach zone: wet sand area between MHW and the mean low water level (MLW), constantly moist, but not saturated, from incoming tide;
(3) **subtidal** or sublittoral beach zone: seawards from MLW to the continental slope.

The subtidal zone becomes more complex when bigger waves cut back a beach and spread out its sediments. Two subtidal subzones can then be distinguished:

(3a) swash beach zone: area where waves rush up the face of the beach and retreat seaward, usually remaining saturated;

(3b) surf beach zone: area between the water line and where breakers form as waves break.

All beach types are characterized by high temporal variability and sand storage both on the beach and in the surf zone. For instance, **low tide bar/rip-beaches** (figure 1b) have a much steeper high intertidal zone (typically 1.6 % or more) than the other beach types. If wave action is strong and/or sediment particle size is fine, the flat **dissipative** beach type (figure 1c) is created, as present on many European beaches, for instance the Netherlands, France, northwest Spain and Scotland (McLachlan & Jaramillo 1995). Sediments are stored in a broad surf zone that may have multiple sandbanks parallel to the beach. **Ultradissipative** beaches (figure 1d) are flat, wide, undistinctive beaches with a slightly tapered inclination (around 1 %). The sediment consists of fine sands (125 – 250 µm) and very fine sands (63 – 125 µm). Due to the relative lower environmental stress, these beaches harbour the most diverse and dense beach communities (McLachlan 1983; McLachlan & Jaramillo 1995; Degraer et al. 2003b). Runnels can form on an ultradissipative beach and they stay submerged over a longer period of time (Speybroeck 2007).

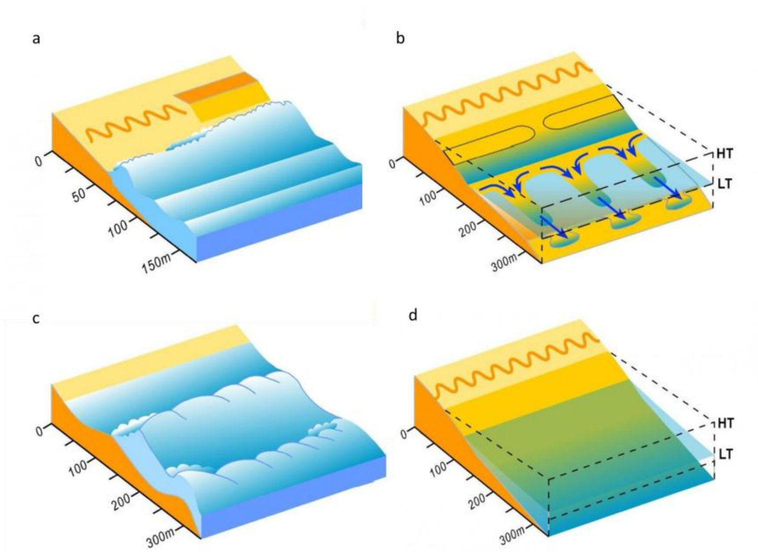

Figure 1: Schematic representation of four beach types: (a) reflective beach; (b) low tide bar/rip beach; (c) dissipative beach and (d) ultradissipative beach (at the courtesy of NIWA, the National Institute of Water and Atmospheric Research of New Zealand, based on figures in (Short 2006))

Beach sand is a naturally occurring granular material composed of finely broken-up rock and mineral particles. The composition of beach sand is highly variable, depending on the local rock sources and conditions. The most common constituent of sand in non-tropical coastal settings is silica (silicon dioxide or SiO_2), usually in the form of quartz. Because of its chemical inertness and considerable hardness, it is the most common mineral resistant to weathering. In tropical coastal settings, where reefs have dominated the ecosystem for millions of years, calcium carbonate ($CaCO_3$), for example aragonite, is the primary form of sand. Beaches in the vicinity of volcanos harbor sand consisting out of tiny fragments of volcanic lava which gives it its black color. Overall beach sand grains are smaller than 1 or 2 mm and larger than silt (< 63 µm). They are divided into five Wentworth classes (table 1) (Wentworth 1922).

Table 1: Beach median grain size divided into Wentworth classes (Wentworth 1922)

Median grain size (mm or µm)	Wentworth class
1 – 2 mm	very coarse sand
500 – 1000 µm	coarse sand
250 – 500 µm	medium sand
125 – 250 µm	fine sand
63 – 125 µm	very fine sand

Coastal waters may be fully saline (35 – 50 ppt), brackish (0.5 – 35 ppt) or nearly fresh (< 0.5 ppt) depending on the vicinity of estuaries, river deltas or melting glaciers. Nutrients are transported by ocean currents and upwelling or they reach coastal habitats through land runoff. Oxygen levels can be increased by wave actions and decreased during algal blooms while carbon dioxide (CO_2) levels influence the acidity of the coastal systems.

For a long time, sandy beaches have been regarded as marine deserts by many biologists and were largely neglected in ecological investigations. Remane (1933) started the sandy beach research on a German beach but it took 50 more years for a first comprehensive overview of the ecological features of sandy beaches (McLachlan 1983). The physical and chemical zonation appeared to induce the apparent dynamic and variable biological zonation. Based on species characteristics and adaptations to an aquatic, terrestrial or amphibian existence, the natural beach zonation is usually most distinct but narrowest at the top of the shore and becomes less clear but widened down shore. Rhythmic migrations of highly mobile organisms shuffle and recreate zones in response to tidal, photic and semi-lunar cycles, substrate moisture, swash activity, slope temperature and turbulence. As the tide rises, zones compress while some populations move in or over the sediment and some enter the water column. The benefits of migration are to keep species (1) in optimal feeding zones with the largest prey and/or nutrient availability, (2) out of reach of bird and fish predators, by concentrating them in the swash zone and (3) in the zone of sediment reworking, reducing the chances of stranding (McLachlan & Jaramillo 1995). On dissipative, fairly undisturbed beaches, zonation patterns can even be triggered by high species abundances causing intraspecific and interspecific interactions (Defeo & McLachlan 2005).

1.2 Threats to coastal zones and sandy beaches

The popularity of coastal regions has led to profound altering of coastal habitats. Initially, the most widespread and pressing threat was habitat loss through draining, dredging and in some way converting to upland habitat, artificial substrate or open water (Crain et al. 2009). With industrialization, additional threats emerged, particularly byproducts of globalization such as invasive species, disease and nutrient pollution in nitrates and phosphates leading to eutrophication. In terms of food production, overexploitation of fish, shellfish, seaweeds and other marine organisms not only diminishes production of the harvested species but also profoundly alters the biological structure of coastal ecosystems (Maes et al. 2005a). On top of this, coastal ecosystems are strongly threatened by climate change due to expected changes in storm and wave regimes, ocean temperatures, circulation patterns, sea level rise, erosion, flooding and altered sediment budgets (Burke et al. 2001; Harley et al. 2006; Jones et al. 2008). From 1950 to 2009, measurements show an average annual global sea level rise of 1.7 ± 0.3 mm per year, with satellite data showing a rise of 3.3 ± 0.4 mm per year from 1993 to 2009 (Bindoff et al. 2007; Nicholls & Cazenave 2010). The resulting higher impact of storm surges could accelerate erosion and associated habitat loss, increase salinity in estuaries and freshwater aquifers, alter tidal ranges, change sediment and nutrient transport and increase coastal flooding. Changing concentrations of CO_2 in ocean waters will lead to acidification and may affect marine productivity or even change the rate of coral calcification (Kleypas et al. 1999).

Of all coastal habitats, sandy beaches are of the highest economic, social and cultural importance to humans as prime recreational assets. More people interact directly with beaches than with any other type of shoreline worldwide (Phillips & Jones 2006; Schlacher et al. 2008). Strong tidal currents are responsible for beach **erosion** worldwide but natural sandy beaches function as a buffer between sea and land, thus protecting the hinterland from scour, inundation and wave erosion (Young & Bryant 1992; Defeo et al. 2009). For centuries, a wide array of human disturbances has shaped and molded sandy beaches with varying impacts, e.g. pollution, eutrophication, tourism, recreation and coastal defence (Brown & McLachlan 2002; Defeo et al. 2009).

2. Belgian coastal zone

The Belgian part of the North Sea (BPNS) is situated on the northwest European continental shelf and covers 3600 km² or 0.6 % of the overall North Sea surface (figure 2). It is often referred to as Belgium's eleventh province as it comprises almost 11 % of the total Belgian surface area (Degraer et al. 2006). The gently sloping underwater landscape is characterized by a continuous succession of sandbanks and swales or gullies, making the BPNS a rather shallow marine system. Average depth is 20 m with a maximum depth of 45 m (Maes et al. 2005a). The tidal regime of the BPNS is semi-diurnal (Baeye et al. 2010) and the mean tidal range descends from about 5 m at the French border to 4.3 m towards the

Dutch border (Fremout 2002). The horizontal motion in a tide wave, i.e. the particle velocity, is called the tidal stream. Most tidal streams are rotary, although the shape of the ellipse traced out by a tidal stream vector, i.e. tidal ellipse, and the direction of rotation may vary. Tidal current ellipses are elongated in the nearshore area and become gradually more semicircular towards the offshore. Maximum current velocities are as such higher and minima lower in the nearshore area than further offshore (Fettweis et al. 2011). The prevailing tidal currents and wave action, also called hydrodynamics, keep the seawater at the BPNS in continuous motion. At high tide, Atlantic water flows through the English Channel into the North Sea. At low tide, part of this water flows back in the direction of the Atlantic Ocean. The dominant southwest-northeast directed current (> 1 m/s) is oriented parallel to the coast and results in a well-mixed homotherm and homohaline water column (Maes et al. 2005b; Degraer et al. 2006; Fettweis et al. 2011). Combined with the constant water supply by major river systems surrounding the North Sea, e.g. Rhine, Meuse, Scheldt, Yser, Authie, Canche and Somme (north to south), and numerous other processes, including wave action, these currents result in a clear seawater gradient: from turbid and nutrient-rich near-coastal water to more transparent and nutrient-poor offshore water (Fettweis et al. 2010). The combination of a complex bathymetry, hydrodynamics and meteorological conditions is also responsible for a high diversity of sediment types on the BPNS varying from very fine mud to coarse sand (Verfaillie et al. 2009).

