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1 **Revised manuscript without annotations**

2

3 **Flood-related risks in Ho Chi Minh City and ways of mitigation**

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6

7 **Abstract**

8 With an ever-growing population of around 10 million inhabitants (officially 7.9 in
9 2013), Ho Chi Minh City (HCMC) is set to become one of the largest cities in South East
10 Asia and already occupies a major economic role in the area. To accommodate the
11 increasing population, the megacity now stretches out in an urban continuum covering
12 more than 800 square kilometers and is currently growing at a rate of 3.2% per year. If
13 the neighboring provinces around HCMC are included, the total population reaches
14 nearly 18 million people.

15

16 This paper attempts to describe the interplay between HCMC and flood-related risks and
17 offer some guidelines to deal with inundations. The potential risks of flooding by rain,
18 tsunami and/or dam failure upstream of the city are evaluated and contextualized
19 within the perspective of climate and human-induced environmental changes. The
20 region is highly vulnerable to the combined effects of subsidence and rising sea levels

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21 and has already led to serious flooding that may extend spatially before the end of the
22 century. We propose possible preventative solutions to urban flooding using a multi-
23 pronged approach to issues regarding urban development and suggest a redevelopment
24 strategy for major infrastructure projects.

25

26 Keywords: adaptation to urban inundation, tropical rain, wave set-up by tides, tsunamis,
27 dam failure, climate change, subsidence, urban planning strategy

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37 **1- Introduction**

38

39 Ho Chi Minh City is a low elevation coastal megacity with a very large and rapidly
40 increasing population. Economic activity is also very high and rising in line with the
41 population increase. Like most megacities in South East Asia or India that were built
42 within a delta's boundaries, HCMC is affected by flood related risks aggravated by the
43 conjunction of heavy rains and high tide levels. This situation is driven by three factors:
44 low elevation of the land above sea level, extensive urban growth yielding to soil
45 subsidence, and an extension of impervious areas resulting in increased runoff.

46 Over the last 300 years, HCMC has gone through several phases of expansion. Because
47 the city is bordered by the Saigon River and intersected by several creeks, water has
48 always been a fundamental part of its identity. In the late 18th and early 19th centuries,
49 the Nguyen Dynasty expanded the canal network to improve waterway transportation
50 and facilitate commercial activity. Under French rule in the first half of the 20th century
51 the urban face of Saigon underwent major changes, in particular the canals intersecting
52 the city center were filled to create tree-lined boulevards (Ton and Truong, 2011).
53 Swampy areas were also filled to build residential areas and concomitantly, the network
54 of remaining canals was progressively used as an open-air sewage system (domestic as
55 well as industrial waste water) (Givental, 2014). Water is now the main focus of all
56 worldwide climate-related issues and HCMC finds itself on the top-ten list of cities
57 categorized as being in the greatest danger of coastal flooding (Small and Nichols, 2003;
58 ISPONRE, 2009).

59 This paper proposes a multiple perspective approach to characterize the principal risks
60 of flooding caused directly by heavy tropical rain and runoff and/or high tide wave-set-
61 up, and ways to mitigate them. First, field measurements were taken throughout the
62 urban area to quantify flooding by rain and to assess the flood risks in those
63 neighborhoods. This quantification is complemented by numerical simulations to
64 characterize the risks of submersion caused by either tsunami waves or the rupture of a
65 dam as well as data related to the expected increase in future sea levels. Once the main
66 results of these flood related risks are cross-referenced and assessed we discuss
67 possible urban planning for Ho Chi Minh City's future development.

68

69 **2- Material methods**

70

71 2.1 Study site

72 HCMC is located in a low-elevation coastal zone in the upper border of the Mekong Delta
73 and 65% of its territory is at an altitude below 1.5 m above sea level (Fig 1). It is
74 characterized by a subtropical monsoon climate with two distinguished seasons. The
75 rainy season extends from May to November with a heavy period from September to
76 October. In total, about 160 rain events occur yearly with an average cumulated rainfall
77 of roughly 2000 mm. Because of the convective pattern of precipitation events, the rain
78 is non-uniformly distributed at the scale of the megacity, with considerable differences
79 from one district to another for a given storm event. This variability at short spatial scale
80 is currently not accounted for in weather forecast reports. In conjunction with heavy
81 precipitation, HCMC is also affected by the combined effects of semi-diurnal tides waves,

82 with amplitude reaching a maximum of 1.5 m, and high water discharge from both
83 upstream rivers; namely the Saigon and Dong Nai rivers.

