

Review

Progress or Regress? A Systematic Review on Two Decades of Monitoring and Addressing Land Subsidence Hazards in Semarang City

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Abstract: 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. Ample monitoring, adaptation, and mitigation measures have been taken to tackle the impact of such coastal hazards for decades in Semarang City. However, to date, land subsidence still has a negative impact on people's quality of life. This brings us to the question of whether the measures are progressing towards better management or going to the opposite side. This paper is aimed to answer that question through an extensive literature review using PRISMA Guidelines to 125 scholarly articles and quantitative supporting analysis. We found that land subsidence is overlooked. Although the monitoring measures are progressing towards better technology utilization, it was not properly integrated into mitigation and adaptation measures. Instead of investing more on developing better urban water management, groundwater extraction still became the preferred water source. Thus, there is a major shift needed with regard to urban activities that need to pay more heed to the environment.

Keywords: coastal city; land subsidence; Semarang; progress



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1. Introduction

Dealing with land subsidence is a massive challenge. Land subsidence is irreversible environmental degradation [1–5] that threatens the future of a city [6,7]. Unlike any other disastrous event, this silent disaster happened at an exceedingly slow rate so that the impact may only be assessed years after [8–11]. Land subsidence portrays the complexities on how urban activities are not merely affecting the surface environment, but also the subsurface resources, as it is caused by changes in and movement of underground materials [3,7]; most importantly, the over-exploitation of groundwater due to the need for providing water sources [4,11–15]. In low-lying coastal cities, land subsidence might cause the climate-related flood-prone areas to broaden [16–18]. Moreover, land subsidence rates are often higher than global ever-rising sea level [19,20]. Consequently, land subsidence can be contributing to the future submerging of coastal cities, making them uninhabitable [3]. Cities are even more vulnerable when the local government and the people are lacking awareness about the hazards and impacts of land subsidence [11]. This may lead to mistakes in decision-making, and thus the measures taken become ineffective [10].

Land subsidence had become the international concern in the last four decades. The United Nations Education, Scientific and Cultural Organization (UNESCO) held the first international level knowledge-sharing of land subsidence on 1965. To date, the working group is continuing their work on assisting cities to better deal with the consequences of unsustainable land and water utilization through the Land Subsidence International Initiative. The international support is ranging from providing better monitoring data

and research on how to include land subsidence in the flooding estimation until how the governance framework that shall be implemented.

To better deal with this hazard, cities need to make significant commitments to taking proactive measures [21]. Innovative and integrative action, as taken by Shanghai, China on integrating groundwater extraction and recharge monitoring and urban development to develop better land use and zoning policy led them to decrease their land subsidence rates by twofold [14]. In Japan, groundwater extraction restrictions had also successfully halted the subsidence rates as their land was stabilized [22]. Unfortunately, not all cities had the capability to do this.

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 [23], joined the Asian Cities Climate Change Resilience Network (ACCRN) in 2009 [24], and took part in the Water As Leverage pilot project [25]. But this city is still under the threat of being sunk [3,26]. Water needs that have increased by more than 960% since 1910 are not fully met by the local water provider [25]. Consequently, the land subsidence rate is still severe, reaching about 24–36 cm/year through 2014–2017 [22]. An estimation by Sarah [27] 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 [28].

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 [5,17,19,28–32]. 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 [19,33] and integrated analysis [3,34–36] and management [28,37–40], in addition to the involvement of multiple-stakeholders [39]. However, comprehensive discussions on land subsidence in Semarang city are still limited. Abidin et al. [41] 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. [10,26,32] who discussed the government’s awareness and people’s adaptation. Quite similar to this research, Bott et al. [19] 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.

This research is aimed to understand the journey of how the Semarang government, people, and researchers explored improvement in taking such an innovative approach in dealing with land subsidence as well as the challenges and limitations in doing so. Specifically, we aim to address the following questions: (1) Is land subsidence monitoring advancing? (2) Are there any similar understandings that land subsidence is a man-made disaster? (3) What is the public’s and the government’s awareness of land subsidence’s enormous impact on coastal ecological and social system?; and (4) How effective are the adaptation and mitigation measures taken by the government and the people?

The following section contains a detailed description of the research methodology. Then, this article presents the initial insight of the result, including a word cloud analysis. It then takes a deep dive into answering the research question in Sections 3.2–3.4. Some key challenges and problems then discussed in Section 4. Conclusions and some lists of recommendations are then presented in Section 5. Lastly, the references and supporting Appendix A (timeline of land subsidence monitoring studies) and Appendix B (annual subsidence rates monitoring result) can be found at the end of this paper.

2. Materials and Methods

A literature review is useful to assess and evaluate prior studies with the aim of finding gaps in knowledge and to better position the need for further research [42]. To do this, we had to dive into numerous resources that fortunately are stored and provided by various databases. In aiming to minimize the bias in choosing the resources, this research used a systematic literature review method [43]. Not merely that, a systematic review also provides the ability to provide answers and understanding that cannot be answered by individual research [44], which is aligned with the aim of this study. One of the most widely accepted guidelines within the scholars for the systematic review is The Preferred Reporting Items for Systematic Reviews, and Meta-Analyses (PRISMA) Guideline [44]. It was used to guide the literature search and iteration process, identify the systemic synthesis path, and generate the initial point of discussion. The guideline consists of a checklist and framework to help systematic reviewers report the analysis by scrapping previous literature in the online academic database. This guideline is used to guide the researcher in providing complete report in systematic review research. Previously, Oliveira et al. [43] used the guideline to explore the role of strategic planning in solving land degradation. Bielecka [45] applied it to understand GIS-Modelling trends in assessing changes in land use.

A literature search executed in July 2021 was done using the Google Scholar (GS), Scopus, and DOAJ databases. The GS databases from Google Corporation was used because it stores a range of scholarly publications such as journal articles, books, opinion letter, etc., from cross-disciplinary fields of study [43]. The data extracted from GS was then combined with the other two databases. The Scopus database from the Elsevier B.V. was added, as it is also contains a large number of peer-reviewed literature [46]. Lastly, the Directory of Open Access Journals or (DOAJ), managed by Lund University is also used, as it is the largest repository that not only provides reputable articles but also allows the public to access them [47]. The words “land” AND “subsidence” AND “monitoring” AND “Semarang” were used as search queries in those three databases. We obtained only three articles from the DOAJ, 11 articles from Scopus, and 1080 articles were initially identified from the GS. However, as the GS has limitations in being too wide and is sorted based on relevance to the keywords, the search threshold was further scaled down to 150–200 of the best compelling articles as recommended by Haddaway et al. [48]. This resulted in a total of 253 articles, which were systematically iterated based on the following criteria: (i) the study location should include the city of Semarang; (ii) the study should be presented as a full report; (iii) the study should substantially discuss land subsidence; and (iv) the literature should not be a duplicate of other resources (Figure 1). Finally, 125 articles were selected from the process to be further reviewed in this paper.

