



1 Water-level attenuation in broad-scale assessments of exposure to 2 coastal flooding: a sensitivity analysis

3 Athanasios T. Vafeidis¹, Mark Schuerch², Claudia Wolff¹, Tom Spencer², Jan L. Merkens¹, Jochen
4 Hinkel³, Daniel Lincke³, Sally Brown⁴, Robert J. Nicholls⁴

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6 ¹*Coastal Risks and Sea-Level Rise Research Group, Department of Geography, Christian-Albrechts University Kiel,
7 Ludewig-Meyn-Str. 14, 24098 Kiel, Germany*

8 ²*Cambridge Coastal Research Unit, Department of Geography, University of Cambridge, Downing Place, Cambridge CB2
9 3EN, UK*

10 ³*Global Climate Forum e.V. (GCF), Neue Promenade 6, 10178 Berlin, Germany*

11 ⁴*Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK*
12

13 *Correspondence to:* Athanasios T. Vafeidis (vafeidis@geographie.uni-kiel.de)
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15 **Abstract.** This study explores the uncertainty introduced in global assessments of coastal flood exposure and risk by not
16 accounting for water level attenuation due to land-surface characteristics. We implement a range of plausible water level
17 attenuation values in the flood module of the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework
18 and assess the sensitivity of flood exposure and flood risk indicators to differences in attenuation rates. Results show a
19 reduction of up to 47% in area exposure and even larger reductions in population exposure and expected flood damages.
20 Despite the use of a spatially constant rate for water attenuation the reductions vary by country, reflecting the differences in
21 the physical characteristics of the floodplain as well as in the spatial distribution of people and assets in coastal regions. We
22 find that uncertainties related to the omission of this factor in global assessments of flood risk are of similar magnitude to the
23 uncertainties related to the amount of SLR expected over the 21st century. Despite using simplified assumptions, as the process
24 of water level attenuation depends on numerous factors and their complex interactions, our results strongly suggest that future
25 impact modelling needs to focus on an improved representation of the temporal and spatial variation of water levels across
26 floodplains by incorporating the effects of relevant processes.

27 28 1. Introduction

29 Increased flooding due to sea-level rise (SLR) is the primary natural hazard that coastal regions will face in the 21st century,
30 with potentially high socio-economic impacts (Kron, 2013; Wong et al., 2014). Broad-scale (i.e. continental to global)
31 assessments of coastal flood exposure and risk are therefore required in order to inform mitigation targets and adaptation
32 decisions (Ward et al., 2013a), related financial needs and loss and damage estimates. Towards these ends, a number of recent
33 studies have assessed the exposure of area, population and assets to coastal flooding at national to global scales (Nicholls,
34 2004; Brown et al. 2013; Jongman et al., 2012a; Ward et al., 2013b; Arkema et al., 2013) as well as flood risk (Hinkel et al.
35 2014).



36 Although the methods for broad-scale coastal-flood exposure and risk assessment vary between studies, flood extent and water
37 depth are usually assessed based on spatial analysis, assuming that all areas with an elevation below a certain water level that
38 are hydrologically connected to the sea are flooded (the “bathtub” method) (Poulter and Halpin, 2008; Lichter et al., 2010).
39 An exception is the study of Dasgupta et al. (2009) who used a simple approach to account for wave height attenuation with
40 distance from the coast. The use of simplified methods for assessing flooding is primarily related to difficulties of using
41 hydrodynamic methods at broad scales. These difficulties are due to the limited availability and large volume of the necessary
42 input data, as well as to the prohibitive computational costs, which render these approaches impractical at global scales
43 (Ramirez et al., 2016). Usually, global applications have utilised elevation data with a spatial resolution of 1km and a vertical
44 resolution of 1m (Mondal and Tatem, 2012; Jongman et al., 2012b; Ward et al., 2014), with only a few recent studies employing
45 higher spatial resolution (90m) datasets (e.g. Hinkel et al., 2014; see also de Moel et al., 2015).

46 Hydrodynamic models are normally used only for local-scale applications. This is because they require detailed data on
47 parameters such as coastal topography/bathymetry and land use in order to represent local-scale processes and to account for
48 hydraulic properties. These data are, however, not always readily available and are associated with large data volumes. A range
49 of simpler inundation models that partly account for hydraulic processes at intermediate scales using medium resolution
50 elevation data (<100m²) have also been applied at subnational scales (e.g., Bates et al., 2010; Wadey et al., 2012; Lewis et al.
51 2015; Ramirez et al., 2016), and these models are beginning to inform analysis at even broader scales (e.g., Vousdoukas et al.,
52 2016). There is also a developing literature on hydrodynamic modelling of water level attenuation over coastal wetlands at the
53 landscape scale (<1km) for saltmarshes (Loder et al., 2009; Wamsley et al., 2009, 2010; Barbier et al., 2013; Smith et al.,
54 2016) and mangrove forests (McIvor et al., 2012; Zhang et al., 2012; Liu et al., 2013). However, the incorporation of the above
55 processes in global models is still very limited.

56 Not accounting for hydrodynamic processes in global models can lead to overestimation of flood extent and water depth.
57 Hydrodynamic models capture processes that are not included in global models, e.g. the effects of surface roughness (both
58 natural and anthropogenic) and channel network density and connectivity (and its effect on landscape continuity) on the timing,
59 duration and routing of floodwaters. For example, inundation extent has been shown in some cases to significantly decrease
60 in urban and residential areas when the built environment is represented in numerical simulations (e.g. tsunami inundation:
61 Kaiser et al., 2011; storm surge inundation: Brown et al., 2007; Orton et al., 2015).