84 HCMC has been experiencing severe accelerated urbanization since the start of the last
85 decade with up to 100% of land surface constructed upon in some sectors (Nguyen,
86 2013). Heavy rain intensity and lack of sewage infrastructure makes the megacity highly
87 vulnerable to flood risk. As shown in the present study, the spatio-temporal dynamics of
88 flooding in HCMC differs significantly when driven by rainfall or river overflow.

89 2.2 Monitoring rain and flood zones

90 Since 2002, a monitoring network has been developed to survey urban flooding at the
91 street scale (Tran Ngoc, 2002) and includes 11 automatic rain gauges distributed all
92 over the city as well as monitoring cameras installed in 2013. This network is completed
93 by visual observations to characterize the submerged areas, i.e., to measure water depth,
94 duration and spatial extension of any inundations. Since 2009, inundation areas have
95 been systematically classified into two typologies: submerged areas are referred to as
96 “old” for those that are regularly submerged from year to year, or “new” for those
97 appearing in different locations from year to year.

98 2.3 Numerical modeling

99 To assess another risk of flooding by tsunami or dam failure, numerical simulations
100 were undertaken with Telemac2D code (Lang, 2010). This software is based on the
101 Barré de Saint Venant equations and assumes 2D shallow water conditions. Initially
102 developed by Electricité de France (EDF), it was chosen for its ability to solve large-scale
103 problems with reasonable computation time.

104 The first case study aimed to evaluate the effects of a tsunami that could occur due to an
105 ocean quake (with different levels) in the East Sea: a potential earthquake area because

106 of its geological structure. Hypothetical numerical runs were conducted by placing the
107 epicenter about 240 km from Vietnam's south coast. The purpose was to determine the
108 spatio-temporal characteristics of tsunami waves and help authorities set up early
109 warning procedures. As presented in Fig 2a, the numerical domain extended up to
110 HCMC. The discretization scheme consisted of 1,045,000 triangular elements, varying in
111 size from 500 to 4,000 m for the seaward extension of the domain to a size of 10 m to
112 describe the streets in the urban context. Different cases of earthquake magnitude
113 corresponding to 7.6, 7.8, 8.0, and 8.35 on the Richter scale were simulated. It took one
114 hour of computation to simulate ten hours using an Intel server cluster on parallel mode
115 with 16 cores.

116 The second case study was undertaken with the same numerical model and grid of
117 discretization, but focused on the domain located upstream of HCMC. It aimed to assess
118 the city's submersion risk in the event of the Dau Tieng dam failure, which is located
119 eighty kilometers upstream of HCMC. This earth dam was constructed between 1981
120 and 1985 for agricultural irrigation in the provinces surrounding HCMC and has a total
121 capacity of 1.58 billion m³ of water and maximum water level of 28 m. The study area
122 (Fig 2b) extended from the Dau Tieng Lake to the estuary and represented a surface of
123 5,000 km². It was discretized with 270,000 triangular elements. The simulation was
124 done for a failure width of 500m, corresponding to a maximum instantaneous flow
125 discharge of 40,000 m³/sec in a section located ten kilometers downstream of the dam.

126

127 **3- Results and discussion**

128

129 3.1 Coupled effects of rainfall and urbanization

130 Fig 3a represents the number of storm events observed in HCMC from 2007 to 2014 and
131 demonstrates that heavy rain events exceeding 100 mm are not rare and can be
132 observed every year. However, important inter annual variability can also be observed.

133 Another important result is that some locations are systematically submerged, yet each
134 year new flood sites can be observed (Fig 3b). The total number of submerged locations
135 was the highest in 2008 (126 locations), as a result of a very sharp increase in building
136 density since the beginning of the 1990's. During this period, the impervious surface
137 increased 8 fold in the flood-prone area and the population increased by 2 fold (Nguyen,
138 2013). This figure also shows that the number of submerged sites changed considerably
139 over the 2008-2015 period. First, it decreased steeply from 2008-2011 to reach a
140 minimum of 30 inundated sites. This can be related to the reduction from 4 to 1 of
141 rainfall events larger than 100mm (Fig3-a) , and also to large scale restructuration of the
142 drainage infrastructure in the downtown area (Tran Ngoc, T.D., 2015). The resurgence
143 of flooding observed in 2013-2014 is likely due to the development of peri-urban zones
144 with poor sewer installation and poor maintenance , and to the increase of rainfall
145 events

146 It also seems that the time needed to reduce flooding (by drainage infrastructure) in the
147 areas transitioning from small houses and gardens in 2008 to full urbanization in 2014
148 was much longer than anticipated, as illustrated in Fig 3c.

