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IMPLICATIONS OF CLIMATE CHANGE TO COASTAL CITIES AND THE NEED FOR ENGINEERS

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Abstract: Issues influencing the sustainability of coastal cities are characterized, reflecting the combination of impending sea level rise and storm surges, and increasing growth in the world's populations in coastal cities. Geologic-time scales are utilized to draw parallels to characterize relevant historical occurrences that help to understand the context of projections of impending sea level rise issue to year 2100. Given that Antarctica holds sufficient water to raise global sea levels by 58 m if the ice were to melt, this indicates that even a small percentage of melting of the polar ice caps, should this occur, will have enormous implications to the sustainability of coastal cities which are projected to hold 12.4 percent of the world's population by 2060. The result is the combination of predicted sea level rise and associated storm surges indicate that drastic measures need to be promoted to improve the sustainability of coastal cities. The need for engineers, and engineering innovation, is going to greatly increase as the world attempts to address the challenges of sea level rise and storm surges. As a specific example of the storm surge effects, Biloxi, Mississippi during Hurricane Katrina experienced a high water mark of 11.4 m.

1 INTRODUCTION

The impacts of climate change are wide-ranging, including notable increases in the intensity and frequency of storms, floods and forest fires, to name but a few. Evidence of devastation is particularly noteworthy from recent examples such as Hurricanes Katrina (New Orleans in 2005), Harvey (Houston in 2017), and Irma (Florida in 2017), recent flood damages in southern Alberta (2013) and Toronto (2013), and fires in Slave Lake (2011) and Fort McMurray (2016). Widespread evidence points to intensification of issues arising from climate change. The magnitudes of these types of events need to be recognized in engineering education, and the profession needs to be encouraging new thinking processes and approaches in engineering practice, not just rebuilding what has been destroyed in recent events.

2 DIMENSIONS OF CLIMATE CHANGE OF INCREASING DIMENSION

To appreciate the need for increasing focus on the impact of climate change in engineering education and professional practice, it is useful to review the increasingly well-established technical bases which provide important insights to the types of events that are proving especially harmful to coastal cities. The intent in this article is to characterize what is becoming apparent with respect to three dimensions: (i) expected sea level rise over the next century, (ii) the intensification of storm surge impacts, and (iii) land subsidence.

2.1 Sea Level Rise

Sea level rise is one of the lines of evidence that supports that the global climate is warming. For example, there is real concern that the Maldives could be significantly under water by 2100 (see https://blogs.scientificamerican.com/news-blog/maldives-drowning-carbon-neutral-by-2009-03-16/).
Evidence is now available which is demonstrating changes in sea level that have occurred over geologic time (see Figure 1, building from base information from Tiner (2016)). While there is strong evidence supporting historical, large increases in sea level (120 m over the time period from 14000 years to 6000 years ago (indicated as Time Span A in Figure 1) as a result of the melting of ice as the last ice age receded, and then were much lower rates of change more recently: 2.0 mm/yr from 6000 years to 2000 years ago. There were then rates of 1.3 mm/yr from 2000 years ago until 1900 (after Horton et al., 2013). These relatively recent rates are indicated within Time Span B in Figure 1.

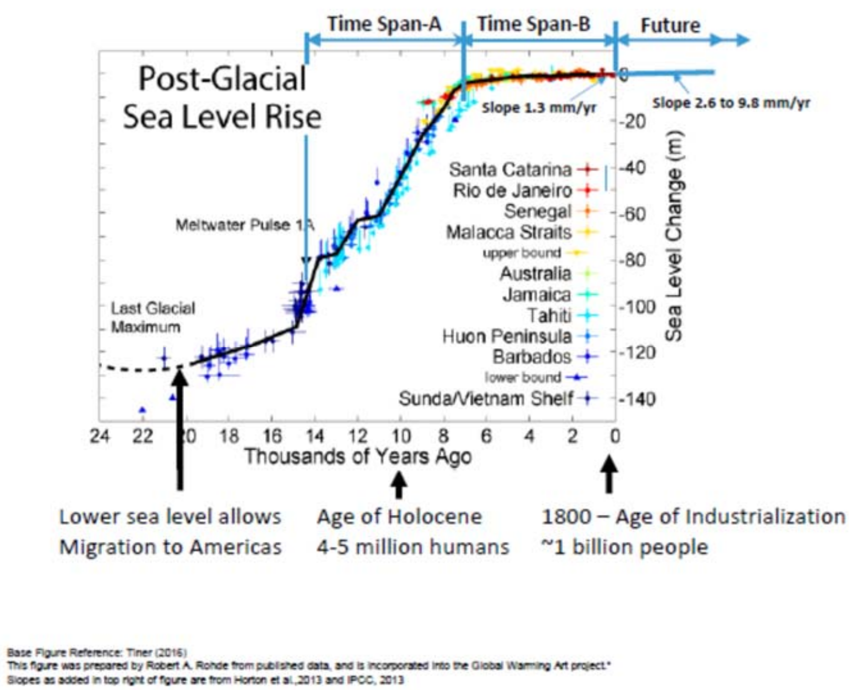

Figure 1 Post – Glacial Sea Level Rise

Given the expectation that sea level rise over the next century is expected to be between 0.26 m and 0.98 m, there is an interesting comparison between Time Span B and the future. The expected future rates of sea level rise are 2 to 7.5 times the rate of increase per year evidenced over the last century. This prediction into the future includes the effects of both thermal expansion of water as well as the progressive melting of the remaining ice sheets and glaciers (IPCC, 2013).

