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Article

Evaluation of Inundation Probability and Inundation Depth through Rainfall–Runoff Analysis

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Abstract: Because of their enclosed nature, underground spaces are more vulnerable to flooding than above-ground structures. As a result, flooding disasters have the potential to cause widespread casualties. Major domestic plan manuals such as 'Waterproof Standards Plan Manual for Underground Space Flood Prevention' suggest that the expected flood height is determined and measures are established to ensure safety for underground facilities located in areas where flooding is expected, but no clear methods and standards are presented. In this study, an inundation prediction chart was prepared by performing a one-dimensional (EPA-SWMM) model analysis using the probability rainfall, respectively. Then, data on the depth of inundation where the underground facility is located were extracted using a two-dimensional (FLO2D) model analysis. Using inundation depth and weather data, the probability of inundation for underground facilities and the expected inundation height were quantitatively evaluated through @RISK. Based on the quantitative assessment, it was determined that there was a 7.7% possibility of inundation in an underground space in the case of a 2 h time frame (average inundation depth: 0.1557 m), and a 13.3% possibility in the case of a 3 h time frame (average inundation depth: 0.1655 m). It would be possible to contribute to the development of countermeasures and manuals for underground space flooding using the quantitative assessment described above.

Keywords: urban flood; inundation risk; hazard probability; underground space; flood depth database

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1. Introduction

The amount of precipitation and the number of precipitation days in the Republic of Korea have continued to increase recently, and flood damage in urban areas has become increasingly severe. In Republic of Korea, heavy rain is defined as rainfall exceeding 50 mm/h, 80 mm per day, or 10% of the annual precipitation per day. According to the 2011 report of the Republic of Korea Meteorological Administration, heavy rains in the 2000s nearly doubled compared to those in the 1970s [1]. These torrential rains cause both underground and surface flooding. In addition to causing losses of life and property, flooding in underground spaces can paralyze overall urban functions, such as suspending subway operations or disrupting communication by damaging the communication infrastructures. These effects have recently become more severe owing to climate change [2]. Therefore, flood prevention measures based on the anticipation of heavy rains are required to prevent or mitigate underground flooding. Based on recent flood damage cases, 94,375 buildings were severely damaged in 2001, and approximately 300,000 underground houses faced increased vulnerability to urban flood damage [3].

The main cause of urban floods is the failure of drainage networks in receiving and transporting stormwaters safely when heavy rainfall occurs, as maximum hydraulic capacity is exceeded. In the worst-case scenario, the pressurized sewer channels and submerged manholes return a large quantity of water to the surface, resulting in urban floods [4,5].

According to the Ministry of Public Administration and Security's 2019 revised report "Water Defense Standards Manual for Prevention of Underground Space," establishing an expected flooding height is critical. Although it is desirable to use a flood inundation risk map for estimating the expected flooding height, it is difficult to do so in Republic of Korea owing to the inadequacy of the present flood inundation risk maps. Therefore, it is recommended to make decisions based on a numerical analysis of the inundation height through simulations or on locally collected historical inundation traces, while considering various flooding-related data [6]. However, in the case of current flood trails, only the flooded area is shown. Through flood depth numerical analysis, the expected flood height can be overestimated or underestimated, and a clear standard cannot be presented.

Numerous studies have been conducted to develop mitigation strategies for underground flood damage and to ascertain its causes. Lee [7] studied climate change, increase in impermeable layers, distortion and aging of sewage pipes, sewage maintenance projects focusing on sewage design standards, facility expansions, prioritizing investments in high-risk flooding areas, and comprehensive watershed management measures. Shon et al. [8] classified areas vulnerable to flooding in a hot spring basin using the storm water management model (SWMM), and Lee and Han [9] used ArcGIS, written in Visual Basic for Applications, to develop an urban flooding analysis model integrating a dual-drainage flooding analysis model and underground flooding processes. Kang [10] used the "Disaster Prevention Institute-Underground Space Flood Model" to reveal the characteristics of underground spaces, analyze the changes in underground spaces over time, and calculate the maximum evacuation time based on a flood analysis performed according to the Pond Model. Joo and Kim [11] developed an evacuation scenario in the event of flooding in underground spaces and tested it through empirical experiments. Subsequently, they developed evacuation routes and flooding countermeasure manuals and suggested enhancements to the underground space facility design policy. Toda et al. [12,13] installed an experimental device for monitoring the flooding processes in underground spaces, conducted a comparative verification using experimental results and numerical models, and performed a flooding analysis in underground spaces with complex structures. Tachi et al. [14] assessed the flood risks in underground spaces, and Inoue and Toda [15] analyzed flood risks. Thus, existing studies have either described flooding situations or assessed the evacuation capacities of parties; however, studies on the likelihood of flooding and flood height in underground spaces owing to heavy rains remain insufficient.

