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Identifying social responses to inundation disasters: a humanity–nature interaction perspective

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Non-technical abstract

Through the global analysis of inundation disasters with regards to population and land elevation, we found that the largest number of people living in low-elevation land was in Asia. Population increase was also most rapid at these locations. Furthermore, through three case studies in Asia, we found that a critical land–water elevation difference was 1.5–2.0 m in relation to the prevention of disasters regarding groundwater and land as public goods, the protection of houses and buildings from tsunamis and the protection of temples from flooding.

Technical abstract

This paper investigates the relationship between social responses and inundation disasters in terms of human–nature interactions. Land–water elevation difference represents an important relationship between land use and access to water and safety. Global analysis of inundation disasters with regards to population and land elevation showed that the largest number of people living in areas where land elevation is below a couple of metres is found in Asia. Population increase was also most rapid at these locations. We conducted three case studies in Asia and found a threshold of the land–water elevation difference to be 1.5–2.0 m in relation to the prevention of disasters regarding groundwater and land as public goods, the protection of houses and buildings from tsunamis and the protection of temples from flooding. We note that a significant time lag could exist between the identification of the natural disaster and the social forces that drive social and regulatory changes.

Social media summary

Social responses should be regarded as important factors in inundation disasters.

1. Introduction

In sustainability studies, the notions of social responses and tipping points, along with those of regime shifts and critical transitions, have attracted attention during the last decade (Milkoreit *et al.*, 2018). Social responses refer to responses to natural disasters by a society. Relevant phenomena have been expressed in terms of the roles of social capital, cultural context and social thresholds, among others. Research on social–ecological systems has contributed to the diffusion of these terms and their diverse usage. Today, social responses have been raised in the context of social tipping points (Bentley *et al.*, 2014). There are also studies on socio-ecological and cultural contexts (Fernández-Giménez, 2017). The meaning given to ‘social tipping points’ is different discipline by discipline (Milkoreit *et al.*, 2018), and these differences have been recognized and discussed in previous research. However, quantitative investigation into the actual critical level of human–nature interaction relating to social responses remains rare. The global scale of the problem and its regional distribution are yet be clarified.

One of the social factors that acts as a threshold of human–nature interaction for sustainable development is the degree of land–water elevation difference, particularly for people living in coastal areas who are at risk of inundation disasters. Land is an essential resource for the development of a sustainable society, because human beings live and build houses and cities on the land, and they use it for agriculture, industry and other economic and social activities. Furthermore, land elevation is a very important factor for the development of a society because humans usually live on the land with water; therefore, the difference between the two levels is a crucial factor for both water use and for preventing disaster. This is particularly true when we suffer from water-related disasters, such as flooding in areas of closer land–water relationship (smaller elevation difference), land subsidence in coastal areas due to excessive groundwater

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pumping and tsunamis in coastal areas due to earthquakes. In these respects, land–water elevation difference could be regarded as a fundamental issue for a sustainable society.

When economic growth, population increase and urbanization occurred in Asia at a rapid pace, these changes were particularly acute in the lower land elevation areas near coastal zones. They increased the carbon footprint and the demand for resources, which was followed by many environmental impacts, such as widespread contamination and decreases in biodiversity. This is why Asia is a ‘hotspot’ of global environmental problems (Taniguchi, 2018). At the same time, the Asian region has benefitted from positive interactions between nature and society through the provision of ecosystem services and through its cultural diversity. For instance, the Asian monsoon supplies the region with ecosystem services through seasonal changes of hydro-meteorological conditions. Asian traditional cultures have evolved over a long period of time and have variously adapted to disasters such as flooding, earthquakes and tsunamis, demonstrating the resilience of these societies. Therefore, Asia is not only a hotspot that created environmental problems, but also has demonstrated the capacity to produce solutions to global environmental issues (Taniguchi, 2018).

Human, social and natural interactions have not been quantitatively understood in an integrated way because of the silo mentality of the discipline and the lack of cross-level integration from the global to the local. In this paper, we quantitatively evaluate the global inundation problem in relation to population and land elevation. Then, we present three case studies in Asia of social responses through the lens of land–water elevation difference. We suggest that various factors such as social activities, natural disasters and the interactions of humanity and nature influence the vertical distance between land and water and its risks to society.

