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Combined Land Subsidence Analysis in Jakarta Based on Ps-InSAR and MICMAC Methods

Kombinasi Analisis Penurunan Muka Tanah di Jakarta Berdasarkan Metode Ps-InSAR dan MICMAC

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ABSTRAK

Penurunan muka tanah menjadi salah satu masalah di kota-kota pesisir delta di dunia, seperti Jakarta. Di kota ini, penurunan tanah sudah merata di seluruh wilayah. Berbagai faktor penyebab penurunan muka tanah dapat menimbulkan dampak secara ekologi, ekonomi, maupun sosial. Dampak yang terjadi umumnya berupa retaknya bangunan dan perluasan banjir. Oleh karena itu, kami perlu melakukan pengukuran dan pemantauan secara cepat dan berkala. Persistent Scatterer Interferometry Synthetic Aperture Radar (PS-InSAR) ialah metode yang digunakan untuk mendeteksi besaran nilai penurunan muka tanah di daerah perkotaan. Metode ini mampu menghasilkan gambar SAR dari distribusi ribuan titik pantau identifikasi faktor penyebab penurunan muka tanah di Jakarta. Hasil PS-InSAR terdeteksi nilai laju penurunan muka tanah rata-rata sebesar -5,71 cm/tahun, yang dominan berada di wilayah Jakarta Utara dan Jakarta Barat. Terdapat beberapa faktor penyebab penurunan muka tanah, kami melakukan analisis faktor ini menggunakan metode MICMAC (Matrix of Cross Impact Multiplications Applied to a Classification). Metode ini membantu mengidentifikasi hubungan dan relevansi antar faktor penyebab penurunan muka tanah. Hasil metode ini menunjukkan bahwa eksploitasi air tanah berlebihan dan konsolidasi alami tanah aluvial sebagai faktor yang berpengaruh signifikan terjadinya penurunan muka tanah di wilayah Jakarta.

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ABSTRACT

Land subsidence is one of the problems in delta coastal cities in the world, such as Jakarta. In this city, land subsidence has been evenly distributed throughout the region. Various factors causing land subsidence can have ecological, economic, and social impacts. The impacts that occur generally include the cracking of buildings and the expansion of flooding. Therefore, we need to carry out measurements and monitoring quickly and regularly. Persistent Scatterer Interferometry Synthetic Aperture Radar (PS-InSAR) is a method used to detect the magnitude of land subsidence in urban areas. This method is capable of producing SAR images from the distribution of thousands of monitoring points to identify factors causing land subsidence in Jakarta. PS-InSAR results detected an average land subsidence rate of -5.71 cm/year, which was dominant in the North Jakarta and West Jakarta areas. Several factors cause land subsidence, we analyzed these factors using the MICMAC (Matrix of Cross Impact Multiplications Applied to a Classification) method. This method helps identify the relationship and relevance between factors causing land subsidence. The results of this method produce excessive groundwater exploitation and natural consolidation of alluvial soil as factors that have a significant influence on land subsidence in the Jakarta area.

1. INTRODUCTION

1.1 Background of the Study

Land subsidence is one of the main problems in coastal cities and deltas worldwide caused by natural and or human activities, including in Indonesia (Buffardi & Ruberti, 2023). This problem has existed since the 1980s until now, due to rapid physical development and exacerbating sustainable development in the future (Pravitasari et al., 2020, 2022; Sarah, 2022). In Indonesia, land subsidence occurs on the North Coast of Java (Pantura), where along the coastline, there are large cities with more than 50 % of the population of Java Island living in coastal areas (Andreas et al., 2019). The results showed that significant land subsidence occurred in Jakarta (Sidiq et al., 2021). There are several causal factors triggered by excessive groundwater exploitation, natural consolidation of alluvial soil, building and infrastructure construction loads, population density (Bott et al., 2021a), economic and industrial activity (Kurnia et al., 2022; Takagi et al., 2021), tectonic activity, and land use patterns (Azeriansyah et al., 2019).