The coastal zone stretches over 67 km, is southwest to northeast directed and consists mostly of sandy beaches with sea walls in front of the cities and dunes in between. For the purposes of this PhD, the Belgian coastal zone has been defined to include the intertidal and shallow subtidal areas between MHW and the 1 nautical mile from the 0 m depth bathymetric contour. Wherever appropriate, we also included the dune area and its very specific ecosystem (figure 2).

Degraer et al. (2003) stated that a gradual transition is visible from west to east, from ultradissipative beaches, with occasional runnels, to low tide bar/rip beaches (see also figure 1 for the beach types). According to Speybroeck et al. (2008a), Belgian beaches are (ultra-)dissipative, macrotidal, and wide from a morphodynamic perspective. Due to the relative lower environmental stress, the western beaches closest to the French border harbor the most diverse and dense beach ecosystem (Cattrijsse & Vincx 2001; Degraer et al. 2003b). The width of the intertidal zone varies from 200 to 700 meters, decreasing towards the east. Belgian beach sand mainly consists of quartz and has an average median grain size varying between 200 µm and 220 µm, with a minimum of 160 µm and a maximum of 380 µm (Speybroeck 2007). It can be said that the surficial sediments along the shallow subtidal Belgian coastal zone fine in a northeast direction although this is largely dependent on the interaction between the morphological features that may cause an enhanced flow-topography interaction (Degraer et al. 2003a). The waves and tidal currents give rise to a residual coastal sediment drift towards the northeast in the subtidal and intertidal beach zones (Van Lancker et al. 2007; Baeye et al. 2010). The dominant southwestern winds induce a northeastern aeolian drift in the supralittoral (Speybroeck 2007). As coarser sediments deposit in places with a strong current or with strong wave action, the grain size increases from west to east and from MLW to MHW (Deronde et al. 2006; Verfaillie et al. 2006; Van Lancker et al. 2007; Speybroeck et al. 2008a).

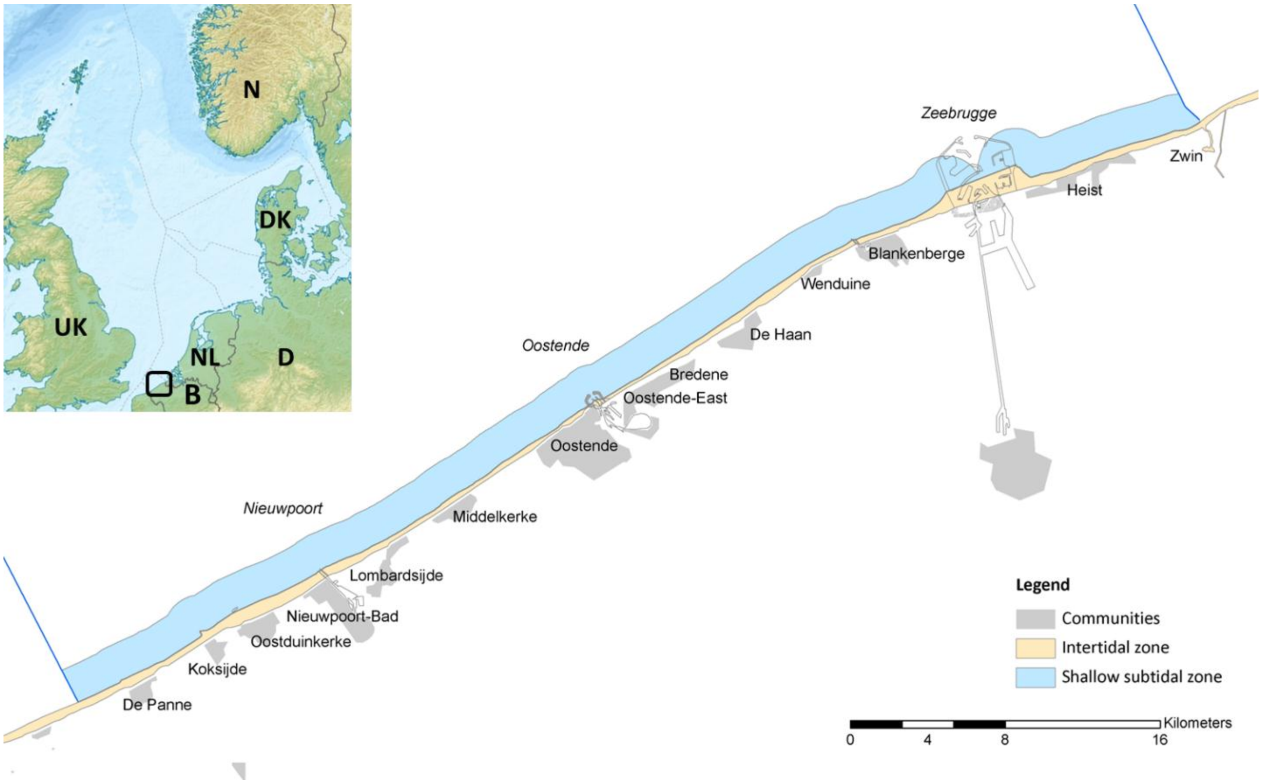

Figure 2: Location of the Belgian part of the North Sea (black box in insert picture) and the Belgian coastal area with its intertidal and shallow subtidal subdivisions; the most important coastal communities and/or sampling locations used in this PhD thesis have been indicated on the map, the three prime harbors are named above their respective locations

3. Belgian coastal ecosystem

Marine biologists have intensively studied the BPNS since the early seventies. A complete overview of all biota, from the plankton to the higher trophic levels still lacks but several components are well known, e.g. benthos and fish populations (Vandepitte et al. 2010a; Vandepitte et al. 2010b). According to the general knowledge, the Belgian marine food web consists of at least 27 mammal species (four are spotted regularly), 75 seabird species, 120 fish species and a huge species diversity in bacteria and viruses, plankton and benthos (Copejans & Smits 2011). Species richness and biodiversity are lower on Belgian beaches but every beach zone has its own characteristic ecosystem with specifically adapted biological components (Speybroeck 2007). The intertidal zone is an unstable environment, prone to repetitive small-scale impact by fast fluctuations in its physical and chemical conditions and irregular large-scale impacts, e.g. storms. In the following paragraphs, the Belgian coastal ecosystem will be illustrated per beach zone, e.g. supra-littoral, intertidal and shallow subtidal zone (figure 3).

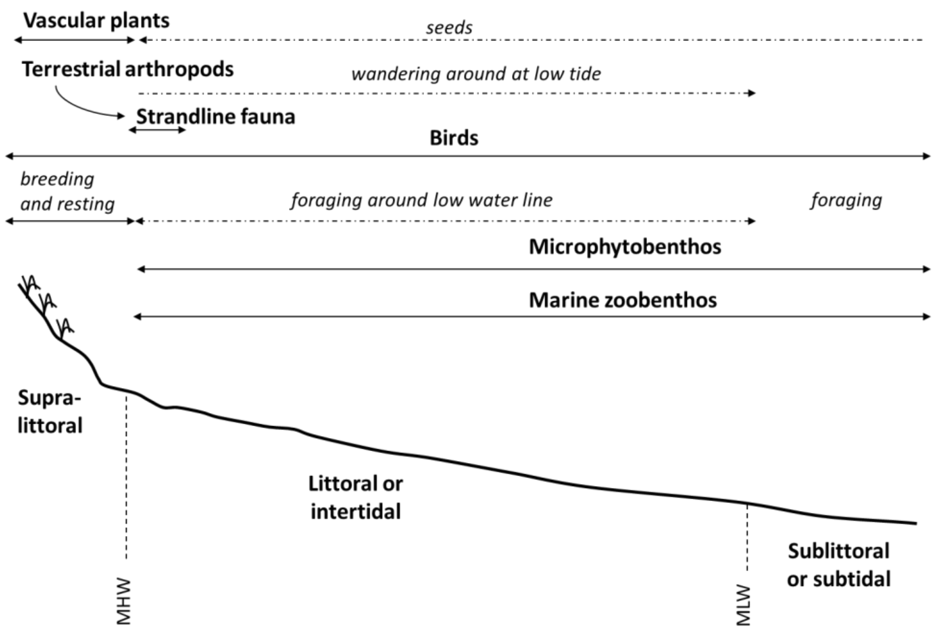

Figure 3: Belgian beach zones with characteristic fauna and flora zonation pattern (adapted from Speybroeck 2007); MHW: mean high water level; MLW: mean low water level

3.1 Supralittoral zone: vascular plants and strandline fauna

The supralittoral ecology, mainly characterized by vascular plants and arthropods (see figure 3), is determined by geomorphodynamics (Provoost et al. 2011). A positive sand budget is essential in this highly dynamic environment. On erosive beaches, strandlines appear and disappear too quickly to settle and develop plant or invertebrate communities. On sedimentary beaches however, vascular plants can sprout, grow and execute an entire phenological cycle, allowing for primary production, a more diverse ecosystem and highly evolved supralittoral vegetation (Speybroeck 2007). Stranded material or wrack, mainly kelp and brown algae, enable rich invertebrate strandline communities. The nutrient influx of decomposing wrack even elevates the vascular plants' vitality and fixates the sediment firmly.

The Belgian supralittoral zone consists of embryonic dunes, dry beach area and strandline. Most vascular plant species are short-lived and adapted to the dynamic nature of this biotope. They disperse and easily colonise strandlines by means of floating seeds that resist seawater for a long time (thalassochory) (Rappé 1996; Rappé 1997). The most common species along Belgian beaches is sea rocket (*Cakile maritima*), often accompanied by prickly saltwort (*Salsola kali*) and sea sandwort (*Honckenya peploides*). All typical species of the supralittoral zone are classified on the Red List as rare to (highly) endangered (Van Landuyt et al. 2006). Phytosociologically, Belgian grey dune vegetation includes moss dunes and dune grasslands mixing with the moss-dominated and lichen-dominated Cladonio-Koelerietalia vegetation. Wild asparagus (*Asparagus prostrates*) is strictly Atlantic and, at least regionally, rare and limited to grey dunes, defined as fixed coastal dunes with herbaceous vegetation in the Coordination of Information on the Environment biotope classification (Evans 2012) in Flanders and Belgium (Provoost et al. 2004).

