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Land subsidence in Jakarta and Semarang Bay – The relationship between physical processes, risk perception, and household adaptation

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ABSTRACT

Sea level rise (SLR) is among the most pressing challenges for urban coastal areas. While geocentric (eustatic) SLR receives widespread attention in politics and media, relative SLR at the coast, mainly caused by land subsidence, is still comparatively under-researched despite much higher rates. This paper introduces a combined natural and social science study to bring subsidence more to the forefront of coastal hazard research. We use data from radar altimetry, GNSS controlled tide gauge stations, and InSAR mapping to characterize regional and relative SLR at Jakarta and Semarang Bay, and focus-group discussions and a standardized household survey to analyze risk perceptions and adaptation.

Our analysis of InSAR, radar altimetry, and corrected tide gauges clearly identifies subsidence as the major coastal threat in our study areas. The InSAR analysis for Semarang shows stable trends of subsidence up to ~100 mm/a. For Jakarta, our analysis reveals more complex spatial and temporal patterns with rates around 60 mm/a; revealing significant changes to previous studies. Our analysis of radar altimetry data since 1993 shows a moderate regional SLR of 2.1 mm/a off Semarang and 3.2 mm/a off Jakarta.

The InSAR data are integrated into our statistical analysis of household responses towards subsidence. We found, that in contrast to fast-onset events, constantly proceeding subsidence becomes normalized in peoples' perceptions and responses are integrated into day-to-day habits. Thus, risk perception is a far lesser determinant of responses towards subsidence than it is for fast-onset events. Hence, our results relativize former assumptions that risk perception and not actual exposure lead to action. Moreover, we found that local people are not willing to vacate highly exposed areas. Their views need to be included in municipal disaster risk reduction, the urgency of which clearly lies on mitigating subsidence effects rather than on building protection against regionally rising sea levels.

1. Introduction

Preparing for and responding to contemporary and future sea level rise (SLR) and coastal flooding are major challenges for low-lying coastal settlements, including the large cities of the Indonesian archipelago. For understanding the different sea level based coastal impacts, it is crucial to distinguish between the relative and the geocentric global/regional SLR. The former is measurable directly at the coastline, and can be impacted by, e.g., land subsidence, changes in the tidal levels, or by an actually rising (eustatic) sea level. The space-based radar altimetry derived geocentric global/regional sea level is independent from any local land movement.

Relative sea level rise due to land subsidence constitutes a major coastal threat. Subsiding areas, such as along Java's northern coast, represent complex coastal geomorphologies and risk constellations. Relative SLR due to land subsidence tends to show significantly higher rates (currently up to 12 cm/a in Northern Jakarta) than the global geocentric SLR driven by, e.g. processes of global warming (~3.2 mm/a,

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cf. Nerem et al., 2018). As an example, within just five years, the megacity Jakarta will experience a relative SLR (at selected spots) similar to the expected cumulative global mean SLR over the next 80 years (Esteban et al., 2020).

Yet, despite significantly higher rates of relative SLR caused by land subsidence in the investigated areas and, thus, stronger impacts on the local population, global geocentric SLR tends to get much higher attention both in the international media and in research. The same is true for national and municipal policy levels, also in Indonesia (cf. Suroso and Firman 2018). In fact, land subsidence is claimed to be “one of the world’s most underrated problems” (Erkens 2018).

Considering the substantial socio-economic impact of subsidence, such as regularly flooded buildings and infrastructure (cf. Saputra et al., 2017; Yan et al., 2020), there is an urgent need to bring subsidence

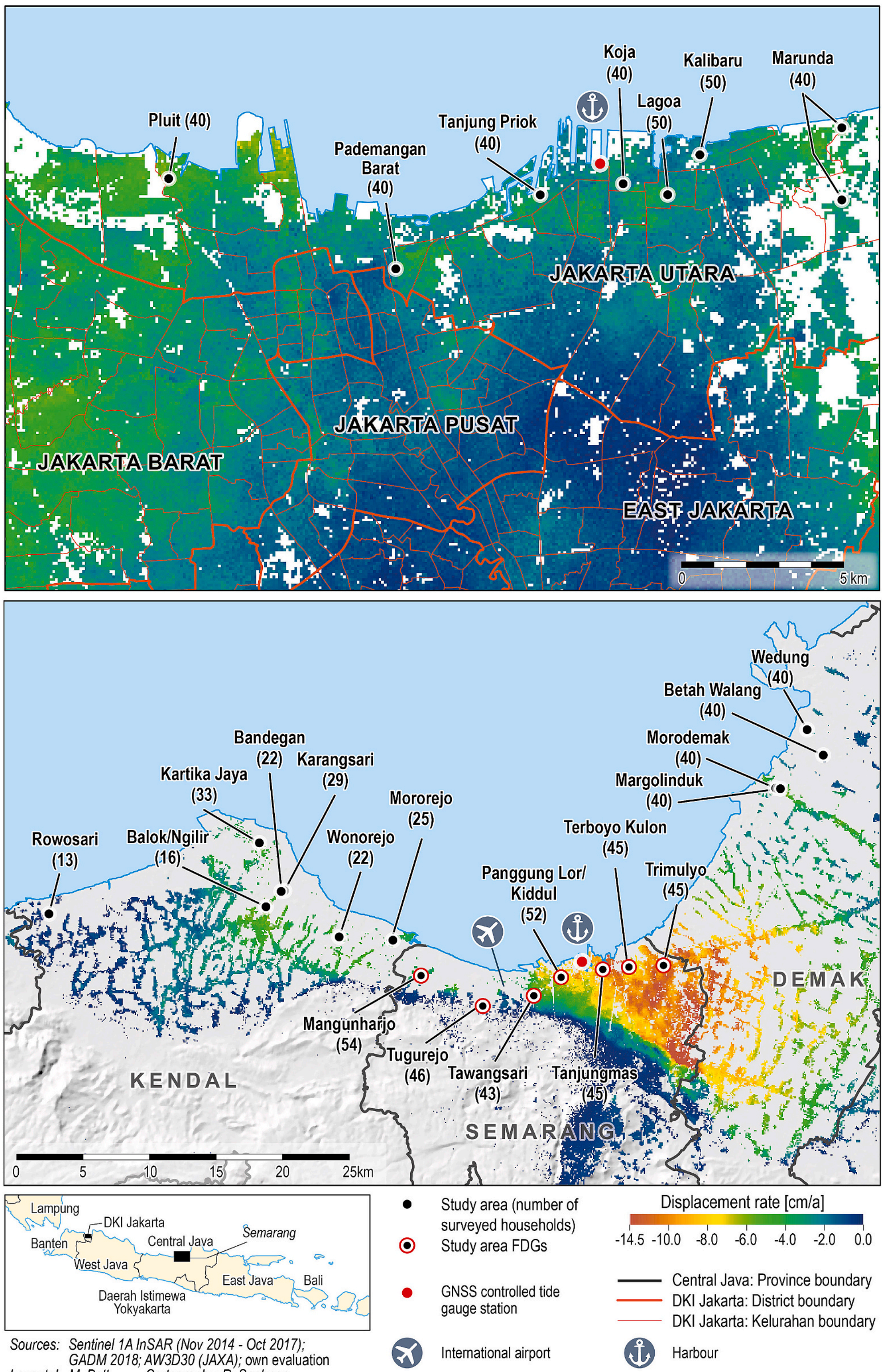

Fig. 1. Study areas and subsidence rates based on InSAR mapping.