62 To our knowledge there is no study that has explored the uncertainty introduced into global models by not accounting for water
63 level attenuation due to hydrodynamic processes related to surface roughness. This paper aims to address this gap. We derive
64 a range of plausible water-level attenuation values from existing literature and implement them in the flood module of the
65 Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework (described in Hinkel et al., 2014). Next, we
66 assess the sensitivity of flood exposure and flood risk indicators to plausible changes in water-level attenuation values under



67 a range of different SLR scenarios. Finally, we compare the uncertainty due to water level attenuation rates with the uncertainty
68 range associated with expected SLR during the 21st Century.

69

70 **2. Methods and Data**

71 **2.1 The Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework**

72 DIVA is an integrated, global modelling framework for assessing the biophysical and socio-economic consequences of SLR,
73 and associated extreme water levels, under different physical and socio-economic scenarios and considering various adaptation
74 strategies (Hinkel and Klein, 2009). DIVA has been widely used for global and continental scale assessments of SLR impacts,
75 vulnerability and adaptation (e.g., McLeod et al., 2010; Hinkel et al. 2010; Brown et al. 2013; Hinkel et al., 2013; Hinkel et
76 al., 2014; Spencer et al., 2016). It is underpinned by a global coastal database which divides the world's coastline (excluding
77 Antarctica) into 12,148 coastal segments (Vafeidis et al., 2008). Each segment contains approximately 100 elements of data
78 concerning the physical, ecological and socio-economic characteristics of the coast. For the purposes of the present study, we
79 focus on the impacts of increased exposure to coastal flooding and potential damages of extreme sea level events (due to the
80 combination of storm surges and astronomical high tides). We used the flood algorithm of DIVA (for details see Hinkel et al.,
81 2014) to estimate potential coastal flood damage, SLR impacts and associated costs.

82 We specifically considered the following five indicators, which progressively include additional components of flood risk:

- 83 1. Area below the 1-in-100 year flood event (km²), an estimate based on elevation data and information on water levels
84 for a single hazard event (i.e. the height of the 1-in-100 year sea flood);
- 85 2. People living in the 1-in-100 year floodplain, a calculation based on spatial data on elevation and population as well
86 as on information for a single hazard event (i.e. the height of the 1-in-100 year sea flood);
- 87 3. Assets in the 1-in-100 year floodplain (US \$), a calculation that uses data on elevation, population, Gross Domestic
88 Product (GDP) and information for a single hazard event (i.e. the height of the 1-in-100 year sea flood);
- 89 4. Expected value of the number of people flooded per year (hereafter, people flooded), a calculation based on elevation
90 and population data and the probability distribution of the hazard (i.e. sea flood heights and their probability of
91 occurrence); and
- 92 5. Expected value of annual damages to assets (hereafter, flood damage) (US \$), a calculation based on elevation,
93 population and GDP data and the probability distribution of the hazard (i.e. sea flood heights and their probability of
94 occurrence).

95 For each coastline segment, a cumulative exposure function for area and population that gives the areal extent (hydrologically
96 connected to the sea) and number of people below a given elevation was constructed. Damages to assets were assessed using
97 a depth-damage function with a declining slope, with 50% of the assets being destroyed at a water depth of one metre (Messner
98 et al., 2007).



99 2.2 Coastal Elevation and Rate of Water level Attenuation

100 To simulate the effect of different values of attenuation at the broad scale, we implemented a stylised elevation profile in order
101 to represent the process of water level attenuation. We assumed that water levels decrease at a constant slope (α) with increasing
102 distance from the coastline. Location-specific coastal profiles for every coastline segment were based on floodplain areas
103 contained within the DIVA database. The database reports total land area within different elevation increments (<1.5m, 1.5-
104 2.5m, 2.5-3.5m, 3.5-4.5m, 4.5-5.5m, 5.5-8.5m, 8.5-12.5m, 12.5-16.5m) for each coastal segment. The elevation dataset that
105 was used for estimating floodplain areas and developing the segment elevation profiles is the Shuttle Radar Terrain Mission
106 (SRTM) Digital Elevation Database (Jarvis et al., 2008) which has a vertical resolution of 1m and a spatial resolution of 3 arc
107 seconds (~90m at the equator).

108 We approximated the average coastal profile for every segment by assuming that elevation continuously increases with
109 distance from the shore. Starting with the lowest elevation increment, the floodplain areas of all elevation increments were
110 cumulatively summed to retrieve the total area below a certain elevation. The total areas are then divided by the segment length
111 to derive the inundation length of the respective floodplain (dx_i).

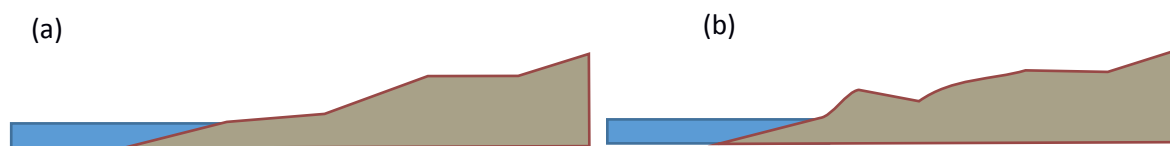
112 To evaluate the representativeness of the assumption of continuously increasing elevation with increasing distance from the
113 shore, we used the original SRTM dataset and calculated the Euclidian distance of each cell to the nearest coastline for every
114 pixel. Mean distances from the coast were calculated for each of the floodplain areas of each segment. Subsequently, we
115 compared these mean distances with the respective average floodplain elevation for each DIVA coastline segment to analyse
116 the validity of the “continuous-increase” assumption. This comparison revealed that 55% of the DIVA coastline segments
117 show either a continuous increase or no change in the mean distance along the elevation profile (Figure 1a), suggesting that
118 elevation does not decrease with distance from the coast. Comparing all elevation increments of all segments (i.e. pairwise
119 comparison of the mean distances of consecutive elevation increments in a segment), there was an increase, or no change, in
120 the mean distance from the coastline in 88% of cases. Only 12% of cases showed a decrease (Figure 1b). This result indicates
121 that the stylised continuous profile (Figure 1a) can be regarded as generally representative of global coastal topography.