From an invertebrate fauna perspective, grey dunes are the most endangered dune habitat, certainly within a Belgian context. Fragmentation of grey dunes due to tall grass and scrub encroachment causes substantial loss of regional biodiversity in Flemish coastal dunes (Provoost et al. 2004) and decreases the number of typical invertebrate species within each isolated patch (Bonte et al. 2002; Grootaert & Pollet 2004; Bonte & Hoffmann 2005). Most characteristic dune invertebrates however, are found in more dynamic habitats such as mobile dunes and young dune slacks (Provoost 2004, Bonte 2005). Besides the sandhopper (*Talitrus saltator*), a number of fly and beetle species make up the most typical Belgian supralittoral fauna. The sandhopper is a dominant species (Lincoln 1979) and plays an important role as primary consumer of the organic strandline matter (Robertson & Mann 1980; Griffiths et al. 1983; Stenton-Dozey & Griffiths 1983; Adin & Riera 2003). Other typical decomposers living in and near the strandline are flies and mosquitoes (Diptera, (Grootaert & Pollet 2004)) and their larvae, predators and parasites, two benthic springtails (Collembola: *Folsomia sexoculata* and *Isotoma maritima*) (Janssens 2002), predator mites (*Gamasina*), feeding on springtails and other invertebrates (Koehler et al. 1995; Salmane 2000) and 14 beetle families (Coleoptera) (Haghebaert 1989) with 46 strandline species. If a natural connection between the dunes and the beach is (still) present, some common dune species (isopods, spiders and carabids) can be encountered in the wrack. Beach restricted spiders (Aranea) are absent on Belgian beaches although Red List dune species may sometimes be found (Maelfait et al. 1998).

3.2 Intertidal and shallow subtidal zone: benthos

Benthic species inhabiting the highly dynamic intertidal and shallow subtidal environment possess a high tolerance towards several forms of environmental stress. Normal seasonal fluctuations within their composition, numbers and biomass are an adaptive feature to physical variation in their habitat (Oliver & Slattery 1976; Buchanan et al. 1978; Adriaanse & Coosen 1991). The onshore – offshore and eastern coast – western coast gradients have been reported for all benthic assemblages (Cattrijsse & Vincx 2001) and for pelagic communities such as the phytoplankton and zooplankton (M'Harzi et al. 1998).

The lower layer of the water column, 1m above the seabed, is inhabited by the **hyperbenthos**, a group mainly consisting of small crustaceans, like shrimp (e.g. *Crangon crangon*) and mysids. They consume detritus, algae and zooplankton and serve as prey for young fish and shrimp (Dewicke et al. 2003). High

densities are reached in regions with a strong input of organic matter to the bottom environment (Mees & Jones 1997; Dewicke et al. 2003; DFO 2004).
In the Belgian coastal zone, hyperbenthos is dominated by mysids (Mees et al. 1994; Mees & Jones 1997; Beyst et al. 2001a). They migrate with the tide in and out the intertidal zone to feed and to escape predators from deeper waters (McLachlan 1983; Gibson & Robb 1996; Beyst et al. 1999b; Gibson & Yoshiyama 1999; Wilber et al. 2003).

The seabed surface is the habitat of the **epibenthos**, a community of large, active organisms, including sea stars, brittle stars, crabs, lobsters, bottom fish and cephalopods. The surf zone supports abundant fish resources comprised of small species and juveniles (Modde & Ross 1981; Ross et al. 1987; Brown & McLachlan 2002; Beck et al. 2003). The diet of these fish changes with their developmental stage and prey availability. Populations are generally denser and more diverse in the summer and early fall (Naughton & Saloman 1978; Saloman & Naughton 1979; Modde & Ross 1981).
The Belgian intertidal zone serves as a nursery for the common littoral crab (*Carcinus maenas*) and a whole range of juvenile flat fish species, e.g. plaice (*Pleuronectes platessa*), sole (*Solea solea*), brill (*Scophtalmus rhombus*), turbot (*S. maximus*) and dab (*Limanda limanda*) (Beyst et al. 1999b). These juvenile flat fish migrate with the tide in and out the high intertidal zone to feed on epibenthos (Mees & Jones 1997; Hostens & Mees 1999) and macrobenthos and to escape predators from deeper waters (McLachlan 1983; Gibson & Robb 1996; Beyst et al. 1999b; Gibson & Yoshiyama 1999; Wilber et al. 2003).

The surf zone and nearshore regions are important migratory routes used by both hyperbenthos and larval and juvenile fish (epibenthos). They travel parallel to the coast and move easily in and out inlets and estuarine nurseries or back and forth between shallow and deeper waters (Hackney 1996; Beyst et al. 2001a; Beyst et al. 2002).

The **microbenthos** consists of unicellular organisms, namely diatoms, ciliates and bacteria, living between and on the sand or silt grains. The **microphytobentos** (MPB) are microscopic algae living on benthic surfaces at the photic marine zone. They are the most important primary producers on apparently unvegetated coastal zones and their biomass supports higher trophic levels.
On Belgian beaches, the MPB consists of dinoflagellates, euglenoids and both epipsammic (<10µm, living on sand grains) and epipelic (free living, forming biofilms) diatoms (Sabbe 1997; Speybroeck 2007; Maria et al. 2011a). The composition and occurrence of MPB on Belgian beaches depends on season, beach height position, hydrodynamics and grain size. The availability of inorganic nutrients, like nitrogen and phosphor is also important but remains poorly studied (Underwood & Kromkamp 1999). The highest levels of MPB appear in summer, due to optimal temperature and light conditions. On muddy sediment this peak shifts to the spring (Sabbe 1997).

Meiobenthos groups all organisms smaller than 1 mm but bigger than 38 µm, living buried in the seabed. This group is characterised by a large variety of invertebrates, including copepod crustaceans (coarser sand) and roundworms or nematodes (finer sands) (McLachlan 1983). Nematodes feed on bacteria, microphytobenthos, other meiofauna, detritus and dissolved organic matter (McLachlan 1983) while copepods prefer microphytobenthos (Granéli & Turner 2002).
In Belgium, knowledge on intertidal meiofauna is restricted to the meiofaunal community of the western part of the coastline (De Panne / Koksijde) (Gheskiere et al. 2002; Gheskiere et al. 2004; Gheskiere et al. 2005; Maria et al. 2011b; Maria et al. 2012a). In general 15 meiofauna taxa were recorded with Nematoda, Harpacticoida and Turbellaria (Martens 1983, 1984; Martens & Schockaert 1986) being the dominant ones. Higher densities were found in the lower intertidal zone while diversity peaked in the middle of this zone. Three semi-separated Nematoda species associations were detected: (1) supralittoral: *Rhabditis sp.* and *Axonolaimus helgolandicus*; (2) high intertidal zone: *Trissonchulus sp.*, *Dichromadora hyalocheile* and *Parachromadorita sp.*; (3) low intertidal zone: e.g. *Odontophora phalarata*, *O. rectangula*, *Cyartonema elegans* and *Chaetonema riemanni* (Gheskiere et al. 2004).

Macrobenthos is generally defined as the organisms measuring over 1 mm long and living buried in the seabed. Of the marine zoobenthos, this group of bivalves, polychaetes, crustaceans and echinoderms is best investigated. On a world-wide scale, crustaceans tend to be most abundant on exposed beaches, while molluscs and polychaetes abound on sheltered beaches (McLachlan & Jaramillo 1995; Elliott et al. 1997). Macrobenthos performs well as an indicator of pollution and stress and plays a key role in the wider beach ecosystem and food web. They feed primarily on faunal detritus and to a lesser extent on algal benthos and detritus (Sundbäck & Persson 1981; Josefson et al. 2002) and they are a major food source for birds and epibenthos. Macrobenthos is less abundant on sandy beaches than meiobenthos but comprises a larger part of the total biomass (Greene 2002).

Around 265 macrobenthic species have been discovered in the BPNS (Elliott et al. 1997; Degraer et al. 1999b; Cattrijsse & Vincx 2001; Degraer et al. 2003b). Their spatial distribution shows variability along the cross-shore gradient (figure 4), from sparse high intertidal to diverse shallow subtidal communities (Speybroeck 2007). A very narrow high intertidal zone is the habitat of the amphipod *Bathyporeia pilosa* and the polychaete *Scolelepis squamata*. The isopod *Eurydice pulchra* and the amphipod *Bathyporeia sarsi* live in a wide zone in the middle of the intertidal area. In the lowest parts of the intertidal zone, several polychaetes, e.g. *Nephtys cirrosa*, and bivalves have to share the space. The current zonation, distribution, abundance and species characteristics of *Bathyporeia pilosa* and *Bathyporeia sarsi* on Belgian beaches are likely to be the result of both niche diversification and character displacement (Van Tomme 2013). Although abiotic factors are defining the upper zonation limits of both amphipods, as has been generally accepted for sandy beaches (McLachlan 1996; McLachlan 2001), recently it was shown that the lower limits can only be explained by a combination of abiotic and biotic forces (Van Tomme 2013). The subtidal zone is a more buffered system, both physically and biologically controlled, mainly by sedimentology and geomorphology. More than 100 species are adapted to several subtidal microhabitats (Van Hoey et al. 2004), making the subtidal zone a species diverse system where competition for food and place reign (Van Hoey et al. 2007b; Van Hoey et al. 2010).