2. Global inundation with regards to population and land–water elevation difference

The sea level has been rising for well over 10,000 years, and climate change has accelerated, increasing the global mean sea level rise at a rate of 1.7 mm/year over the last century, with a higher rate of 3.2 mm/year over the last couple of decades (Church & White, 2011; Fleming *et al.*, 1998, Kemp *et al.*, 2011; Sweet & Park, 2014). In order to highlight the gravity of the situation, we analyse the relationship between population and land elevation. Table 1 shows the distributions of populations in each continent living in areas where elevation is below 1, 3 and 5 m in 2010 (CIESIN, 2013). These data are extracted from the ‘Urban–Rural Population and Land Area Estimates, Version 2’, which is from the NASA Socioeconomic Data and Applications Center. Although the tipping point of land elevation from three case studies was 1.5–2.0 m, there is no global data on the population living in areas where elevation is below 2 m; therefore, in this study we used the global data on the population living in areas where elevation is below 1 and 3 m. The total population counts living in areas where the elevation is below 1 and 3 m in 2010 are 7.50×10^8 and 1.68×10^9, respectively. The largest proportions of these populations were found in Asia for all elevation categories, followed by Europe for areas where the elevation is below 1 and 3 m, and then by Africa for areas where the elevation is below 5 m. The total land area where the elevation is below 3 m in Asia is 2.10×10^5 km^2, which represents 26.5% of the total global land area where the elevation is below 3 m (7.94×10^5 km^2 in 2010). Table 1 shows the population distributions in each continent living in areas where elevation is below (a) 1 m and (b) 3 m in 2010. In Asia, 44.1 million people (58.7% of the total population) lived in areas where the elevation is below 1 m, and 112.3 million people (66.6% of the total population) lived in areas where the elevation is below 3 m. Figure 1 shows the country-level population distributions of those living in the areas where elevation is below 1 and 3 m in Asia. The greatest number of people was found in China (42.8 million), followed by India (19.8 million), Vietnam (12.4 million), Japan (8.8 million) and Bangladesh (7.7 million) in areas where elevation is below 3 m.

Figure 2 shows the changes in population numbers living in areas where the elevation is (a) below 1 m and (b) below 3 m in 1990, 2000, and 2010. As can be seen from Figure 2a, the population living in Asia increased most rapidly from 33.5×10^6 in 1990 to 40.7×10^6 in 2000 and to 44.1×10^6 in 2010 in areas where elevation is below 1 m. It increased from 85.7×10^6 in 1990 to 101.4×10^6 in 2000 and to 112.3×10^6 in 2010 in areas where elevation is below 3 m (Figure 2b). The annual rate of increase during the 20-year period in Asia was 0.528×10^6/year in areas where the elevation is below 1 m and 1.33×10^6/year in areas where elevation is below 3 m. The rate of population increase was fastest in Asia, followed by Africa (0.18×10^6/year in areas where the elevation is below 1 m).

There are several factors that decrease of the elevation difference between the land surface and water surface. One of them is land subsidence, which is still occurring in many areas around the world, particularly in coastal cities, including Jakarta, Manila and others. This phenomenon is usually caused by the tragedy of the commons (Hardin, 1968), expressed in the forms of complimentary groundwater use.

The second factor is flooding and tsunamis, which cause a temporary decrease in the elevation difference between the land surface and water surface. Furthermore, flooding causes significant social damage through the loss of people’s lives and property. Prevention of flooding is an important issue for the development of a sustainable society.

The third factor is the long-term effect, such as sea level rise, caused by global warming. According to the Intergovernmental Panel on Climate Change (IPCC) AR5 WG1 report (IPCC, 2014), sea level rise globally is predicted to be 0.64 m (0.45–0.82 m) in Representative Concentration Pathway (RCP) 8.5, 0.48 m (0.33–0.63 m) in RCP 6.0, 0.47 m (0.32–0.63 m) in RCP 4.5 and 0.41 m (0.26–0.55 m) in RCP 2.6 from 1985–2005 to 2080–2100. In the case of RCP 8.5, the rate of sea level rise is 0.67 m/100 years. Therefore, the tipping point of land elevation in relation to sea level rise will be 1.5 m in height in 223 years and 2 m in height in 298 years in the case of RCP 8.5.

3. Evaluation of humanity–nature interactions in social responses to inundation

3.1. Social factors of inundation from different perspectives

This study on global inundation has so far focused on the relationship between population and land elevation. However, human activity such as land subsidence by excessive groundwater pumping could aggravate the social damages, while natural disasters such as flooding and tsunamis could cause further serious human and social damages. Therefore, it is important to bring social activities to the study of inundation relating to natural disasters. This study identified the social factors of coastal inundation and demonstrated their impacts on inundation through three case studies in Asia, as is shown in Table 2.

Table 1. Population and land area by elevation at each region in 2010.