149 Another consequence of intensive urbanization is that soil subsidence has reached a rate
150 of 0.02 to 0,04 m/yr in some sectors and is illustrated in Fig 4a. This subsidence is
151 greatest in the city center along the Saigon River (districts 7, 12, Binh Thanh, Thu Duc)
152 and in the southwest peri-urban sectors (districts 6, 8 and Binh Chanh). In these sectors,
153 old traditional houses have been demolished to make way for high-rise buildings (some

154 of them more than 50 floors) and commercial centers. Subsidence here is the result of
155 intensive groundwater pumping to secure building basements and is also linked to the
156 construction of a new underground metro system due for completion in 2019. Dinh et al.
157 (2015) also demonstrated the impact of geology because the most severe rates of
158 subsidence were observed in the Holocene silt loam areas along the Saigon River and in
159 the southwest of the city. It is obvious that this process leads to an accumulation of
160 runoff and limits the evacuation by gravity of the flooded zones.

161 Overall, it is clear the city has several flood-prone areas with submersion levels varying
162 from 0.15 to 0.65 m (Fig 4b – produced by the Earth Observation Service of ESA)
163 resulting from rainfall variability and/or high tide wave set-up and that both are
164 impacted by subsidence. Comparison between figures 4a and 4b clearly demonstrates
165 this conjunction between subsidence and flooding.

166 3.2 Incidental flooding driven by wave propagation

167 Two numerical simulations were performed to determine the flood risk for several
168 districts along the Saigon River that could result in wave propagation originating from
169 either a tsunami in the East Sea or a reservoir dam failure upstream of HCMC,
170 respectively.

171 For a quake reaching an intensity of 8.0 on the Richter scale, the average celerity of a
172 tsunami's waves from the earthquake's epicenter to the estuary is about 20.5m/sec. The
173 change in sea level height after 1.5 hours is presented in Fig 5a. The tsunami's peak
174 arrives at the estuary after approximately 3.25 hours and here the highest water level
175 attains seven meters. The wave reaches downtown HCMC after an additional 4.5 hours
176 (Fig 5b) and induces a wave between 1.5 and 3 m above the initial street level according
177 to the different simulations considered. It is worth noting that during propagation along

178 the mangrove fringe, tsunami waves could be greatly dissipated by this type of
179 ecosystem (Barbier et al., 2008). It was not possible to include this mitigating effect in
180 our simulation but it should be taken into consideration in the future.

181 The second case study of failure at the Dau Tieng dam is presented in Fig 6. The flood
182 wave has an amplitude that decreases rapidly from a peak of nearly 18 m at 20 kms
183 downstream of the dam to less than one meter in the city center. As shown in Fig 6, the
184 fluctuations due to tidal forcing (dashed black line) are comparable to those related to
185 the impact of dam failure (solid black line). From this, it seems clear that HCMC is
186 moderately vulnerable in the event of dam failure at Dau Tieng. The existence of a
187 floodplain located upstream of HCMC where discharged water can spread may explain
188 these simulated results. While the spread would protect HCMC's infrastructure and
189 inhabitants, it would undoubtedly cause major damage in the upstream agricultural
190 zones.

191 The conclusion that can be drawn from these simulations is that the risk of flooding
192 from a tsunami would most likely be much larger than from dam failure.

193

194 **3.3- Long-term vulnerability**

195

196 A realistic flood risk assessment and its long-term evolution should also take into
197 account the effects of human-induced climate change. A series of scientific works
198 coordinated by the Intergovernmental Panel on Climate Change (IPCC) and summarized
199 in its 5th IPCC Report (part 2, Impact, Adaptation and Vulnerability, March 2014)
200 underlines that without a drastic reduction (50%) in greenhouse gas emissions, the area
201 of South Vietnam could be seriously affected by the conjunction of two effects:

202 - from a hydrometeorological perspective, an increase in the occurrence of typhoons and
203 extreme rainfall (by 10 to 20%) is anticipated, with a strong impact on river flow and
204 riverbank erosion.

