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Megacities in the coastal zone: Using a driver-pressure-state-impact-response framework to address complex environmental problems

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A B S T R A C T

The purpose of this study was to elaborate on the role of coastal megacities in environmental degradation and their contribution to global climate change. Although only less than 4 percent of the total world's population resides in coastal megacities, their impact on environment is significant due to their rapid development, high population densities and high consumption rate of their residents. This study was carried out by implementing a Drivers-Pressures-States-Impacts-Responses (DPSIR) framework. This analytical framework was chosen because of its potential to link the existing data, gathered from various previous studies, in causal relationship. In this text, coastal megacities have been defined as cities exceeding 10 million inhabitants, situated in "near-coastal zone". Their high rates of the consumption of food, water, space and energy were observed and linked to the high performance rates of related economic activities (industry, transportation, power generation, agriculture and water extraction). In many of the studied coastal megacities, deteriorated quality of air and water was perceived, which can, in combination with global warming, lead to health problems and economic and social disturbance among residents. The extent of problems varied between developing and developed countries, showing higher rates of population growth and certain harmful emissions in megacities of developing countries, as well as more problems regarding food and water shortages, sanitation, and health care support. Although certain projections predict slowdown of growth in most coastal megacities, their future impact on environment is still unclear due to the uncertainties regarding future climate change and trajectories of consumption patterns.

1. Introduction

Coastal megacities can be viewed as a symbol of today's human pressures on coastal systems because of the environmental consequences which emerge from their development. The main objective of this study was to elaborate on the role of coastal megacities in environmental degradation and their contribution to global climate change. This research will also try to point out major governance gaps in managing the coastal megacities, as well as issues that should be considered in future research. Another important segment of this study was to examine the potential of using the driver-pressure-state-impacts-responses (DPSIR) framework in studying complex interactions between coastal megacities and the environment, as well as to elaborate on the potential benefits and limitations of using such approach. The data used in this paper originates from different sources and serves to illustrate the extent of megacities' impact on the environment.

1.1. Definition of a coastal megacity

A single definition of a coastal megacity cannot be easily derived. First, there is an inconsistency in megacities' population threshold in the literature, with megacities defined as cities exceeding 1, 8, and 10 million people (Cross, 2001). According to the United Nations (UN), megacities are defined as urban agglomerations with at least 10 million inhabitants (UN, 2008). Another dilemma is how to determine the exact distance and elevation within which megacities can be referred to as coastal. Klein et al. (2003) argue that there is always a certain degree of subjectivity present in this discussion. For

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example, Sao Paulo is usually not considered coastal because of its position (800 m above the sea level), even though it is situated less than 50 km from the coast (Nicholls, 1995). In this paper, the megacities which will be considered coastal are the ones situated in a “near-coastal zone” - area within 100 m elevation and 100 km distance from the coastline (Nicholls and Small, 2002). However, although they do not fit into a “near-coastal zone” definition, Dhaka, Kolkata and Cairo will also be considered coastal in this text, since they are directly affected by marine processes, such as a sea level rise, due to their deltaic setting.

Finally, in this study, coastal megacities are defined as cities located in an area within 100 m elevation and 100 km distance from the coastline and exceeding 10 million inhabitants. Dhaka, Kolkata and Cairo will be subjoined to this group of cities because of the features discussed above. According to these parameters, the total number of 14 coastal megacities in the world can be established for the year 2007 (Fig. 1), majority of them settled in the developing countries (countries with lower per capita income) (UN, 2008).

1.2. The driver-pressure-state-impacts-responses (DPSIR) framework

The driver-pressure-state-impacts-responses (DPSIR) framework is a tool which models the environmental processes in order to develop appropriate management responses. Its development requires an integration of social, economic and natural science information in order to understand the external forcing effects of social and economic changes, and to assess the impacts of coastal resource systems on human welfare. The DPSIR framework evolved from the pressure-state-response (PSR) model which was originally developed by the Organization of Economic Co-operation and Development (OECD) in 1993. This model was further developed by European Environmental Agency (EEA) in 1999, which led to the DPSIR model as it is known today (Jago-on et al., 2009). Since then, the DPSIR framework has been widely adopted in many environmental and coastal management studies.

The DPSIR framework starts with *drivers* or *driving forces*, which emerge from people’s needs to satisfy their primary (food, water, shelter, energy) and secondary requirements (mobility, entertainment, culture). Drivers lead to *pressures* on the environment, which are usually the result of production and consumption processes, such as an excessive use of resources and emissions into the environment. The pressures result in *state,* which represents a degree of environmental quality and it is reflected in physical, biological and chemical conditions of the environment. The changes in these conditions may have environmental and economic *impacts* on ecosystems such as altered biodiversity or reduced resource availability, and ultimately on social and economic features of the society and human health as well. *Responses* present a set of societal and policy makers’ prioritisations with the aim to reduce the undesired impacts as much as possible by affecting any part of the chain between the drivers and the impacts (Gabrielsen and Bosch, 2003; Kristensen, 2004; Rogers and Greenaway, 2005) (Fig. 2).

2. Driving forces of environmental problems related to coastal megacities

2.1. Urbanization

Although population is mainly steadily increasing in coastal megacities, this trend is much lower than it has been predicted in

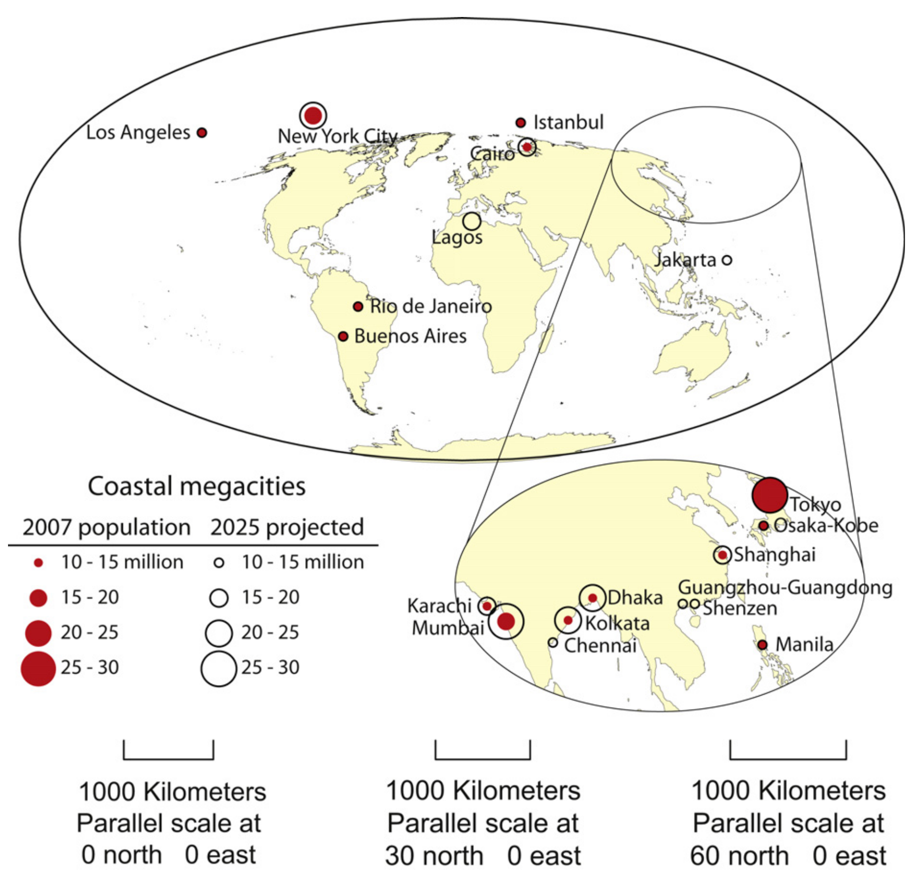

Fig. 1. Global map of coastal megacities.