Three main software platforms were employed to analyze the above articles. Microsoft Excel was used to manually iterate the articles and to visualize quantitative data. Atlas.ti 9.1 was used for computer-aided coding analysis, word cloud generation, as well as code and categorical network development. In addition, Mendeley Desktop 1.19.8 was used as a reference manager. Data visualization was done using Origin 9.1., a software that can create multiple x- and y-graphics.

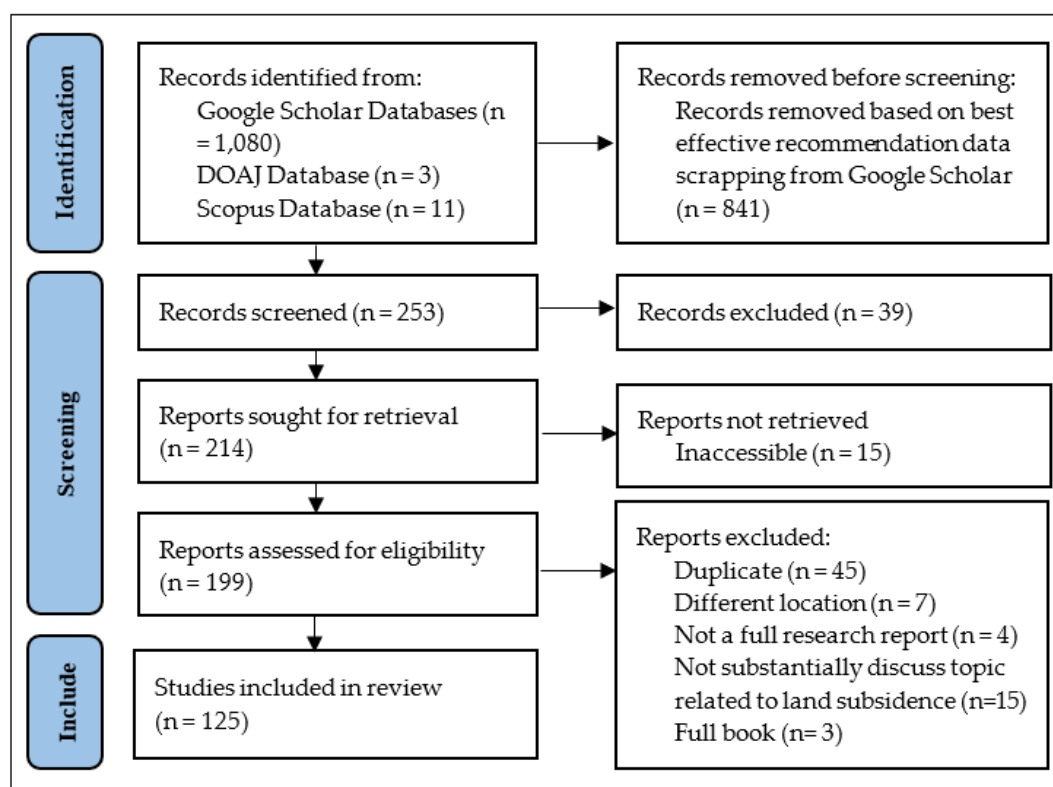


Figure 1. PRISMA systematic review flow diagram showing the process of the literature screening process.

3. Results

3.1. 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%). We also included other academic sources such as theses, reports, and book chapters. According to the year-based tabulation, as shown in Figure 2, 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.

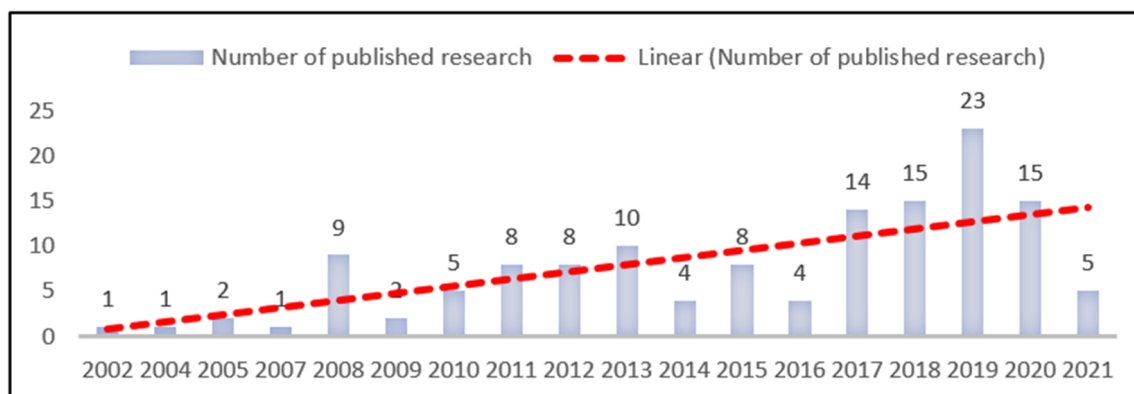


Figure 2. The increasing number of land subsidence research.

Another initial insight was gained from a word cloud generated using Atlas.ti. As shown in Figure 3 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 we 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 3; lower left) is relatively small and comparable to that for “management” and “adaptation”.

