# Urbanization and Climate Change Hazards in Asia

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## 1 Introduction

United Nations forecasts of urban population growth suggest that over the quarter century from 2000 to 2025, Asian countries will see a net increase of more than one billion people in their cities and towns, a quantity that vastly outnumbers the expected rural population increase in these countries and which dwarfs all anticipated growth in high-income countries (United Nations 2012). In the 25 years after 2025, the United Nations foresees the addition of another one billion urban-dwellers to Asian populations, with the rural populations of these countries forecast to be on the decline. Close to 60 percent of all the city growth in the world will occur in the cities of Asia. This growth seems to be disproportionately located in the regions of poor countries, some of which appear to be environmentally insecure. Some of these poorer regions of the world—particularly deltaic regions—are expected to feel the brunt of climate-related change in the coming decades.

Yet where precisely, and which populations, in these regions has not been systematically assessed. This paper documents the current locations of urban-dwellers in Asia of ecologically delineated zones that are expected to experience the full force of climate change: the low-elevation coastal zones, areas susceptible to inland flooding (apart from coastal sources), and the arid regions known to ecologists as drylands. Low-lying cities and towns near the coast will most probably face increased risks from storm surges and flooding; those in drylands are expected to experience increased water stress and episodes of extreme heat, as well as flash flooding.

Because seaward hazards are forecast to increase in number and intensity as climate change takes hold, and coastal areas are disproportionately urban, it is especially important to quantify the exposure of urban residents in low-elevation coastal zones, and to understand the likely implications for their health. While potential coastal flooding in cities has received attention, in part because the long-term implications of rising sea-levels and change coastal zones, increasing precipitation, in general, and more extreme weather events will also lead to greater flood risks to city-dwellers from in-land water sources. In this paper, flood exposures from in-land water sources are also estimated, not only because some coastal cities are also at risk of flooding from in-land waterways, but climate-induced flooding may impact non-coastal rivers, and regions of deltaic countries farther from the coast.

Another vulnerable ecosystem—drylands—contains (globally) far larger populations than found in the LECZs. Much of the discussion of climate change for drylands has focused on the rural implications—but what will it mean to be an urban resident of the drylands? Asia is home to some of the world's largest dryland cities, some of which are already under considerable water stress due to city population growth (McDonald et al. 2011); the impact of climate-change related water scarcity will not start to be realized until mid-century after which population sizes of rapidly growing countries will have stabilized. Dryland cities tend to be located near rivers, as historically rivers have provided water resources, trading opportunities and so forth. In others, dryland cities too may face flooding risk.

In the paper, we review three types of urban climate-change related exposures: coastal flooding, inland flooding, and aridity. We describe exposures in terms of land area and population. We end with an illustrative discussion of the importance of identifying other measures of vulnerability that should be explored, where the data permit.

## 2 What climate-related risks face city dwellers?

According to current forecasts, sea levels will gradually but inexorably rise over the coming decades, placing large coastal urban populations under threat around the globe. Alley et al. (2007) foresee increases of 0.2 to 0.6 metres in sea level by 2100, a development that will be accompanied by more intense typhoons and hurricanes, storm surges and periods of exceptionally high precipitation. Many of Asia's largest cities are located in coastal areas that have long been cyclone-prone. Mumbai saw massive floods in 2005, as did Karachi in 2007 (Kovats and Akhtar 2008; World Bank 2008). A coastal flood model used with the climate scenarios developed for the Intergovernmental Panel on Climate Change (IPCC) suggests that the populations of the areas at risk, and the income levels of these populations, are critical factors in determining the health consequences of such extreme-weather events (Kovats and Lloyd 2009).

Whether from coastal or in-land sources, urban flooding risks in developing countries stem from a number of factors: impermeable surfaces that prevent water from being absorbed and cause rapid runoff; the general scarcity of parks and other green spaces to absorb such flows; rudimentary drainage systems that are often clogged by waste and which, in any case, are quickly overloaded with water; and the ill-advised development of marshlands and other natural buffers. When flooding occurs, faecal matter and other hazardous materials contaminate flood waters and spill into open wells, elevating the risks of water-borne, respiratory and skin diseases (Ahern et al. 2005; Kovats and Akhtar 2008).

The urban poor are often more exposed than others to these environmental hazards, because the only housing they can afford tends to be located in environmentally riskier areas, the housing itself affords less protection and their mobility is more constrained. The poor are likely to experience further indirect damage as a result of the loss of their homes, population displacement and the disruption of livelihoods and networks of social support (Hardoy and Pandiella 2009). Kovats and Akhtar (2008, p. 169) detail some of the flood-related health risks: increases in cholera, cryptosporidiosis, typhoid fever and diarrhoeal diseases. They describe increases in cases of leptospirosis after the Mumbai floods of 2000, 2001 and 2005, but caution that the excess risks of this disease due to flooding are hard to quantify without better baseline data. They also note the problem of water contaminated by chemicals, heavy metals and other hazardous substances, especially for city-dwellers who live near industrial areas.

The principal characteristics of drylands are succinctly summarized by Safriel et al. (2005, p. 651) as follows: "Drylands are characterized by low, unpredictable, and erratic precipitation. The expected annual rainfall typically occurs in a limited number of intensive, highly erosive storms." Safriel et al. (2005, p. 626) estimate that drylands cover 41 per cent of the Earth's surface and provide a home to some 2 billion people. Developing countries account for about 72 per cent of this land area and some 87–93 per cent of the drylands population (the range depends on how the former Soviet republics are classified). McGrahanan et al. (2005) estimate that about 45 per cent of the drylands population is urban.

Almost by definition, water shortages plague drylands ecosystems. In this ecosystem, there is an estimated 1,300 cubic meters of water available per person per year, well below the 2,000 cubic meter threshold considered sufficient for human well-being and sustainable development (Safriel et al. 2005, pp. 625, 632). In the dryland areas where rivers are currently fed by glacier melt, the flows from this source will eventually decrease as the glaciers shrink, rendering flows in some rivers seasonal (Kovats and Akhtar 2008). Cities dependent on these sources of water. The areas fed by the Indus river in Pakistan, for example, will eventually need to find alternatives (Committee on Himalayan Glaciers, Hydrology, Climate Change, and Implications for Water Security 2012).

## 3 Methods and data

Urban flood risks are estimated in the following way. Urban areas are delineated by the Global Rural–Urban Mapping Project (SEDAC 2008; Balk 2009). Typically, these urban extents include not only the core urban center, but also the peri-urban area that surrounds most medium and large-sized cities. The size of GRUMP extents have been compared to other possible urban extents (Tatem and Hay 2004; Tatem et al. 2011) and are found to be larger than those based on conventional remote sensing classification of built-up areas.[1] However, GRUMP is the only spatial database indicating urban areas with global coverage (Balk 2009). In addition to identifying urban extents, GRUMP supplies population estimates at a spatial resolution of 1 kilometer.

The data used to estimate flood risks come from two rather different sources. In coastal areas, the low-elevation coastal zone (LECZ) serves as a proxy for exposure to risk, rather than historic or projected data on actual coastal flood events. The LECZ is defined as land area contiguous with the coastline up to 10 meters elevation, based on the measure from the Shuttle Radar Topography Mission (SRTM) elevation data set (McGranahan, Balk, and Anderson 2007). Although sea-level rise is not expected to reach 10 meters above the current mid-tide elevations, at least in the foreseeable future, with storm surges, the 10 meters elevation leaves a large margin of safety regarding direct flooding. Sea-level rise and storm surges can certainly cause damage to people living well above the high-water level, through saline intrusion into the groundwater, for example. However, the principal reason for choosing this elevation is that estimates based on elevations below 10 meters could not be considered globally reliable, particularly in some types of coastal areas such as those characterized by mountainous bays.

Exposure to in-land flood risk is estimated from global flood frequency dataset developed for the 2009 Global Assessment Report on Risk Reduction (GAR) report (ISDR 2009). In contrast to the LECZ data to estimate coastal population and land at risk, the GAR data are modeled data based on recorded flood frequency events. (Modeling is used to fill in missing data and to transform the extents of flood events into a single gridded data format.) The standard for flood-risk is considered to be exposure to flooding at least twice within a one-hundred year period[2] Therefore, in our calculations urban land or persons at risk of in-land flooding are considered to be those in areas which are expect to have flooded at least twice in the past 100 years. (Higher levels of flood frequency may also be calculated, as well mean expected flood frequencies for urban areas.)

Both the LECZ and GAR data are then overlaid with the GRUMP data to estimate population (as well as land area) within each urban area at risk of flooding, and similarly the dryland ecosystem data are used to estimate persons at risk in arid urban areas. Additional details on the data and methods are found in the appendix.