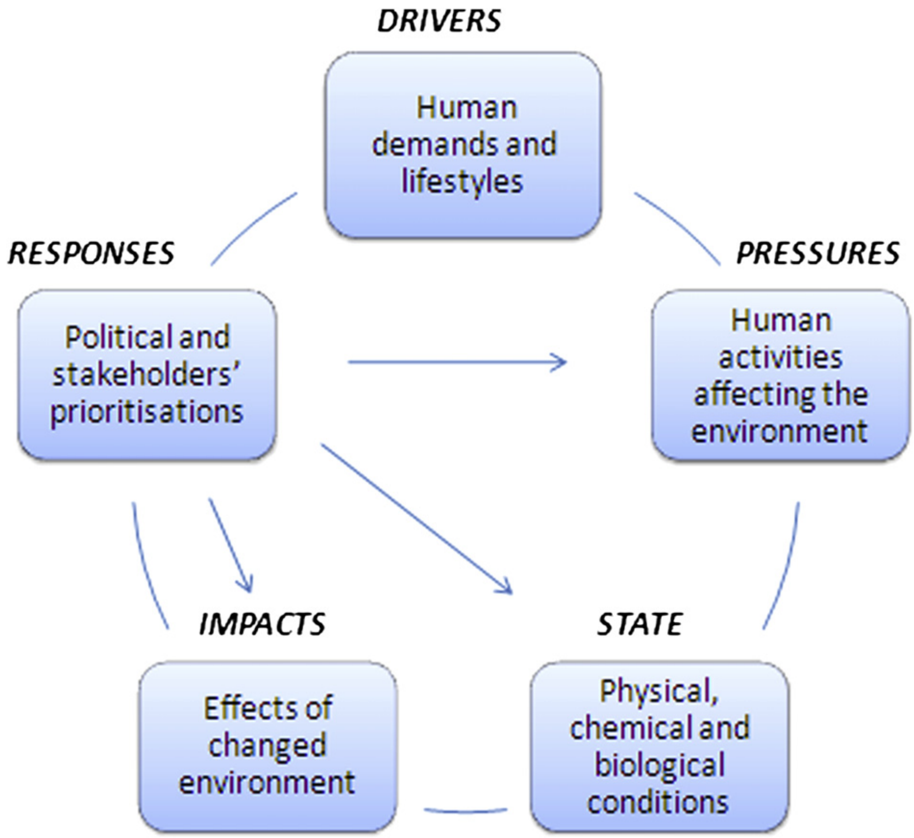

Fig. 2. The DPSIR framework scheme (adapted from Shah, 2000, page no.7).

the past. The growth trend was more prominent in the period from 1960s to 1980s, while today, although still present in most megacities, it is significantly lower (Cohen, 2004; Satterthwaite, 2005). This decline in urbanization rate has been partly related to faster-than-expected decline in the fertility rate and the ageing of population (growing number of elderly people) in less developed countries, where megacities are mainly located (Brockerhoff, 1999).

Apart from the population growth due to the positive birth/death ratio, the rural-to-urban and urban-to-urban migration can also be considered as one of the major drivers in the megacities-related DPSIR scheme. Migration towards urban areas has been traditionally directed towards coastal areas because of numerous economic opportunities and environmental amenities that coasts provide: water as an easier mean of transportation and trade, better defence positions, harbours for fishing and other fleets, and their recreational and tourist potential (Timmerman and White, 1997; Jiang et al., 2001). Big urban centres are usually perceived by migrants as potential for greater employment, education opportunities and economic advantages (including foreign capital inflow) (Brockerhoff, 1999). Recently, urban-to-urban migration is becoming increasingly important, especially in urban areas in Latin America and Africa (UN-Habitat, 2008).

Population growth and high population densities are driving megacities to expansion. The rates of expansion of coastal megacities often exceed the rates of population growth. In Los Angeles metropolitan area, the rates of population increase were 45% for the period between 1970 and 1990, while its urbanized area expanded by about 300% (Tibbetts, 2002). Urban expansion, also known as "urban sprawl", along with the construction of urban, tourism and transportation facilities, is highly related to the decrease in arable land, loss of habitat and biodiversity, and the degradation of air and water quality (Penning de Vries et al., 2002; Zhao et al., 2006).

2.2. Power generation, energy consumption and industry

Power generation and the related energy consumption (especially in the industrial and household sectors) in coastal megacities have a great impact on the environment. Different types of energy sources are predominant in different megacities: oil in Manila, natural gas in Mumbai, coal in Shanghai and Kolkata, and hydroelectric power in Los Angeles (Decker et al., 2002). Since different sources of energy tend to have different degrees of environmental degradation, coastal megacities also have different degree of environmental pressures regarding the types of fuel they predominantly use. For example, environmental degradation related to energy consumption is especially prominent in Asian megacities, because of their high dependence on coal as a primary source of energy (Guttikunda et al., 2003). Furthermore, different types of industries have different levels of energy consumption and hence, different "roles" in environmental impacts (Phdungsilp, 2006). For example, heavy industry and automobile industry consume much more energy than electronic and agricultural industry.

2.3. Urban and maritime transport

Urban transport is the main driver of air pollution in urban areas, especially in the megacities of developing countries. Although the citizens of megacities in the developed countries own considerably more vehicles than the ones in the developing countries, the number of vehicles owned in the megacities of developing countries is increasing (Decker et al., 2000; Cameron et al., 2004). In Shanghai, for instance, the number of motor vehicles increased 13-fold in the last 30 years (Decker et al., 2000). In addition, the vehicles in the developing countries are usually poorly maintained; they have highly-polluting two stroke engines and more emissions per kilometre than the ones in the developed countries (Haq et al., 2002).

Since most of the coastal megacities are harbours of global importance, maritime transport and the related construction operations are particularly significant for their development. Rapid development of megacities' harbours, especially the ones in Asia, exerts environmental pressures such as oil spills, loss of habitat, algal blooms and the introduction of alien species through the ballast waters discharge (Wolanski, 2006). Furthermore, the straightening and widening of channels, in order to provide and maintain passage for big ships, leads to alterations in hydrological and sediment flux. Apart from the degradation of coastal environment, an increased pace of maritime transport contributes to the decline in air quality through the emissions of hazardous compounds from the ships' diesel engines (Joseph et al., 2009).

