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## Sand, rarer than one thinks

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Sand and gravel are mined world-wide and account for the largest volume of solid material extracted globally. Formed by erosive processes over thousands of years (John, 2009), they are now being extracted at a rate far greater than their renewal. Furthermore, the volume being extracted is having a major impact on rivers, deltas and coastal and marine ecosystems (Fig. 1), results in loss of land through river or coastal erosion, lowering of the water table and decreases in the amount of sediment supply. Despite the colossal quantities of sand and gravel being used, our increasing dependence on them and the significant impact that their extraction has on the environment, this issue has been mostly ignored by policy makers and remains largely unknown by the general public.

#### 1. Why is this issue important?

Globally, between 47 and 59 billion tonnes of material is mined every year (Steinberger et al., 2010), of which sand and gravel, hereafter known as aggregates, account for both the largest share (from 68% to 85%) and the fastest extraction increase (Krausmann et al., 2009). Surprisingly, although more sand and gravel are mined than any other material, reliable data on their extraction in certain developed countries are available only for recent years (Krausmann et al., 2009). The absence of global data on aggregates mining makes environmental assessment very difficult and has contributed to the lack of awareness about this issue.

One way to estimate the global use of aggregates indirectly is through the production of cement for concrete (concrete is made with cement, water, sand and gravel). The production of cement is reported by 150 countries and reached 3.7 billion tonnes in 2012 (USGS, 2013a). For each tonne of cement, the building industry needs about six to seven times more tonnes of sand and gravel (USGS, 2013b). Thus, the world's use of aggregates for concrete can be estimated at 25.9 billion to 29.6 billion tonnes a year for 2012 alone. This represents enough concrete to build a wall 27 m high by 27 m wide around the equator.

Added to this are all the aggregates used in land reclamation, shoreline developments and road embankments (for which the global statistics are unavailable), plus the 180 million tonnes of sand

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Fig. 1. Beach sand mining in Sierra Leone.

**Table 1**

Summary of the main consequences of extraction of aggregates.

<b>Biodiversity</b>	Impacts on related ecosystems (for example fisheries)
<b>Land losses</b>	Both inland and coastal through erosion
<b>Hydrological function</b>	Change in water flows, flood regulation and marine currents
<b>Water supply</b>	Through lowering of the water table and pollution
<b>Infrastructures</b>	Damage to bridges, river embankments and coastal infrastructures
<b>Climate</b>	Directly through transport emissions, indirectly through cement production
<b>Landscape</b>	Coastal erosion, changes in deltaic structures, quarries, pollution of rivers
<b>Extreme events</b>	Decline of protection against extreme events (flood, drought, storm surge)

used in industry (USGS, 2012). Aggregates also contribute to 90% of asphalt pavements and 80% of concrete roads (Robinson and Brown, 2002). China alone built 146,400 km of road in one year (EDE, 2013) – an indication of the world demand for aggregates.

Taking all these estimates into account, a conservative estimate for the world consumption of aggregates exceeds 40 billion tonnes a year. This is twice the yearly amount of sediment carried by all of the rivers of the world (Milliman and Syvitski, 1992), making humankind the largest of the planet's transforming agent with respect to aggregates (Radford, 2005).

This large quantity of material cannot be extracted (Fig. 1) and used without a significant impact on the environment (Sonak et al., 2006; Kondolf, 1994). Extraction has an impact on biodiversity, water turbidity, water table levels and landscape (Table 1) and on climate through carbon dioxide emissions from transportation. There are also socio-economic, cultural and even political consequences. In some extreme cases, the mining of marine aggregates has changed international boundaries, such as through the disappearance of sand islands in Indonesia (New York Times, 2010; Guerin, 2003).

