

An Analysis of Sinkhole-Prone Areas Through Hydro-Geomorphological Analysis

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Abstract: Sudden sinkhole events pose a threat to the property and life of citizens in large cities with dense social infrastructures. Sinkholes take place around the living areas of people due to sudden climate changes and urban development and there is a need to analyze and investigate them to make a total plan for urban disaster measures. This study set out to collect hydro-geomorphological information from sinkhole areas, analyze their characteristics from a hydro-geomorphological perspective with the Analytic Hierarchy Process (AHP) and GIS spatial analysis tools and identify sinkhole-prone areas. The study calculated the weighted rates of multiple factors identified before by applying the AHP theory. Based on the factors identified to evaluate sinkholes, the study selected and built spatial information including the sinkhole maps covering their locations. Such GIS spatial analysis techniques were used to obtain the analysis results of identified spatial information that reflected hydro-geomorphological characteristics. The findings led to the identification of sinkhole-prone areas from a hydro-geomorphological perspective. It was also found that adjacency, flow inclination of underground water and underground water levels of hydro-geomorphological factors turned out to have significant connections with sinkholes in the identified areas and that the possibility of sinkholes were high in non-residential areas. The spatial analysis with GIS produced the results shown in the risk of sinkholes in figure which categorized the risk of sinkholes into A, B, C and D for spatial presentation. Category A accounted for 27% which means that it was very vulnerable to sinkholes from a hydro-geomorphological perspective. The study analyzed the hydro-geomorphological characteristics of multiple factors of sinkholes with the GIS analysis technique and found that the risk of sinkholes was high around residential areas and in the roads, thus, raising a need for the urban facility management agencies to manage sinkholes systematically. In addition, the urban administration staff needs to conduct analysis and research on sinkholes by making active use of GIS and upgrade and apply the risk index of sinkholes on an ongoing basis based on the results. These findings may serve as major, basic data in the fields of urban disaster prevention and urban planning in the future and raise a need for extended research to integrate the field of facility management.

Key words: Sinkhole, hydro-geomorphological, GIS, spatial analysis, AHP, administration

INTRODUCTION

In large cities, all kinds of infrastructures are concentrated with the continuity of reckless development underground as well as on the ground due to the ongoing demand for urban infrastructure. Most of all, the sprawling development of all sorts of underground facilities including subway stations has caused the abrupt discharge of underground water and thus, the outbreak of various accidents including sinkholes. The frequency of sinkholes has recently increased due to complex causes such as the rising discharge volumes and expanding variability of underground water levels caused by sudden rainfall following the changing natural environment, development of underground facilities and damage to underground pipes of all kinds. Sinkholes take place suddenly with no signs in advance and lower the quality of life for citizens in addition to damaging human life and

property. There has been recent research on sinkholes with various physical investigation techniques and probing technologies such as radar satellite images (Bai *et al.*, 2012; Iqbal *et al.*, 2015; Pathak *et al.*, 2009). This research predicted sinkholes and investigated countermeasures, developed a technology to assess the danger of sunken roads, devised a system to detect sinkhole voids or evaluated environmental influences to prevent sinkholes (Kim, 2016b). Most of these studies, however, remained at the level of monitoring sinkholes or focusing on the maintenance of underground facilities, providing few practical findings to prevent urban disasters (Kim, 2016a). Thus, there is a need for specific findings to predict and prevent sinkholes in order to reduce all sorts of events and property damage related to sinkholes in urban areas with a concentrated population. It is also required to take specific measures for urban development and systematic underground water

management based on them. The present study aimed to conduct spatial analysis for sinkhole risk factors with GIS, AHP and hydrological and geomorphological spatial information dynamically related to sinkholes and make a prediction of sinkhole-prone areas based on the results.

MATERIALS AND METHODS

Causes of sinkholes and the analysis of their risk:

Sinkholes are also called land subsidence and dolines, the latter of which is a scientific term. Sinkholes happen when the ground can no longer endure the pressure of discharging matters that used to take up space in the ground. There are two major causes of sinkholes: hydro-geomorphological ones and manmade ones due to urban development. In the former case, sinkholes happen in the areas with a high percentage of limestone which easily makes void space underground in the alluvial layers and in the fault planes. When limestone interacts with underground water, it melts and creates a void. When there are rapid environmental changes such as intensive rainfall in Summer, they can cause a crack in the limestone area and thus increase the possibility of rapidly expanding voids underground. In South Korea, most of the territory is comprised of granite and gneiss layers but there is a broad distribution of limestone areas which hold the possibility of voids underground. In the latter case, there are all sorts of construction related to underground structure installation in cities with a concentration of infrastructure of all kinds and they can cause the discharge of underground water and thus, sinkholes. Another major cause of sinkholes in this case is the damage of underground facilities due to all sorts of construction. Table 1, the major causes of sinkholes include topographical and geological ones, the discharge and changing level of underground water due to the development of underground water tube wells and the overpumping of underground water, water leaks in water supply and sewerage pipes, development and poor management of coal mines in abandoned mine areas and others including earthquakes (Kim and Kim, 2013).