2.4. Food production (agriculture, aquaculture, fisheries)

Urban populations have higher levels of food consumption and different nutrition patterns when compared to rural populations. Urban growth increases the demand for food but, at the same time, reduces the availability of arable land. Increased incomes lead to a nutrition shift in terms of greater animal protein demand, especially in certain groups of urban population (Popkin, 1999, 2001).

It is difficult to estimate the total amount of consumed food products in megacities, especially on a city basis, due to complex and diffuse production and delivery systems of food. However, Decker et al. (2000) note that the dwellers of New York consume 20,000 tons of various types of food daily. Current demand for fish and fish products is increasing as well. This is particularly significant for Asian dwellers, since Asians eat more fish per capita than the world's average (Yasmeen, 2001).

2.5. Water consumption

Urban growth patterns are closely related to an increase in water consumption and, therefore, an increase in water demand. Although the majority of megacities are situated in coastal areas and near river deltas, approximately 30% of the megacities' population lives in arid areas and around 10% in desert areas (e.g., Cairo, Karachi). These megacities will therefore likely face problems with water supply. Apart from agriculture, power generation and industry, domestic water usage is being consumed on a large scale, mainly for drinking, cooking, bathing and cleaning.

There are obvious differences between water consumption levels between the cities of developed and the developing countries. Tokyo and Osaka consume 6.96 and 2.43 million m^3 of water per day respectively, while Dhaka consumes 900 thousand m^3 of water per day (Decker et al., 2002).

2.6. Tourism

An increase in leisure time, as well as improved communication and transport systems, are closely related to an increase in tourism, accompanied by an increase in transport and the emissions of greenhouse gases (GHGs). Tourism can also be linked to some other undesired environmental impacts, especially in coastal zones, which emerge from the changes in land use (such as habitat loss), energy and water use (pollution), biotic exchange (loss of biodiversity), and exchange and dispersion of diseases (Gössling, 2002). Although many coastal megacities attract a large number of tourists with their cultural reputation (e.g., Cairo, Istanbul, New York) and leisure resorts (e.g. Rio de Janeiro), their importance as global business centres also attracts an increasing number of people for business purposes, conferences etc, also known as "business tourism" (Hall, 2000).

3. Pressures emerging from the development of coastal megacities

3.1. Solid and liquid waste, nutrient pollution and oil spills

Megacities are one of the biggest generators of domestic and industrial waste in all types and forms. Generally, coastal megacities in the developed countries generate more waste than the ones in the developing countries, but also have a much higher efficiency of waste collection. For example, Tokyo generates around 66,000 t^2/day of solid waste while Dhaka generates "only" 780 t^2/day. However, at the same time, Tokyo collects 99% of its waste while Dhaka collects only 50% (Decker et al., 2000).

Surface and groundwater reserves are particularly affected since water is a major transporter of all kinds of waste. Industrial and urban wastewaters are sources of all kinds of microbial, organic and inorganic contaminants in the nearby water bodies (Grimm et al., 2008). Poor water quality in some megacities can also be linked to agricultural activities through release of nutrients, such as nitrates (NO_3^-), nitrites (NO_2^-), ammonium (NH_4^+) into the nearby streams, which can seriously deteriorate the water quality (Clavel et al., 2008; Umezawa et al., 2008).

Regarding the oil spills, the most characteristic connection to coastal megacities is leakage from ships, mainly in the harbour areas, but also to land-based sources such as refineries, municipal wastes and urban runoffs as well. However, oil spills are mainly caused by accidental discharges and show no particular trend in occurrence (Jacinto et al., 2006).

3.2. Gas emissions into the atmosphere

Megacities are one of the largest point sources of air pollution plumes which mainly consist of large amounts of criteria pollutants, ozone precursors, aerosols and greenhouse gases, which can severely affect the atmosphere (Molina and Molina, 2004; Butler et al., 2008).

In previous publications on megacities' contribution to air pollution, in many cases, high levels of CO, NO_x, SO_2, O_3, H_2SO_4, HCOH, particulate matter, volatile and non-volatile organic compounds from domestic, industrial, energetic and other sectors were observed (Molina and Molina, 2004; Butler et al., 2008; Chan and Yao, 2008; Gurjar et al., 2008). Furthermore, increased levels of GHGs emissions such as CO_2 are expected to take place in megacities, due to higher living standards and material affluence, than in the rural areas and smaller cities (Dhakal, 2004). Indeed, the emissions in Kolkata increased from 13 to 15.2 Tg/year for the 1990–1995 period. In Manila, the total CO_2 emissions increased from 3.5 Tg/year in 1981 to about 9 Tg/year in 2000, from the electricity consumption perspective only (Imura, 2003). However, although the cities in developing countries show an increase in total CO_2 emissions, cities in the developed countries seem to be much greater contributors. For example, New York City produced 58.3 Tg/year of CO_2 in 2005 (Dodman, 2009).

3.3. Alterations of natural hydrological and sediment flux

Many diverse human activities, such as the digging of irrigation channels, building of flood-protection foundations, damming, exploitation of groundwater aquifers, development of roads, highways, airports and harbours, disrupt the natural stream and sediment flows (Rosenberg et al., 2000; Jiang et al., 2001). Synergistic effect of all these activities significantly alters the natural sediment loads and impact the local erosion/accretion rates (Zhang et al., 2006). Furthermore, an increase in building density, pavements and asphalt, related to urbanization, results in an increase of impervious surfaces. This causes major problems in case of increased runoff events and floods, since it severely changes the natural hydrology and decreases the drainage capacity (Faulkner, 2004; Grimm et al., 2008). Construction in the areas of coastal megacities does not only reflect in altered hydrological and sediment flux. Multi-story buildings in megacities increase the surface area for absorbing solar energy and reduce the heat loss due to evaporative cooling. Ultimately, this results in megacities having higher air and surface temperatures than their rural surroundings, especially at night (Grimm et al., 2008). This effect, known as the "urban heat island" (UHI), mostly affects coastal megacities with massive structures, such as Tokyo and Shanghai (Phdungsilp, 2006).

3.4. Pressures on groundwater resources

Excessive groundwater mining is not leading only to groundwater scarcity but also to environmental degradation and land subsidence, which enhances the effects of sea level rise and can result in coastal erosion (Shanahan, 2009). The majority of "hotspots" of groundwater depletion due to the over extraction were found in the areas of coastal megacities in the developing countries: Mumbai, Karachi, Kolkata, Dhaka, Manila, Buenos Aires, Cairo, Istanbul and Rio de Janeiro among others (Penning de Vries et al., 2002). In Dhaka, for example, the rates of groundwater withdrawal increased from 41.000,000 m^3/day in 1988 up to 2.272,000,000 m^3/day in 2002 (Hoque et al., 2007). For Dhaka, these pressures are particularly significant because the city's water supply is almost entirely dependent on the groundwater sources (Penning de Vries et al., 2002; Hoque et al., 2007). In Manila, groundwater extraction shows an increasing trend. In 1930, it was only 20,000 m^3/day, while in 1970 it increased to around 250,000 m^3/day. In 1981, the rate of daily groundwater withdrawal in Manila was around 913,000 m^3 (Jago-on et al., 2009).