# 4 Results

We find that Asia is more vulnerable to flooding than other regions. Earlier studies at the national level (McGranahan, Balk, and Anderson 2007) showed that 13 percent of the total population of Asia and 18 percent of the urban population is situated in the Low Elevation Coastal Zone. This compares to 10 percent of total population and 13 percent of urban population, globally. Similar high comparative proportions of total and urban land are found in low-lying coastal areas of Asia relative to other continents. These areas are not only at greater risk of future sea-level rise, but of flooding due to coastal flooding arise from more frequent and intense storm systems.

Building on this national level work, we estimate the population exposures in 2025 using simple linear extrapolation of the United Nations national-level urban population growth estimates (UN, 2010). We find that

[1]In the usual approach, land-cover classifications are used to measure urban areas. The land-cover approach takes the absence of vegetation as a means of indicating which areas are urban.(That is, these sensors are meant to detect primarily vegetation, so either the absence of it, or when vegetation is identified in a mixed pattern, is used as a means to a classification of urban areas.) This method usually produces smallish urban 'footprints'; and where cities are very green or suburban areas very green, it does less well to capture those green areas. But this type of classification produces a smaller urban area that probably correspond more closely with city-proper type definitions of localities (though this has not been empirically evaluated). It was an innovation for GRUMP to use the night-time lights which does not measure vegetation but rather illuminated area which is almost always cities. This is the only globally consistent proxy for urban (as opposed to the land-cover classification method which is subjective and local or continental at 1-kilometer resolution). Sometimes the source of light is not a city but an industrial parks or mines, but in the version of the lights data used for GRUMP (a product called "stable city lights"), mining operations (and other sources of lights at night like this) were removed. The lights extend beyond the city-proper in almost all cases, and as a result capture the surrounding suburban and peri-urban area. In countries that tend to light-up at night for economic or cultural reasons, cities may appear disproportionately larger, though this too has not been empirically evaluated.

[2]The flood extent data used by the GAR report are based on a hydrological model but the events that serve as a backbone to estimate flood frequency come from a 30-year observation period rather than a 50-year one. To protect somewhat against underestimation of flood-frequencies, missing data in the flood extent was assigned a value of 2 (per 100 years). This is a known limitation of the data set.

over 300 million city dwellers were at risk of coastal flooding in 2010 and by 2025, the projection is for 430 million persons at risk. In terms of inland-flooding, about 250 million urban Asians were found to be at risk in 2010 and that by 2025 this number will reach 350 million.

Tables 4 and 3 (column 4) presents the proportion of a city's population at flood risk, and can be taken as an indicator of vulnerability to in-land and coastal flooding, respectively. Apart from these well-documented risks, it is noteworthy that Asian cities are far more densely populated than cities any all other continents. Table 5 shows population density of cities in Asia, Africa and Latin American (shown by South America and North America, from which Canada and the US are omitted). The average density shown here has been calculated in two ways: in the first three columns we see continental summaries of urban land area and urban population (expressed in 1000s), and the overall population density of cities. But this estimate is not an average of the density of cities themselves. That mean density is shown in the final column of the table; in the two columns preceding it, the average land area and average population for cities in each continent is also given. By both methods, Asian cities are unambiguously more dense than those in other continents.

Table 5 also shows that African cities are also considerably denser than cities in the Americas with densities much closer to Asian cities. Unlike Africa, cities in Asia in addition to be denser are also much more populous than those in other continents. The average urban area (of urban settlements of 5,000 persons or more) has 720 persons per square kilometer in Asia, as compared with about 500 in Africa. The high density of population in Asian cities is similarly found in Asian coastal cities, placing very concentrated population at risk of coastal flooding, as seen as Figure3 and Figure4.

The distribution of risks of urban flooding within Asia is not uniform across countries. The risks of in-land flooding are distributed across countries that have seacoasts as well as those which are landlocked (see Table 1). About three-quarters of the urban population of Cambodia is at risk of in-land flooding. Around 35 percent of the urban population of Bangladesh, Vietnam, Lao, and Thailand are similarly at risk. One-fifth of the urban population of China and 12 percent of India, totally more than 120 million persons (in 2000) are at risk of in-land flooding. Even the urban population of landlocked countries have substantial shares at risk: Tajikistan (16%), Bhutan (15%), Afghanistan (13%), Nepal (13%), and Kyrgyzstan (12%).

In contrast to in-land flood risk, the risk of coastal flooding in Asian cities is heavily concentrated in Southeast region with all countries (except landlocked Laos) facing substantially high proportions of their population at risk (see Table 2). In addition, half of the city residents of Bangladesh, 20% of Taiwanese urbanites, and 18% of China's urban population are at risk of coastal flooding.

There are 38 Asian cities with populations of 1 million or more (as measured in 2000) situated in low-lying coastal areas,as seen in Table3, and 17 such cities at risk of in-land flooding, as seen in Table4. Clearly, some major cities face enormous challenges: 99 percent and 98 percent of population in Phnom Penh and Hanoi (highlighted in red), respectively, are at risk of in-land flooding. Lesser fractions of these cities population, about 10 percent and 40 percent of these city's population are at risk of coastal flooding as well. Other large cities face much greater risk from coastal sources, while also facing some risk from in-land sources: such as, Kolkata (88% coastal, 15% in-land) and Shanghai (90% coastal, 25% in-land). A small handful of very large cities are at heightened risk, in that they have more than 50 percent of populations at risk of both coastal and in-land flooding: Dhaka, Bangladesh; Ho Chi Minh City, Vietnam; Palembang, Indonesia; Tianjin, China. Bangkok, Thailand which has over 90% of its population at risk of coastal flooding has somewhat of less than 50% of its population at risk of in-land flooding. Figures 1 and 2 depict the vulnerabilities of major Asian cities.

Over 60 cities of 100,000 persons and above have all of their land area in the LECZ. Asia has over 750 urban settlements of at least 5,000 population (most being much larger) whose populations are fully situated in low-lying zones at risk of coastal flooding, and about half as many with 100 percent of their populations at risk of in-land flooding. These smaller cities and towns are especially noteworthy because they are the urban areas which are experiencing much faster rates than large cities. Further, some of these cities are found in close proximity to vulnerable large cities. Agglomeration economies have many benefits for growth (World Bank 2009), but to the extent that they share flood risks, these issues should be accounted for in planning.

The highest risk of flooding—that is, flood frequencies of every other year—is highly concentrated. Of all cities and towns with over 10,000 persons at very high risk of in-land flood frequency (i.e., at least every other year), all such cities are found in three countries (in Asia): Bangladesh, China, and India (not shown in Table). Given the poor state of the Bangladesh economy, this is likely to pose an especially large burden there. Even for China and India, strategies to manage these risks—whether through technology, land use regulation or other policies, or climate adaptation strategies—are essential.

While this paper has focused on the hazards associated with flooding, it is important to note that much of the land area of Asia is arid or semi-arid. Dryland cities pose different problems, largely associated with water supply but also flooding (McDonald et al. 2011). Over 11,000 cities and towns are located in drylands. (Of the 22,000 possible towns and cities in Asia, slightly less than 3,000 are found in the LECZ, and close to 9000 face some sort of inland flood risk.) More than 80 cities of over 1 million persons are located in dryland ecosystems, as shown in Table 7. In contrast to cities situated in the LECZ, there are many more cities found in arid environments (and many cities in both arid areas and the LECZ). Like cities at risk of inland-flooding, there are many small cities that are situated in drylands. Unlike cities in the LECZ, where often only some part of the land area or population is found in this higher-risk zone, cities in dryland ecosystems are entirely contained in drylands. (This is partly dependent on the way drylands are measured.) Dryland cities require that attention is shifted by deltaic south and southeast Asia, and coastal China, to western Asian countries. While cities and India and China remain prominently high on this list, the focus is expanded to include: Pakistan, Iraq, Burma and Uzbekistan, and Turkey among many others.

While this analysis has not systematically assessed multiple risks for cities, it is clear that India and China, in particular, face many different types of climate-change risks: flooding, including that from inland sources as well as that from seaward hazards, and increasing aridity and the associated potential problems of water scarcity. Delhi is the largest city that notably shares the risks of being arid and flood-prone, but it is not alone. Climate adaptation must be tailored to the type of risk present in a given place, but the national and regional and, in some locations, city-specific dialogues must include all that are present. Because the risks of drought are often felt in the medium term, whereas flood events appear to have an acute quality, planning may require somewhat different types of horizons for these different hazards.