205 - from an ocean perspective, an increase of the sea surface temperature to 30°C or more
206 in the South Pacific zone combined with the melting of Antarctica ice sheet could produce
207 a sea-level rise of 1 m by the end of this century if greenhouse gas emissions continue
208 unabated, as recently analyzed by R.M de Conto, D. Pollard (2016) on the basis of
209 innovative numerical simulations coupling ice sheet and climate dynamics

210 The situation will certainly be exacerbated by the impact of human activities on soil
211 subsidence at both the urban and regional scale. In addition to the megacity situation
212 discussed in section 3.1 and presented in Fig 4, agricultural practices in the Mekong
213 Delta are responsible for a very worrying situation, as pointed out by Erban et al.
214 (2014). Through a set of observations obtained by satellite radar imagery over the delta
215 from 2006 to 2010, the authors clearly highlighted a rate of soil subsidence varying
216 between 0.02 and 0.04 m/year and an average decrease by 0.30 m per year of
217 groundwater levels. A similar interplay between groundwater levels and soil subsidence
218 was also reported by Dinh et al. (2014) for the HCMC region.

219 Consequently, the subsidence of soil at the regional scale could be higher than the rise in
220 sea level by the end of this century. The cumulative effects could result in the lowering
221 of the average soil level with respect to the sea level by 0.03 to 0.05 m/year; in other
222 words, a 1.5 to 2.5 m rise in a 50 year period. The submersion of the quasi totality of the
223 coastal fringe is to be feared: the loss of agricultural land (notably rice) due to
224 salinization and the consequent migration of millions of inhabitants would have an

225 enormous impact. A significant part of this migratory flux would probably be in the
226 direction of HCMC, where large areas could also be submerged.

227

228 **3.4- Urban planning strategy**

229

230 In light of these results, it seems evident that to achieve sustainable development there
231 needs to be revision of Ho Chi Minh City's urban development policies with a much
232 greater emphasis on and integration of flood management strategies. For the time being,
233 the city's rate of urbanization is advancing at an alarming rate, with former wetlands
234 being filled and transformed into new development areas such as Phu My Hung and Thu
235 Thiem. The megacity's continual expansion raises questions about the capacity of the
236 soil to absorb runoff and its impact on floods (Kim and Ho, 2014). Since 2008,
237 authorities in HCMC have been developing a Master Plan of coordinated urban
238 expansion to be in place by 2025. This plan proposes the adoption of a multi-center city
239 model with four major development areas and several additional urban projects. As can
240 often be observed, there is a gap between planning and reality (ADETEF, 2012). Experts
241 and local policy makers are in agreement that alternative measures need to be
242 integrated (Lempert et al., 2013). In particular, investment in infrastructure needs to
243 comply with land use policies, construction law and urban planning in order to
244 implement the concept of a sustainable city at different scales. Furthermore, the
245 development of urban areas alongside existing waterways and in low-lying swampy
246 areas is met with institutional, technical and financial challenges.

247 At the institutional level, the challenge is to implement a coherent urban planning policy
248 by breaking it down into national, regional and urban levels. It is crucial to promote a

249 transversal approach (land use, urban planning and water management), to adopt a
250 multi-scale vision, and to avoid single-sector and single-project approaches (Eckert and
251 Waibel, 2009). At the technical level, development of relevant urban planning tools is
252 required at the planning stage: environmental impact studies should be enforced to
253 ensure sustainable water balance when a wetland site is filled. Setting-up monitoring
254 networks and access to acquired data is a prerequisite to develop robust scenarios
255 coupling measurement, statistics and numerical simulations. A further challenge
256 concerns the need for innovative construction techniques adapted to the geology of
257 particular sites. This would include the construction of underground works such as
258 metro lines and basement parking areas.

259 These challenges have been debated during workshops with policymakers in order to
260 consider the water-related problems of urbanization in an integrated way. For example,
261 the rivers and channels in HCMC were long considered as being for transport only, but
262 they are now also considered as recreational areas and important for the city's identity
263 as they improve the quality of life for residents. Recent urban development projects in
264 the HCMC metropolitan area have already brought major improvements by greening
265 riverbanks and improving water quality in the creeks and Saigon River.

266 One of the main challenges for Ho Chi Minh City's future is to allocate more space to
267 green and blue belts in planned layouts. Urban multi-functional basins (Fig 7a) could
268 respond to hydrological and environmental issues by preserving areas for storm water
269 retention and storage of tidal flow volumes (rising tide). They could also integrate urban
270 and landscape planning at different scales (PADDI, World Bank, 2014).