studies to the forefront of coastal hazard research and to work in interdisciplinary teams of natural and social scientists. Studying land subsidence in itself requires incorporating both natural and anthropogenic processes, which in sum cause land subsidence. Natural causes of subsidence, such as compaction of unconsolidated alluvial soils, oxidation of organic materials, earthquakes, glacial isostatic adjustments, and geological evolution of the underground, are often strongly amplified by human activities, such as land reclamation, excessive fluid extractions (e.g. ground water, natural gas, or crude oil), fracking and mining activities, and high surface loads from buildings and infrastructure (Minderhoud et al., 2020). The highest subsidence rates, therefore, often correspond with densely populated coastal settlements (Bott et al., 2018; Marfai et al., 2015; Minderhoud et al., 2018), which is also evident in our study areas where human activities, especially ground water extraction, are the strongest driver of local subsidence rates (Fig. 1). Because the sinking land becomes relatively lower towards the local sea level, this relative sea level rise strongly increases the local risk towards coastal flooding. Thus, subsidence is at its core a complex socio-environmental process and people in coastal urban areas are both drivers of and subject to this multi-dimensional hazard (cf. Kraas et al., 2016).

The interplay of human and natural risks in coastal zones calls for new approaches in disaster risk reduction to systematically analyze and manage the impacts of contemporary and future coastal hazards (cf. Gill and Malamud 2017; Wong et al., 2014). On the one hand, reliable measurements from radar altimetry, InSAR, GNSS, and tide gauges are required to quantify the physical processes (cf. Yan et al., 2020). On the other hand, a better understanding of human socio-economic vulnerabilities and adaptation processes is crucial to guide disaster risk reduction strategies.

While there is former research on regional SLR for specific cities along the coast of North Java (inter alia: Joesidawati et al., 2017; Marfai 2014; Marfai and King 2008), a comprehensive analysis of relative SLR versus geocentric global and regional SLR has been lacking so far. The estimation of local subsidence and the resulting relative SLR requires the combination of different geodetic measurements, which are not always (freely) available. In the past, land subsidence has been measured using classical repeated spirit leveling along selected lines and, since the early 1990s, with Global Navigation Satellite Systems (GNSS). Both technologies provide vertical displacements and rates at discrete points but miss most of the smaller-scale spatial patterns. With the launch of the European ERS-1 mission, synthetic aperture radar (SAR) technology has allowed for interferometric SAR (InSAR) mapping of primarily vertical surface displacements of larger areas, thus, providing new insights into the spatial-temporal evolution of land subsidence (Gens and van Genderen 1996). Combining the spatial InSAR patterns with point-wise GNSS estimates provides area-wide subsidence information that is consistent among the different geodetic techniques. The GFZ and Badan Informasi Geospasial (BIG) (Cibinong/Indonesia) established GNSS-controlled tide gauges in Semarang and Jakarta to allow for comprehensive scientific analyses. These data are then directly integrated into the statistical analysis of a larger-scale social science household survey, allowing us to analyze human risk perceptions and resulting response action in comparison to the actual exposure of these households.

This interdisciplinary research on land subsidence is relevant from a social science perspective, since the impacts of slow onset eustatic SLR on human behavior are often not directly measurable and remain largely hypothetical (cf. Esteban et al., 2020). Analyzing subsiding areas that are already affected today by high rates of (relative) SLR and resulting coastal flooding provides an opportunity to learn about socio-economic consequences and adaptation processes towards a globally rising eustatic sea level in the future.

The laboratories for disaster risk management and the implementation of strategies lie at municipal and communal levels in cities and villages exposed to flooding (cf. Kraas et al., 2016). Here, marginalized and poor people living on flood plains and along riverbanks are affected the most (cf. Leitner and Sheppard 2018). Especially in the Global South, these households often have to take on roles that would otherwise be the responsibilities of governmental disaster risk management agencies (Adger et al., 2003). Thus, local households need to develop, organize, and implement their own bottom-up strategies to reduce risk and to live with floods and subsidence.

So far, the number of studies on human responses to land subsidence remains limited as well and most of them focus only on top-down management approaches (inter alia: Esteban et al., 2020; Saputra et al., 2019; Seijger et al., 2017). A combined interdisciplinary analysis and data integration offer an opportunity to gain a deeper understanding of what determines social responses to land subsidence and natural hazards in general. In this paper, we understand responses to natural hazards as an umbrella term for both short-term and reactive coping as well as long-term and proactive adaptation (cf. Gallopín 2006). We focus on individual practices at the household level to analyze which responses are taken and why. Gaining better knowledge about households' adaptation pathways and risk perceptions is crucial to understand drivers and barriers that enable or hamper coastal adaptation at the local level. Along this line, our empirical evidence contributes new knowledge about the so far underrated process of land subsidence as well as advance the understanding of individual adaptation processes. The latter remains under-researched compared to the research on human responses to other coastal hazards. Our findings shall help to develop appropriate disaster risk reduction policies.

This study contributes to ongoing debates about coastal disaster risk reduction by combing geodetic measurements with geographical research on human adaptation processes. The main research questions of our study are:

(1) What are the physical and anthropogenic drivers of SLR and subsidence in the North Javanese context? What are the current rates and variability?
(2) How do local households, as the ones at the frontline of exposure, respond to these coastal hazards, and what factors – including physical ones – determine their response actions?

To this aim, this study presents the results of interdisciplinary mixed-methods research conducted in Jakarta and the Semarang Bay area. The methods used consist of InSAR analysis, radar altimetry, GNSS and tide gauge measurements as well as focus group discussions and a standardized household survey. Jakarta and Semarang Bay represent prominent cases to study as they display some of the highest subsidence rates worldwide.

In the following, we proceed to our methodology and the characteristics of our study areas, before we present the physical land subsidence measurements to answer the first research question. These findings will then be integrated into the social science analysis on households' responses. We answer the second research question on household responses by addressing how their perceptions of risk and adaptive capacities work as drivers or barriers for response action. The discussion consolidates all results before concluding the paper.