## 2. What are the findings?

The demand for aggregates stems from a wide range of sectors, including production of glass, electronics and aeronautics. However, its largest use is in construction (see example on Dubai in Box 1) and land reclamation (see example on Singapore in Box 2). The trend for aggregates extraction can be estimated using cement production as a proxy. This has multiplied three-fold in the last 20 years from 1.37 billion tonnes of cement in 1994 to 3.7 billion tonnes in 2012 (USGS, 2013a) mainly as a result of rapid economic growth in Asia (UNEP and CSIRO, 2011), and spurred by China's development, which in 2012 absorbed 58% of the world cement production, or 2.15 billion tonnes (Fig. 2). Five countries – China (58%), India (6.75%), the United States (2%), Brazil and Turkey – produce 70% of the world's cement (USGS, 2013c). However, cement demand by China has increased

**Box 1–Dubai**

The city of Dubai in the United Arab Emirates is among the world's most spectacular architectural developments, albeit one that has put significant pressure on marine aggregates. The Palm Jumeirah, an artificial set of sand islands (see below), required 186.5 million cubic metres (385 million tonnes) of sand and 10 million cubic metres of rock, and cost US\$12 billion (Jan De Nul group, 2013). Its own marine sand resources being exhausted, Dubai imported sand from Australia, for example, to build the Burj Khalifa tower (Delestrac, 2013), the highest building in the world at 828 m. While such development is impressive, in 2013, 31% of office space was vacant in the centre of Dubai (Jones Lang LaSalle, 2013). The Palm Jumeirah was quickly followed by a second Palm project, The Palm Jebel Ali, and then by The World islands project, a set of 300 artificial islands representing a map of the world. The World project cost US\$14 billion to construct and required 450 million tonnes of sand. Only a very small number of these islands currently host infrastructures. These land reclamation projects exhausted all of the marine sand resources in Dubai (Delestrac, 2013).



**Left:** Dubai February 2002 ASTER image. **Right:** July 2012 ASTER image. The two Palm islands and The World artificial islands required more than 750 million tonnes of sand. Images processed and analysed by UNEP/GRID-Geneva.

exponentially by 437.5% in 20 years, while use in the rest of the world increased by 59.8% (Fig. 2). Each Chinese citizen is currently using 6.6 times more cement than a U.S. citizen (USGS, 2013a). Demand continues to increase with new infrastructure and renewal of existing infrastructure (roads, bridges, dams, houses) – all dependent on the availability of aggregates.

Sand was until recently extracted in land quarries and riverbeds; however, a shift to marine and coastal aggregates mining has occurred due to the decline of inland resources. River and marine aggregates remain the main sources for building and land reclamation. For concrete, in-stream gravel requires less processing and produces high-quality material (Kondolf, 1997), while marine aggregate needs to be thoroughly washed to remove salt. If the sodium is not removed from marine aggregate, a structure built with it might collapse after few decades due to corrosion of its metal structures (Delestrac, 2013). Most sand from deserts cannot be used for concrete and land reclaiming, as the wind erosion process forms round grains that do not bind well (Zhang et al., 2006).

### 2.1. Impact on the environment

In developing countries, mining and dredging regulations are often established without scientific understanding of the consequences, and projects are carried out without environmental impact

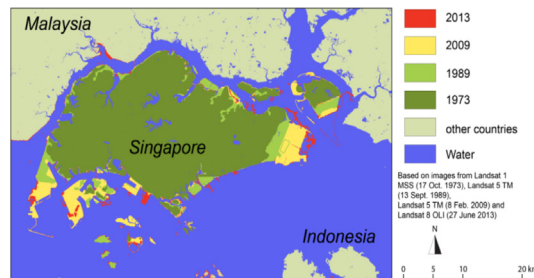
**Box 2–Singapore**

Singapore is developing rapidly and its population has increased by a factor of three since 1960, from 1.63 million to 4.84 million inhabitants in 2010. Given its small area, Singapore needed more space for its infrastructure development. To respond to this demand, the city has increased its land area by more than 20% in the last 40 years (an addition of 130 km<sup>2</sup>), mostly by using aggregates to reclaim land from the sea (see map).