3.5. Loss of coastal and marine habitats

Many coastal megacities grow rapidly over river deltas, leading to forest clearings, wetland draining and the destruction of salt marshes, mangroves, seagrasses and other valuable coastal habitats (Jiang et al., 2001; Tibbetts, 2002). Apart from the urban expansion of coastal megacities, the dwindling of coastal habitats is exerted by an increase in agriculture and related land amelioration. In Shanghai, more than 78000 ha of land were converted for industrial and agricultural purposes since the 1960s (Shi et al., 2001). Massive land reclamation is not only related to urban expansion and agriculture. Deforestation, for example, can be a result of increased demand for timber, while mangroves are heavily used in woodchip industry and aquaculture. The loss of seagrass meadows has also been a priority issue since the pollution and eutrophication related to urban wastewater discharge intensify the depletion of their coverage (Orth et al., 2006; Waycott et al., 2009). A great amount of land is being converted for tourism purposes as well, especially in coastal zones.

3.6. Pressures on fish stocks

The demand for fish products is increasing, especially in Asian megacities, which leads to pressures on fish stocks, especially since the fishing industry is stagnating (Yasmeen, 2001). It has been established that today the role of overfishing in determining the size of fish stock exceeds the role of environmental factors (Pontecorvo and Schrank, 2001).

Unfortunately, the data on exact fishing fleet pressures related to particular megacities is rather scarce. On a global level, the production of marine capture fisheries has increased from 19 million tons in 1950 to about 80 million tons in the mid-1980s. However, the trends in the annual rate of increase in the total catch of marine fish decreased to nearly zero percent in the 1990s (Garcia and De Leiva Moreno, 2001). This indicates that the world oceans have reached their maximal production under the present fishing regime. Increasing demands for fish and exhausted fishing potential will likely push the fish industry towards aquaculture. However, aquaculture activities can also be related to certain environmental pressures, such as mangrove loss, the introduction and transfer of invasive species, the spread of parasites and diseases, the release of chemicals, nutrients and wastes in general etc (Primavera, 2006).

4. State of the environment

4.1. Air quality and noise pollution in coastal megacities

Air quality in megacities is deteriorating because of the intensive gas emissions into the atmosphere. The data from the late 1990s showed that Dhaka and Shanghai exceeded the World Health Organisation (WHO) standards in SO_2 concentrations (50 $\mu g/m^3$); as well as in NO_2 concentrations (40 $\mu g/m^3$). The air quality regarding total suspended particles (TSP) was also deteriorated in the majority of megacities, among which Karachi, Cairo and Dhaka had very high TSP concentrations (Gurjar et al., 2008). Indoor air pollution, mostly originating from biomass and coal used for cooking and heating, represents a big problem, especially in poorly ventilated slum areas (HCSS, 2009).

Noise pollution, resulting mainly from air and especially road traffic, usually exceeds the non-hazardous levels in megacities (Murthy et al., 2001). It can result in adverse effects on human emotional and physical health (Vlahov and Galea, 2002).

Regarding the concentrations of GHGs, it is important to note that they also occur naturally in the environment and, thus, it is hard to distinguish the actual extent of the megacities' contribution. The only way to estimate the contribution of megacities would be to track the changes in the emission trends of the GHGs, which was discussed in the *Pressures* section.

4.2. Water quality in water bodies adjacent to coastal megacities

Coastal megacities often affect the water quality of adjacent water bodies (streams, ponds, estuaries, coastal water belts etc) directly through the discharge of potentially hazardous compounds or through the freshwater inflow from upstream.

Nutrient concentrations can serve as indicators of the degree of environmental change, due to the fertilizer usage in agriculture, industrial and municipal wastewater discharge, deforestation etc. In Changjiang estuary near Shanghai, concentrations of dissolved inorganic nitrogen (DIN) have increased 3-fold in the 1980–2000 period, parallel with 3-fold increase in fertilizer usage (Zhang et al., 2006). Nutrient pollution leads to an increase in eutrophication episodes, which is normally followed by a rapid increase in phytoplankton cells (also known as algal blooms), which eventually get disintegrated by bacterial activity, leading to oxygen depletion in the bottom layers (Meyer-Reil and Köster, 2000; Grimm et al., 2008). An increased occurrence of harmful algal bloom episodes has also been observed in Tokyo Bay (Furukawa and Okada, 2006), Manila Bay (Jacinto et al., 2006) and in the water bodies near Shanghai (Yeung, 2001). Apart from an increased occurrence of harmful algal blooms, the level of biological contamination can be reflected in the number of pathogens. In Mahim Bay near Mumbai, the levels of coliform bacteria reach up to 1900/l mainly because of the untreated wastewater discharges (Murthy et al., 2001).

Since industrial and domestic discharges, in combination with shipping activities and port operations, are the biggest sources of trace metals, aquatic environment near coastal megacities is particularly affected. Furthermore, organic pollutants such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) also tend to accumulate in the vicinity of urban waste discharges, such as in the case of Shanghai's coastal environment (Shi et al., 2001; Zhang et al., 2006).

Changes in aquatic ecosystems near coastal megacities can also occur due to the misbalance of some essential physic-chemical features. An increase in sea surface temperature (SST) can be a consequence of a thermal pollution; while the changes in salinity, apart from the salt water intrusion, can also be human induced – after the construction of jetties in Changjiang Estuary the salinity has increased up to 10–15 (Zhang et al., 2006).

Pressures related to coastal engineering lead to the change of natural rates of sediment deposition and altered hydrological fluxes. In Changjiang Estuary near Shanghai, the entrapment of sediment was substantial after the start of water storage for the Three Gorges Dam in 2003- it has decreased around 3-fold on annual basis (Saito et al., 2007).

Phytoplankton blooms and related oxygen depletion, invasive species, engineering activities, pollution and overfishing lead to a decrease in total fish catch. In Tokyo Bay, the total fish catch decreased by more than double in the 1950–1990 period despite the improvement in fishing techniques (Furukawa and Okada, 2006). In Manila Bay in the 1980s, an increase in the catch of invertebrates, shrimps and squids can be related to the removal of their predators. Indeed, a decrease in the catch of large-size fish for the 1940s-1980s period was recorded (Sugiyama et al., 2004; Jacinto et al., 2006).

4.3. The state of potable water quality in coastal megacities

Most of the megacities' surface waters have high concentrations of metals, bacteria, suspended solids, ammonia, and phosphates because of the intensive economic activities present in the area (Decker et al., 2002). In Istanbul, for example, nutrient discharge is considered to be the biggest threat for the contamination of drinking water reservoirs (Baykal et al., 2000). High levels of iron, chromium and arsenic were registered in Kolkata's drinking water reservoirs; while in Karachi, the contamination of groundwater sources with chromium, cadmium, lead, arsenic, and nickel was recorded (Rahman et al., 1997; Basu and Main, 2001). Important contaminants of potable water sources can also consist of pathogens and other microorganisms, which can seriously endanger human health: in Karachi, almost every source of drinking water had high levels of bacterial contamination in respect to the WHO standards (Rahman et al., 1997). Degraded water quality in groundwater reservoirs of some megacities can be related to the sea level rise and the related salt water intrusion (Yeung, 2001; Bigio, 2003; Klein et al., 2003).