Therefore, this study quantified the probability of flooding and flood height in underground spaces owing to heavy rain at subway entrances serving as representative underground spaces. The Gangnam area of Seoul Metropolitan City (with a history of flooding in 2010 and 2011) was selected as the study area. The parameters were corrected for the numerical analysis model for heavy rain in 2011. Flood hazard map for each scenario was prepared using the probability of rainfall. For each scenario, a flood depth database was constructed by extracting the flood depth for each grid for the entrance of the underground space located in the flood hazard map. After calculating the probability of rainfall for causing flooding in the underground space, stochastic modeling was applied along with the inundation depth database. In addition, the probability of flooding in the underground space and expected flooding height were quantitatively evaluated. Based on this study, we contribute to the establishment of flood countermeasures and procedural manuals for underground spaces.

2. Materials and Methods

To begin analyzing the flooding data, a preliminary database of flooding depths was established for the target basin. To create a database of flooding depths, a SWMM model (FLO-2D) was inspected and corrected based on historical flood damage data, and an appropriate rainfall scenario was constructed. The time distribution of the constructed rainfall scenario used the Huff distribution, which is widely used in practical domestic businesses. Currently, when handcrafted structures are designed in Republic of Korea, the

Huff 3rd quartile is frequently used to calculate the peak flood volume. However, in this study, all quartiles used four distributions to account for the characteristics of the urban flooding. The flooding in urban areas was simulated using the Environmental Protection Agency-SWMM and FLO-2D models. The FLO-2D model is approved by the Federal Emergency Management Agency and employs finite difference method as a mathematical model for river flows and flood analyses [16]. The appropriate range for the research basin was determined using topographic maps and geographical information system (GIS) data, and a grid was constructed for analyzing the flood waves using continuous and momentum equations. Heavy rain events on 21 September 2010 were used to verify the flood damage analysis results, and a preliminary flooding depth database was established using rainfall scenarios as the input data for the parameters in the verified flooding model. Only the flood depth data for the entrance of the underground space were classified and used as analysis data, as this was the analysis point for the flooding.

The simulation occurrence method was used to quantify the probability of flooding owing to heavy rain in accordance with the random occurrence method. The simulation occurrence method is largely based on the premise that each inundation depth in a data series follows a distinct theoretical probability distribution and is independent of the others. The Monte Carlo method is frequently used in the simulations. To use this method, the type of probability distribution must first be determined; then, a theoretical probability density function is obtained by determining the parameters of the probability distribution [17]. In this study, an appropriate probability distribution type and its parameters were determined, and random numbers with the same distribution type were generated to calculate the probability of the inundation depth, as well as to provide a quantitative evaluation. The formulas and input variables used in each step were written using Microsoft Excel and analyzed by Monte Carlo simulation using the statistical package @RISK [18]. The simulation operation selected the probability distribution type for the flooded depths by applying a batch fit, and the generator seed used iteration results of 10,000 or greater as the final simulation result using the random number method. Figure 1 shows the flowchart of this study.

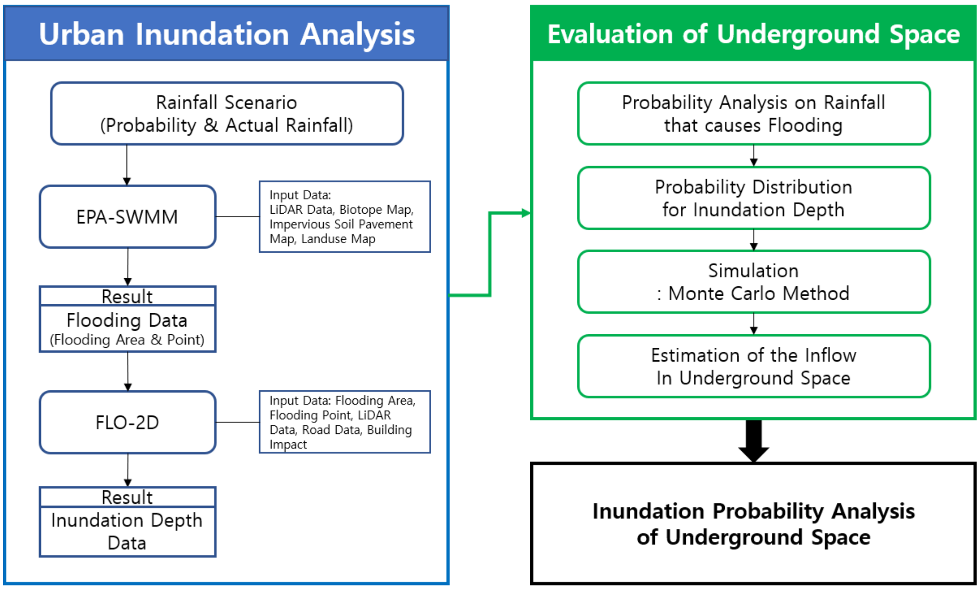


Figure 1. Study Process.

