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Towards sustainable land subsidence mitigation in Semarang and Demak, Central Java: Analysis using DPSIR Framework

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Abstract: The Semarang-Demak plain has experienced intense human intervention over the last 40 years, thereby causing land subsidence. This study aims to assess long-term conditions in the study area using the drivers-pressures-state-impacts-response (DPSIR) framework to mitigate land subsidence. Methods include analysis of land subsidence, socioeconomic, surface, and subsurface data, as well as spatial analysis. Results show that rapid population growth and economic activities are major driving forces, manifesting as pressures exerted from overexploitation of groundwater, increasing building and infrastructure loads, and decreasing non-built areas. Groundwater overexploitation reduced the artesian pressure in the 1980s, forming depression cones of the groundwater level from 5 to 30 m below mean sea level. From 1984 to the present, the constructed areas have increased more than tenfold, with Semarang City possessing the most densely built area. Based on our findings, we propose responses consisting of surface water utilization, spatial building regulation, and rigorous groundwater and land subsidence monitoring. Moreover, we encourage the strengthening of law enforcement and inter-sectoral management to ensure the successful land subsidence mitigation.

Keywords: coastal area, driver-pressure-state-impact-response (DPSIR), land subsidence, mitigation, response, Semarang-Demak plain

INTRODUCTION

Integrated environmental evaluation to support decision-makers regarding policy-making and management measures is an important task. Analyses using the driver-pressure-state-impact-response (DPSIR) framework have been widely accepted for modelling an environmental problem that leads to appropriate management response [Sekovski *et al.* 2012]. Coastal areas are the home to approximately 600 mln people (around 7.7% of the world's population) and host megacities across the world [UN 2017]. Coastal areas are attractive for occupancy due to their low-lying topography, fertile agriculture at river deltas, rapid physical development, and more; however, these areas are highly susceptible to environmental problems [Neumann *et al.* 2015; Syvitski 2008]. The DPSIR framework has been used previously to address various environmental problems in the coastal areas, including land subsidence, degradation of groundwater supply and quality, seawater intrusion, increased flooding, poor sanitation, and other urbanisation related problems [Jago-On *et al.* 2008; Kaneko, Toyota 2011; Karageorgis *et al.* 2006; Mattas *et al.* 2014].

Semarang City and Demak Regency are coastal cities in the Central Java Province that have become urban development centers on the north coast of Java. This area is part of the main corridor for the national economic development scheme in the Masterplan for Acceleration and Expansion of Indonesia Economic Development, year 2011–2025. The Semarang-Demak coastal plain has been known to experience land subsidence since the 1980s, and it continues presently at an alarming rate [Abidin *et al.* 2013; Rahmawan *et al.* 2016; Widada *et al.* 2020a]. The land subsidence has caused enormous physical and economical effects, such as increased flooding, destruction of buildings and infrastructure, constant costs for infrastructure repairs, and the degradation of the community's health quality and welfare. Due to the significance of this study area, providing immediate solutions to land subsidence problem is crucial, which requires integrated environmental assessment to support the regional planning and management.

There have been numerous studies on land subsidence and its social aspect on the Semarang-Demak region [HAMDANI *et al.* 2020; MARFAI *et al.* 2007; WIDADA *et al.* 2020b]; however, those studies were often presented as separate entities. Nevertheless, decision-makers require an integrated point of view that presents a simple yet comprehensive representation. To answer this immediate need, the DPSIR framework is applied to optimise management of the Semarang-Demak coastal plain and develop a useful aid for the local stakeholders to implement a scientifically sound policy. We propose a set of measures and actions toward sustainable development and land subsidence management in the Semarang Demak coastal plain using on science-based findings. The DPSIR framework is used in this paper to: (1) assess the environmental drivers, pressures, and the current state; (2) identify impacts and; (3) recommend the appropriate response to the land subsidence problem.

Land subsidence is lowering of the earth's surface that can be caused by natural and anthropogenic causes or a combination of both. Natural subsidence can be caused by the natural compaction of sediment, dewatering of organic soils, and tectonics, while the anthropogenic drivers of subsidence are predominantly caused by the excessive withdrawal of groundwater and addition of surface loads (e.g., high rise buildings) [CUI, TANG 2010; DOKKA 2006; GAMBOLATI *et al.* 1999; HOLZER, GALLOWAY 2005; KOOI 2000]. Essentially, the land subsidence problem relates to changes in surface and subsurface conditions. Data collection for this study includes subsurface studies on the engineering and hydrogeology of Semarang Demak coastal plain to determine the vulnerability of the subsurface units to subsidence while identifying exploitable groundwater aquifer units. Groundwater withdrawal data, land subsidence rate monitoring, land-use changes, and socioeconomic data are also investigated. Based on these factors, the DPSIR framework was applied, and appropriate measures for land subsidence management are proposed.

STUDY MATERIAL AND METHODS

STUDY AREA AND SUBSURFACE CONDITION

This study takes place in the Semarang-Demak plain, which located on the north coast of Java at coordinates 6.87 to 7.03°S and 110.37 to 110.69° E and, covering an area of approximately 335 km^2.

The study area occupies a large coastal plain composed of alluvial deposits of gravel, sand, silt, and clay of Holocene age, bordered by the Quaternary volcanic hills and Tertiary sediment at the south, as shown in the geological map (Fig. 1). VAN BEMMELEN [1949] noted that muddy sedimentation in Semarang-Demak occurred at least 500 years ago. The silting up of the Semarang-Demak plain still occurs, as revealed from the advancement of the shoreline from 1695 [VAN BEMMELEN 1949; MARFAI *et al.* 2008; TOBING *et al.* 2000].

The alluvial deposit covering the Semarang-Demak plain lies unconformably on top of the Damar formation of volcanic

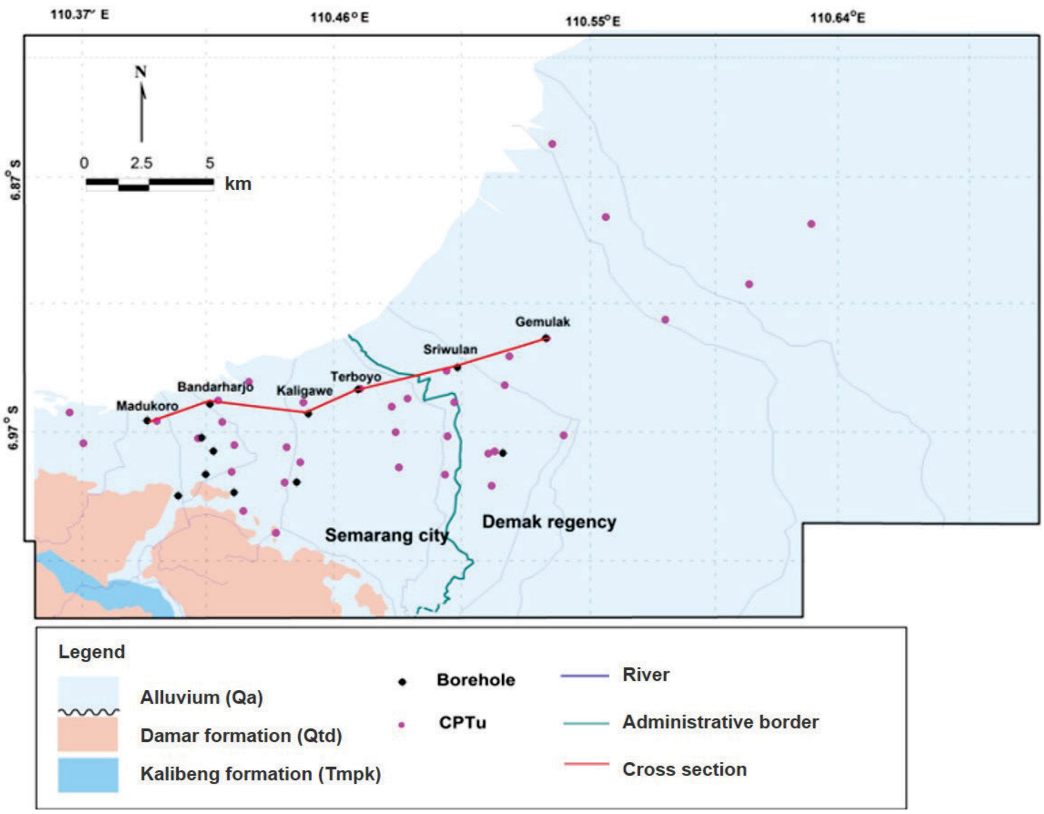

Fig. 1. Geological map of Semarang-Demak plain; source: THADEN *et al.* [1996]

breccia, conglomerates, and sandstone [THADEN *et al.* 1996]. The thickness of the alluvial deposit ranges from 5 to 130 m, varying spatially from south to north by becoming thicker towards the north coast (Fig. 2). The bulk of the alluvial deposit in the subsurface condition consists of thick calcareous and shell-bearing clay intercalated with thin lenses of sand [VAN SCHAECK MATHON 1975]. The Semarang-Demak clay has a notably high compressibility and possesses active clay characteristics, making it prone to subside under its own weight [SARAH *et al.* 2018]. A typical cross-section of the study area subsurface is depicted in Figure 2.

Figure 2 shows that the subsurface of the study area is dominated by thick compressible clay with sand and gravel intercalations, with a built environment at the surface. The land use at the surface is mostly built areas of office buildings, housing settlements, and industrial estates. The water-bearing layers in the subsurface comprise the Quaternary deposit aquifer (Qa) and the Damar formation aquifer (QTd) [PUTRANTO, RUDE 2016], as shown in Figure 2. The Qa system consists of clayey sand, fine to coarse sand, and gravels; these are sandwiched between shelly plastic clay as the aquitard, while the QTd consists of water-bearing rocks from a volcanic origin.

The intensive land use on the surface inevitably requires water; as such, when the surface water supply is inadequate, groundwater exploitation is expected. Previous geodetic surveys carried out in Semarang-Demak show the occurrence of land subsidence on the order of 1.0 to >10 $cm \cdot y^{-1}$, and overall subsidence of 20–150 cm over the period of 2008–2016 [ABIDIN *et al.* 2013; ANDREAS *et al.* 2019; CHAUSSARD *et al.* 2013]. This silent disaster of land subsidence attributed to the ongoing compaction of the recent alluvial deposit, which consists of thick compressible clay, to the overpumping of groundwater, and to the loads of buildings.

DRIVERS-PRESSURES-STATE-IMPACTS-RESPONSE ANALYSIS SCHEME

The DPSIR framework is adapted to assess the environmental condition in the Semarang Demak region to develop the appropriate mitigation measures to tackle land subsidence impacts. Despite several criticisms on the applicability of DPSIR, this framework remains the simplest means to understand the cause-effect dynamics of the environmental system [CARR *et al.* 2007; GARI *et al.* 2015; MATTAS *et al.* 2014]. The DPSIR framework is adapted based on the explanation from KRISTENSEN [2004]:

- driver: anthropogenic activities resulting from human and societal needs could affect environmental conditions, such as urbanisation, population increase, and economic growth;
- pressures: the results of driving forces exerting pressures on the environment. In this study, the pressures include: i) groundwater overexploitation, as marked by the rapidly declining piezometric level, ii) changes in land use;
- state: the state of the environment is affected as a result of the pressures; the environmental state in the study area comprises the vulnerable alluvial deposit (dominated by a thick, soft compressible clay layer) that has been pressurised by groundwater overexploitation and changes in land use; the state of the clay layer is quantified as the thickness of the soft clay layer and its overconsolidation ratio (*OCR*);
- impacts: the state changes bring about environmental or economic impacts, such as land subsidence, increased floodings, in building and infrastructure damage, and more;
- response: a set of measures taken to reduce the impacts and repair the current state.