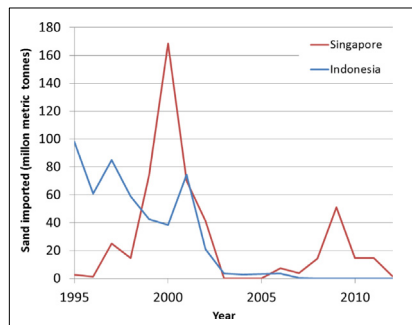
Having imported a reported 517 million tonnes of sand in the last 20 years, Singapore is by far the largest importer of sand world-wide (UN Comtrade, 2014; Aquaknow, 2014) and the world's highest per capita consumer of sand at 5.4 tonnes per inhabitant.

Sand is typically imported mostly from Indonesia, but also from the other neighbouring countries of Malaysia, Thailand and Cambodia. Export of sand to Singapore was reported to be responsible for the disappearance of some 24 Indonesian sand islands. It is reported that this triggered political tensions regarding maritime borders between the two countries (New York Times, 2010; Guerin, 2003).

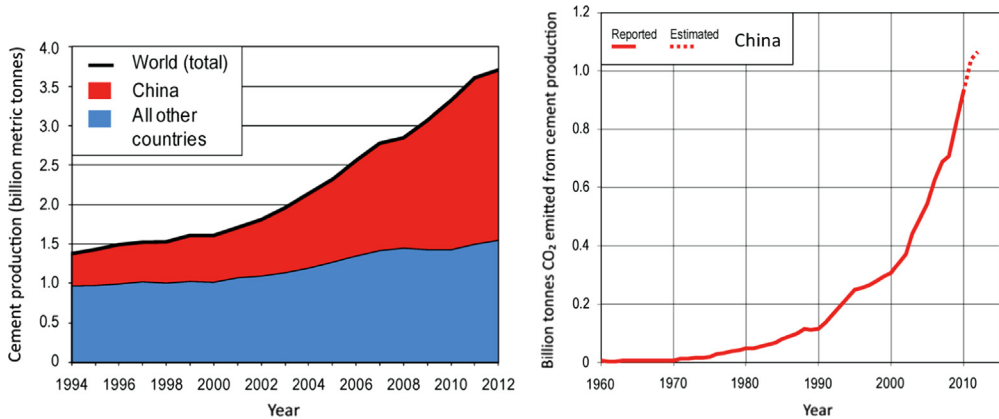
The reported sand exported from Indonesia to Singapore declined sharply since a temporary ban declared in February 2002 (Guerin, 2003). Other neighbouring countries are now reporting few exports to Singapore. Overall, the reported total amount of sand imported by Singapore (517 million tonnes) and the sum of sand exports to Singapore from its four neighbouring countries (637 million tonnes) does not match (see graph left), showing an underestimation of 120 million tonnes of sand imports. Obviously, these statistics do not include illegal imports and highlight the need for better monitoring. There is also an alleged illegal sand trade (Global Witness, 2010). As the price of sand increases, so does the traffic of sand by local mafias (Global Witness, 2010; Milton 2010; Handron, 2010). The average price of sand imported by Singapore was US \$3 per tonne from 1995 to 2001, but the price increased to US \$190 per tonne from 2003 to 2005 (UN Comtrade, 2014).



A map of Singapore shows its area increasing from 1973 to 2013. Remote sensing analysis: UNEP/GRID-Geneva.



Indonesia's reported sand exports to Singapore versus reported imports by Singapore from Indonesia in millions of tonnes. Data sources UN Comtrade 2014 (Natural sand except sand for mineral extraction, 1995–2012).



**Fig. 2.** Left: Cement production from 1994 to 2012 in billion metric tonnes. Sources: Emissions of CO<sub>2</sub> – from Cement Production (CDIAC) as in UNEP Environment Data Explorer (EDE, 2014). Right: Emissions of carbon dioxide from cement production in China.

assessments (Maya et al., 2012; Saviour, 2012). As a result, aggregate mining has affected the provision, protection and regulation of ecosystem services.

