Use of high-resolution elevation data to assess the vulnerability of the Bangkok metropolitan area to sea level rise

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Abstract:

Using high-resolution elevation data (2 m × 2 m), obtained during a 2012 aerial Lidar survey as part of the Chao Phraya River basin flood management project in Thailand, we assessed the impact of sea level rise due to climate change on the Bangkok metropolitan area. The area below the current median tide of 1.11 m was estimated to be 2,520 km², with a vulnerable population of 3.9 million, equivalent to 23% of the total population of the Bangkok metropolitan area. In the worst-case scenario of Representative Concentration Pathway (RCP) 8.5 (sea level rise of +1.10 m), the affected area would extend to 6,140 km², increasing the estimated vulnerable population by 86% to 7.2 million. With a sea level rise of less than +1.10 m, the affected area would extend from the Chao Phraya River mouth to Suphan Buri, which is about 80 km inland; however, the density of the vulnerable population would increase. The results of this study suggest that sea level rise adaptation measures, such as migration and settlement, must be developed as soon as possible.

KEYWORDS LiDAR; vulnerability; sea level change; climate change; Tha Chin River; Chao Phraya River

INTRODUCTION

In 2019, the International Panel on Climate Change (IPCC) published the Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019), the third in a series of special reports produced for the Sixth Assessment Report (AR6). This report assessed the current status and likely future changes in the ocean and cryosphere associated with ongoing global warming, as well as the risks and opportunities these changes create for ecosystems and people, and possible strategies for adaptation and governance to mitigate future risk. Importantly, this report represented the first consensus among the scientific community on the likely extent of sea level change (SLC).

All people depend directly or indirectly on oceans and the cryosphere for their livelihoods. The 4 million people (10% of whom are indigenous) living in the Arctic, 680 million living in low-altitude coastal areas (about 11% of the world’s population in 2010), 670 million living in alpine areas (about 10% of the world’s population in 2010), and 65 million living in developing small island countries are most directly affected by oceanic and cryosphere changes (IPCC, 2019).

Even if rapid and significant greenhouse gas (GHG) emission reductions are achieved in the future, oceanic and cryosphere changes will continue. If high GHG emissions continue, the impact of long- and ultra-long-term changes on future generations will be more severe. Under the Representative Concentration Pathway (RCP) 8.5 scenario, which includes high GHG emissions by 2100, ocean heat absorption will be 5–7 times higher (vs. 2–4 times for RCP2.6, which includes low GHG emissions), and the ocean surface temperature will increase by 3–4°C, compared with today. RCP8.5 predicts an SLC of 0.84 m (range: 0.61–1.10 m) by 2100 (vs. 0.43 m [range: 0.29–0.59 m] for RCP2.6), and the frequency of extreme sea level events, such as storm surges, will also increase (IPCC, 2019).

Sea level rise projections, and an understanding of the uncertainties therein, are essential for informed mitigation and adaptation decisions. Horton et al. (2020) reexamined their projections for future global mean sea level (GMSL) rise based on data provided by 106 experts. The revised upper limit estimates and increased uncertainty within the data were due to recent influential studies showing the contribution of meltwater from unstable ice cliffs in the Antarctic ice sheet to GMSL rise.

Translating sea level projections into estimates of population exposure is critical for coastal planning, and for assessing the benefits of climate change mitigation measures and costs of climate change adaptation measures. Digital elevation model (DEM) data are indispensable for such analyses. However, due to military, political, economic, and technical factors, a limited number of countries and regions have access to high-resolution DEMs. Shuttle Radar Topography Mission (SRTM) data have become the standard resource for extreme coastal water level (ECWL) analyses in areas lacking high-quality or affordable elevation data (Lichter et al., 2011; Jongman et al., 2012; Hinkel et al., 2014).

McGranahan et al. (2007) provided the first review of population and urban settlement patterns in the Low Elevation Coastal Zone (LECZ). They found that the LECZ had 2% of the global land area, 10% of the global population, and 13% of the global urban population, and reported that a combination of mitigation, migration, and change of resi-
dence was required to reduce the risk of climate change-related disasters in coastal settlements. Neumann et al. (2015) analyzed a variety of coastal hazards, including sea level rise and its projected impact on coastal populations at the global and regional scales by 2030 and 2060. Using data obtained from DEMs, SRTM, and other models, including AW3D30 (Tadono et al., 2016), MERIT DEM (Yamazaki et al., 2017) and CoastalDEM (Kulp and Strauss, 2018), global mean SLC values have been reported to be comparable to the “positive vertical bias” of a major DEM (Kulp and Strauss, 2019). Using the 3-arcsecond (90-m) version of CoastalDEM, these authors estimated that 1 billion and 230 million people live less than 10 and 1 m, respectively, from a high tide line.