Table 1: In-land flood risk estimates for Asian countries

| | | Estimates Based on Named Grump Extents (2000) | | | | | |
|---|---|---|---|---|---|---|---|
| **Developing Member Economies** | **ISO3V10** | **GRUMP Estimate of Urban Population (2000)** | **Urban Land Area (km2)** | **Urban Population (2000) at in-land flood risk** | **Urban Land Area (km2) at in-land flood risk** | **% Urban Population at in-land flood risk** | **% Urban Land Area at in-land flood risk** |
| **Central and West Asia** | | | | | | | |
| Afghanistan | AFG | 4,319,906 | 1,805 | 540,078 | 430 | 12.5% | 23.8% |
| Armenia | ARM | 2,701,200 | 1,489 | 198,941 | 192 | 7.4% | 12.9% |
| Azerbaijan | AZE | 4,244,780 | 5,760 | 254,474 | 526 | 6.0% | 9.1% |
| Georgia | GEO | 3,063,351 | 3,242 | 319,048 | 369 | 10.4% | 11.4% |
| Kazakhstan | KAZ | 8,781,633 | 11,258 | 860,190 | 1,561 | 9.8% | 13.9% |
| Kyrgyz Republic | KGZ | 1,547,700 | 2,921 | 189,534 | 367 | 12.2% | 12.6% |
| Pakistan | PAK | 48,111,184 | 24,780 | 3,092,548 | 2,230 | 6.4% | 9.0% |
| Tajikistan | TJK | 1,745,045 | 3,506 | 286,229 | 408 | 16.4% | 11.6% |
| Turkmenistan | TKM | 2,010,483 | 5,592 | 64,777 | 620 | 3.2% | 11.1% |
| Uzbekistan | UZB | 9,522,296 | 14,828 | 813,736 | 1,615 | 8.5% | 10.9% |
| ***Region Summary*** | | *86,047,578* | *75,181* | *6,619,555* | *8,318* | *7.7%* | *11.1%* |
| **East Asia** | | | | | | | |
| China, People's Rep. of | CHN | 423,730,208 | 247,469 | 90,700,145 | 45,610 | 21.4% | 18.4% |
| Hong Kong, China | | | *No Inflooding found in the data* | | | | |
| Korea, Rep. of | KOR | 38,372,540 | 18,529 | 2,920,496 | 1,010 | 7.6% | 5.5% |
| Mongolia | MNG | 1,452,056 | 1,150 | 176,968 | 190 | 12.2% | 16.5% |
| Taipei,China | TWN | 14,113,644 | 12,214 | 890,354 | 668 | 6.3% | 5.5% |
| ***Region Summary*** | | *477,668,448* | *279,362* | *94,687,964* | *47,478* | *19.8%* | *17.0%* |
| **South Asia** | | | | | | | |
| Bangladesh | BGD | 30,691,712 | 9,853 | 10,954,609 | 3,721 | 35.7% | 37.8% |
| Bhutan | BTN | 148,428 | 192 | 21,504 | 30 | 14.5% | 15.5% |
| India | IND | 301,205,728 | 192,899 | 36,056,326 | 25,564 | 12.0% | 13.3% |
| Maldives | | | *No Inflooding found in the data* | | | | |
| Nepal | NPL | 2,718,889 | 2,526 | 160,508 | 214 | 5.9% | 8.5% |
| Sri Lanka | LKA | 4,223,072 | 3,302 | 792,244 | 442 | 18.8% | 13.4% |
| ***Region Summary*** | | *338,987,829* | *208,771* | *47,985,191* | *29,971* | *14.2%* | *14.4%* |
| **Southeast Asia** | | | | | | | |
| Brunei Darussalam | BRN | 222,328 | 1,058 | 1,634 | 14 | 0.7% | 1.3% |
| Cambodia | KHM | 1,879,902 | 641 | 1,428,121 | 641 | 76.0% | 100.0% |
| Indonesia | IDN | 81,381,744 | 30,958 | 4,394,972 | 2,417 | 5.4% | 7.8% |
| Lao PDR | LAO | 889,893 | 1,058 | 302,825 | 276 | 34.0% | 26.1% |
| Malaysia | MYS | 13,905,574 | 13,455 | 495,254 | 749 | 3.6% | 5.6% |
| Myanmar | MMR | 12,456,011 | 4,483 | 2,361,353 | 1,050 | 19.0% | 23.4% |
| Philippines | PHL | 24,867,986 | 8,201 | 3,713,398 | 968 | 14.9% | 11.8% |
| Singapore | | | *No Inflooding found in the data* | | | | |
| Thailand | THA | 20,776,316 | 26,438 | 6,070,291 | 7,002 | 29.2% | 26.5% |
| Viet Nam | VNM | 17,405,768 | 5,840 | 6,716,973 | 1,893 | 38.6% | 32.4% |
| ***Region Summary*** | | *173,785,521* | *92,132* | *25,484,820* | *15,010* | *14.7%* | *16.3%* |
| ***Overall Summary for ADB regions*** | | *1,076,489,376* | *655,447* | *174,777,530* | *100,777* | *16.2%* | *15.4%* |

Table 2: Coastal flood risk estimates for Asian countries

| | | LECZ Estimates (2000) from McGranahan et al. | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Developing Member Economies** | **ISO3V10** | **GRUMP Estimate of Urban Population (2000)** | **Urban Land Area (km2)** | **Urban Population (2000) at coastal flood risk** | **Urban Land Area (km2) at coastal flood risk** | **Landlocked** | **% Urban Population at coastal flood risk** | **% Urban Land Area at coastal flood risk** |
| **Central and West Asia** | | | | | | | | |
| Afghanistan | AFG | 4,319,906 | 1,805 | 0 | 0 | 1 | 0.00% | 0.00% |
| Armenia | ARM | 2,701,200 | 1,489 | 0 | 0 | 1 | 0.00% | 0.00% |
| Azerbaijan | AZE | 4,244,780 | 5,760 | 0 | 0 | 1 | 0.00% | 0.00% |
| Georgia | GEO | 3,063,351 | 3,242 | 230,982 | 159 | 0 | 7.54% | 4.92% |
| Kazakhstan | KAZ | 8,781,633 | 11,258 | 0 | 0 | 1 | 0.00% | 0.00% |
| Kyrgyz Republic | KGZ | 1,547,700 | 2,921 | 0 | 0 | 1 | 0.00% | 0.00% |
| Pakistan | PAK | 48,111,184 | 24,780 | 2,227,119 | 364 | 0 | 4.63% | 1.47% |
| Tajikistan | TJK | 1,745,045 | 3,506 | 0 | 0 | 1 | 0.00% | 0.00% |
| Turkmenistan | TKM | 2,010,483 | 5,592 | 0 | 0 | 1 | 0.00% | 0.00% |
| Uzbekistan | UZB | 9,522,296 | 14,828 | 0 | 0 | 1 | 0.00% | 0.00% |
| ***Region Summary (coastal countries only for at risk estimation)*** | | *86,047,578* | *75,181* | *2,458,101* | *523* | | *4.8%* | *1.9%* |
| **East Asia** | | | | | | | | |
| China, People's Rep. of | CHN | 423,730,208 | 247,469 | 78,277,824 | 33,243 | 0 | 18.47% | 13.43% |
| Hong Kong, China | HKG | 5,744,131 | 728 | 811,925 | 104 | 0 | 14.13% | 14.21% |
| Korea, Rep. of | KOR | 38,372,540 | 18,529 | 2,034,832 | 1,369 | 0 | 5.30% | 7.39% |
| Mongolia | MNG | 1,452,056 | 1,150 | 0 | 0 | 1 | 0.00% | 0.00% |
| Taipei,China | TWN | 14,113,644 | 12,214 | 3,022,216 | 2,604 | 0 | 21.41% | 21.32% |
| ***Region Summary (coastal countries only for at risk estimation)*** | | *483,412,579* | *280,090* | *84,146,796* | *37,320* | | *17.5%* | *13.4%* |
| **South Asia** | | | | | | | | |
| Bangladesh | BGD | 30,691,712 | 9,853 | 15,428,668 | 4,522 | 0 | 50.27% | 45.90% |
| Bhutan | BTN | 148,428 | 192 | 0 | 0 | 1 | 0.00% | 0.00% |
| India | IND | 301,205,728 | 192,899 | 31,515,286 | 11,441 | 0 | 10.46% | 5.93% |
| Maldives | MDV | 6,421 | 3 | 6,421 | 3 | 0 | 100.00% | 100.00% |
| Nepal | NPL | 2,718,889 | 2,526 | 0 | 0 | 1 | 0.00% | 0.00% |
| Sri Lanka | LKA | 4,223,072 | 3,302 | 961,977 | 744 | 0 | 22.78% | 22.52% |
| ***Region Summary (coastal countries only for at risk estimation)*** | | *338,994,250* | *208,774* | *47,912,352* | *16,710* | | *14.1%* | *8.0%* |
| **Southeast Asia** | | | | | | | | |
| Brunei Darussalam | BRN | 222,328 | 1,058 | 24,965 | 256 | 0 | 11.23% | 24.15% |
| Cambodia | KHM | 1,879,902 | 641 | 281,944 | 137 | 0 | 15.00% | 21.33% |
| Indonesia | IDN | 81,381,744 | 30,958 | 22,720,666 | 8,176 | 0 | 27.92% | 26.41% |
| Lao PDR | LAO | 889,893 | 1,058 | 0 | 0 | 1 | 0.00% | 0.00% |
| Malaysia | MYS | 13,905,574 | 13,455 | 3,687,052 | 3,775 | 0 | 26.51% | 28.06% |
| Myanmar | MMR | 12,456,011 | 4,483 | 4,512,823 | 1,087 | 0 | 36.23% | 24.24% |
| Philippines | PHL | 24,867,986 | 8,201 | 6,807,578 | 1,872 | 0 | 27.37% | 22.83% |
| Singapore | SGP | 3,922,319 | 512 | 550,057 | 62 | 0 | 14.02% | 12.04% |
| Thailand | THA | 20,776,316 | 26,438 | 12,471,874 | 9,207 | 0 | 60.03% | 34.83% |
| Viet Nam | VNM | 17,405,768 | 5,840 | 12,862,429 | 3,877 | 0 | 73.90% | 66.39% |
| ***Region Summary (coastal countries only for at risk estimation)*** | | *177,707,840* | *92,645* | *63,919,387* | *28,448* | | *36.1%* | *31.1%* |
| ***Overall Summary for ADB regions(costal countries only for at risk estimation)*** | | *1,086,162,247* | *656,690* | *198,436,636* | *83,002* | | *18.97%* | *13.73%* |