271 An integrated territorial approach needs to account for the specific context of the
272 estuary and the city. It should connect sites with surrounding neighborhoods by

273 prioritizing the entity of 'the park ' and enhancing the river embankment's value. This
274 would help the city to adopt a more sustainable urbanization policy, particularly in the
275 implementation of city water infrastructure projects, and to mitigate and reduce
276 flooding hazards. In addition, upgrading and use of the water network will also create
277 favorable conditions for the development of waterway transportation and river tourism.
278 In 2012, the Centre de Prospective et d'Etudes Urbaines de Ho Chi Minh Ville (PADDI)
279 proposed several courses of urban action relating to large civil engineering projects for
280 dike network construction in order to reduce the risk of flooding, for example:

281 - Reducing flow velocity by facilitating the spread of the rising tide flow upstream.

282 - Developing storm water storage facilities away from tidal influence in order to reduce
283 the discharge flow in sewage networks after a storm (or a dam failure) and the risks of
284 overflow on roads at high tide.

285 - Facilitating rain water infiltration by preserving natural environments or installing
286 storm water infiltration ponds.

287 A good example is the upcoming creation of a new urban area by the name of Thu Thiem,
288 which is presently a swamp in one of the meanders of the Saigon River (Fig 7b). The
289 plan includes a residential area and large urban park that takes into account possible
290 inundation and includes an artificial lake for water retention. Because of its strategic
291 location just in front of the city center, Thu Thiem should have the capacity to mitigate
292 tidal floods and high water events through man-made canals, lakes and mangrove areas
293 and at the same time to accommodate over 130,000 residents.

294

295 **4- Conclusion**

296

297 The mitigation of water related risks is a priority for many megacities, especially those
298 located in low-elevation tropical coastal areas. Considering the vulnerability of HCMC
299 and its economic importance at the regional scale, a multidisciplinary approach has been
300 adopted to evaluate the interplay between urban development planning and flood-
301 related risks within the framework of natural hazards and of climate and human-
302 induced changes.

303 In recent years, many studies have been conducted to assess the vulnerability of this
304 megacity to rainfall induced flooding. Based on spatial monitoring of rainfall and of the
305 flooded areas, the results showed that the risk is especially intense during building
306 construction phases. Maintenance of the drainage network appears to be a simple and
307 essential measure to ensure optimal functioning of properly sized sewers.

308 We further analyzed the risk of flooding by tsunami or dam failure. The numerical
309 simulations undertaken show that HCMC is more vulnerable to inundation by tsunami
310 than by dam failure. This asymmetric response of the watershed to wave propagation
311 mainly results from topographic effects. In the event of a dam failure, wave energy
312 would be rapidly dissipated by spreading out over the flood plain upstream of HCMC.
313 The habitations and infrastructure of this rural region would undoubtedly be severely
314 affected. In the case of a tsunami, wave energy would be amplified during its
315 propagation into the river network. It is worth noting that the dissipation of wave
316 energy during its landward propagation into the mangrove fringe has not been taken
317 into account in the present simulation and could mitigate the effects presented in the
318 simulations.

319 Recent satellite based observations of the megacity and of the Mekong Delta, have
320 demonstrated that without a drastic reduction in greenhouse gas emissions the
321 combination of both the effects of soil subsidence and the expected impact of climate
322 change on rising sea levels could lead to submersion of a large part of the Lower Mekong
323 Basin, including low elevation areas of HCMC within a period of 30 to 50 years.

324 The current Master Plan for HCMC will be revised in the next few years. As part of this
325 process, the Department of Urban Planning and Architecture (DUPA) is currently
326 working on methodology to integrate climate change issues into the new urban plan,
327 especially to assign specific land use as a key adaptive instrument. An example of this
328 new plan of action is that HCMC is also developing some sectorial measures to build
329 retention basins in several districts, and to limit urban extension in the wetlands. It is
330 clear that integrating sea defense services provided by mangrove areas should be a
331 prerequisite to any planned seaward urbanization.

332 The development plans can only be efficient if there is coordination between national
333 and local authorities as well as technical departments. The “Climate change Office”,
334 established in 2012, will undoubtedly play a major role in the implementation of
335 measures to increase the resilience of the city.

