Monitoring and Addressing Land Subsidence Hazards in Semarang

Subjects: Environmental Sciences

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Land subsidence is a major cause of environmental degradation. It increases the exposure of global sea level rise-related disasters in coastal cities lying on young sediment. This article reviews the advancement of measures in dealing with this hazard taken by researchers, the government, and the people.

Semarang land subsidence coastal spatial planning

1. Background

Semarang City, a coastal city in Central Java Province, Indonesia, is one of the national strategic activity centers that connects the eastern and western part of the island. This 373-kilometre square city is home to about 1.8 million people. Well known as “the city where its rivers are flooding”, the government had acted with regard to flooding-related issues, as they pioneered participation in the 100 Resilient Cities program[1], joined the Asian Cities Climate Change Resilience Network (ACCRN) in 2009[2], and took part in the Water As Leverage pilot project[3]. But this city is still under the threat of being sunk[4][5]. Water needs that have increased by more than 960% since 1910 are not fully met by the local water provider[3]. Consequently, the land subsidence rate is still severe, reaching about 24–36 cm/year through 2014–2017[6]. An estimation by Sarah [7] stated that land subsidence in this city has caused 3.5 trillion rupiah (±245 billion USD) in economical loss. However, this hazard is not well incorporated into their planning and development policies[8].

Land subsidence in coastal cities is a complex environmental problem. It is related to urban development and land utilization that does not comply with the ecological threshold. Economic activity undertaken by industry is exploiting the groundwater, social justice where the local residents having limited access to water, the building loads that is hard to control so then exceeding its bearing capacity, as well as the geological phenomenon where the subsiding land of this city is actually lying on a young sediments that is still in the process of natural compaction [9][10][11][12][13][14]. To achieve comprehension of the complexities and dynamics of the socio-ecological system and further address the risk of land subsidence, there is a need for an inter-disciplinary approach[11][15] and integrated analysis[4][16][17][18] and management [19][20][21][22][23], in addition to the involvement of multiple-stakeholders [22]. However, comprehensive discussions on land subsidence in Semarang city are still limited. Abidin et al. [24] comprehensively assessed the characteristics, impact, and causes of land subsidence in Semarang. Nevertheless, they did not address criticisms of governmental measures or the current adaptive measures undertaken by the community. Another comprehensive study was undertaken by Saputra et al. [11][25][26] who discussed the government’s awareness and people’s adaptation. Quite similar to this research, Bott et al. [27] also assessed the risk perception and adaptation measures taken by the locals, but they first explored the physical processes. However, those studies only partially discuss the multi-year progress and possible improvements with regard to how this city deals with land subsidence.

2. Data Description and Initial Insight

The three most dominant sources of the reviewed literature were Conference Proceedings (37%), International Journals (31%), and National Journals (26%). According to the year-based tabulation, as shown in **Figure 1**, there was an increment in land subsidence research in the last two decades. Although there was a decline from 2019 to 2020, the number of published research followed a linear trendline. Another significant decrease happened between 2020–2021, presumably related to the execution period of this study. Such increment is a positive sign of progress in understanding land subsidence.