#### 2.1.1. Impact on marine biodiversity

The mining of marine aggregates is increasing significantly. Although the consequences of substrate mining are hidden, they are tremendous (Fig. 3). Marine sand mining has had an impact on seabed flora and fauna (Krause et al., 2010). Dredging and extraction of aggregates from the benthic (sea bottom) zone destroys organisms, habitats and ecosystems and deeply affects the composition of biodiversity, usually leading to a net decline in faunal biomass and abundance (Desprez et al., 2010) or a shift in species composition. Long-term recovery can occur only where original sediment composition is being restored (Boyd et al., 2005).

Aggregate particles that are too fine to be used are rejected by dredging boats, releasing vast dust plumes and changing water turbidity, resulting in major changes to aquatic and riparian (i.e. river banks) habitats over large areas (Ashraf et al., 2011).

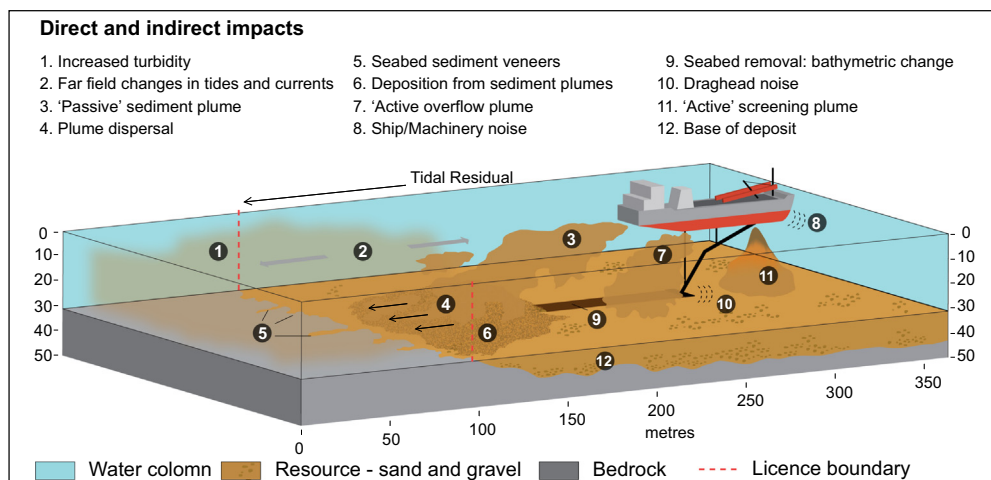
#### 2.1.2. Impact on inland biodiversity and rivers

The mining of aggregates in rivers has led to severe damage to river basins (Sreebha and Padmalal, 2011), including pollution and changes in levels of pH (Saviour, 2012). Removing sediment from rivers causes the river to cut its channel through the bed of the valley floor (or channel incision) both upstream and downstream of the extraction site. This leads to coarsening of bed material and lateral channel instability. It can change the riverbed itself (Kondolf, 1997). The removal of more than 12 million tonnes of sand a year from the Vembanad Lake catchment in India has led to the lowering of the riverbed by 7–15 cm a year (Padmalal et al., 2008). Incision can also cause the alluvial aquifer to drain to a lower level, resulting in a loss of aquifer storage (Kondolf, 1997). It can also increase flood frequency and intensity by reducing flood regulation capacity. However, lowering the water table is most threatening to water supply (Myers et al., 2000) exacerbating drought occurrence and severity as tributaries of major rivers dry up when sand mining reaches certain thresholds (John, 2009).

#### 2.1.3. Coastal and inland erosion

Erosion occurs largely from direct sand removal from beaches, mostly through illegal sand mining. It can also occur indirectly, as a result of near-shore marine dredging of aggregates, or as a result of sand mining in rivers (Kondolf, 1997). Damming and mining have reduced sediment delivery from





**Fig. 3.** Direct and indirect consequences of aggregates dredging on the marine environment. Graph adapted from Tillin et al., 2011.

ivers to many coastal areas, leading to accelerated beach erosion (Kondolf, 1997). Onshore sand mining in coastal dune systems such as those in Monterey Bay, California, in the United States, can also lead to long-term erosion, in this instance, 0.5–1.5 m a year (Thornton et al., 2006).