336

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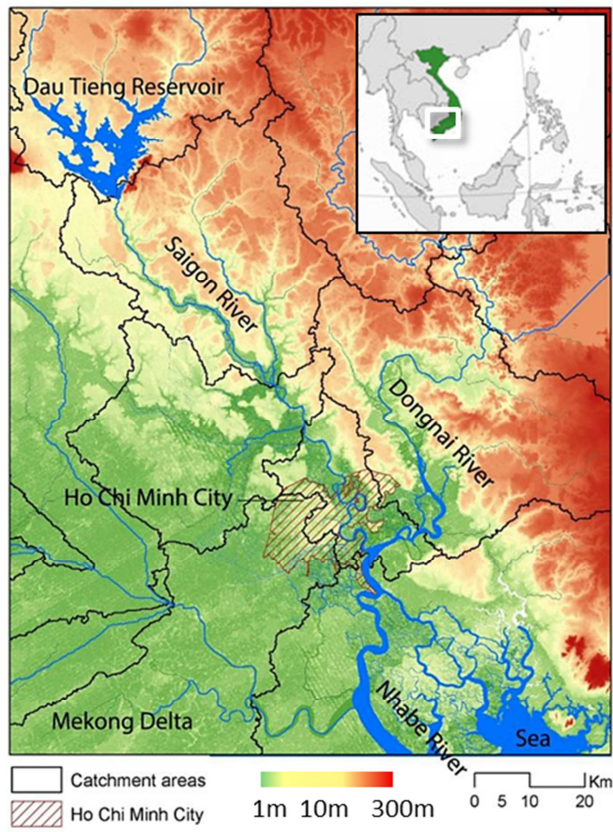
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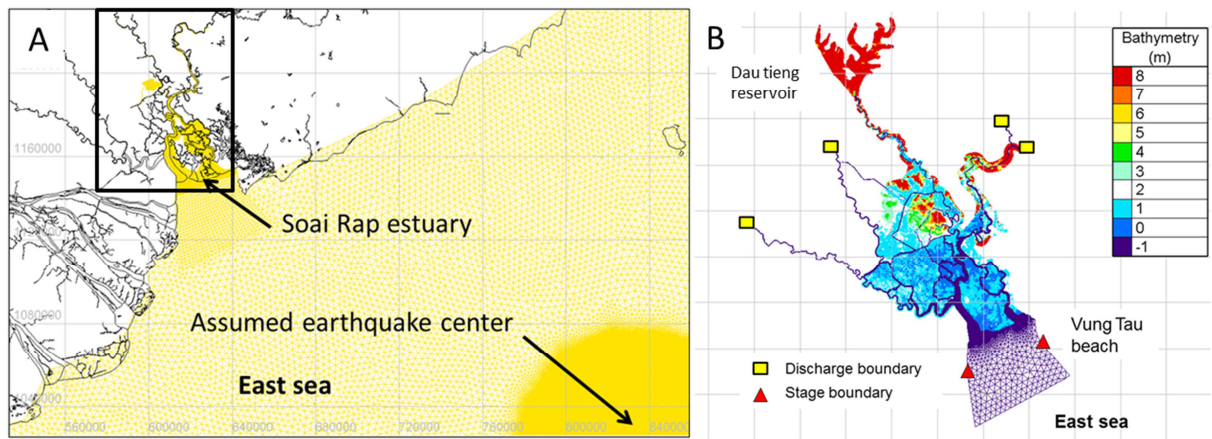