122

123

124

125



126 **Figure 1: Stylised coastal profile with (a) continuous and (b) discontinuous increase in elevation with distance from the shore.**

127 We then adjusted the coastal profile using a range of possible attenuation rates that represent different water surface slopes.
128 Depending on the applied value for water level attenuation, the slope (α) of the inundating water surface was employed to

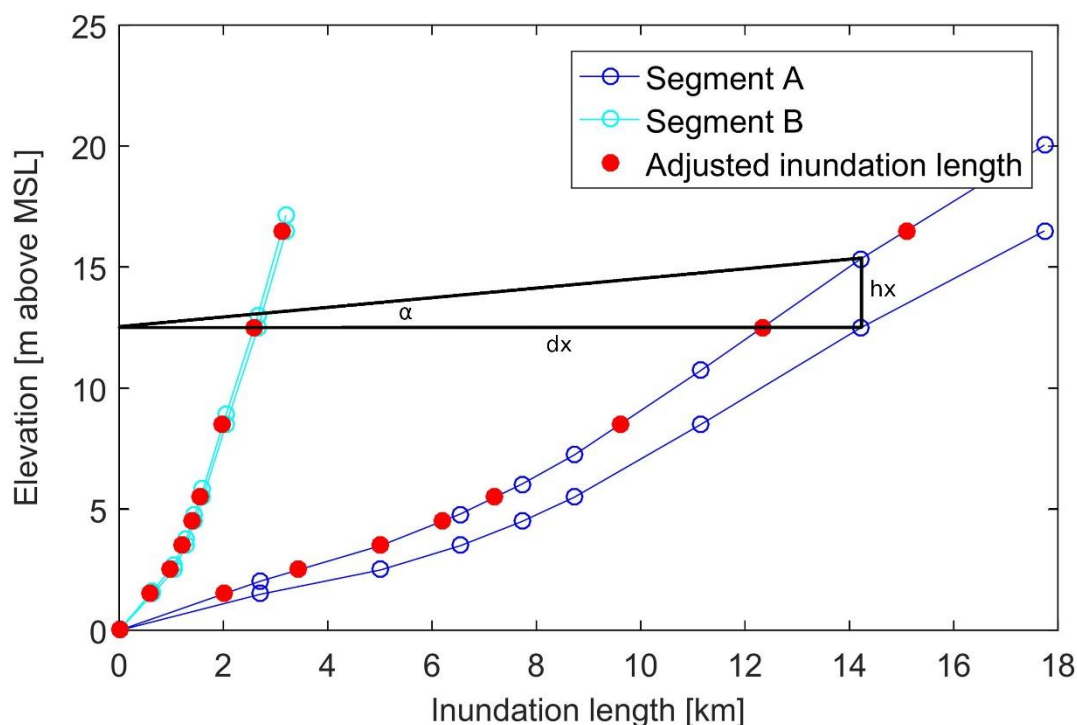


129 modify (incline) the coastal profile. Based on this slope, the coastal profile is thereby elevated by the amount of the water level
 130 reduction (hx_i) computed at a distance dx_i (Fig. 1):

131
$$hx_i = \tan(\alpha) * dx_i \quad (\text{equation 1})$$

132 In this way the original floodplain areas and inundation depths are reduced in order to account for the reduced (i) inundation
 133 length (dx) and (ii) inundation depth (hx) (see Fig. 2).

134



135

136 **Figure 2: The stylised coastal profile, based on the floodplain areas in the DIVA database (lower line), for two characteristic**
 137 **coastline segments (A with a flat and B with a steep profile). Water level attenuation is accounted for by elevating the coastal**
 138 **profile according to equation 1 (upper line). Red dots on the adjusted coastal profile indicate the inundation length in the case of a**
 139 **water level with a constant slope of α , which represents the attenuation rate and for an incident water level equal to the**
 140 **corresponding increment height.**

141 For the sensitivity analysis we used the following range of attenuation rates for inclining the water surface in order to represent
 142 a constant water level attenuation and the associated reduction in water levels (α): 0, 10, 20, 50 and, following discussion with
 143 experts in the field, 100cm/km. This range embraces the values reported in the literature (Table 1), where water level under
 144 storm conditions has been shown to decrease with distance from the coast. For reviewing the literature we employed the ISI
 145 Web of Knowledge and based our search on the keywords “surge”, “attenuation”, “water-level”. We selected studies that



146 directly reported values of water level reduction with distance and did not include studies focussing on wave attenuation. We
 147 must note that the aim was not to carry out a systematic literature review but rather to identify a range of values that could be
 148 used for our sensitivity analysis. The identified studies all relate to coastal wetland environments; although there are published
 149 studies of localised water level dynamics from flow-form interactions in urban and other settings, we have not come across
 150 similar landscape-scale assessments for other landuse types. Therefore we extended this review, where reported attenuation
 151 values were up to 70cm/km, by directly contacting experts with experience in field or modelling studies. Following their
 152 suggestions we decided to investigate attenuation rates of up to 100 cm/km as an upper limit.