2. Methods

2.1. Interferometric synthetic aperture radar (InSAR) for fine-scale subsidence mapping

We analyze InSAR maps using Sentinel-1A (launch 04/2014) data of the European Copernicus Programme to derive spatially resolved subsidence signals for Jakarta and Semarang Bay. The Sentinel-1A data are freely available with a repeat cycle of 12 days. The average displacement rates and time series are estimated using Persistent Scatterer InSAR analysis (Hooper et al. 2004, 2012). For both cities, InSAR data in ascending satellite orbits are used as they provide results with smaller internal variances. Assuming the horizontal displacement is negligible, we converted the line-of-sight values to true vertical ones by using the satellite antenna configuration. Permanent GNSS measurements at the tide gauges (Schöne et al., 2011) are used to constrain and convert the InSAR vertical displacements to consistent geocentric velocities. To evaluate the precision of the InSAR results, we calculate the root mean square (RMS) of the vertical displacement rates for areas where no displacement would be expected. The RMS in Jakarta is approximately 0.6 cm/a, while it is 0.4 cm/a in Semarang. We interpret any displacement exceeding those RMS values as reliably detected signals. For the statistical analyses of the household survey (chapter 4.2), the subsidence rates have been directly extracted for the nearest InSAR geo-located scatterer point.

2.2. Regional and local sea level mapping

Understanding the impact of sea level changes on coastal communities requires long-term sea level measurements on the global, regional, and local scale. Along coastlines and in harbors, tides and sea level are traditionally measured spot-wise by tide gauges, providing tidal ranges, surges, lowest astronomical tides for nautical charting, and sea level changes relative to the land. Few tide gauges have a centennial or even longer history (e.g. Amsterdam starting 1700 or Manila starting in 1901), but most have a much shorter past. Since 1992, an increasing number of tide gauges has been equipped with continuous GNSS for vertical height control (Schöne et al., 2009). This technique allows to separate SLR (measured with radar altimetry) and vertical land movement (e.g. subsidence), allowing us to compare the derived sea level heights from tide gauges with radar altimetry.

The regional and local sea level change is analyzed using radar altimetry (Fig. 2) for the off-shore characterization of the SLR and tide gauge data for estimating coastal trends of sea level. The tide gauge data is available at the Permanent Service for Mean Sea Level (Holgate et al., 2013, Permanent Service for Mean Sea Level (PSMSL), 2018), the University of Hawaii Sea Level Center (UHSLC, Caldwell et al., 2015), the Indonesian Mapping Agency (BIG) and the German Research Centre for Geosciences (GFZ; see Illigner et al., 2015). All data have been visually inspected for outliers, drifts, and jumps and corrected accordingly. The tide gauge data for Kolinamil (Jakarta) and Semarang are corrected for their vertical trends using the GNSS at the tide gauges (Schöne et al., 2011; Illigner et al., 2015) for consistency with the radar altimetry derived sea level and for analyzing the regional radar-altimetry derived versus the relative tide gauge-derived sea level trends.

Space-based radar altimetry for global and regional SLR estimation is analyzed using the Altimeter Data and Processing System (ADS) developed and maintained by GFZ (Schöne et al., 2010), applying the most up-to-date environmental and geophysical corrections. Altimetric sea level time series are derived from a combination of different radar altimeter missions starting from 1993.

2.3. Focus group discussions and household survey

For the analysis of socio-economic impacts, we conducted eight focus group discussions (FGD) with community members in Semarang City in 2016, supported by three student assistants from the Gadjah Mada University (UGM). This method was used to collect primary qualitative

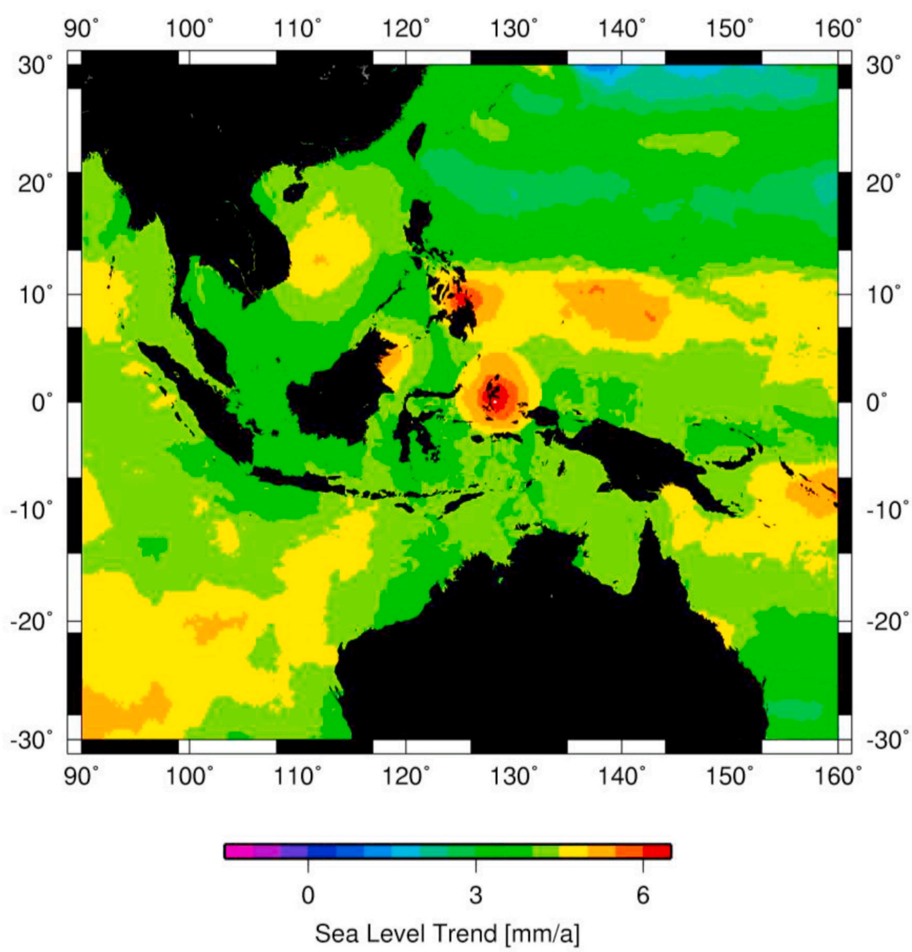

Fig. 2. Regional Sea Level Change in the Southeast Asia area from April 1993 till October 2020.

information and to examine the participants' communication patterns and collective adaptation strategies.

Subsequently, we developed a quantitative questionnaire-based household survey. In 2017, we surveyed a total of 950 households (300 in North Jakarta and 650 in the Semarang Bay area) with the assistance of students from the Diponegoro University (UNDIP) and the University of Indonesia (UI). The respondents were questioned about their entire households, which we defined as the smallest entity for collective decision-making. The 950 surveyed households represent 2248 female and 2122 male household members. After data cleaning, we were able to match 882 of the 950 households with the respective subsidence rate obtained from InSAR.

The study areas for the survey include seven urban quarters (Kelurahan) in the district of North Jakarta and 18 quarters in the Semarang Bay area (seven Kelurahan in Semarang City and eleven villages, Desa, in the adjacent rural and peri-urban districts Demak and Kendal). All study areas are located in close proximity to the coastline and/or along riverbanks, therefore, they are prone to flooding and subsidence (Fig. 1). All surveyed households belong to low and lower-middle income classes. The study areas include traditional fishing communities, factory worker areas, and neighborhoods of the lower urban middle class.