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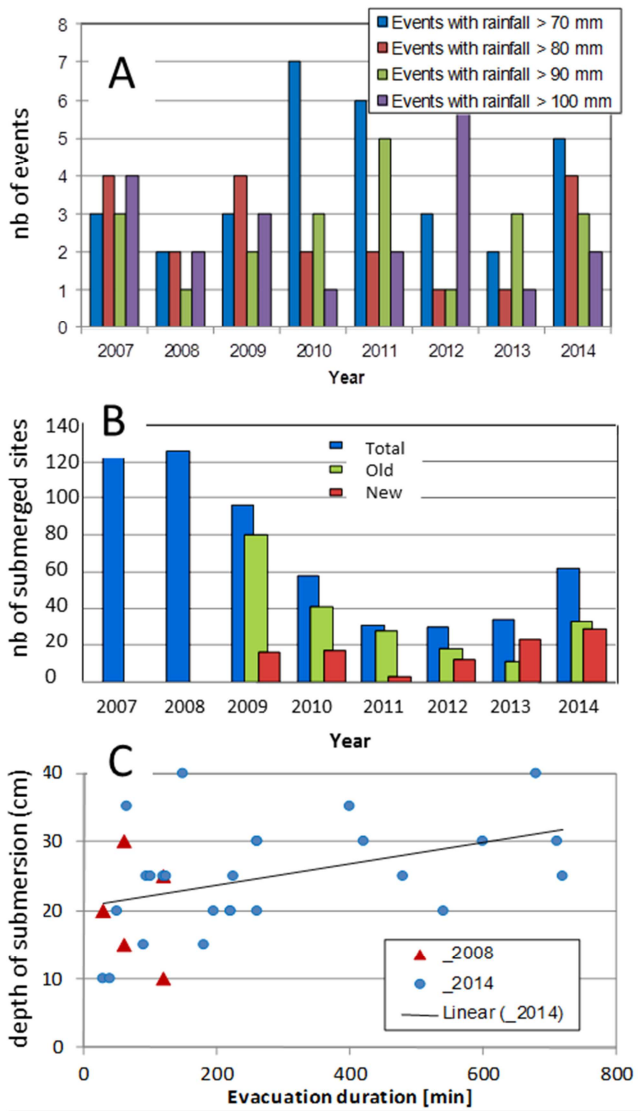
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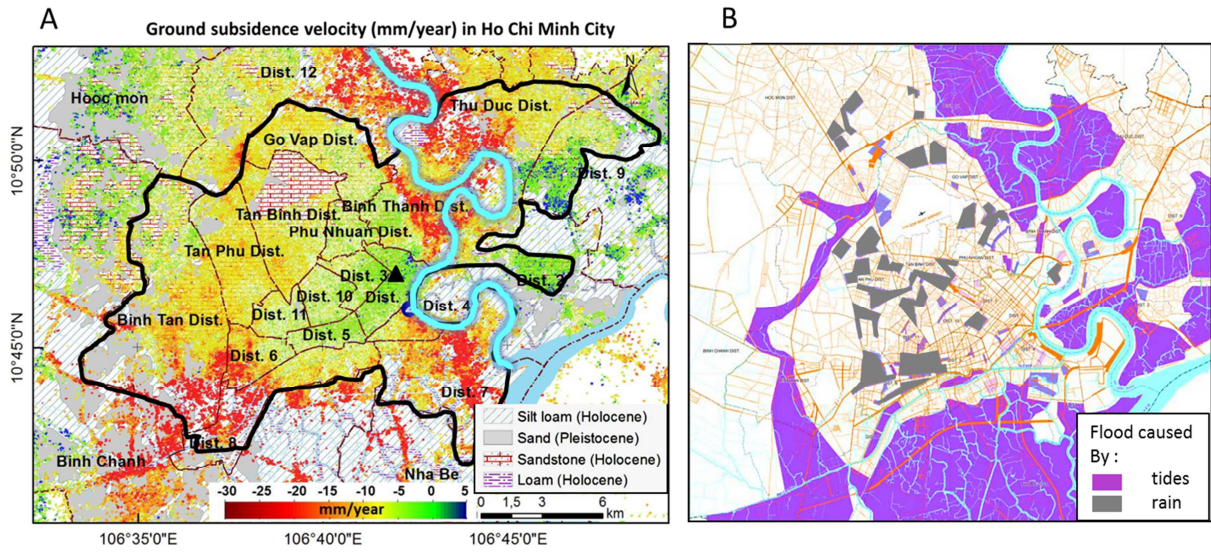
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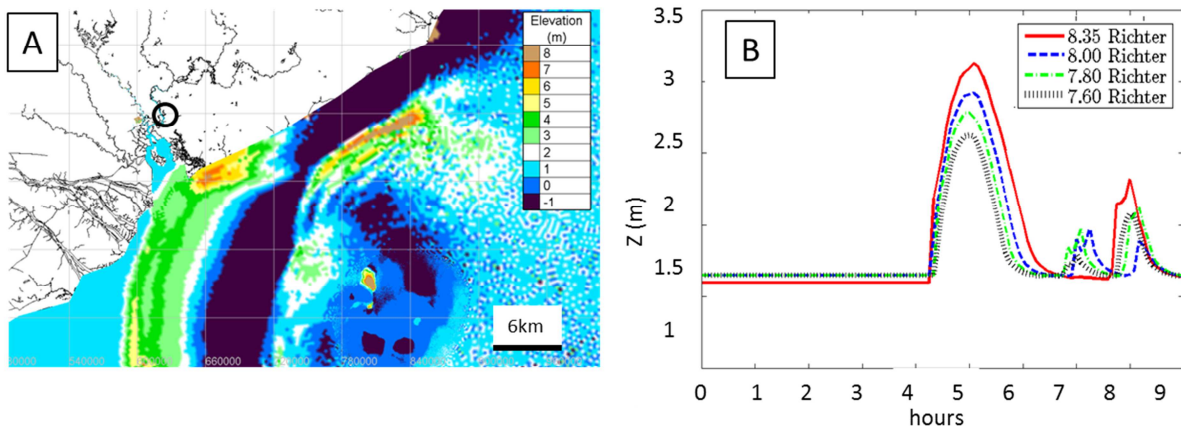