The average slope of the basin was calculated using the Seoul LiDAR data from ArcGIS, and the impermeability rate was calculated using the Seoul City Ecological Patterns in 2015. According to the Biotop Map and Article 24 of the Seoul Metropolitan City Urban Planning Ordinance, specific plants and animals form a living community and refer to biological habitats clearly distinguished from other places on the surface, using land use presented in the impermeable soil pavement among the eight topics. The NRCS (SCS) Curve Number method was used as the effective rainfall calculation method, and the CN value was calculated using ArcGIS to calculate the land use and land cover. The slope, length, and specifications of the remaining pipes were calculated using data from the Seoul Metropolitan Government Sewage Management Computer System.

3. Research Area and Establishment of Database

3.1. Study Area

The Gangnam area is the second most expensive place in Republic of Korea, but it is vulnerable to inundation. Before 2010, there was much inundation with various damage as a result of human life. After 2010, the flood incident in the study area occurred a total of five times in 2010, 2011, 2012, 2020, and 2022. The area surrounding Gangnam Station is relatively low-lying compared to other areas. In terms of geographical characteristics, Gangnam Station is located in the middle of the basin, and rainwater from the covered rivers, highway, five metro station flows, and gathers around Gangnam Station. In particular, most of the rainwater flows almost on the road surface because there is little room for rainwater to penetrate into the ground, such as with an asphalt pavement. In addition, it has a complex sewage pipe network, indicating that it is a high-risk area for flooding owing to heavy rains [19].

The Nonhyeon, Yeoksam, Seocho-3, Seocho-4, and Seocho-5 drainage basins surrounding Gangnam Station (Seoul City, Republic of Korea; Figure 2) were selected as the designated areas, with a total area of 739.21 ha. The target site is served by the Seocho and Sapyeong flood pumping stations, and all rain in these areas is channeled through the Banpo Stream. Figure 2 shows a schematic of the sewer network used in the study area.