To answer the second research question on household responses to land subsidence, besides qualitative data, we apply a logistic regression model (Hox, 2010). The underlying odds-equation is: $Pi/(1-Pi) = exp(\beta 0 + \beta 1xi)$. The left term represents the logarithmic probability, with Pi describing the probability of households to elevate their houses. Xi stands for the independent variables, e.g. the subsidence rate derived from InSAR. Parameter β0 represents the constant term (log odds) and β1 indicates how the odds differ (Tranmer and Elliot 2008).

3. Study areas: Jakarta and the Semarang Bay area

The megacity of Jakarta, with 10 Mio. inhabitants in the core municipal area, is one of the most prominent examples of urban land subsidence, recently gaining international media reputation as 'the sinking city' (Colven 2020; Garschagen et al., 2018). Jakarta is situated in a low and flat alluvial plain at the mouth of the Ciliwung River. The geological situation of the Jakarta basin consists of a 200–300 m thick sequence of Quaternary deposits overlying Tertiary sediments (Yong et al., 1995; Purnomo 2019). In 1926, first observations of land subsidence in metropolitan Jakarta were reported by Dutch surveyors who repeated levelling lines (Schepers 1926). In 1978, new evidence of subsidence was observed by cracks in a bridge, which fostered the establishment of a network of levelling points with re-measurements in 1982, 1991, 1997, and 1999 (Abidin 2005). Later, this levelling network was augmented by GNSS points observed by periodic re-surveys and, finally, upgraded to continuous operation (Abidin et al., 2008).

The topographical heights are ranging from more than 40 m in the South to areas below sea level, the latter are estimated at 40% of the city area (The World Bank 2011). As a consequence of high subsidence rates, flood risks have been increasing, peaking in the strong flood events in Jakarta in December/January 2019/2020, causing 67 casualties and about 28,000 displacements (ACAPS 2020).

Contrary to prevailing media narratives focusing on SLR, flooding in Jakarta is mainly caused by inland rain and river floods and much less by SLR and tidal impacts. Nine major rivers flow from the hilly hinterland to Jakarta Bay and cause severe flooding during heavy rainfall (Marfai et al., 2015). Nevertheless, provincial engineering and technical solutions have been focusing on the expected effects of eustatic SLR so far, such as a 30 km sea wall and the envisioned large-scale 'Great Garuda Sea Wall Project' (cf. Colven 2017; Colven 2020).

In Semarang, subsidence has probably existed for over 100 years (Andreas et al., 2019). First geodetic monitoring of subsidence is reported for a few sparse points from 1991 to 1996 (Marfai and King 2007) revealing rates of up to 81 mm/a. More systematic studies using various geodetic techniques started in 1999 (Abidin et al., 2013; Lubis et al., 2011). The geological situation of Semarang is characterized by marine sediments and alluvial deposits along the coast but with volcanic rocks of the Damar formation in the South-West of Semarang City (Marfai, 2003; Kühn et al., 2010). Thus, the subsidence is limited to the northern and north-eastern parts of the city. The marine sediments mainly consist of clay with intercalation of sandstone layers, while the alluvial deposits consist of clay and sand with a thickness of more than 80 m (Kühn et al., 2010).

The regional sea level of Semarang differs slightly from the situation near Jakarta. The analysis of radar altimetry data in this region shows a SLR of 2 mm/a between 1993 and 2020, with an annual variation of up to 20 cm. Events such as El Niño/La Niña are clearly visible in our altimetric time series. Here, the SOI has significant impacts on decadal variations. In shorter terms of, e.g. 3–5 years, our data displays that the regional sea level may rise and fall with rates of more than 20 mm/a.

While Semarang, in its lower lying parts located on alluvial plains, shows a similarly high exposure towards land subsidence (Abidin et al., 2013), the major flooding risk in Semarang City (population approx. 1.5 Mio.), however, are the daily high-tidal floods of the already low-lying areas (Harwitasari and van Ast 2011; Marfai and King 2008). In case of heavy rainfall, the floods become even more destructive, since the water cannot drain off into the sea. Municipal plans here include the construction of an embankment-toll-road-structure parallel to the coastline (interview with BAPPEDA Semarang). Nevertheless, high subsidence rates contest structural sea defense systems since every built structure further increases the surface load leading to higher subsidence and locks in water from the hinterland.

Despite the recognition of the actual risks resulting from land subsidence, public debates and political planning in both cities still tend to ignore the main root causes: excessive groundwater extraction and high urban surface loads. Public groundwater regulations remain weak both in monitoring and enforcing (cf. Colven 2020; Saputra et al., 2017). Public debates are mostly circling around adaptation measures of retreat and (forced) resettlement. In 2019, the government of Indonesia announced the relocation of the national capital from Jakarta to Kalimantan. While retreat can indeed be an effective adaptation strategy (cf. Abel et al., 2011; Alexander et al., 2012, Niven and Bardsley, 2013), moving the capital could create 'a city left behind', as only the relocation of governmental institutions and buildings is foreseen. Most of the population and industry are likely to stay (voluntarily), but the public funds required for disaster risk reduction in Jakarta will probably be invested in Kalimantan (cf. Neise and Bott 2020). Even smaller-scale resettlement schemes within Jakarta, such as 4000 resettled households for the regulation of the Ciliwung River, are creating conflicts between the local communities and the provincial government, often having the adverse effect of eroding the adaptive capacity of affected communities (Garschagen et al., 2018; Leitner and Sheppard 2018).

4. Results

In the following, we first focus on the findings of sea level changes and land subsidence in both cities. Setting this natural science background is required to establish an understanding of current and future exposure before moving to include these results into the analysis of contemporary households' risk perceptions and hazard responses.

4.1. Regional sea level variations in south East Asia

The average climate-driven global geocentric SLR is currently estimated at ~3.2 mm per annum (cf. Nerem et al., 2018), which is continuously measured by space-based radar altimetry since 1991. Due to the superimposition of the global geocentric SLR by oceanographic-related drivers, trends may vary regionally between ±15 mm/a (Fig. 2). Additionally, our altimetry data indicate that annual sea level variations and major events such as El Niño and La Niña cause notable positive or negative sea level deviations, which in South East

Asia may reach up to 40 cm.

4.2. Characterization of relative SLR and subsidence

4.2.1. Jakarta

According to our radar altimetry analysis (since 1993), sea level offshore Jakarta shows a positive trend of ~3.1 mm/a about equal to the global mean (Fig. 3). Prominent events causing dynamic sea level changes, such as El Niño/La Niña (e.g. 1997 and 2011), are visible in the time series, but their effects do not alter the generally positive trend. On multi-year scales, the sea level trend is dominated by decadal variations likely associated with the Southern Oscillation (SOI). The annual sea level variations are small with amplitudes of less than 20 cm. In Jakarta, three tide gauges are in operation – two in the subdistrict Tanjung Priok and one in Penjaringan. The GNSS-controlled tide gauge Kolinamil that is in operation since 2012 by GFZ and BIG (Fig. 1), shows linear subsidence of 6 mm/a; the GNSS-corrected sea level trend since March 2014 is −11 mm/a. This value is in agreement with the −8.5 mm/a for the altimetric time series of the same period. The other two tide gauges give no clear indications of sea level trends. The tidal range at Kolinamil is about 1 m (i.e. average high-tide = 0.5 m above mean tidal height); some high-tides are up to 80 cm above the mean tidal height.