Factors causing land subsidence can impact the urban environment, including ecological, economic, social, and infrastructure. In general, the impact is the reclaiming of buildings and infrastructure as well as the extent of the tidal flood area (Abidin et al., 2015). Land subsidence measurement and monitoring in an area must be done periodically to minimize the effects. In principle, monitoring uses several methods to detect the magnitude of subsidence in urban areas, namely the PS-InSAR method (Azeriansyah et al., 2019; Sofiadin, 2019). The use of this method is to look for points that have the potential for land subsidence in the study area (Widodo et al., 2022). Several researchers have carried out monitoring with PS-InSAR, such as Kumar et al. (2020), Sidiq et al. (2021), Widodo et al. (2022), and Hussain et al. (2022). The use of PS-InSAR is highly recommended because its broad spatial basis produces thousands of monitoring points and effective and efficient data processing. This method provides a better understanding of the spatial variations in land subsidence, which is a weakness of GPS and monitoring well methods (Abidin et al., 2011; Andreas et al., 2018). Understanding the phenomenon of land subsidence also requires stakeholder involvement, especially understanding the factors that are the main causes of land subsidence in Jakarta.

This research also analyzes the causes of land subsidence using the MICMAC method. This method helps to identify the relationship and relevance between factors and reveal the causal chain of a system so that it is helpful for future scenarios (Ariyani et al., 2022). The use of the MICMAC method to analyze the factors causing a natural or human disaster has been carried out by Ariyani et al. (2022) regarding floods and Ahmad et al., (2019) regarding liquefaction. Meanwhile, literature studies have yet to be found to analyze land subsidence factors. Therefore, MICMAC begins with formulating the problem and identifying the related factors. Furthermore, MICMAC analyzed the relationships between factors and weighted these relationships based on the degree of mobility and dependence between factors (Benjumea-Arias et al., 2016).

1.2 Purpose of the Study

The combination of PS-InSAR and MICMAC is a new method proposed in this research. The purpose of this measurement is to get an idea of the current status of land subsidence in relation to spatial and temporal trends in Jakarta. Meanwhile, the MICMAC approach is used to identify significant factors causing land subsidence in Jakarta.

2. METHODS AND MATERIALS

2.1 Methods

This study uses the PS-InSAR method with multi-image SAR image data. The process of running data and spatial analysis are conducted using the SARPROZ software by Daniel Perissin (Perissin, 2022). Another tool used in this research is the MICMAC software (version 5.3.0). The MICMAC software can be downloaded via the LaProspective website at http://www.laprpective.fr. The main ingredient of this research is to look for the factors that cause land subsidence.

2.2 Materials

Related to the PS-InSAR method, we used C-Band SLC Sentinel-1A SAR data obtained from the European Space Agency (ESA), which is publicly accessible. The acquisition of ascending image data was used in the period January 2021-December 2022 for the Jakarta area; 24 image data were selected, as seen in Table 1.

The main ingredient of MICMAC analysis is the factors that cause land subsidence. Based on a review of scientific literature that has been published in the last 5 years, we found 7 factors causing land subsidence which can be seen in Table 2

Table 1. Details of data acquisition of this research.

Date of Acquisition			
08 Jan 2021	19 Jul 2021	15 Jan 2022	26 Jul 2022
13 Feb 2021	12 Aug 2021	20 Feb 2022	19 Aug 2022
21 Mar 2021	17 Sept 2021	16 Mar 2022	24 Sept 2022
14 Apr 2021	23 Oct 2021	21 Apr 2022	18 Oct 2022
20 Mei 2021	28 Nov 2021	15 Mei 2022	23 Nov 2022
13 Jun 2021	22 Dec 2021	08 Jun 2022	17 Dec 2022

Tabel 2. List of significant factors identified from the literature review

Code	Label	Factors	Source
F1	exp_water	Excessive exploitation of groundwater	(Sidiq et al., 2021)
F2	alluvial	Natural consolidation of alluvial soils	(Sidiq et al., 2021)
F3	exp_builld	Building and infrastructure construction expenses	(Bott et al., 2021a)
F4	popdens	Population density	(Bott et al., 2021a)
F5	economy	Economic and industrial activity	(Kurnia et al., 2022; Takagi et al., 2021)
F6	tectonic	Tectonic activity	(Andreas et al., 2019)
F7	land use	Land use patterns	(Azeriansyah et al., 2019)