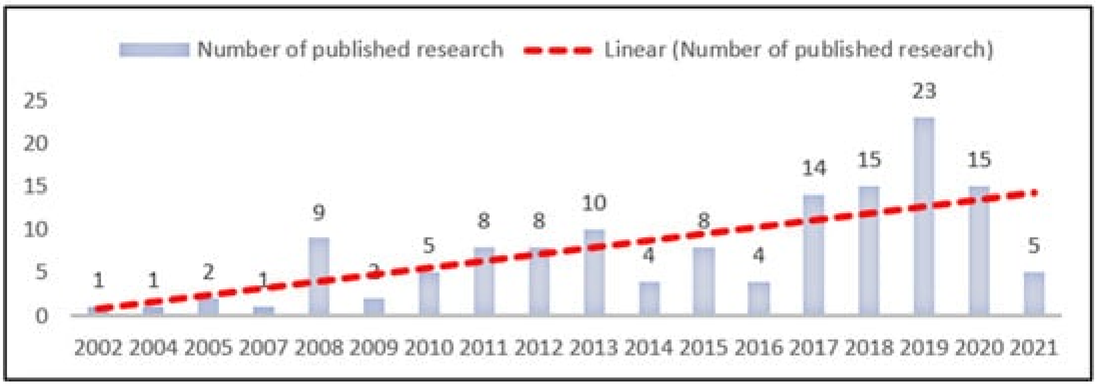

Figure 1. The increasing number of land subsidence research.

Another initial insight was gained from a word cloud generated using Atlas.ti. As shown in **Figure 2** below, “water” and “groundwater” are among the most discussed terminologies in the reviewed papers, as their font size is larger than the other. This shows that the water management perspective is deeply included in land subsidence discussions. The word cloud also provides a preliminary understanding on the broadness of topics reviewed in this paper. Although used “monitoring” as part of the search query, it does not necessarily mean that the papers generated from the search are limited to monitoring measures. This explains why the font size for the term “monitoring” (**Figure 2**; lower left) is relatively small and comparable to that for “management” and “adaptation”.

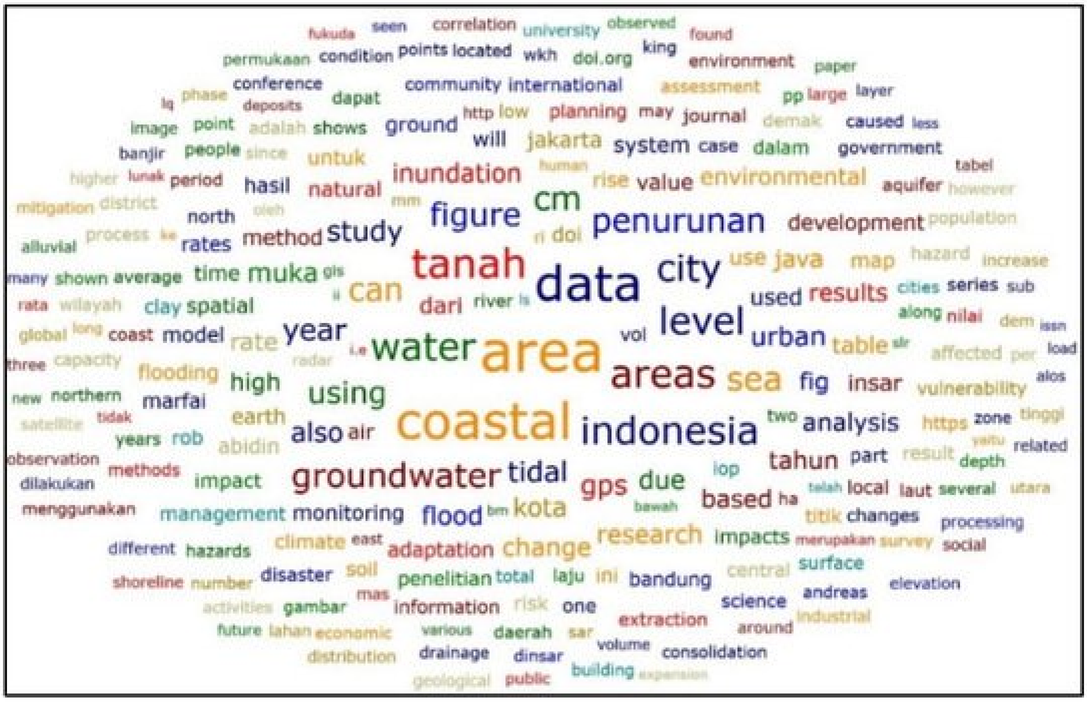

Figure 2. Word cloud generated from literatures reviewed in this paper using Atlas.ti 9.1. Only words with a minimum of 131 mentions were included, while “Semarang” and “Land Subsidence” were excluded from the analysis. Font size indicates frequency of terminology use, in which larger font size shows that the word is mentioned more often in the reviewed papers.