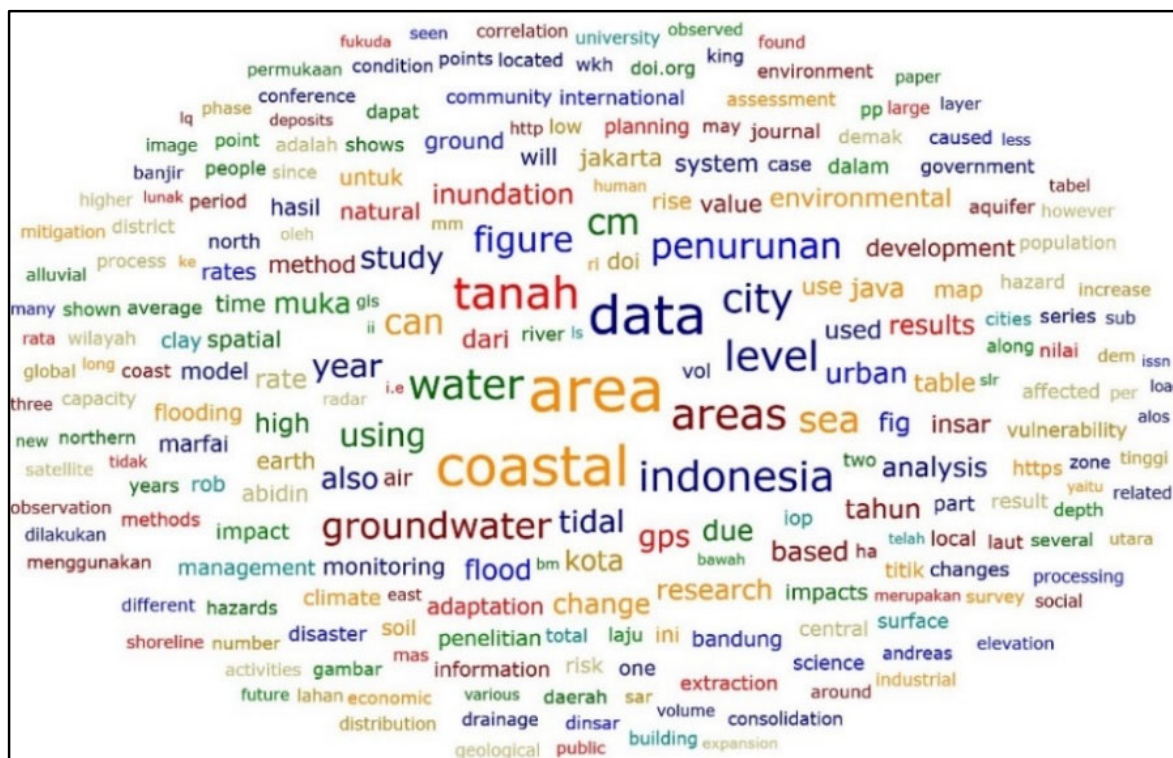


Figure 3. Word cloud generated from literatures reviewed in this paper using Atlas.ti 9.1. Only words with a minimum of 131 mentions were included, while “Semarang” and “Land Subsidence” were excluded from the analysis. Font size indicates frequency of terminology use, in which larger font size shows that the word is mentioned more often in the reviewed papers.

3.2. 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 [1,49,50] by assessing elevation changes over time [2,22] and to estimate future conditions [3,51]. This is also the initial step in mitigating the risk of land subsidence [1,52–54]. Effective monitoring measures is necessary to help developers or individuals to take the best action in adapting to subsidence [8]. Better management of land utilization and water supply could also be achieved [2,3,8,53,55,56].

The most severe land subsidence rates were reported in the northeastern part of the coastal area in Semarang [35,57–65]. According to the spatial estimation, land subsidence occurs in 32.92% of the city area, which is about 128.65 km² [66]. The western part of the city has a relatively lower risk for land subsidence [35,58,67]. 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) [52,61,68,69]; (2) industrial areas [1,70–72]

(Genuk District [4,5,70,73], North Semarang District [4,69]); (3) housing areas [52,70,74]; 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 [60,63]. On the other hand, benchmark data assessed by Suprabadevi et al. [65] showed that the highest accumulative subsidence rate was observed at 33.5 cm in 2008–2011.

As shown in Figure 4, 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.

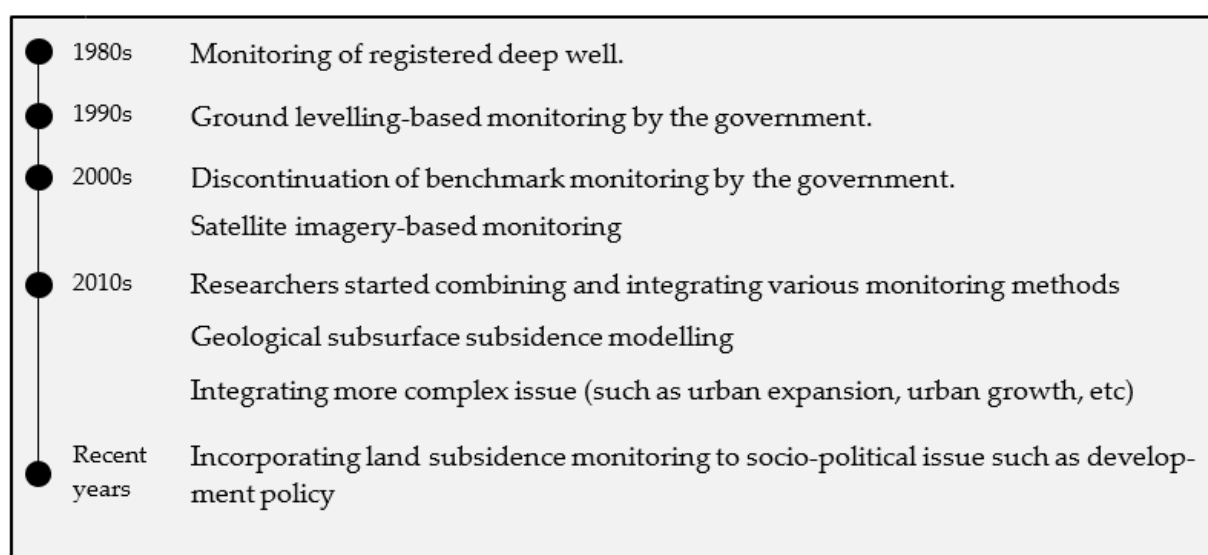


Figure 4. Historical timeline of land subsidence monitoring in Semarang [3,22,25,28,30,36,51,54,75,76].

Monitoring is done in various models that might lead to different results corresponding with different perceived impacts [61,70]. This has the potential to mislead the mitigation and adaptation projects [75]. 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 [63] by comparing digital elevation models between two satellite images [77]. Another method, microgravity, effectively measures subsidence based on geological elevation [78]. The Global Positioning System (GPS) is also a remarkable method [63]. 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 [57]. Others prefer to utilize InSAR as a complementary technique to confirm each other’s results and to test for data reliability [22,60,71,76,79], to confront [34], or merely to highlight any differences [49]. 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 [60,63]. On the other hand, benchmark data assessed by Suprabadevi et al. [65] 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.

3.3. 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 [57] 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 [34,41,49,52,64,77,80–82]. Fakhri Islam [79] and Yastika et al. [22] 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 [41,52,53]. Masvika [83] 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 [7] 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 [84] 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. [85] 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 [86] 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 [22,49], groundwater extraction has increased exponentially since then [87]. Some other researchers argue that land subsidence in Semarang has happened since the early 20th century [50,53,61,87]. The

superimposed analysis, where two or more spatial data are 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 [71]. Research dedicated to assessing the correlation between the decrease in groundwater levels and land subsidence has proven that both variables are highly correlated [2,49,56,88–92]. In areas experiencing severe subsidence, such as Kaligawe and Genuksari, they also possess a deficit in groundwater [17]. Groundwater extraction has increased because local piped water provision companies cannot fulfil the entire city's domestic and industrial water demand [6,13,25,28,93–96]. On the other side, young alluvium sediments where those activities occur have high groundwater potential [29,97]. Land subsidence also induces seawater intrusion, which leads to hydraulic conductivity increments and subsequently increases the subsidence or consolidation rates [98].

Land subsidence is also correlated with urban growth expansion [4,30,54,69,99,100]. Land-use change due to industrial area development has occurred in the coastal areas [86]. 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 [101]. Consequently, this caused water recharge disturbance, an increase in groundwater use, and soil overburdening due to increased building loads [1,3,92]. Urbanization in the form of coastal land reclamation also caused land subsidence [102]. Land reclamation projects led to land progression towards the sea [103]. 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 [104]. Abidin et al. [41] 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 [105] 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 [37].

Although agreeing with the views of other researchers, Kasfari [56] 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 [106]. 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, we could preliminary conclude that land subsidence in the case of Semarang is mainly anthropogenically induced. As also shown in the code-network in Figure 5, the natural process has limited contribution to land subsidence in Semarang. But to understand the impact of manmade activities to the environment, we shall understand how the natural process is going through. The technical practice of this understanding is well presented by Dong et al. [107], who utilizes the geotechnical approach as a control for land use development.