The latest research indicates that at least 83% of the expected storm surge inundation damage associated with sea level rise in Europe could be avoided if coastal dikes are raised in approximately one third of the entire European coastline (Vousdoukas et al., 2020).

Bangkok is one of the largest megacities in Southeast Asia, and is also among the world capitals most vulnerable to the impact of disasters caused by a combination of sea level rise and river flooding (Dutta, 2011). In 2011, Thailand experienced the worst flood in its history, and faced a major crisis due to the combined effects of the flooding and storm surges (Komori et al., 2012). The risk of coastal flooding is very high in central Bangkok because it is a flat, lowland area with land subsidence, which makes it difficult for inland water to drain to the sea (Phien-wej et al., 2006). After the 2011 flood, a highly precise DEM was created using LiDAR aerial survey data of the flooded area, with the support of the Japanese government (Japan International Cooperation Agency, 2012).

Global DEMs have a limited ability to assess the effects of fine-scale SLCs. In this study, we used a high-precision, high-resolution DEM (2 m × 2 m) based on LiDAR aerial surveys and IPCC estimates of SLC to assess the vulnerable population in the Bangkok metropolitan area to future SLC.

DATA AND METHODS

The study area was the lower Chao Phraya River basin, including the Bangkok metropolitan area, which contains 16% of the population of Thailand and is responsible for 44% of its gross domestic product (GDP) (Ministry of Digital Economy and Society, 2019). The lower Chao Phraya River basin, especially from Ayutthaya to the river mouth, is a low-lying area with a very gentle slope; it is therefore at high risk of flood inundation. Thailand experienced severe floods in 1983, 1995, 1996, 2002, and 2006. The worst of these floods occurred in 2011; it affected Thailand’s socioeconomic status as well as its global industrial activities. In 2012, Japan International Cooperation Agency (JICA) conducted a LiDAR (Light Detection And Ranging) aerial survey as part of the Chao Phraya River basin flood management project (JICA, 2012). As shown in Figure 1, the target area of the survey was about 24,700 km² of flooded land along the lower Yom and Nan Rivers, and the Chao Phraya River running from Bangkok to the southern part of Sukhothai Province (about 420 km northward). The technical standards of the survey were in accordance with those of the Japanese Ministry of Land, Infrastructure, Transport and Tourism. The region was within Universal Transverse Mercator (UTM) Zone 47N, and the World Geodetic System 1984 (WGS84) ellipsoid was used (ITRF2008). The height standard was the mean sea level (MSL). Topographic data for a 2-m grid with an accuracy of less than 0.25 m were generated. Rectangles in

Figure 1. Map of Thailand and the Bangkok metropolitan area (AMSL: altitude above mean sea level, z_mean: mean height in a 2 km × 2 km mesh)
Figure 1 indicate data that cannot be disclosed to the public; these include prohibited areas, where flyovers are forbidden, and secured military and civil aviation areas. Most of these areas are generally uninhabited; therefore, their exclusion had no significant impact on the analysis. A total of 5,940,821,177 meshes (23,763 km$^2$) were included in this analysis, as provided by the Royal Irrigation Department of the Thai government.

Following this, analysis of tidal data acquired by the Thai government at King Chulalongkorn Fort (13°32'23'', 100°35'5'') from August 1, 2016 to September 30, 2019 was performed (Figure S1). The highest and lowest elevations observed during this period were 3.12 m above MSL and −1.08 m below MSL, respectively, with a mean of 0.99 and median of 1.11 m above MSL. Population vulnerability was therefore assessed based on the median elevation of 1.11 m above MSL.

To assess the vulnerable population, we used 30-arcsecond (approximately 1-km) population data obtained from the LandScan 2016 Global Population Database (U.S. Department of Energy, Office of Scientific and Technical Information, 2017). The high-resolution DEM and population data were treated as point data, with the closest points within the search area spatially combined into approximately 2-km meshes.

**RESULTS**

Figure S2 shows the relative frequency distribution of the high-resolution DEM data (2 m × 2 m) used in the analysis. The data were generally distributed into two peaks: one between 0 and 1 m in the Bangkok metropolitan area and one above 10 m in the northern region. Of the total target region, 41.3% was below an elevation of 5 m due to extensive low-lying coastal areas. DEM data for an area of about 2 km × 2 km (average of 951,750 meshes) were analyzed; the elevation of this area is shown in Figure 1. The median and standard deviation (SD) of each mesh is shown in Figure S3; the average elevation of this region is less than 5 m above sea level, except beyond 100 km north of the river mouth. Higher elevation was observed on the east side of Nakhon Sawan due to the presence of small hills in the north–south direction. The SD of the elevation of the flatter region (from the estuary to about 100 km north thereof) was small, and analysis of the large meshes in the 2 km × 2 km area was straightforward.