3. Advancement in Land Subsidence Rate Monitoring Measures

Land subsidence rate monitoring is assessing land elevation differences between a specific time range. This process could be used to provide a comprehensive understanding of the spatial pattern, rates, and displacement of land subsidence [1][28][29] by assessing elevation changes over time [2][30] and to estimate future conditions [3][31]. This is also the initial step in mitigating the risk of land subsidence [1][32][33][34]. Effective monitoring measures is necessary to help developers or individuals to take the best action in adapting to subsidence [9]. Better management of land utilization and water supply could also be achieved [2][3][9][33][35][36].

The most severe land subsidence rates were reported in the northeastern part of the coastal area in Semarang [37][38][39][40][41][42][43][44][45][46]. According to the spatial estimation, land subsidence occurs in 32.92% of the city area, which is about 128.65 km^2 [47]. The western part of the city has a relatively lower risk for land subsidence [37][39][48]. Land use activities that are related to the highest subsidence rates are: (1) port and sea transportation activities at Tanjung Emas Harbour (Pelabuhan Tanjung Emas) [32][42][49][50]; (2) industrial areas [1][51][52][53] (Genuk District [4][5][51][54], North Semarang District [4][50]); (3) housing areas [32][51][55]; and (4) an old city post-Dutch quarter tourism area [2].

As shown in Appendix A, the maximum annual subsidence rates observed in the coastal area of Semarang are up to 15–19 cm/year. The rates in 2008–2010 were relatively steady, while an increase was observed in 2010 and so forth [41][44]. On the other hand, benchmark data assessed by Suprabadevi et al. [46] showed that the highest accumulative subsidence rate was observed at 33.5 cm in 2008–2011.

As shown in **Figure 3**, in the 1980s, monitoring was done based on geodetic measurement using the ground-levelling technique by installing grounded concrete piles or conducting a ground survey using Global Positioning System (GPS) tools. However, as this method relies on the subsiding ground, its stability and continuity are questionable. Hence, in the 2000s, satellite imagery that can encompass a wider area and better data availability was used for long-term monitoring. Critical reviews also stated that this method had flaws, such as overestimation and the “no-subsidence” bias caused by low coherence data.

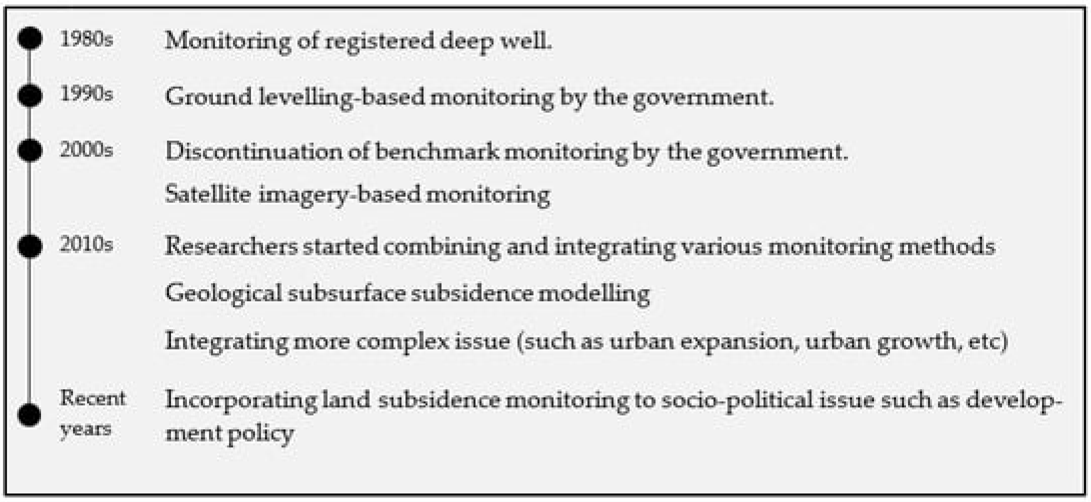

Figure 3. Historical timeline of land subsidence monitoring in Semarang [3][30][56][19][57][58][31][34][59][60].