153

Event type	Landcover type	Location	Rate of water-level reduction	Method	Source
Storm surge	Bare land and Marsh	Modelled platform +0.5 m above sea level	10 cm / km (no vegetation, no channels) 26 cm / km (100% vegetation cover, no channels) 8 cm / km (100% vegetation cover, channel network)	Numerical modelling	Temmerman et al., 2012
Hurricane Isaac (2012)	Marsh	Louisiana	Up to 70cm/km water level reduction in presence of vegetation; 37 % reduction of total inundation volume	Numerical modelling	Hu et al., 2015
Hurricanes	Marsh	Multiple	1 m per 14.5 km 6.9 cm/km (range from 1m per 5km to 1m per 60km 20 - 1.7 cm/km)	Field Study	Corps of Engineers (1963) – In Wamsley et al., 2010
Hurricane Andrew (1992)	Marsh	Louisiana	1m per 20km-23.5km 5 - 4.3 cm/km	Field Study	Lovelace 1994
Hurricane Rita (2005)		Louisiana	1m per 4km to 1m per 25km 25 – 4 cm/km	Field Study	McGee et al. 2006 in Wamsley et al., 2010
Hurricanes	Mangroves Marsh	Florida	9.4 - 4.2 -cm/km	Field Study	Krauss et al., 2009



Wilma (2005) and Charley (2004)					
Hurricanes	Mangroves	Louisiana	23.3 – 1.7 cm/km	Field Studies	McIvor et al., 2012 (from various studies)
Hurricane Wilma (2005)	Mangroves	South Florida	Up to 50 cm/km (6-10 cm per km in the absence of mangroves)	Field study & modelling	Zhang et al., 2012
Hurricanes	Mangroves	South Florida	7.7 - 5.0 cm/km	Modelling	Liu et al., 2013

154 **Table 1: Water level reduction rates, for different types of landcover, as reported in the literature.**

155

156 **2.4 Sea-Level Rise and Socio-Economic Scenarios**

157 For global SLR in 2100 from a 1985 – 2005 baseline, we used three scenarios: the 5% quantile of the low Representative
 158 Concentration Pathway (RCP) 2.6; the median of the medium scenario RCP 4.5; and the 95% quartile of the high scenario
 159 RCP 8.5. These scenarios are represented by SLR estimates of 29, 50 and 110 cm (by 2100), respectively and were developed
 160 in the Inter Sectoral Model Intercomparison Project Fast Track (for full details see Hinkel et al., 2014). Once mean sea level
 161 is determined, future extreme water levels are obtained by displacing upwards extreme water levels for different return periods
 162 (as included in the DIVA database) with the rising sea level, following what has been observed to occur by Menendez and
 163 Woodworth (2010).

164 We used a single shared socio-economic pathway (SSP), namely SSP2, to represent changes in coastal population and assets.
 165 SSP2 reflects a world with medium assumptions between the other four SSPs, in terms of resource intensity and fuel
 166 dependency as well as GDP and population development (O’Neil et al., 2014). Finally, we ran the DIVA model using a no-
 167 dike scenario, where no defence measures for preventing coastal flooding are present.

168

169 **3. Results**

170 We present results for five different attenuation rates, across the five indicators that progressively include additional
 171 components of flood risk.

172



173 **3.1 Reduction of current flood exposure and risk**

174 Table 2 shows the results from the “bath tub” model (0 cm/km) and both the absolute and percentage reductions in the values
 175 of the five indicators against this baseline.

176

	0 cm/km	10 cm/km	20 cm/km	50 cm/km	100 cm/km
Water Level Attenuation Rate		(% reduction)	(% reduction)	(% reduction)	(% reduction)
Area below the 1-in-100 year flood [km²]	621,721	520,423 (16.3%)	473,044 (23.9%)	395,525 (36.4%)	328,661 (47.1%)
People below the 1-in-100 year flood [million]	159	101 (36.4%)	85 (46.1%)	69 (56.3%)	58 (63.0%)
Assets below the 1-in-100 year flood [billion US\$]	5,920	4,177 (29.4%)	3,692 (37.6%)	3,099 (47.7%)	2,651 (55.2%)
People flooded [million/yr]	124	78 (37.3%)	67 (46.2%)	54 (56.6%)	45 (63.3%)
Flood damages to assets for the 1-in-100 year flood [billion US\$/yr]	2,987	2,145 (28.2%)	1,906 (36.2%)	1,594 (46.6%)	1,372 (54.1%)

177 **Table 2: Reduction, relative to the bathtub method, of five indicators of global exposure and risk, for different water-level**
 178 **attenuation rates. Values are for a medium SLR scenario (median of the medium scenario RCP 4.5; 50 cm by 2100)**

179

180 Our results show that the inclusion of constant water-level attenuation rates in the assessment of flooding results in large
 181 differences in the values of the five indicators. For example, the area exposed to the 100-year flood in 2100 reduces by up to
 182 47% with the use of different attenuation rates. A rate of 10cm/km, which has been assigned to non-vegetated surfaces, results
 183 in an area reduction of 16% while a rate of 50cm/km, which has been measured in mangroves, can result in a reduction of 36%
 184 (see Table 2). Interestingly, the number of people in the 100-year floodplain reduces to 58 million for an attenuation rate of
 185 100 cm/km. This is a reduction of 63%, which is larger than the respective reduction in assets (55%) and in area (47%). This
 186 result reflects the high population density near the coast that has been reported in previous studies (Neumann et al., 2015).
 187 Flood damages from the 1-in-100 year event are reduced in similar proportion, totalling a reduction of more than 1.4 trillion
 188 US\$ globally, for an attenuation rate of 100 cm/km.



