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Future flood losses in major coastal cities

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Flood exposure is increasing in coastal cities[1,2] owing to growing populations and assets, the changing climate[3], and subsidence[4–6]. Here we provide a quantification of present and future flood losses in the 136 largest coastal cities. Using a new database of urban protection and different assumptions on adaptation, we account for existing and future flood defences. Average global flood losses in 2005 are estimated to be approximately US$6 billion per year, increasing to US$52 billion by 2050 with projected socio-economic change alone. With climate change and subsidence, present protection will need to be upgraded to avoid unacceptable losses of US$1 trillion or more per year. Even if adaptation investments maintain constant flood probability, subsidence and sea-level rise will increase global flood losses to US$60–63 billion per year in 2050. To maintain present flood risk, adaptation will need to reduce flood probabilities below present values. In this case, the magnitude of losses when floods do occur would increase, often by more than 50%, making it critical to also prepare for larger disasters than we experience today. The analysis identifies the cities that seem most vulnerable to these trends, that is, where the largest increase in losses can be expected.

A first screening study[1] provided a global overview of flood exposure in world coastal cities. The exposure metric can be viewed as a worst case scenario, but it does not estimate average annual losses, which is a standard metric in disaster risk management planning. To do so, it is necessary to take into account infrastructure-based adaptation (for example, dykes) and the vulnerability of populations and assets. Here, we assess economic average annual losses (AAL) in 136 coastal port cities, using a method developed for assessing city-level flood risk[7] and a new database of urban coastal protection (Methods).

Present aggregated average annual flood losses in the 136 cities are estimated at approximately US$6 billion per year. Table 1 ranks the most vulnerable cities in 2005 using two different metrics of vulnerability. In the left column, the table shows a ranking in terms of AAL, taking into account all potential floods and existing protection. The AAL estimates can be compared to more sophisticated approaches. For instance, the annual losses in New Orleans are estimated at US$600 million, close to the US$650 million estimates from the Interagency Performance Evaluation Taskforce[8]. In the right column, cities are ranked according to relative vulnerability, namely the ratio of AAL to the city's gross domestic product (GDP). This value can be understood as the share of the city's economic output that should be saved annually to pay for future flood losses. The 20 cities most vulnerable according to this last indicator are also presented in Fig. 1.

The ranking in terms of exposure includes mainly rich-country cities (Supplementary Table S4). On average, however, rich cities are better protected than poorer ones, and the ranking in terms of absolute flood losses contains more cities from developing countries. In relative terms, developing-country cities are even more vulnerable, with only three cities from developed countries in the top 20 (New Orleans, Miami and Tampa—Saint-Petersburg). Moreover the ranking in absolute terms (left column) includes mainly capital cities, whereas secondary cities are more often represented in the ranking in relative terms (right column). This difference suggests that risk management efforts may be lower in secondary cities.

Table 1 shows the importance of existing flood defences: in a city such as Amsterdam, exposure is extremely high (US$83 billion of assets exposed to the 100-year flood), but AAL do not exceed US$3 million, because estimated defence standards are the highest that exist globally. On the other hand, a city such as Ho Chi Minh, in Vietnam, has a 100 year exposure of only US$18 billion, but the lower level of protection means that the city is affected by small floods on a frequent basis, resulting in large estimated average costs. In relative terms, Ho Chi Minh City has one of the largest vulnerabilities, with AAL reaching 0.74% of local GDP. The ratio of AAL to local GDP exceeds 1% for two cities, Guangzhou and New Orleans. The vulnerability of New Orleans has been reduced however by recent post-Hurricane Katrina investments and is likely to be reduced further in the near future[9].

Another conclusion from Table 1 is the concentration of losses in only a few cities. Only 13 cities have average losses in excess of US$100 million, and three American cities (Miami, New York City and New Orleans) explain 31% of the global aggregate losses in the 136 cities, because of their high wealth and low protection level. Adding Guangzhou, the four top cities explain 43% of global losses. Also, the US seems particularly vulnerable, with 6 American cities in exposure ranking, 8 in the ranking by absolute AAL, and 3 in the ranking by relative AAL. As coastal flood risks are highly concentrated, flood reduction actions in a few locations could be very cost-effective.

