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Land Subsidence Susceptibility Projection for Palembang Slum Area by Complex MCDM-AHP Technique

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Highlights:

- Groundwater withdrawal is the major cause of land subsidence and usually occurs in rapidly developed and highly populated areas.
- Land slope, sediment type, lithology, wetlands, river networks, and land gradient have a direct influence on subsidence susceptibility.
- The high correlation between predicted land subsidence susceptibility and slum areas shows that the occurrence of land subsidence has a high relationship with residential activities and land surface properties.

Abstract. Land subsidence is a geomorphological event that affects Earth's structure and physiognomy. This phenomenon occurs when the groundwater volume changes and results in the movement and sinking of sediment. Several studies have been conducted to identify major causes or factors that may lead to land subsidence. It was found that land subsidence intensity is influenced by several factors, i.e. terrain slope and aspect, land use, soil moisture content, and distance to a river. Population density contributes to continuous changes in land use. Deep investigations of factors that contribute to land subsidence such as population density are important. This study investigated the relationship between land subsidence and population density contributing to continuous land-use changes. The study area was a highly populated slum area along the Musi River in Palembang, Indonesia. Factors that have high contributions to land subsidence were considered in developing a land subsidence susceptibility map. Susceptibility analysis was done using the Analytical Hierarchy Process (AHP) method. Land subsidence features were associated with slum features and the result revealed a significantly high correlation ($r = 0.844$) between actual land subsidence areas and the developed susceptibility map.

Keywords: *Analytical Hierarchy Process (AHP); land subsidence; land use; Multi-Criteria Decision Making (MCDM); slum.*

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1 Introduction

Land subsidence is a global problem where land sinks due to changes in land structure, groundwater withdrawal, unplanned land use, or land cover. Human activities such as urbanization continuously change the structure of the land, which can lead to land subsidence events. Land subsidence events not only change the land structure and elevation but also any structures on it such as buildings, road channels, sewerage systems, and underground pipelines and cables. Land subsidence can also induce other natural disasters, such as floods. Land subsidence negatively impacts the environment, human health, and economic activities locally. According to Giuseppe, *et al.* [1], groundwater withdrawal is the main cause of land subsidence, usually occurring in rapidly developed and highly populated areas.

Natural land subsidence involves unconsolidated sediments and underground minerals as well as carbonate suspension. There are also man-made factors related to land and water use that influence the land subsidence process. Natural land subsidence is initiated when the stress distribution changes and subsurface sediments are compacted. The stress distribution can change due to the pumping of groundwater, initiating a modification of fluid-dynamic properties. The pumping of groundwater for withdrawal purposes introduces disturbances to the local geology. The process of land subsidence involves the deformation and compaction of rock and sediments, which can cause changes in stresses among sediments under the influence of fluid, as recognized by previous researchers. The total geostatic load acting on an aquifer, a reservoir containing beds and caprock, is balanced by pore pressure and subsurface sediment stresses. As the fluid level declines, the pressure drops and the rocks' ability to support the sediment load breaks down. The load is then transferred through the sediments which move the stress from fluid to solid elements and increase the sediment stress level. This leads to the draining of fluid, which then compacts and compresses the formation and sediments underground. The compaction of subsurface layers impacts the ground surface and results in subsidence.

Previous studies done by researchers worldwide involved the discovery of acute factors that influence the occurrence of land subsidence. The main factor contributing to the development of land subsidence is the overexploitation of groundwater [2]. Mineral dissolution is one of the mechanisms that contribute to the formation of sinkholes and land subsidence. Moreover, wetlands that contain saturated organic soils can initiate land subsidence due to oxidation. Global warming which causes climate change has an indirect impact on the occurrence of subsidence. Glacial isostatic adjustments move the Earth's crust, draining the groundwater and causing land to subside.

Researchers have developed land subsidence studies to identify factors that influence its susceptibility. Their findings have shown that land slope, sediment type, lithology, wetlands, river networks, and land gradient have a direct influence on subsidence susceptibility. There are also man-made factors, such as continuous changes of land use and land cover due to urbanization, sewerage areas, and deforestation [3].