A brief illustration of the DPSIR framework for the Semarang-Demak coastal plain is presented in Figure 3, showing the cause–effect relationship of the environmental system. It also shows that responses must be based on sound socio-economic and natural conditions and directed to all aspects, from the driving force to the impacts.

DATA COLLECTION AND ANALYSIS

Available data related to the economic growth and population were collected from the local and central authorities as well as relevant references. Data evaluation was performed to identify the driving forces of the land subsidence. Further data in this study comprises hydrogeological data, subsurface profile, and engineering properties collected from land subsidence and hydrogeological investigations in Semarang-Demak during the period of 2000–2017 as well

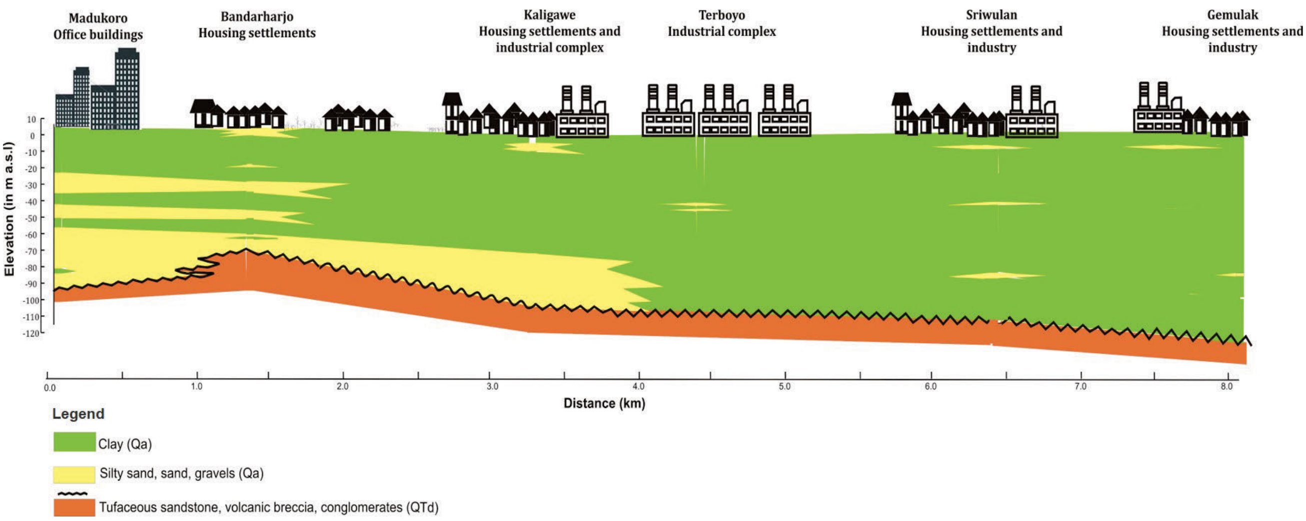

Fig. 2. Typical cross-section of Semarang-Demak subsurface; Qa = the Quaternary deposit aquifer, QTd = the Damar formation aquifer; source: own elaboration

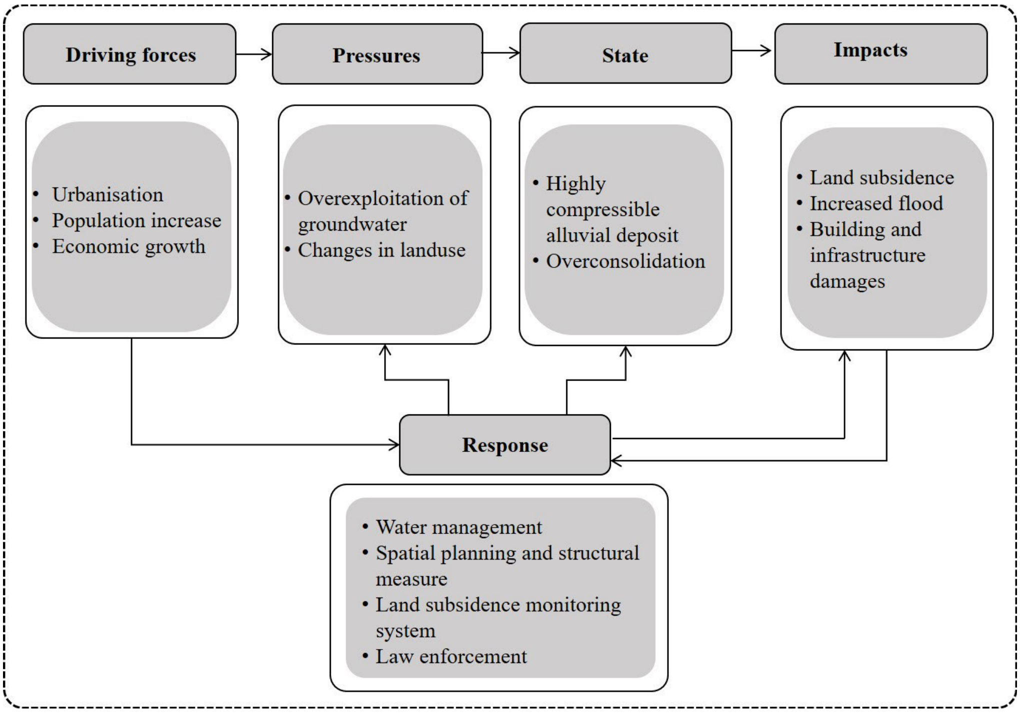

Fig. 3. Scheme of DPSIR framework for land subsidence problem in the Semarang-Demak coastal plain; source: own elaboration

as other relevant reports and references prior to 2000 and more recent sources. Hydrogeological data of groundwater usage and piezometric levels were used to analyse the environmental pressure caused by groundwater resource exploitation. Land use changes resulting from rapid economic and population growths were analysed from multi-temporal satellite imagery (from 1986 to 2016) from Google Earth. Increases in built area and diminishing open-spaced area were quantified from digitising of the Google Earth imageries with a geographic information system package.

To understand the state of the subsurface condition, an analysis was performed using borehole and cone penetration test (CPTu) data collected during previous land subsidence investigations by the authors. From 13 boreholes and 34 CPTu data collected, the distribution of boreholes and CPTu locations in the study area are provided in the geological map (Fig. 1). A previous study pointed that the upper clay layer in the study area is highly compressible and prone to subside due to its weight [Sarah *et al.* 2018]; this phenomenon is further exacerbated by increased loadings from buildings and groundwater exploitation. We characterise the consistency of the cohesive layer (i.e., clay) using the classification from standard penetration test (SPT) *N*-value that categories the clay layers from very soft to a hard consistency (Tab. 1).

SPT tests were performed at each borehole, and the equivalent SPT value was conveniently estimated from CPT data using an empirical formula from Robertson [2006], as the following:

$$\frac{\frac{q_c}{p_a}}{N_{60}} = 8.5\left(1 - \frac{I_c}{4.6}\right) \quad (1)$$

where: q_c = the cone tip resistance (MPa), p_a = the atmospheric pressure (MPa), N_{60} = the equivalent SPT *N*-value at 60% hammer energy (number of hammer blows to penetrate 30 cm of soil), and I_c = the soil behaviour type index.

Table 1. Correlation of standard penetration test (SPT) *N*-value with clay consistency

Consistency	SPT *N*-value (blows·0.3 m^{-1})
Very soft	0–2
Soft	2–4
Medium	4–8
Stiff	8–15
Very stiff	15–30
Hard	>30

Explanation: *N* = number of blows.
Source: Bell [2007], modified.

Naturally, the layers with very soft to soft consistencies are the most susceptible strata to subsiding. To elucidate the spatial distribution of the soft clay layer, soft clay thicknesses are mapped to show the vulnerable state of the subsurface.

The state of the alluvial clay deposit is responsive to changes from the groundwater pressure from the deep aquifer, and to surface disturbances, such as building and reclamation loads and surface dewatering prior to development. The clay property, namely its overconsolidation ratio (*OCR*) [Day 2009], allows the characterisation of the soil's stress history. The *OCR* is the ratio between the past effective stress (also known as preconsolidation pressure) to the present effective stress:

$$OCR = \frac{\sigma_p}{\sigma'} \quad (2)$$

where: σ_p = the preconsolidation ratio (kPa) and σ' = effective stress (kPa).

An $OCR < 1$ occurs when soil is considered under-consolidated given existing overburden pressure (e.g., when the soil has undergone rapid deposition and not enough time has elapsed to consolidate under its own weight). An $OCR = 1$ occurs when the soil has never been subjected to a vertical effective stress greater than its existing overburden. An $OCR > 1$ happens when soil has been subjected to a disturbance or previous vertical effective stress greater than its existing vertical effective stress. The recent soil deposit has an $OCR \leq 1$, indicating under-consolidation or normal consolidation.

Overconsolidation can be caused by changes in total stress, pore water pressure, or soil structures [Day 2009]. Total stress change can be caused by removing overburden or past structures. Pore water pressure change can result from deep pumping of aquifers, changes in the phreatic groundwater table, and desiccation. Soil structure changes can be caused by chemical alteration and environmental changes. *OCR* values are calculated using consolidation tests on undisturbed samples from boreholes; they were also estimated from CPTu measurements during land subsidence investigation dated 2014–2017. The distribution of *OCR* values represents change imposed by pressures (e.g., declining piezometric level and increasing built area) to the state of the alluvial clay. By analysing the driving forces, pressures, and state of the Semarang-Demak coastal plain subsurface, it is possible to relate the impacts using their root causes and propose appropriate measures. The rate of land subsidence in Semarang-Demak is evaluated from previous reports and references on land subsidence monitoring.

RESULTS

DRIVING FORCE

The coastal plain of Semarang-Demak has attracted urbanisation. The city began to expand due to increases in industrialisation and economic growth. Semarang City, as the capital of the Central Java Province, has the largest population in the study area of 1.7 mln as of 2017. According to the Central Statistical Agency [BPS 2021a, b], the population of Semarang and Demak exhibited an increasing trend of 1.03–1.09% over the period of 1990–2017 (27 years; Fig. 4).

Figure 4 shows that Semarang City is more populated than Demak Regency, as urbanisation is more intensive in the city than in the Demak suburb. The population density in Semarang City is 4,289 people·km^{-2} while Demak Regency has 1,271 people·km^{-2}. The increasing population growth has caused a significant urban expansion, including economic development. The fast economic growth is equivalent to increasing consumption, investment, industrialisation, physical development, and many more activities that drive pressures to the environmental system. Here, we define the economic growth as the gross regional domestic Product (GRDP) that sums up the economic condition based on all activities in a specific region. GRDP data was obtained from the Central Statistical Bureau (BPS) of Semarang City and the BPS of Demak Regency [BPS 2021a, b], and it was taken as GRDP value at current market prices (Fig. 5).