The data of Ministry of Environment and Ministry of Public Safety and Security report that there were over 40 sinkholes around the nation in the last 10 years (2005~2016) and that Seoul recorded the biggest number of sinkholes. The major causes of sinkholes were natural occurrences, underground development and damaged water supply and sewerage pipes. It was also reported that the forms and sizes of sinkholes varied widely from small to large. Chosen as the subject area, Cheonan City is a local autonomous entity that is active with urban development and attraction of businesses. It has recently

Table 1: Major causes of sinkholes

Causes	Areas of occurrence	Characteristics
Geographical	Steeply sloped underground water level/limestone areas	Rapid movement of Long-term progress
Discharge of underground water	Tube wells/understructure construction sites	Long-term movement of underground water, Rapid movement of underground water
Leakage in water and sewerage pipes	Pipe burial sites	Rapid movement of underground water
Others	Abandoned mine areas/earthquake areas	Long-term progress, Rapid progress

Table 2: Current status of sinkhole (Cheonan-si)

ID	Years	Areas of occurrence	Causes	Scale (depth×width×wide) (m)
1	2011	Residential areas	Ground subsidence	0.5×0.5×0.5
2	2014	Main trunk roads	Underground discharge of sewage	2×2×10
3	2015	Main trunk roads	Underground discharge of sewage	1×0.5×1
4	2015	Commercial areas	Underground discharge of rainwater	2×1.5×2
5	2016	Residential areas	Underground discharge of sewage	1×1×2
6	2016	Residential areas	Underground discharge of sewage	2×1×1

started its broad development of underground water tube wells in the urban development process which means that it is time for the city to prepare measures to prevent urban disasters related to sinkholes due to the discharge of underground water. There were six recent sinkholes in the city in the last 6 years (Table 2).

The 6 sinkholes took place near residential areas or main trunk roads with a huge traffic volume with two of them happening at the same site. The average depth of the six sinkholes was 1.4 m which is bigger than 1.2 m, the national average depth. The average depth of underground utilities was 1.2, 1.5, 1.0, 1.7 and 0.7 m for water supply and sewerage pipes, electricity, gas, heating and communication, respectively which suggests close relations between sinkholes and the safety of underground utilities. Sinkholes are on the rise in Cheonan like the rest of the nation (Choi, 2016; Kim, 2013). Most sinkholes happen suddenly with no particular signs in advance. Sinkholes can be assessed with road surface images or modified measurement equipment, inspection equipment for road conditions such as physical investigation equipment and prediction techniques using radar satellite images (Kim and Kim, 2011; Lee, 2010; Deb *et al.*, 2004). The old evaluation techniques for sinkholes find the discharge of underground water due to damaged underground utilities as the major cause of sinkholes and accordingly use the concept of exploring the underground from the ground surface (Lim and Kang, 2015; Tistory, 2014). There is however, a need to assess the causes of sinkholes with a hydro-geomorphological

analysis technique, since, sinkholes are very closely related to such geomorphological characteristics as geology and underground water level. Sinkholes happen due to complex hydro-geomorphological factors which include topography, geology, underground water level and adjacency analysis results. The present study made an overall review of previous research findings and the applicability of topographical spatial information to figure out the causes of sinkholes and selected topography, geology, underground water information and location of tube well around the hydro-geomorphological field.

To analyze sinkhole-prone areas is needed to quantify the multiple selected factors. That is, there is a need to make decisions about the priority and weight of multiple factors. Many evaluation models have been developed to support the decision-making process and they have made various progress according to evaluation techniques, goals and subjects. These approaches can be applied to the entire or part of evaluation process. In a multi-factor evaluation model in general, the grade scopes are divided by the evaluation factors identified for the given question and then the grade scores are assigned to each grade scope. In a multi-purpose, multi-factor decision-making question, however, the hierarchical structure of evaluation factors can promote the effectiveness of evaluation further based on multiple factors whose relative importance varies. Analytic Hierarchy Process (AHP) can be a desirable decision-making technique when it is applied under the guidance of an experienced expert with the theoretical foundation. In AHP, hierarchy represents the abstract nature of the overall structure to figure out the interactions and influences of factors that make up the whole and holds a form of connection from the overall alternative to lower-level alternatives and further to the factors affecting the lower-stage alternatives. It is thus, needed to arrange the component factors and measure the relative importance of factors within the hierarchy in order to set a hierarchical structure. AHP is a multiple decision-making tool used in a situation of quantitative and qualitative problems. It is especially useful for building a hierarchical structure in decision-making situations for the issues that lack information and are pressed for time and identifying preference by granting weight to them. AHP undergoes the basic procedures of defining a problem, building a hierarchical structure for the problem and doing pairwise comparison by the stages in the hierarchical structure.