Figure S4 compares LiDAR, SRTM and MERIT elevation data, from East to West across the center of Bangkok. Table S1 shows the fundamental statistic of the LiDAR, SRTM, and MERIT elevation data in Figure S4. The median tide level, 1.11 m, is also shown in Figure S1. As mentioned above, LiDAR data in and around the Chao Phraya River are not available, so are treated as missing data. SRTM and MERIT show a generally similar trend, but there is little similarity between them and the LiDAR data. In particular, LiDAR can be considered more advantageous than SRTM and MERIT for assessing sea level rise due to large differences (> 5 m) in the central area.

To assess the vulnerability of the Bangkok metropolitan area to SLC, we used the global MSL (GMSL) rise ranges (+0.61 to +1.11 m) scenarios by the IPCC (2019). In this study, a median tide level of 1.11 m was used as a reference, and assessments were performed at +0.1-m increments.

Changes in sea level and affected areas are shown in Figure 2. The area of land with an elevation below the median tide level of 1.11 m was 2,520 km$^2$. The area below a tide level of 1.70 m (current median tide level 1.11 +0.59 m), which is the maximum predicted for the RCP2.6 scenario, represents a 76% increase to 4,446 km$^2$, while that below a tide level of 2.21 m (current median tide level 1.11 +1.10 m), which is the maximum predicted for the RCP 8.5 scenario, represents a 144% increase to 6,140 km$^2$. A mean SLC of +0.43 m for the RCP 2.6 scenario affected about 1.5 times the area affected under the current sea level, and an MSL change of +0.84 m for the RCP 8.5 scenario affected about 2 times the area affected under the current sea level. The rate of increase in the affected area was relatively constant, ranging from 12–14% per +0.1 m.

Distribution maps of the area affected by SLC for each RCP scenario are shown in Figure 3. Regions in which more than 80% of the total area is below the current median tide level of 1.11 m include Samut Prakan, and parts of Samut Sakhon and eastern Bangkok Metropolis (Figure 3a). The areas affected under the maximum SLC of the RCP 2.6 scenario (median tide level, 1.70 m above MSL) included all of Samut Prakan, Bangkok Metropolis, and Samut Sakhon, as well as southern lowland parts of Suphan Buri, which is about 80 km inland from the estuary along the Tha Chin River. The area affected under the RCP8.5 scenario (median tide level, 2.21 m above MSL) extended to Pathum Thani, Nonthaburi, and Nakhon Pathom, in addition to the three provinces affected under all scenarios; the risk of SLC in areas with high population and property concentrations is very high under this scenario. Thus, under the RCP8.5 scenario (Figure 3d), the risk of SLC would be greater inland than along the coast. In particular, the risk was significantly higher along the Tha Chin River, which flows down the Nakhon Pathom and Suphan Buri.

The proportions of the population vulnerable to SLC changes under each RCP scenario are shown in Figure 4. The vulnerable population was determined by multiplying...
the population within the 2 km × 2 km mesh by the rate of SLC. The estimated vulnerable population residing below the current median tide level of 1.11 m is 3.9 million; that for the RCP2.6 scenario (median tide level, 1.70 m; i.e. +0.59 m) is 59% higher, at 6.2 million, and that for the RCP8.5 scenario (median tide level, 2.21 m; i.e. +1.10 m) is 86% higher, at 7.2 million. Thus, the vulnerable populations of the current, RCP2.6, and RCP8.5 scenarios represent 35%, 56%, and 66%, respectively, of the latest (2019) Bangkok metropolitan area total population estimate of 10.9 million (Bangkok, population 5.7 million; Samut Prakan Province, population 1.3 million; Nonthaburi Province, population 1.3 million; Pathum Thani Province, population 1.2 million; Nakhon Pathom Province, population 0.6 million; Samut Sakhon Province, population 0.6 million) (Department of Provincial Administration, 2020). The vulnerable population increased by 10% for every +0.1 m, up to an SLC of +0.5 m, after which the rate of increase began to subside; from +1.00 m to +1.10 m, the vulnerable population increased by only 4%.

Figure 5 shows the relationship between rates of increase in the area affected by SLC and the vulnerable population.

Figure 3. Distribution maps showing the proportion of area at elevations of (a) ≤1.11 m (current median tide level), (b) ≤1.70 m (worst case scenario for Representative Concentration Pathway [RCP] 2.6), and (c) ≤2.21 m (worst case scenario for RCP8.5). (d) Relative increases from (a) to (c).

Figure 4. Sea level change and associated increases in the vulnerable population.