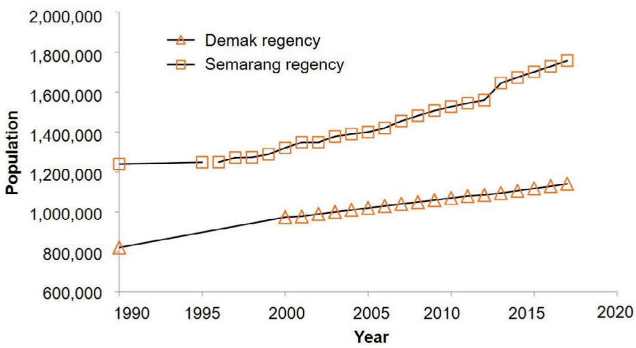

Fig. 4. Population of Semarang City and Demak Regency (1990–2017); source: own elaboration based on BPS [2021a, b]

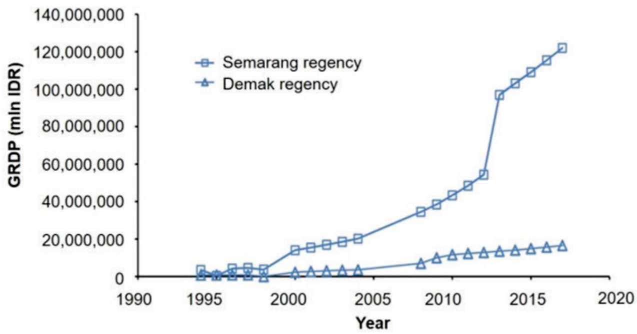

Fig. 5. Gross regional domestic products (GRDP) at current market price in Semarang City and Demak Regency (1994–2017); 1 mln IDR = USD67.20; source: own elaboration based on BPS [2021a, b]

Figure 5 shows that the GRDPs of Semarang City and Demak Regency differ significantly, with the recent GRDP of Semarang City equalling about seven-folds that of Demak Regency and its economy is accelerating much faster. The driving force exerted by economic activities in Semarang City is much higher than that of Demak Regency, which is reflected in the pressures exerted on the environment. The latter are explained in the next section.

PRESSURES

Pressure from groundwater exploitation

Inadequate surface water supply has led to the extensive use of groundwater. Two types of aquifer systems exist in the study area: unconfined and confined aquifers. The unconfined aquifers are of limited quantity and readily replenished by precipitation; making their depletion negligible. The most exploited groundwater comes from confined aquifers; in the study area, the confined aquifers consists of the Quaternary deposit aquifer (Qa), and Damar formation aquifer (QTd) [Putranto, Rude 2016]. The increased groundwater extraction in the study area is represented by a significant rise in the numbers of registered wells tapping confined aquifers and the volume of groundwater extraction in Semarang City after 1980 (Fig. 6). Figure 6 also indirectly shows that city development started to increase after 1980 and accelerated fast from 1990 to 2006.

Major groundwater users in Semarang are the domestic, commercial, government, and industrial sectors. Figure 6 shows the recorded volume of groundwater extracted from 1900 to 2006. Significant increasing groundwater extraction were observed from 1990–2006; the groundwater extracted increased at the rate of 3.37 mln m^3·y^{-1} over the that period. There are no published records of groundwater extraction volume after 2006, with fewer monitoring measure taking place. While the volume of water extracted from different sectors has not been revealed, the high demand for

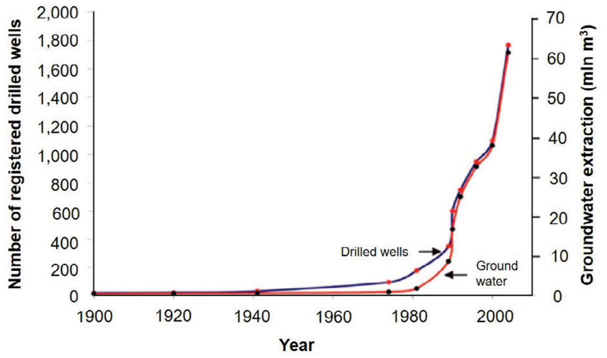

Fig. 6. Development of registered groundwater extraction and number of drilled wells in Semarang City; source: MURDOHARDONO [2007]

groundwater led to overexploitation, causing the piezometric level of the confined aquifer to decline. Monitoring of groundwater levels from 1950 to 2017 showed those levels declining in Semarang City and Demak Regency (Fig. 7), allowing the relative contribution of groundwater usage in each sector to be inferred.

Well monitoring in Semarang City is represented by wells in Pelabuhan, Tambaklorong, and PRPP, while the Demak Regency is represented the Gemulak well. The Pelabuhan well is located in the port of Semarang, surrounded by industrial areas, while the Tambaklorog well is located in a dense housing settlement, the

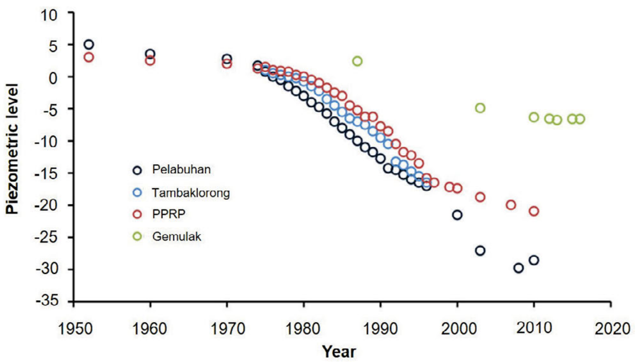

Fig. 7. Piezometric levels in Semarang City and Demak Regency; source: own elaboration based on MARSUDI [2001] and TAUFIQ [2010]

PRPP well is located in a combination of settlement, commercial, and government areas, and the Gemulak well is located in a sparse housing settlement. Figure 7 shows that from 1950 to 1976, artesian pressure existed in Semarang City aquifers. During 1977 to 1980, the piezometric levels in Semarang City started to decline; the rate of decline in Pelabuhan, PRPP, and Tambaklorog wells was 1.2, 0.29, and 0.33 $m \cdot y^{-1}$, respectively. From 1981 to 1996, the piezometric heads were rapidly declining at the rate of 0.87 $m \cdot y^{-1}$ for the Pelabuhan, 1.02 $m \cdot y^{-1}$ for the PRPP, and 1.0 $m \cdot y^{-1}$ for the Tambaklorog. After 1996, a fast piezometric drop was seen in Pelabuhan well from 1997 to 2010 (0.81 $m \cdot y^{-1}$), and a slower rate was observed for the PRPP well (0.34 $m \cdot y^{-1}$). The monitoring well in Tambaklorog was discontinued after 1996.

In Demak Regency, monitoring data shows that artesian pressure existed in 1987; after that, the piezometric head gradually declined until 2010 at the rate of 0.38 $m \cdot y^{-1}$. After 2010, the groundwater monitoring in this well was carried out by the Central Java provincial government. The monitoring results showed that the piezometric head was declining at the rate of 7 $cm \cdot y^{-1}$ from 2010 to 2016. Analysing the piezometric-level decline in Semarang and Demak areas shows that the fastest decline occurred in industrial area, followed by the mix of settlement, commercial, and government areas, dense settlement, and sparse settlement. We deduced that the industrial sector is the major user of groundwater. Industries residing along the Semarang-Demak north coast consist of textile, steel, plastic, paper, and food manufacturers [BPS 2019]. Due to limited monitoring, the type of industry consuming most water remains undetermined. Due to changing laws and authorities, the central government (represented by the Indonesian Geological Agency – Ind. Badan Geologi) has ceased groundwater monitoring since 2010. Many of the monitoring wells have been discontinued, and groundwater monitoring is currently carried out by the provincial government to a lesser extent; therefore, it is difficult to obtain recent data.

Despite the limited recent data, spatial distributions of piezometric heads from different time series can be illustrated using data from 1984 and 2010 (Fig. 8), showing that the earlier piezometric heads in Semarang City decreased markedly (by contour values of less than 0 m MSL) and small piezometric head

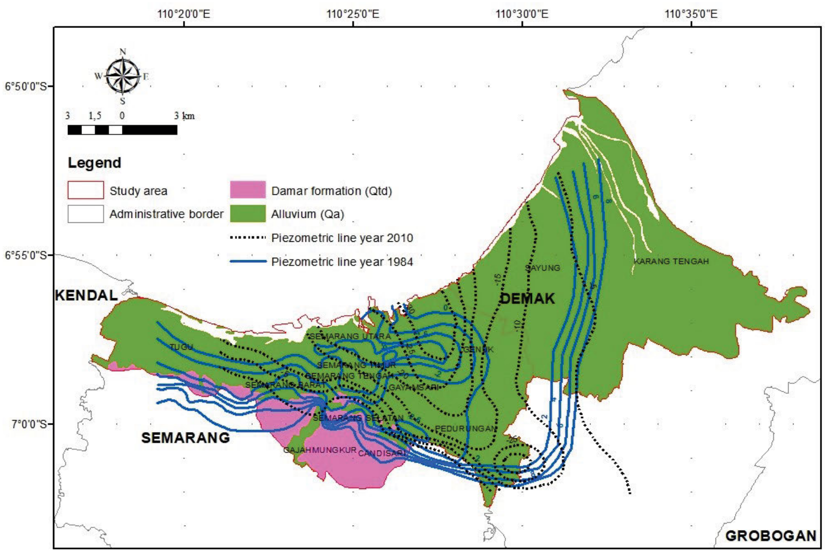

Fig. 8. Piezometric contours of the confined aquifer in 1984 and 2010; source: TAUFIQ [2010]

depressions began to form in the area. Meanwhile, the piezometric heads in the eastern part (Demak Regency) were positive in 1984, indicating free flow (artesian) wells existed. Piezometric levels in Semarang City were very low in 2010, with contours showing values of 15 to 30 m below MSL. Figure 8 shows the development of a greater area of groundwater cone that covers almost all of Semarang City's alluvial plain. In Demak Regency, the piezometric head observed in 2010 shows less decrease compared to that in Semarang City. Figure 8 indicates that groundwater exploitation pressurised the subsurface environment in Semarang and Demak, while greater pressure was exerted in Semarang City.

study area; these decreased to 77.76% in 1994. The open land and vegetation continued to decrease, reaching 55% of the study area in 2021. It can also be seen that the development of constructed areas increased significantly, going from 3.47% of the total study area in 1984 to 39.10% in 2021. Figure 9 clearly shows that the majority of the construction took place in Semarang City. As the unbuilt area decreased, development of the newly constructed area pushed towards the eastern part belonging to the Demak Regency administration.