2.3 Research Procedure

The case study for this research is the administrative area of Jakarta, with an area of 661.5 km^2 located on the coast of Java Island. The research location can be seen in Figure 1. Furthermore, based on Sentinel-1A data obtained from Table 1, we selected the area according to the study boundaries. For the process of selecting this area, the SARPROZ software has been used, the results of which can be seen in Figure 2 below. PS-InSAR is the development of conventional InSAR and DInSAR techniques to overcome problems related to temporal and geometric decorrelation (Azeriansyah et al., 2019). The use of the PS-InSAR spatial analysis approach to identify areas that have the potential for land subsidence in coastal urban areas was also used by several previous authors (Azeriansyah et al., 2019; Kumar et al., 2020; Widodo et al., 2022). PS-InSAR utilizes long-term multitemporal SAR image observation data to detect potential coherence points (Widodo et al., 2022). Therefore, this study uses the PS-InSAR method with multi-image SAR image data. PS-InSAR requires at least 20 SAR images to perform analysis in C-Band data (Syahputri et al., 2021). In this study, 24 SAR images were used to be paired to create master and slave images. The process of running data and analysis was conducted using SARPROZ software. The flowchart of this study refers to Figure 3. The Atmospheric Phase Screen (APS) process is chosen in the SARPROZ software process (Figure 3) based on the amplitude stability index (ASI). Based on research (Hussain et al., 2022), ASI > 0.75 is the acceptable threshold reference points. This study used an ASI threshold of 0.8 and temporal coherence of 0.9 as the basis for selecting a gap point to ensure the accuracy of the PS-InSAR analysis (Razi et al., 2018). The temporal coherence and connections chart for Jakarta City can be seen in Figure 4. Apart from using PS-InSAR to determine areas with potential for land subsidence, we also used MICMAC analysis to determine what are the main causal factors for land subsidence in the study area.