4.4. Decrease in coverage of coastal vegetation

Major problems regarding the estimation of megacities' influence on the decrease in vegetation coverage is related to data, since the data collection is done more frequently on a national or global than on a city level. Sanli et al. (2008) illustrated the deforestation issue on city level on the example of Istanbul where the population growth of 33% resulted in the loss of 3–4% of the surrounding forest area in the period of just 13 years (1992–2005). In Rio de Janeiro's Guanabara Bay, 90% of mangroves and salt marshes were removed mainly because of the development of beaches for tourism purposes (De sherbinin et al., 2007). In the Manila Bay, out of around 54,000 ha of mangrove forest in 1890, only 2000 ha were left in 1990 due to the conversion into aquaculture and salt beds, urban expansion and industrial development (Jacinto et al., 2006).

4.5. Land subsidence due to the excessive groundwater withdrawal

The contribution of the anthropogenic groundwater withdrawal in coastal subsidence (45 cm/century) will be as three times higher than the natural one (15 cm/century) (Nicholls and Lowe, 2004). Because of the increasing demand for groundwater, especially in Asian megacities, high rates of coastal subsidence were observed: in Manila between 5 and 9 cm/year, in Osaka around 8.2 cm/year, in Shanghai 6 cm/year and in Tokyo 2.7 cm/year (Rodolfo and Siringam, 2006). Frequently, the rates of subsidence exceed the maximum projected rates of sea level rise which increases the intensity of negative impacts on coastal megacities, especially in low-lying areas. Therefore, with greater subsidence, sea level rise, floods and erosion, will have stronger impacts on these areas (Nicholls, 1995; Nicholls and Lowe, 2004).

5. Impacts of altered environmental conditions

5.1. Impacts on coastal stability - coastal erosion

Coastal erosion is a result of changes in natural flux of water and sediments, often caused by of various human pressures, such as damming, mining, irrigation and engineering in coastal zones. The intensity of coastal erosion episodes is usually being exacerbated with climate change-related sea level rise and an increased runoff due to intensive precipitation, as well as by a massive removal of coastal vegetation such as salt marshes and mangroves, which serve as a sort of "natural coastal protection" (Smit et al., 2001; Nicholls and Tol, 2006). Coastal megacities in low-lying deltaic regions are particularly prone to coastal erosion due to their location (Klein et al., 2003; Kasperson and Dow, 2005). Shanghai, for example, was partly founded on accreted sediments and today it is particularly prone to erosion effects, mainly due to the reduction in sedimentation rates because of the damming upstream (Saito et al., 2007).

5.2. Decline in biodiversity

The importance of coastal megacities as global harbours stimulates heavy marine traffic, which leads to increased turbidity, sediment loads and other physical alterations, and it is also one of the major sources of exotic species through the discharge of ballast waters (Tamburri et al., 2002). For example, 113 documented alien species were introduced into the Hudson River Basin in the vicinity of New York, which accounts for 4–60% of the documented well-known species (Decker et al., 2002). Furthermore, in the Changjiang Estuary near Shanghai, because of the pollution with metals and dredging activities, benthic fauna decreased from 150 to 160 species in 1970s to only 10–20 in 2002 (Zhang et al., 2006).

5.3. Changes in ecosystem functions due to the decline in coastal and marine flora and fauna

Massive removal of any type of coastal and marine vegetation decreases potential carbon sinks and, therefore, contributes to the effects of global warming (Zhao et al., 2006). In addition, the removal of coastal vegetation, such as salt marshes and mangroves, weakens the prevention of coastal erosion episodes and increases sea water intrusion, e.g. in the case of massive mangrove removal in the vicinity of Rio de Janeiro (De sherbinin et al., 2007). The destruction of mangroves has a negative impact on the fisheries as well, since mangroves are important nursery areas for juvenile fish (Jiang et al., 2001). In case of seagrasses, their decline results in lower primary production, reduced sediment stabilization and nutrient trap, and the loss of nursery for fish and shellfish (Orth et al., 2006). The decline in some fish species leads to the destabilization of food web which affects many other pelagic and benthic communities. However, the decline in fish catch and the related environmental implications are not only a result of overfishing, but also of oxygen depletion due to eutrophication, which leads to fish refuge or even fish kills (Meyer-Reil and Köster, 2000; Clavel et al., 2008).

5.4. Impacts of environmental degradation and global warming on human health

Megacities are particularly vulnerable to health issues, mainly because of higher rates of senior, more vulnerable population (Kasperson and Kasperson, 2001; Kasperson and Dow, 2005). Today, health problems in urban areas seem to be more prominent in the developing than in the developed countries and are mainly related to inadequate water supply, the contamination of drinking water and solid waste generation (Vlahov and Galea, 2002). In Mumbai, some 30% of all diseases are water-borne diseases, such as diarrhoea, malaria, typhoid, intestinal worms etc (Kumar Karn and Harada, 2002). However, not all health threats in megacities are water related: there is a correlation between the concentration of air pollutants in the atmosphere and lung cancer, cardiopulmonary and premature mortality in many megacities (Molina and Molina, 2004). Declining indoor air quality leads to risks of child pneumonia and other respiratory infections (Kjellstrom et al., 2007). High emissions of diesel exhaust particles, ambient total suspended particles, particulate matter, ozone and other air pollutants in megacities can be lead to an increase in allergic rhinitis and asthma (Chowgule et al., 1998; Ebtekar, 2009; and Ghosh et al., 2010).

Increased temperatures in megacities, due to the global warming and UHI, favour the reproduction and survival rates of infectious agents (such as protozoa, bacteria and viruses), and the related vector organisms (mosquitoes, ticks and sand-flies) (Patz et al., 2005). The urban heat island effect (UHI) can also be related to increased mortality during the heat waves in megacities, e.g. in the case of Shanghai in 2003 (Tan et al., 2007). Furthermore, exposure to in megacities can lead to some adverse effects on human health such as hearing impairment, hypertension and ischemic heart disease (Vlahov and Galea, 2002).

5.5. Social and economic impacts

Social and economic performance is also affected by environmental degradation and climate change, resulting in various economic adjustments and feedbacks from coastal societies.

Agricultural production is often hindered by the loss of agricultural land due to the urban expansion, and air, soil and water contamination. This leads to the loss of jobs in the agricultural sector, rise in food imports and, ultimately, the inability to satisfy the food demands (Pingali, 2006). Local fishing industries also experience losses after environmental degradation. In the Manila Bay, for example, during four days of harmful algal blooms, the price of fish and shellfish dropped by around 75%, which led to the loss of more than two million US dollars in the local shellfish industry (Jiang et al., 2001).