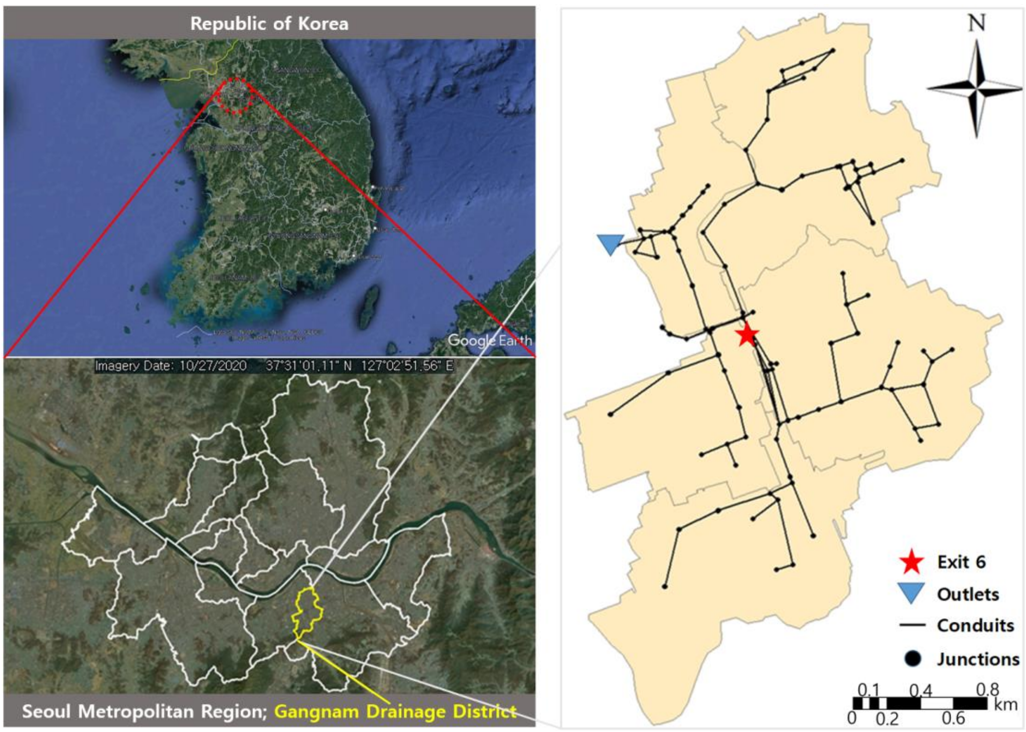
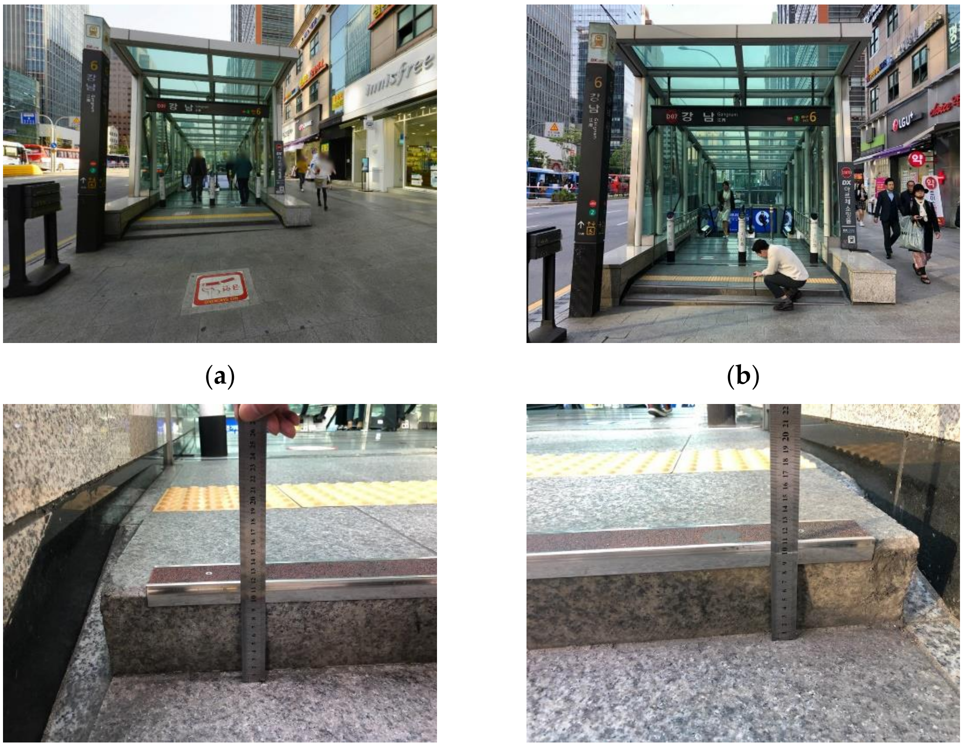


Figure 2. Study Area: Gangnam Drainage District.

Within the research area, there are eight subway stations and one underground roadway. In addition, there are 86 entrances to the subway system, 74 of which are walkable. Numerous entrances to underground spaces are located throughout the research basin. The analysis began by selecting one of the entrances. The criteria for selecting the location were as follows: it should be within the inundation range of the scenario rainfall and where the flooding depth was higher than the entrance boundary stone or the height of the stairs in the underground space. Exit 6 was designated to have a large floating population owing to morning and evening commuters. The stairs at Gangnam Station Exit 6 were approximately 11 cm high on the right and 12 cm high on the left, that is, not significantly higher than those at other entrances. Figure 3 shows the data pertaining to the height of the stairs at Exit 6 of Gangnam Station.



(**a**) (**b**)

(**c**) (**d**)

Figure 3. Stairway Height at Exit 6 of Gangnam Station: (**a**) Facade; (**b**) Height Measurement; (**c**) Left Height; (**d**) Right Height.

3.2. Study Model

The SWMM was developed with the support of the United States Environmental Protection Agency (EPA). It is a simulation model that is capable of short-term and long-term outflow simulations for urban drainage areas. EPA-SWMM is an EPA-provided SWMM. In addition to EPA-SWMM, SWMM has several derived programs that include InfoSWMM, PC-SWMM, and XP-SWMM. In the Republic of Korea, XP-SWMM and EPA-SWMM are mostly used for urban drainage calculation. However, XP-SWMM cannot be used to construct large drainage areas, because it has limited drainage area composition. However, EPA-SWMM has no restrictions on the composition of the drainage area, and the coding allows for free control of the drainage area's pipes, weirs, and other related facilities. In addition, because the program source code is public, it has the advantages of being general-purpose, and highly scalable in future programs. In this study, flood damage analysis was performed using EPA-SWMM which allows the input of detailed drainage area, such as the impermeable area of the drainage area, and it has the advantage of analyzing the amount of flooding to predict how much flood damage will occur.