Subsidence along the Jakarta Bay coast is highly variable. Averaged over 10 years, the area of Penjaringan, the westernmost part of North Jakarta, shows rates of as much as 85 mm/a, and in the Tanjung Priok area, the rate is up to 40 mm/a (Abidin et al., 2011). In our InSAR analysis from November 2014 to January 2018 (Fig. 1), the maximum subsidence rates along the coast are currently less than 60 mm/a, with most areas showing rates of less than 25 mm/a. For the area of the Kolinamil tide gauge, the GNSS-derived rate of 6 mm/a is confirmed by InSAR. A previous study of Chaussard et al. (2013) using ALOS InSAR between 2007 and 2009 shows rates of more than 200 mm/a in some local areas, but with a high spatial variability. Areas that showed high subsidence in their study (e.g. Muara Baru, Cengkareng) are now subsiding at a lower rate of about 60 mm/a, which can be explained by the relocation of factories out of this area (cf. Neise and Revilla Diez, 2019). Comparing our InSAR results with previous analyses (Abidin 2005; Abidin et al., 2015; Chaussard et al., 2013; Djaja et al., 2004), the subsidence in Jakarta shows not only a high spatial but also an even higher temporal variability.

Comparing the values of the current sea level trend and the tidal range with the subsidence in Jakarta clearly identifies the latter as the main driver for coastal hazards. The global and regional sea level trends as well as decadal variations are significant but stay well below the rates of subsidence. The tides in Jakarta may play a role during rain events preventing water drainage to the sea, but some areas of Jakarta below mean sea level, e.g. Pluit, already need to continuously pump river water up into the sea.

4.2.2. Semarang

In 2012, a GNSS-controlled tide gauge was installed by GFZ and BIG (Illigner et al., 2015). The harbor location is in an area of severe subsidence, which is clearly visible in the landscape (Fig. 1). The GNSS at the tide gauge shows a linear vertical negative trend with 100 mm/a. The tide gauge time series gives a SLR relative to the land of 89 mm/a; after correction for the local subsidence, the sea level trend is slightly negative with −11 mm/a. This value is in agreement with the regional sea level trend derived from radar altimetry; the trend for the period of the tide gauge operation (03/2012–03/2020) is −8.6 mm/a.

The subsidence of the wider geographical area derived from Sentinel-1A InSAR between November 2014 and October 2017 closely follows the geological situation: The southern parts (Damar formation) are stable while the areas close to the coast, such as Kendal, North Semarang, and Demak, are affected by subsidence (Fig. 1). The coastal area of Semarang City displays the largest subsidence rates with values of 120 mm/a. This strong subsidence is probably due to the higher population density and industrial activity, thus, increased water pumping by many local wells. Large areas of Kendal and Demak are dominated by farmlands, which allow InSAR analyses only along major roads and settlements. The subsidence rates in both areas are around 60 mm/a. Previous studies (e.g. Chaussard et al., 2013; Islam et al., 2017; Lubis et al., 2011) confirm our more recent results, which indicate an ongoing linear subsidence process.

In summary, all of the coastal areas under study are experiencing a strong relative SLR. This increase is largely due to natural and especially anthropogenically caused subsidence rather than regional climate-

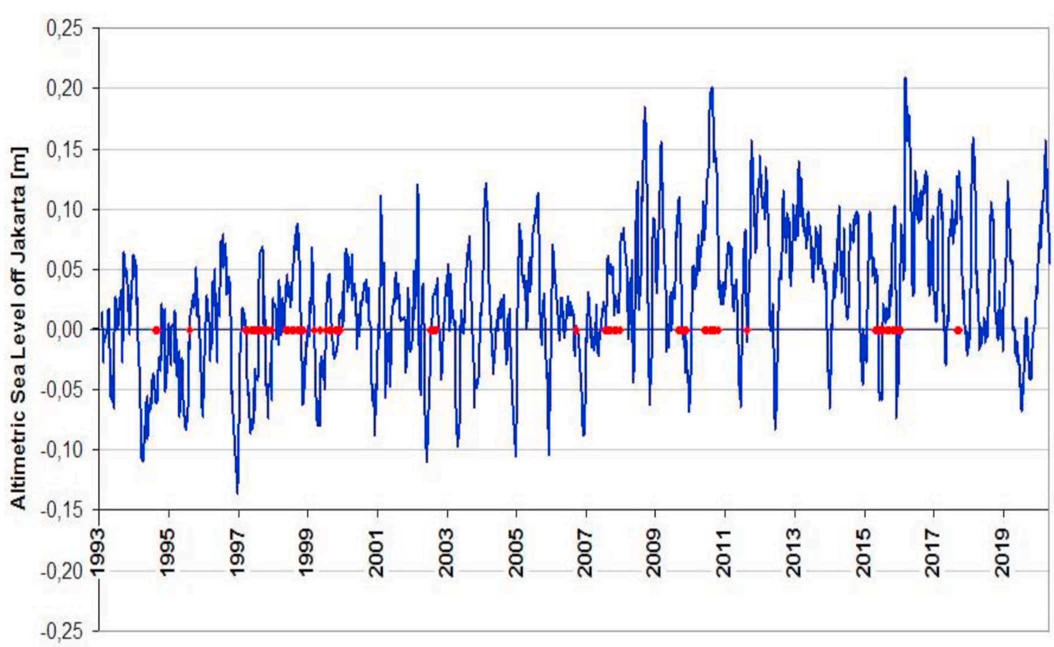

Fig. 3. Radar altimetry derived sea level change off Jakarta (blue) with El Niño indices (red) from https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/detrend.nino34.ascii.txt.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

related sea level change. Any annual or longer-term changes in the sea level are only of minor importance for local coastal hazard threats.

Having established land subsidence as the main driver of local sea level changes and coastal hazards in Jakarta and Semarang Bay, we now take a look at the response strategies of local households.

4.3. Household responses to subsidence

In order to analyze peoples' hazard responses, we first examine their risk perceptions and narratives in comparison to the actual exposure to subsidence obtained from InSAR data. Risk perception does not necessarily correlate with the actual measurable physical exposure. Yet, how a certain hazard is perceived strongly shapes if and what kind of response action is taken (Adger 2003; Bott et al., 2019, Hudson et al. 2020). People need to first be aware of their exposure and second see it as a risk for their lives or livelihoods. Thus, a mismatch between actual exposure and risk perception could explain why people remain inactive even in face of severe risk. This leads us to our first hypothesis:

H1. Responses to land subsidence are guided by the perceived risk and not the actual exposure.