Monitoring is done in various models that might lead to different results corresponding with different perceived impacts [42][51]. This has the potential to mislead the mitigation and adaptation projects [59]. As there is limited research showing accumulative subsidence rates, this may also lead to a bias for the actual subsidence events. The Interferometric Synthetic Aperture Radar (InSAR) is a common method used to analyze the rates of subsidence [44] by comparing digital elevation models between two satellite images [61]. Another method, microgravity, effectively measures subsidence based on geological elevation [62]. The Global Positioning System (GPS) is also a remarkable method [44]. Some researchers argue that InSAR is better than the other because it could monitor surface deformation in a large area without risking any device on the subsiding yet unstable soil [38]. Others prefer to utilize InSAR as a complementary technique to confirm each other’s results and to test for data reliability [30][41][52][60][63], to confront [64], or merely to highlight any differences [28]. Effective monitoring measures could then be defined as (i) using a combined method, which primarily relies on satellite data (using InSAR) which then supported by field survey and observation (using GPS) and (ii) the ability to provide information not merely about yearly rates but also about the accumulative subsidence.

Primarily, monitoring measures is dominated by the backcasting technique. The timeline of land subsidence research as shown in Appendix B are all a backcasting estimation (from the recent years and backwards), except from Marfai [3] that also used the forecasting measurement (from recent years and forward). Monitoring measures also dominated by the assessment of the average annual rates rather than the accumulative rates. As shown in Appendix A, the maximum annual subsidence rates observed in the coastal area of Semarang are up to 15–19 cm/year. The rates in 2008–2010 were relatively steady, while an increase was observed in 2010 and so forth [41][44]. On the other hand, benchmark data assessed by Suprabadevi at al. [46] showed that the highest accumulative subsidence rate was observed at 33.5 cm in 2008–2011. The annual rates were almost consistent in the previous decades; this may cause the misunderstanding that land subsidence is a normal condition in Semarang and the subsidence rates in this city will always remain the same. As there is limited research showing accumulative subsidence rates, this may lead to a bias for the actual subsidence events. In addition, accumulative subsidence rates are essential to indicate the urgency of taking further measures in subsiding areas.

4. Debates on Anthropogenic Subsidence Narratives

Understanding the cause and impact of subsidence is essential in choosing the best adaptation and mitigation measures. Various perspectives regarding this matter may lead to comprehensive understanding, yet at the same time confuse what the priorities are. Researchers, in general, agree that land subsidence is a type of ground surface deformation [38] caused by the consolidation process that lowered the upper soil layer. However, there are ongoing debates on whether the cause is the natural consolidation of young sediment or anthropogenic stressors.

Geological researchers prefer to consider land subsidence as a natural process. Geomorphological processes, mainly sedimentation, have led to land compaction in the coastal areas of Semarang in recent geological years. The coastal area relies on young alluvium sediments that still undergo the process of natural consolidation [64][24][28][32][45][61][65][66][67]. Fakhri Islam [63] and Yastika et al. [30] indicated that the land subsidence spatial pattern is similar to the young alluvial soil spatial pattern. Such areas consist of a thick, soft layer of clay, gravel, and silt [24][32][33]. Masvika [68] did a borehole analysis and then agreed with this proposition.

There are some theoretical understandings and empirical analyses that suggest that land subsidence in Semarang’s urbanized coastal area is anthropogenic. In his book, Pipkin [8] categorized natural subsidence as that with a rate of below 4 cm/year. Another argument from Kuehn et al. [2] stated that natural subsidence “rarely exceeds 1 cm/year”. Geological research for a land subsidence estimation by Sophian [69] showed that although subsidence does occur in areas where natural consolidation is ongoing, this phenomenon could become more severe due to the increasing construction and infrastructure loads in the future. The author reported that land overburdening contributes to half of the subsidence events. Recently, Sarah et al. [70] addressed the debate through natural compaction analysis. They stated that land compaction in Semarang is mainly caused by groundwater exploitation, which results in an over-pressured soil layer. They found that the rate of natural subsidence is relatively low (0.3 cm/year) compared to that of the anthropogenic subsidence (17 cm/year). Therefore, they concluded that natural compaction in the case of Semarang is “hardly present”.