The FLO-2D is a two-dimensional flood routing model that combines hydrology and hydraulics. The hydrological component is a rainfall-runoff model, with an overland flow model that simulates the movement of the flood volume around the grid. Flow conveyed into the channel is routed using the one-dimensional Saint Venant wave equation. FLO-2D is useable for a wide variety of applications, for example, flood mitigation studies, storm drain modeling, dam breach analysis, surface and ground water interactions, mud flows, and sediment transport. Key features of the FLO-2D model include a Graphical User Interface (GUI), Grid Developer System (GDS), and Mapper. The features allow the user to process and edit the grid data, graphically edit hydraulic structures, and create flood risk and flood hazard maps. FLO-2D is capable of processing different types of topographical data and can be coupled with the third-party software EPA-SWMM, which is used in this study.

The @RISK software is an add-in tool for Microsoft Excel that helps making better decisions through risk modeling and analysis. It performs this using a technique known as Monte Carlo simulation. @RISK's Monte Carlo analysis computes and tracks many different possible future scenarios in risk model, and shows the probability of each occurring. In this way, @RISK shows virtually all possible outcomes for any situation. This probabilistic approach makes @RISK a powerful tool that can be used to judge which risks to take and which ones to avoid, and it is used in this paper.

3.3. Calibration of Urban Flooding Analysis

To ensure the reliability of the database, inspection and correction were performed by applying the concept of actual heavy rain to the mathematical 1D/2D model. For the 1D model, the input data of the SWMM model were constructed by calculating the outflow curve index (CN) to identify the initial surface penetration of the impermeability, slope, and rainfall. Sewage irrigation and manholes were used for sewage network data, as provided by the Water Regeneration Planning Division of the Urban Safety Office in Seoul. In addition, a mid-class land cover map and Biotop map provided by Seoul were used to calculate the impermeability rate and CN value of the basin. The roughness coefficient proposed by Ha proposed was also used [20].

To conduct the FLO-2D analysis, topographic elevation data (digital elevation models) with five grids were generated from aviation light detection and ranging data, and detailed road and building topography data were considered for the 2D analysis.

Cho et al. [21] demonstrated that when the effects of buildings and roads are considered, the suitability results are better than when they are ignored. In particular, in densely populated urban areas such as Seoul, the consideration of buildings and roads has a significant impact on the calculation of accurate flooding areas and depths. The roughness coefficient was set to 0.025 based on Equations (1) and (2), that is, the methods for calculating the composition roughness coefficient used by Son et al. [22] in their analysis of urban flooding in Seoul.

$$n^2 = n_0^2 + 0.020 \times \frac{\theta}{100 - \theta} \times h^{\frac{4}{3}} \tag{1}$$

$$n_0^2 = \frac{n_1^2 A_1 + n_2^2 A_2 + n_3^2 A_3}{A_1 + A_2 + A_3} \tag{2}$$

where n is the composition roughness coefficient, n_0 is the bottom roughness coefficient, and θ is the building-coverage ratio. Here, $n_1 = 0.060$ (farmland), $n_2 = 0.047$ (road), and $n_3 = 0.050$ (others). A_1 denotes farmland area, A_2 denotes a road area, A_3 denotes other areas, and h is the water depth.

There are 34 automated weather stations (AWSs) operating throughout the Seoul basin, with the Seocho and Gangnam AWSs located in close proximity to the target basin. The model was examined and corrected in this study by averaging the rainfall events on 21 September 2010, as recorded by these two AWSs. The analysis of the 1D SWMM model revealed that the manhole overflowed at seven points, as depicted in Figure 4c. A 2D analysis was performed using the overflow amount as the input data, based on data from the National Disaster Management System (NDMS) point-by-point reporting points. Since 2009, disaster register has been computerized and managed through the NDMS's disaster management system, and disaster history and damage information have been recorded therein. As the NDMS report data were only available as branch data, the flooded area and NDMS point data, that is, 2D analysis results, overlapped in the GIS. The accuracy of the 2D analysis results was reviewed by comparing the NDMS report point data in the flooded area with the total number of report points in the basin.