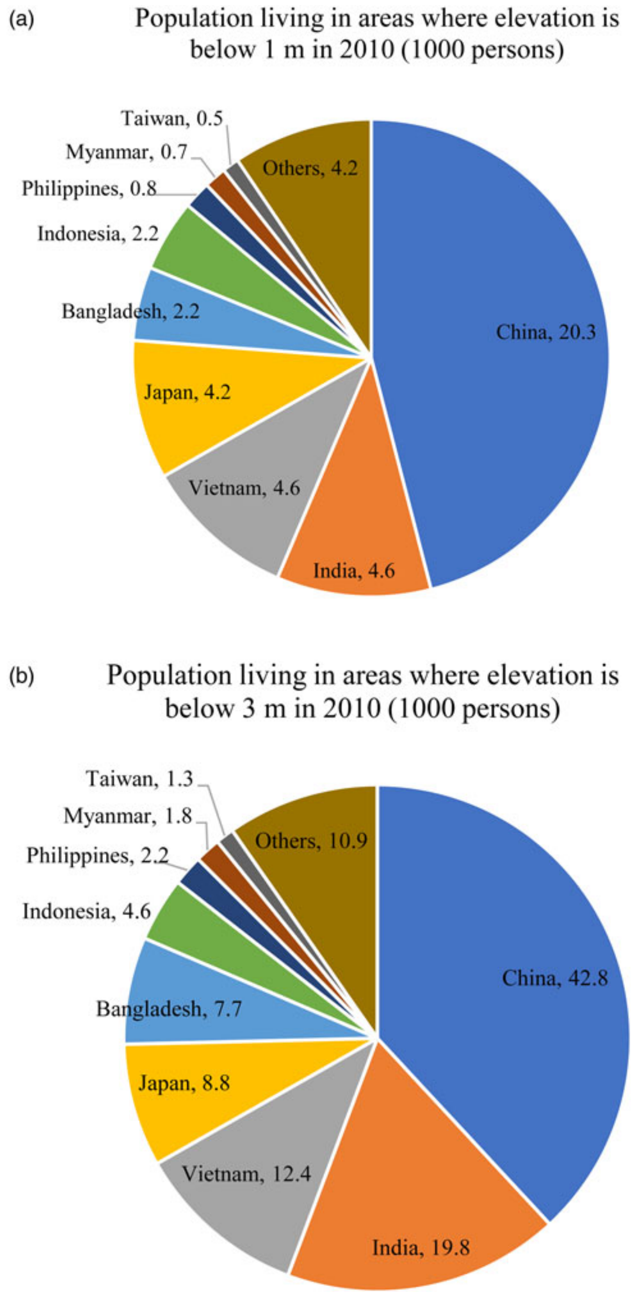
Region	Population living in area (persons)			Land area (km^2)		
	Elevations <1 m	Elevations ≤3 m	Elevations ≤5 m	Elevations ≤1 m	Elevations ≤3 m	Elevations ≤5 m
Africa	10,701,203	20,592,435	33,852,488	24,132	50,964	91,451
Eastern Africa	471,908	1,042,367	2,552,513	1953	7299	20,417
Middle Africa	69,747	199,214	505,857	549	999	3202
Northern Africa	8,405,339	14,071,877	19,885,520	12,041	21,880	31,099
Southern Africa	25,803	39,081	108,337	261	1281	2437
Western Africa	1,728,407	5,239,896	10,800,261	9329	19,505	34,297
Americas	4,282,543	10,533,323	21,488,897	199,075	325,213	483,689
Caribbean	228,585	595,278	1,307,391	2953	8422	19,335
Central America	351,952	1,076,458	2,186,239	12,444	28,679	51,196
North America	2,073,122	4,708,512	8,664,818	161,936	228,455	293,939
South America	1,628,884	4,153,075	9,330,449	21,741	59,656	119,220
Asia	44,139,307	112,270,958	239,899,101	74,005	210,285	412,015
Eastern Asia	25,959,386	54,690,973	110,110,334	32,441	71,074	127,357
South-Eastern Asia	8,985,362	33,881,975	71,586,260	23,356	73,132	158,323
Southern Asia	7,476,517	18,881,934	50,120,299	11,394	44,140	88,111
Western Asia	1,718,043	4,816,077	8,082,207	6814	21,939	38,224
Europe	15,806,145	24,577,389	32,189,097	114,590	184,194	251,259
Eastern Europe	1,957,342	2,918,021	3,700,516	58,136	100,660	145,564
Northern Europe	1,477,018	3,651,891	5,651,373	15,176	26,999	36,390
Southern Europe	2,865,058	4,923,741	6,729,727	11,403	17,971	23,192
Western Europe	9,506,727	13,083,736	16,107,481	29,875	38,564	46,113
Oceania	260,265	652,563	1,426,690	9373	23,441	54,119
Australia and New Zealand	187,529	540,212	1,207,918	6843	19,759	48,598
Melanesia	38,436	63,159	131,017	1925	2599	3852
Micronesia	21,703	30,373	54,741	263	491	754
Polynesia	12,597	18,818	33,015	342	592	914
Total	75,189,463	168,626,667	328,856,273	421,174	794,098	1,292,533

3.2. Social responses to land subsidence in Asian megacities

The Research Institute for Humanity and Nature, Japan, conducted an interdisciplinary research project, called 'Human impacts on subsurface environment in Asia', from 2006 to 2011 in seven Asian megacities: Tokyo, Osaka, Bangkok, Manila, Jakarta, Seoul and Taipei (Taniguchi, 2011; Taniguchi *et al.*, 2009). The purposes of this project were to evaluate subsurface environmental problems such as land subsidence, groundwater contamination and subsurface warming and to relate them to different stages of urbanization in Asia. Interactions between surface/subsurface and subsurface/coastal environments under the pressures of climate variability and human activities were analysed.