Table 3: Large cities with high coastal flood risk

**Cities with over 1 million persons in the LECZ: Estimates of populations and land area at risk**

| City Name | Country | Population (2000) at flood risk | % of City Population | GRUMP Estimate of City (or Agglomeration) Population (2000) | City Area (km2) | City Area (km2) at flood risk | % area in flood |
|---|---|---|---|---|---|---|---|
| ADDAMMAM | Saudi Arabia | 1,284,390 | 79% | 1,614,460 | 2,578 | 2,051 | 79% |
| BANGKOK | Thailand | 8,800,710 | 93% | 9,437,410 | 5,990 | 4,805 | 80% |
| CHANGZHOU | China | 2,039,980 | 98% | 2,061,010 | 366 | 362 | 99% |
| CHENNAI | India | 2,854,580 | 36% | 7,755,660 | 1,343 | 393 | 29% |
| CHITTAGONG | Bangladesh | 2,388,670 | 72% | 3,294,730 | 838 | 517 | 61% |
| DHAKA | Bangladesh | 4,973,990 | 54% | 9,045,090 | 1,419 | 874 | 61% |
| HANGZHOU | China | 3,145,470 | 55% | 5,675,750 | 1,495 | 931 | 62% |
| HANOI | Viet Nam | 1,092,580 | 40% | 2,688,050 | 665 | 429 | 64% |
| HO CHI MINH CITY | Viet Nam | 4,425,950 | 79% | 5,582,420 | 1,225 | 890 | 72% |
| JAKARTA | Indonesia | 5,998,600 | 30% | 19,608,000 | 4,090 | 870 | 21% |
| JIANGYIN | China | 1,195,320 | 96% | 1,234,340 | 508 | 492 | 96% |
| KARACHI | Pakistan | 2,221,670 | 20% | 10,937,800 | 1,823 | 224 | 12% |
| KHULNA | Bangladesh | 1,130,170 | 99% | 1,131,130 | 395 | 394 | 99% |
| KOLKATA | India | 14,098,900 | 88% | 15,847,000 | 2,292 | 1,441 | 62% |
| MUMBAI | India | 8,055,930 | 46% | 17,401,700 | 2,113 | 848 | 40% |
| NANJING | China | 1,428,850 | 36% | 3,959,320 | 1,346 | 524 | 38% |
| NANTONG | China | 1,032,900 | 99% | 1,035,070 | 287 | 286 | 99% |
| NIIGATA | Japan | 1,002,500 | 68% | 1,462,960 | 2,490 | 1,244 | 49% |
| NINGBO | China | 1,697,390 | 85% | 1,983,190 | 910 | 779 | 85% |
| PALEMBANG | Indonesia | 1,309,310 | 94% | 1,390,140 | 529 | 473 | 89% |
| PANJIN | China | 1,044,840 | 100% | 1,044,840 | 690 | 690 | 100% |
| QINGDAO | China | 1,042,330 | 27% | 3,843,730 | 1,226 | 339 | 27% |
| QUANZHOU | China | 1,149,310 | 19% | 5,856,060 | 2,426 | 486 | 20% |
| QUEZON CITY - MANILA | Philippines | 3,350,510 | 23% | 14,401,700 | 2,163 | 346 | 15% |
| SHANGHAI | China | 13,699,400 | 90% | 15,083,700 | 2,460 | 2,416 | 98% |
| SHANTOU | China | 3,639,690 | 63% | 5,703,540 | 1,703 | 1,084 | 63% |
| SHENZHEN | China | 10,602,900 | 38% | 27,782,500 | 8,776 | 4,319 | 49% |
| SURABAYA | Indonesia | 3,801,970 | 76% | 4,981,240 | 1,403 | 777 | 55% |
| SURAT | India | 2,210,400 | 60% | 3,626,050 | 1,565 | 300 | 19% |
| SUZHOU | China | 1,286,780 | 95% | 1,342,770 | 403 | 368 | 91% |
| TAIPEI | Taiwan | 3,663,590 | 20% | 18,125,500 | 11,028 | 2,299 | 20% |
| TAIZHOU | China | 1,246,840 | 65% | 1,909,750 | 637 | 423 | 66% |
| TIANJIN | China | 5,498,720 | 100% | 5,498,720 | 2,081 | 2,081 | 100% |
| TOKYO | Japan | 21,290,300 | 27% | 76,302,000 | 43,141 | 7,954 | 18% |
| UJUNGPANDANG | Indonesia | 1,164,100 | 85% | 1,363,810 | 429 | 295 | 68% |
| WENZHOU | China | 2,033,410 | 53% | 3,778,190 | 1,406 | 755 | 53% |
| WUXI | China | 1,257,340 | 91% | 1,380,840 | 437 | 397 | 91% |
| YANGONCITY | Myanmar | 2,781,690 | 66% | 4,158,070 | 840 | 587 | 69% |

NB: This table is based on cities that have at least 1 million persons exposed to Low Elevation Coastal Zone.

Table 4: Large cities with high in-land flood risk

**Top Twenty Asian cities with persons exposed to at least a 1:50 year flood: Estimates of populations and land area at risk**

| City Name | Country | Population (2000) at flood risk | % of City Population | 1:100 year flood frequency (mean) | GRUMP Estimate of City Population (2000) | City Area (km2) | City Area (km2) at flood risk | % area in flood |
|---|---|---|---|---|---|---|---|---|
| Phnum Penh | Cambodia | 988,020 | 99% | 14 | 1,002,990 | 207 | 204 | 99% |
| Ha Noi | Viet Nam | 887,231 | 97% | 7 | 913,994 | 186 | 182 | 98% |
| Wuhan | China | 5,282,380 | 82% | 22 | 6,457,380 | 1169 | 956 | 82% |
| Palembang | Indonesia | 1,115,160 | 80% | 11 | 1,390,140 | 529 | 257 | 49% |
| Patna | India | 1,110,040 | 72% | 34 | 1,532,760 | 604 | 436 | 72% |
| Dhaka | Bangladesh | 5,400,650 | 60% | 57 | 9,045,090 | 1419 | 680 | 48% |
| Nanjing | China | 2,217,720 | 56% | 5 | 3,959,320 | 1346 | 749 | 56% |
| Ho Chi Minh City | Viet Nam | 2,811,610 | 50% | 5 | 5,582,420 | 1225 | 306 | 25% |
| Tianjin | China | 2,753,680 | 50% | 2 | 5,498,720 | 2081 | 795 | 38% |
| Bangkok | Thailand | 4,360,500 | 46% | 6 | 9,437,410 | 5990 | 2165 | 36% |
| Hangzhou | China | 1,152,880 | 37% | 11 | 3,095,240 | 667 | 187 | 28% |
| Zhenjiang | China | 893,026 | 33% | 6 | 2,688,050 | 665 | 252 | 38% |
| Shanghai | China | 3,701,250 | 25% | 2 | 15,083,700 | 2460 | 292 | 12% |
| Pusan | So. Korea | 1,218,670 | 25% | 4 | 4,967,500 | 1555 | 196 | 13% |
| Quezon City-Manila | Philippines | 2,939,830 | 20% | 22 | 14,401,700 | 2163 | 198 | 9% |
| Changsha | China | 1,126,470 | 20% | 3 | 5,675,750 | 1495 | 290 | 19% |
| Delhi | India | 2,702,590 | 16% | 2 | 16,842,200 | 3755 | 455 | 12% |
| Kolkata | India | 2,298,870 | 15% | 22 | 15,847,000 | 2292 | 417 | 18% |
| Shenzhen | China | 1,790,110 | 6% | 2 | 27,782,500 | 8776 | 939 | 11% |
| Tokyo | Japan | 3,489,690 | 5% | 2 | 76,302,000 | 43141 | 1609 | 4% |