However, even if subsidence poses a severe risk in the eyes of local people and financial means are available for responses, action is not necessarily being taken (cf. Hudson et al. 2020). Further assets, such as human and social capital (education and social networks) together with symbolic capital, meaning power and prestige, might determine whether action is taken or not. People do not only need to be aware of a risk and able to act, they also need to be convinced that acting is within their personal power (Adger et al., 2007). Adaptive capacities are strongly driven by self-evaluations (cf. Mortreux and Barnett 2017). Perceiving oneself as incapable of changing a situation might be a real barrier to adaptation even if there is a realistic chance to do so (cf. Adger et al., 2007; Hudson et al. 2020; Mortreux and Barnett 2017). Accordingly, our second hypothesis is as follows:

H2. Exposure and financial means are not the only factors influencing hazard responses. 'Softer' factors such as symbolic capital and individual perceptions of adaptive capacities further determine adaptive action.

In the following, we first take a look at risk perception and responses to land subsidence using qualitative data and descriptive statistical analysis, followed by a more detailed binary logistic regression analysis of house elevation as the most practiced household response to land subsidence.

4.3.1. Risk perception and responses to subsidence

We found a highly significant correlation between the subsidence rates obtained from InSAR and the self-assessed exposure of respondents (Wilcoxon rank-sum test, p-value: 0.0000). Overall, 57% of surveyed respondents stated that their building is subsiding. The higher the measured subsidence rates, the more likely people perceive their house as exposed.

Despite this correlation, our data shows that subsidence is not the most severe environmental risk in the eyes of local people. This mismatch between risk perception and actual exposure lies in the normalization of this omnipresent and constantly proceeding hazard. Floods (tidal and river) are perceived as much more problematic compared to the root causes of land subsidence. Our FGDs indicate that, in the eyes of the local people, floods are seen as something manageable and they expect effective governmental initiatives on top of their individual response measures. This view is also supported by local media narratives and governmental disaster risk reduction planning, which focus on managing floods by infrastructure-technical solutions.

In contrast, subsidence is seen as something 'natural' that affects everybody in the surrounding communities. *"Land subsidence […] is the law of nature.* 5 cm *per year is part of the law of nature."* (FGD Tawangsari). *"It's the characteristic of the area."* (FGD Terboyo Kulon). *"All parts of the coastal areas in this village are prone to land subsidence, all areas, starting from the coast up to the main road. Even, up to Demak, all areas have subsided."* (FGD Tawangsari). Thus, subsidence has become an integral part of the living environment of local people and hence is not perceived as a severe 'risk'. Due to the perception of subsidence as something 'natural' and 'commonplace', dealing with its consequences has also become a habit, an integral part of households' routines (cf. Bott and Braun 2019). Our survey data support these qualitative findings. We asked respondents to self-nominate the most important risks their household is facing. Floods accounted for 63% of the answers, while subsidence only for 9%. These responses clearly underestimate the actual exposure to subsidence and the number of households which are affected.

Since flooding ranks higher on people's risk perceptions, household response strategies primarily concern flood protection. Small-scale measures such as building sand sack walls, raising house thresholds, sleeping in beds instead of on the floor, installing private pumps, or planting mangroves are practiced. These measures allow local households to accommodate and hence live with most flood incidents, which usually show a high frequency but low magnitude (cf. Bott and Braun 2019). Nevertheless, single extreme events caused by rain and river floods during the monsoon season, such as the flood in Jakarta in December and January 2019/2020, exceed the response capacities of individual household measures. An Indonesian study on the social aspects of coastal flooding on Java was published by Hardoyo et al. (2016).

Despite the low account on risk perception, land subsidence imposes a strong actual risk in itself. Subsidence, and especially ground water extraction below buildings, causes houses to sink into the ground. At a certain level, houses become almost inaccessible, light is blocked out, and furniture becomes hard to fit in. Cracks in the walls threaten the integrity of the building structure. Moreover, the flood risk is strongly aggravated. The higher the subsidence rates, the more frequently floods become problematic for local households (Wilcoxon rank-sum test, p-value: 0.0000). To counteract the negative vertical land movement resulting in apparent 'sinking' of houses, owners elevate their houses every five to ten years, depending on the local subsidence rates: The higher the subsidence rate the more likely houses are elevated by their residents and owners (Wilcoxon rank-sum test, p-value: 0.0000). For these elevations, usually, the roof is taken off of a building, the floor is filled with sand, the walls are heightened, and finally, the roof is put back in place. Many private homes in low and lower income subsiding areas in Jakarta and Semarang show signs of former elevations.

Not only houses but also roads are frequently elevated to keep low-lying coastal areas accessible. In contrast to house elevations, which are private matters, road elevations are funded by municipal governments and political parties. About one quarter of the surveyed households (23%) participates in road elevation by soliciting public funds or by supporting the construction work with manual labor. This infrastructure elevation increases the pressure to elevate on low-income households because their buildings become relatively lower compared to the new elevated street level. There is *"a competition […] between the house and the road. Road elevation is always followed by house elevation."* (FGD Pangung Lor).

So far, most households are still able to accommodate to the effects of land subsidence. Nevertheless, the money invested in house elevation is a financial burden and thus lacking for other investments. *"There are many people who have many children, their incomes cannot afford house reconstruction."* (FGD Terboyo Kulon). The absolute minimum elevation costs for a tiny and single store house in low-income areas account for about 800 US $. Only 13% of the households in need of elevation ($n = 501$) in our survey had saved this amount of money at the time of the interview. The higher the subsidence rate the more difficult it is for these households to save money for elevation (Wilcoxon rank-sum test, p-value: 0.0011). Those people, who cannot afford to elevate, install pumps to drain their buildings from flood water. According to our FGDs, the poorest families even use standard pool pumps to drain their buildings.

Despite the continuous subsidence and repeatedly required elevation, local people are not planning to leave low-lying coastal areas. In line with the risk perception of subsidence as something 'natural and common', 93% of surveyed households are planning to stay where they live. Moreover, there is no significant correlation between the plans to move and the subsidence rate obtained from InSAR data (Wilcoxon rank-sum test, p-value: 0.8062). This finding supports current research on 'climate-induced migration' that conceptualizes migration as a multi-causal phenomenon which cannot be explained by simple push-pull factors (cf. Bernzen et al., 2019; Black et al., 2011). Major reasons for persisting in these multi-risk coastal environments are social cohesion (staying close to neighbors, friends, relatives), affordability, and local job opportunities. Fishermen and fish farmers rely on direct access to the sea. Furthermore, many factories are located on low-lying coastal plains (Neise and Revilla Diez, 2019). Subsidence, or any coastal hazards for that matter, are rarely taken into account in municipal spatial planning. Thus, many industrial zones have already been located and still are further announced in subsidence areas (expert interview UNDIP; cf. Suroso and Firman 2018). Even important infrastructures such as train stations and airports are located there (Fig. 1).

4.3.2. What drives individual house elevation?

To analyze which factors drive taking adaptive measures at the household level (hypotheses 1 and 2), we focus on house elevation as the most common and vastly practiced response to subsidence in our study areas. In a more detailed binary logistic regression analysis, we therefore, operationalize whether households have elevated their houses in the last five years (yes = 1) as the dependent binary variable. Because only respondents who perceive themselves as affected by land subsidence were asked about elevation practices, the number of observations is reduced to n = 501 in this analysis.