189 Despite using a global value for the attenuation rate for every model run, the reduction in impacts is not uniform across the
 190 globe and can vary considerably between different countries. Some examples are given in Table 3, where accounting for water
 191 level attenuation can reduce area exposure by up to 77% in China, 57% in Bangladesh and 56% in the USA. At the same time,
 192 the reduction in annual flood costs follows a different trend, with exposed assets reducing by up to 71% in China, 49% in
 193 Bangladesh and 25% in the USA, reflecting differences in the physical characteristics of the floodplain as well as in the spatial
 194 distribution of people and assets in the coastal regions of these three countries.

195

Water Level Attenuation Rate	0 cm/km	10 cm/km (reduction)	20 cm/km (reduction)	50 cm/km (reduction)	100 cm/km (reduction)
Area below 1-in-100 year flood					
(km ²)					
Bangladesh	7723.38	6006.7 (22%)	5374.86 (30%)	4291.14 (44%)	3326.18 (57%)
China	48002.08	29240.27 (39%)	22532.22 (53%)	14971.79 (69%)	10999.83 (77%)
USA	42354.83	34984.95 (17%)	30595.83 (28%)	23870.76 (44%)	18846.31 (56%)
Assets below 1-in-100 year flood					
(billion \$US)					
Bangladesh	58	43 (25%)	39 (32%)	34 (41%)	31 (49%)
China	2244	1260 (43%)	1021 (54%)	794 (64%)	642 (71%)
USA	267	250 (6%)	240 (10%)	221 (17%)	200 (25%)

196 **Table 3: Absolute and relative reduction of the 1-in-100-year floodplain area and associated exposed assets when applying different**
 197 **water-level attenuation rates for Bangladesh, China and USA. Values assume a medium SLR scenario (median of the medium**
 198 **scenario RCP 4.5; 50 cm in 2015).**

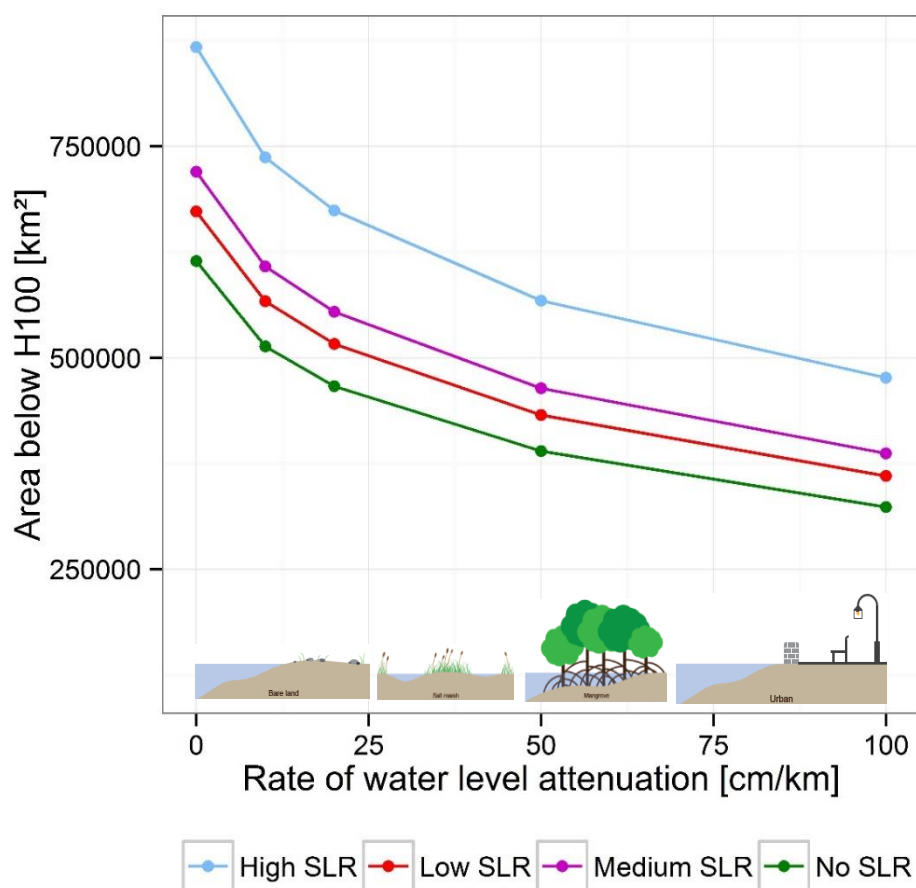
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200 3.2 Comparison of attenuation rate uncertainty with sea-level rise uncertainty

201 Figure 3 illustrates the area of land located below the 1-in-100 year storm surge level (H100), plotted against the different
 202 attenuation rates for water level change. The inclusion of linear water-level attenuation in the assessment of flooding results



203 in large differences in the calculation of area exposure for all SLR scenarios. The extent of the 100-year floodplain in 2100
 204 (Figure 3) reduces substantially under all SLR scenarios. This reduction amounts up to 36% and 46% of the total exposed area
 205 for the medium SLR scenario (median of the medium scenario RCP 4.5; 50 cm by 2100), and water level attenuation rates of
 206 50cm/km and 100 cm/km respectively. The relative reduction is marginally smaller for the high SLR scenario compared to the
 207 medium-, low- and no-SLR scenarios. Importantly, the overall difference in the extent of the area of the 100-year floodplain
 208 between the no- and high-SLR scenarios is smaller than the difference in area extent between the 0 and 20cm/km water level
 209 attenuation rates under any scenario. This indicates that when assessing area exposure, accounting for even relatively moderate
 210 rates of water level attenuation can be of equal importance to the differences that result from different scenarios of SLR. This
 211 analysis, therefore, strongly suggests that uncertainties related to the omission of this factor in global assessments of flood risk
 212 are of similar magnitude to the uncertainties related to the magnitude of SLR expected over the 21st century.