It is noteworthy that ninety-nine percent of the world's fresh water is in the polar ice caps and the vast majority of this 99 percent is in the Antarctic. The area of Antarctica is $14x10^6$ km^2 or approximately twice the size of Australia or the continental US, and is covered on average, by 2750 m (9000 ft) of ice and 150 m (500 ft) of land above current sea level in Antarctica. At the South Pole, ice thickness peaks at 4776 meters (Antarctica Glacier, 2016; http://www.antarcticglaciers.org/antarctica/ten-antarctic-facts/). As a result of these enormous volumes of ice, Antarctica holds sufficient water to raise global sea levels by 58 m if all of the ice melted (Antarctica Glacier, 2016); however, while there is sufficient water in the Antarctic ice cap to raise the sea levels by 58 m, melting of the Antarctic ice cap over the next century is expected to be modest and is incorporated into the above noted increase in sea levels (McBean and Huang, 2017).

2.2 Storm Surges

While the increases in sea level noted above appear initially as relatively modest, one of the most significant dangers to coastal cities are storm surges. To demonstrate the serious magnitude of impacts of storm surges, one only needs to consider evidence from Hurricane Katrina in 2005 which generated an 8.47 m surge (Knabb et al., 2006). When the storm surge magnitude of 8.47 m is combined with the tidal effect plus the storm tide break when the waves reach shallow water, the result in Biloxi, Mississippi was a high water mark of 11.4 m (Fritz et al., 2007). Further, as Tebaldi et al. (2012) indicated, 'Once in a century' storm surges may become 'once in a decade surges'. Clearly, it is not feasible to build walls to protect coastal cities against storm surges.

2.3 Land Subsidence

While tidally-driven coastal flooding is one of the most visible signs of sea level rise, one must also consider the impact of subsidence arising from the extraction of groundwater as an equally challenging problem. The 'pave, pipe and pump' philosophy that has dominated such areas as Houston for over a century has resulted in parts of Houston dropping between 3 and 4 m since the 1920s (Harden, 2016; Galloway et al., 1999).

In Beijing, approximately two-thirds of water supply in recent years for the city of 21 million, has been obtained by overexploiting groundwater at a rate of 10×10^8 m^3/yr. The result has been the maximum mean subsidence rate of 0.13 m/yr (Zhou et al., 2016). Further, four hundred of 655 cities in China rely to a large extent on groundwater extraction, with 65 % of municipal water supplies in northern China being derived from groundwater. Examples of subsidence also include Jakarta which has incurred 4 m of subsidence in 35 years (10 to 20 cm/yr). Subsidence now exceeds coastal, absolute sea level rise by a factor of 10 for many coastal cities (Chaussard et al., 2013).

In addition to the subsidence impact, the resulting ingress of salt water into aquifers depleted by overexploitation damages the ability to use groundwater for beneficial purposes.

3 POPULATION GROWTH

Coincident with the challenges that are evolving for coastal regions is the dramatic growth in the world's population now living in coastal low-lying areas. Most of the world's megacities are located in the Low-Elevation Coastal Zone, or LECZ (Brown et al., 2013), and many are situated in large deltas.

Table 1. Populations of LECZ and of the World, with Time (as per Neuman et al., 2015)

Year	Population in the LECZ (in billions)	World Population (in billions)	Percentage of world population living in the LECZ
2000	0.63	6.1	10.3
2030	0.88-0.95	8.7	10.1-10.9
2060	1.4	11.3	12.4

As Neuman et al. (2015) and Merkens et al. (2016) have indicated, the populations residing in the LECZ are predicted to increase by more than half a billion people and reach the proportions listed in Table 1, i.e. 12.4%, of the world's population, is projected to be in the LECZ by 2060.

With increasingly large percentages of the world's population expected to live on, or near, coastlines, and with intensifying impacts arising from climate change (measured by rising ocean levels, stronger hurricanes/typhoons, severe storm surges and land subsidence), there are important implications to coastal cities as a result of their location.

4 COASTAL CITY IMPACTS

The top 20 cities (of 136 port cities around the world that have more than one million inhabitants) most exposed to coastal flooding, are indicated in Figure 2. Logic dictates that the economic threats to these coastal cities are enormous (population levels and level of commerce and trade activity) from rising seas, increased frequency, and subsidence (in cities which are prone to subsidence). It is also noted that Montreal is 101st on the list of cities studied (after Hallegatte et al., 2013). Given both Vancouver's ranking on this list (13th on the list), as well as the substantial international roles of Canadian engineers, the implications of climate change need to be captured in our awareness (McBean, 2017).