We include an independent variable for subsidence rates obtained from InSAR to control for the actual hazard exposure (Table 1). Furthermore, we use variables on financial and physical capital to test for house ownership and the individual capacities to afford elevation.

Table 1
Overview of independent variables.

Independent variable	Mean	Std. Dev.	Min	Max
Exposure				
Subsidence rate (cm)	5.96	3.22	0.1	12.9
Financial & physical capital				
Savings > 800 US$ (yes = 1)	0.10		0	1
House ownership (yes = 1)	0.92		0	1
No. of house floors	1.18	0.44	1	5
Social capital & persistency				
Trust in neighbors (yes = 1)	0.87		0	1
Participation in community meetings (yes = 1)	0.48		0	1
Plans to relocate (yes = 1)	0.09		0	1
Years of residency	35.58	14.28	5	70
Human & symbolic capital				
Highest level of formal education (high school/tertiary education = 1)	0.76		0	1
Self-assessment of personal influence (high = 1)	0.25		0	1
Leader position (head of RT, RW, PKK) (yes = 1)	0.16		0	1
Further adaptive measures & risk perception				
Private pump (yes = 1)	0.02		0	1
Participation in road elevation (yes = 1)	0.28		0	1
Floods are perceived as problematic (yes = 1)	0.26		0	1
Higher subsidence rates expected in future (yes = 1)	0.44		0	1
Heard about SLR (yes = 1)	0.48		0	1

Social capital is included to test for social networks and mutual support within the neighborhood which might facilitate taking adaptive measures (cf. Bott and Braun 2019; Braun and Aβheuer 2011). Persistency at a place of residence usually increases social cohesion. People who have a stronger attachment to place are more likely to take in-situ adaptation measures (cf. Bott et al., 2019; Marshall et al., 2012). Human capital variables are included to control for education and knowledge levels. Furthermore, independent variables on symbolic capital are included to control for the influence of power and self-evaluated capabilities (hypothesis 2). The two independent variables on road elevation and private pumps are used to check for the influence of other response strategies. Finally, we control for the perception of coastal hazards to check for the influence of risk perception on explaining whether action is taken or not (hypothesis 1).

With binary logistic regression models, only multicollinearity needs to be controlled for (Backhaus et al., 2016). In our analysis, the variance inflation factors (VIFs) for the independent variables show a mean VIF of 1.21, thus, multicollinearity can be ruled out (O'Brien 2007). We have checked for spatial autocorrelation by using robust standard errors.

We run the model in 5 steps: first with subsidence rates only (m1), followed by the inclusion of financial and physical capital (m2), then social capital and persistency (m3), succeeded by human and symbolic capital (m4), and finally further response strategies and risk perceptions (m5). This way of breaking down the model is used to visualize and analyze the robustness of significant influences of single variables contributing to the final model. All but one significant independent variable maintain significance throughout all models, thus, the results are robust. In the following, we discuss the estimated effects of an independent variable in the final model (m5) if the margin of error is not higher than 10% (Table 2; cf. Gelman and Stern 2006).

The subsidence rates obtained from InSAR data show highly significant results. Thus, the faster the building is sinking the higher the likelihood to elevate. While this result was to be expected, it still underlines the relevance of actual exposure towards hazards in taking action. Thus, in spite of the relatively low risk perception of local people evident in the qualitative data, land subsidence strongly triggers response action.

Financial and physical capital show significant influences on house elevations as well. This finding can be explained by the costs of elevation work. Moreover, house owners are more likely to invest in their property than tenants, and wealthier people are more likely to invest in two-story buildings. Despite highly significant results on the effect of subsidence rates and financial and physical capital, they are not the only influential factors in explaining the individual response of house elevation. Higher levels of formal education and symbolic capital show significant positive results, as well. Our data show that tertiary education correlates with action taking. Moreover, more educated households tend to have higher income levels.

Particularly interesting is the role of symbolic capital. The self-assessment of whether respondents feel able to make their village a better place is positively correlated with house elevations. This finding confirms former research on the value action gap (cf. Adger et al., 2007) and underlines that the perception of personal power and adaptive capacities strongly influences whether to get active or not (H2). Thus, even if a household is exposed and has the financial means and know-how to elevate, adaptive action can be impaired if people feel powerless and incapable of making a difference. Symbolic capital and self-assessed capabilities can therefore be strong drivers of or barriers to adaptation.

Regarding further adaptive measures, the model shows significant correlations with participating in road elevation. This result can be explained by our qualitative findings, demonstrating that public road elevation often forces house owners to privately elevate their buildings. Therefore, only households able to elevate their homes are motivated to join in elevating the road.

Finally, the regression model (m5) shows that in contrast to our first hypothesis, risk perception does not strongly influence response

Table 2
Logistic regression analysis for house elevation.

VARIABLES	Odds ratio (standard error)	Odds ratio (standard error)	Odds ratio (standard error)	Odds ratio (standard error)	Odds ratio (standard error)
	m1	**m2**	**m3**	**m4**	**m5**
Exposure					
Subsidence rate	**1.142*****	**1.164*****	**1.168*****	**1.184*****	**1.161*****
	(0.0345)	(0.0385)	(0.0386)	(0.0423)	(0.0444)
Financial/physical capital					
Savings > 800 US$		**4.613*****	**4.755*****	**4.107****	**3.886****
		−2.480	−2.575	−2.396	−2.340
House ownership		**3.152*****	**3.254*****	**2.739*****	**2.708*****
		−1.171	−1.239	−1.020	−1.013
No. of house floors		**7.120*****	**7.434*****	**4.940*****	**5.362*****
		−3.251	−3.629	−2.372	−2.623
Social capital & persistency					
Trust in neighbors			0.996	0.819	0.787
			(0.320)	(0.272)	(0.276)
Participation in community meetings			**1.872*****	1.206	1.085
			(0.393)	(0.273)	(0.255)
Plans to relocate			0.568	0.543	0.549
			(0.231)	(0.211)	(0.218)
Years of residency			0.995	0.997	0.996
			(0.00725)	(0.00785)	(0.00824)
Human & symbolic capital					
High level of formal education				**1.719****	**1.492***
				(0.399)	(0.360)
Self-assessment of personal influence				**4.166*****	**4.353*****
				−1.534	−1.644
Leader position				1.631	1.836
				(0.693)	(0.779)
Further adaptive measures & risk perception					
Private water pump					0.970
					−1.112
Participation in road elevation					**1.925****
					(0.508)
Floods are perceived as frequently problematic					1.050
					(0.271)
Higher subsidence expected in future					1.099
					(0.260)
Heard about SLR					**1.796*****
					(0.406)
Constant	0.946	0.0296***	0.0252***	0.0295***	0.0226***
	(0.185)	(0.0222)	(0.0218)	(0.0248)	(0.0200)
Observations	501	501	501	501	501
Pseudo R^2	0.0294	0.1238	0.1414	0.1912	0.2152
Robust see form in parentheses					
***p < 0.01, **p < 0.05, *p < 0.1					

measures towards subsidence. Both perceptions about future subsidence and flood risk remain insignificant in our final model. Only households who know about SLR are significantly more likely to elevate their houses. This result might indicate proactive action in anticipation of future events. However, since this knowledge strongly correlates with higher education levels, it cannot be ruled out that it might just be a further indicator for human capital.