Figure 9 also indicates that intensive development started in the 1990s, as marked by the expansion of the constructed area in all directions. In 2004, the development of the constructed area

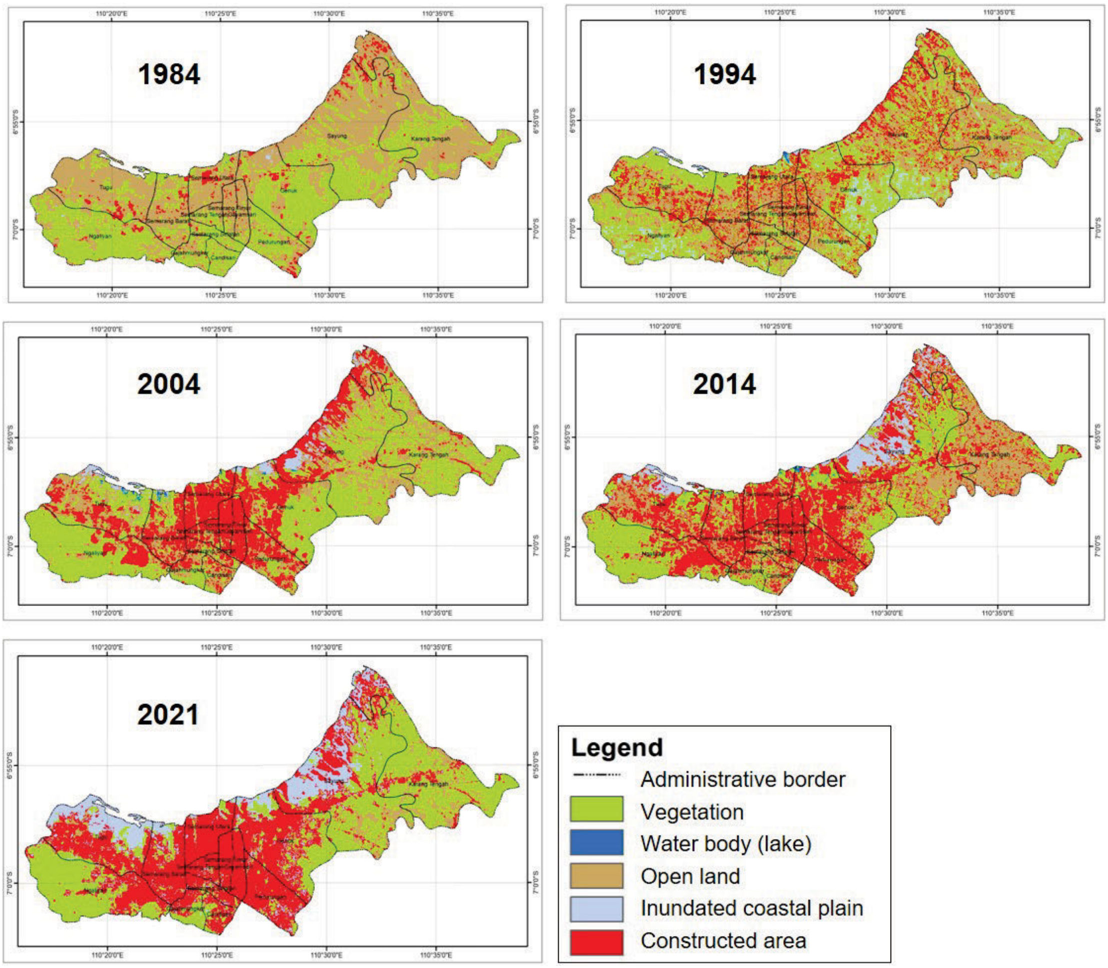

Fig. 9. Changes in land-use in the study area; source: own study

Pressure from changes in land use

While groundwater represents the pressure that originated from the subsurface condition, the changes in the surface condition also pressured the environmental condition leading to land subsidence. Vast development and population growth pressured changes in land use, with more built areas being required to accommodate increasing activities. Unbuilt areas are represented by land uses of vegetation, open land, water body, and coastal plain. Land use changes in Semarang City and Demak Regency from 1984 to 2021 are presented in Figure 9 and Table 2.

Figure 9 and Table 2 show that, from 1984 to 1994, the land use in the study area is dominated by open land and vegetation. In 1984, open land and vegetation made up 96.26% of the total

Table 2. Land use changes in Semarang-Demak plain

Land use	Area (km^2) in				
	1984	1994	2004	2014	2021
Vegetation	121.85	114.07	116.84	77.11	106.70
Water body (lake)	0.05	0.26	0.91	0.75	–
Open land	200.72	146.50	119.31	116.01	46.55
Inundated coastal plain	0.86	19.58	8.45	23.59	50.83
Constructed area	11.61	54.55	89.52	117.59	131.02

Source: own study.

was expansive towards the northeast coastal plain, yet in 2014, the density of the constructed area in the north-east decreased due to inundation. Coastal inundation is thought to have resulted from the combined effect of sea-level rise and land subsidence. In 2014, the inundated coastal area accounted for 7.04% of the study area, increasing to 15.17% in 2021. This twofold increase of inundated area is seen in the northwest and northeast of the coastal plain.

The limited space available for regional development could put more pressure on the study area. As Semarang City is running out of unbuilt area, further physical development is to be directed toward the east (i.e., the border area between Semarang City and Demak Regency), as stated in the Spatial Planning Regulation of the Semarang City No. 11, for the year 2011–2031 [Peraturan Daerah … No. 14]. This policy potentially increases pressure on the Demak Regency region.

State

The state of the Semarang Demak subsurface, based on engineering and hydrogeochemistry properties, is discussed in detail by Sarah *et al.* [2018; 2020]. As depicted in Figure 2, the upper clay layer is responsible for the land subsidence hazard in the study area, as its thickness and engineering properties are prone to large settlements. To illustrate the current state of the subsurface, a map of the thickness of soft compressible clay thickness is presented in Figure 10.

Figure 10 shows that the thickness of the clay layer in the upper part of the subsurface varies from 20 to more than 50 m thick; however, Figure 10 shows the thickness the upper part (i.e., the soft clay having *N*-SPT value of 0–4, indicating very soft to soft consistency, Tab. 1). The soft clay consistency indicates low bearing capacity and the ease of the subsurface to subside. Figure 10 shows that the soft clay thickness in Semarang City varies from 0 to 16 m. Soft clay is not found at the southern part of the Semarang City, as the clay layer near the Damar rock formation is of medium to hard consistency, while at the north part, zero thickness of soft clay layer corresponds to the absence of clay at the upper part (i.e. sand layer exists). Generally, in Semarang City alluvial plain, soft clay is thickest at the north near the coast and becomes less thick toward the south. A similar tendency is found in Demak Regency, but the soft clay layer is much thicker here (11 to 25.5 m thick). From the south alluvial plain towards the north coast of Demak Regency, the soft clay layer contour increases from 11 to 17 m, and at the northeast, the soft clay layer is the thickest (22.0 to 25.5 m). Figure 10 indirectly indicates that the northeast of the study area has the lowest bearing capacity, making it most prone to subsidence under anthropogenic pressures.

The state of the alluvial clay deposit is known to be affected by changes in piezometric groundwater level and loading conditions. The distribution of *OCR* values (measured during 2014–2017) is presented in Figure 11, showing that most of the *OCR* values in Semarang City range from 1.5–4.7, indicating overconsolidation has occurred. The high OCR contours of 3.3–4.7 are found in the south Semarang alluvial plain, and *OCR* contours of 2.1–3.5 are found in the north Semarang. The high *OCR* values represent that the clay has been overconsolidated due to the high piezometric level drop in that area (Fig. 7) and due to the increased density of the built area (Fig. 9). In west Semarang, the clay layer is overconsolidated to a lesser degree (*OCR* 1.1–2.3), which correlates with the lesser piezometric drop (Fig. 7) and sparsely built area. An *OCR* value of less than one occurs in the west at an unbuilt area, indicating a possibility of no groundwater overexploitation.

Toward the east to the Demak regency, *OCR* values are seen to decrease to less than one, implying the clay is under-consolidated. Underconsolidation means the soil is subject to compaction due to its own weight or natural compaction. Correlations between Figure 7 and 9 indicate the lack of influence from the disturbances due to groundwater overexploitation and spatial development. Although the land subsidence in Demak area currently has a lower rate compared to that of Semarang

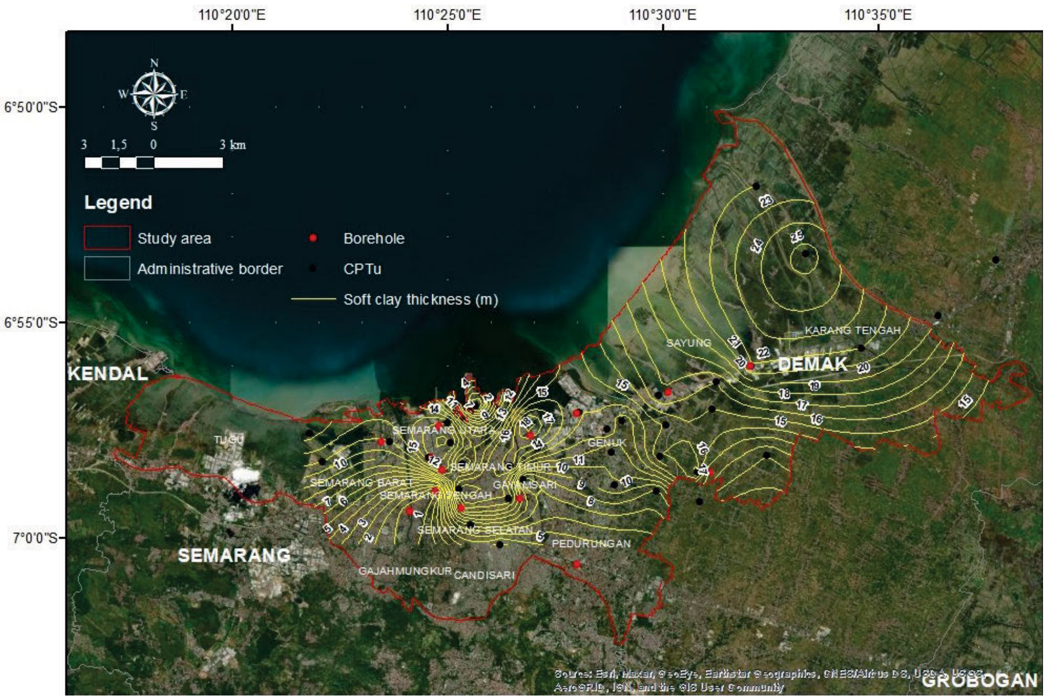

Fig. 10. Map of soft clay thickness in Semarang-Demak plain; source: own study

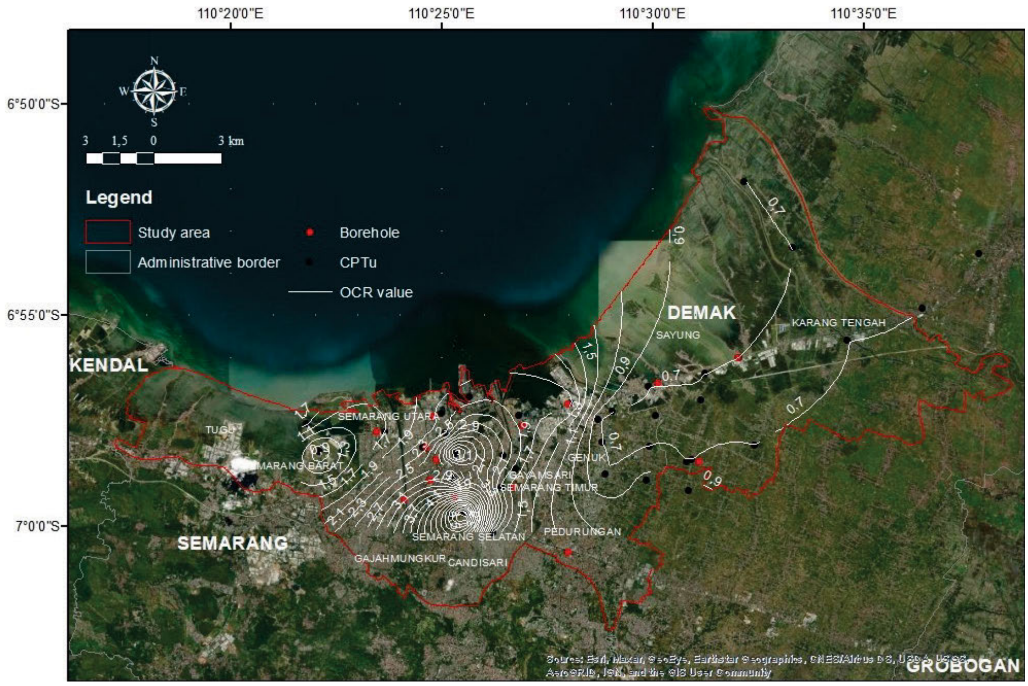

Fig. 11. Map of overconsolidation ratio (*OCR*) of Semarang-Demak clay; CPTu = Cone Penetration Test with pore water measurement; source: own study

City, future development in Demak regency must be carefully considered. As the soft clay layer is thicker in the Demak area, groundwater overexploitation and built area increases will have a more intense impact on the subsidence rate.