$$Goodness\ of\ Fit(\%) = \frac{Number\ of\ NDMS\ included\ in\ the\ calculated\ flood\ area}{Total\ number\ of\ NMDS} \times 100 \quad (3)$$

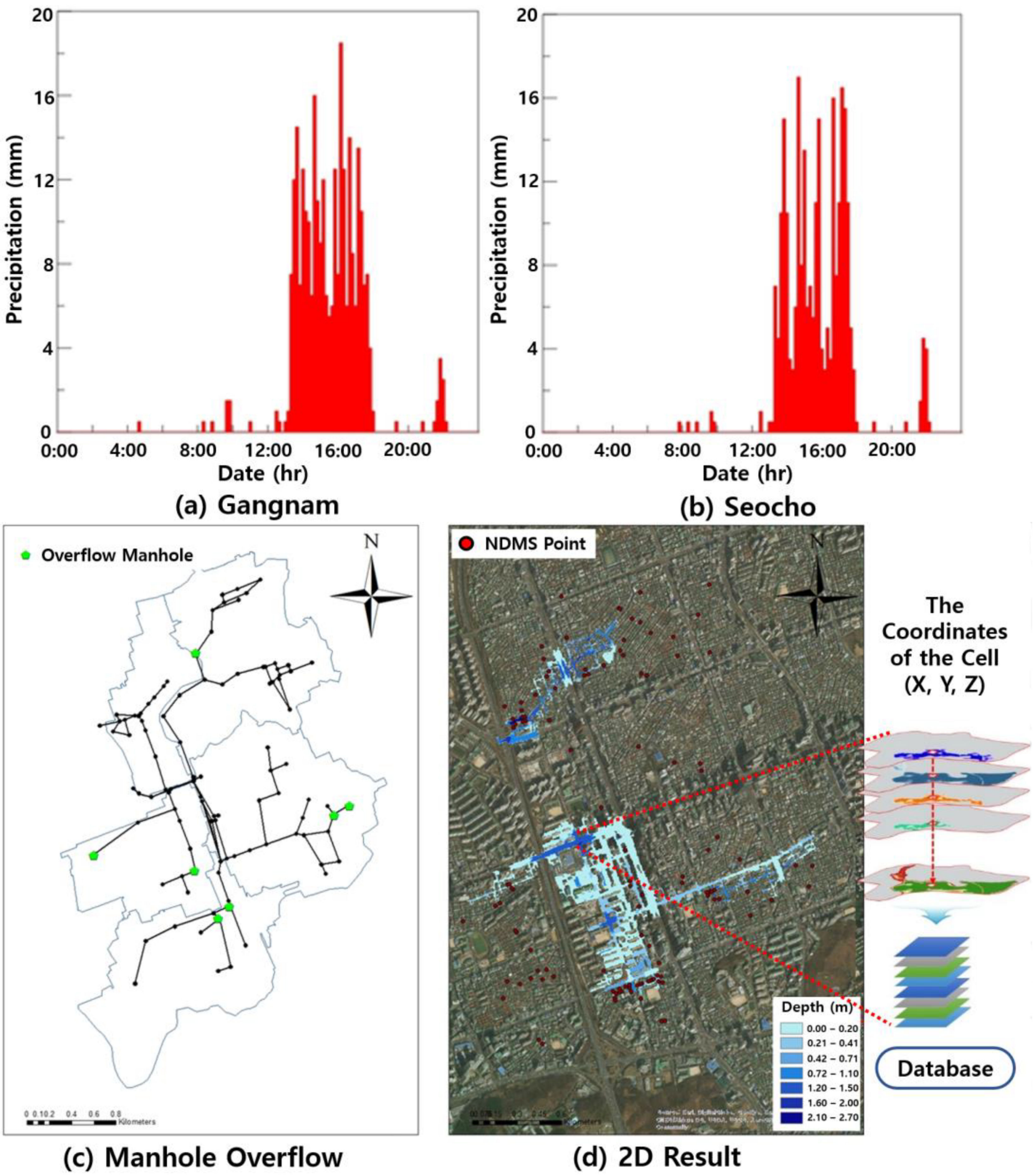


Figure 4. Comparisons of National Disaster Management System (NDMS) Data with 2D Results.

The roughness coefficient proposed by Ha [20] was used for SWMM model, and the surface roughness coefficient proposed by Son [21] was used for the FLO-2D model. As a result of Equation (3), 82 points were included in the calculation results. The number of NDMS enclosed in the calculated flood area was obtained by generating polygons for the flooded area in ArcGIS and overlapping NDMS points, and then calculating the suitability by dividing the entire resident report points (118 point) in the drainage basin.