In the early stage of urbanization in Asia, the dominant demand of water for industrial and domestic use in the city was met by groundwater, because of its easy access and because it provided inexpensive, clean and stable water. As groundwater consumption increased in Asian coastal cities, the groundwater level decreased drastically, and various subsurface environmental problems such as land subsidence, groundwater salinization and dissolved oxygen reductions occurred (Taniguchi, 2011). Therefore, the shift in reliable water supply from groundwater to surface water occurred in Asian coastal cities, one after another (Taniguchi, 2018; Taniguchi *et al.*, 2009).

Figure 3 shows the land subsidence in Tokyo, Taipei and Bangkok due to excessive groundwater pumping. After the severe land subsidence that occurred in Tokyo and in Osaka from the 1930s to the 1960s, in Bangkok from the 1970s to the 1990s and in Jakarta and Manila in the 2000s to the 2010s, regulation of groundwater use took effect, and water supply shifted to surface water (Taniguchi, 2018). Such land subsidence occurred because the aquifers in these coastal cities consisted mainly of sedimentary formations with clay layers that compacted as the groundwater was pumped out (Taniguchi, 2018). Figure 3 also shows the year of the regulation of groundwater pumping after land


(a) Population living in areas where elevation is below 1 m in 2010 (1000 persons)

(b) Population living in areas where elevation is below 3 m in 2010 (1000 persons)

Fig. 1. Population (× million) living in areas where elevation is below (a) 1 m and (b) 3 m in 2010 in Asian countries.

subsidence. As can be seen from Figure 3, groundwater pumping came to be regulated when the land subsidence reached 1.4 m in 1961 in Tokyo, 2.1 m in 1978 in Taipei and 1.8 m in 1996 in Bangkok. Therefore, the critical point of land subsidence for societies was 1.4–2.1 m in the sedimentary formation area with clay layers in Asian cities. A land subsidence of 1.4–2.1 m decreases the land–seawater elevation difference in the coastal area, thus increasing the risk of flooding. This is an example of social responses as changes in land elevation due to land subsidence ushered in a social decision (regulation of groundwater pumping), leading to a regime shift in water supply.

Land subsidence is a typical environmental problem that is caused by the so-called 'the tragedy of the commons' (Hardin, 1968), because the use of groundwater without payment by free-riders and inefficient management of groundwater cause the common damage of land depletion. Although there are some criticisms of 'the tragedy of the commons' (Berkes *et al.*, 1989), in this case, the 'commons' are groundwater and land as public goods, the responsibility for management of which stakeholders should share. According to the results of land subsidence in Asian cities (Figure 3), each society experienced the common damage of land depletion when the level of land elevation was reduced by 1.4–2.1 m compared with previous levels, because this might increase the risk of flooding due to decreasing the land–seawater elevation difference in the coastal area. These depletions occurred gradually; therefore, the regulation of groundwater pumping was usually delayed, and it took a long time to reach an agreement for regulation, which are common phenomena in global environmental issues. The regulation of groundwater pumping in order to prevent land subsidence took 41 years in Tokyo, more than 18 years in Taipei and 16 years in Bangkok. The time it took from the beginning of the land subsidence to the regulation of groundwater pumping became progressively shorter in Asia because of the 'follower's benefit', even though the problem of land subsidence itself happened in each case. However, these three cities experienced a similar magnitude of land subsidence (1.4–2.1 m) when they reached their agreement to regulate groundwater pumping. Even after regulation of groundwater pumping had begun in some areas in the cities, land subsidence continued in other areas within the cities. The first city, Tokyo, experienced the greatest subsidence prior to adaptation.

3.3. Social responses to building destruction by tsunamis in Japan

The second case study of the social responses to land–water elevation difference concerns the case of the tsunami caused by the Great East Japan Earthquake (GEJE), which occurred on 11 March 2011. The GEJE caused severe causalities, including the deaths of over 17,500 people and 2848 people being reported missing, as well as a huge social and economic damages of approximately 210 billion USD (World Bank, 2012). Most of the damage was caused by the tsunami, which reached a height of over 25 m above sea level at its maximum.

Figure 4 shows the ratios of each category of damaged houses and buildings in the tsunami immersion area of 535 km^2. The total area of complete destruction amounted to 99 km^2, the area of large-scale partial destruction and partial destruction amounted to 58 km^2 and other affected areas amounted to 363 km^2 (Ministry of Land, Infrastructure and Transport, 2011). As can be seen from Figure 4, the ratio of complete destruction of houses and buildings was less than 12% when the water depth of the tsunami was less than 1.5 m. However, this ratio increased to over 35% when the water depth reached between 1.5 and 2.0 m, and to over 70% when it reached over 2.0 m above sea level.

The results show that the critical depth of the water (land–water elevation difference) for the destruction of houses and buildings caused by the tsunami was 1.5–2.0 m, because the ratio of complete destruction of houses and buildings doubled after the 2.0 m threshold (from 35% to 70%). This is an example of the human–nature interaction in the land–water relationship.