IMPACTS

Impacts are related to the surface manifestations caused by the drivers and pressures. The most evident impact is land subsidence, followed by secondary impacts of increased flooding and damages to buildings and infrastructures. Land subsidence in Semarang City has been monitored using various methods of levelling [MARFAI, KING 2007], Global Positioning System GPS [ABIDIN *et al.* 2013], and synthetic-aperture radar SAR interferometry [CHAUSSARD *et al.* 2013; LUBIS *et al.* 2011; WIDADA *et al.* 2020b], while the land subsidence rate in Demak Regency has rarely been measured. Previous monitoring in Semarang City resulted in a similar land subsidence rate of 0–15 cm·y^{-1}. Monitoring by SIDIQ *et al.* [2021] captured the land subsidence rate in the whole study area, Semarang City and Demak Regency (Fig. 12), showing that the

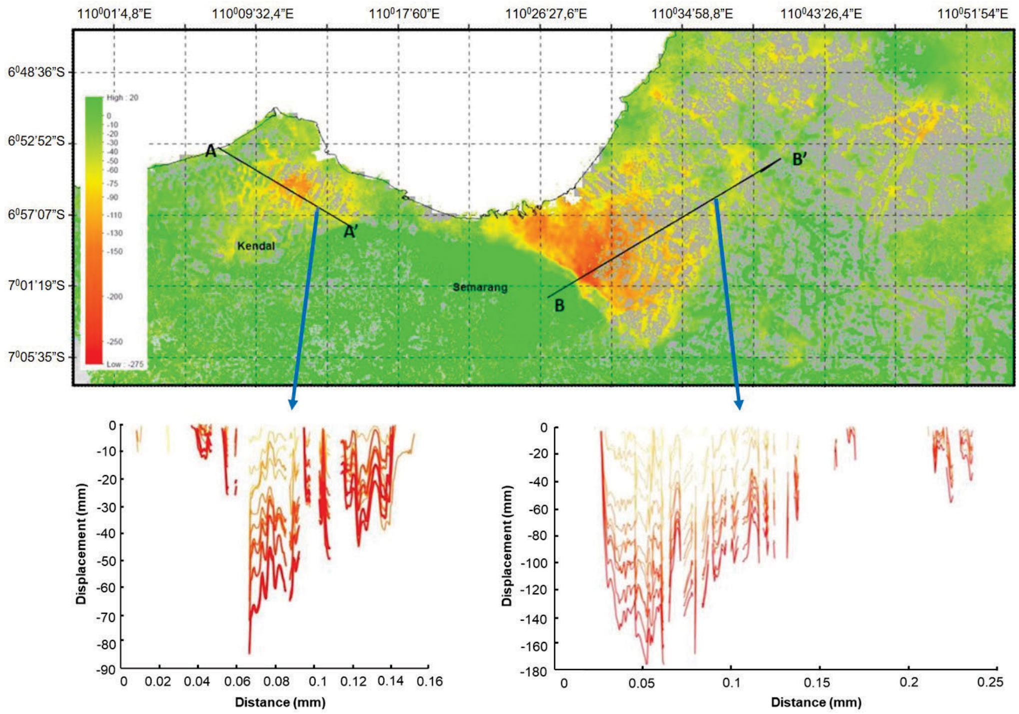

Fig. 12. Land subsidence rate in study area; source: SIDIQ *et al.* [2021]

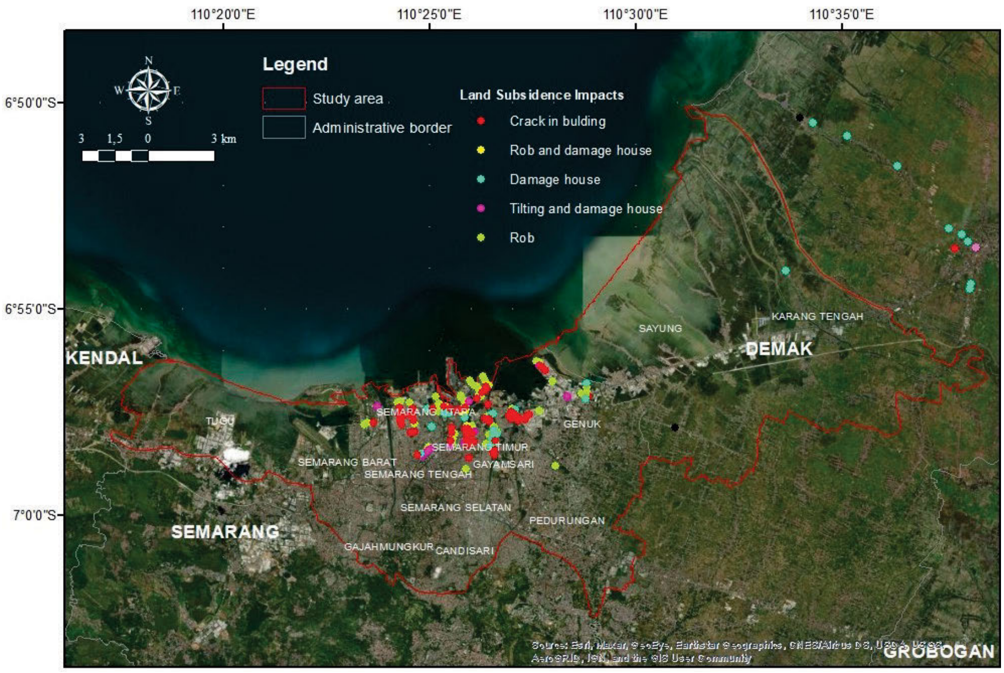

Fig. 13. Distribution of land subsidence impacts in Semarang Demak plain; source: Abidin *et al.* [2013], and field observations

land subsidence rate is highest on the north coast and lower toward the east, west and south, except near B section of in the Mranggen area of Demak Regency that corresponds to its industrial complex. Generally, the land subsidence rates in the study area range 0–3 $cm·y^{-1}$ in the northeast Demak coastal area to 3–9 $cm·y^{-1}$ along Semarang north coast.

Secondary impacts of coastal flooding were widely observed in the study area along with damage to buildings and infrastructures, as presented in Figures 9 and 13. There were two types of flooding in the study area: seasonal flooding during the rainy season and the tidal flooding. The recent flood, caused by high rainfall intensity in 23–26 February 2021, paralysed the entire city, affecting 90,590 people and submerging 9,169 houses in flood water levels approximately 10–75 cm [ReliefWeb 2021]. Flooding due to tidal inundation (known by locals as "rob") is a regular disaster experienced in the study area during high tides. Increased inundated land is evident in the north Semarang and northwest Demak coasts, causing many buildings and settlements to be flooded permanently and abandoned [Andreas *et al.* 2017; Widada *et al.* 2020a]. Figure 13 shows spots that experience regular intermittent flooding, while Figure 9 and Table 2 indicate the increasing permanent flooded area (over 1984–2021) mainly due to tidal inundation. Land subsidence aggravates the tidal inundation, causing many areas to be continuously flooded. Figure 9 shows that the flooded area extends inland at the northwest and northeast parts of the coastal plain. Spots that suffer regular flooding are located in Madukoro, Kaligawe, and Terboyo, hindering daily mobility and economic activities.

Mapping and surveying of the damages to buildings and infrastructures were carried out by Abidin *et al.* [2013], Putra *et al.* [2020] and the authors of this paper. Putra *et al.* [2020] classified infrastructure damages as light, moderate, and heavy, including cracks in tilted and subsided structures, walls, and foundations, Light damage corresponds to up to 10% of main structures and 30% of supporting components, while moderate damage encompasses up to 40% of the supporting components and 50% of the main structures, and the heavy damage corresponds to building collapse or greater than 60% of main structures failure.

Cracks in buildings and infrastructures were found to be wide spread in Semarang City and Demak Regency. Foundation failures were not uncommon due to the low bearing capacity of the clay soil coupled with the subsidence process. Roads required frequent maintenance due to floods and settlements, with road pavements requiring regular annual raising to cope with the lowering of the land surface. Many buildings and housing settlements near the coast were permanently inundated, forcing people and economic activities to flee. Putra *et al.* [2020] stated that most of the damages were light to moderate, yet frequent and prolonged flood events could eventually cause heavy damage to buildings and infrastructures.

Impacts related to land subsidence hazards relate more to physical damages rather than people's lives; nevertheless, these impacts have directly affected people's livelihoods. Poor sanitation has resulted from drainage system damage caused by flooding and subsidence. People and economic mobility are also hindered by frequent flooding. Buildings and other structures near the coast have required frequent repairs, and many have been left derelict due to inundation. Coastal flooding is projected to get worse under subsidence and sea-level rise scenarios. It has been predicted that major floods could reach into the central city, covering an 11.5 km^2 area or 287% larger than the 2013 flood area [Irawan *et al.* 2021]. Direct economic loss due to physical damages in Semarang City, encompassing economic costs of road, bridges, house, and building damages has been estimated to reach 3.5 trn IDR, roughly USD250 mln [Sarah *et al.* 2014].

RESPONSE

The driving forces of urbanisation, population increase and economic growth are inevitable in the development of an urban area. To ensure sustainable development, balanced use of the environmental resources must be managed. Groundwater and land are resources under pressure from overexploitation and increased spatial density. The state of highly compressible alluvial clay is prone to external disturbances, as exhibited by over-consolidation. Resultant impacts are land subsidence, increased flooding, and building and infrastructure damage. Responses to the driver-pressure-state-impacts (DPSI) are specifically addressed in this subsection.

Our responses are catagorised as relating to: i) water management, ii) spatial planning and structural measures, and iii) land subsidence monitoring and law enforcement. Water management is a measure to ensure surface and groundwater are utilised for growing population and economic activities (D) with minimal environmental impacts. Such management requires integrated efforts from the government and stakeholders. Over-exploitation of groundwater (P) indicates unsuccessful water management, causing the thick deposit alluvial clay (S) to undergo land subsidence, causing secondary impacts of flood and structural damages (I). Responses that address this DPSI are prioritising surface water utilisation, artificial recharging, and groundwater monitoring (R). Artificial groundwater recharging can be carried out to replenish the exhausted deep confined aquifer. Water sources for artificial recharging can be rain harvesting, rivers, and ponds. Prior to injection into the deep aquifer, the water must undergo treatment to improve its quality, preventing aquifer contamination. Artificial recharging can uplift the alluvial clay within its elastic range (S), thereby improving subsidence condition. Groundwater exploitation management coupled with artificial recharge has been proven successful in controlling land subsidence rates [Chen *et al.* 2007; Ting *et al.* 2020; Yang *et al.* 2020].