Terrain slope and aspect are among the factors that influence land subsidence occurrence. Changes in terrain gradient or slope and underground fissures initiate land subsidence. However, the relationship between the slope degree and land subsidence is still under investigation [4]. Meanwhile, changes in land use and land cover merely contribute to subsidence susceptibility as the structure and groundwater balance change in arid and semi-arid climates. Ref. [5] studied subsidence rate variation related to different types of land use and found that the lowest subsidence rates occur on undisturbed land such as wetland forest, while the highest susceptibility of land subsidence rates occurs in mixed agricultural and highly-dense population areas, also known as slum areas. Meanwhile, there has also been a substantial increase in the occurrence of land subsidence in mangrove areas. The rate of subsidence has increased due to the characteristics of mangrove areas, which are located near the coast and are classified as unstable sediment structures despite not being disturbed by human activity. In mangrove areas, sediment is continuously deposited, forming an incoherent base [6].

Road networks are another unnatural factor that influences land subsidence susceptibility. This feature gradually alters terrain stability, which further induces land subsidence. Norbazlan & Biswajeet [7] concluded that slopes close to road networks are unstable. Hence, land subsidence susceptibility is higher in areas close to road networks.

Other factors that can influence land subsidence susceptibility are sedimentation and soil characteristics. Subsidence usually occurs in loam and sand areas due to their low elasticity compared to clay and peat. Widada, *et al*. [8] have studied the influence of lithology and rock type on land subsidence occurrence and found a high occurrence of land subsidence at thick and soft layer structures. This is due to the compression of the soft layer when force is imposed by any structures on its upper layer.

Several studies have been conducted to discover the relationship between land subsidence-prone areas and rivers. Previous researchers have concluded that areas close to a river are more likely to encounter land subsidence and landslides due to erosion of the soil caused by the streaming of water [9]. Hence, the closer the area to a river the higher the possibility of land subsidence occurring. Figure

1 shows the relationship between the discussed factors that lead to higher land subsidence susceptibility and the importance of land subsidence analysis.

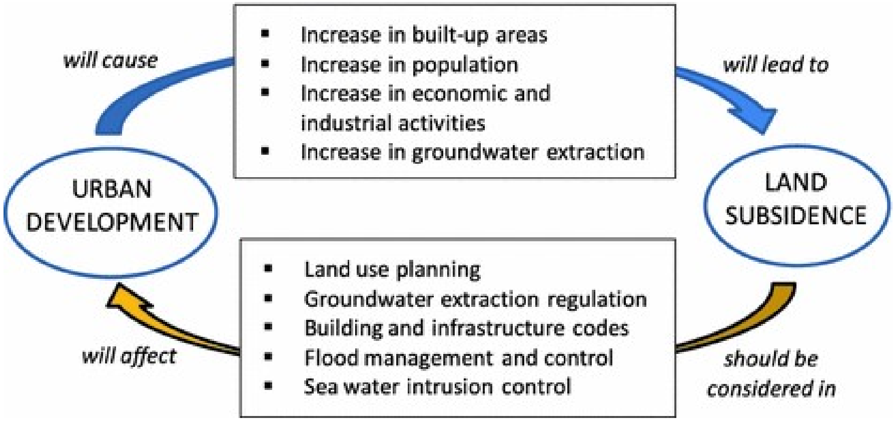


Figure 1 Factors that lead to land subsidence and their impact. (Source: Abidin *et al.* 2015).

Figure 1 illustrates the impact of urban development on land subsidence susceptibility by the increase of a number of closely related factors such as increased built-up area coverage caused by population increase. The expansion of an urban area also increases local economic and industrial activities, resulting in increased groundwater extraction. These urban developments may lead to land subsidence activity. Hence, it is important to consider land subsidence susceptibility in land-use planning, the development of groundwater extraction regulation, codes for building and infrastructure, and finally in controlling and managing flooding and seawater intrusion.

This study attempted to relate the tendency of land subsidence occurrence to slum areas. Densely populated areas have high rates of subsidence occurrence. Abidin, *et al.* [10] conducted a study on the subsidence rates and concluded that the degree of subsidence is high in slum areas due to a combination of two man-made subsidence drivers. These drivers are 1) a wastewater system that lowers the groundwater level and its overexploitation, and 2) changes of sediment structures for construction of buildings and facilities for urbanization purposes. A sewage tank is a man-made reservoir that collects domestic and industrial waste that is supplied by a drainage system. This reservoir changes the structure of the underground land and water, which then leads to instability of the land structure due to erosion and groundwater leakage [2]. Land subsidence is initiated at the floor of the reservoir and deteriorates over time. This study aimed to predict the possibility of land subsidence occurrence in Palembang, Indonesia by simulating all causing factors related to the area.