At the same time, the results also suggest that the difference between land elevation and water elevation is closely related to the physical features of human beings. It is no coincidence that the height of 1.5–2.0 m of water, which was the tipping point

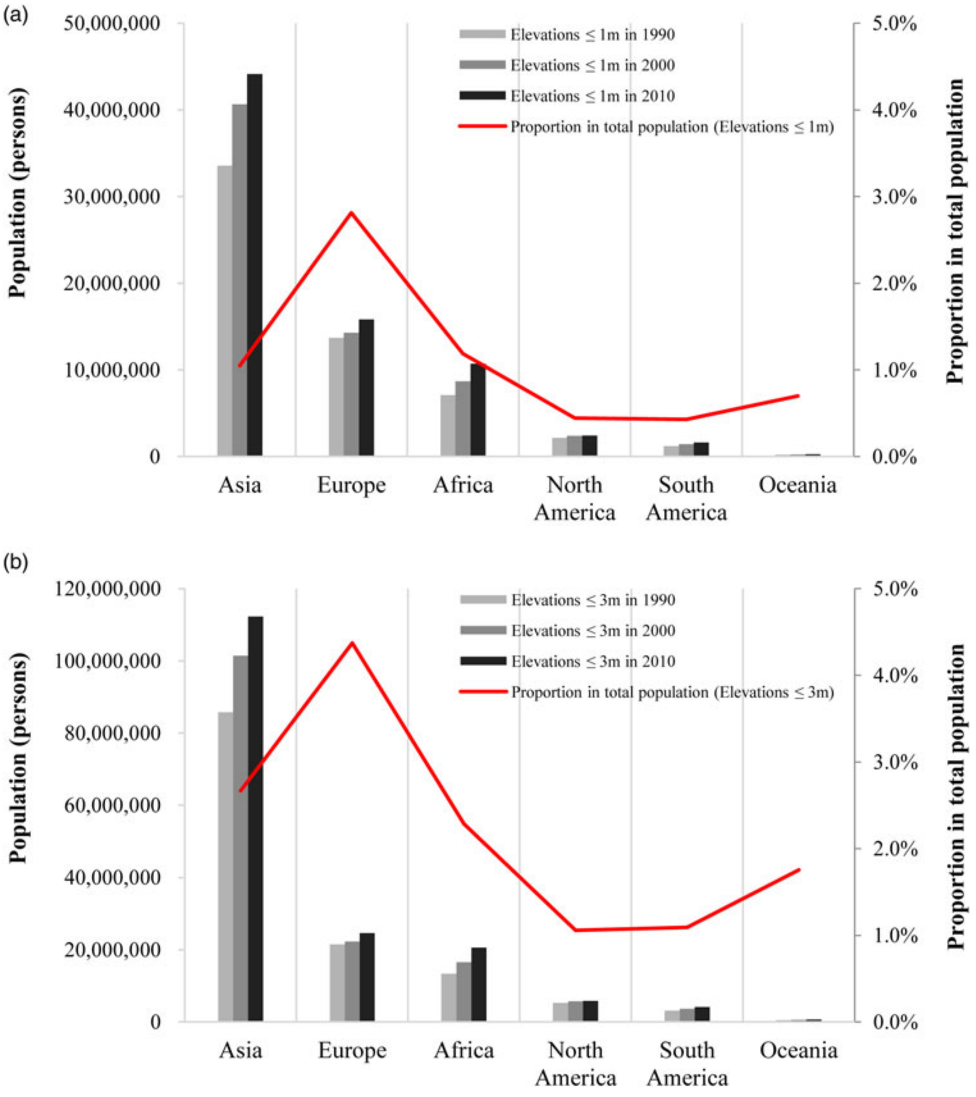


Fig. 2. Population living in areas where elevation is below (a) 1 m and (b) 3 m in 1990, 2000 and 2010 in each continent.

Table 2. Tipping points of inundation from the different perspectives of three cases.

	Case 1	Case 2	Case 3
Study area	7 Asian megacities (Taniguchi, 2011; Taniguchi *et al.*, 2009)	Coastal area in Japan (Ministry of Land, Infrastructure and Transport, 2011)	Bangkok, Thailand (Chanyotha *et al.*, 2011)
Social responses	Land subsidence	Flooding water depth	Land elevation of temples
Measurement objectives	Impacts of social activities	Impacts of natural disasters	Impacts of interactions between humanity and nature
Factors influencing social elements	• Groundwater pumping • Subsurface warming • Urbanization	• Natural disasters (e.g., destruction of houses and buildings by a tsunami)	• Tides • Artificial drainage • Buddhist beliefs (e.g., location of temples

for the destruction of houses and buildings by the tsunami, is almost equivalent to the height of human beings. In developed countries, industrial and commercial buildings are taller than this. Nevertheless, we need to recognize that the height (1.5–2.0 m) of the water depth (difference between land and water elevation) acts as a critical point of consideration for tsunami disasters.