Empirical research articles further disclosed that land subsidence in Semarang is mainly caused by the overexploitation of groundwater by the urban activity, industries and domestic users. Hadi [71] found that people in the subsiding areas are consuming water from their neighbour's deep wells. Some researchers believed that subsidence has occurred since the 1980s, when the population started to grow rapidly [30][28], groundwater extraction has increased exponentially since then [72]. Some other researchers argue that land subsidence in Semarang has happened since the early 20th century [29][33][42][72]. The superimposed analysis, where two or more spatial data are is overlapped and analysed using certain spatial analyst software such as ArcGIS, confirms that land subsidence is limited to areas where the aquifer system is overused [52]. Research dedicated to assessing the correlation between the decrease in groundwater levels and land subsidence has proven that both variables are highly correlated [2][28][36][73][74][75][76][77]. In areas experiencing severe subsidence, such as Kaligawe and Genuksari, they also possess a deficit in groundwater [18]. Groundwater extraction has increased because local piped water provision companies cannot fulfil the entire city's domestic and industrial water demand [6][14][56][19][78][79][80][81]. On the other side, young alluvium sediments where those activities occur have high groundwater potential [82][83]. Land subsidence also induces seawater intrusion, which leads to hydraulic conductivity increments and subsequently increases the subsidence or consolidation rates [84].

Land subsidence is also correlated with urban growth expansion [4][57][34][50][85][86]. Land-use change due to industrial area development has occurred in the coastal areas [71]. For example, a total of 698 ha of land in coastal cities has been shifted from agricultural to built-up areas between 1998 and 2008 [87]. Consequently, this caused water recharge disturbance, an increase in groundwater use, and soil overburdening due to increased building loads [1][3][77]. Urbanization in the form of coastal land reclamation also caused land subsidence [88]. Land reclamation projects led to land progression towards the sea [89]. Marshland in coastal areas was buried in developing housing and infrastructures. Combined spatial and temporal analysis showed that the urban development in Semarang was heading towards the coasts in 1998–2018 [90]. Abidin et al. [24] explained that the sedimentation process in Semarang's shoreline is significantly progressing towards the sea, with an average rate up to 8 m/year from 1965 to the early 1990s. A long-term shoreline analysis from 1903–2003 by Marfai [91] also demonstrated that the 100-year-old coastal seaward progression was not only a result of natural sedimentation but also infrastructure development. Furthermore, reclamation also has a negative impact, as it may change wave patterns, potentially leading to erosion in surrounding areas [20].

Although agreeing with the views of other researchers, Kasfari [36] believes that urban growth determined by population growth will not affect the severity of land subsidence. They came to this conclusion based on their assessment of population and the rates, and they found that the most populated areas are experiencing the slowest subsidence. At the same time, the most sparsely populated international airport is experiencing the fastest subsidence. The subsidence in the new airport development zone is presumably due to required man-made and technologically induced subsidence to stabilize the land, so there will be no subsidence in the future [92]. Therefore, the prior argument might be less relevant to deny the fact that urban development, the anthropogenic stressors, is causing land subsidence.

Based on these insights, land subsidence in the case of Semarang is mainly anthropogenically induced. As also shown in the code-network in **Figure 4**, the natural process has limited contribution to land subsidence in Semarang. The technical practice of this understanding is well presented by Dong et al. [93], who utilizes the geotechnical approach as a control for land use development.