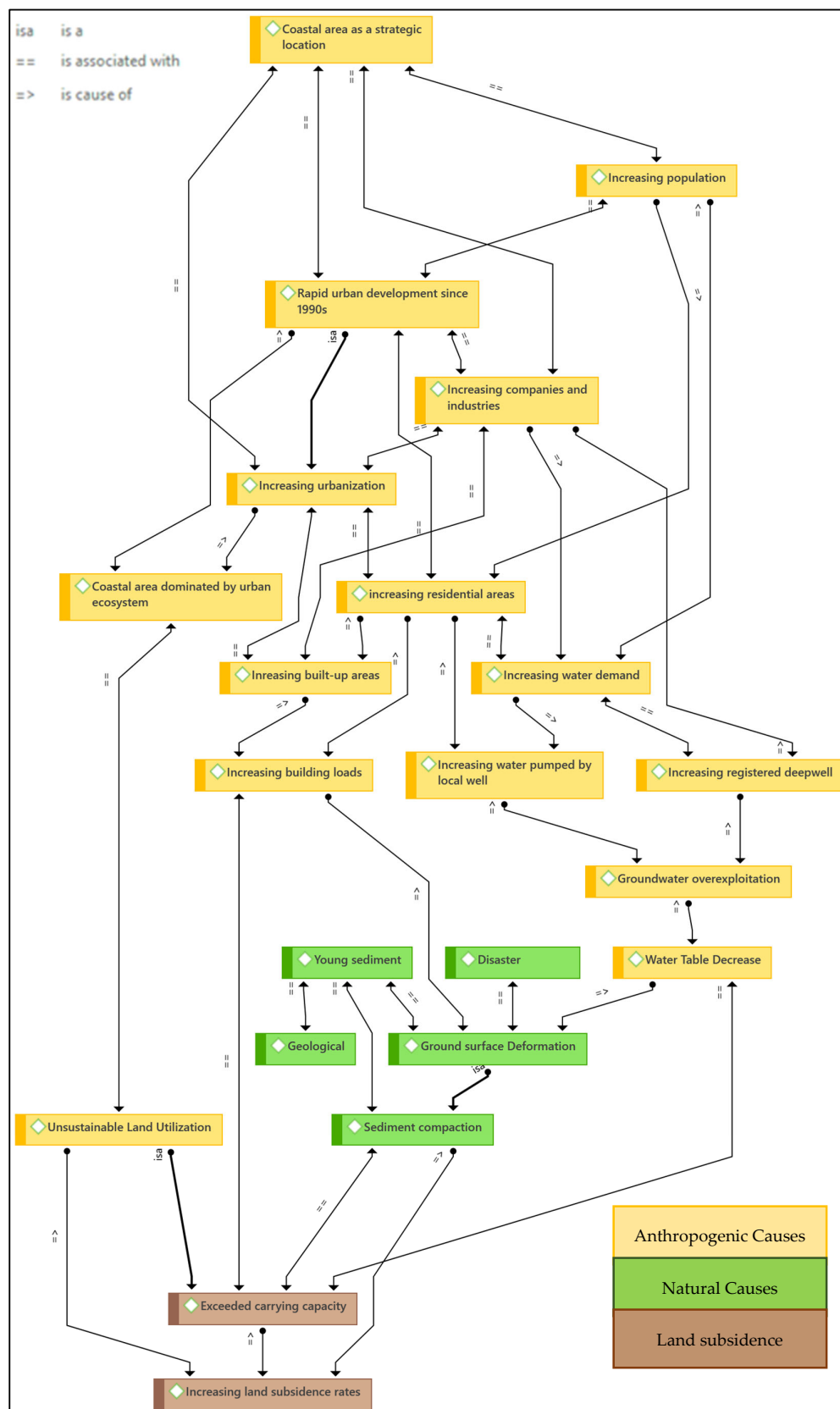


Figure 5. Code-network for the identification of land subsidence causes in Semarang.

3.4. 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 [108]. It also induced erosion, leading to the removal of 1764.5 ha of land in Semarang coastal areas [109]. Suripin and Helmi [109] assessed that the rate of shoreline retreat in 1991–2009 reached 178 m/year. Andreas et al. [63] 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 [33] 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 [27,85,109].

Table 1. Land subsidence impact.

Impact	References
Degrading Environmental condition	
Worsening tidal flooding exposure	[4,8,9,25,29,35,39,41,50,51,63,70,84,108,110–113]
Submerged/loss of land	[4,49,54,63,65,83,109,114]
Changing shoreline	[105,115]
Seawater intrusion	[53,71,101,108,116–118]
Physical Infrastructure Destruction	
Sinking and abandoned house/building	[9,19,76,119]
Damaging building, road, drainage system	[2,8,22,33,76,89,119–121]
Economical Loss	
Increasing cost of maintenance (household and government)	[2,8,118]
Land value decrease	[122]
Property value decrease	[114]
Disruption in economic activities	[62,114]
Worsening Social Quality of life	
Lowering quality of life	[8,19,58,70,72,76,119]
Disrupting local people's day-to-day activity	[26,41,65,114,123,124]
Increasing coastal vulnerability	[2,5]
Increasing harmful sanitation-related diseases such as Malaria, Dengue, Labtoferosis, etc.	[31,52,124,125]

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 [27]. A land value assessment by Utami et al. [122] 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 6, measures taken by both stakeholders are dominated by those that are aimed to tackle coastal flood impact [28,32,102]. 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 [126,127]. 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 [33,124,128]. 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 [40,126–128], the task force working on land subsidence is focused only on monitoring. The spatial planning document does not incorporate land subsidence either [28]. 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 [33] 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. [72].