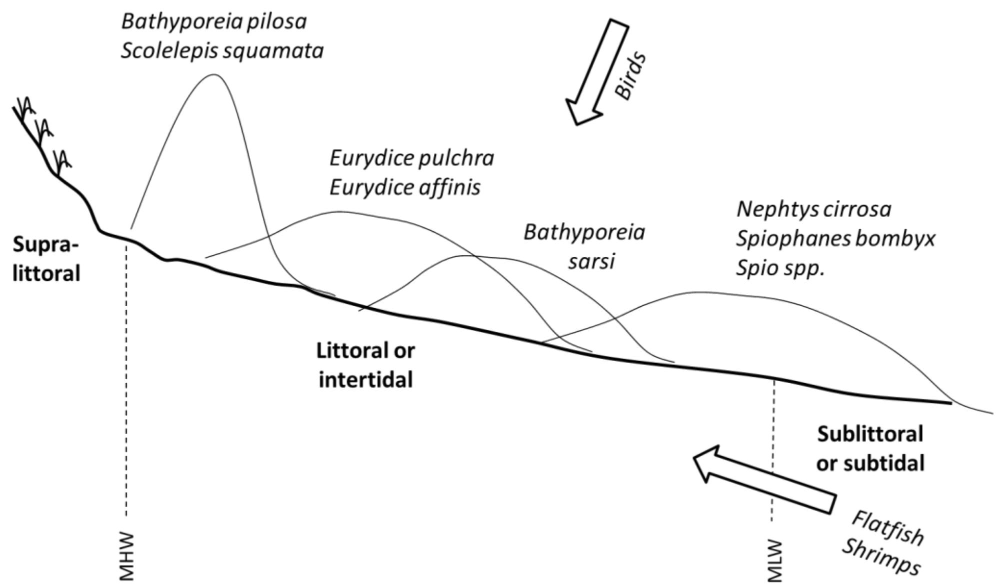

Figure 4: Zonation pattern of different Belgian macrobenthic species (adapted from Van Tomme 2013, originally adapted from Speybroeck 2007); MHW: mean high water level; MLW: mean low water level

Runnels on ultradissipative beaches were largely neglected in macrobenthos beach research because they need a different sampling strategy than generally applied. They contain a benthic fauna resembling the subtidal communities (Boulez 2002). Both in abundance and diversity, this fauna exceeds that of neighbouring sand banks since the runnels stay submerged over a longer period of time and contain higher levels of organic matter (Speybroeck 2007). Recent meiobenthos studies indicated that nematode communities from runnel and sandbar habitats are significantly different, illustrating the importance of microhabitat heterogeneity (Maria et al. 2012b).

3.3 From supralittoral to shallow subtidal: birds and seals

Some bird species use one or several beach zones for resting, nesting, moulting, breeding, foraging or any combination of these activities. The supralittoral zone is an important area in our region for birds, especially in winter and during migration. The intertidal and shallow subtidal zones form an important foraging area for many birds that feed primarily on macrobenthos. Seal activity on beaches is closely related to tidal cycles. At low tide, seals like to rest on sand banks, sand flats, hard defence structures, like groins, or even floating devices, like pontoons and buoys that allow for easy escape in case of hazard or danger. If the sand banks or sand flats offer enough peace and quiet, they could even be used as spawning areas.

In the Belgian supralittoral zone, turnstone *Arenaria interpres* feeds on strandline material (Smit & Wolff 1981; Becuwe et al. 2006). Only three Red List species can breed here, e.g. Kentish plover *Charadrius alexandrinus,* little tern *Sternula albifrons* and common ringed plover *Charadrius hiaticula*. These three breeding birds are threatened with extinction (Vermeersch et al. 2004) and their breeding distribution is limited to Zeebrugge port and the adjacent reserve 'Baai van Heist' (Stienen & Van Waeyenberge 2002; Courtens & Stienen 2004; Stienen & Van Waeyenberge 2004; Stienen et al. 2005). Intertidal macrobenthos of easily penetrable, wet substrates along the edges of gullies and along the MLW are the primary food source for many gulls and wading birds, e.g. oystercatcher *Haematopus ostralegus*, dunlin *Calidris alpina* and sanderling *Calidris alba* (Engledow et al. 2001; Stuer 2002; Speybroeck et al. 2005a; Speybroeck et al. 2005b). At high tide, they use the supralittoral to rest or gather before moving to high water roosts located on groins or near larger tidal flats, e.g. reserves 'IJzermonding' and 'Baai van Heist' (figure 2). The shallow subtidal Belgian waters and their associated food resources are of international importance for a number of seabirds, at least in a specific season (Seys 2001; Van Waeyenberge et al. 2001; Stienen & Van Waeyenberge 2002). These species are common scoter *Melanitta nigra*, crested grebe *Podiceps cristatus*, little gull *Larus minutus*, little tern, common tern *Sterna hirundo* and sandwich tern *Sterna sandvicensis*. Internationally of less importance but with a strong coastal connection are black-headed gull *Chroicocephalus ridibundus* and common gull *Larus canus* (Spanoghe 1999; Spanoghe & Devos 2002).

Seals are only sporadically spotted in the Belgian coastal waters, with harbor seal *Phoca vitulina* and grey seal *Halichoerus grypus* as most common visitors (De Smet 1978; Rappé 1983; Van Gompel 1983; Haelters 1999; Degraer et al. 2009; Jonckheere 2011). Both seals preferentially prey on benthic fish and small crustaceans in shallow waters. Since 2008, a small (maximum count of 16) but resident group of harbor seals stays at the Belgian coast. They currently prefer the estuaries of both the Schelde and Ijzer rivers as resting areas though one groin in Koksijde (Ster der Zee) seems to have served the same purpose (Jonckheere 2011). All Belgian beaches are too heavily used and too gently sloped to accommodate seals as these two factors both hinder fast escape into the sea in case of hazard or danger (Degraer et al. 2009).

4. Threats to the Belgian sandy beach ecosystem

An inventory of coastal evolution in the European Union showed 55 % of the coastline to be stable, 19 % to be suffering from erosion problems and 8 % to be depositional. The remaining 18 % of the coastline cannot be assigned to any of the categories (Airoldi et al. 2005). Research based on sequential beach profiling revealed that a natural cycle explains the periodical behavior of erosion and accretion on Belgian beaches (De Moor 1979; De Moor & Bloome 1988). Strong tidal currents are responsible for beach erosion at more than 50 % of the Belgian coastline (Deronde et al. 2006). Along the western coast, beaches are mostly stable and accreting. Further east to Oostende, beach sedimentology does not evolve in accordance with any clear trend. Beaches from Bredene to Wenduine and beaches in front of dykes with a rather pushed-forward position, e.g. Knokke, show increasingly irregular beach profiles. They have been and are still subjected to severe management measures which provoked a permanent erosive situation (De Moor & Bloome 1988; De Wolf et al. 1993; De Wolf 2002; Speybroeck 2007). The harbor walls of Belgian's biggest harbor, Zeebrugge, have profoundly altered the beach morphodynamics and morphology of all beaches situated at its eastern side, creating a deviation from the gradual transition in beach types along the Belgian coast (Deronde et al. 2008). Beaches closest to the Dutch border are more or less stable. Erosion only occurs on the beach at the mouth of the nature reserve 'Zwin' (figure 2).

4.1 Coastal defence along the Belgian coastline

Since the Middle Ages, man has strived to keep the Belgian coastline at its position or even move it seaward by drastically altering beaches up to the point where they are no longer capable of providing their natural coastal defence services. The low elevation of the Belgian beaches makes them even more vulnerable to detrimental erosive forces, sea level rise, storms and the consequent higher possibility of hinterland flooding. Unfortunately, human retreat in areas of low-value land and relocation is not achievable because of resistance to regulation of this coastal defence approach by both the general public and politics and the high economic value placed on coastal and port properties (Grober 1992). Instead, a large part of Belgium's only 67 km of shoreline is protected by hard defence constructions, like groins, concrete dykes, seawalls and revetments (figure 5) (Hanson et al. 2002). However, the construction and enhancement of these structures enhanced beach erosion (Airoldi et al. 2005; Defeo et al. 2009) and destroyed important ecosystem functions (Martin et al. 2005). These hard barriers also lead to the 'coastal squeeze' phenomenon whereby less and less space is available for natural coastal processes to accommodate eroding forces or adjust to the changes in sea level, storms and tides (Doody 2005; Schlacher et al. 2007; Nicholls & de la Vega-Leinert 2008). Nowadays, confidence has been established in soft coastal defence techniques, like nourishment (Dankers et al. 1983; Adriaanse & Coosen 1991; Charlier et al. 1998; Basco 1999; Peterson et al. 2000; Brown & McLachlan 2002; Finkl & Walker 2002; Greene 2002; Hamm et al. 2002; Hanson et al. 2002)**.** The philosophy behind **nourishment** is based on the consideration that when a stretch of coast is sediment-starved, it could be more appropriate to import sediment and let nature do its job, rather than desperately try to counteract natural forcing factors to keep the remaining sediment. There are however, no universal nourishment concepts. Examples of basic design objectives for a well-defined period are: (1) improving coastal stability by keeping the MLW position seawards of a selected position, (2) improving coastal protection to maintain a certain amount of sand (m^3 per m) or (3) increasing and maintaining a certain beach width.

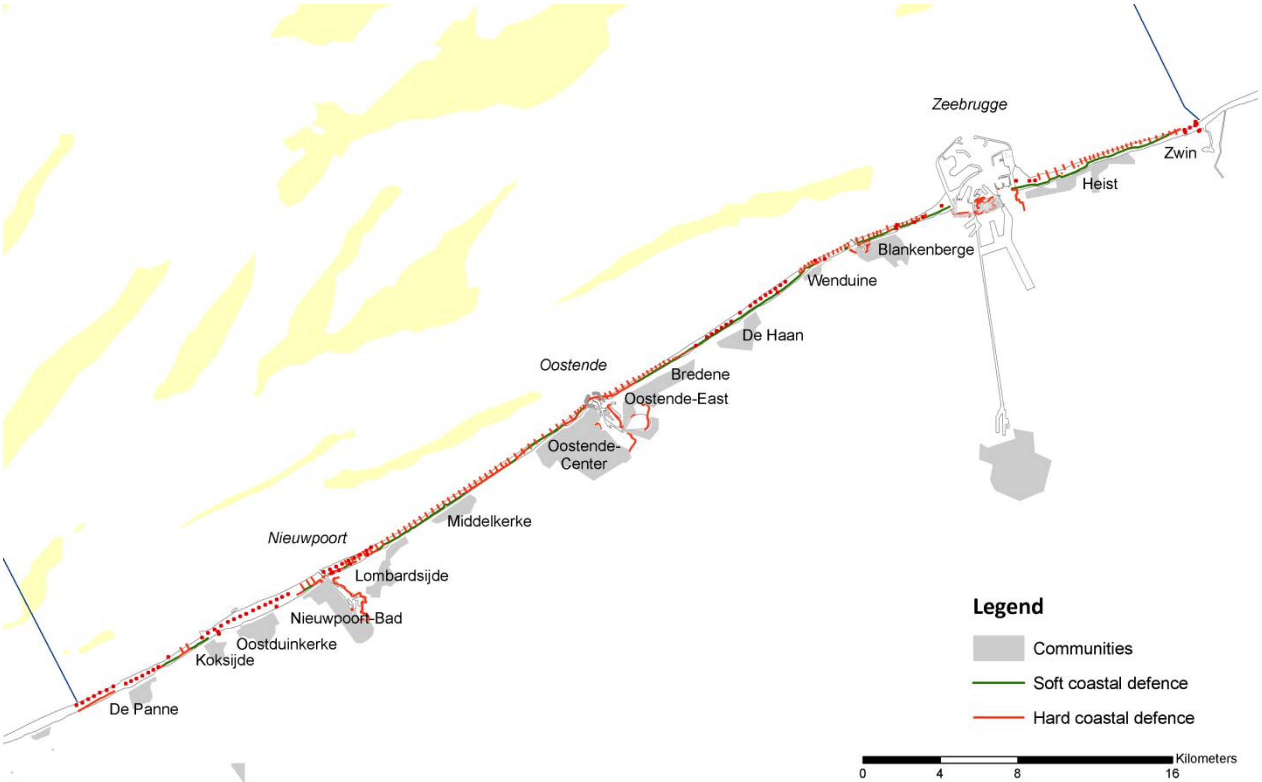

Figure 5: Hard and soft coastal defence structures along the Belgian coastline (shapefiles from (Belpaeme & Konings 2004)