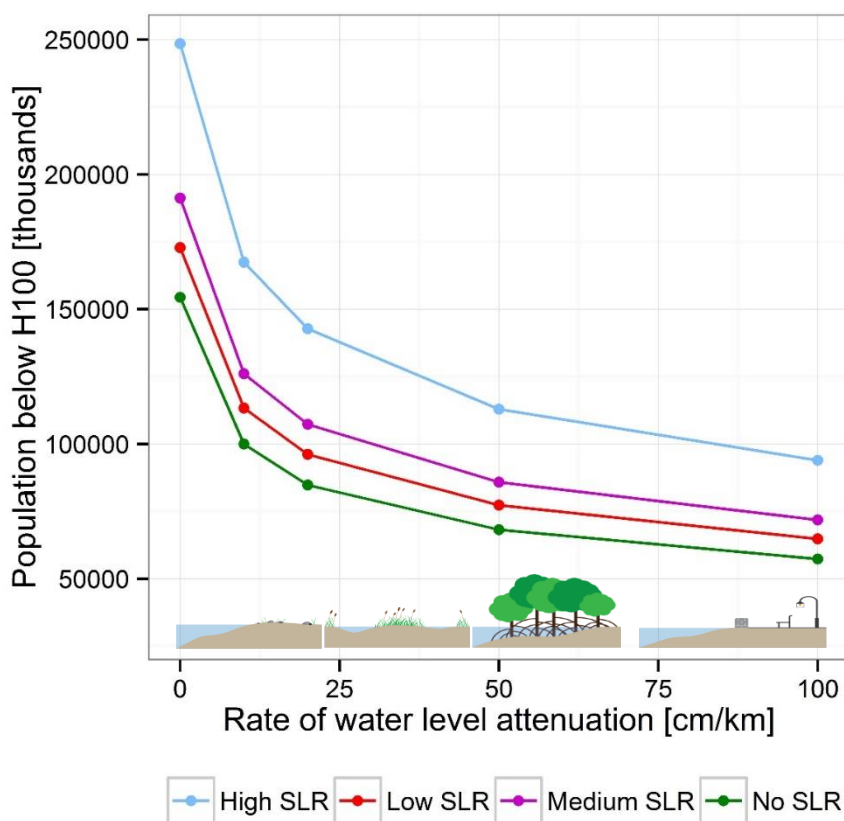
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214 **Figure 3: Global total extent of the 100-year floodplain, for different water level attenuation rates and SLR scenarios.**



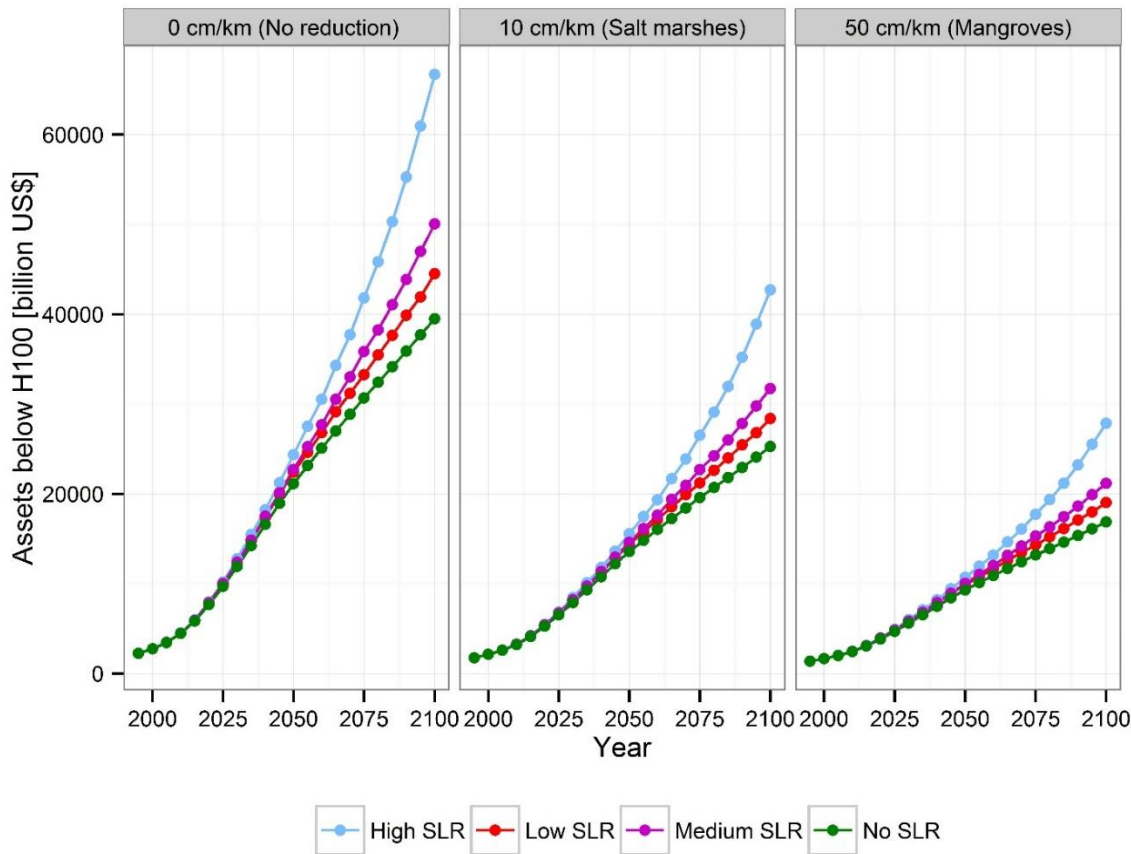
215 An attenuation of water levels of 10 cm/km, a typical value reported in wetlands (Table 1), results in a reduction of 100,000
216 km² of area exposed to the 1-in-100-year flood under the no-SLR scenario. This increases to 130,000 km² under the high SLR
217 scenario. It is also noteworthy that this, rather moderate, attenuation rate can shift impacts (in terms of area exposure) in time
218 by approximately 30 years (under all SLR scenarios).