A hierarchical structure should be built to use AHP. The first step is to decide the weight of each evaluation criterion through a one-on-one comparison. The next step

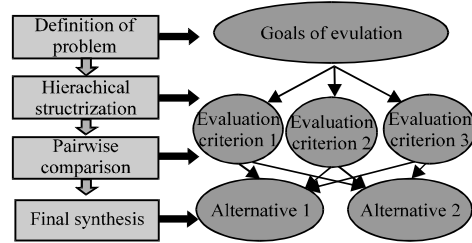


Fig. 1: Concept of AHP

is to assess the preference of design criteria for each evaluation criterion through a one-on-one comparison and make the final choice by converting them into the evaluation value of each alternative from the perspective of a final decision. Here, the evaluation criteria can be further divided into various stages with their importance kept at the same level as independent from one another. The present study calculated the weighted rates of multiple factors identified before by applying the AHP theory (Fig. 1). The relative weight of each factor was determined based on expert opinions and previous research data.

RESULTS AND DISCUSSION

Analysis of sinkhole-prone areas: The spatial scope of this study was Cheonan City. Based on the factors identified to evaluate sinkholes, the study selected and built spatial information including the sinkhole maps covering their locations (Fig. 2), geology (Fig. 3), underground water level (Fig. 4), tube wells (Fig. 5), river networks, DEM and flow path slope of groundwater (Fig. 6). The Korea geodetic datum (central starting points) was set as the reference coordinate system for the topographical spatial information. In addition, topological relations were established with the attributes built in a database to enable manipulation and analysis on the GIS system. The locations of sinkholes were field surveyed to check their geodetic locations and sizes.

Such GIS spatial analysis techniques as GIS map algebra, query, proximity, overlay and surface analysis were used to obtain the analysis results of identified spatial information that reflected hydro-geomorphological characteristics. Vector and raster spatial data should be put to the proximity, overlay and hydrological feature analysis of risk factors in order to analyze sinkhole-prone areas from a hydro-geomorphological perspective. Vector-based data is especially used in proximity and overlay analysis while raster-based data is used in hydro-geomorphological feature analysis. The hydro-geomorphological factors of sinkholes applied in the