NB: Flood frequency mean ranges from 2 (2-in-100 years) to 100 (annual flooding); the mean represents the average values of flood risk in a given city; the estimates of population and area at risk measure risk of any flooding.

Figure 1: Population at risk of inland flooding in Asian cities

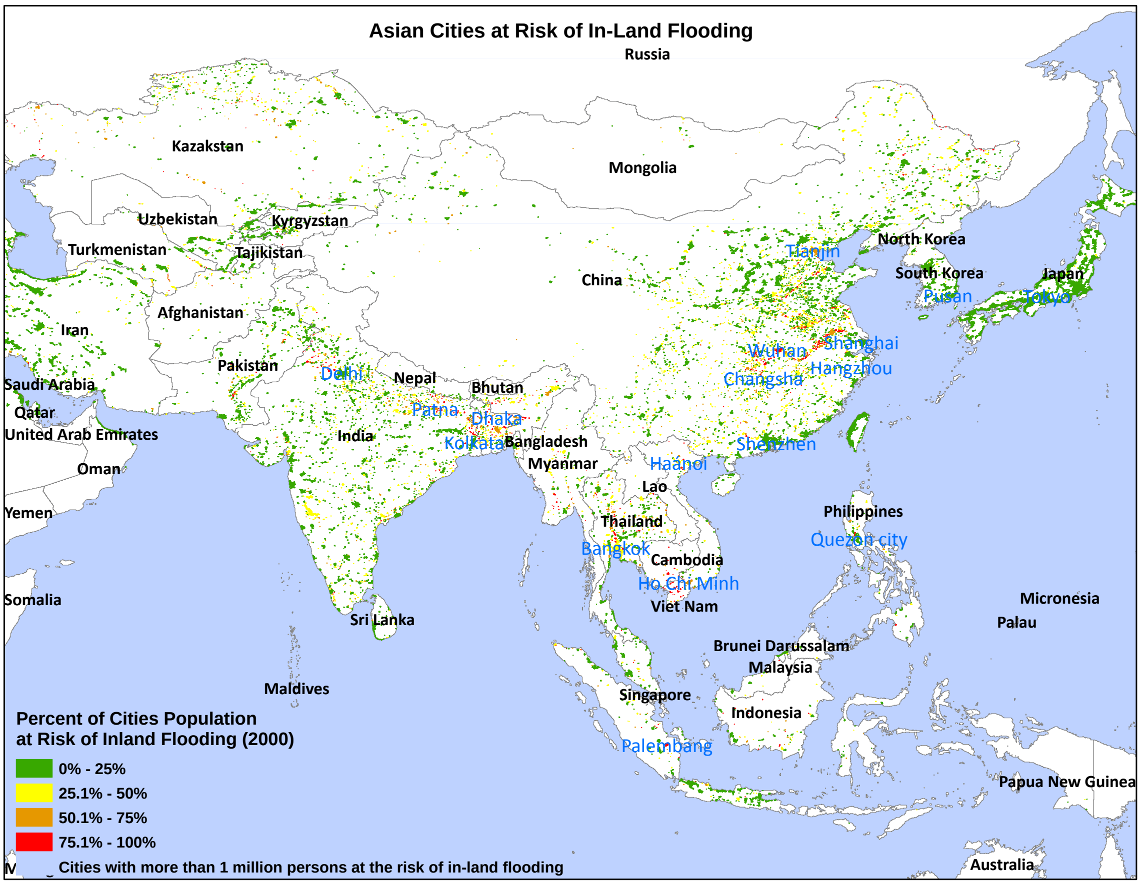

Figure 2: Population at risk of coastal flooding in Asian cities

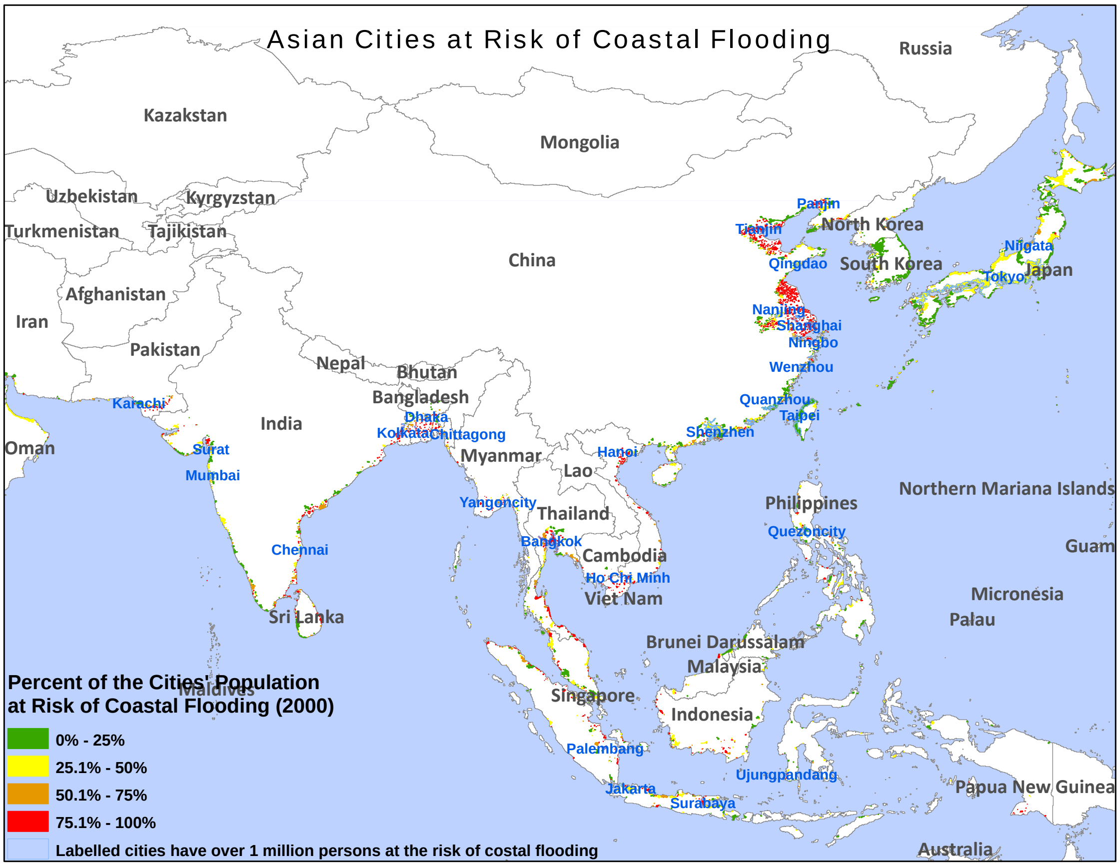

Figure 3: Population Density,Asian Cities

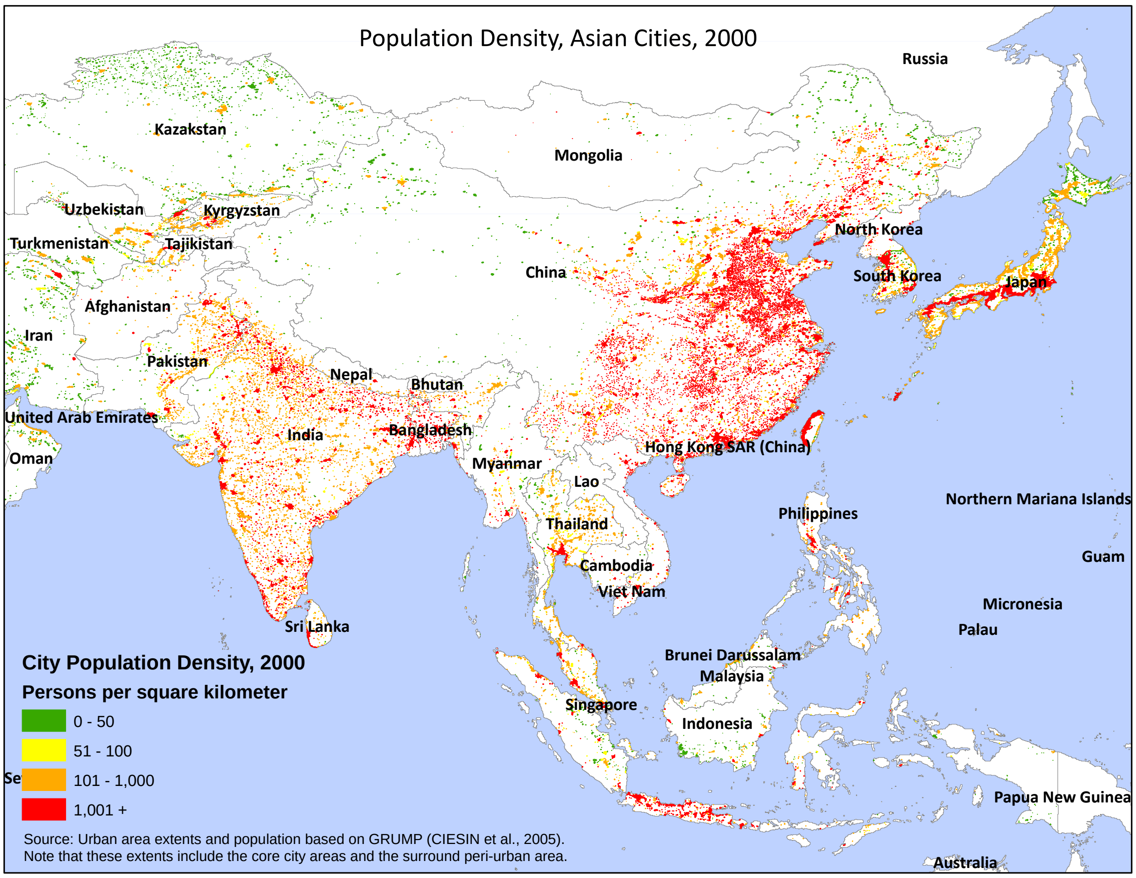

Figure 4: Population Density,Asian Cities

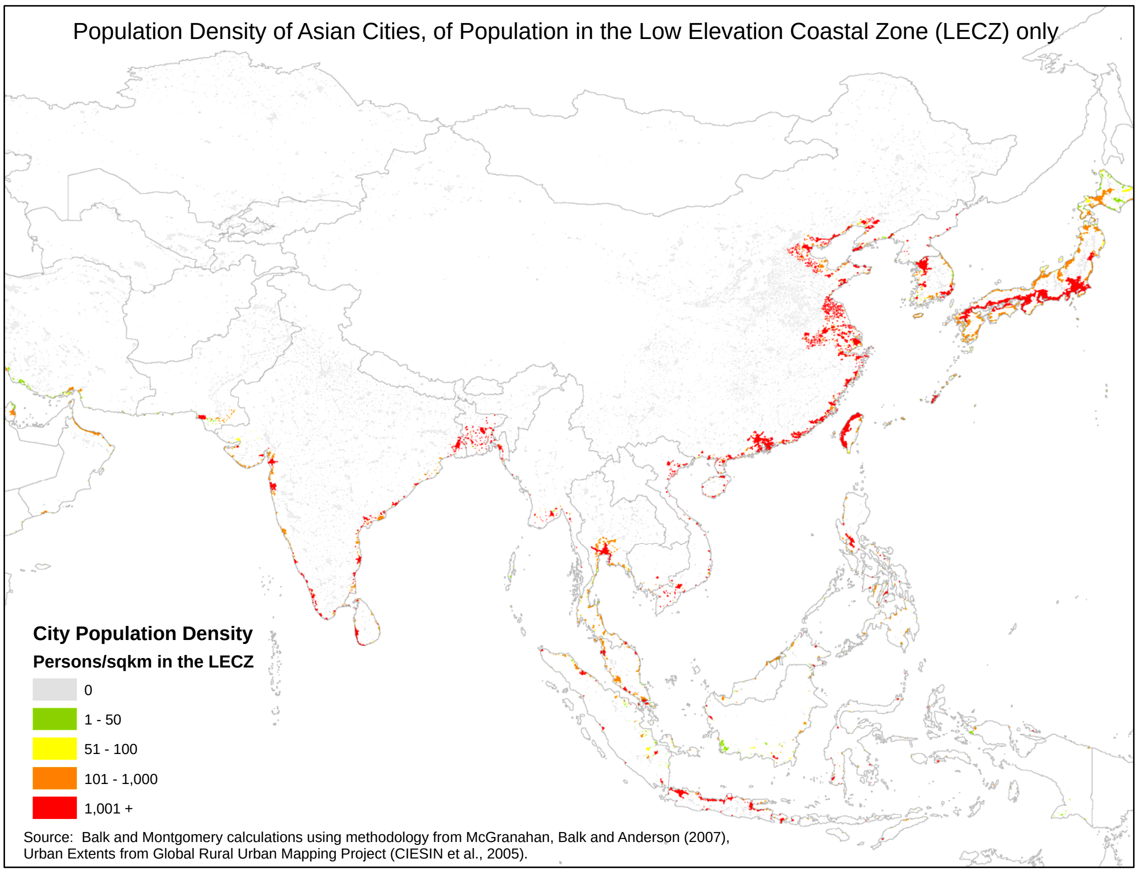

Table 5: Overall urban and city population densities, by continent.

| Continent | Overall Urban Area ($km^2$) | Overall Urban Population (1000s) | Overall Urban Density (pop per $km^2$) | Average City Area ($km^2$) | Average City Population (1000s) | Average City Density (pop per $km^2$) |
|---|---|---|---|---|---|---|
| South America | 475,489 | 220,224 | 463 | 63 | 29,320 | 132 |
| Asia | 1,453,871 | 1,515,783 | 1043 | 65 | 67,723 | 720 |
| Africa | 309,826 | 279,703 | 903 | 53 | 48,266 | 506 |
| North America | 187,913 | 92,066 | 490 | 84 | 41,285 | 158 |

Table 6: Asian population at risk of in-land and coastal flooding

| Flood Risk Type | 2000 | 2010 | 2015 |
|---|---|---|---|
| In-land Flood | 186,819,142 | 254,267,944 | 352,536,858 |
| Coastal Flood | 238,430,413 | 318,360,180 | 431,050,302 |

Table 7: Cities with over 1 million persons in arid regions: Estimates of population and land area at risk