2 Data Acquisition

The study site selected for this study was located in Palembang, South Sumatra Province, Indonesia. Palembang's topography is relatively flat with an elevation not more than 5 m above mean sea level [11]. The total area of Palembang is 401km^2 and is divided into 18 districts. Palembang has high slum areas, especially along the Musi River, and the slum areas are situated in wetland areas [12]. Slum containment in Palembang is based on a population density of 100 people per hectare (ha).

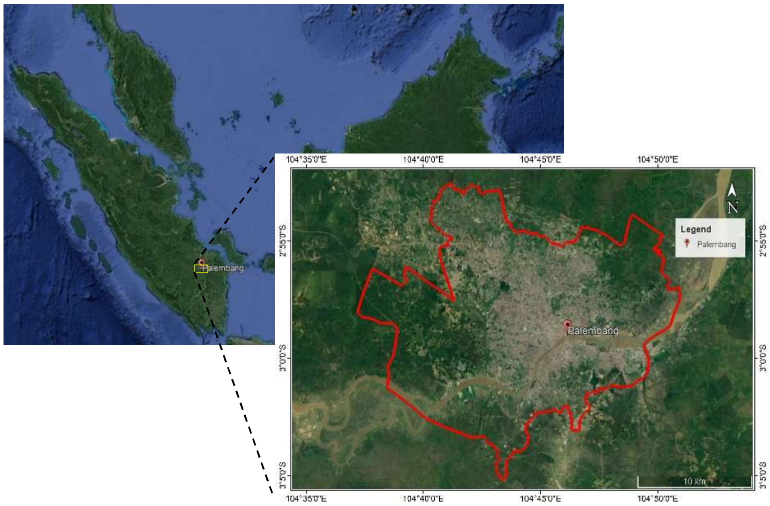


Figure 2 The study location in Palembang, Indonesia (Source: Google Map).

The data used in this study was provided by the Kota Tanpa Kumbahan (KOTAKU) program that aims to reduce the total sewerage area in Palembang through strategic planning by government authorities. This program supplied land-use data, lithology, residential area, road and river networks, and sewage area data for the study. These data were acquired using ground measurements during on-site visits covering the whole of Palembang. These data were gathered from Geoportal Sumatera Selatan, an Indonesian government-authorized portal that provides geospatial information of features in Palembang. Digital Elevation Model (DEM) data was provided by the Geospatial Information Agency of

Indonesia. This raster data was derived using digital stereophotogrammetry. The resolution of the DEM data was 8 m and the terrain elevation ranged between 0 and 41 m. This raster data was used to generate terrain slope and aspect for further analysis in the land subsidence susceptibility study.

3 Methodology

A land subsidence susceptibility map was derived by using the AHP technique. AHP is a mathematical technique that uses ranking for making complex decisions. Besides ranking, AHP also provides judgment scales and a consistency test. In this method, a ratio scale and consistency index is derived using the eigenvector and eigenvalue method. In summary, AHP prioritizes selection criteria from the most important to the least important factor [13].

The AHP process in predicting land subsidence susceptibility involves several phases, i.e. problem modeling, weight evaluation, weight aggregation, and sensitivity analysis. This study started with problem modeling, which was done by the establishment of the objectives and criteria to be ranked. Then, the difference among the factors was assigned as weight. The weight of the criteria was calculated by expanding the comparison matrix and comparing with the local weight all alternatives. The evaluation scales of pairwise comparison related to the AHP process for factors that influence land subsidence are shown in Table I.

Table 1 Land subsidence factors and their weight values.

Weight Value	Criteria	Explanation
1	Terrain slope	The terrain slope is associated with gravitational forces. Steep slopes are less stable compared to flatter surfaces [14].
2	Terrain aspect	The terrain aspect is the angle of the slope. It influences subsidence by rain, sun, and wind exposure [7].
8	Land-use change	Land use is the main anthropogenic factor that influences land subsidence. Disturbed land is more likely to experience land subsidence compared to undisturbed land [15].
8	Slum area	Slum areas, or high population density areas, result in extensive conversion of land use [16].
8	Sewage area	Sewage as aquifer recharge causes soil erosion and accelerates land subsidence [17].
9	Lithology	Sedimentary rock has a higher tendency to experience land subsidence [9].
9	Distance to road	Land closer to constructed roads is less stable [18].
9	Distance to river	The tendency of land close to a river experiencing landslides is higher due to soil erosion [2].
9	Soil type	Loam and sand have a higher possibility to experience subsidence compared to clay and peat [8].