Figure 5. Relationship between increases in affected area and the vulnerable population.
ble population. Up to +0.3 m of SLC, this relationship generally increased as a 1:1 ratio; however, above +0.3 m, the rate of increase in the vulnerable population was smaller than that of the affected area; as the gap widened, the rate of increase of the vulnerable population slowed. Since the central region of the densely populated Bangkok metropolitan area was originally located in a low-lying area, the rate of growth of the vulnerable population was expected to slow as the area affected by SLC extended to less densely populated areas. Therefore, there is an urgent need to adapt to SLC in areas below 1.41 m above MSL, where SLCs of +0.3 m are predicted.

Figure 6 shows distribution maps of vulnerable population density. For the current median tidal level of 1.11 m, the vulnerable population is extremely concentrated within a zone from central to western Bangkok Metropolis. For a median tide level of 1.70 m (+0.59 m; RCP2.6), the vulnerable population is further concentrated in central Bangkok Metropolis, spreading to the north and with an increase in Samut Sakhon city center. For a median tide of 2.21 m (+1.10 m; RCP8.5), the vulnerable population extends further north to the southern part of Pathum Thani. Compared with the current risk level, under the maximum-risk RCP8.5 scenario (Figure 6d) the vulnerable population density is increased in central Bangkok Metropolis, near the provincial borders between Bangkok Metropolis and Nonthaburi, and between Bangkok Metropolis and Samut Sakhon. Although these increases do not represent a large increase in the vulnerable population at the regional scale, the vulnerable population density was higher in these regions.

**DISCUSSION AND CONCLUSION**

Vulnerability to SLC due to climate change in the Bangkok metropolitan area was assessed using high-precision, high-resolution DEM data obtained by Lidar aerial surveys. The estimated area below the current median tide level of 1.11 m was 2,520 km², with a vulnerable population of 3.9 million (23% of the population of the Bangkok metropolitan area). In the worst-case scenario of RCP2.6, including an SLC of +0.59 m, the affected area extended to 4,446 km², with the vulnerable population increasing by 59% to an estimated 6.2 million people. Under the worst-case scenario of RCP8.5, including an SLC of +1.10 m, the affected area extended to 6,140 km², with the vulnerable population increasing by 86% to 7.2 million people. The area where SLC was less than +1.10 m extended from the Chao Phraya River mouth to Suphan Buri, about 80 km inland; under these conditions, the size of the vulnerable population did not increase, but it became denser. At elevations below 1.41 m (+0.3 m SLC), the affected area and vulnerable population are predicted to increase proportionally; therefore, it is necessary to improve not only migration and settlement policies, which are key for adapting to SLC due to climate change, but also urban structure in regions with a high-density vulnerable population.
population.

Due to the limited availability of high-quality homogeneous data, this study evaluated the impact of sea level rise on the Bangkok metropolitan area based on average tide levels. It is important that both flooding and tide level values are discussed simultaneously because the study area overlaps the storm surge and flood areas. If the peak flooding and tide levels coincide, catastrophic flooding can be expected. A detailed analysis of the frequency and timing of storm surges and floods should be performed to determine the combined risk of storm surges and flooding.

Furthermore, as mentioned in Figure S3, the accuracy and resolution of the elevation data are extremely important factors when assessing the risk posed by sea level rise; these factors clearly affect the results, especially in low-lying areas (such as the study area). Interpretation using SRTM would result in a significant underestimation of flood risk and should be used carefully. Since very accurate DEM data are limited and LiDAR is very technical and expensive, it is impractical to develop data for the entire world. Increasing the accuracy of elevation data is essential for assessing the risks of both river flooding and sea level rise in low-lying areas and constitutes a global challenge.

In conclusion, the findings of this study should prove interesting and important to stakeholders including government agencies, communities, and the private sector, not only in the Bangkok Metropolitan area but across the whole of Thailand. In particular, it should be considered whether Bangkok and industrial parks in Ayutthaya, which are important manufacturing sites at the global scale, will continue to be suitable locations for manufacturing industries in the future.

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SUPPLEMENTS

Figure S1. Time series of tide level at King Chulalongkorn Fort (13°32’23”, 100°35’5”; see Figure 1) from August 2016 to September 2019 (AMSL; altitude above mean sea level)

Figure S2. Relative frequency distribution of high-resolution elevation data of the lower Chao Phraya River basin (AMSL; altitude above mean sea level)

Figure S3. Distribution maps of the median and standard deviation of LiDAR elevation data (AMSL; altitude above mean sea level, z_median; median value in a 2 km × 2 km mesh, z_stdev; standard deviation in a 2 km × 2 km mesh)

Figure S4. LiDAR, SRTM and MERIT elevation data, from East to West across the center of Bangkok (AMSL; altitude above mean sea level, see also Figure S3)

Table S1. Fundamental statistic for the LiDAR, SRTM, and MERIT elevation data, from east to west across the center of Bangkok (Figure S3)

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