**Cities with over 1 million persons in Dryland Ecosystems: Estimates of Populations and land area at risk**

| | City Name | Country | Population (2000) in Dryland ecosystem | % of City Population | GRUMP Estimate of City (or Agglomeration) Population (2000) | City Area (km2) | City Area (km2) in Dryland ecosystem | % area in Drylands Ecosystem |
|---|---|---|---|---|---|---|---|---|
| 1 | Dehli | India | 16,842,200 | 100% | 16,842,200 | 3,755 | 3,755 | 100% |
| 2 | TEHRAN | Iran | 12,148,700 | 100% | 12,148,700 | 5,834 | 5,834 | 100% |
| 3 | KARACHI | Pakistan | 7,872,770 | 71% | 10,937,800 | 1,823 | 1,564 | 85% |
| 4 | BEIJING | China | 7,790,290 | 85% | 9,123,730 | 3,473 | 2,670 | 76% |
| 5 | AHMADABAD | India | 6,322,630 | 100% | 6,322,630 | 1,879 | 1,879 | 100% |
| 6 | BAGHDAD | Iraq | 6,177,890 | 100% | 6,177,890 | 1,939 | 1,939 | 100% |
| 7 | HYDERABAD | India | 5,918,310 | 100% | 5,918,310 | 2,063 | 2,063 | 100% |
| 8 | LAHORE | Pakistan | 5,702,620 | 100% | 5,702,620 | 974 | 974 | 100% |
| 9 | XIAN | China | 5,614,630 | 100% | 5,614,630 | 1,477 | 1,477 | 100% |
| 10 | TIANJIN | China | 5,395,010 | 98% | 5,498,720 | 2,081 | 1,960 | 94% |
| 11 | JERUSALEM | Israel | 4,316,620 | 85% | 5,062,990 | 5,607 | 5,039 | 89% |
| 12 | HANDAN | China | 4,229,430 | 100% | 4,229,430 | 2,440 | 2,440 | 100% |
| 13 | YANGONCITY | Myanmar | 4,158,070 | 100% | 4,158,070 | 840 | 840 | 100% |
| 14 | TASHKENT | Uzbekistan | 3,922,570 | 100% | 3,922,570 | 1,897 | 1,897 | 100% |
| 15 | ARRIYAD | Saudi Arabia | 3,667,100 | 100% | 3,667,100 | 4,956 | 4,956 | 100% |
| 16 | SHIJIAZHUANG | China | 3,553,790 | 100% | 3,553,790 | 1,116 | 1,116 | 100% |
| 17 | HARBIN | China | 3,508,070 | 100% | 3,508,070 | 1,230 | 1,230 | 100% |
| 18 | TAIYUAN | China | 3,443,030 | 100% | 3,443,030 | 1,660 | 1,660 | 100% |
| 19 | PUNE | India | 3,432,540 | 100% | 3,432,540 | 1,071 | 1,071 | 100% |
| 20 | JIDDAH | Saudi Arabia | 3,405,580 | 86% | 3,946,760 | 3,873 | 3,342 | 86% |
| 21 | ANKARA | Turkey | 3,283,930 | 100% | 3,283,930 | 1,828 | 1,828 | 100% |
| 22 | TANGSHAN | China | 3,184,210 | 79% | 4,018,530 | 2,101 | 1,601 | 76% |
| 23 | BANGALORE | India | 3,036,010 | 100% | 3,036,010 | 1,615 | 1,615 | 100% |
| 24 | JINAN | China | 2,748,330 | 100% | 2,748,330 | 771 | 771 | 100% |
| 25 | RASHT | Iran | 2,746,820 | 90% | 3,031,380 | 6,328 | 5,866 | 92% |
| 26 | ZHENGZHOU | China | 2,512,400 | 100% | 2,512,400 | 612 | 612 | 100% |
| 27 | DUBAYY | United Arab Emirates | 2,460,960 | 99% | 2,481,220 | 6,831 | 6,758 | 98% |
| 28 | NAGPUR | India | 2,430,220 | 100% | 2,430,220 | 715 | 715 | 100% |
| 29 | CHENNAI | India | 2,358,480 | 30% | 7,755,660 | 1,343 | 777 | 57% |
| 30 | JAIPUR | India | 2,301,760 | 100% | 2,301,760 | 900 | 900 | 100% |
| 31 | LUCKNOW | India | 2,276,530 | 100% | 2,276,530 | 849 | 849 | 100% |
| 32 | FAISALABAD | Pakistan | 2,247,320 | 100% | 2,247,320 | 669 | 669 | 100% |
| 33 | AMMAN | Jordan | 2,223,740 | 100% | 2,223,740 | 1,460 | 1,460 | 100% |
| 34 | IZMIR | Turkey | 2,211,750 | 93% | 2,361,610 | 1,260 | 1,180 | 93% |
| 35 | ESFAHAN | Iran | 2,023,520 | 100% | 2,023,520 | 3,377 | 3,377 | 100% |
| 36 | MASHHAD | Iran | 2,021,790 | 100% | 2,021,790 | 1,837 | 1,837 | 100% |
| 37 | DURGBHILAINAGAR | India | 1,996,530 | 94% | 2,122,790 | 975 | 921 | 94% |
| 38 | PESHAWAR | Pakistan | 1,961,200 | 100% | 1,961,200 | 1,307 | 1,307 | 100% |
| 39 | ZIBO | China | 1,939,480 | 100% | 1,939,480 | 1,060 | 1,060 | 100% |
| 40 | GAZA AND ASHSHATI CAMP | Palestinian Territory | 1,905,860 | 93% | 2,048,620 | 1,399 | 1,370 | 97% |
| 41 | INDORE | India | 1,820,040 | 100% | 1,820,040 | 1,090 | 1,090 | 100% |
| 42 | VARANASI | India | 1,743,170 | 100% | 1,743,170 | 629 | 629 | 100% |
| 43 | SALMIYA | Kuwait | 1,734,290 | 94% | 1,841,080 | 3,953 | 3,893 | 98% |
| 44 | LUOYANG | China | 1,692,920 | 100% | 1,692,920 | 454 | 454 | 100% |
| 45 | LANZHOU | China | 1,690,560 | 100% | 1,690,560 | 883 | 883 | 100% |
| 46 | XINXIANG | China | 1,654,060 | 100% | 1,654,060 | 626 | 626 | 100% |
| 47 | ALLAHABAD | India | 1,575,870 | 100% | 1,575,870 | 533 | 533 | 100% |
| 48 | CHANDIGARH | India | 1,572,790 | 100% | 1,572,790 | 582 | 582 | 100% |
| 49 | SURAT | India | 1,572,160 | 43% | 3,626,050 | 1,565 | 1,370 | 87% |
| 50 | ADANA | Turkey | 1,557,210 | 73% | 2,110,640 | 1,930 | 1,424 | 73% |
| 51 | PATNA | India | 1,532,760 | 100% | 1,532,760 | 604 | 604 | 100% |
| 52 | GUJRANWALA | Pakistan | 1,526,830 | 100% | 1,526,830 | 521 | 521 | 100% |
| 53 | BAODING | China | 1,518,220 | 100% | 1,518,220 | 370 | 370 | 100% |
| 54 | VIJAYAWADA | India | 1,516,180 | 100% | 1,516,180 | 658 | 658 | 100% |
| 55 | VADODARA | India | 1,480,980 | 100% | 1,480,980 | 580 | 580 | 100% |
| 56 | BAOTOU | China | 1,463,450 | 100% | 1,463,450 | 1,258 | 1,258 | 100% |
| 57 | KANPUR | India | 1,454,910 | 100% | 1,454,910 | 836 | 836 | 100% |
| 58 | BISHKEK | Kyrgyz Republic | 1,437,780 | 100% | 1,437,780 | 1,453 | 1,453 | 100% |
| 59 | ALMAATA | Kazakhstan | 1,434,100 | 92% | 1,543,690 | 1,696 | 1,399 | 82% |
| 60 | AGRA | India | 1,409,280 | 100% | 1,409,280 | 378 | 378 | 100% |
| 61 | BHOPAL | India | 1,393,040 | 100% | 1,393,040 | 511 | 511 | 100% |
| 62 | HYDERABAD | Pakistan | 1,392,390 | 100% | 1,392,390 | 1,053 | 1,053 | 100% |
| 63 | DUSHANBE | Tajikistan | 1,369,900 | 100% | 1,369,900 | 1,277 | 1,277 | 100% |
| 64 | ALEPPO | Syrian Arab Republic | 1,360,410 | 100% | 1,360,410 | 895 | 895 | 100% |
| 65 | SANAA | Yemen | 1,349,100 | 100% | 1,349,100 | 678 | 678 | 100% |
| 66 | PUYANG | China | 1,346,220 | 100% | 1,346,220 | 905 | 905 | 100% |
| 67 | DAQING | China | 1,324,800 | 100% | 1,324,800 | 2,023 | 2,023 | 100% |
| 68 | MULTAN | Pakistan | 1,306,500 | 100% | 1,306,500 | 449 | 449 | 100% |
| 69 | QIQIHAER | China | 1,299,230 | 100% | 1,299,230 | 502 | 502 | 100% |
| 70 | ADDAMMAM | Saudi Arabia | 1,218,510 | 75% | 1,614,460 | 2,578 | 1,947 | 75% |
| 71 | TBILISI | Georgia | 1,195,920 | 100% | 1,195,920 | 773 | 773 | 100% |
| 72 | DAMASCUS | Syrian Arab Republic | 1,183,450 | 100% | 1,183,450 | 1,561 | 1,561 | 100% |
| 73 | SHIRAZ | Iran | 1,150,030 | 100% | 1,150,030 | 1,279 | 1,279 | 100% |
| 74 | LUDHIANA | India | 1,109,350 | 100% | 1,109,350 | 463 | 463 | 100% |
| 75 | NASHIK | India | 1,107,270 | 100% | 1,107,270 | 492 | 492 | 100% |
| 76 | TIRUCHIRAPPALLI | India | 1,093,220 | 100% | 1,093,220 | 454 | 454 | 100% |
| 77 | TABRIZ | Iran | 1,079,460 | 87% | 1,233,200 | 1,218 | 1,011 | 83% |
| 78 | YEREVAN | Armenia | 1,062,070 | 100% | 1,062,070 | 591 | 591 | 100% |
| 79 | AS-SIB | Oman | 1,051,410 | 91% | 1,149,390 | 2,782 | 2,469 | 88% |
| 80 | XINING | China | 1,039,310 | 100% | 1,039,310 | 402 | 402 | 100% |
| 81 | HUHEHAOTE | China | 1,025,270 | 100% | 1,025,270 | 683 | 683 | 100% |
| 82 | JIAOZUO | China | 1,006,900 | 100% | 1,006,900 | 446 | 446 | 100% |
| 83 | DATONG | China | 1,002,300 | 100% | 1,002,300 | 1,468 | 1,468 | 100% |