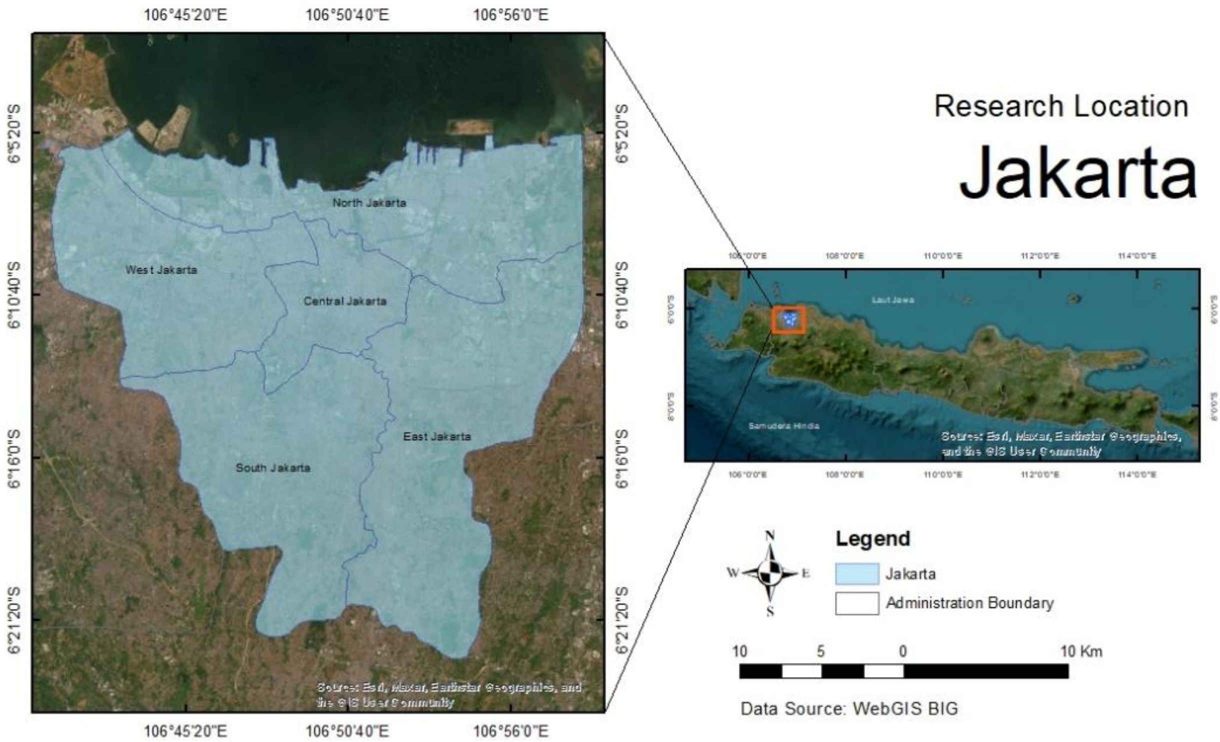

Figure 1. Research location

Figure 2. Footprint area selection of Sentinel-1A data in this case study

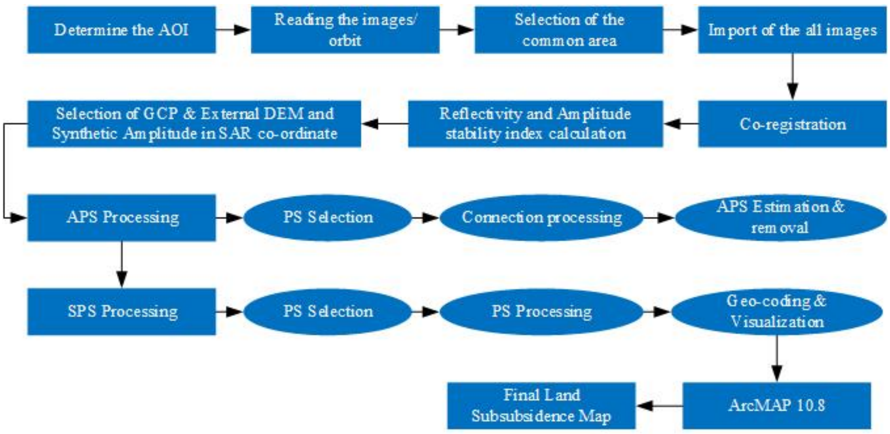

Figure 3. Flowchart of PS-InSAR processing on SARPROZ software (Modified form Hussain et al., 2022; Kumar et al., 2020)