Table 1 shows the priority of each factor in relation to land subsidence occurrence that was assigned according to their weight value. Weight value 1 was considered as a factor with a low influence on land subsidence susceptibility, while 9 is considered as a factor with a very strong and direct influence. A medium-weight value (from 3 to 7) reflects a moderate influence on land subsidence occurrence and evaluation against other factors requires experience and judgment.

The next step in the AHP process is weight aggregation and involves mathematical analysis after a hierarchical ranking has been determined [19]. The comparison matrices are constructed according to the following equation:

$$A = \begin{bmatrix} a^{11}a^{12} & \dots & a^{1n} \\ a^{21}a^{22} & \dots & a^{2n} \\ a^{n1}a^{n2} & \dots & a^{nn} \end{bmatrix} \tag{1}$$

where

$[A_{ij}] = i, j, = 1, 2, \dots n,$
$A_{ij} = 1$ for $i=j$,
$A_{ij} = 1/ A_{ij}$ for $i \neq j$

The matrix of dimension n × n (n is the number of comparison factors) is inserted into the above equation to calculate the criteria's weight with an alternative weight through a normalization procedure. The calculation of the total data in each row can be done using the following equation:

$$Wi = \sum_{j=1}^{n} aij, i = 1, 2, \dots n \tag{2}$$

The normalization of all factors' weights is done with the following equation:

$$Wi = \frac{\sum_{j=1}^{n} aij}{\sum_{k=1}^{n}\sum_{j=1}^{n} akj}, i = 1, 2, \dots n \tag{3}$$

Finally, the alternative weights are determined with the following equation:

$$B \times V = \begin{bmatrix} b^{11}b^{12} & \dots & b^{1n} \\ b^{21}b^{22} & \dots & b^{2n} \\ b^{n1}b^{n2} & \dots & b^{nn} \end{bmatrix} \begin{bmatrix} v^{1} \\ v^{2} \\ v^{n} \end{bmatrix} \tag{4}$$

The above equation shows that the rows contain the weights of the factors and the criteria are presented in the columns. Meanwhile, element *v* reflects the transpose of each factor's weight and finally, the global weight is obtained by applying an operation on matrix *b* and *v*. Finally, the consistency of the selection derived by the AHP process is measured by using Eqs. (5)-(7) [20]. The consistency test starts with the calculation of the maximum eigenvalue using Eq. (5):

$$Eigenvalue_{max} = \frac{1}{n} = \sum_{i=1}^{n} \frac{(Aw)I}{wi} \tag{5}$$

Then, the maximum eigenvalue is inserted into Eq. (6) to derive the consistency index, *CI*:

$$CI = \frac{(Eigenvalue_{max} - n)}{n-1} \tag{6}$$

Then, the consistency ratio, *CR*, is derived using the following equation:

$$CR = \frac{CI}{Random\ Average\ CI} = \frac{(Eigenvalue_{max} - n)}{r(n-1)} 100\% \tag{7}$$

A consistency ratio of less than or equal to 10% indicates inconsistency but is still acceptable, while a consistency ratio of more than 10% means a revision of the weight value assignment of each factor needs to be considered. The derived map of land subsidence susceptibility was then compared to the existing sewage and slum areas that were believed to have a high relationship with land subsidence occurrence. The results are discussed in the following section.

4 Results and Discussion

The weight value assigned to each factor produced a map according to the criteria that had previously been set. Terrain slope, terrain aspect, distance to a river, and roads were reclassified to 10 classes. This was because the overlay process based on weight only accepts an integer raster as input. The reclassification process is a data treatment process where the optimal criteria needed for the estimation of land subsidence can be derived for standardization [19]. It is used to maximize the precision of the land subsidence susceptibility assessment. The terrain slope was reclassified to 10 classes with an interval of approximately 5°, while the terrain aspect, which indicates the direction of the slope, was classified with an interval of 35°. Distance to a river and roads was classified into intervals of 10 km for each class. Each class was assigned a single value according to their weight, as listed in Table 1.

All elements of the land-use and lithology raster were assigned a single value so mathematical operations could be performed on the raster-based on the criteria weight. Biswajeet, *et al*. [7] mention that almost all land subsidence events occur in karst areas where limestone and marble rocks are dissolved by water. The elements in the land-use raster were assigned the scale values as shown in Table 2.

Table 2 Land-use categories and their scale values.