To develop possible future patterns of drivers of risk to 2070, our analysis introduces three scenarios for socio-economic changes and six for environmental change. From there, we retain four main scenarios: SEC assumes only socio-economic changes, derived from OECD and UN scenarios; SEC-S adds subsidence to scenario SEC (40 cm in 2050 in the cities subjected to subsidence); and SLR-1 and SLR-2 add optimistic and pessimistic sea-level rise scenarios to SEC-S, respectively (with 20 cm and 40 cm in 2050). Here, we report results for 2050, but results for 2030 and 2070 are available in the Supplementary Information.

With no adaptation, the projected increase in average losses by 2050 is huge, with aggregate losses increasing to more than US$1 trillion per year in scenarios SLR-1 and SLR-2 (Supplementary Table S6). All cities experience a similar increase

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Table 1 | City ranking by risk (AAL) and relative risk (AAL in percentage of GDP) for 2005.

Ranking by AAL (US$ million)					Ranking by relative AAL (percentage of city GDP)				
	Urban agglomeration	100 year exposure	AAL, with protection (US$ million)	AAL, with protection (percentage of GDP)		Urban agglomeration	100 year exposure	AAL, with protection (US$ million)	AAL, with protection (percentage of GDP)
1	Guangzhou	38,508	687	1.32%	1	Guangzhou	38,508	687	1.32%
2	Miami	366,421	672	0.30%	2	New Orleans	143,963	507	1.21%
3	New York—Newark	236,530	628	0.08%	3	Guayaquil	3,687	98	0.95%
4	New Orleans	143,963	507	1.21%	4	Ho Chi Minh City	18,708	104	0.74%
5	Mumbai	23,188	284	0.47%	5	Abidjan	1,786	38	0.72%
6	Nagoya	77,988	260	0.26%	6	Zhanjiang	2,780	46	0.50%
7	Tampa—St. Petersburg	49,593	244	0.26%	7	Mumbai	23,188	284	0.47%
8	Boston	55,445	237	0.13%	8	Khulna	2,073	13	0.43%
9	Shenzen	11,338	169	0.38%	9	Palembang	1,161	27	0.39%
10	Osaka—Kobe	149,935	120	0.03%	10	Shenzen	11,338	169	0.38%
11	Vancouver	33,456	107	0.14%	11	Hai Phòng	6,348	19	0.37%
12	Tianjin	11,408	104	0.24%	12	N'ampo	507	6	0.31%
13	Ho Chi Minh City	18,708	104	0.74%	13	Miami	366,421	672	0.30%
14	Kolkata	14,769	99	0.21%	14	Kochi	855	14	0.29%
15	Guayaquil	3,687	98	0.95%	15	Tampa—St. Petersburg	49,593	244	0.26%
16	Philadelphia	22,132	89	0.04%	16	Nagoya	77,988	260	0.26%
17	Virginia Beach	61,507	89	0.15%	17	Surat	3,288	30	0.25%
18	Fukuoka—Kitakyushu	39,096	82	0.09%	18	Tianjin	11,408	104	0.24%
19	Baltimore	14,042	76	0.08%	19	Grande_Vitória	6,738	32	0.23%
20	Jakarta	4,256	73	0.14%	20	Xiamen	4,486	33	0.22%

A comparison with a ranking by exposure is proposed in the Supplementary Information.