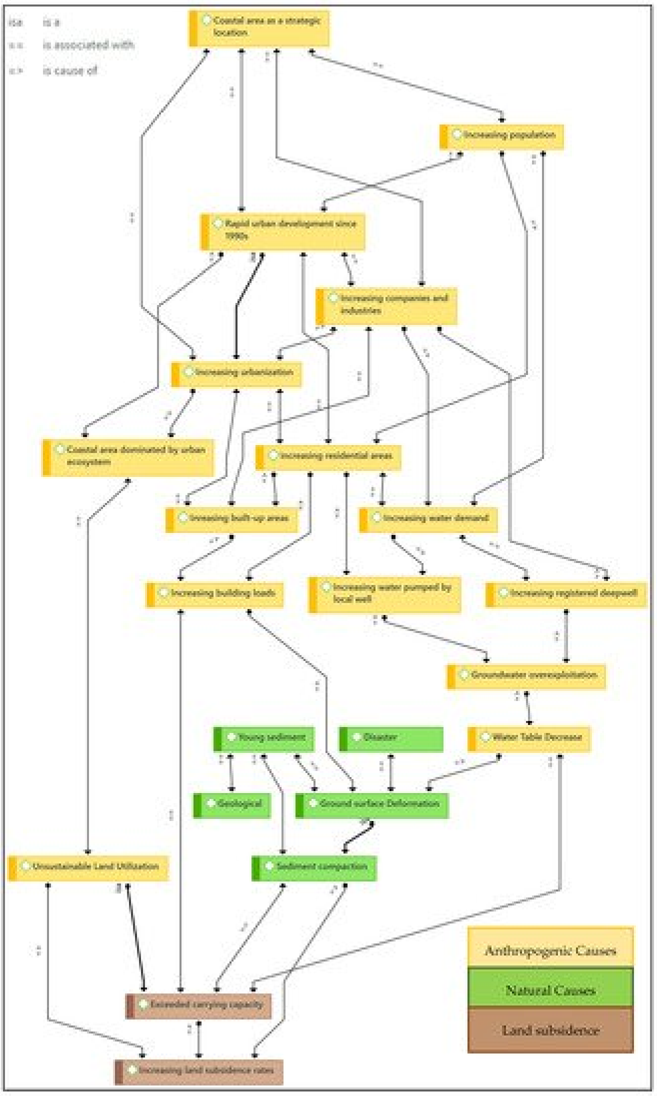

Figure 4. Code-network for the identification of land subsidence causes in Semarang.

5. People and Public Official Awareness on Land Subsidence Impact and Their Responses

Land subsidence in low-lying coastal areas created an enormous impact on the city. As discussed in the literature (see **Table 1**), subsidence has brought the land elevation below sea level. Local land subsidence is the most influential factor that worsens tidal flooding [94]. It also induced erosion, leading to the removal of 1764.5 ha of land in Semarang coastal areas [95]. Suripin and Helmi [95] assessed that the rate of shoreline retreat in 1991–2009 reached 178 m/year. Andreas et al. [44] used high-resolution satellite imagery analysis to show that the areas surrounding Tanjung Mas and the north-eastern coast of Semarang had been submerged. Marfai [96] predicted that the coastal areas of Semarang city will be submerged further. Land subsidence might cause Semarang to lose its coastal areas in the future [7][70][95].

Table 1. Land subsidence impact.

Impact	References
Degrading Environmental condition	
Worsening tidal flooding exposure	[4][9][10][56][82][37][22][24][29][31][44][51][69][94][97][98][99][100]
Submerged/loss of land	[4][28][34][44][46][68][95][101]
Changing shoreline	[91][102]
Seawater intrusion	[33][52][87][94][103][104][105]
Physical Infrastructure Destruction	
Sinking and abandoned house/building	[10][27][60][106]
Damaging building, road, drainage system	[2][9][30][96][60][74][106][107][108]
Economical Loss	
Increasing cost of maintenance (household and government)	[2][9][105]
Land value decrease	[109]
Property value decrease	[101]
Disruption in economic activities	[43][101]
Worsening Social Quality of life	
Lowering quality of life	[9][27][39][51][53][60][106]
Disrupting local people's day-to-day activity	[25][24][46][101][110][111]
Increasing coastal vulnerability	[2][5]
Increasing harmful sanitation-related diseases such as Malaria, Dengue, Labtoferosis, etc.	[112][32][111][113]