There is some debate as to the most effective nourishment position to achieve optimum protection. Possible locations include the upper beach and dune face (i.e. backshore nourishment), the intertidal beach (i.e. beach or profile nourishment) and the shallow foreshore zone (i.e. foreshore nourishment). Backshore nourishment benefits are immediate, but if the sediment is primarily sand, it will be rapidly redistributed along-shore or across the beach face by waves and currents to form a new equilibrium profile (Greene 2002). Beach nourishment anticipates this redistribution, and provides shoreline protection by helping to dissipate wave energy before it reaches the dunes. Foreshore nourishment also anticipates the gradual redistribution of sand into the beach system but the technique is mostly used in areas where coastal protection measures have steepened the coastal profile or in areas with a long-term sediment deficit. Periodic **beach nourishment** has rapidly become a widely applied protective measure worldwide, for both short-term emergencies (i.e. storm-induced erosion) as well as long-term issues (i.e. structural erosion and sea level rise). It is generally considered as the less harmful beach management option because it safeguards the natural dynamics of the coast (Hamm et al. 2002). Beach nourishment projects can be augmented with dune construction and hard structures to provide a desired level of protection at the site (Greene 2002). In 1956, Belgium undertook the largest beach nourishment project in the world at that time on the beach of Knokke (De Moor & Bloome 1988). Since then, the entire Belgian coastline is regularly nourished to physically maintain and safeguard its beaches. Unfortunately, there are no reliable data available to provide an overview of the whereabouts or regularity of the multiple nourishment projects performed since 1956. Acute and maintenance nourishment projects are performed on a regular basis on several Belgian beaches but the information concerning these projects remains poorly documented. The problem lies with the defragmentation of duties and responsibilities along the Belgian coastline with information scattered between coastal communities, local governments, the Flemish and Belgian government (prior to federated Belgium). Figure 5 gives an overview of the current position of several hard and coastal defence structures. On 10 June 2011, the Flemish government approved The Integrated Coastal Safety Plan. This plan contains a series of measures and alternatives to be taken between now and 2050, guarding against the danger of a superstorm and preventing present and future flooding (Mertens et al. 2008). For the next years, Belgian beaches will thus face a multitude of coastal defence activities, including large-scale long-term beach nourishment projects.

However, being an impact, beach nourishment does put a pressure on the biota living on, in and around sandy beaches (Speybroeck et al. 2006a). Peer-reviewed impact studies and adequate information on the consequences of nourishment however are scarce (Jones et al. 2008; Leewis et al. 2012; Schlacher et al. 2012). It remains difficult to predict the impact of nourishment on the beach ecosystem and to suggest possible ecological adjustments to nourishment projects. Species and their habitat could be impacted directly, indirectly or even via cumulative effects in a number of different ways including direct mortality, sublethal impairment and degraded habitat (Essink 1999; Greene 2002). The ecological effects of nourishment can generally be divided into three main groups (Speybroeck et al. 2006a): effects related directly to aspects of the construction phase of the nourishment project (1) and effects related to quality (2) or quantity (3) characteristics of the nourishment sediment (figure 6). Sand for beach nourishment operations is mostly obtained near shore or offshore although nearby channel dredging can also provide the necessary sediment. The total impact effect is influenced by place, time and size of the nourishment project next to the chosen nourishment technique and strategy.

Greene (2002) stressed the possibility of temporal and spatial cumulative effects and the synergisms between them both. Since nourishment is a temporary solution, periodic long lasting additions of sand every three to ten years are constantly required to maintain the width of the beach (Grober 1992). Currently, little is known of the physical and ecological effects of these repeated nourishment projects but they can initiate compaction of the beach sediment, long term elevated turbidity and permanently altered sediment composition and beach morphology. The combined effects of simultaneous nourishment projects along an entire coastline should be considered as well. Several short projects are advised over long lasting huge ones, especially in areas where short term morphological changes are unpredictable (Adriaanse & Coosen 1991; Löffler & Coosen 1995; Peterson et al. 2000).

Furthermore, interpretation of nourishment study results must be done with caution. Natural disturbances, like storms, spatial patchiness and natural variability of sandy beach organisms complicate analyses of beach nourishment impacts (Hamm et al. 2002; Hanson et al. 2002; McLachlan & Dorvlo 2005). Natural variation in temperature, salinity, wave climate and weather can mediate changes in benthic diversity, possibly masking or preventing detection of nourishment effects (Greene 2002). Subsequently, most beach nourishment studies could not differentiate natural variation from nourishment impacts (Reilly & Bellis 1983; Peterson & Manning 2001; Van Dalfsen & Essink 2001; Greene 2002; Hamm et al. 2002; Hanson et al. 2002; Wilber et al. 2003; Kuang et al. 2011). It is also important to clearly state and define the term 'recovery' within this context. Full recovery should be defined by (long-term) biological, ecological and physical processes controlling recolonization and succession. The time scale for achieving populations similar to those found prior to nourishment is in any case at least one year, mainly due to pronounced discontinuities in distribution of populations and seasonal fluctuations (Leewis et al. 2012; Schlacher et al. 2012). Benthic recovery will depend on the nourishment survival rate of already present organisms, migrating and recolonizing capabilities of adults and recruitment of young stadia of nearby populations through dispersal. One might consider a benthic community to be recovered when at least 80 % of the species diversity and biomass has been restored (Essink 1999). One should bear in mind that biomass recovers at a more rapid rate than the diversity of species (Adriaanse & Coosen 1991) and pioneer populations, such as polychaetes and other annelid worms, may temporarily exceed the original populations in numbers of individuals and diversity. The severity of the temporary disruption caused to birds and seals is dependent on their activities during the nourishment period as well as on their reliance degree on the nourishment areas. In general, it is assumed that human activities disturb birds within a 500 m radius and seals within a 1500 m radius (Adriaanse & Coosen 1991). Little remains known of recovery rates, overall ecological effects, effects on subtidal communities, large-scale and long-term effects, preferably studied over several seasons and years (Greene 2002). In combination with insufficient baseline data, these knowledge gaps hinder conclusive measurement of beach nourishment effects beyond one year (Grober 1992).

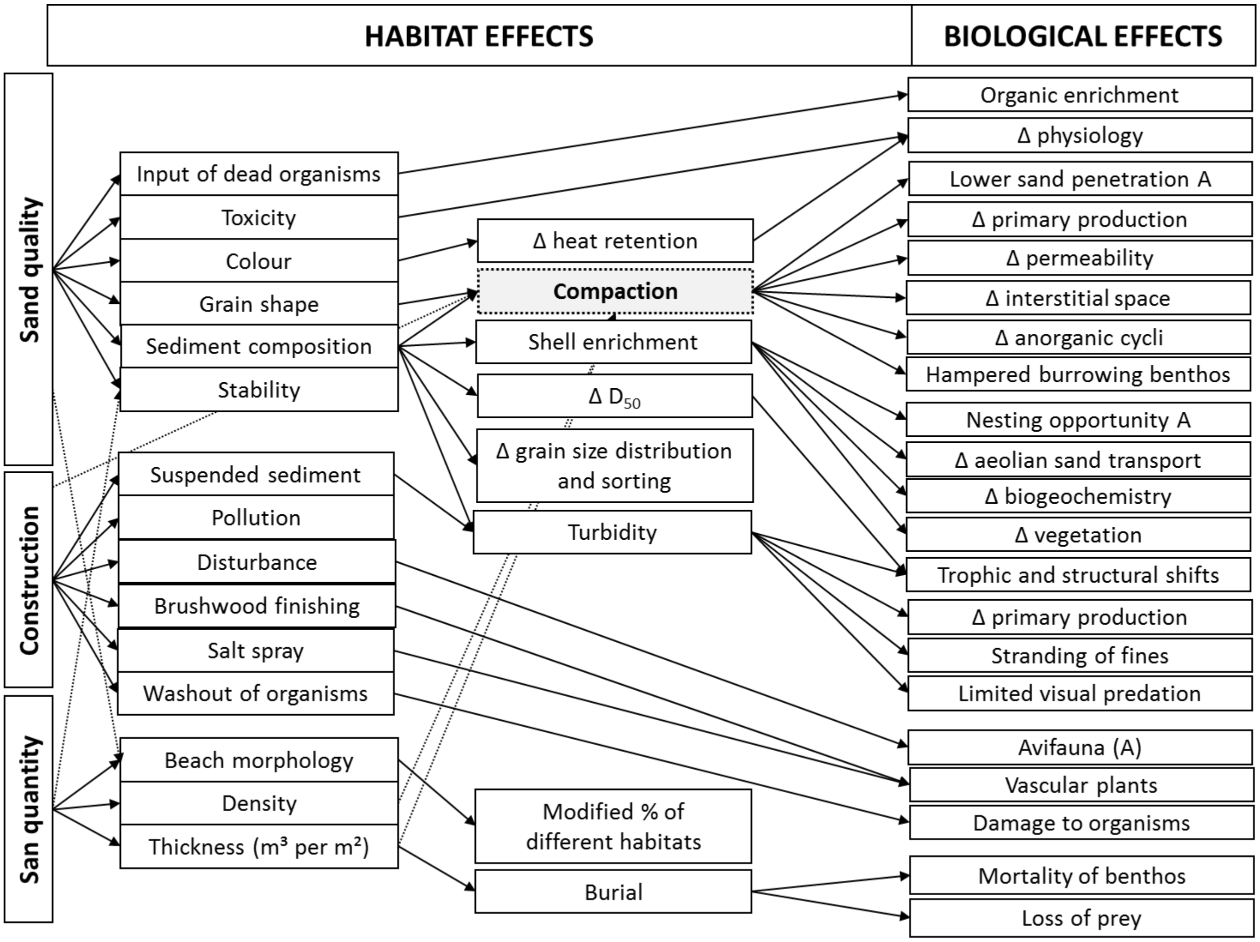

Figure 6: Integrated network of the ecological effects of beach nourishment (Speybroeck et al. 2006a)