Land-use type	Scale value
Swamp bush	5
Open land area	6
Swamp	6
Residential area	9
Mixed dryland agriculture	7
Shrubs	3
Dryland agriculture	4
Paddy field	5
Dry and swamp forest	5
Secondary forest	1
Plantation	7
Urban area	8
Water bodies	7

Clay, silt, and sand in the lithology raster were assigned a scale value of 1; sand, mud, and coal were assigned a scale value of 9; and swamp deposits were assigned a scale value of 5. The geometric intersection of the map derived from this arithmetic process was then calculated, with slum and sewage areas to identify the final area of the land subsidence approximation. Figure 3 shows the land susceptibility map derived by weighted overlay tools that join the sets of factors to identify the spatial relationship between them.

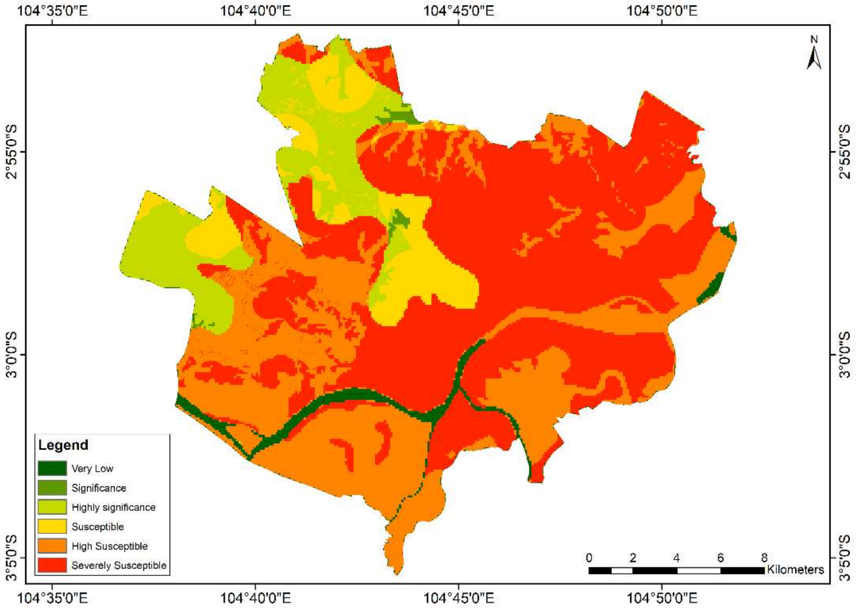
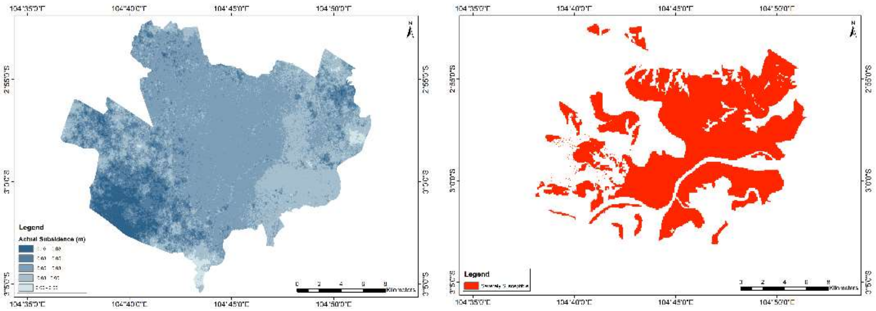


Figure 3 The derived land subsidence susceptibility map.

The derived land subsidence susceptibility map in Figure 2 represents each susceptibility zone by number. Zone 0 represents zones with no land subsidence occurrence while zone 9 represents areas with very high land subsidence susceptibility.

Figure 4 shows a comparison between actual land subsidence events in the study area and the result derived in this study. The actual land subsidence events were collected and processed by Geoportal Sumatera Selatan through site surveys in the study area. The actual land subsidence map in Figure 3(a) shows that the land in Palembang subsided in a range between 0.03 and 0.16 m below mean sea level. Land subsidence has developed in the whole Palembang area; only 3% of the area has not experienced land subsidence. The result shown in Figure 3(b) illustrates that the predicted subsidence areas derived in this study cover 76.8% of the study area.



(a) (b)

Figure 4 Actual land subsidence events (a) and predicted land subsidence (b) in Palembang, Indonesia.