Poor water quality and a combination of climate conditions usually lead to water shortages in coastal megacities. In Mumbai and Kolkata for example, frequent water shortages are the result of a combination of sources: altered seasonality of rainfall, floods, salt water intrusion and the contamination due to the poor drainage and wastewater systems (Murthy et al., 2001; Nair, 2009). Water scarcity can also be a result of unequal distribution of water and the quality of water supply, even within the megacity itself. In Mumbai, for example, water supply is apportioned 45 L per person a day for people living in informal settlements, while the people living in private owned houses get 135 L per person a day (Murthy et al., 2001; Kumar Karn and Harada, 2002). Resource scarcity usually does not lead to direct violence, although in the case of water this could change. According to some projections, if some sharing agreements are not found for the Nile and Ganges Deltas by 2025, the competition for water could lead to regional instability and potentially result in migration or even conflicts (Kasperson and Kasperson, 2001; Gilman, 2007).

Besides agriculture and water sector, the tourism economy is also affected - the shifts in tourism are usually determined by human-induced environmental degradation. In Mumbai for example, inadequate waste disposal caused deterioration in the aesthetic value of adjacent beaches and, consequently, led to a decline in tourism (Li, 2003). In addition, tourism can also be affected by increasing erosion episodes in the coastal area, which requires further investments in the coastal protection. Shifts in agriculture, water pollution and shortages, deforestation, desertification and extreme weather events can lead to mass migrations of people further in land ("environmental refugees") (Kasperson and Kasperson, 2001; Barnett and Adger, 2007; Gilman et al., 2007).

Coastal populations are exposed to climate change effects and extreme weather events which makes the probability of economic losses (through damaged property for example) and human casualties higher (Yeung, 2001; McGranahan et al., 2007). Cross (2001) argues that megacities have greater resilience to hazards when compared to small towns, mainly due to better warning and protection systems. However, there is an increasing concentration of population on potentially hazardous locations in coastal megacities, especially in informal settlements of megacities in developing countries, thus making it a social issue (Klein et al., 2003). In Bombay and Buenos Aires, they can be found on low-lying areas prone to flooding, while in Rio de Janeiro they are located on hilly areas prone to landslides and mudslides (Satterthwaite, 2005; De sherbinin et al., 2007) (Fig. 3).

6. Management responses

6.1. Management responses related to water management

In all response tactics regarding the water management, efficient governance plays an important role. It seems that decentralized water management system and the participation of private sector achieve more success in adequate water supply (Kötter and Friesecke, 2009). One of the most common governance practices regarding water management is the establishment of "pricing system" - higher water prices which helps to regulate the water consumption and demand. In urban areas it can be very effective because it provides funds for investments in water supply systems for all sectors (Jeppesen et al., 2006; Moe and Rheingans, 2006). However, water pricing effect weakens over time because people adjust to new prices relatively soon. Quantity restrictions have proven to be a more efficient solution (Meinzen-Dick and Appasamy, 2002). There is also a popular "polluters pay" principle in which the companies are motivated to reduce the amount of waste simply because of higher taxing (Jeppesen et al., 2006).

Regarding the technological improvements, they can be discussed in terms of leakage detection technology, rainfall and flood forecasting, and the improvements in monitoring techniques (Bigio, 2003; Jeppesen et al., 2006). Since various types of waste are not being treated in many coastal megacities before being discharged into water bodies, the improvements in waste treatment technologies are also crucial (Meinzen-Dick and Appasamy, 2002).

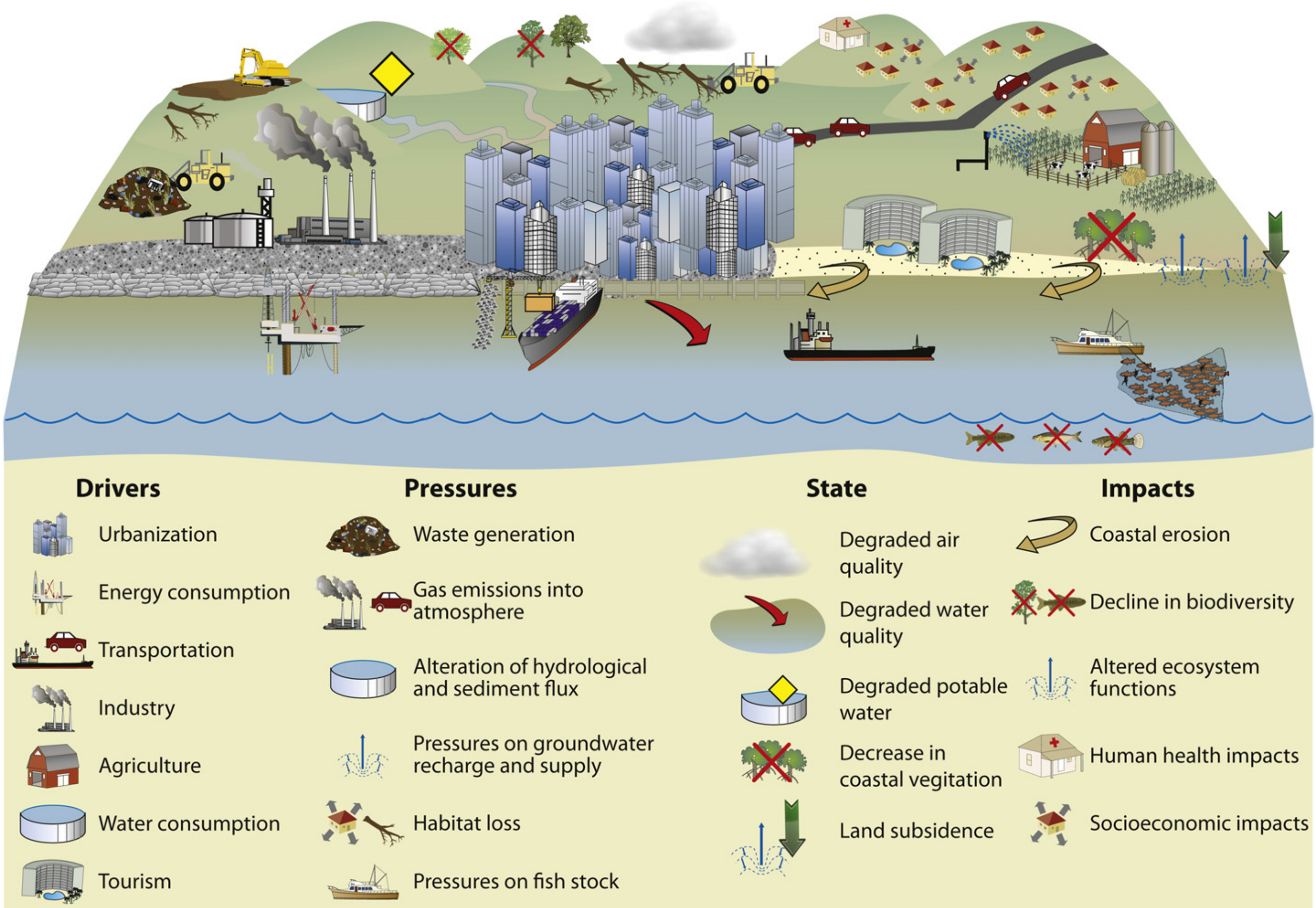

Fig. 3. Drivers, Pressures, State and Impacts regarding megacities in the coastal zone.