By 2100, global average sea level rise is expected to reach 0.26–0.55 m under the best-case scenario (of 70% reduction of greenhouse gas emissions), and nearly one metre under unabated increase in greenhouse gas emissions (IPCC, 2013a). This problem is particularly acute for small islands states, where retreat options are limited. In the Maldives, a few of the largest and highest islands, such as the capital city, Male, are being consolidated to ensure they can host the population displaced from low-lying islands. To strengthen the city, a large amount of sand is being imported to Male, to be used in building higher towers and coastal protection. The sand is taken from offshore sand islands. Paradoxically, the sands extracted for the protection measures in Male are leading to the lowering of some islands, increasing the need to relocate their populations (Delestrac, 2013).

Lake Poyang, the largest freshwater lake in China, is a distinctive site for biodiversity of international importance, including a Ramsar Wetland. It is also the largest source of sand in China (De Leeuw et al., 2010) and, with a conservative estimate of 236 million cubic metres a year of sand extraction, may be the largest sand extraction site in the world. By comparison, the three largest sand extraction sites in the United States combined represent 16 million cubic metres a year (De Leeuw et al., 2010). Sand mining has led to deepening and widening of the Lake Poyang channel and an increase in water discharge into the Yangtze River. This may have influenced the lowering of the lake's water levels, which reached a historically low level in 2008 (De Leeuw et al., 2010).

#### 2.1.4. Impact on climate

The transport of large quantity of aggregates, sometimes over long distances, has a direct impact on greenhouse gas emissions. The indirect impacts of aggregate mining come from the production of cement. For each tonne of cement, an average of 0.9 tonnes of carbon dioxide are produced (Mahasenan et al., 2003; USGS, 2012).<sup>1</sup> The Carbon Dioxide Information Analysis Center (CDIAC) estimates that 1.65 billion tonnes of carbon dioxide emissions were from cement production in 2010 alone, or nearly 5% of total greenhouse gas emissions (EDE, 2014). Total carbon emissions from cement amount to eight billion tonnes of carbon (equivalent of 29.3 billion tonnes of carbon dioxide)

<sup>1</sup> In CDIAC computation the ratio used is 0.49. However, most scientific publications are using a ratio between 0.73 and 0.99 (Mahasenan et al., 2003), or 0.87–0.92 t of carbon dioxide (USGS, 2012).

(IPCC, 2013b, p. 474) and has increased from 3% in the 1990s to 4% of greenhouse gas emissions from 2000 to 2009 (IPCC, 2013b, p.489).

## 2.2. Economic impact

Aggregates are, in most cases, a free resource, but their extraction comes at the expenses of other economic sectors and local livelihoods. Tourism may be affected through beach erosion (Kondolf, 1997), while fishing — both traditional and commercial — can be affected through destruction of benthic fauna (Cooper, 2013; Desprez et al., 2010). Agriculture could be affected through loss of agricultural land from river erosion (John, 2009) and the lowering of the water table (Kondolf, 1997). The insurance sector is affected through exacerbation of the impact of extreme events such as floods (Kondolf, 1997), droughts (John, 2009) and storm surges through decreased protection of beach fronts (Thornton et al., 2006; John, 2009). The erosion of coastal areas and beaches affects houses and infrastructure (Thornton et al., 2006; John, 2009). A decrease in bed load or channel shortening can cause downstream erosion including bank erosion and the undercutting or undermining of engineering structures such as bridges, side protection walls and structures for water supply (John, 2009; Padmalal et al., 2008).