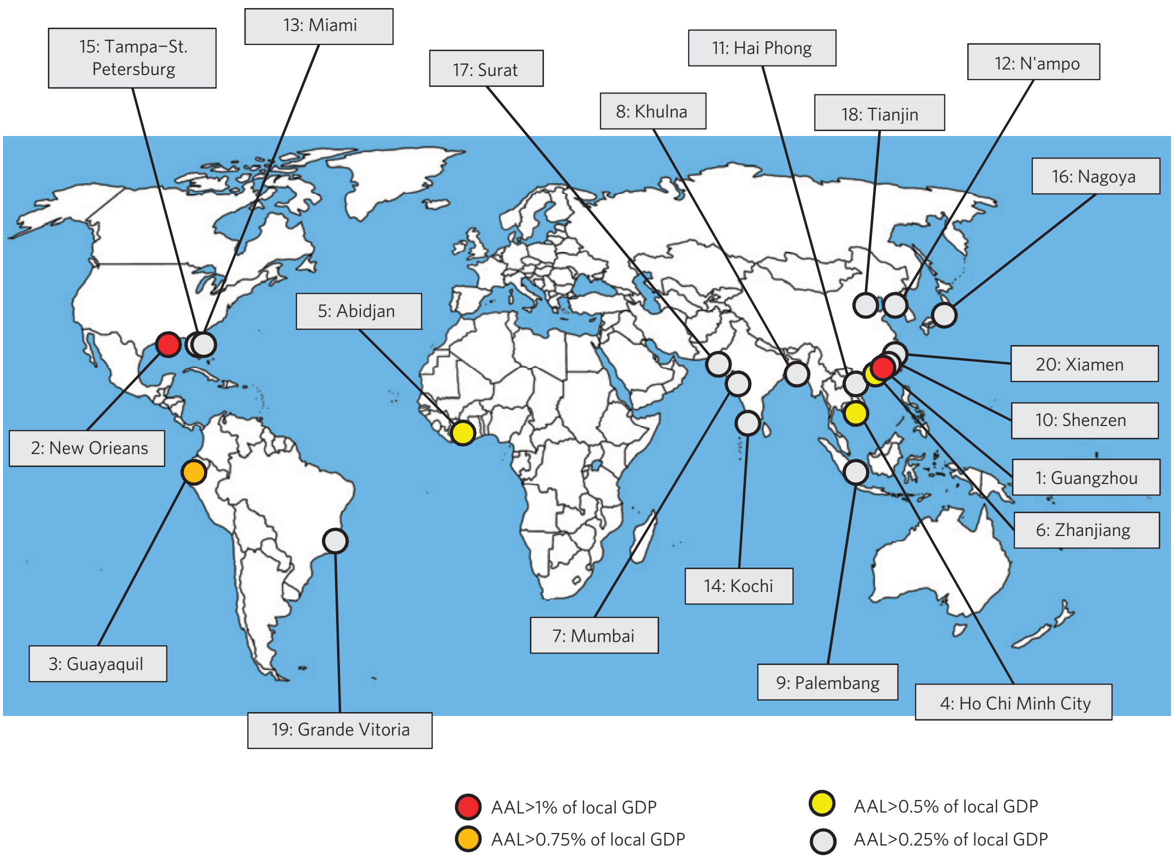

Figure 1 | The 20 cities where the relative risk is larger in 2005, that is, where the ratio of AAL with respect to local GDP is the largest. More information in Table 1.

Table 2 | The 20 cities with the highest loss in 2050, assuming scenario SLR-1 and adaptation option that maintains flood probability (option PD).

Urban agglomeration	Scenarios with socio-economic change alone (SEC)		Scenarios with socio-economic change, subsidence, sea-level rise and adaptation to maintain flood probability (scenarios SLR-1, and adaptation option PD)		
	AAL (US$ million)	AAL (percentage of city GDP)	AAL (US$ million)	Increase in AAL compared with 2005 (%)	AAL (percentage of city GDP)
Guangzhou (S)	11,928	1.32%	13,200	11%	1.46%
Mumbai	6,109	0.47%	6,414	5%	0.49%
Kolkata (S)	2,704	0.21%	3,350	24%	0.26%
Guayaquil (S)	2,813	0.95%	3,189	13%	1.08%
Shenzen	2,929	0.38%	3,136	7%	0.40%
Miami	2,099	0.30%	2,549	21%	0.36%
Tianjin (S)	1,810	0.24%	2,276	26%	0.30%
New York—Newark	1,960	0.08%	2,056	5%	0.08%
Ho Chi Minh City (S)	1,743	0.74%	1,953	12%	0.83%
New Orleans (S)	1,583	1.21%	1,864	18%	1.42%
Jakarta (S)	1,139	0.14%	1,750	54%	0.22%
Abidjan	826	0.72%	1,023	24%	0.89%
Chennai (Madras)	825	0.12%	939	14%	0.14%
Surat	905	0.25%	928	3%	0.26%
Zhanjiang (S)	806	0.50%	891	11%	0.55%
Tampa—St. Petersburg	763	0.26%	859	13%	0.29%
Boston	741	0.13%	793	7%	0.14%
Bangkok (S)	596	0.07%	734	23%	0.09%
Xiamen (S)	572	0.22%	729	27%	0.29%
Nagoya (S)	564	0.26%	644	14%	0.30%

'S' indicates that the city is prone to significant subsidence. Most of these cities are located in deltaic regions, where subsidence influences local sea level in 2050.

in risk. In the absence of adaptation, the impact of environmental change is much larger than the effect of socioeconomic change. These numbers should not be considered as predictions, but they demonstrate the need for adaptation, because inaction would result in unacceptably high losses.