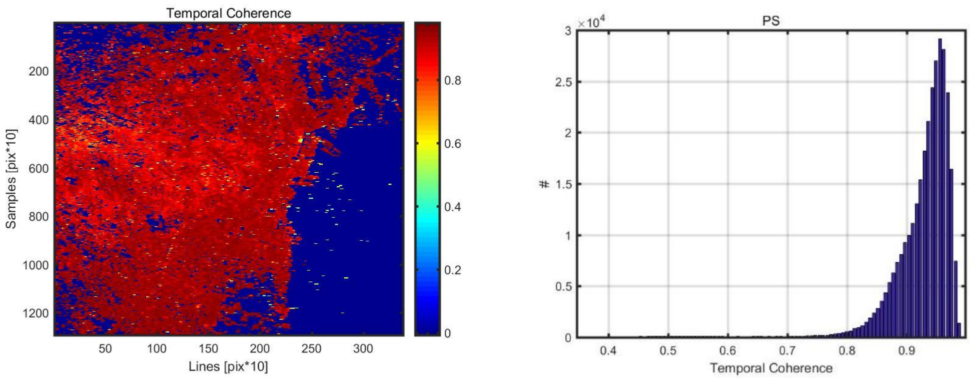

Figure 4. The graphs between the temporal coherence PS chart

There are two main stages in MICMAC analysis, namely understanding the scope of the system problem to be studied and analyzing the results of the factor position map in the quadrants. The initial stage requires the involvement of experts, specialists, and the community through Focus Group Discussions (FGD) to obtain an assessment of the system being studied (Fauzi, 2019; Stratigea, 2013). According to Hora (2004), the number of experts who are adequate and have high precision is 3 to 7 expert respondents with the criteria of knowing the object being studied and the research location well. The main ingredients of the analysis as an expert assessment are in Table 2; we consider all the factors causing land subsidence and then identify the main drivers that can change the system. The factors used in the MICMAC analysis were made into a matrix of the relationship between the influences and dependencies between factors. The MICMAC analysis approach to obtain relationships between factors in a system problem was also used in several previous studies (Ahmad et al., 2019; Ariyani et al., 2022). The relationship between elements in MICMAC can be written through the cross-matrix, as seen in Table 3. Filling in the cross-matrix, which describes the unidirectional relationship between factors in Table 3, is done by quantifying the relationship between factors using a scale of 0 to 3 and P. According to Godet (1994), the numbers and letters have the following meaning: 0 = no influence; 1 = weak influence relationship; 2 = moderate impact; 3 = strong influence relationship; and P = potential relationship (cannot be determined by agreement). This scale is used as a guide for assessing the relationship between factors causing land subsidence. The results of the questionnaires were collected from 7 expert sources in the field of land subsidence control from government agencies and universities. These experts are members of the land subsidence control experts in Pantura. Then, we conducted in-depth interviews in an FGD. The data were adjusted according to the expert's perception of the phenomenon of land subsidence. All expert's assessment results were selected based on the median value, as shown in Table 4.

3. RESULTS AND DISCUSSION

3.1 PS-InSAR Implementation Results

Processing results of Table 1 of Sentinel-1A radar image data using the PS-InSAR method in the Jakarta City areas can be seen in Figure 5. Meanwhile, the visualization output from SARPROZ in the form of an automatic sparse point distribution is overlaid with Google Earth without any borders administrative area. The resulting spare points totaled 309071 monitoring points. By using the PS-InSAR implemented in SARPROZ, we can monitor the land subsidence deformation of Jakarta City. Monitoring can be done with points that have the potential for land subsidence. As a general description regarding the spatial distribution of land subsidence can be seen in Figure 6, we overlay the number of sparse point distributions with the administrative boundaries of Jakarta for monitoring points, producing a total of 161206 points. The results of the PS-InSAR method show land subsidence and uplift in the study area. Based on PS-InSAR results, land subsidence is -5.71 cm/year (red to pink), and uplift is 3.8 cm/year (pink to blue). Using the same technique, the results from Sidiq et al. (2021) show a relatively close rate of decline of up to 5 cm/year in the 2016-2020 period. The use of techniques other than PS-InSAR, such as leveling and GPS methods, sometimes produces very different values at monitoring points (Sarah, 2022).

The results of this study show that land subsidence in Jakarta is evenly distributed throughout the region. For sub-regions that have the potential to experience land subsidence, the largest average is in North Jakarta and West Jakarta, and parts of East Jakarta. In this area, it shows that the risk of land subsidence impacts is higher, supported by population density and industrial economic activity. Figure 6 (a and b) is an example of the results of monitoring points from PS-InSAR implemented in SARPROZ. Figure 6 (a) represents a densely populated residential area, while Figure 6 (b) represents an area of economic and industrial activities, which is also indicated as a factor causing land subsidence in the Jakarta area. The use of PS-InSAR spatial analysis was also carried out by Bott et al. (2021b) and Widodo et al. (2022), that land subsidence is evenly distributed, dominantly occurring in North Jakarta and West Jakarta. This land subsidence is thought to be caused by population density and industrial economic activity (Widodo et al., 2022). These results are an initial identification to see what factors cause spatial land subsidence. In addition, to confirm the identification results, a correlation of the results of the system assessment by experts was carried out. The assessment was carried out to find out what are the main factors causing land subsidence in the study area.

Tabel 3. Matrix of inter-factor relationships in MICMAC.

	F1	F2	F3	-	Fn	Influence (Y-Axis)
F1	0	(F1,2)	(F1,3)	-	(F1,n)	$\sum_{j=1}^{n}(F1,j)$
F2	(F2,1)	0				
F3	(F3,1)		0			
-	-			0		
Fn	(Fn,1)				0	
Dependence (X-Axis)	$\sum_{i=1}^{n}(Fi,1)$					

Tabel 4. Matrix rating scale from experts.