This shows that all parameters involved in this study influence land subsidence susceptibility. It also explains the land subsidence events in almost all areas of Palembang, as shown in Figure 3(a). Terrain slope and aspect play an important role in determining land subsidence areas due to their close relationship with gravitational forces. As land slopes in Palembang range between 0° and 89.9°, characterized as flat to very steep land, the current study is supported by [7]. This study concluded that higher slopes have a higher tendency to sink compared to lower slopes. Furthermore, slope stability is a key factor in determining the degree of damage caused to buildings and land structures by land subsidence [4]. Land use is an anthropogenic factor that leads to land subsidence occurrence. Vegetation is the most dominant land use and its influence on land subsidence susceptibility varies with the type of vegetation [21]. Secondary forest is a type of vegetation that has little influence on land subsidence susceptibility due to its deep-rooted structure, because of which it can hold soil and land and preserve groundwater. Other vegetation such as paddy and mixed-crop areas have a high potential to contribute to land subsidence events because they cause changes in soil permeability and stability. Mangrove and swamp forest areas most likely promote land subsidence due to the location of these areas, i.e. in delta plains close to the coast, and are considered geologically young [22]. The land use in Palembang changes constantly due to natural and anthropogenic forces, especially in highly populated areas. Meanwhile, lithology and sediment types contribute to land deformation, thus initiating land subsidence because of the shrinkage of rock mass stability as a result of tectonic disruption [3]. Palembang consists of 94.6% swamp deposit, 5.3% clay, silt, and sand, while the remaining area consists of sand, mud, and coal.

Further processing revealed the intersection between high land subsidence susceptibility areas and slum areas in the derived map, as shown in Figure 5.

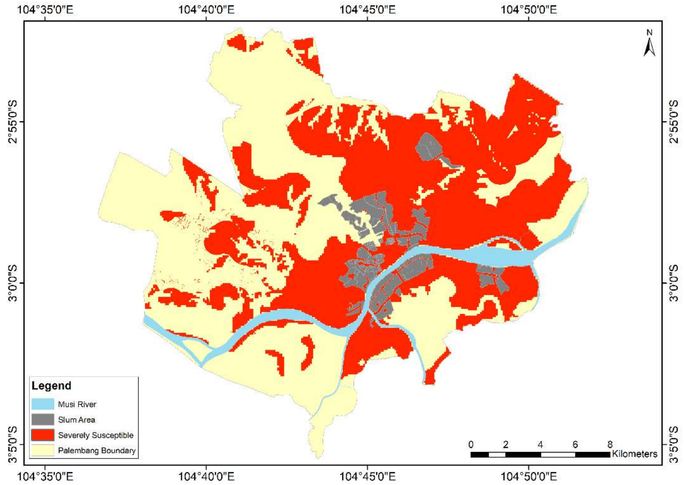


Figure 5 Map showing the intersection between high land subsidence susceptibility areas and slum areas.

Figure 5 illustrates the total predicted land subsidence areas derived in this study, covering 84.4% of the highly populated slum areas in Palembang. This shows that the occurrence of land subsidence has a high relationship with residential activities and land surface properties. The high percentage of land subsidence occurrence in slum areas shows that overcrowded and squalid urban areas mostly inhabited by underprivileged people in one small area contribute to land subsidence occurrence. It can be concluded that an increase in population will increase the rate of land-use changes and weight. This situation will contribute to more land subsidence events, which is in agreement with Minderhoud, *et al.* [5], who studied the connection between land-use changes and subsidence events in the Vietnamese Mekong Delta. Changes in land use result in a reduction of land elasticity. The softening of the ground lowers the infiltration rate of the soil and initiates a downward movement of the land. The infiltration rate is reduced due to the penetration of fine particles into non-cohesive soil, reducing soil volume and resulting in land compression. On the other hand, malfunctioning drainage systems may also lead to the sinking of an urban area. This study discovered the relationship between disturbed areas such as slums, drainage systems such as sewerage, mixed-crop agriculture, and urban with land subsidence events. Land-use changes initiate land subsidence through long-term effects towards the groundwater level, which change the hydrostatic pressure and cause land compaction.

5 Conclusion

The main contribution of this study consists of relating land-use changes to land subsidence occurrence. A high rate of land-use changes, for example in highly populated areas, may result in high susceptibility of land subsidence. Adjustment of groundwater recharge, for example in drainage or sewage areas, was also found to contribute to land subsidence occurrence. In conclusion, this study agrees with previous researchers who concluded that land-use changes contribute to land subsidence occurrence.

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