3.4. Social factors of land elevation of the temples in Bangkok

The third case study of the social factors of land–water elevation difference was carried out in Bangkok, Thailand. The water in *khlongs* (canal) is essential to people's livelihoods in Bangkok, as they are used daily for transport and drinking purposes. Any

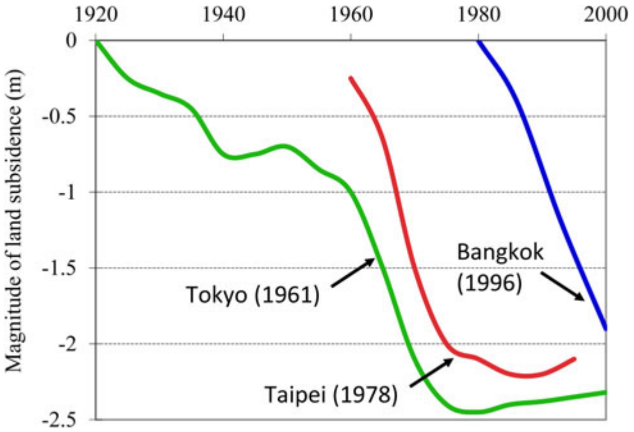


Fig. 3. Magnitudes of land subsidence in Tokyo, Taipei and Bangkok (after Taniguchi, 2011) and years of the beginning of the regulation of groundwater pumping.

changes to their conditions can substantially affect this part of the water cycle and people's livelihoods. For instance, the water level in *khlongs* changes with the tides, while *khlongs* should also serve as a drainage system during flooding. In order to examine the water cycle in the area, individual elements of the water cycle and how they are related must be examined in detail. Thus, some of the results of a study of water quality using tracers such as radon are presented in order to reveal the relationship between the water in Bangkok's *khlongs* and groundwater in the surrounding areas.

Measurements of the radon concentration and the electrical conductivity of water (the total number of dissolved ions in the water) were taken in order to analyse the water quality in Khlong Bangkok Yai on the west bank of Chao Phraya River, Bangkok (Chanyotha *et al.*, 2011). Normally, electrical conductivity and radon concentration in groundwater is much higher than in rainwater; therefore, where groundwater is discharged can be evaluated by determining the level of electrical conductivity and radon concentration in the water in *khlongs*. Measurement results revealed that a higher conductivity and a higher radon concentration were found in the water in *khlongs* where temples are located. Conductivity might increase as a result of artificial drainage. While drained water coming into contact with the air was normally found to have a lower radon concentration, higher concentrations of radon were normally found near temple locations. These facts suggest that discharge of groundwater with a higher radon concentration into the *khlongs* had occurred near the temple. In actuality, the water in wells and *khlongs* at the Wat Inthsram temple were linked hydrologically (Chanyotha *et al.*, 2011). This was apparent since tidal effects and water flows were also observed in this well.

One of the possible explanations for such a high concentration of radon in *khlongs* at the front of temples is that when land was donated for the construction of such temples, those who wished for the site of the temple to be long-lasting selected sandy ground (permeable ground) at a somewhat higher elevation with relatively better ground conditions.

In support of this hypothesis, Tomosugi (1989) cited the mobilization of 20,000 workers to fill in and drain wetlands during repair work (1789–1796) on Wat Chetuphon (known colloquially as Wat Pho, with a statue of the Buddha entering Nirvana). In the Thon Buri Period, the Royal Palace was to be built on the site of a Chinese community that was located on a sandbar in the marshes at a slightly higher elevation. The Chinese were relocated to south of Khlong Ong Ang outside the city ramparts, according to more recent research (Tasaka, 1998). In both cases, when important buildings such as temples were constructed, land with better ground, such as a sandbar (thus being permeable), was selected. Had this not been the case, the sand would have been filled up and the water would have drained off.

In order to test this hypothesis, differences in the elevation of the ground where temples are located were examined, and the results are shown in Figure 5. The elevations of 836 sites with temples were assessed using a digital elevation model, and this indicated that the average elevation was 5.4 m (Figure 5). In contrast, for the target areas that was analysed, the elevations in the centre of the city with the 836 temples had an average height of 3.9 m above sea level. Clearly, the average elevation of the sites where temples were located was 1.5 m higher than that of their surroundings. When a temple was located on land with a slightly higher elevation, a groundwater flow system in which groundwater flowed at the shallowest level (i.e., a local groundwater flow system) was achieved. The likelihood is that *khlongs* were the outlets of this groundwater discharge.

The fact that high radon concentrations were found in Bangkok's *khlongs* near temple constructions suggests that the groundwater discharges into *khlongs*. The radon signal (water quality) is always higher (which suggests groundwater discharge) at the front of the temples, which are located 1.5 m higher than the surrounding areas. Therefore, micro-groundwater flow systems exist from higher elevation (temples) to lower elevation (canals). In other words, the desire for temples to last without experiencing disasters such as floods might through action in the form of selecting a site with good ground (and thus being permeable) such as a sandbar that is elevated slightly higher than the surroundings may have affected the natural environment (in this instance, the quality of water in *khlongs*). If this is the case, then religious sentiments (Aoki, 1979) and the sense of reverence of the people in Bangkok who believe in Buddhism may be linked to this specific use of the natural environment. This supposition suggests that human sentiments and piety may affect nature (water quality) in unexpected – and hence largely unintended – ways (Taniguchi, 2009, 2010). The connection between the quality of water in *khlongs* and people's piety may be interpreted as a result of the 'interaction of humanity and nature'.