Surface water utilisation (R) needs to be pushed forward in order to reduce groundwater exploitation (P). Improved groundwater condition will result in slower rate of clay compaction (S), reducing land subsidence and its secondary impacts (I). Monitoring groundwater level (R) would ensure the successful prioritising of surface water over groundwater and artificial recharging, addressing the designated DPSI.

According to Indonesian Government Regulation No. 43, Article 25 [Peraturan Pemerintah No. 43], groundwater utilisation for all purposes (including the industrial sector) must be secondary to surface water utilisation, when surface water is inadequate, and with the condition that groundwater conservation must be prioritised. Clean water demand in Semarang City and Demak Regency could be met by surface water, provided by the local water supply company (PDAM) through their extensive pipeline networks. In 2019, PDAM in Semarang City was capable of servicing 61% of the total network area (i.e., 60% of the Semarang municipal area) [Pratama *et al.* 2020]. PDAM in Demak Regency has only been capable of servicing 44% of the total network area, which is merely 23% of the Regency administrative area [Abdi *et al.* 2019]. Most PDAM clients are households, while industrial sectors are more inclined to use groundwater due to the PDAM's inability to provide their required water quantity and debit continuity [Valentino 2013].

Clean water demand for Semarang City in 2013 was 84,430,702 m^3 annually [Bappeda 2013]. Currently, PDAM Semarang City can deliver 49,698,227 m^3 of water that (59% of the demand). For Demak Regency, the water demand in 2013 was 41,822,412.480 m^3, of which PDAM Demak was only able to distribute 12,709,729 m^3, less than 31% of the total demand [Peraturan Bupati … No. 20]. It was therefore inevitable for some households and industries to use groundwater to meet their water demands. As efforts to prioritise surface water use is paramount, the use of groundwater requires close monitoring, producing data useful to the assessment of groundwater conditions so that any measures for controlling groundwater exploitation can be readily determined. We propose increasing the small number of existing groundwater monitoring wells to a grided network of monitoring wells throughout the study area. The quality of monitoring must also be improved.

Our second response relates to spatial planning and structural measuring. Population growth, urbanisation, and economic development (D) have driven denser building (P), which affects the subsurface condition in terms of its bearing capacity (S). As more loads placed upon the soft subsurface, subsidence, flood, and physical damages take place (I). Spatial planning of the Semarang City and Demak Regency require regulation based on both surface and subsurface conditions (R). Apart from apparent surface conditions, surface designations of built and unbuilt areas must also consider subsurface condition (e.g., are areas underlain by soft or hard ground, what water availability exists from surface and subsurface sources, what is the rate of subsidence experienced at each site). To lessen the adverse impacts of land subsidence upon building and infrastructure (I), specific building regulations must be enacted that accounts for engineering requirements when building on soft grounds (R). Development for new buildings, housing, and infrastructure must consider the engineering properties of foundation strata and the conservation of the water-bearing layers in the subsurface. Besides spatial planning, structural measures also play an important role in reducing floods (I). To lessen the coastal flooding, greater flood prevention structure must be built to complement the existing dyke, pump and polder system (R). Dykes, levee, seawalls are the types of flood prevention structures that can be built in the study area, but these structures cannot fully eliminate coastal flooding risk when the design water level is exceeded.

Our third response is regarding land subsidence monitoring and law enforcement. This response relates to the previous DPSI and respective responses. The previous proposed responses will not manifest unless the government and stakeholders are involved in the management of the land subsidence area. To ensure the successful implementation of the responses related to water management, spatial planning and structural measure, land subsidence monitoring and law enforcement must be carried out (R). We propose an integrated network of groundwater and land subsidence monitoring using combinations of groundwater monitoring wells, extensometer, and geodetic surveys.

It is imperative to assign clear responsibilities to central and local authorities to prevent responsibility overlap and misinformation, as well as to enact law enforcement consistently. For instance, controlling groundwater exploitation is presently within the authority of local governments. Monitoring of production wells should be carried out regularly, and any violations (e.g., illegal wells, over-exploitation) must be penalised accordingly. However, local governments have been perceived as reluctant to increase monitoring quality, as many violators remain undetected and unpunished [Valentino 2013]. The appropriate response for this problem is strengthening the local government through direct involvement of central law authorities to create a deterrent effect is made.

DISCUSSION

Driver-pressure-state-impact-response (DPSIR) application has enabled the identification of driving factors that pressurised the coastal environment of the Semarang–Demak plain. Interconnection between drivers and pressures to the current state allows the impacts to be recognised, enabling suitable focused responses. In Semarang City and Demak Regency, economic activities are centered in the northern coastal plain, consisting of government and business activities, manufacturing and industries, housing, and service-related sectors. Economic growth and urbanisation relate strongly to the groundwater condition. Higher economic growth and urbanisation stress the groundwater condition, as revealed by the higher rate of groundwater level decline in Semarang City compared to Demak Regency.

The decline of groundwater levels in deep aquifer has stressed the environment, indicating groundwater resource depletion, as well as groundwater level declines that affect overlying soil layers. The lowering of groundwater level is equivalent to lessening the pressure of the water-bearing layer (i.e., aquifer). To reach stress equilibrium, the overlying aquitard (i.e., clayey soil) adjusts by releasing excessive pressure via dewatering. The dewatering of the aquitard layer causes the soil to compress, which is known as land subsidence (a slow process occurring over an extensive area). The very high spatial density of Semarang City has caused land subsidence to affect almost the entire north coastal plain. In Demak Regency, the land use is not as dense but precautions must be made considering the thick, soft, compressible soil deposit in the area.

To achieve prosperity and better lives for its people, the government should still push for economic development, exerting more pressure on the coastal environment. As economic growth is expected to increase, the environment must endure many negative impacts that can either persist or diminish. To achieve a sustainable coastal environment and simultaneously cope with the impacts, appropriate responses must be taken to lessen or even halt the adverse conditions. Some of the proposed measures have been implemented by the government, however, more integrated approaches must be made.

A response to regulate groundwater use has been enacted by Regional Regulation of Central Java Province No. 3 of 2018 [Peraturan Daerah … No. 3]. The regulation states that groundwater exploitation is prohibited in the red zone, particularly the north coastal area. The Regional Regulation of Semarang Municipal No.7 of 2014 [Peraturan Daerah … No. 7] states that, to mitigate flood and increase surface water supply, some plans have been realised, such as the construction of Jatibarang reservoir, embankment, pumping stations, pump houses, retention ponds, and sea embankments, as well as the construction and optimisation of a drainage system, the elevation of subsided roads, the manufacture of water barrier walls, and the cleaning of drainage canals.

Prioritising surface water use remains difficult to achieve due to limited surface water source and inefficient management of surface water distribution. As mandated by law to comply with immediate surface water demand, the government has built the Jatibarang dam in 2015 to supply clean water and hydroelectricity for Semarang City. Works commenced in 2020 for the construction of Jragung dam to cater for Demak Regency and parts of Semarang City. Although the results would not be felt immediately, this is an optimistic path towards less use of groundwater. Increased surface water sources must be followed by increased pipe networks for distribution and effective management, decreasing water loss and maintaining debit continuity.

Monitoring of groundwater level is technically carried out by local government, but previous monitoring by the central government was not handed over effectively, causing reduced coverage and a still evident gap in monitoring data. Groundwater monitoring remains insignificant under the local government, rendering transfer of knowledge and law reinforcement necessary. Immediate and long-term measures, such as building flood protection systems and artificial recharging the deep aquifers must be carefully planned and executed. Spatial planning policy must consider the land subsidence and its associated impact along with the state of unstable ground. Building density and weights must be regulated accordingly so as not to increase pressure on the subsurface.

Land subsidence has begun to be recognised as a significant environmental problem by the Indonesian government. A land subsidence working group was established in 2020 by the Coordinating Ministry for Maritime and Investment Affairs, uniting central and local governments with academics, and nongovernmental agencies to solve land subsidence problem [Kemenkomarves 2020]. Previously the Coordinating Ministry for Marine and Investment Affairs released a road map for land subsidence mitigation and adaptation in the coastal lowland [Kemenkomarves 2019]. The road map consisted of three main objectives to be achieved in 2020–2025: 1) establishing a coordinating agency for land subsidence mitigation and adaptation program; 2) establishing a national mapping and monitoring system for land subsidence; 3) handling the ten main sources of land subsidence problems in Indonesia. The first objective was achieved by establishing the working group in 2020, while the second and third objectives are ongoing. Analysing past and current government responses shows that an integrated approach has been embraced. Previous government responses tended to be localised and sporadic, lacking in control and enforcement. As a result, the subsurface condition is heavily pressurised and the resulting impacts (e.g., land subsidence rate, flooding, physical damage) have become worse over time. The current government response, while belated, is strengthened on the national level as stipulated in the Mid-Term National Development Plan (RPJMN) 2020–2024 [Peraturan Pemerintah No. 18]. Under the RPJMN 2020–2024, local governments are obliged to: i) increase PDAM service in coastal area to reduce and eventually stop groundwater exploitation; ii) disseminate information to industries that imposes restriction on groundwater exploitation; iii) develop disaster-resilient infrastructure; iv) improve the subsidence monitoring system; and v) construct coastal protection structures.

Overall, the identification of drivers, pressures, and state of the study area has enabled a realistic set of responses. The key response to all other measures island subsidence and groundwater monitoring, which can directly indicate the success rate of maintaining the coastal environment. Land subsidence monitoring has been carried out by erecting stable benchmarks in several government-owned sites and with space geodetic methods. However, groundwater monitoring is still lacking and requires improved quantity and quality.

CONCLUSIONS

The root-cause interaction between DPSIs of the Semarang-Demak coastal environments has been well understood using the DPSIR framework. Based on our study, rapid population growth and economic development drive long-term effects on the coastal environment. We found that the increasing economic development in the early nineties pressurised the coastal environmental conditions, manifesting inland use and groundwater conditions that showed abrupt and accelerating change. Urbanisation and higher economic gains resulted in greater pressures. Higher population density and economic activities in Semarang City have created further environmental pressures, as revealed by the densely constructed area land use and deeper piezometric groundwater level than the Demak Regency.

The natural state of the Semarang–Demak coastal plain is composed of the alluvial deposit consisting primarily of a thick, compressible clay layer at the upper part. The thickness of the soft clay layer can reach 4–25 m near the coast and becomes thicker toward the northeast. Thicker soft clay layer amplifies its vulnerability to subsidence. The land subsidence rate in Semarang and Demak ranges from 0–15 $cm{\cdot}y^{-1}$, with Demak Regency experiencing a slower rate of 0–3 $cm{\cdot}y^{-1}$. The associated impacts (e.g., coastal flooding, damage to buildings and infrastructures) are widespread with the most noticeable being increased coastal flooding since 2014, as marked by a wide area of the northwest and northeast being permanently inundated. Although the subsidence rate is slower in Demak Regency, the combined land subsidence and sea-level rise contributed to the loss of land in the area.