There are also possibilities of using storm water for toilet flushing, small-scale urban agriculture and irrigation which, in a way, contribute to the recycling of nutrients from excess fertilizer usage e.g. in Tokyo (Decker et al., 2002).

The savings of water can also be done with simple sanitation improvements. For example, low flush, dual flush and vacuum flush toilets save from 20 to 40% of per capita water use compared to conventional flush toilets (Moe and Rheingans, 2006).

6.2. Management responses related to the improvement of air quality and the reduction of greenhouse gas emissions

The improvement of air quality and reducing the GHGs emissions in megacities is usually aimed at the advancements in the most contributing sectors regarding the energy consumption: transportation, industry, agriculture and household sector.

Regarding the transportation, some urban planning schemes can help minimize the contribution of transportation to the air quality and GHGs levels. Relocation of business centres and government offices to sub-urban areas (e.g. in Tokyo and Shanghai) and the so-called "re-densification" of megacities are some of the solutions (Morichi, 2005; Kötter and Friesecke, 2009). Some of the government's administrative actions and the proposed technical improvements, such as mandatory frequent CO testing and the installation of catalytic converters for cars, contribute to the reduction in air pollution in megacities (Mohan and Tiwari, 2000). An improvement in air quality, due to the shift in fuel usage, was achieved in Mumbai after the introduction of unleaded petrol and compressed natural gas (CNG) in Dhaka (Mohan and Tiwari, 2000; Haq et al., 2002).

For industrial and rural sector in megacities, the levels of pollutant emissions are prescribed by legislative regulations, mainly on a national level. The regulation of the release of air pollutants in the industrial sector is usually done by some technical improvement, such as the installation of filters and scrubbers at the end of the emission pipelines or chimney stacks (Haq et al., 2002). In poor urban communities, switching from wood, dung and charcoal to a more efficient fuels such as kerosene, LPG (liquefied petroleum gas) and biogas could reduce the indoor pollution and, hence, the health risks (Kjellstrom et al., 2007).

6.3. Management responses aimed at adaptation to the sea level rise

Because of the uncertainties about the extent to which the reduction of the GHGs emissions will reflect on the effects of climate change, the adaptation approach has always been discussed as a necessary complement to mitigation options (Smit et al., 2001; Nicholls and Lowe, 2004). Adaptive capacity is closely related to the financial one, and will therefore be considerably smaller in the developing countries (Smit et al., 2001). Furthermore, raising the awareness of the potential threats of climate change impacts and the establishment of early warning systems regarding extreme weather events is crucial, especially among the most vulnerable coastal populations (Bigio, 2003; Klein et al., 2003).

In coastal zones, adaptation measures regarding the sea level rise and the related salt water intrusion consider, among others, increased robustness of infrastructural designs and long-term investments such as seawalls, dikes, breakwaters and other coastal protection infrastructure (Nicholls, 1995; Nicholls and Mimura, 1998; Bigio, 2003). Recently, soft protection methods of coastal environments, such as beach nourishment, are also very popular (Peterson and Bishop, 2005). Rehabilitation and the plantation of mangroves can also reduce the impacts of sea level rise by acting as a natural sea defence (Kelly and Adger, 2000). In agriculture, the plantation of flood resistant and salt-tolerant varieties is essential in low-lying areas prone to the intrusion of salt water (Smit et al., 2001). Improving the drainage facilities is also being implemented: in Dhaka for example, the recovery of drainage channels seems to be essential for reducing the retention of flood water and hence, decreasing the health risks (Alam and Rabbani, 2007).

An increase in flexibility or coping capacity includes, among others, raising buildings above the flood levels to minimize the damage. Migration and relocation of urban coastal population is also an option which should be supported by removing migration barriers (such as the establishment of eco-corridors) (Smit et al., 2001).

6.4. Management responses aimed at conservation of biodiversity and coastal flora and fauna

Major challenges, when trying to mitigate the biodiversity-related threats in the developing countries, are mainly economic: the shortage of conservation resources (both expertise and funding) and corrupt national institutions (Sodhi et al., 2004). The regulations for ship cleaning, their discharge and the banning of some hazardous compounds seem to be successful in the prevention of damage in coastal ecosystems. Coastal vegetation threatened by the spread of non-native species can be partially recovered by a planned restoration/re-cultivation of native species. Proclamation of protected areas appears to be most successful in protecting the biodiversity as well as the public awareness and the local community involvement in the conservation and monitoring programs (Sodhi et al., 2004; Duarte et al., 2008).

Regarding responses for pressures related to fisheries, most countries have in place some sort of limited licensing schemes. The establishment of individual, company or community-held quotas (IQs) and Total Allowable Catch (TAC) is being considered and, recently, more implemented. This is usually integrated with a series of technical measures to regulate the vessels, gear, fishing areas and duration of fishing time (e.g. closed seasons); or catch characteristics (e.g. minimum landing size, stage of maturity), etc (Garcia and De Leiva Moreno, 2001; Pauly et al., 2005). Establishing the inshore "marine reserves" or no-take zones to protect coastal species has also proven to be of great importance (Pauly et al., 2005).Table 1

7. Discussion: potential for improvement of current environmental state in coastal megacities

An earlier discourse on environmental, social and economic concerns regarding the coastal megacities could be interpreted as a pessimistic point of view. However, there are many uncertainties in the future development of coastal megacities, and some of them may "leave some room" for further improvement of the current environmental situation (Table 2).

Sustainable development in coastal megacities faces various obstacles because unclear physical boundaries of megacities lead to difficulties when determining regulatory boundaries, which makes their planning and regulation actions extremely difficult. Indeed, the legal-jurisdictional boundaries are often proposed by politicians and decision-makers who, in most cases, adapt legislation to their own interests (Kraas, 2007). The obstacles for quality governance are reflected in the fact that urban governing is being, in most cases, fragmented among various agencies, corporations and municipalities. For example, Kolkata's administration is divided by 107 government agencies, while Metro Manila is composed of dozens neighbouring cities which form a single, unplanned megacity (Schiavo-Campo and Sundaram, 2000). Local, regional, and national agencies are often unsuccessful in working together on coastal management issues. In Shanghai, for example, about twenty different agencies control all kinds of activities in the coastal zone without being administered by some higher-level governing organisation, which resulted in overlapping jurisdictions and extremely poor cooperation between these agencies (Shi et al., 2001). Furthermore, in China in general, the lack of communication is enhanced by clashes between the private-sector

Table 1
Examples of management responses regarding certain environmental problems in coastal megacities.