We then consider adaptation and how it will alter losses. We assume first that adaptation action increases coastal flood defences to maintain a constant probability of flooding (adaptation option: present design, PD). The increase in aggregate AAL is much lower in this case. Owing to socio-economic change, there is still a ninefold increase in aggregate losses, from US$6 to US$52 billion per year, but this is made more manageable by the fact that these cities are also much richer. However, rising water levels still increase AAL: subsidence by 12% and sea-level rise by an additional 2–8%, reaching between US$60 and 63 billion per year.

Table 2 shows the top 20 cities in terms of AAL in 2050 in the scenario with subsidence and optimistic sea-level rise (SLR-1), with adaptation to maintain present flood probability. Guangzhou remains the most vulnerable city, with AAL exceeding US$13 billion. With socio-economic change alone, AAL in Guangzhou would be around US$12 billion per year in 2050 (a 17-fold increase in absolute terms). Subsidence and sea-level rise are thus responsible for an additional 10% increase, that is, a 10% increase in the AAL-to-GDP ratio. Indeed, even if the probability of coastal flooding is unchanged thanks to upgraded coastal defence infrastructure, the fact that a larger share of existing assets is protected by these defences means that annual losses will rise relative to local GDP. For instance, sea-level rise and subsidence increase the AAL-to-GDP ratio by 54% in Jakarta and by 24% in Abidjan even if present flood probabilities are maintained thanks to better defences. In other words, the world sees no more floods, but each flood is more destructive owing to sea-level rise and subsidence, even with better defences. This effect reinforces a trend that can be expected from socio-economic change alone, even in the absence of environmental change.[10]

Figure 2 shows the 20 cities where the increase in average annual losses between 2005 and 2050 is greatest in relative terms; detailed numerical values are provided in Supplementary Table S7. In Alexandria, for instance, maintaining flood probability leads to an increase by 154% in AAL. These most vulnerable cities are distributed all over the world, with a concentration in the Mediterranean Basin, the Gulf of Mexico and East Asia. Even though absolute levels of risk are sometimes low in these cities, they can be considered as adaptation hotspots because this is where flood risks are likely to increase the most in relative terms.

To avoid any increase in risk, an adaptation policy needs to do more than maintain present flood probability. Rather, maintaining present levels of risk (relative to local GDP) in the context of rising sea levels, subsidence and socio-economic changes requires adaptation policy that reduces flood probability over time. In the adaptation option termed present losses, an upgrade in defence is thus calibrated to cancel the impact of environmental changes and to maintain present losses on average relative to local wealth, keeping aggregate losses at US$52 billion.

For each city, we estimate the increase in defence standard that would maintain the relative risk level (that is, keep constant the ratio of average annual losses to local GDP). The required increase in protection is larger than local sea-level rise. For instance, in Alexandria, protection needs to be raised by 67 cm, for a 60 cm rise in local sea level; this corresponds to moving from a 100-year design standard to a 270-year design standard (that is, a division by 2.7 of the probability of flooding). In other cities (Supplementary Table S7) the increase in dyke height is between 2 and 8 cm larger than sea-level rise. This increase corresponds to a significant increase in the standard of protection, that is, to a large decrease