Under the DPSIR framework, appropriate responses have been formulated to aid in policy-making and implementation. A set of measures has been proposed that include physical and non-physical actions. While some of the proposed measures have been applied by the authorities, encouraging results have not come. Rigorous policy drawing and implementation must be carried out, along with proper management and law enforcement. Although it will take some time for encouraging results to appear, it is possible to stop and prevent the damaging impacts of land subsidence. This study has many limitations, particularly regarding restricted availability of data due to unreported data, loss of archives and reports, and changing government policy. Furthermore, more comprehensive inputs would be valuable for updating this DPSIR model.

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REFERENCES

ABDI S., UTOMO S. 2019. Sistem Pelayanan Air Bersih Di Perumahan Pucang Gading Dalam Mendukung Tercapainya Sustainable Development Goals [Clean water service system in Pucang Gading Housing to support the achievement of sustainable development goals]. Prosiding Seminar Nasional Multidisiplin Ilmu dan Call For Papers Unisbank ke-5: Optimalisasi Bonus Demografi Indonesia Dalam Era Revolusi Industri 4.0 [Proceedings of the 5th Multidisciplinary National Seminar and Call For Papers Unisbank: Optimizing Indonesia's Demographic Bonus in the Era of the Industrial Revolution 4.0]. Vol. 5. [Access 9.08.2022]. Available at: https://www.unisbank.ac.id/ojs/index.php/sendi_u/article/view/7374

ABIDIN H.Z., ANDREAS H., GUMILAR I., SIDIQ T.P., FUKUDA Y. 2013. Land subsidence in coastal city of Semarang (Indonesia): Characteristics, impacts and causes. Geomatics, Natural Hazards and Risk. Vol. 4 p. 226–240. DOI 10.1080/19475705.2012.692336.

ANDREAS H., ABIDIN H.Z, GUMILAR I., SIDIQ T.P., SARSITO D.A. 2019. On the acceleration of land subsidence rate in Semarang City as detected from GPS surveys. In: E3S Web of Conferences. Vol. 94, 04002. DOI 10.1051/e3sconf/20199404002.

ANDREAS H., ABIDIN H.Z., SARSITO D.A. 2017. Tidal inundation ("Rob") investigation using time series of high resolution satellite image data and from insitu measurements along northern coast of Java (Pantura). In: 2nd Transdisciplinary Research on Environmental Problems in Southeast Asia. 20–22.09.2016 Bandung, Indonesia. Eds. M. Sakakibara, A. Saepuloh, I.A. Kurniawan. IOP Conferences Series: Earth and Environmental Science. Vol. 71. DOI 10.1088/1755-1315/71/1/012005.

Bappeda 2013. Penyusunan Rencana Induk Sistem Penyediaan Air Minum (RISPAM) Kota Semarang [Composing the Semarang City Drinking Water Supply System Master Plan (RISPAM)]. Semarang. Badan Perencanaan Pembangunan Daerah Kota Semarang.

BELL F.G. 2007. Engineering geology. 2nd ed. Oxford. Butterworth-Heineman. ISBN 978-0-7506-8077-6 pp. 593.

BPS 2019. Profil industri besar dan sedang Kota Semarang 2019 [Profile of large and medium-sized industries in Semarang city] [online]. Semarang. Badan Pusat Statistik Kota Semarang. ISBN 978-623-95123-3-0 pp. 44. [Access 4.01.2021]. Available at: https://semarangkota.bps.go.id/publication/2020/11/30/fa72c8bf-d80ee2f3639ba477/profil-industri-besar-dan-sedang-kota-semarang-2019.html

BPS 2021a. Kabupaten Demak dalam angka 2021 [Demak Regency in figures 2021] [online]. Demak. Badan Pusat Statistik Kabupaten Demak. [Access 27.02.2021]. Available at: https://demakkab.bps.go.id/publication/2021/02/26/4c67df8f88d4775ddbe4a420/kabupaten-demak-dalam-angka-2021.html

BPS 2021b. Kota Semarang dalam angka 2021 [Semarang City in figures 2021] [online]. Semarang. Badan Pusat Statistik Kabupaten Semarang. [Access 27.02.2021]. Available at: https://semarangkota.bps.go.id/publication/2021/02/26/cf7000f79cd1c7015c2939fc/kota-semarang-dalam-angka-2021.html

CARR E.R., WINGARD P.M., YORTY S.C., THOMPSON M.C., JENSEN N.K., ROBERSON J. 2007. Applying DPSIR to sustainable development. International Journal of Sustainable Development and World Ecology. Vol. 14 p. 543–555. DOI 10.1080/13504500709469753.

CHAUSSARD E., AMELUNG F., ABIDIN H., HONG S.H. 2013. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. Remote Sensing of Environment. Vol. 128 p. 150–161. DOI 10.1016/j.rse.2012.10.015.

Chen C.T., Hu J.C., Lu C.Y., Lee J.C., Chan Y.C. 2007. Thirty-year land elevation change from subsidence to uplift following the termination of groundwater pumping and its geological implications in the Metropolitan Taipei Basin, Northern Taiwan. Engineering Geology. Vol. 95 p. 30–47. DOI 10.1016/j.enggeo.2007.09.001.

Cui Z.D., Tang Y.Q. 2010. Land subsidence and pore structure of soils caused by the high-rise building group through centrifuge model test. Engineering Geology. Vol. 113 p. 44–52. DOI 10.1016/j.enggeo.2010.02.003.

Day R.W. 2009. Foundation engineering handbook: Design and construction with the 2009 international building code. 2nd ed. New York. The McGraw-Hill Companies, Inc. ISBN 978-0-0717-4009-8 pp. 1008.

Dokka R.K. 2006. Modern-day tectonic subsidence in coastal Louisiana. Geology. Vol. 34 p. 281–284. DOI 10.1130/G22264.1.

Gambolati G., Teatini P., Tomasi L., Gonella M. 1999. Coastline regression of the Romagna region, Italy, due to natural and anthropogenic land subsidence and sea level rise. Water Resources Research. Vol. 35 p. 163–184. DOI 10.1029/1998WR900031.

Gari S.R., Newton A., Icely J.D. 2015. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. Ocean and Coastal Management. Vol. 103 p. 63–77. DOI 10.1016/j.ocecoaman.2014.11.013.

Hamdani R.S., Hadi S.P., Rudiarto I., Purnaweni H. 2020. Do we care enough? Revisiting land subsidence and coastal spatial planning policy in Semarang, Indonesia. In: The 5th International Conference on Energy, Environmental and Information System (ICENIS 2020). E3S Web of Conferences. Vol. 202, 06005. DOI 10.1051/e3sconf/202020206005.

Holzer T.L., Galloway D.L. 2005. Impacts of land subsidence caused by withdrawal of underground fluids in the United States. Reviews in Engineering Geology. Vol. 16 p. 87–99. DOI 10.1130/2005.4016(08).

Irawan A.M., Marfai M.A., Munawar Nugraheni I.R., Gustono S.T., Rejeki H.A., Widodo A., Mahmudiah R.R., Faridatunnisa M. 2021. Comparison between averaged and localised subsidence measurements for coastal floods projection in 2050 Semarang, Indonesia. Urban Climate. Vol. 35, 100760. DOI 10.1016/j.uclim.2020.100760.

Jago-On K.A.B., Kaneko S., Fujikura R., Fujiwara A., Imai T., Matsumoto T., ..., Taniguchi M. 2008. Urbanization and subsurface environmental issues: an attempt at DPSIR model application in Asian cities. Science of the Total Environment. Vol. 407 p. 3089–3104. DOI 10.1016/j.scitotenv.2008.08.004.

Kaneko S., Toyota T. 2011. Long-term urbanization and land subsidence in Asian megacities: An indicators system approach. In: Groundwater and subsurface environments: Human impacts in asian coastal cities. Ed. M. Taniguchi. Berlin. Springer p. 249–270. DOI 10.1007/978-4-431-53904-9_13.

Karageorgis A.P., Kapsimalis V., Kontogianni A., Skourtos M., Turner K.R., Salomons W. 2006. Impact of 100-year human interventions on the deltaic coastal zone of the Inner Thermaikos Gulf (Greece): A DPSIR framework analysis. Environmental Management. Vol. 38 p. 304–315. DOI 10.1007/s00267-004-0290-8.

Kemenkomarves 2019. Peta jalan mitigasi dan adaptasi amblesan (subsiden) tanah di dataran rendah pesisir [Roadmap for mitigation and adaptation of land subsidence in coastal lowlands]. Jakarta. Kementerian Koordinator Bidang Kemaritiman dan Investasi RI, Yayasan Lahan Basah (Wetlands International Indonesia), Institut Teknologi Bandung (ITB)] pp. 72. [Access 14.08.2021]. Available at: https://indonesia.wetlands.org/id/publikasi/peta-jalan-road-map-mitigasi-dan-adaptasi-amblasan-subsiden-tanah-di-dataran-rendah-pesisir-2/

Kemenkomarves 2020. Rumuskan Program Kerja Pokja Land Subsidence, Pemerintah Telusuri Wilayah Pantura Jateng [Formulate the Land Subsidence Working Group Working Program, the Government Explores the Pantura Region of Central Java] [online]. Jakarta. Kementerian Koordinator Bidang Kemaritiman dan Investasi RI [Access 24.06.2021]. Available at: https://maritim.go.id/detail/rumuskan-program-kerja-pokja-land-subsidence-pemerintah-telusuri

Kooi H. 2000. Land subsidence due to compaction in the coastal area of The Netherlands: The role of lateral fluid flow and constraints from well-log data. Global and Planetary Change. Vol. 27 p. 207–222. DOI 10.1016/S0921-8181(01)00067-4.

Kristensen P. 2004. The DPSIR framework. In: Workshop on a comprehensive / Detailed assessment of the vulnerability of water resources to environmental change in Africa using river basin approach [online]. Nairobi. UNEP Headquarters. [Access 21.02.2021]. Available at: http://fis.freshwatertools.eu/files/MARS_resources/Info_lib/Kristensen(2004)DPSIR%20Framework.pdf

Lubis A.M., Sato T., Tomiyama N., Isezaki N., Yamanokuchi T. 2011. Ground subsidence in Semarang-Indonesia investigated by ALOS–PALSAR satellite SAR interferometry. Journal of Asian Earth Sciences. Vol. 40 p. 1079–1088. DOI 10.1016/j.jseaes.2010.12.001.

Marfai M.A., Almohammad H., Dey S., Susanto B., King L. 2008. Coastal dynamic and shoreline mapping: multi-sources spatial data analysis in Semarang Indonesia. Environmental Monitoring and Assessment. Vol. 142 p. 297–308. DOI 10.1007/s10661-007-9929-2.

Marfai M.A., King L. 2007. Monitoring land subsidence in Semarang, Indonesia. Environmental Geology. Vol. 53 p. 651–659. DOI 10.1007/s00254-007-0680-3.

Marfai M.A., King L., Sartohadi J., Sudrajat S., Budiani S.R., Yulianto F. 2007. The impact of tidal flooding on a coastal community in Semarang, Indonesia. Environmentalist. Vol. 28 p. 237–248. DOI 10.1007/s10669-007-9134-4.