219 Similar patterns can be observed for the exposure of population to the 1-in-100-year flood (Figure 4). An attenuation rate of
220 50cm/km, a value that has been reported in mangrove forests (Table 1), leads to a reduction of more than 50% in the exposure
221 of population in 2100, under the high SLR scenario, bringing the number of people at risk in the 100-year floodplain down by
222 136 million. Moreover, an attenuation of 20cm/km leads to a reduction in risk to 106 million people, making population
223 exposure lower than the exposure under no SLR when attenuation is not considered. Again, this result suggests that accounting
224 for water level attenuation may be equally important to accounting for SLR uncertainty when assessing the exposure of people
225 to coastal flooding due to SLR.



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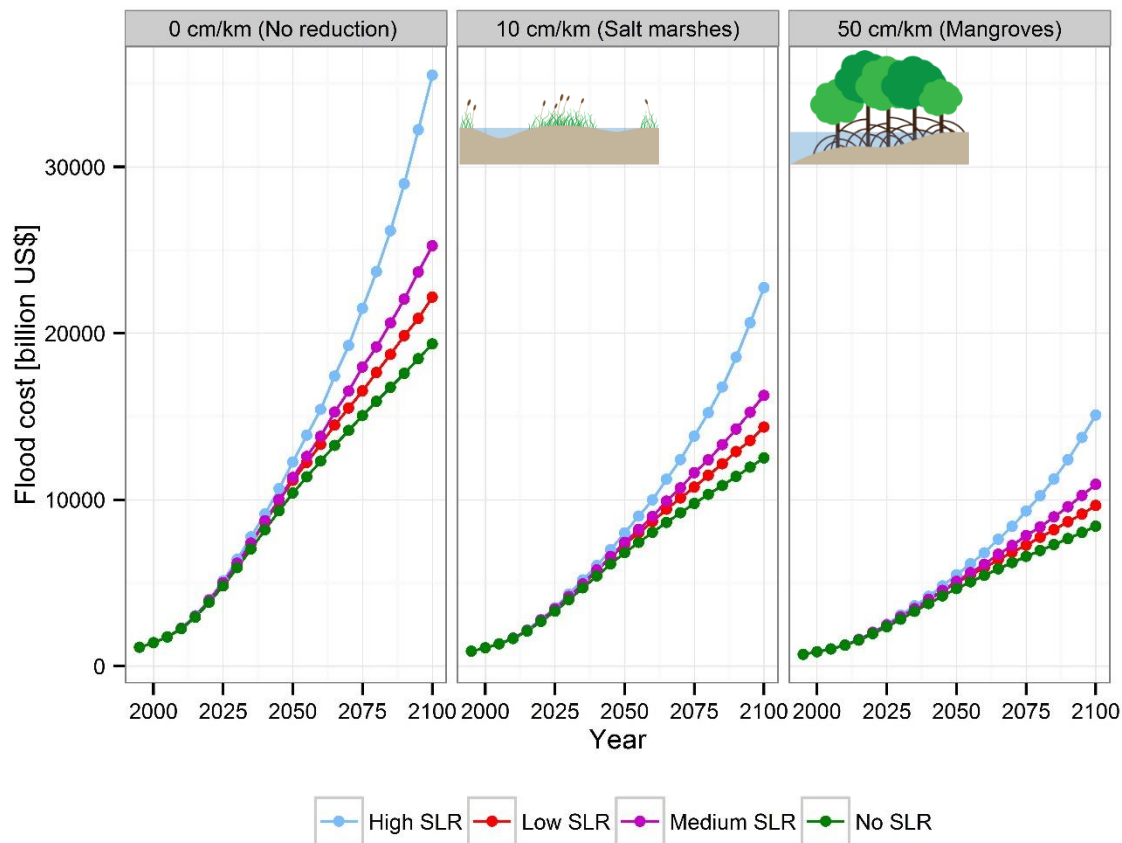
227 **Figure 4: Global estimates of population in the 100-year floodplain for different water-level reduction rates (Table 1) and SLR**
228 **scenarios.**



229

230 **Figure 5: Temporal evolution of the amount of assets that are located in the 100-year floodplain for different water-level reduction**
 231 **rates (Table 1) and SLR scenarios.**

232 Similar trends can be seen in the value of assets exposed to the 1-in-100-year flood, under all scenarios, when accounting for
 233 water level attenuation (Figure 5). A constant attenuation of 20cm/km would result in a decrease in the exposure of assets of
 234 approximately 37% in 2100, for a medium SLR scenario, whereas reductions of up to 48% can be seen in assets exposure
 235 when an attenuation rate of 50 cm/km is used. At the same time, damages also reduce considerably by the introduction of water
 236 level attenuation rates (Figure 6). For example, the use of an attenuation rate of 10 cm/km results in a 28% reduction in damages
 237 to assets in 2100 for the 1-in-100 year flood. The larger decrease of assets' exposure due to water level attenuation compared
 238 to population and area exposure is due to the fact that, besides the decrease of the flood area extent, water level attenuation
 239 leads to an additional reduction of flood depth with distance from the coast. As water depth is an important parameter for
 240 calculating damages to assets (Thieken et al., 2005; Penning-Rowse et al., 2013), depth reduction further reduces the exposure
 241 of assets due to flooding.