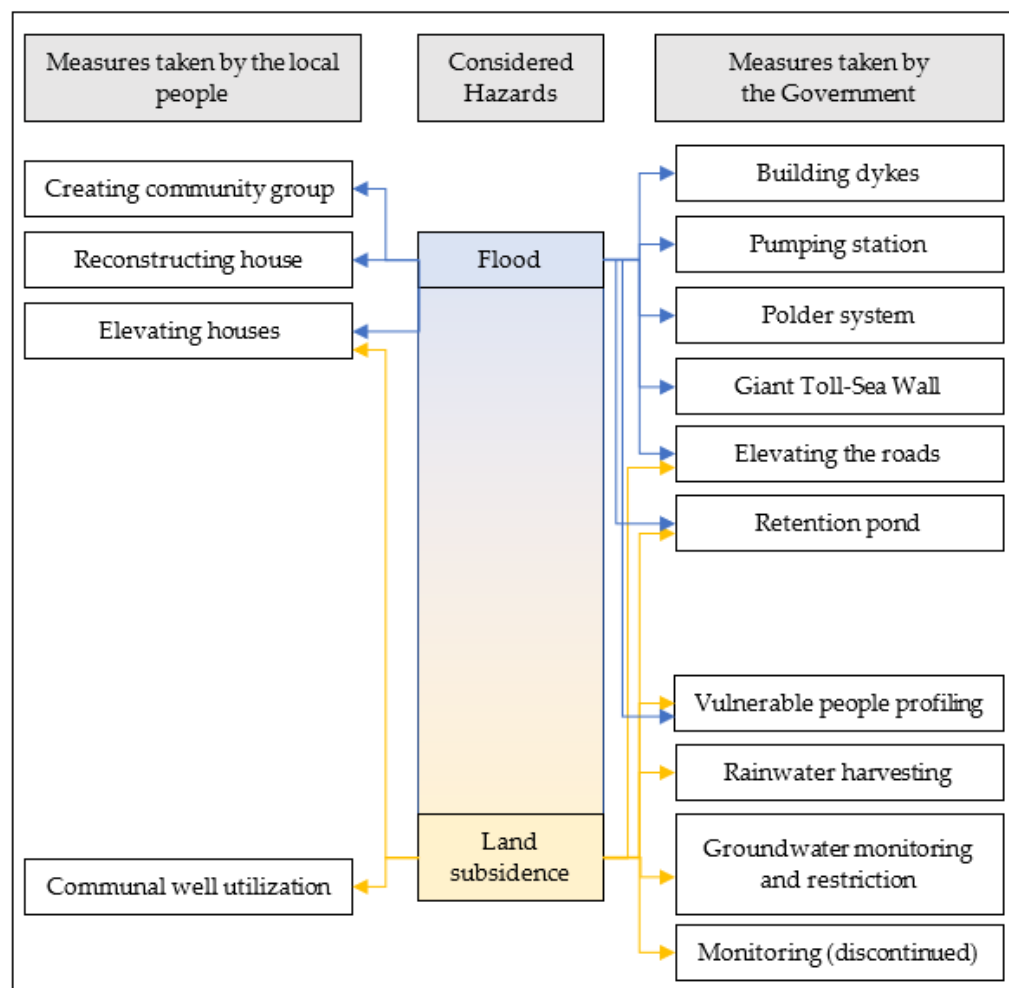


Figure 6. Graphical mapping of measures taken by the government and the people based on considered hazards.

People living in the coastal villages are aware that the tidal flood inundation they suffer from is caused by land subsidence [19,39,127–129]. 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 [128,130,131]. 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 [123,130,131]. Even those with higher incomes are reluctant to move because they do not wish to lose their asset ownership in the subsiding areas [131].

Various strategies to adapt to tidal floods and land subsidence have been reported. Fauziah [132] 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 [124]. Some people use communal wells to fulfill their freshwater needs [130]. They regularly reconstruct their house, such as making overhead furniture to protect their assets during the flood [123,133,134]. 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 [19,124,125]. This has been done at least every five years, as reported by Hadi [124]. People also used trash to build dikes and protect their housing from tidal floods [133].

Critically speaking, these measures are not optimal [135], and may give the false impression of harmony. They could only provide simple, short-term physical solutions that do not necessarily improve the environment [128]. 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 [26] as a vicious cycle that the people shall escape. The reason behind it is well-explained by Saharom [136], 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 [124].

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 [19].

4. Discussion

4.1. The Unprioritized: Land Subsidence Rate Management

If land subsidence management is prioritized, the conversation will shift from how much dryland we could save from coastal flooding to how slow the subsidence rates are. In Tokyo and Shanghai, strategies to tackle subsidence are focused on doing whatever it takes to slow down the rates and to stabilize the land [6,22]. According to the local context, Abidin et al. [120] stated that to slow down or to stop land subsidence, the effectiveness of structural measures to protect from coastal flooding should be increased. The land cannot be brought back to its original condition, but its subsidence rate may be slowed down to an acceptable level (below <1 cm/year) so that the impact will not be as harsh as it is nowadays. Such priority also brings us to the discussion of the ineffectiveness of dykes or other structural constructs [120,133] and the enhancement of geological measurement in assessing land subsidence management progress. Measures taken shall aim for the improvement of the bearing capacity of the subsiding layer of land [137], the elevation of the decreasing water table [138], and the implementation of integrated water management from watershed to the coasts [33].

As reviewed above, people, government, and researchers tend to discuss flood management more intensively rather than to prioritize land subsidence. Land subsidence itself is considered as one of the predictors in mapping tidal flood exposure in a city [109,111,113,139–142], which is also known as comprehensive flood mapping [141]. As subsidence is a complex process, flood estimation is generally based on the average land subsidence rate [126], despite the fact that the range itself is vast. Therefore, there is more to work on to improve flood mapping efforts [119]. From the technological perspective, the official method for subsidence monitoring is yet well-established [22,63]. Effective monitoring techniques should not only rely on the advancement of technology, data, or software used, but they should also be economically feasible, systematic, continuous, and precise [8,22,55].

Saputra [32] assessed that the government and people do not channel their awareness about land subsidence towards actions for adaptation and management. Reflecting on the local people's perspective, they prioritize flood over land subsidence mitigation because they perceive that the impact of land subsidence is moderate and not immediate and thus they do not feel the need to focus on it today [128]. In contrast, tidal flood impact is easily visible and it affects them severely every year [128]. However, if we focus more on tidal floods, the expected outcome will be directed towards expanding dry areas, which is non-achievable in a land area that continues to subside. Prioritizing land subsidence as the root cause of coastal flooding is therefore critical.

4.2. *The Less-Considered: Urban Water Management*

Prioritizing the slowing down of land subsidence rates will drive our focus towards achieving more sustainable water management. This shift is important in managing land subsidence [22,51]. As previously discussed in Section 3.3, anthropogenic stressors play an influential role in causing land subsidence. Consequently, human activity shall be radically changed in order to fully implement this shift. The anthropogenic activity and unsustainable groundwater use, is the only one we could control among other land subsidence causes if there is no other physical intervention to reduce the geological loads and control deformation [63]. The goal is to optimize surface water supply so that both the industry's actors and households do not need to exploit the groundwater. The city could provide a better piping system, prevent further excessive groundwater extraction, and balance the water recharge to decrease subsidence to an acceptable rate. Such practices have previously been successfully implemented to control the rates of subsidence in Tokyo, Japan [22] and to prevent further destruction. Relating to this goal, the government has developed some water policies such as the creation of a tax for groundwater extraction through City Regulation Number 08/2011 and the delineation of a groundwater restriction and limitation zone through Semarang City Regulation Number 02/2013 [32]. Although these policies were established years ago, recent research has found that groundwater levels are still decreasing [52].

The groundwater in the coastal areas is unsuitable for consumption. Based on an assessment by Putranto [143], such groundwater is categorized as critically-damaged and not consumable due to its high salinity and heavy metal contamination. This corresponds with Rahmawati and Marfai [101], showing that coastal groundwater consists of mostly saline water. Due to seawater intrusion exaggerated by land subsidence and groundwater extraction, groundwater salinity had increased by a hundredfold throughout 1998–2005, and by 2050, more than half of Semarang's groundwater is projected to become saline and unsuitable for consumption [101]. Buchori et al. [144] predicted that the seawater intrusion might spread to the city centre. Land subsidence may also cause seawater contamination in surface water, leading to an increase in salinity [101]. Therefore, even though relying on surface water might seem to be the most feasible way to deal with groundwater conservation, the water has to be treated before use [25].