4.2 Guidelines for ecologically good practice of beach nourishment along the Belgian coastline

Speybroeck (2006) formulated general guidelines for an ecologically good practice of beach nourishment. From a technical point of view coarser grain sizes produce a steepe, more stable and longer lived nourishment (Finkl 2002). However, to limit the ecological impact, nourishment sands with a **comparable sediment composition** to that of the natural sediment should be used, to allow swift recovery of the benthic fauna (Parr et al. 1978; Nelson 1993; Löffler & Coosen 1995; Peterson et al. 2000) and to avoid a sharp transition from dissipative to reflective beaches (Anfuso et al. 2001). While the impact of sediment color is largely unknown it seems precautionary to use sands with the **same color** as the original sediment. **Toxic substances** should be absent (Adriaanse & Coosen 1991). The preferred time of nourishment is entirely site-specific, depending on the nature and location of the beach and the species inhabiting or exploiting it (Speybroeck et al. 2006a). Spring and early summer provide for least restricted work windows and the nourishment has the greatest chance to stabilize before winter storms start to erode and redistribute the beach. When aiming at a minimal ecological impact in mesothermic zones of the northern hemisphere, nourishment should be completed within a **single winter**, starting after October and ending around March. A number of **smaller projects** (<800 m in length of shore) is preferred over a single large nourishment project (Adriaanse & Coosen 1991; Löffler & Coosen 1995; Peterson et al. 2000). The short distance between nourished and unnourished beach strips allows swift recolonization, depending on species-specific dispersal capacities. Planktonic larvae can disperse over distances well beyond 1000 km. Unfortunately, dispersal distances of permanent meiofauna are limited to 10 km and postlarvae and juveniles are restricted to 10 m. Adult macrobenthos can cover only 1 m or less so their dispersal capacities are very low (Günther 1992). Most benthic species will be less seriously affected if **sediment deposition** is restricted to 0.2 to 0.3 m. No clear best choice can be made among backshore, beach and foreshore nourishment. It seems advisable to decide on the **nourishment technique** in respect to the local natural values of the beach ecosystem. Each strategy has its major impact on a different part of the beach. Choices will have to be made in view of the vulnerability of the organisms residing in each beach zone. Moreover, nourishment needs to be as **cost-effective and efficient** as possible. Costs for a nourishment scheme depend on the source of material, transport methods, volumes required, the need for hard control structures, like groins and breakwaters, the need for secondary defences, expected scheme life before topping up and the amount of minor works undertaken to enhance the dune system (Charlier et al. 1998). Hence, it is indispensable to strive for ecological and economic beach nourishment projects.

5. Governance in the Belgian coastal zone

In the Belgian coastal zone, different government levels exercise competences, including international institutions, the federal government, the Flemish Region, the Province of West Flanders and ten coastal municipalities (figure 7). The federal and regional responsibilities are exclusive, having legal responsibilities only within their precise geographical boundaries, and equivalent with no hierarchy between the standards issued by each group (Cliquet et al. 2007; Cliquet & Decleer 2007). This complex institutional context can cause substantial problems through overlap, conflicts and gaps (Cliquet 2001; Maes et al. 2005b; Douvere 2008). The federal government has jurisdiction over the entire BPNS, including the Exclusive Economic Zone (EEZ, more than 12 nautical miles) and the Territorial Sea (between the MLW and 12 nautical miles). Within this regard, the shallow subtidal coastal zone (between MLW and 1 nautical mile) falls under federal jurisdiction. Federal competences include, among others, environmental policy and protection of the marine environment, wind farms at sea, shipping, military activities, aggregate extraction, cables and pipelines. The Flemish regional authority governs the inland territory, estuaries and inland waters, and the coastal waters above the MLW, including the intertidal coastal zone. The Flemish Region is competent for policy areas such as nature policy on the beach and the hinterland, recreation, ports, fishing, dredging, piloting and coastal defence (Cliquet 2001; Maes et al. 2005b; Cliquet et al. 2007). Within the BPNS, the environmental policy competences are thus shared between the federal and regional levels (Herrier et al. 2005). Dialogue is vital to ensure that Belgium speaks with a single voice within numerous international organisations and bodies (Cliquet et al.

2010). This is the prime task of the steering group on seas and oceans of the Coordination Committee for International Environmental Policy (CCIEP 1995) (Cliquet 2001; Cliquet & Maes 2001). On a day-to-day basis, this group is steered by the Directorate General for the Environment at the Federal Public Service. Specifically for the Belgian coastal zone, the Coordination Centre for Integrated Coastal Zone Management encourages and promotes sustainable and integrated management by allowing a platform to discuss cross-sectorial themes between the federal, Flemish and provincial policy levels (Cliquet 2001).

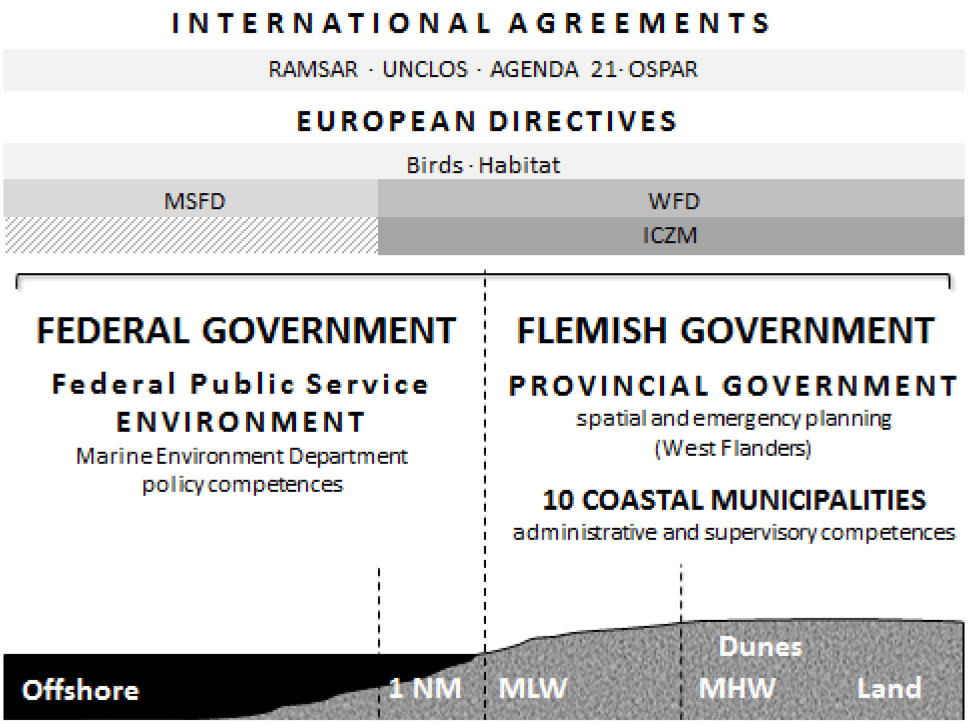

Figure 7: Coastal legal system in Belgium; 1NM: 1 nautical mile; MLW: mean low water level; MHW: mean high water level; WFD: Water Framework Directive, MSFD: Marine Strategy Framework Directive; ICZM: Integrated Coastal Zone Management (Laporta 2012)

Some of the most important international expectations and obligations in Belgium are to be found in the Convention on Biological Diversity, the Ramsar and OSPAR Conventions, the combined Birds (BD) and Habitats Directive (HD) (Natura 2000), the Water Framework Directive (WFD), the Marine Strategy Framework Directive (MSFD) and the Integrated Coastal Zone Management Directive (ICZM) (see Appendices – Chapter 1 for a more detailed description). On 13 March 2013, the European Commission launched a proposal to improve the planning of maritime activities at sea and the management of coastal areas (Commission 2013a). The proposal now takes the form of a draft directive and it will aim to establish a common European framework for maritime spatial planning and integrated coastal management in EU Member States, with a view to ensure that the growth of maritime and coastal activities and the use of resources at sea and on coasts remain sustainable. The Commission proposal will be considered by the Council of the European Union and the European Parliament. Once adopted, the new initiative will become EU law. In Belgium, a public consultation of the draft directive runs from 2 June 2013 to 29 September 2013 includingly.

In order to meet these international obligations, Flanders drafted the Decree on the Protection of Coastal Dunes (1993) and the Decree concerning Nature Conservation and Natural Environment (1997) (Herrier & Killemaes 2001). The main purpose of these Decrees was to protect the diversity in habitats and species and the entire dune environment with its natural characteristics. Up to that point, the ever expanding construction and urbanization of the Belgian coastline, also known as the Atlantic Wall, threatened to destroy the entire Belgian dune ecosystem. According to the Decrees, designated dune areas have to be at least 2 ha, with a high biological value or they should be deemed irreplaceable areas on the basis of their shape and geomorphological characteristics. A construction ban in the dunes was implemented with nature conservation and coastal defence as its only conceptions.