A lack of proper scientific methodology for river sand mining has led to indiscriminate sand mining (John, 2009), while weak governance and corruption have led to widespread illegal mining (Saviour, 2012; Ashraf et al., 2011). Sand trading is a lucrative business, and there is evidence of illegal trading such as the case of the influential mafias in India (Ghosh, 2012).

In Morocco, half of the sand — 10 million cubic metres a year — comes from illegal coastal sand mining (Au fait, 2011). Sand smugglers have transformed a large beach into a rocky landscape between Safi and Essouira (Economiste, 2005; Khardijamal, 2011). Sand is often removed from beaches to build hotels, roads and other tourism-related infrastructure. In some locations, continued construction is likely to lead to an unsustainable situation and destruction of the main natural attraction for visitors — beaches themselves.

## 3. What are the implications for policy?

The lack of adequate information is limiting regulation of extraction in many developing countries (Sreebha and Padmalal, 2011). Access to data is difficult, and data are not standardised. There is limited collaboration/co-ordination between the marine scientific research establishments and the marine aggregates industry (Velegarakis et al., 2010). Except in the European Union, regulation efforts are few, especially in developing countries (Sreebha and Padmalal, 2011). Lack of monitoring systems, regulatory policies and environmental impact assessments have led to indiscriminate mining, triggering severe damage to the environment and related ecosystem services.

### 3.1. Reducing consumption of sand

One way to reduce consumption of sand is to optimise the use of existing buildings and infrastructure. Recycled building and quarry dust material can be a substitute for sand. Despite the very high value of minerals found in the sand, it is mostly used for concrete or is buried under highways. Concrete rubble should be recycled to avoid using aggregates, at least for low-quality uses (Kondolf, 1997). Recycling glass bottles would also reduce sand consumption.

Substitutes for sand are available. Khamput (2006) showed that quarry dust could be used to replace sand in general concrete structures. The replacement of sand by up to 40% of incinerator ash exhibits higher compressive strength than regular cement mortars (Al-Rawas et al., 2005). Some desert sand can be used if mixed with other material (Cisse et al., 2012; Zhang et al., 2006). There are alternatives for building houses, including wood, straw and recycled material. However, the current building industry is geared toward concrete know-how and equipment. Training of architects and engineers, new laws and regulations, and positive incentives are needed to initiate a shift for lowering our dependency on sand. Renewable and recycled materials need to be targeted for building houses and roads.



### 3.2. Tax on aggregates extraction to create incentives on alternatives

The current situation will continue unless sand extraction is correctly priced and taxed so that other options become economically viable. Despite the increasing rarity of sand, in the United States the price of sand has remained very stable, fluctuating from US\$4.50 to US\$6.7 a tonne between 1910 and 2013 (USGS, 2012).<sup>2</sup> Because sand is still very cheap — sand itself is freely accessible; only extraction costs need to be covered — there is little or no incentive to induce a change in our consumption.

Alternative sources of sand and gravel, which accumulate at the bottom of dams, can also be targeted. Their use would address the problem of these aggregates accumulating which leads to a reduced capacity of dams to store water and could result in the dams' water intakes being blocked. Dams regularly release large amounts of water to flush out aggregates. Although currently more expensive, aggregates could be extracted from the dams.

### 3.3. Reducing the negative consequences of extraction

The environmental impact of in-stream mining might be avoided if the annual bed load were calculated and the mining of aggregates restricted to that value or less (Ashraf et al., 2011). Local environments should be studied to define the limits of acceptable changes (Cooper et al., 2011; Cooper, 2013).

### 3.4. Policies

Whilst it is critical for political leaders to take appropriate measures, the mining of aggregates has not yet reached their political agenda. This is primarily because sand loss has not yet reached a level of scarcity that would threaten the economy. Few, if any, measures are being implemented (see Box 3), with the notable exception of the European Union, and the United Kingdom in particular (Velegrakis et al., 2010; Tillin et al., 2011). There is a need for regulating sand extraction in both national and international waters. Experts recommend that large-scale mining, quarrying and reclamation activities should be authorized only after sound scientific assessment shows there would be limited impact on the environment (Maya et al., 2012). Other policy actions include the introduction of scientific mining operations, followed by ecological restoration. Greater consideration of substitute and sustainable use of the resource could drastically reduce impact on the environment (Chauhan, 2010).