Unlike the industrial sector, domestic users do not require a permit for groundwater use. As shown in Figure 7, the number of consumers of the local freshwater provider company was increased in 2004–2014. This was followed by a stagnancy in 2014 to 2017, after which the number continued to increase. It is a good sign that people are more likely to meet their water needs from sustainable piped water. However, these data do not cover any household or consumer that uses a combination of piped and deep-well water as freshwater sources.

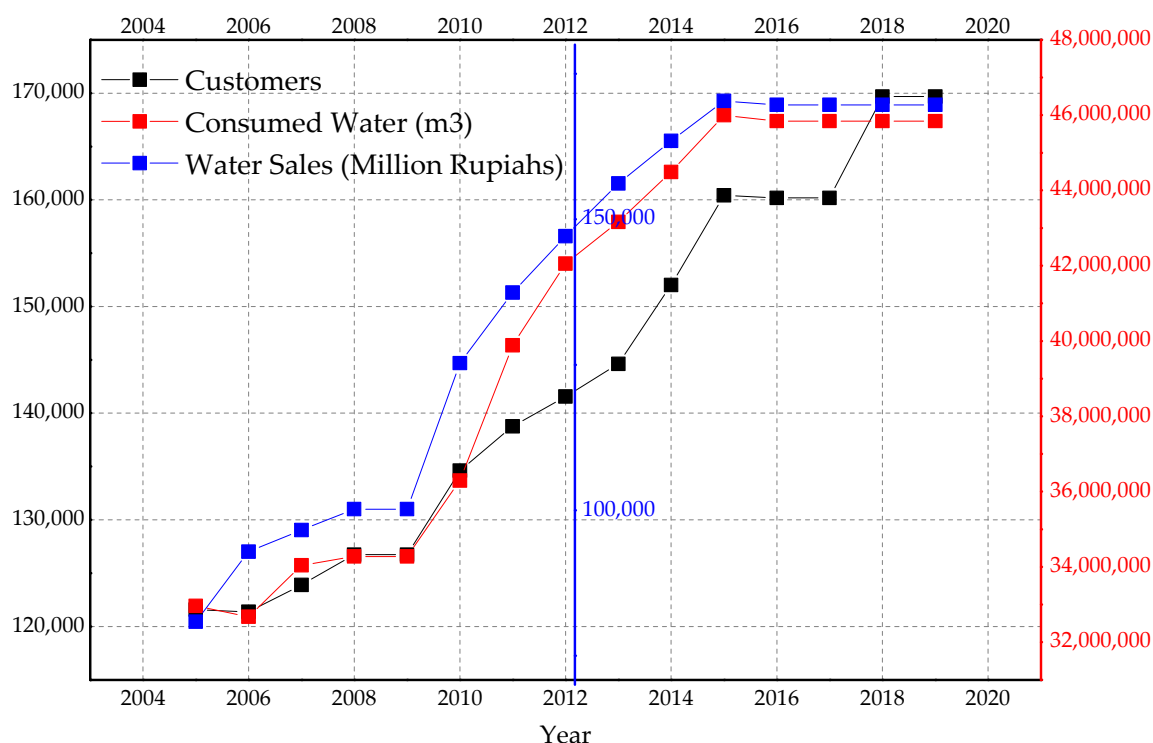


Figure 7. Multi-year trends of water consumption. Source: Bureau of Statistics, Semarang City.

As existing water supply cannot meet water demand [25,145,146], a need to develop a plan for water alternatives is crucial [126]. Unfortunately, this is not an issue that is generally discussed in the literature. Among the reviewed articles, Beek et al. [25] and Hadi et al. [38] were the only ones who discussed alternate solutions to fulfil water demand aside from groundwater extraction. The first article proposed two ideas for water alternatives. The first is the reuse of industrial wastewater for short-term water alternative measures. The second is to develop better water infrastructure to ensure water hygiene. Hadi et al. [38] assessed the use of water retention ponds as fresh water sources integrated with the Giant Sea Wall plan, as well as the measures in reusing surface water through wastewater management, and water source alternative development to cease groundwater extraction. Related to this, the ongoing rainwater harvesting project is had not achieve its maximum potential [97] and its contribution towards reducing land subsidence rates is unclear [32].

On the contrary, the Semarang City Government is still constructing deep wells aiming to provide water for urban residents that is still unreachable by the local water company. As seen in Figure 8, they spent more than two billion rupiah per year (around \$140,000) to create what they called an artificial water spring which is actually a deep well. In the 2013–2014 report, they had mentioned that they are aware that this project might actually give more stress to the land and could possibly worsen the occurrence of land subsidence. They also stated that these wells are not in the restriction zone of groundwater extraction.

Earlier in 2020, PT Witteveen Bos Indonesia released a report about land subsidence assessment under the Netherlands-Indonesia cooperation of water management. This is one of the multiple stakeholder initiative practices in Semarang, as this report is developed by a consortium that comprises Witteveen + Bos, Royal HaskoningDHV, Diponegoro University, TwynstraGudde, and Ellipsis Earth Intelligence. As Semarang is one of their focal study cases, it might be a good sign for the better water management in Semarang as long as the government is willing to fully support this initiative and be ready for a major change in Semarang's water provision and management.

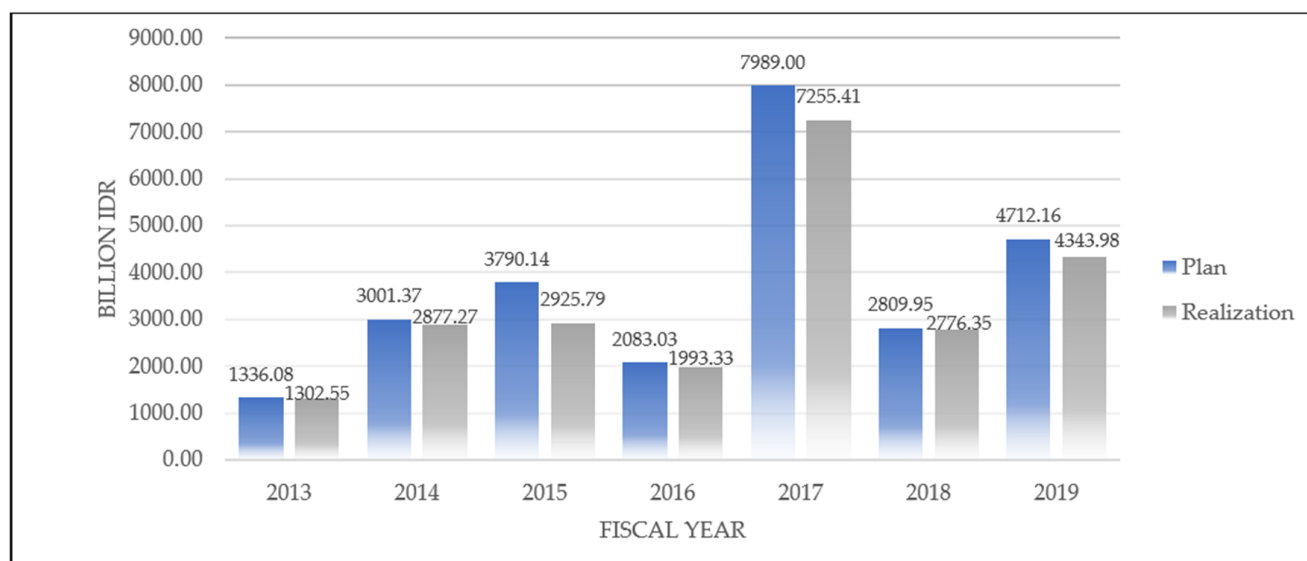


Figure 8. Government yearly spending for deep well construction. (Data taken from Semarang City Mayor’s Accountability report from semarangkota.go.id, accessed on 16 November 2021).