In 1999, the law of the protection of the marine environment in sea areas under Belgian jurisdiction (Wet Marien Milieu, MMM, in 1999, amended in 2005) established the legal basis for the conservation, restoration and development of nature and the protection of the BPNS against sea-related pollution (Maes et al. 2005b). The general principles of environmental law are summarized in this important act:

(1) prevention principle: prevention is better than cure;
(2) precautionary principle: preventive measures must be taken if there are grounds for concern regarding pollution;
(3) principle of sustainable management: human activities must be managed in such a way that the marine ecosystem remains in a condition which ensures the continued use of the sea;
(4) polluter pays principle: the costs of measures to prevent and fight pollution are to be borne by the polluter;
(5) principle of restoration: if the environment is damaged or disrupted, the marine environment must be restored to its original condition as far as is possible; and
(6) principle of objective liability: the party having caused the damage to or disruption of the environment in sea areas as a result of an accident or an infringement of the law is obliged to remedy this, even if they are not at fault.

In addition, the MMM law established the basis for creating five types of marine reserves: (1) integral marine reserves, (2) specific marine reserves, (3) Special Protection Areas (SPAs) and Special Areas of Conservation (SACs), (4) closed zones for certain activities all year or part of the year and (5) buffer zones in which the restrictions on the activities are less strict than in the marine reserves. For each designated marine protected area, a policy plan must be drawn up (Cliquet et al. 2007). Before and during activities requiring a permit, there is a general obligation to prepare a report on the environmental effects (at the initiative of the applicant) and to undertake environmental assessment (carried out by the government).

The following implementing decrees have been issued in the context of the MMM act:

(1) Royal Decree of 12 March 2000 on the procedure for dumping certain substances and materials in the North Sea (Belgian Official Journal of 4 April 2000);
(2) Royal Decree of 21 December 2001 on the protection of species (Belgian Official Journal of 14 February 2002): complete protection of sea mammals and offshore seabirds (Table 2);
(3) Royal Decree of 7 September 2003 on the procedure for permits required for certain activities in sea areas (Belgian Official Journal of 17 September 2003);
(4) Royal Decree of 9 September 2003 on the assessment of environmental effects (Belgian Official Journal of 17 September 2003);
(5) Royal Decree of 8 July 2005 on the simplified procedure for assessment of environmental effects (Belgian Official Journal of 14 July 2005);
(6) Royal Decree of 14 October 2005 on the installation of special protection areas and special zones for nature conservation (Belgian Official Journal of 31 October 2005), i.e. Natura 2000;
(7) Royal Decree of 14 October 2005 on the conditions for community agreements concerning special protected marine areas (Belgian Official Journal of 31 October 2005);
(8) Royal Decree of 5 March 2006 on the establishment of a focused marine reserve in the sea areas under the Belgian jurisdiction and amending the Royal Decree of 14 October 2005 imposing special protection areas and special areas for conservation in marine areas under the jurisdiction of Belgium (Belgian Official Journal of 27 March 2006);
(9) Royal Decree of 23 June 2010 on the establishment of a framework for achieving good surface water status (Belgian Official Journal of 13 July 2010), i.e. Water Framework Directive;
(10) Royal Decree of 23 June 2010 on a marine strategy for the Belgian marine areas (Belgian Official Journal of 13 July 2010), i.e. Marine Strategy Framework Directive;
(11) Royal Decree of 20 July 2012 on the drafting of a marine spatial plan for the BPNS, excluding the intertidal zone. This plan will organize all spatial and temporal human activities based on a long term vision and clear economic, social and ecological objectives (Belgian Official Journal of 28 November 2012).

More recently, the Flemish Decree on the establishment of the updated monitoring of the water status pursuant to Article 67 and 69 of the Decree of 18 July 2003 relating to the integral water policy was drafted on 26 April 2013 and published on 23 July 2013.

To the present day, there is still no comprehensive legal framework or code specific for the whole Belgian coastal zone nor for either its marine (the federal level) or land part (the Flemish level). There are even no legal instruments on the integrated management of the coastal zone. However, the Belgian federal government is working on a marine spatial plan (as stated in the Royal Decree of 20 July 2012).

6. Current coastal governance status in Belgium and Flanders

In the BPNS, excluding the intertidal zone, Belgium currently counts one SAC (Vlaamse Banken), one contested SAC (Vlakte van de Raan), 3 SPAs (Western coast, Poldercomplex and Zwin), one integral marine reserve (Baai van Heist) and one Ramsar site (Vlaamse Banken) (figure 8) (Cliquet & Decleer 2007; Cliquet et al. 2010). In the coastal zone, including the intertidal and supralittoral zone, Flanders designated five SPAs (Westkust, IJzermonding, Poldercomplex, Kustbroedvogels Zeebrugge-Heist and Zwin), two SACs (Polders and Duingebieden, including Ijzermonding and Zwin), two beach reserves (Baai van Heist and Ijzermonding), two Ramsar sites (Zwin and Ijzermonding) and scattered protected dune areas, mostly incorporated in the SACs (figure 8) (Decleer 2007; Degraer et al. 2010).

For Belgium and Flanders, the annexes to the HD and BD list 16 marine and coastal habitat types (table 2). Different federal and Flemish jurisdiction recognize some level of protection for 17 coastal seabirds, 5 sea mammals, 2 bats, 6 fish, 2 reptiles, 2 amphibians, 2 invertebrates and 2 plants (table 3). Under the Natura 2000 obligation, Flemish and Belgian conservation objectives and measures (regional; G-IHDs) have been drafted to represent the reference situation of its threatened habitats and species (Degraer et al. 2009; Regeringsbesluit 2010). For each SPA and SAC, a set of fine-tuned measures (site-specific; S-IHD) and a management plan are to be drafted.

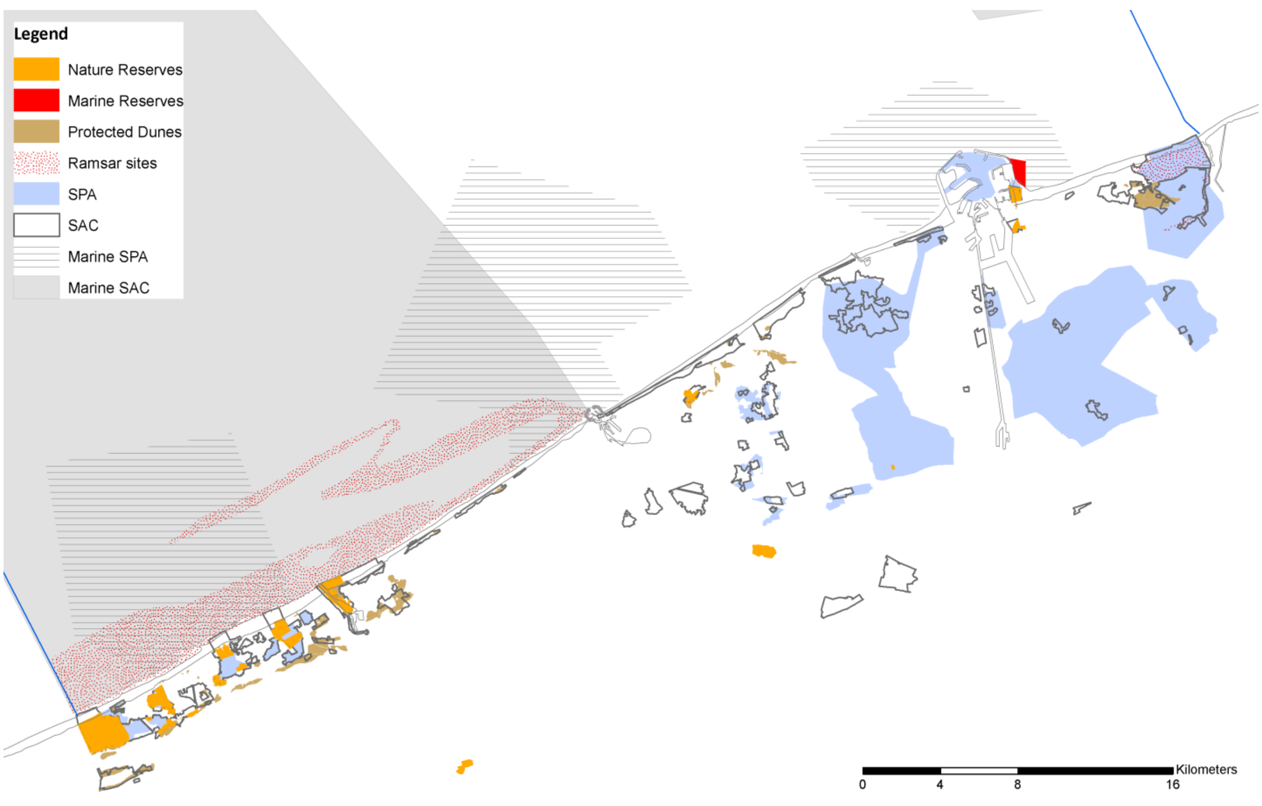

Figure 8: Protected areas along the Belgian coastline, both under federal and Flemish jurisdiction

Table 2: Overview of marine and coastal habitat types in Belgium and Flanders, according to the Habitat Directive

Habitat Directive code	Habitat description
1110	Sandbanks which are slightly covered by sea water all the time
1130	Estuaries
1140	Mudflats and sandflats not covered by seawater at low tide, including sandy beaches
1170	Reefs
1310	Salicornia and other annuals colonizing mud and sand
1320	Spartina swards *Spartinion maritimae*
1330	Atlantic salt meadows *Glauco-Puccinellietalia maritimae*
2110	Embryonic shifting dunes
2120	Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)
2130	Decalcified fixed dunes with fixed coastal dunes with herbaceous vegetation (grey dunes)
2150	Atlantic decalcified fixed dunes (*Calluno-Ulicetea*)
2160	Dunes with *Hippophaë rhamnoides*
2170	Dunes with *Salix repens ssp. argentea* (*Salicion arenariae*)
2180	Wooded dunes of the Atlantic, Continental and Boreal region
2190	Humid dune slacks
3140	Hard oligo-mesotrophic waters with benthic vegetation of Chara spp.