	Factors						
	1	**2**	**3**	**4**	**5**	**6**	**7**
F1							
F2							
F3							
F4							
F5							
F6							
F7							

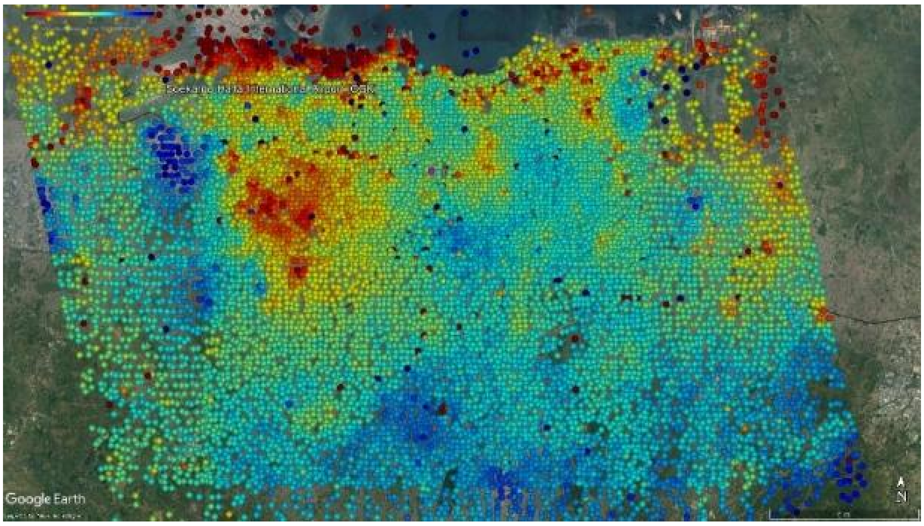

Figure 5. Land subsidence sparse point distribution based on PS-InSAR

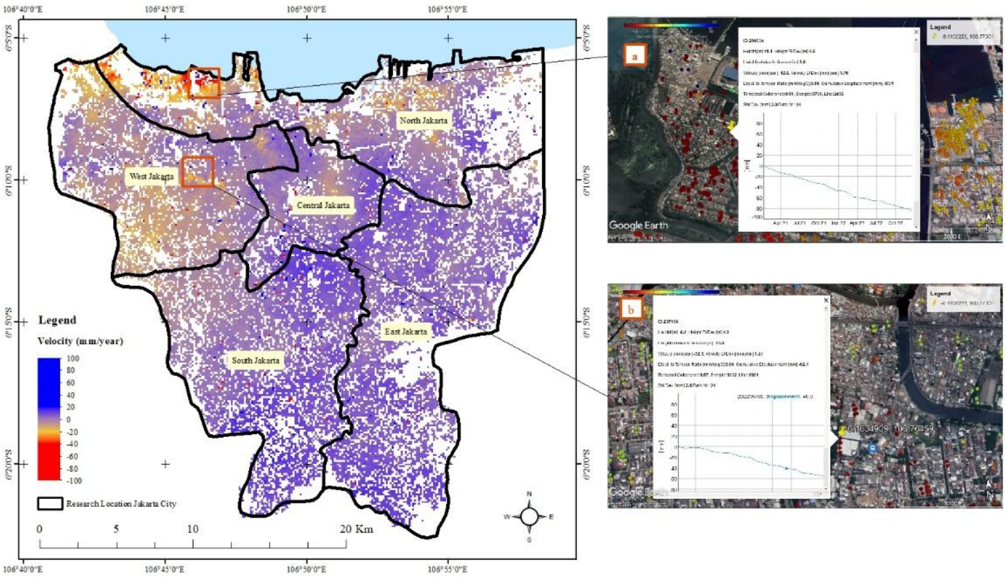

Figure 6. The deformation map of the Jakarta area is linked to monitoring

3.2 Results of Analysis with MICMAC

Based on the results of the expert questionnaire in Table 4, a Direct Influence Matrix (MDI) was created in MICMAC, as seen in Figure 7. From the results of Figure 7, a mapping of factors in MICMAC will be produced, as seen in Figure 8. The factors in MICMAC analysis are divided into four quadrants, namely Influence Factors or Main Driving Factors (I), Relay Factors (II), Dependent Factors (III), and Autonomous Factors (IV). Quadrant I means factors that have a significant influence on the system or problem. In Quadrant I in Figure 8, it appears that excessive groundwater exploitation (exp_water) and natural consolidation of alluvial soil (alluvial) are factors that have a significant influence or are key factors for problems in the system. In other words, these two factors are the main triggers for land subsidence in Jakarta. For the Jakarta area, Widodo et al. (2022) stated that around 60% is caused by excessive groundwater exploitation for residential purposes and commercial activities. However, the other 40% is caused by alluvial soil consolidation. Meanwhile, Hakim et al. (2020) stated that prestigious residential areas such as apartment buildings and housing, as well as small commercial and industrial areas, mostly use groundwater as their water source.