The analyses of the elevations of temple locations and the quality of water in *khlongs* showed that the people in Thailand chose temple locations that were a little higher and that were sandy with permeable soil. Thus, greater groundwater discharge into the canals occurred near these temples. The belief in Buddhism and temples may have affected the levels of water quality in the area, which demonstrates the relationship between nature and humanity in Thailand. Therefore, these results show that the critical elevation difference between the land with temples and the surrounding area was 1.5 m for protecting temples from flooding in Bangkok. People in Bangkok, who mostly believe in Buddhism, even sacrifice their own houses so that the temples can survive during flooding, such that the elevation of the land with temples is 1.5 m higher than that of the surrounding areas.

3.5. From social factors to global inundation

Although the case studies of the social factors of humanity–nature interactions are limited, the critical level for the land–water

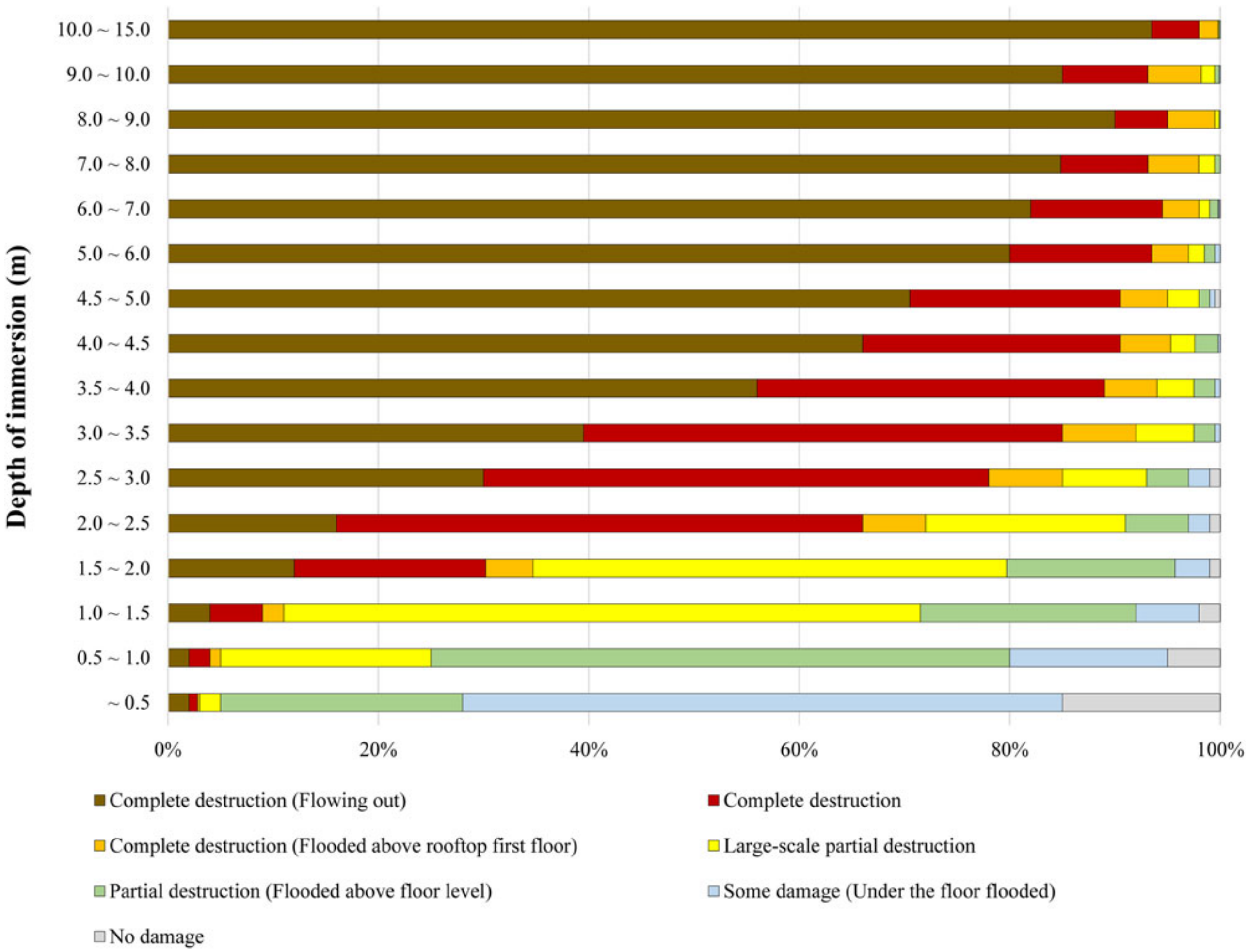


Fig. 4. Ratio of each category of the destruction of houses and buildings classified by the water depth of the tsunami that was caused by the Great East Japan Earthquake on 11 March 2011.