In summary, the results show that individual response action towards land subsidence (analyzed with the example of house elevation) strongly depends on the actual exposure and less on perceived risks. Thus, hypothesis 1 is partially contradicted with regard to slowly emerging land subsidence. Our qualitative data provide an explanation of why risk perception is less influential for taking action in the case of land subsidence. The data show that the slowly proceeding hazard of land subsidence is perceived as something 'normal' and provokes continuous responses, which became integrated into habits and routinized practices of local people (cf. Bott and Braun 2019). Thus, we found that in contrast to fast onset events, responses to continuously and slowly progressing land subsidence are less directly related to (higher) risk perceptions.

Furthermore, exposure and financial/physical capital are not the only influencing factors in explaining house elevations as a major means of taking action. Self-perceived personal capabilities are also strongly influencing individual adaptive responses. Thus, hypothesis 2 could be verified.

5. Concluding discussion and policy implications

This study has addressed the so far under-researched topic of land subsidence in disaster risk reduction. We have combined data from radar altimetry, GNSS-controlled tide gauge stations, and InSAR mapping with social science studies on risk perception and household hazard responses to bring the urgent issue of land subsidence more to the forefront of coastal hazard research.

Our analysis of relative SLR in the coastal areas of Jakarta and Semarang Bay clearly identifies subsidence as the major coastal threat for people living in these areas. Although propagating the current trends into the future is difficult, Church et al. (2013) predict a regional SLR of about 50 cm (total RCP4.5 ensemble mean) to 70 cm (total RCP8.5 ensemble mean) until 2100. Assuming a constantly continuing subsidence, the relative SLR in Semarang will supersede the RCP8.5 scenario after 7 years and in Jakarta after 12 years. Another study by Bender et al. (2020) analyzing Late Holocene sea level changes (6 ka BP) found that sea level highstands for the Makassar Strait were about 2.4 m higher than today, which is an upper-bound value for the region and our analysis. The subsidence rates of Jakarta and Semarang Bay exceed even this Holocene highstand within a few decades, putting the focus of action clearly on mitigating subsidence effects rather than regional SLR. Otherwise, even under just continuing as before, a tipping-point could be reached, after which the low-lying coastal urban areas are no longer habitable.

From a social science perspective, focusing on land subsidence allows us to study human responses to slowly emerging SLR already today. Thereby, we found that perceived risk and actual exposure influence human responses differently for fast- and slow-onset events. In contrast to high magnitude but low frequency coastal hazards (such as cyclones or tsunamis), land subsidence and its almost constantly visible effects become normalized in people's perceptions and responses are integrated into day-to-day habits. Thus, risk perception is a far less strong determinant of action taking towards subsidence than it is for fast-onset events.

In line with other empirical studies, we found that people in coastal zones oppose relocation but instead try to accommodate to higher flood levels (cf. Bott and Braun 2019; Bott et al., 2020; Esteban et al., 2020). This finding should be directive for governmental disaster risk reduction strategies. The current focus on resettlement of urban poor populations in Indonesian (and other Global South countries') hazard management strategies goes contrary to household and community-based adaptation. Therefore, adaptation measures at the local level should be more focused on better coordinating top-down and community-based strategies while actively involving the local population (cf. Triyanti et al., 2017).

Yet, despite their surprisingly high response capacities, households and local communities alone are not able to sustainably counteract the impacts of area-wide (relative) SLR. Household strategies for dealing with land subsidence remain short-term and repetitive. Moreover, the same house construction and elevation techniques are used in all our study areas. New, innovative measures could not be identified. This result might hint at a lock-in in local response mechanisms. In addition, small-scale, individual solutions can contribute to maladaptive outcomes. While the elevation of buildings makes sense from an individual owner's point of view, these measures do not represent a sustainable hazard response in the long run, because they further increase the surface load of buildings and infrastructure. Other individual measures such as constructing buildings on piles driven into the ground, as in the Netherlands, are also impracticable due to the thickness of the subsiding layers of Quaternary and marine deposits (80 m in Semarang and even 200–300 m in Jakarta).

Yet, there still might be some construction optimizing options. A recent study by Minderhoud et al. (2020) on the Mekong Delta found that building foundations can significantly reduce the subsidence rates of buildings. Even shallow foundations were found to reduce rates and deep foundations resulted in much lesser building subsidence rates compared to the surrounding land surface. Other research indicates that low-cost floating buildings or lighter wooden structures might significantly reduce the risk towards (relative) SLR (cf. English et al., 2017). For example, projects are carried out in Louisiana (USA), Jamaica, and Vietnam to develop and test options for low-costs amphibious retrofitting of small single family houses (BFP 2019). Finally, additional top-down structural and technical options of accommodating coastal hazards (cf. Bott and Braun 2019) could further improve the ability of local households to live in a frequently flooded environment, such as submergible infrastructure, early warning systems, or formal insurances.

Nevertheless, to efficiently counteract relative SLR and to keep low-lying sinking coastal areas habitable, adaptation alone will not be sufficient. Large-scale mitigation strategies are required. Taking into account the rapid population growth and economic development of many coastal cities, the fresh water use is continuously increasing along with the resulting land subsidence from ground water extractions (Yan et al., 2020). Therefore, one pressing mitigation strategy to counteract land subsidence would be the drinking water supply of Jakarta and Semarang from surface water instead of groundwater. Another task would be the declaration of no-development zones in spatial plans, to protect sensitive coastal zones and to provide retention areas and coastal set-back zones. The example of Tokyo shows that land subsidence can indeed be stopped within a few years by a combination of large-scale engineering-technical measures and spatial planning (cf. Bucx et al., 2015; Erkens et al., 2015). To date, however, Jakarta's municipal disaster risk reduction strategies remain guided by short-term solutions and unconnected projects (Esteban et al., 2020). A shift from past trajectories towards a sustainable urban transformation is not identifiable (cf. Esteban et al., 2020; Garschagen et al., 2018).

Further interdisciplinary research is required to better understand, develop and implement adaptation and mitigation strategies towards the complex socio-environmental hazard of land subsidence. Both community-based and top-down strategies are required to achieve long-term and sustainable hazard risk reductions. Thereby, the interests of local people need to be considered and included in government policies to avoid maladaptation. The focus should be on urban areas since they are both drivers and subjects to land subsidence; and strategies have to be implemented at the municipal level. The future will show whether coastal urban areas around the globe will be able to break out of historical path-dependencies of single protective infrastructure measures and achieve a comprehensive sustainable urban transition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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