Marsudi 2001. Prediksi laju amblesan tanah di dataran aluvial semarang Propinsi Jawa Tengah [Prediction of land subsidence rate in the alluvial plain of Semarang, Central Java Province]. Institut Teknologi Bandung (ITB) pp. 176.

Mattas C., Voudouris K.S., Panagopoulos A. 2014. Integrated groundwater resources management using the DPSIR approach in a GIS environment: A case study from the Gallikos River Basin, North Greece. Water. Vol. 6(4) p. 1043–1068. DOI 10.3390/w6041043.

Murdohardono D., Tobing M.H., Sayekti A. 2007. Over pumping of ground water as one of causes of sea water inundation in Semarang City. [International Symposium and Workshop on Current Problems in Groundwater Management and Related Water Resources Issues in the Southeast and East Asia Region]. [3–8.12.2007 Bali, Indonesia].

Neumann B., Vafeidis A.T., Zimmermann J., Nicholls R.J. 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding – A global assessment. PLoS One. Vol. 10 p. 1–34. DOI 10.1371/journal.pone.0118571.

Peraturan Bupati Kabupaten Demak Nomor 20 Tahun 2014 tentang Rencana Induk Sistem Penyediaan Air Minum Kabupaten Demak [Regent Regulation (PERBUP) of Demak Regency Number 20 of 2014 concerning the Master plan for the Demak Regency Drinking Water Supply System] [online]. [Access

22.02.21]. Available at: https://peraturan.bpk.go.id/Home/Details/215238/perbup-kab-demak-no-20-tahun-2014

Peraturan Daerah Kota Semarang No. 14 tahun 2011 tentang Rencana Tata Ruang Wilayah Kota Semarang [Regional Regulation (PERDA) of Semarang City No. 14 of 2011 concerning Spatial Planning of the City of Semarang] [online].[Access 22.06.2021]. Available at: https://jdih.semarangkota.go.id/ildis_v2/public/dokumen/data_dokumen/LD_Perda_14_2011.pdf

Peraturan Daerah Kota Semarang No. 7 tahun 2014 tentang Rencana Induk Sistem Drainase Kota Semarang tahun 2011–2031 [Regional Regulation of the City of Semarang Number 7 of 2014 concerning Master Plan of Semarang City Drainage system 2011-2031] [online]. [Access 20.06.2021]. Available at: https://jdih.semarangkota.go.id/ildis_v2/public/pencarian/53/detail

Peraturan Daerah Provinsi Jawa Tengah No. 3 tahun 2018 tentang pengelolaan air tanah [Regional Regulation of Central Java Province No. 3 of 2018 concerning groundwater management] [online]. [Access 24.06.2021]. Available at: https://peraturan.bpk.go.id/Home/Details/75102/perda-prov-jawa-tengah-no-3-tahun-2018

Peraturan Pemerintah No. 18 Tahun 2020 Rencana Pembangunan Jangka Menengah Nasional tahun 2020–2024 [Government Regulation No. 18 of 2020 National Medium Term Development Plan (RPJMN) 2020–2024] [online]. [Access 20.05.2021]. Available at: https://jdih.bappenas.go.id/peraturan/detailperaturan/1037

Peraturan Pemerintah Republik Indonesia No. 43 tahun 2008 tentang air tanah [Government Regulation of the Republic of Indonesia No. 43 of 2008 on groundwater] [online]. [Access 24.06.2021]. Available at: https://peraturan.bpk.go.id/Home/Details/4857/pp-no-43-tahun-2008

Pratama F.A, Rahdriawan M., Wahyono H., Damayanti M., Artiningsih A. 2020. Estimasi daya beli air PDAM masyarakat permukiman kumuh kelurahan Mangkang Wetan, Semarang [Estimation of water purchasing power of PDAM slum communities, Mangkang Wetan Village, Semarang]. Jurnal Riptek. Vol. 14 p. 134–52.

Putra S.I., Hermawan F., Hatmoko J.U.D. 2020. Penilaian kerusakan dan kerugian infrastruktur publik akibat dampak bencana banjir di kota Semarang [Damages and losses assessment of public infrastructure due to the impact of Semarang City flood]. Wahana Teknik Sipil Jurnal Pengembangan Teknik Sipil. Vol. 25 (2) p. 86–97. DOI 10.32497/wahanats.v25i2.2154.

Putranto T.T., Rude T.R. 2016. Hydrogeological model of an urban city in a coastal area, Case study: Semarang, Indonesia. Indonesian Journal on Geoscience. Vol. 3 p. 17–27. DOI 10.17014/ijog.3.1.17-27.

Rahmawan L.E., Yuwono B.D., Awaludin M. 2016. Survei pemantauan deformasi muka tanah kawasan pesisir menggunakan metode pengukuran GPS di Kabupaten Demak tahun 2016 (Studi kasus: Pesisir Kecamatan Sayung, Demak) [Monitoring of the earth surface deformation in the coastal area using GPS survey in Demak Regency 2016 (case study: Coastal Sayung sub-district, Demak)]. Jurnal Geodesi Undip. Vol. 5 p. 44–55.

ReliefWeb 2021. Flooding in Semarang City, Indonesia – Flash update #1 [online]. [Access 24.06.2021. Available at: https://reliefweb.int/report/indonesia/flooding-semarang-city-indonesia-flash-update-1

Robertson P.K. 2006. Guide to in-situ testing [online]. Signal Hill, California. Gregg Drilling & Testing Inc. pp. 87. [Access 20.06.2021]. Available at: http://www.geoplanning.it/test/wp-content/uploads/2012/02/Guide-to-in-situ-testing.pdf

Sarah D., Hutasoit L.M., Delinom R.D., Sadisun I.A. 2020. Natural compaction of Semarang Demak alluvial plain and its relationship to the present land subsidence. Indonesian Journal on Geoscience. Vol. 7 p. 273–289. DOI 10.17014/ijog.7.3.273-289.

Sarah D., Hutasoit L.M., Delinom R.M., Sadisun I.A., Wirabuana T. 2018. A physical study of the effect of groundwater salinity on the compressibility of the Semarang-Demak aquitard, Java Island. Geosciences. Vol. 8, 130. DOI 10.3390/geosciences8040130.

Sarah D., Satriyo N.A., Mulyono A., Soebowo E. 2014. Kajian awal estimasi kerugian fisik akibat amblesan tanah di Kota Semarang. Dalam: Prosiding Pemaparan Hasil Penelitian Pusat Penelitian Geoteknologi LIPI 2014: Peran Penelitian Geoteknologi Untuk Menunjang Pembangunan Berkelanjutan di Indonesia [Preliminary assessment on the physical losses due to land subsidence in Semarang City. In: Proceedings of the Research Center for Geotechnology LIPI 2014: The Role of Geotechnology to Support Sustainable Development in Indonesia]. Lembaga Ilmu Pengetahuan Indonesia (LIPI) Pusat Penelitian Geoteknologi. 1–2.12.2014 Bandung, Indonesia. Eds. H. Harjono, R. Delinom, E.P Utomo p. 37–44.

Sekovski I., Newton A., Dennison W.C. 2012. Megacities in the coastal zone: Using a driver-pressure-state-impact-response framework to address complex environmental problems. Estuarine Coastal and Shelf Science. Vol. 96 p. 48–59. DOI 10.1016/j.ecss.2011.07.011.

Sidiq T.P., Gumilar I., Meilano I., Abidin H.Z., Andreas H., Permana A. 2021. Land subsidence of Java north coast observed by SAR interferometry. In: 3rd Southeast Asian Conference on Geophysics. 3–5.11.2020 Bandung, Indonesia. Eds. Zulfakriza, A. Hendriyana, E. Saygin, C. Chhun. IOP Conference Series: Earth and Environmental Science. Vol. 873. DOI 10.1088/1755-1315/873/1/012078.

Syvitski J.P.M. 2008. Deltas at risk. Sustainability Science. Vol. 3(1) p. 23–32. DOI 10.1007/s11625-008-0043-3.

Taufiq N.Z.A. 2010. Penyelidikan konservasi airtanah di Cekungan Airtanah Semarang- Demak, Provinsi Jawa Tengah [Investigation of groundwater conservation in Semarang-Demak groundwater basin, Central Java Province]. Pusat Geologi Tata Lingkungan, Badan Geologi.

Thaden R.E., Sumardirdja H., Richards P.W. 1996. Peta Geologi Lembar Semarang- Magelang, Jawa, skala 1:100.000 [Geological map of Semarang-Magelang Quadrangle, Java, scale 1:100,000]. Pusat Survei Geologi, Badan Geologi.

Ting C.S., Chiang K.F., Hsieh S.H., Tsao C.H., Chuang C.H., Fan K.T. 2020. Land subsidence and managed aquifer recharge in Pingtung Plain, Taiwan. In: Proceedings of the International Association of Hydrological Sciences. Vol. 382 p. 843–849. DOI 10.5194/piahs-382-843-2020.

Tobing M.H.L., Syarief E.A., Murdohardono D. 2000. Penyelidikan geologi teknik amblesan tanah di Kota Semarang dan sekitarnya, Provinsi Jawa Tengah [Engineering geological investigation on land subsidence in Semarang City and its surrounding, Central Java Province]. Pusat Geologi Tata Lingkungan, Badan Geologi [Center for Environmental Geology, the Geological Agency].

UN 2017. Factsheet: People and oceans [online]. In: The Ocean Conference. New York. United Nations. [Access 20.06.2021]. Available at: https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf

Valentino D. 2013. Kajian pengawasan pemanfaatan sumberdaya air tanah di kawasan industri Kota Semarang [Assessment of the monitoring of the groundwater utilization in industrial area in Semarang City]. Jurnal Wilayah dan Lingkungan. Vol. 1(3) p. 265–274. DOI 10.14710/jwl.1.3.265-274.

VAN BEMMELEN R.W. 1949. The geology of Indonesia. Vol. 1A. The Hague, Netherlands. Martinus Nijhoff. ISBN 978-9-0247-1171-0 pp. 799.

VAN SCHAECK MATHON F.M.A. 1975. Analysis of groundwater conditions on the basis of existing data: A study of the East Semarang-Demak plain Central Java. In: Seminar on groundwater development for the purpose of irrigation. Surabaya. Department of Public Works Republic of Indonesia pp. 1–23.

WIDADA S., ZAINURI M., YULIANTO G., SATRIADI A., JATIWIJAYA Y., HELMI M. 2020a. Mitigation of floodwaters inundation due to land subsidence in the coastal area of Semarang City. In: The 5th International Conference on Tropical and Coastal Region Eco Development. IOP Conference Series: Earth and Environmental Science. Vol. 530 p. 17–18. DOI 10.1088/1755-1315/530/1/012006.

WIDADA S., ZAINURI M., YULIANTO G., SATRIADI A., WIJAYA Y.J. 2020b. Estimation of land subsidence using sentinel image analysis and its relation to subsurface lithology based on resistivity data in the coastal area of Semarang City, Indonesia. Journal of Ecological Engineering. Vol. 21 p. 47–56. DOI 10.12911/22998993/127394.

YANG T., YAN X., HUANG X., WU J. 2020. Integrated management of groundwater exploitation and recharge in Shanghai based on land subsidence control. Proceedings of the International Association of Hydrological Sciences. Vol. 382 p. 831–836. DOI 10.5194/piahs-382-831-2020.