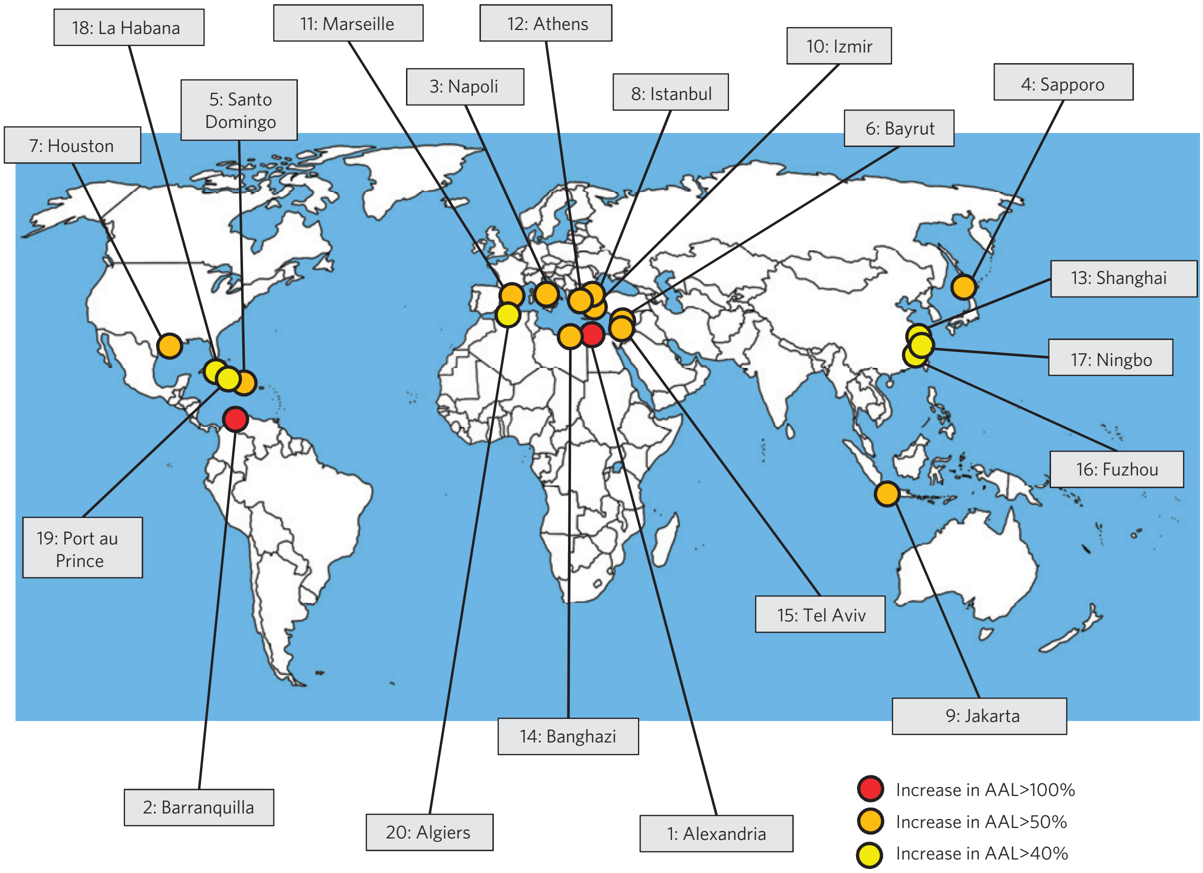

Figure 2 | The 20 cities where AAL increase most (in relative terms in 2050 compared with 2005) in the case of optimistic sea-level rise, if adaptation only maintains present defence standards or flood probability (PD). More information in Supplementary Table S7.

in the probability of flooding (for example, a division by 1.6 in Jakarta and Shanghai).

Even if the relative risk level is maintained, flood consequences would be much higher in a world with sea-level rise and better protection. In Alexandria in 2050, for instance, the probability of a flood may decrease by 2.7 owing to better defences, but if a flood occurs the total losses triple from US$17 billion (with socio-economic change alone) to US$51 billion, a tripling due to environmental changes alone. Results for other cities are presented in Supplementary Table S7. Many cities would experience losses that are more than 50% larger if an event exceeds the post-adaptation protection level. Hence, the world's coastal cities become more dependent on flood defences, but also more vulnerable once failure or overtopping occurs.

Finally, Table 3 looks at present city characteristics that influence the vulnerability in 2050. It shows that cities that grow rapidly, have large populations, are poor, exposed to tropical storms, and prone to subsidence are over-represented in the top 20 for absolute AAL (the cities from Table 2). However, these drivers are not as relevant for the relative increase in annual average loss with adaptation option PD (the cities from Fig. 2). Only subsidence seems to be a consistently good determinant of vulnerability for both absolute and relative measures of change, with twice as many cities with subsidence in the top 20 based on the two indicators (absolute and relative losses). The cities most vulnerable in relative terms may thus not be the ones suggested by the present situation and historic floods, nor are they the ones that necessarily attract the most research and analysis today with respect to managing risk.