Thus, approximately 70% (82/118) of the suitability data were analyzed by calculating the suitability for the NDMS reporting points and flooding analysis. As the area comprised five grids in the front direction, water could not spread through the narrow roads between buildings; however, the verification results were considered sufficient for constructing a pre-submerging depth database.

3.4. Database of Inundation

The rainfall scenario composition was critical in this study and was selected as a probability of rainfall. To calculate the probability of rainfall, we extracted the annual maximum rainfall series by duration from the observation data (1961–2015) of the Seoul Meteorological Observatory. The probability of rainfall was calculated for frequencies of 2, 3, 5, 10, 20, 30, 50, 70, 80, and 100 years, and rainfall scenarios were created based on the time distribution using all quartiles from the Huff first quartile to fourth quartile (Table 1). In total, 120 scenarios with durations of 1 h, 2 h, and 3 h were created. A 1D SWMM model was run using these data as input, followed by a 2D flooding analysis model simulation based on applying the calculated amount of overflow from the manholes. In the SWMM model, Ha [20] optimized parameter using PEST in the automatic correction technique was used. The initial boundary conditions are the water level of the pipeline and rainfall which probability rainfall for each frequency was used. As for the water level of pipeline, the external water level of river was used. At this point, the calculated overflow point of the manhole is matched (overlapped) with the position of the FLO-2D grid (5 m $\times$ 5 m), and then the 10 min overflow of the manhole is used as input data.

Table 1. Total Amount of Rainfall for Duration and Frequency.

Rainfall Duration (min)	Frequency (Year)									
	2	3	5	10	20	30	50	70	80	100
60	48.7 mm	56.8 mm	65.9 mm	77.2 mm	88.1 mm	94.4 mm	102.2 mm	107.3 mm	109.3 mm	112.7 mm
120	70.0 mm	81.7 mm	94.8 mm	111.2 mm	126.9 mm	135.9 mm	147.2 mm	154.6 mm	157.6 mm	162.5 mm
180	82.7 mm	98.8 mm	116.7 mm	139.2 mm	160.8 mm	173.2 mm	188.7 mm	198.9 mm	202.9 mm	209.7 mm

In total, 120 1D and 2D models were simulated, and a preliminary flooding depth database was created by classifying the grid's flooding depth data as obtained through the 2D analysis by coordinates. Table 2 summarizes the maximum flooding area based on the 2D analysis results. The flooded area for a rainfall duration of 3 h is smaller than that for 2 h. The Huff rainfall distribution for the first, second, third, and fourth Huff quartiles is used for the analysis; this causes the maximum flooded area to differ depending on the rainfall duration.

Table 2. Database for Analysis.

Scenario		Rainfall Duration	Max. Flooded Area (km^2)	Scenario		Rainfall Duration	Max. Flooded Area (km^2)
Result of 2D simulation	2 yr	1 h	0.085	Result of 2D simulation	30 yr	1 h	0.565
		2 h	0.086			2 h	0.604
		3 h	0.083			3 h	0.566
	3 yr	1 h	0.174		50 yr	1 h	0.638
		2 h	0.118			2 h	0.696
		3 h	0.106			3 h	0.638
	5 yr	1 h	0.333		70 yr	1 h	0.679
		2 h	0.307			2 h	0.769
		3 h	0.249			3 h	0.728

Table 2. *Cont.*

Scenario		Rainfall Duration	Max. Flooded Area (km^2)	Scenario		Rainfall Duration	Max. Flooded Area (km^2)
	10 yr	1 h	0.436		80 yr	1 h	0.702
		2 h	0.477			2 h	0.785
		3 h	0.402			3 h	0.746
	20 yr	1 h	0.523		100 yr	1 h	0.724
		2 h	0.566			2 h	0.823
		3 h	0.539			3 h	0.746

4. Analysis of the Probability of Floods by Rainfall

Actual rainfall data from Seoul's AWS were collected, and the probability of flooding was analyzed (Figure 5). Although rainfall data from 2007 to 2014 were requested from the Meteorological Administration, 10-min rainfall data were collected from 28 points for the 2007–2009 period, 26 points for the 2010–2011 period, 25 points for 2012, 29 points for 2013, and 28 points for 2014. Owing to the organization of rainfall data by year and time period, only data from June to October were selected, as the majority of rainfall occurred during the flood season. In addition, rainfall not measured for a period of more than 24 h was excluded from the data analysis for the probability calculation to consider the rainfall-free time.