Issue	Governance Measures	Technological Improvements	Best Management Practices
Water quantity and quality	• Water Pricing[*] • Polluters pay[†] • Quantity restrictions[‡]	• Wastewater treatment[‡] • Leakage detection[†] • Technologies for saving water[*]	• Reuse of storm water and wastewater[§]
Air quality	• Urban planning schemes to reduce commuting[¶] • Regulation of public transport and industrial emissions[‖]	• Catalytic converters for personal vehicles[‖] • Shift in fuel usage[**]	• "Green" transport (bicycles, metro)[¶]
Sea level rise	• Rising settlements on higher elevation[††] • Opening of eco-corridors[††]	• Hard and soft protection systems[‡‡]	• Planting the flood resistant and salt-tolerant species in agriculture[††]
Conservation of coastal flora and fauna	• Proclamation of biosphere reserves[§§] • Restoration of native species[§§] • Regulation regarding fisheries and discharge from vessels[¶¶]	• Introduction of less devastating fishing techniques and improvement of discharge treatment[¶¶]	• Participation of local communities in conservation and restoration projects[§§]

[*] Moe and Rheingans (2006).
[†] Jeppesen et al. (2006).
[‡] Meinzen-Dick and Appasamy (2002).
[§] Decker et al. (2002).
[¶] Morichi (2005), Kötter and Friesecke, 2009.
[‖] Mohan and Tiwari (2000), Haq et al. (2002).
[**] Haq et al. (2002), Kjellstrom et al. (2007).
[††] Smit et al. (2001).
[‡‡] Kelly and Adger (2000), Bigio (2003), Peterson and Bishop (2005).
[§§] Sodhi et al. (2004), Duarte et al. (2008).
[¶¶] Garcia and De Leiva Moreno (2001), Pauly et al. (2002), Pauly et al. (2005).

Table 2
Recommendations for potential improvement of current environmental situation of coastal megacities.

Goal	Challenge	Recommendation
• Defining responsibilities for the management of coastal megacities	• Administrative fragmentation due to the difficulties in determining the physical and administrative boundaries of coastal megacities	• Empowerment of local authorities • Improvement in local-national and public-private cooperation • Switching the policy aims from sector-level to a holistic urban level
• Improved environmental state as a result of economic development	• Reducing social inequity • Insufficient participation of local communities	• Using the advantage of big financial capacity of megacities • Include local people in environmental programs
• Implementation of the DPSIR framework	• Generic definition of its components and related subjectivity • No uniform system of environmental indicators • Issues with data relevance	• Developing an unique system of environmental indicators • Collection of data on urban level

and government interests in coastal zones (Tibbetts, 2002). Therefore, the empowerment of local authorities and an improvement in local-national coordination seems to be essential. In addition, the existing policies mainly focus on individual sectors in megacities. Switching the aim of policies from sector-level to holistic urban level is essential. However, it is important to note that, in reality, central state governments usually do not permit high level of autonomy to local and urban authorities when they gain the capacity (and income) to make decisions “on their own”. On one hand, this can prevent particularistic interests of privileged groups and municipalities from taking advantage of the megacities’ uncontrolled expansion. On the other hand, it is often just a result of the lack of understanding for local megacities’ problems and demands. However, although the eagerness and capability for participation is usually on a low level, decentralisation in decision-making is being increasingly accepted (Kraas, 2007).

The financial and institutional capacity of coastal megacities is, in theory, the greatest advantage in tackling social challenges and enhancing environmental protection. However, it seems that this capacity is not really directed to the most immediate issues that need to be solved. There is no other explanation than this, because it seems a bit paradox that megacities with such financial capacities still battle with the increasing urban poverty and the growth of informal settlements which additionally aggravates the social inequality.

Community participation is something that is often neglected in the management of coastal megacities (Kullenberg, 2001). In some Indian cities the projects of slum-upgrading have not succeeded because the local residents were not able to participate in these projects. The understanding of gender, ethnic, tribal and racial differences by local communities can be crucial in sustaining the vitality and structure of urban settlements. This is especially important in coastal megacities because of intensive migration, which can cause major disruptions in informal social structures. Finally, the long-term sustainable development seems to heavily depend on the prevailing political culture (Myllylä and Kuvaja, 2005). Community’s willingness for some concrete action is often discouraged by nonexistent political motivation, bureaucracy and corruption. The mistrust of dwellers in informal settlements towards politicians often results in an increasing uncertainty regarding any investment in their living environment.

Finally, how appropriate is the DPSIR framework is as a management tool in addressing the environmental problems of coastal megacities? Like any other management method, the DPSIR framework has its advantages and disadvantages in argumentation on the given subject.

The greatest quality of the DPSIR framework lies in its ability to provide cause–consequence relationship between the anthropogenic activities and complex environmental processes in a descriptive and a rather simple way (Borja et al., 2006; Karageorgis et al., 2006). The DPSIR also stands out in its capabilities for organizing the collected data, which provides scientists with greater insight regarding the policy formulation and implementation. It should also help the stakeholders and managers to better understand the significance of natural systems in decision-making, and the consequences of economic activities.

One of the major issues about the credibility of the DPSIR framework is the data relevance. On a wider spatial scale, such as the one in this study, the data is usually gathered from various sources, under different rules and procedures, in a time span of several years, which can make their joint application problematic. The availability of data is considerably reduced, especially in the developing countries which are embracing just the development of the environmental statistics. In addition, many environmental analysis and data-gatherings have been performed on a national and not on a city level, which was pointed out on several examples earlier in the text. Furthermore, responses proposed when dealing with a certain problem are not necessarily applicable for each coastal megacity. Each megacity is an entity of its own and is characterized by particular problems which may not be predominant elsewhere.

However, it seems that the applicability and simplicity of the DPSIR framework are often counterpoised with a rather generic definition of its components, which leaves room for subjectivity (Giupponi, 2007). For example, establishing the driving forces of environmental changes can be a matter of subjective appraisal among several causes and not necessarily all of them get included into the framework. In order to avoid this subjectivity, it is essential to develop a unique set of environmental indicators. Their establishment is significant for clarifying the relations between certain variables and to define the extent of the environmental impact on a particular anthropogenic activity - in this way the comparison between the extent of environmental impact between coastal megacities would be more convenient (Pirrone et al., 2005; Rogers and Greenaway, 2005). A comprehensive set of environmental indicators would also enable establishing joint multi-disciplinary databases, monitoring networks, simulation models etc.

Despite these disadvantages, in this study, the DPSIR framework has also proven to be depictive and clear in “drawing a circle” from people’s demands to policy responses regarding the coastal megacities. It is questionable whether this extremely wide range of issues would be appropriately covered and assembled by any other management technique.

8. Conclusions

A comprehensive DPSIR framework was developed in order to examine the potential of using this framework in studying complex interactions between coastal megacities and the environment. The DPSIR proved to be simple, clear and well-organized management tool, which confirms how useful this framework can be, even for studying complex environmental phenomena. However, the DPSIR needs some adjustments, such as establishment of unique set of indicators, in order to make monitoring of environmental state and impacts in megacities clearer, and therefore finding a way to more appropriate management responses easier.

Despite the rather negative 'outlook' that megacities can have in environmentalist point of view, at the same time they have vast potential for improvement in the environmental compartment, primarily because of their financial capacity. Urbanization rates are slowing down and local communities seem to increasingly recognize the environmental threats and participate in various environmental protection programs. Because of this potential for improvement, more research on coastal megacities should take place in the future.

On the hand, the main problem regarding the environment in megacities still remains – high consumption of goods and services due to different living standards. Therefore, the major question remains unanswered: are the dwellers of coastal megacities willing to forfeit their commodities for the sake of the environment?

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