Table 3: Overview of Belgian coastal species protected under different federal and Flemish jurisdiction

MMM	Scientific name	Common name	Natura 2000	Scientific name	Common name
Reptiles	*Caretta caretta*	Loggerhead sea turtle	Bats	*Myotis mystacinus*	Whiskered bat
	Chelonia midas	Green sea turtle		*Plecotus auritus*	Brown long-eared bat
Fish	*Acipenser sturio*	European sea sturgeon	Birds	*Caprimulgus europaeus*	European nightjar
	Alosa alosa	Allis shad		*Charadrius alexandrinus*	Kentish plover
	Alosa fallax	Twait shad		*Ciconia ciconia*	White Stork
	Coregonus oxyrhynchus	/		*Dendrocopos medius*	Middle spotted woodpecker
	Lampetra fluviatilis	European river lamprey		*Egretta garzetta*	Little egret
	Petromyzon marinus	Sea lamprey		*Larus melanocephalus*	Mediterranean Gull
Mammals	*Halichoerus grypus*	Grey seal		*Larus minutus*	Little gull
	Lutra lutra	European otter		*Lullula arborea*	Woodlark
	Phoca vitulina	Harbour seal		*Luscinia svecica*	Bluethroat
	Phocoena phocoena	Harbour porpoise		*Nycticorax nycticorax*	Black-crowned night heron
	Tursiops truncatus	Atlantic bottlenose dolphin		*Pernis apivorus*	European honey buzzard
				Platalaea leucorodia	Eurasian Spoonbill
Natura 2000	Scientific name	Common name		*Podiceps cristatus*	Great crested grebe
Plants	*Apium repens*	Creeping marshwort		*Recurvirostra avosetta*	Pied avocet
	Liparis loeselii	/		*Sterna albifrons*	Little tern
Invertebrates	*Vertigo angustior*	Narrow-mouthed whorl snail		*Sterna hirundo*	Common tern
	Vertigo moulinsiana	Desmoulin's whorl snail		*Sterna sandvicensis*	Sandwich tern
Amphibians	*Triturus cristatus*	Great Crested newt			
	Epidalea calamita	Natterjack toad			

Regarding the WFD, only the Federal River Basin District Management Plan (RBMP) for the coastal waters falls within the scope of this PhD. Based on the existing monitoring of the OSPAR Convention, a total of six monitoring sites are regularly surveyed for hydromorphological parameters and biological (macrobenthos and phytoplankton: chlorophyll a and *Phaeocystis*) and abiotic Quality Elements (oxygen, salinity, pH and nutrients: e.g. dissolved inorganic nitrogen DIN and phosphorus DIP). No heavily modified or artificial water bodies have been designated in this RBMP. The Program of Measures lists and defines in general terms the current and future basic and supplementary measures necessary to improve the ecological and chemical status of the RBMP. Even specific supplementary measures are included for those water bodies likely to fail in the achievement of the environmental objectives by 2015. Within the scope of ICZM, Belgium has pioneered with the development and implementation of a set of 24 coastal sustainability indicators by broad public participation (Maelfait et al. 2006; Maelfait & Belpaeme 2007; Maelfait & Belpaeme 2009). The implementation of the MSFD in Belgium showed a lot of progress in 2012. Next to an initial assessment and a socio-economic analysis of the Belgian marine waters (subtidal waters, MLW to offshore), the 'Good Environmental Status (GEnvS) and defined environmental targets were described. A monitoring program (2014) and a measures program (2016) should be drafted in the near future. To meet all these EU directives, Belgium is trying to unify the regional conservation objectives and measures (G-IHDs, Natura 2000), good ecological status (WFD) and good environmental status (MSFD).

7. Aims of the PhD thesis

The overall aims and underlying research questions of this PhD study are:

(1) to investigate the *in situ* impact effects of an ecological beach nourishment on the macrobenthos of Belgian sandy beaches

   a. What is the natural spatial and temporal macrobenthic variability within the Belgian beach ecosystem and what are the main macrobenthic zonation patterns on Belgian sandy beaches?
   b. What is the relationship between relevant abiotic factors, such as beach elevation, sediment structure, total organic carbon and total organic matter, and the macrobenthos on Belgian sandy beaches?
   c. What are the *in situ* effects of ecological beach nourishment on macrobenthos?
   d. What sediment type can be recommended for use in beach nourishment projects, based on the sediment preference of the four dominant macrobenthic species (*Scolelepis squamata, Eurydice pulchra, Bathyporeia pilosa and Bathyporeia sarsi*) of the Belgian sandy beaches?

(2) to use this knowledge in order to provide protocols and tools for managing the Belgian beach ecosystem in a sustainable way, such as:

   a. a prediction model, based on the relationship between abiotic factors and the occurrence of benthos, birds, fish and shrimp.
   b. a biological valuation analysis of the intertidal and shallow subtidal Belgian coastal zone and an exploration of its applications for marine spatial planning of two space-use conflicts at the Belgian coast, being flood protection, by means of beach nourishment, and nature conservation.
   c. a series of guidelines based on scientific results from monitoring data, experiments, BVMs and model predictions.

In order to achieve these goals, following topics and aspects were investigated :

Examining the natural spatial and temporal variation on Belgian beaches

The natural variability and spatial patchiness of organisms on the sandy beach complicate the study and analyses of impacts on the macrobenthos. In order to understand both trends and disturbances and quantify possible impact effects against the natural fluctuations, long time series of abiotic and macrobenthic data of 16 Belgian beaches have been analysed, sampled over 14 years.

Unraveling possible impact effects of an ecological beach nourishment with monitoring data

Beach nourishment has rapidly become a widely applied coastal defence measure on Belgian sandy beaches, because it effectively safeguards the beach ecosystem against structural erosion when applied under certain ecological conditions. A Before After Control Impact (BACI) design has been set up to scientifically evaluate the *in situ* impact effects of the ecological beach nourishment on the soft sediment macrobenthos of the Belgian beach of Lombardsijde.

Protocols and tools for ecologically adjusted beach nourishment

Optimizing technical aspects of beach nourishment remains essential in order to minimize the impact effects on the natural ecology of the beaches. By means of experiments and model predictions, benthic responses to varying environmental conditions and different beach nourishment aspects can help in ecologically adjusting nourishment projects. To this end, a nourishment simulation model for the Belgian beach ecosystem has been created. The simulation model predicts short-term changes in beach macrobenthos species richness in response to changes in beach profile and grain size following beach nourishment and elucidates how these changes in community composition potentially feedback on the abundance of dominant species of higher trophic levels (birds, fish and shrimp). Furthermore, all available biological and ecological information for the shallow Belgian coastal zone was compiled for calculating an intrinsic biological value for several subzones of the Belgian beaches. These biological valuation maps (BVMs) can be used as reliable and meaningful baseline maps for spatial planning, marine policy and management approaches. These maps allow for the integration of 'natural/ecological values' at an early stage of policy development and implementation. Both model predictions and BVMs are valuable decision support tools as they represent the consequences of different management decisions in an illustrative way.

Guidelines for ecologically good practice of beach nourishment and sandy beach management

Management of sandy beaches is a multi-faceted and complex endeavor, where the interests of several stakeholders need to be combined. Based on scientific results from monitoring data, experiments, BVMs and model predictions, a series of guidelines has been provided.

8. Outline of the PhD thesis

Apart from the general introduction and discussion, this thesis is a compilation of research articles, either published or to be submitted for publication. Each chapter is therefore intended to be an autonomous part, which can be read separately from the other chapters. Inevitably, there is some overlap between the introduction and discussion sections of the different chapters but given the variety of topics, this overlap should not hinder the general readability of this PhD thesis. Cited literature is compiled in a single list at the end of the thesis. Chapter 4 has been carried out and written in close co-authorship with the first author Joke Van Tomme. Chapter 5 has a shared first authorship with Joke Van Tomme. All other chapters have the candidate as first author.

Chapter 1 (general introduction) gives an overview of the sandy beach ecosystem, illustrated by the focus habitat of this PhD, namely the Belgian beaches. Its ecosystem components, food web and threats are thoroughly discussed with a prime focus on coastal defence structures and their impact on the beach ecosystem. The current status of the governance in the Belgian coastal zone is documented to provide for a better understanding of beach spatial management in Belgium. The study described in **Chapter 2, "Assessment of the ecological characteristics of the Belgian beaches prior to the implementation of the Belgian Master Plan for Coastal Safety",** tries to describe and update our knowledge of the intertidal and shallow subtidal Belgian coastal areas on both spatial and temporal scales. For this study, data from 1997 to 2011 were analysed, encompassing 16 intertidal and 10 shallow subtidal coastal zones, sampled over 8 years in 3 different seasons. The main aims were to partition the macrobenthic variance and describe both the relationship between five abiotic factors and the macrobenthos and the macrobenthic zonation patterns. In **Chapter 3 "The monitoring of 'ecological' beach nourishment on macrobenthos, within a Special Area of Conservation (SAC) along the Belgian coast"**, a Before After Control Impact (BACI) design was set up to scientifically evaluate the possible impact effects of the ecological beach nourishment on the soft sediment macrobenthos of the Belgian beach of Lombardsijde. The information in Chapter 2 is used as a broad reference scale against which possible impact effects can be measured. Beach nourishment typically alters the sediment grain size and beach profile of the nourished beach. **Chapter 4**, titled **"Macrofaunal sediment selectivity considerations for beach nourishment programmes"**, examines the sediment preferences of Belgian sandy beach macrofauna both in single-species and combined-species conditions. This information can help in adjusting the technical beach nourishment aspects to minimize ecological impact.

Since beach nourishment has become generally applicable on Belgian beaches, and an ecosystem based management is indispensable, information on the response of the complete sandy beach ecosystem to the altered physical environment is needed. Therefore a model was developed in **Chapter 5, "Assessing the impact of beach nourishment on the intertidal food web through the development of a mechanistic-envelope model"**, predicting responses of all ecosystem components after nourishment using both the available knowledge and knowledge obtained in this PhD study. As different scenarios can be tested in this model, optimizing various technical aspects of beach nourishment will be one of the model's main advantages. In **Chapter 6, "Marine biological valuation of the shallow Belgian coastal zone: a space-use conflict example within the context of marine spatial planning"**, we used the marine biological valuation method in order to assess the marine biological value of the shallow Belgian coastal zone for the support of ecosystem-based marine spatial planning. The resulting biological valuation maps were then used to explore the applications of BV on two space-use conflicts at the Belgian coast, mainly flood protection, by means of beach nourishment, and nature conservation. **Chapter 7, "An ecosystem approach towards Belgian coastal policy",** is a general discussion. The conservation goals of sandy beaches are given from a biologist's perspective and translated towards beach nourishment recommendations and policy guidelines for an ecosystem-based, integrated sandy beach management.