While recognizing the limitations and uncertainties in this analysis, three important policy conclusions can be drawn that are robust across a range of plausible assumptions. First, failing to adapt is not a viable option in coastal cities. It is difficult to estimate the cost of these adaptation options, as it depends on the specific context for each city and on selected approaches and technologies. On the basis of anecdotal evidence from a few cities[11–14], a few billion US dollars per city in initial investment—plus approximately 2% of the initial investment cost in annual operation and maintenance costs—is the possible order of magnitude for adaptation costs[15]. Hence, indicative annualized values with 5% interest rates are about US$350 million per year per city, or approximately US$50 billion per year for our 136-city sample. These estimated aggregate adaptation costs are far below our estimate of aggregate damage losses per year in the absence of adaptation, and of the same order of magnitude as residual losses with adaptation (Supplementary Table S6). These estimates include only flood risks and do not encompass all weather risks that these cities face; see, for instance, ref. 16 for a global analysis of wind damage from tropical cyclones.

Second, managing coastal flood risk requires doing more than maintaining today's standard of protection (and present probability of flooding). In practice, probability of flooding will need to be reduced to maintain flood risks at today's levels.

Last, improving standards of protection could maintain or reduce risk levels and decrease the number of floods, but the magnitude of losses when floods do occur will still increase. This result points to the limitations of what infrastructure-based adaptation can achieve. As illustrated by the recent landfall of hurricane Sandy on the east coast of the United States, there is a need to prepare at the local, national and international level for larger floods and the disasters that ensue. Such preparations can include strengthening disaster planning measures, including early warning and evacuation systems, more comprehensive insurance

Table 3 | The fraction of cities in the five categories (fast growing, large population, low income, subject to tropical storms and subject to subsidence) in the full sample of 136 cities, and in two top 20 categories using different indicators.

	Fast-growing city (local GDP growth in 2005 larger than 5% per year)	Large population (larger than 5 million in 2005)	Low income (GDP per capita in 2005 less than US$5,000)	Subject to hurricane and tropical storms	Prone to significant subsidence
All 136 cities	40%	19%	27%	51%	27%
Top 20 in terms of AAL in 2050 (adaptation option PD; Table 2)	65%	55%	40%	95%	55%
Top 20 in terms of increase in AAL (adaptation option PD; Fig. 2)	40%	15%	20%	45%	40%

schemes and other forms of post-disaster response to quickly rebuild affected communities.

Methods

Flood risks are analysed following ref. 7. The population exposure is taken from a previous analysis[1]. Exposed population was translated into exposed assets using an estimate of produced capital per inhabitant drawing on recent work from the World Bank[17]. The DIVA database provides information about extreme water levels[18]. We create a first database for coastal defences; this is based on collected evidence on existing defences where possible, and the authors' expert estimates to complete the defence database (Supplementary Information).

Then, we calculate the probability of different flood levels in each city (within the flood defences) using three simple models for defence failure or overtopping. Even though absolute risk levels depend on the failure model, the relative effect of sea-level rise and subsidence on losses is relatively robust to this uncertainty.

From the probability of the various flood levels in the city, and from data on assets that are exposed at different flood levels, flood asset losses are estimated using depth–damage functions for 6 categories of assets.

To assess future losses, we use two socio-economic scenarios[19]: an OECD-based growth scenario in which urban populations grow at the same rate in all cities, following an extrapolation of UN urbanization scenarios; and the OECD-based growth scenario in which city population is capped at 35 million inhabitants. We assume that future assets in the city have the same elevation distribution as existing assets.

The six scenarios of environmental change combine: two assumptions on subsidence (no subsidence, or a 40 cm subsidence in 2050 in all cities subject to it); and three assumptions about sea-level rise (none, 20 cm, or 40 cm in 2050). Combined with socio-economic scenarios and adaptation options, these lead to 108 scenario combinations. Results for the 108 scenarios and input data and model codes are available in the Supplementary Information. The analysis presented here considers only four scenarios of the total number of scenarios (see text). All scenarios use the simplest defence failure model, the maximum protection level, and constrain cities to no more than 35 million inhabitants.

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Author contributions

The four authors designed the study, interpreted results and authored the paper. S.H. developed and ran the models. R.N. and C.G. provided expert input on depth–damage curves and coastal protection.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.H.

Competing financial interests

The authors declare no competing financial interests.