### 3.5. Conclusion

Sand and gravel represent the highest volume of raw material used on earth after water. Their use greatly exceeds natural renewal rates. Moreover, the amount being mined is increasing exponentially, mainly as a result of rapid economic growth in Asia (UNEP and CSIRO, 2011). Negative effects on the environment are unequivocal and are occurring around the world. The problem is now so serious that the existence of river ecosystems is threatened in a number of locations (Kondolf, 1997; Sreebha and Padmalal, 2011). Damage is more severe in small river catchments. The same applies to threats to benthic ecosystems from marine extraction (Krause et al., 2010; Desprez et al., 2010; Boyd et al., 2005).

A large discrepancy exists between the magnitude of the problem and public awareness of it. The absence of global monitoring of aggregates extraction undoubtedly contributes to the gap in knowledge, which translates into a lack of action. As this issue is truly a major emerging one, there is a need for in-depth research. The implementation of a monitoring mechanism regarding global aggregate extractions and trade would shed light on the magnitude of this issue and bridge the current data and knowledge gap (Velegrakis et al., 2010). This would also raise this issue on the political agenda and perhaps lead to an international framework to improve extraction governance, as the current level of political concern clearly does not match the urgency of the situation.

<sup>2</sup> Price translated in 1998 U.S. dollars — i.e., value is transformed to allow comparison through time regarding purchasing power and inflation. In absolute U.S. dollars, the price has doubled during this period.

**Box 3—Relevant existing policies**

Activity-based regulations and land and marine protection are the two policy frameworks that govern extraction of aggregates. Land and marine protected areas do include restrictions on extraction of aggregates within their limits. However, extractions near these protected areas can indirectly affect these sites, such as in the case of sand extraction near Poyang Lake in China (a Ramsar site), which affected the lake water level and turbidity.

No international conventions regulate the extraction, use and trade of land-based sand (sand quarry, riverine and lake aggregate). Due to operational costs, most marine aggregate extractions are carried out at short distances from landing ports and at water depths of less than about 50 m. As these activities occur close to shore, they generally are under national jurisdictions. The same applies to Exclusive Economic Zones or to the Continental Shelf, where coastal states exercise sovereign rights to explore and exploit natural resources (Radzevičius et al., 2010). Hence the need to have appropriate national policies.

Several important international conventions exist. The United Nations Convention on the Law of the Sea, 1982 (UNCLOS) provides for the delimitation of maritime zones and regulates rights and obligations in respect of usage, development and preservation for these zones, including resource mining (Radzevičius et al., 2010).

A number of regional conventions have been ratified with the aim of minimizing the impact of human activities and that include, directly or indirectly, references to aggregate exploitation. These include the Convention for the Protection of the Marine Environment of the North East Atlantic, 1992 (OSPAR Convention), the Convention on the Protection of the Marine Environment of the Baltic Sea Area, 1992 (Helsinki Convention), the Convention for the Protection of the Mediterranean Sea against Pollution, 1976, and Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean, 1995 (Barcelona Convention). However, there are no specific guidelines for the management of marine aggregates extraction under the Barcelona Convention. Others include the Convention for the International Council for the Exploration of the Sea (ICES), 1964, the Convention on Environmental Impact Assessment in a transboundary context, 1991 (ESPOO Convention), the Protocol on Strategic Environmental Assessment, 2003 (SEA Protocol), and the Protocol on land-based sources of pollution from the Convention for the Protection and Development of the Marine Environment in the Wider Caribbean Region (Cartagena Convention).

The governance is not coherent and includes several layers of regulations between national and international conventions. There are no global standards (Velegakis et al., 2010; Radzevičius et al., 2010).

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