# A Appendix: Flood Data and Methodology for Estimating City Populations at Risk

Drawing on the methodology developed by McGranahan, Balk, and Anderson (2007) to estimate urban population exposures in the Low Elevation Coastal Zone (LECZ) and in drylands Balk et al. (2009), this appendix—largely developed by Michael Brady under the supervision of Deborah Balk—describes and evaluates three recent global spatial datasets for use and integration with global population (i.e., GRUMP) data to construct new estimates of urban population and land area at risk of flooding from in-land water sources rather than coastal ones. The three datasets to evaluate are: Inland Flood Frequency and Inland Flood Risk (ISDR 2009); Inland water ecosystem from the Millennium Ecosystem Assessment.

This document also outlines methods used to generate a set of Asia urban physical exposure to a set of water-related hazards. Three population exposure variables were estimated—inland flooding, coastal flooding, and exposure to inland and coastal flooding and areas affected by drought.

# B Data Description

This section provides brief descriptions of the datasets used to estimate Asia urban settlement physical exposure. Table 8 below shows basic information about the datasets used.

Table 8: Data Description

| Dataset Name | Resolution | Dataset Source |
|---|---|---|
| GRUMP Population | 1km | SEDAC (CIESIN et al. 2008) |
| Land Area Grid | 1km | SEDAC (CIESIN et al. 2008) |
| Inland Flood Frequency Grid | 1km | GAR 2009 |
| LECZ | 1km | McGranahan et al., 2007 |
| Dry Land Grid | 1km | Millennium Ecosystem Assessment (see McGranahan et al, 2005) |
| Inland Water Ecosystem | 1km | Millennium Ecosystem Assessment (see McGranahan et al, 2005) |

## B.1 Inland Flood Frequency Data

Inland flood exposure estimates for the current project use a global flood frequency dataset developed for the 2009 Global Assessment Report on Risk Reduction (GAR) (ISDR 2009). The data include a 1-kilometer resolution flood probability raster grid of estimated riverine flood frequencies within a hydrologically modeled 1-percent chance flood geographic extent. Below is a brief description of the data, development methods, and accuracy limitations.

**Dataset Description** In the flood frequency grid, raster cell values range from 2 to 99, indicating the number of times a location is expected to flood within a 100 year period. The cell value 2 was assigned to locations without frequency data, while all other cell values are based on observed flood frequencies. The areas without frequency observations were originally assigned a value of 1 (since the modeled extents are based on a 1/100 year flood), but were replaced by values of 2 (or 2 floods expected within a 100 year period) to account for an expected higher frequency of less severe floods, as to not underestimate flood exposure as these locations (personal communication, Pascal Peduzzi, UNEP, May 23, 2012).

**Flood Frequency and Flood Extent Data Development** For the GAR (2009) inland flood dataset, frequency estimates were based on 21 years of Centre for Research on the Epidemiology of Disasters (CRED) Emergency Events Database (EM-DAT) extreme flood occurring between 1980 and 2000 (UNDP 2004; ISDR 2009). Peduzzi, Dao, and Herold (2005) geo-referenced the EM-DAT flood data (which is collected by administrative boundary—usually national level) to affected watersheds using methods developed by Burton, Kates, and White (1993) to increase the spatial accuracy of the flood information. Flood frequency was found by dividing the number of floods observed in a watershed by 21 years (UNDP 2004). Nine years of Dartmouth Flood Observatory (DFO) satellite observed floods including more than 400 extreme events provided additional frequency information to supplement the land-based frequency data (ISDR 2009) (and Pascal Peduzzi, UNEP, May 23 2012). A paper is being written on the modeling of flood extents. Peduzzi says methods are similar to Peduzzi et al. (2012). The nine years of DFO satellite observations were also used to calibrate the modeled 1% flood extents (ISDR 2009).

## B.2 Flood Risk Data

The following papers provide a clear discussion of methods by which the GAR 2009 flood risk data were constructed: Peduzzi et al. (2009); UNDP (2004); ISDR (2009).

## B.3 Inland Water Ecosystem

The inland water ecosystem data from the Millennium Ecosystem Assessment (Finlayson and D'Cruz 2005, pp. 553–554) were evaluated but not used in this analysis (though they have been used elsewhere, e.g., McGrahanan et al. (2005)).

> Inland water systems encompass habitats such as lakes and rivers, marshes, swamps and floodplains, small streams, ponds, and cave. These have a variety of biological, physical, and chemical characteristics. As coastal wetlands (such as estuaries, mangroves, mudflats, and reefs) are considered in elsewhere in the Millennium Ecosystem Assessment [Chapter 19], the broad definition of wetland adopted by the Convention on Wetlands in 1971, which includes inland, coastal, and marine habitats, is not used in this chapter. All inland aquatic habitats, however, whether fresh, brackish, or saline, as well as inland seas, are considered. As there is no clear boundary between inland and coastal ecosystems, this delineation is indicative only and is not strictly applied where there are strong interactions between the biodiversity, services, and pressures that affect inter-connected habitats. Rice fields, aquaculture ponds, and reservoirs are included.

Like drylands, these data represent an ecosystem. It was decided that since direct estimates of flood exposure (extent and risk) were available, that those latter data sets would be preferable.

## B.4 Geoprocessing Methods

A set of basic statistics were generated in a GIS to estimate several Asia urban settlement flood exposure variables. The input datasets (Table **??** above) are used to produce exposure estimates through a calculations of zonal statistics: Inland flood area exposed; Inland flood population exposed; Mean Inland Flood Frequency; Coastal flood area exposed; Coastal flood population exposed; Drylands area exposed; and Drylands population exposed.

## B.5 Exposure Geo-processing

The total urban land area and population exposed to the following conditions were estimated in a GIS:

- Any inland flooding, effectively showing exposure to the 1-percent chance inland flood extents for all of Asia urban areas.

  Area and population exposure estimates were also generated for a set of flood frequency intervals, to show urban exposure to several flood frequency ranges.

- Coastal flooding - low elevation
- Inland and coastal flooding, and dry lands

**Geo-processing - Inland Flood Exposure** Urban settlement extent polygons (see Population data) were converted from vector files to raster grids to provide the urban masks (or zones) that set the spatial boundaries for including (or excluding) a value raster cell in the summary statistics results (i.e. GIS zonal statistics). The area and population grids provided the raster cell value information. The area and population grid cells that overlapped the population mask were summed for each settlement unit, respectively. A unique (for Asia dataset) urban ID number (i.e. URBID) provided the cell values, so each mask unit could be identified throughout the geo-processing steps.

The same process outlined above was followed to generate statistics for a set of flood frequency ranges. Zonal statistics were generated for each frequency interval by providing each of the interval files as the value grid one at a time, effectively only showing area and population exposure to the specified frequency range (e.g., 10–25 / 100 year event). It was decided not to use buffers around the flood grids. Python programming language was used to generate the above statistics.

## B.6 Error and Uncertainty

The GIS procedure and analysis contain both source and processing errors (Veregin 1996). The source errors dominate in both the population and flood data as it is impossible to determine exactly the extent of either. The vector to raster conversion of the population data presents a processing error as the relatively course cell size and urban boundary size and shape make it impossible to line boundaries up perfectly. (For more information on the population data conversations from vector to raster, see `http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=nl&ds=4`.

More information about error and uncertainty in the flood data can be found at `http://sedac.ciesin.columbia.edu/data/set/ndh-flood-hazard-frequency-distribution.txt`. A buffer was applied to the flood frequency zones to account for source errors. "The frequency range is classified into deciles, 10 classes of an approximately equal number of grid cells. Deciles are the chosen method of dissemination due to considerations of confidence with the data." For more information on source errors, and see `http://www.geog.ucsb.edu/~good/papers/103.pdf` and other papers by Goodchild and colleagues (Goodchild and Gopal 1989; Goodchild 1991) and Wade et al. (2003)

# References


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