Towards the city center, it has caused damage to buildings and streets and degraded people's quality of life. The economic loss caused by subsidence in Semarang is estimated at 3.5 trillion Rupiah or 247.9 million USD [7]. A land value assessment by Utami et al. [109] stated that areas impacted by tidal floods and land subsidence suffer from land price stagnation and decrease.

Both the people and the government overlook the matter of land subsidence. As shown in **Figure 5**, measures taken by both stakeholders are dominated by those that are aimed to tackle coastal flood impact [19][26][88]. This contrasts with the fact that the government already knew the importance of tackling land subsidence. They instead took limited measures in dealing with land subsidence. The government initiated subsidence monitoring three decades ago [3] yet discontinued the measure in 2000. In the same year, they also profiled the areas and the people under the risk of land subsidence [114][115]. The Semarang Government had also collaborated with GIZ in developing land subsidence monitoring data in 2013. Unfortunately, this project was also discontinued. The government has taken structural (building dykes, pumping stations, flood gates, polder systems, etc.) as well as non-structural measures (seed funding, developing compensation plan, community empowerment, etc.) to mitigate the impact of tidal flooding [96][111][116]. They even created specific task forces that focused on every coastal issue and worked on monitoring, law enforcement, and infrastructure improvement. Unfortunately, as reported previously [23][114][115][116], the task force working on land subsidence is focused only on monitoring. The spatial planning document does not incorporate land subsidence either [19]. This might be due to the fact that land subsidence is not considered as a disaster in the national disaster management law. According to Marfai's [96] analysis on the comprehensive flood management system in Semarang, the government of the city did not provide housing or water alternatives. This finding resonates with what was previously reported by Abidin et al. [53].