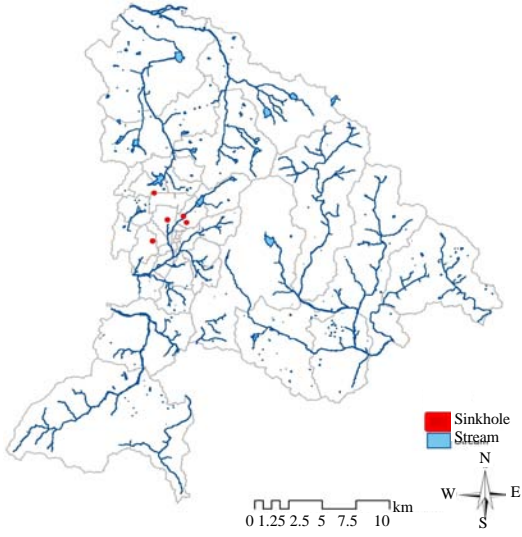


Fig. 2: Sinkhole location

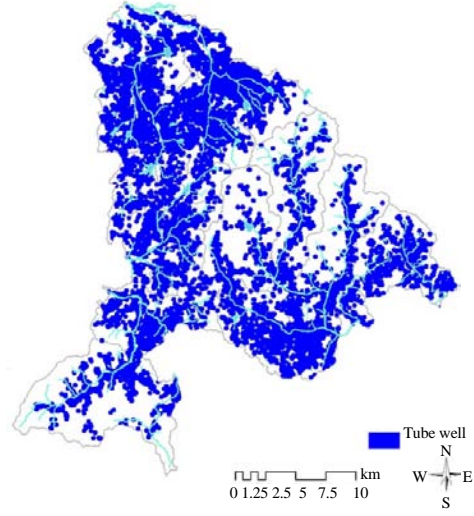


Fig. 5: Tube well

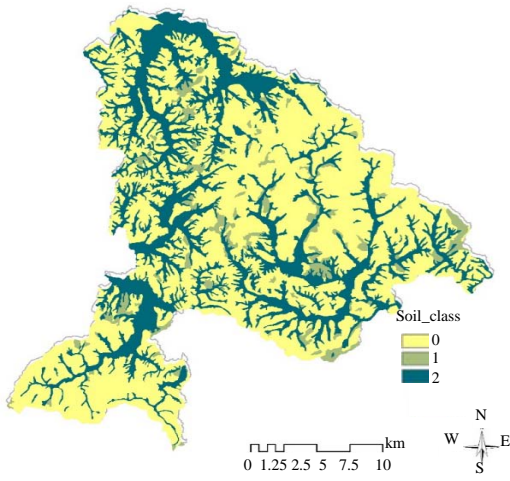


Fig. 3: Geology

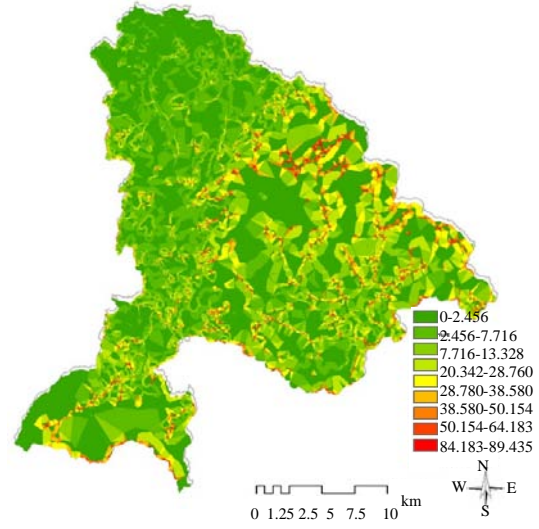


Fig. 6: Flow path slope of groundwater

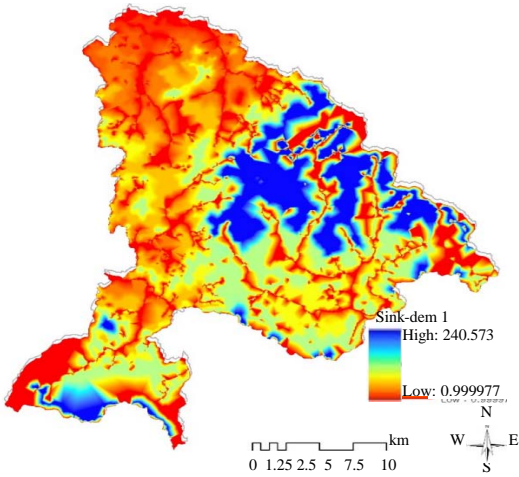


Fig. 4: Underground water level

Table 3: The risk factors and RIW of sinkholes

Factors	Evaluation characteristics	AHP weight
Geology	Faults/alluvial layers/limestone	0.124
Soil	Drainage properties	0.043
Groundwater level	Groundwater level	0.272
Flow path slope of groundwater	Inclination distribution	0.190
Proximity	Distance to the discharge point of underground water	0.371

study were geology, soil, underground water level, flow inclination of underground water and adjacency. Table 3 shows the relative weighted rates of factors analyzed with AHP.

In fault, alluvial layer and limestone areas, geological features melt in contact with underground water which lead to a void underground. The subject area has a

geological feature based on the unconsolidated formation of weathered rock fragments which means sinkholes can happen in the area due to intensive rainfall and other causes. The drainage characteristics of each soil group can be categorized according to the hydrological classification criteria of soil groups. There was an even distribution of A (very good), C (bad) and D (very bad) soil groups in the subject area. Given the current distribution of sinkhole occurrences in Cheonan, sinkholes usually happened in the lower underground water level zones rather than the higher ones. The study also identified the distance between the discharge sites of underground water and the sinkholes and the flow inclination of underground water as the risk factors of sinkholes and conducted analysis of them. Equation 1, the analysis of sinkhole-prone areas involved the optimal proximity analysis, inter-data overlay analysis and hydro-geomorphological feature analysis by applying the influential zone, shortest distance and weight between the reference points and the subject elements:

$$S = O_v \left[\left(\sum_{i=1}^n a_i + N_i + W_i \right)_{P,v}, \left(L_i, \frac{C_{i,j}}{D_{i,j}} \times 100 \right)_{H,r} \right] \quad (1)$$