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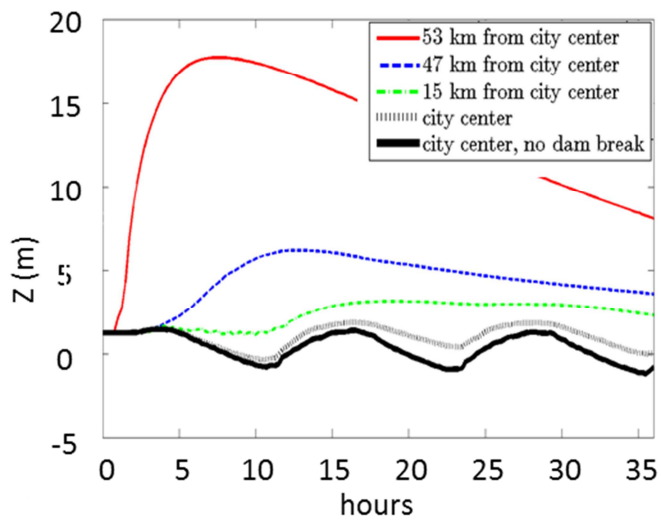
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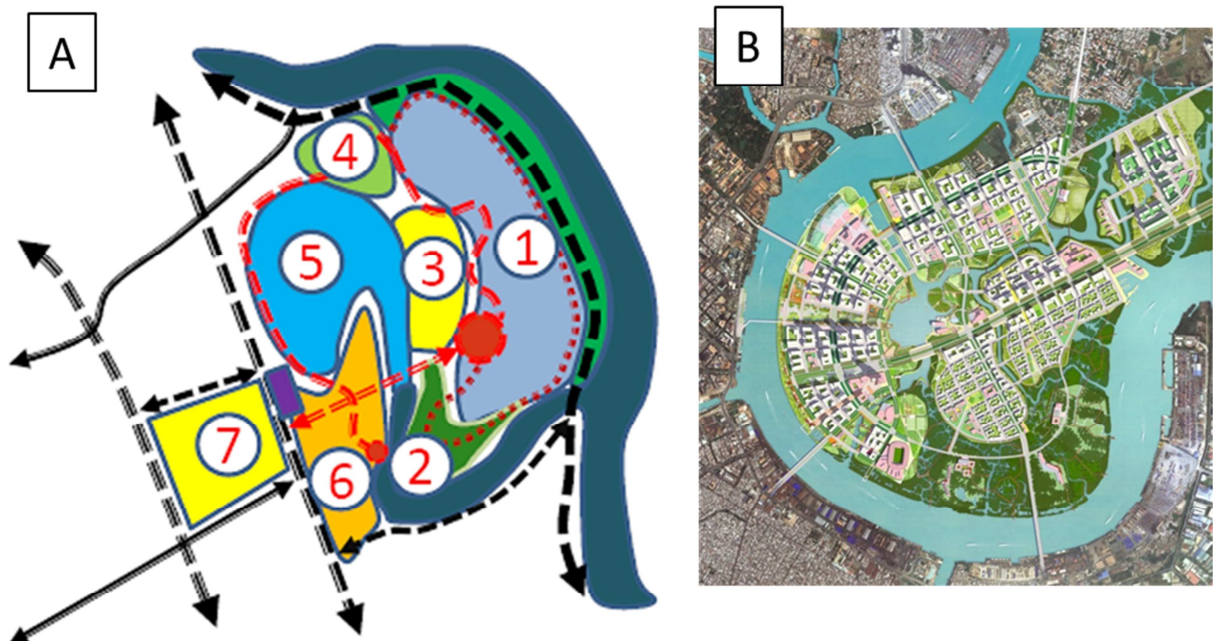
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