	1 : exp_water	2 : aluvial	3 : exp_builld	4 : popdens	5 : economy	6 : tektonic	7 : landuse
1 : exp water	0	3	2	3	3	0	3
2 : aluvial	1	0	3	2	3	1	3
3 : exp builld	2	0	0	3	2	0	2
4 : popdens	2	1	1	0	3	0	2
5 : economy	1	0	2	3	0	0	2
6 : tektonic	0	0	0	0	0	0	1
7 : landuse	0	1	2	2	2	0	0

Figure 7. Matrix of Direct Influence (MDI) in MICMAC

Furthermore, Quadrant II has a sensitive influence on problems but is not very significant compared to Quadrant I factors. Factors in this position include the burden of building and infrastructure construction (exp_build), population density (popdens), and industrial economic activity (economy). In Quadrants III and IV, factors depend on each other. Quadrant III has factors that depend a lot on other factors but have little influence. The factor here is land use patterns (landuse). Furthermore, in the last quadrant, Quadrant IV, these factors do not have much influence or influence other factors in the system. In this quadrant, only tectonic activity (tectonic) has no significant effect on land subsidence in Jakarta.

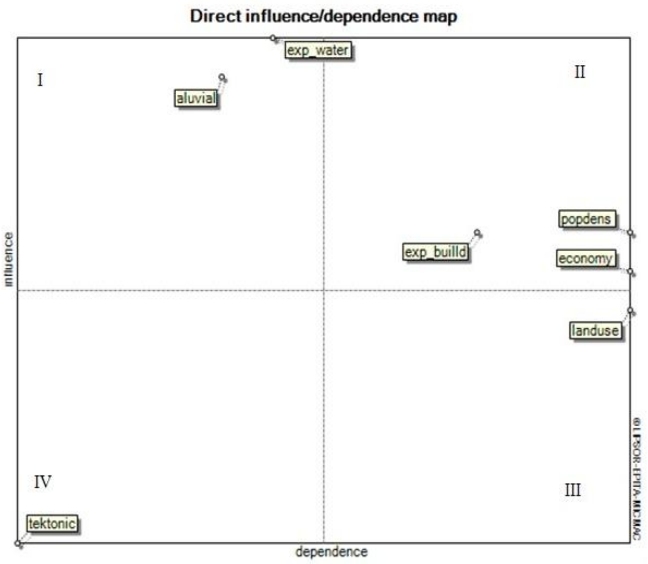

Figure 8. The direct influence factor causes land subsidence

The results of the map analysis of factor positions in the quadrants are an important first step in deeper analyzing land subsidence in Jakarta. From these results, we took the significant factors in Quadrant I to be the main causes of land subsidence in Jakarta. It is used as an adaptation and mitigation material for land subsidence phenomena. Therefore, it is necessary to develop sustainable groundwater management policies to avoid over-exploitation, which can cause land subsidence. Government intervention and strong regulations are needed to slow or stop land subsidence, as various studies show that the main cause of land subsidence is excessive groundwater exploitation.

4. CONCLUSION

The use of PS-InSAR is effective because it is able to provide fast and precise information. Measuring the rate of land subsidence using time-series processing in PS-InSAR succeeded in obtaining rate values and identifying factors causing spatial subsidence. The results show that Jakarta is still experiencing land subsidence evenly in various regions, with an average value of -5.71 cm/year. The dominant areas where land subsidence occurs are West Jakarta and North Jakarta. Excessive groundwater exploitation and alluvial soil consolidation are key factors causing land subsidence in this city.

Government intervention and strong regulations are needed to slow or stop land subsidence. Rules for controlling groundwater extraction have been issued in Jakarta, require supervision to ensure they are properly implemented and must be complied with comprehensively. Furthermore, this research requires regular measurements every year continuously to see trends in the rate of decline. Moreover, regulations for controlling land subsidence have been issued; this is used to monitor before and after the regulations are issued what conditions will be like now and in the future.

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