242

243 **Figure 6: Comparison of temporal evolution of sea-flood damage estimates for attenuation rates of 0, 10 and 50 cm/km, for different**
 244 **SLR scenarios.**

245

246 **4. Discussion and Conclusions**

247 The results of this study highlight the importance of accounting for the effects of hydrodynamic processes when assessing the
 248 impacts of coastal flooding at national to global scales. In particular, water level attenuation from the interaction of extreme
 249 inundation events with vegetated surfaces can lead to considerably lower estimates of exposure of land area and population to
 250 coastal flooding. Furthermore, this effect can lead to large reductions in potential damages, as lower water depths combined
 251 with smaller flood extents give significantly lower flood-damage costs. The reduction in exposure and risk is especially
 252 pronounced for water level attenuation rates of up to 20cm/km, rates which are typical of tidal wetlands.



253 Importantly, the effects of accounting for water level attenuation appear to be as important in assessing impacts as accounting
254 for uncertainties related to the total magnitude of SLR that is commonly employed for impact analyses. In many of the cases
255 that we explore, the difference in impacts between the no- and high-SLR scenarios is lower than the difference in impacts
256 between a no-attenuation and the attenuation scenario of 10 cm/km. This is of relevance in environments where the floodplain
257 substantially extends inland, such as in many of the world's deltas and coastal plains.

258 It is widely acknowledged that the use of simplified methods, such as the bathtub method, can provide useful first-order
259 estimates of global impacts of SLR and associated flooding. Although an overestimation of flood extent and depth with the
260 use of the bathtub method should be generally anticipated, the reduction that we observe with the use of water level attenuation
261 rates does not necessarily reflect the actual impacts. These are likely to depend on additional factors which are usually not
262 considered in global assessments. For example, damage to assets is based solely on water depth. Factors such as high local
263 flow velocities from channelized flow, storm wave impacts, inundation by saline water and sedimentation from flood waters
264 are not taken into account. Such contributory factors can lead to an increased cost of damages and thus counteract the lower
265 impacts predicted from the use of a water level attenuation term alone. Furthermore, the analysis reported here is predicated
266 on the assumption of a continuous increase in elevation with increasing distance from the shore. This study shows that whilst
267 this assumption holds true for the majority of coastal segments, there are segments where this assumption does not hold true.
268 In these cases model outputs may poorly describe flood areas, flooded population numbers and asset damages and incorrectly
269 predict the effect of changes in the rate of water level attenuation. Nevertheless, and despite these caveats, our results emphasise
270 the importance of accounting for uncertainties in impact assessments stemming from an inadequate consideration of water
271 level attenuation over coastal plains.

272 Our approach means to provide an illustration of the potential effects of water level attenuation, as this process is not constant
273 throughout the floodplain and depends on numerous parameters beyond the type of the surface cover. These factors include
274 storm duration, wind direction, water depth and vegetation traits (Resio and Westerink, 2008; Smith et al., 2016; Stark et al.,
275 2016). Furthermore, applying a constant slope to account for water level attenuation is a strong simplification, since this will
276 vary between different storm events, but also under the influence of SLR. Nevertheless, given the very high sensitivity of the
277 outputs to small changes in water level reduction and the obvious lack of sufficient data on the actual effect of different types
278 of surface on attenuating water levels during surges, we suggest that future work needs to focus on quantifying the water level
279 attenuation terms for different land uses. Thus, for example, both Brown et al. (2007), in the case of modelled flooding
280 following storm surge-induced sea defence failure, and Kaiser et al. (2011), in the case of modelled tsunami wave impacts,
281 have shown that disregarding buildings and associated infrastructure (roads, gardens, ditches) when assessing inundation can
282 lead to a large overestimation of the extent of flooding. Furthermore, given the large range of uncertainty with respect to the
283 actual values of water level reduction associated with just one surface cover, wetland habitat (Table 1), future impact modelling
284 needs to focus on a better understanding of the temporal and spatial variation of water levels across floodplains showing a
285 wide variety of landuse types and human occupancy, including densely urbanised regions (e.g. Lewis et al., 2013; Blumberg



286 et al., 2015). This work should include, but also go beyond, quantifying the water level reduction of coastal wetlands in order
287 to enable broad-scale models to incorporate, initially in a stylised manner, the effects of water level attenuation.

288 Given that coastal wetlands can efficiently attenuate surge water levels, the results of this study give a first estimate of how
289 much of an impact reduction may result from the implementation of large-scale, ecosystem-based flood risk reduction
290 management schemes (e.g. Temmerman et al., 2013). In addition, achieving lower water levels through the establishment of
291 coastal wetlands not only reduces impacts but may also affect the timing of potential adaptation tipping points by extending
292 the anticipated lifetime of adaptation measures. This would allow the development of alternative adaptation pathways, a
293 sequential series of linked adaptation options triggered by changes in external conditions (Barbier, 2015), for coastal regions.

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