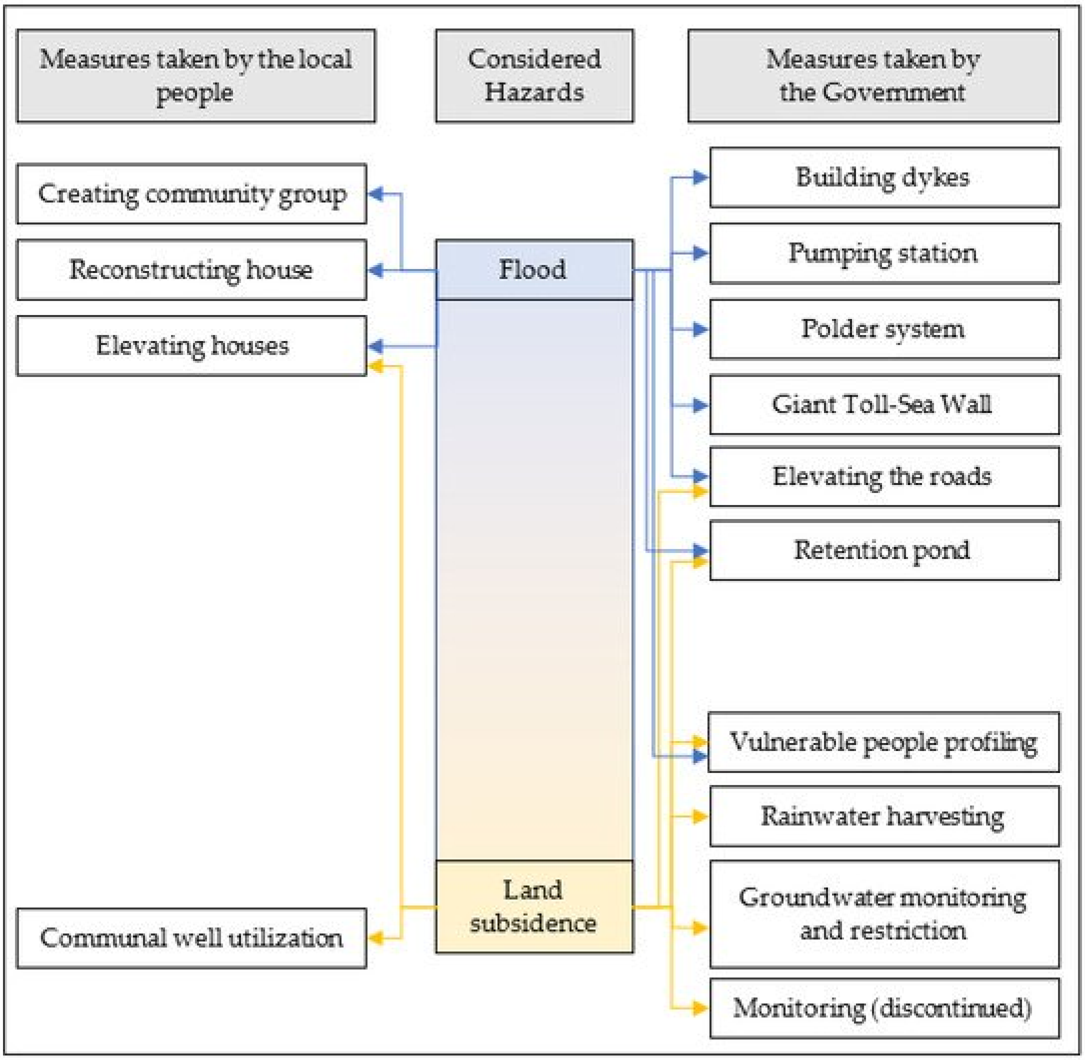

Figure 5. Graphical mapping of measures taken by the government and the people based on considered hazards.

People living in the coastal villages are aware that the tidal flood inundation they suffer from is caused by land subsidence [27][22][115][116][117]. They know the hazards and risks of such a situation, yet they end up adapting to it rather than moving to a safer location due to several reasons [116][118][119]. As mentioned above, affordable housing and water source alternatives are not available. Those who do not have the economic power to obtain housing at a safer location elsewhere have no option but to stay. For some, they refuse to relocate because their livelihood relies on the coastal ecosystem [110][118][119]. Even those with higher incomes are reluctant to move because they do not wish to lose their asset ownership in the subsiding areas [119].

Various strategies to adapt to tidal floods and land subsidence have been reported. Fauziah [120] found that the social and economic capital highly influence people's adaptability. People in tidal flood-impacted areas established community groups (*paguyuban*) to strengthen their social capital [111]. Some people use communal wells to fulfill their freshwater needs [118]. They regularly reconstruct their house, such as making overhead furniture to protect their assets during the flood [110][121][122]. Their perceived ability to adapt, as a result of the belief that they could improve their environment, also pushes them to elevate the position of their house in respect to surrounding grounds [27][111][113]. This has been done at least every five years, as reported by Hadi [111]. People also used trash to build dikes and protect their housing from tidal floods [121].

Critically speaking, these measures are not optimal [123], and may give the false impression of harmony. They could only provide simple, short-term physical solutions that do not necessarily improve the environment [116]. Moreover, measures to elevate the housing grounds create more load to the soil and consequently accelerate the land subsidence rate. This problem is referred to by Saputra [25] as a vicious cycle that the people shall escape. The reason behind it is well-explained by Saharom [124], that people are keen to adapt to the situation, but they are not knowledgeable about ideal housing systems and the use of sustainable and durable materials. The people themselves are aware of such limitations [111].

On the other hand, some people showed a degree of acceptance. They no longer consider tidal floods or land subsidence as a hazard. They believe that tidal flooding is a natural phenomenon that comes from God, and land subsidence is also a natural occurrence that affects everyone in the coastal areas [27].

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