4.3. Problems in Spatial Planning

Spatial planning played an influential role in dealing with land subsidence. In Shanghai, China, measures to control the land subsidence rates included the increment of land use allocation for green belt and green spaces as well as decreasing the amount of the building plot ratio which was mentioned in their urban plan in 2003 [6]. One of the most successful parts of Shanghai’s spatial planning policy that is able to slow the subsidence rates from 12 mm/year to 6 mm/year is the land subsidence zoning policy [6,10]. The success here is proven by a strong combined monitoring assessment between groundwater withdrawal, groundwater recharge, and subsidence rates monitoring. In contrast, Semarang City still had a long way to go to follow this best practice.

Shanghai and Semarang had some relatively similar potential measures to be taken through spatial planning, such as the stipulation of a green zone, the development of stricter and better building regulations, the mandate to integrate strategic environmental assessments in the spatial planning policy, as well as the stipulation of land subsidence zones. In the Semarang City case, there was only the stipulation of a groundwater extraction restriction zone where we found it contrary with our finding mentioned in Section 4.2 where the government is still preferring to extract groundwater to provide water. In the context of a land use zone, there is another dilemma. Coastal areas are considered protection zones, yet at the same time, they are being allocated as reclamation areas [32]. Furthermore, it is of the highest concern that land subsidence is not a priority and not fully accommodated in spatial planning policies [32]. The monitoring results alone are not yet accommodated into environmental impact assessments as an accompanying document for every planning policy. Content analysis by Hamdani et al. [28] showed that land subsidence rates are incorporated well enough in the environmental assessment document. The problem is how these data are articulated in the policies. There are no specific measures in tackling land subsidence. This type of disaster is not yet considered as a disaster, as reported by the expert team on Land Subsidence for the Coordinating Ministry of Maritime and Investment Affairs in the Republic of Indonesia. Consequently, it is no surprise that the policy does not accommodate the land subsidence and any other potentially derived hydro-meteorological hazards [144].

Monitoring measures shall be integrated into decision-making to tackle uncertainties and rapid changes in this era. Researchers still dominate the monitoring process at the moment. Our review showed that there is an abundance of researchers voluntarily dedicating their time to assess the current, past, and future subsidence rates in Semarang. On the other side, the government had taken a path in defining land subsidence in Semarang. Instead of making it public as any other monitoring measure, the result of continuous monitoring had not been published from the 1980s to date [22], and no data is available publicly for research purposes [144].

5. Conclusions and Recommendations

Dealing with land subsidence is not easy work. As it is a slow onset disaster, realizing its occurrence is already a huge task to undertake. Monitoring measures dominated by researchers are actually progressing towards technology advancement. In addition, there were also enough intensive empirical evidence-based discussions to conclude that the land subsidence happens in Semarang is human-induced. Unfortunately, those facts are overlooked. The monitoring result is not being incorporated into related policies or programs. Contradictory actions are still found in tackling land subsidence rates, such as restricting groundwater extraction but still using it as the source for water provision, as well as still stipulating that the subsided area is not welcome for new development. Adjusting urban activities and land utilization, which are most important in tackling this anthropogenic subsidence, are still progressing nowhere. On the other hand, although the people had such a great social capital potential, but it is not followed by proper support financially and politically. Thus, false harmony is bringing them progressing backwards by unknowingly bringing their area more vulnerable to future subsidence.

Dealing with land subsidence understood as the implication of unsustainable development then needed a paradigm and a practical shift. In the policy area alone, Indonesian regulations, where the study case policy is referred to, need to shift in regard to define what is considered as a disaster. Future planning and development of coastal cities shall respect the dynamics of submerged land induced by land subsidence. We have listed some room for improvements in planning in Table 2. In the context of monitoring, city officials and researchers could start to find out the accumulative subsidence. The decision-making process shall accommodate land subsidence data in an exemplary manner and shift political interests towards a belief in sustainable development. Future work is needed to understand reliable pathways for creating better water management and land use policies that correspond with current challenges relevant to land subsidence. There is a need for further research that is focused on primary data, such as by interviewing stakeholders and understanding current discussions on the incorporation of land subsidence into spatial planning policies.

Table 2. Room for improvements in spatial planning.

Potential	Current Problems/Issues/Challenges	Room for Improvements
Progress in developing comprehensive coastal spatial planning [33]	Land subsidence (and any other coastal hazards) is rarely incorporated in spatial planning [19,28,32]	Designating land subsidence prone areas in the spatial planning policy [69]
	Some vulnerable areas are dedicated as land reclamation development areas [32,37]	Stipulating no-development zones/limiting the development or regarding the deteriorating coastal areas as conservation zones [19,69]
	Lack of access to land subsidence data [2]	Developing interactive and transparent platform for land use planning [32]
	Lack of monitoring [72,102]	

Table 2. Cont.

Potential	Current Problems/Issues/Challenges	Room for Improvements
Increasing urbanization (population, housing, and industries)	Land use mapping has not been successfully used to control activities in subsiding areas [126]	Strengthening law enforcement [40]
	Land loss due to permanent flood or coastal erosion [2,3,54,63,83,102,108,127]	Developing fair land compensation mechanism
	The housing boom that relies on groundwater [1,54,70,103]	Controlling housing/real estate development [82]
	Groundwater crisis [73]	Regular monitoring and reporting on land-use change impact to the environment [40] by optimizing the use of geospatial data [9] Shift to proactive planning [69]
	High urban surface loads [9,19,92]	
	Unsustainable land use change [30,54,60,69,101,103]	
High participation in relevant initiatives [33,39]	Toll-road development that will potentially increase future urban development [147]	
	Temporary adaptation [40,72,133]	
	Unintegrated embankment development that worsens flooding [108]	
	Ineffective mitigation [72,102]	

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Appendix A

Recapitulation of yearly subsidence rates monitored by various methods and studies. At early stage, technical methods such as using Benchmark (a pipe-sized concrete) is used to monitor the rates. As technology development were arising, researchers started utilizing satellite imagery. Despite that high-tech method are more promising, researchers continue to use conventional ways, such as GNSS, to compare and prove the reliability of their data.

Table A1. Recap of 30 years of Land subsidence rates observation.