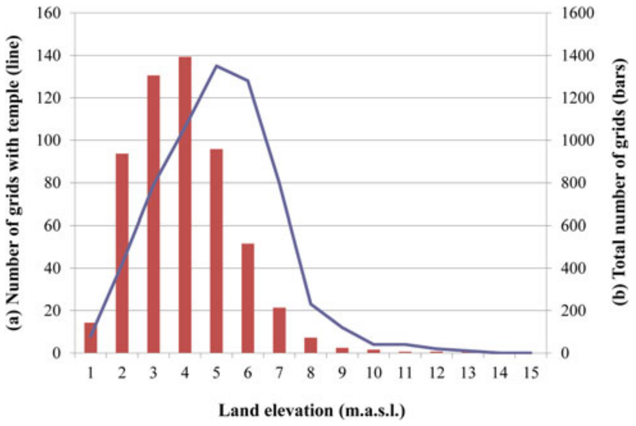


Fig. 5. The land elevation distributions (metres above sea level; m.a.s.l.) of (a) 836 sites with temples (line) and (b) target areas in the city of Bangkok (bars) using a digital elevation model (after Taniguchi, 2011).

elevation difference was found to be approximately 1.5–2.0 m through these three case studies in Asia.

In the case of land subsidence in Asian cities, societies could not stand when land depletion reached more than 1.4–2.1 m. This amount of land depletion causes significant damage to houses, roads and infrastructure, as well as flooding in coastal areas; therefore, some new action, such as the regulation of groundwater pumping, was needed. Adaptation to and prevention of flooding and tsunamis are also important for developing sustainable societies in Asia. In the case of the GEJE, the ratio of complete the destruction of houses and buildings drastically changed at the critical water depth of 2.0 m of the tsunami. In the case of Bangkok, people have chosen the locations of their temples at elevations that are 1.5 m higher than the surrounding areas in order to prevent flooding. Therefore, all three case studies show that a similar critical level of land–water elevation difference (1.5–2.0 m) is a threshold for the adaptation to and prevention of natural and human-induced disasters such as land subsidence, tsunamis and flooding. The results of these three case studies may appear to be a coincidence, but this paper has pointed out that this 1.5–2.0 m is approximately the same as the height of human beings, which seems to have become the critical social factor for inundation risk in terms of the land–water elevation difference in human–nature interactions.

In terms of the land–water elevation difference from the three case studies, 2 m is the crucial depth of water for natural and human-induced disasters, such as land subsidence, tsunamis and flooding. Our results show that 7.50×10^8 to 1.68×10^9

people lived at lower than this level of elevation globally in 2010 across an area of 4.21×10^5 to 7.96×10^5 km^2. The risk that these people are shouldering should attract more attention for global sustainability.

4. Conclusions

In this paper, the social factors affecting the relationships between land and water elevation have been evaluated in relation to the prevention of and adaptation to disasters through three case studies relating to land subsidence, tsunamis and flooding in Asia. The first case study concerns land subsidence caused by excessive groundwater pumping, which occurred in Asian coastal cities one after another, arguably as a result of 'the tragedy of the commons'. Each Asian city experienced a similar magnitude (1.4–2.1 m) of land subsidence by the time they reached an agreement regarding the regulation of groundwater pumping in order to save the groundwater and land as public goods. The second case study relates to the damage to houses and buildings caused by the tsunami during the GEJE. The results show that the crucial water depth at which the destruction of houses and buildings occurred as a result of the tsunami was 1.5–2.0 m. After crossing this point, the complete destruction of houses and buildings drastically increased.

The third case study relates to the location of temples in Bangkok. The analyses of the elevation of temple locations along *khlongs* showed that the people in Thailand chose slightly higher and sandy locations with permeable soil as temple locations so that the site would last longer, as a result of which greater groundwater discharge occurred near the temples into the canals. The belief in Buddhism and temples may have affected the levels of water quality in the area, which reflects the particular relationship between nature and humanity in Thailand. This episode shows that the land–water elevation difference of 1.5 m is the social threshold of nature–human interaction for the protection of temples in Bangkok from flooding.

All three case studies show a similar level of tipping point of land elevation (1.5–2.0 m) for the adaptation to and the prevention of the natural and human-induced disasters such as land subsidence, tsunamis and flooding. The global analysis of the relationship between population and land elevation shows that the number of people who live where elevation is below this level of land elevation was largest in Asia. The population increase was also most rapid in this region. Analyses of sea level rise towards the tipping point of land elevation show that the tipping point will be reached will be 1.5 m in height in 223 years and 2 m in height in 298 years in the case of RCP 8.5.

People need to live as closely to water as possible for efficient water use. However, living too close to water can lead to inundation disasters such as flooding and tsunamis. The three case studies show that, in addition to the distance from the water, it is essential to examine the 'land–water elevation difference' and 'human–nature interactions' in order to understand how inundation disasters occur.

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