Where:

- S = The risk index of Sinkholes
- v = Vector-based analysis
- P = Proximity analysis
- a = The influential zone of each factor
- N = The shortest distance between the factors
- W = The weight
- H = The hydro-geomorphological factor analysis
- O = Overlay analysis
- C = The altitude difference between the subject locations
- D = The Distance between the subject locations
- L = The underground water level
- r = Raster-based analysis
- i and j = Factors

AHP was applied to calculate the risk index of sinkholes based on the risk factors of sinkholes. While proximity and flow inclination of underground water of sinkhole risk factors were closely related to the occurrence of sinkholes, soil and geological factors did not have significant effects on the risk of sinkholes. In recent years, however, changes to the meteorological environment tend to become more and more sudden in frequency and alteration which means that they should also receive major attention for management, since, the fluidity of ground and underground soil can increase severely due to such factors as intensive rainfall. The

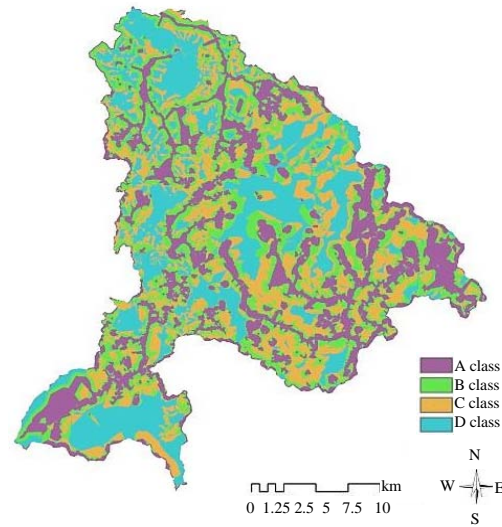


Fig. 7: Risk of sinkholes

Table 4: Analysis results of the risk of sinkholes

Classes	Non-residential areas (km ²)	Residential areas/roads (km ²)	Residential areas (km ²)	Roads (km ²)
A	159.513	0.050	09.906	4.045
B	143.784	0.043	11.855	3.413
C	126.892	0.034	09.754	2.693
D	149.388	0.044	11.056	3.429

spatial analysis with GIS produced the results shown in the risk of sinkholes in Fig. 7 which categorized the risk of sinkholes into A, B, C and D for spatial presentation. category A represents the highest risk of sinkholes at 173.502 km², being followed by category B at 159.094 km², category C at 139.374 km² and category D which is the lowest risk of sinkholes at 163.906 km² (Table 4). Category A accounted for 27% which means that it was very vulnerable to sinkholes from a hydro-geomorphological perspective. In terms of space, category A accounted for 2% of residential areas, 1% of roads and 25% of other non-residential areas, category B accounted for 2% of residential areas, 1% of roads and 23% of other non-residential areas, category C accounted for 2% of residential areas, 0.4% of roads and 20% of other non-residential areas and category D accounted for 2% of residential areas, 1% of roads and 23% of other non-residential areas.

The study analyzed the hydro-geomorphological characteristics of multiple factors of sinkholes with the GIS analysis technique and found that the risk of sinkholes was high around residential areas and in the roads, thus, raising a need for the urban facility management agencies to manage sinkholes systematically. In addition, the urban administration staff needs to conduct analysis and research on sinkholes by

making active use of GIS and upgrade and apply the risk index of sinkholes on an ongoing basis based on the results.

CONCLUSION

The present study analyzed the hydro-geomorphological characteristics of sinkholes with topographical spatial information and GIS analysis technique. Most of the previous studies focused on damage to the underground utilities due to deterioration and the maintenance of underground facilities to find the causes of sinkholes but hydro-geomorphological characteristics determine the flow features of underground water and cause underground voids which means it is essential to analyze them in the evaluation of sinkhole occurrence and risk. This study assessed the analysis values of geology, soil, underground water level, flow inclination of underground water and adjacency in the subject area and analyzed the risk of sinkholes; thus, identifying four risk categories. Category A accounted for 27% of the whole, being considerably vulnerable to sinkholes. It was 91.1, 6.7 and 2.2% for non-residential areas, residential areas and roads, respectively which indicates that the risk category was lower in non-residential areas than in residential areas and roads and thus, raises a need for the management of non-residential areas in relative terms. The likelihood of sinkholes was higher in residential areas than in the roads which means that the current policy of intensive road management should be reconsidered. These findings may serve as the basic data in the prediction and management of sinkholes and also in the work and decision-making of urban disaster prevention.

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