Monitoring Period		Observed Rates (cm/year)		Method	Ref
Start	End	Min.	Max.		
1996	1984	8.1	n/a	Benchmark data	[3]
	1991	2.4	0.7	Benchmark data	[3]
	1993	5.9	2.4	Benchmark data	[3]
	1997	16.5	0.7	Benchmark data	[3]
2005	2006	11.33	0.267	Benchmark data using Geodetic point (TTG)	[61]
2002	2006	>15	<1	Stable points network (SPN) technique Friedrich using Synthetic Aperture Radar satellite images	[2]
2003	2007			DInSAR	[22]
2007	2008	15	n/a	InSAR	[50]
2007	2008	11	3	DInSAR	[77] *
2007	2009	15	n/a	Benchmark data; Static survey using DGPS trimble SR 20	[70]
2008	2009	0.8	13.5	GPS surveys	[50]
2007	2009	8	0	InSAR	[1]
2002	2009	15	1	Numerical method (Terzaghi)	[53]
2008	2009	12.4	1	GPS	[65]
2008	2009	8.1	n/a	DInSAR	[60]
2007	2009	14.13	0.78	DInSAR	[81]
	2009	107	8.4	1D Terzaghi	[82]
	2009	103.7	17	PLAXIS	[82]
2008	2009	13.5	n/a	GPS	[41]
2007	2010	8	n/a	DInSAR	[59]
2009	2010	20.4	0	GPS	[65]
2009	2010	9.9	n/a	DInSAR	[60]
2009	2010	18.7	n/a	GPS	[41]
2007	2011	32	0.5	DInSAR	[57]
2007	2011			DInSAR	[22]
2010	2011	10.5	0	GPS	[65]
2008	2011	33.5	1.6	Benchmark data	[65]
2008	2011	11.2	0.53	Benchmark data	[65]
2010	2011	10.7	n/a	GPS	[41]
2013	2015	13.935	0.835	GPS Analysis of MIT	[64]
2010	2015	3.4	0.4	Benchmark data	[58]
2011	2015	15.4	0.2	GPS	[58]
2008	2016			GPS	[63]
2015	2016	20.91	0.77	DInSAR	[79]
2015	2016	13.7	3.4	GPS	[49]
2014	2017	4.5	0	PS-InSAR	[88]
2014	2017	4.5	0	PS-InSAR	[34]
2015	2017			DInSAR	[22]
2016	2017	18.3	0.3	GPS	[49]
2016	2017	10.239	0.422	PS-InSAR -Stanford Method of Persistent Scatterers (StaMPS)	[80]
	2017	0.3	0.03	Microgravity	[148]
2017	2018	19.1	0.1	GPS	[49]
2015	2018	15.8	0.1	Small Baseline Area Subset (SBAS)	[66]
2015	2018	6.753	0	PS-InSAR	[62]
2018	2019	7.796	1.795	GNSS	[68]
2017	2019	12.1	n/a	DInSAR	[35]
2017	2019	12.7	0	DInSAR	[52]

* Only covered Kaligarang faulty area.

Appendix B

Timeline of land subsidence monitoring studies analysed in this paper. Only one study used forecasting approach Marfai and King [3], whereas majority of land subsidence monitoring research is focused on monitoring and reviewing current or past conditions.

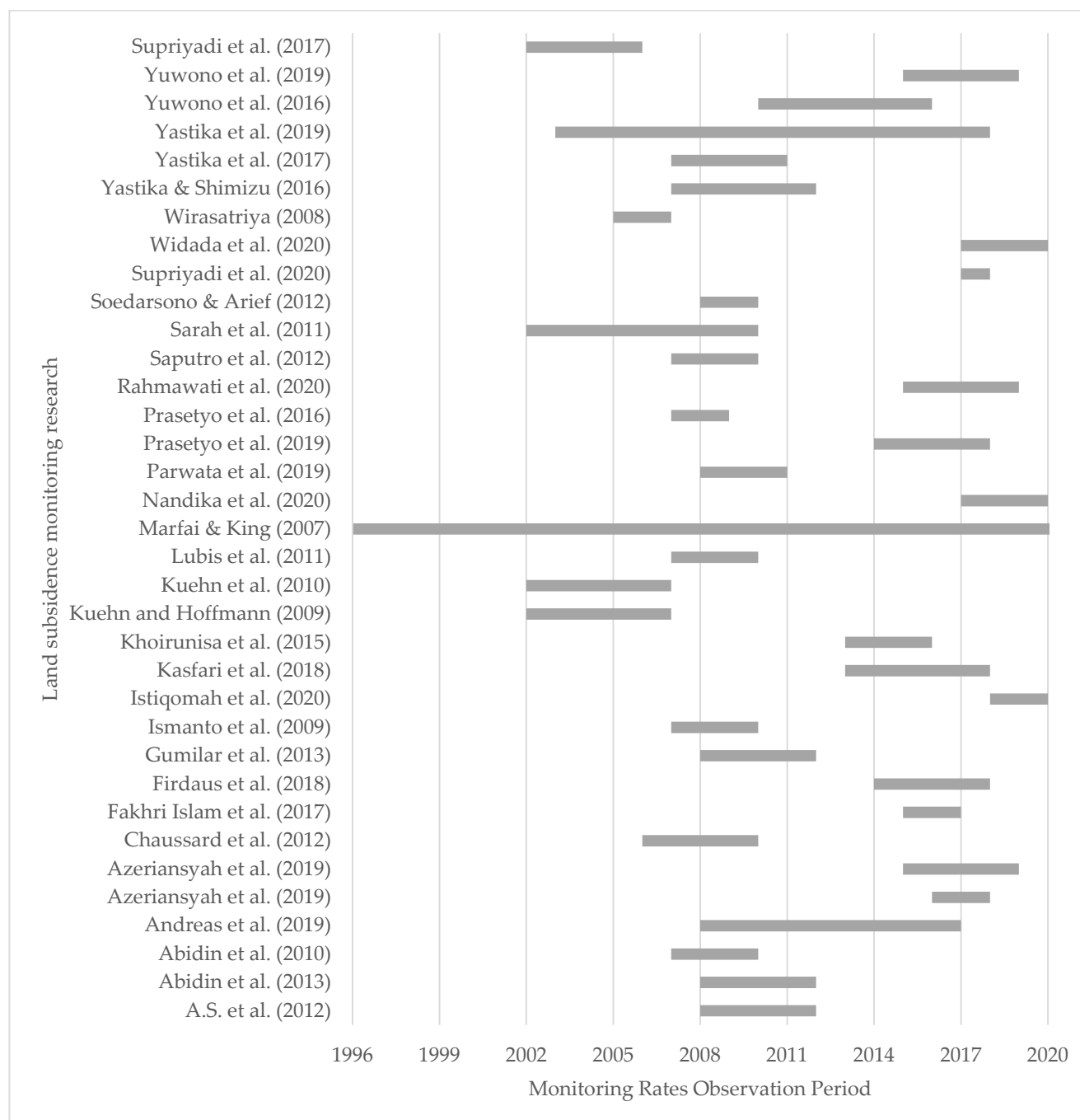


Figure A1. Land subsidence monitoring observation timeline [1,2,4,22,41,50,52,53,56–59,61–68,70,74,77–82,88,89,148].

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