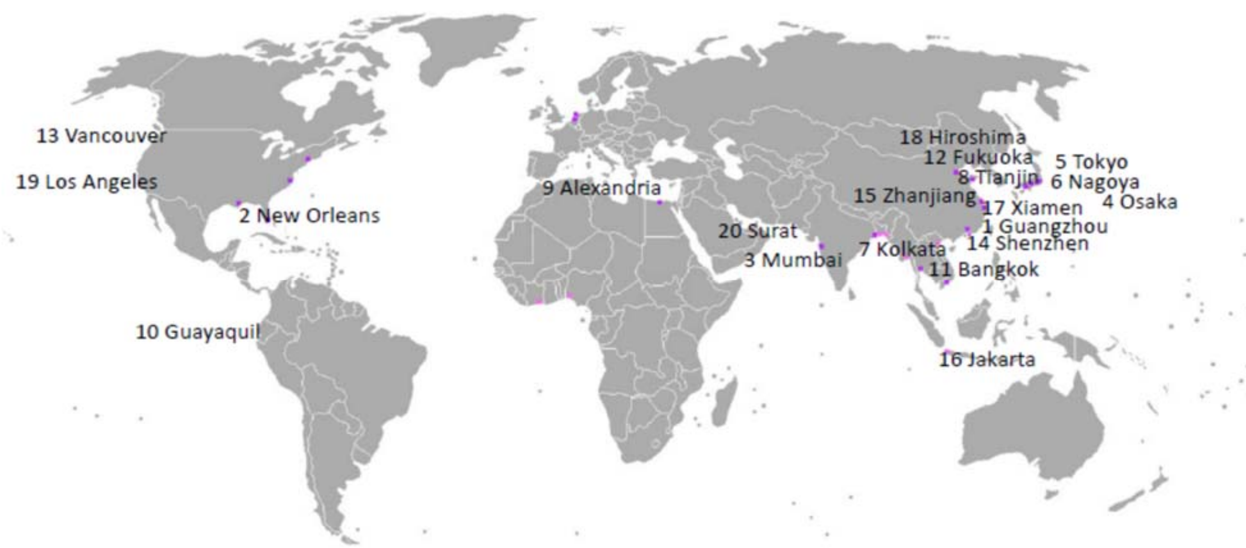

Figure 2. The Top 20 Cities Exposed to Coastal Flooding (after Hallegatte et al., 2013)

Sea level rise predictions indicate that a 400 mm (15 in) rise would result in 7 to 10 million refugees in Bangladesh alone, and a rise of 200 mm (8 in) would create 740 thousand climate refugees in Nigeria (IPCC, 2013). Further, the most susceptible countries in terms of populations at risk include China, India, Bangladesh, Indonesia, Viet Nam, Egypt, Nigeria, and The Netherlands. Bangladesh has 40% of its population in the LECZ, and The Netherlands has 73% of its population in the LECZ (Neuman et al. 2015). Clearly, the potentials for climate refugees are not restricted to desertification and economic opportunities.

Responses to these issues are challenging, both in general, and in specifics. Clearly, walls cannot be built high enough to protect coastal cities, and the engineering profession needs to be considering an array of options. A few of the possibilities include:

i. Opportunities to stop or decrease the impacts: better management of subsidence must be addressed (for susceptible cities); re-establish lost wetlands as a friction barrier to protect coastal cities;

ii. Relocating some activities: Land use planning to reduce exposure, including focusing of new development away from the floodplain and preserving space for future infrastructure development; selective relocation needs to be more actively pursued, away from existing city areas to reduce exposure more rapidly than is possible by only focussing on new development;

iii. Making some aspects of coastal cities more robust against failure: since hard infrastructure is only part of the answer, make designs more resilient both with respect to over-topping and when conveyance capacity is insufficient to handle the hydraulic loads; energy grids in North America are fragile and need to become more robust; building regulations need to be upgraded (e.g. flood-proofing) and/or building retrofitting;

iv. Developing more protection and awareness: developing early warning systems and evacuation plans; increasing reliance upon renewable energy; increasing protection through risk-sharing using insurance and re-insurance needs to be expanded.

This list of options needs to continue to be expanded, to encourage innovative thinking.

5 CONCLUSIONS

With the many dimensions as clearly evidenced in the preceding, increased global warming is both obvious and ominous. There is no question that sea levels have risen, and this will continue. The projected increases in sea levels over the next century are expected to be between 0.26 m and 0.98 m from current conditions. However, the implications to coastal cities are much more than sea level rise alone, with storm surges, wave breaking and subsidence, and increased 'populations at risk', all of which are of much greater importance.

Enhanced engineering options need to be considered now, not as just reconstruction of what has been destroyed in the 'last event'. There is no planet 'B', we need to encourage new thinking processes and approaches in engineering practice.

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