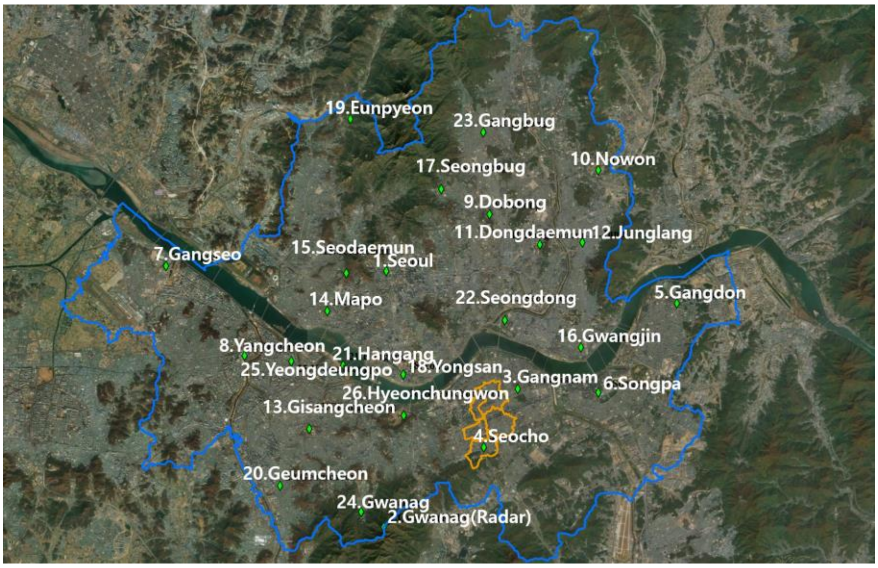


Figure 5. Seoul Automated Weather Station (AWS) Locations.

The rainfall duration that causes flooding in the underground space was analyzed using the historical data. Evidently, no actual observed rainfall equivalent to the rainfall associated with the 1-h rainfall scenario occurred for establishing a past database; thus, this scenario was excluded from this study. In the case of the 2-h scenario, when the rainfall exceeded 113 mm, the flooding of the ground began, with the grid in front of Gangnam Station's Exit 6 flooding to a depth of more than 11 cm. In addition, for 3 h, the depth of flooding was determined as 11 cm or greater owing to the low rainfall threshold of 131.5 mm (established as the standard rainfall for flooding in underground spaces).

The maximum rainfall was calculated for each duration of 2–3 h using the selected AWS rainfall data. For each point, the maximum rainfall was ranked, and the number of rainfall events (approximately 10 years in frequency) with 113 mm or more of rainfall within 2 h and 131.5 mm or more within 3 h were analyzed. The rainfall data from the

AWS indicated that the maximum rainfall exceeded 113 mm and 131.5 mm only in 2010 and 2011, respectively. Therefore, we conducted data analysis using only rainfall data from 2010, when the rainfall intensity was high and flood damage was widespread throughout Seoul. Figure 6 shows the 2-h and 3-h maximum rainfall for each observation station point, with the two orange lines representing 113 mm and 131.5 mm, respectively. The maximum rainfall for 2 h was 171.0 mm, whereas that for 3 h was 232.5 mm.

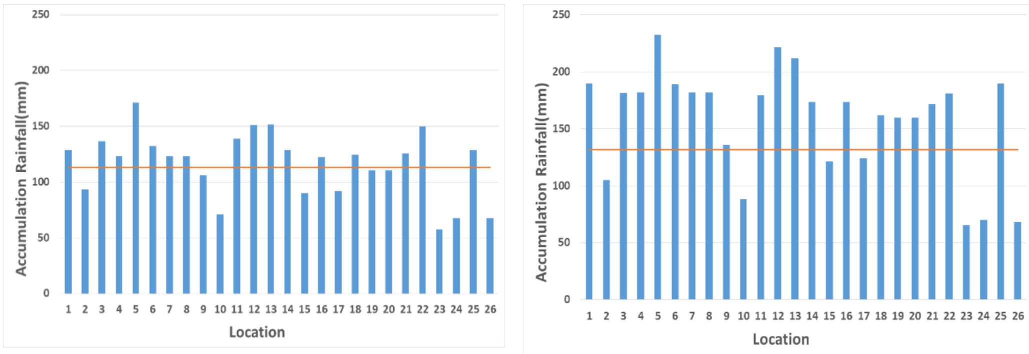


Figure 6. Maximum Precipitation by Location: (**a**) 2 h; (**b**) 3 h.

The probability of flooding owing to rainfall was calculated by assuming that all rainfall observed in Seoul's' AWS fell within the designated basin. This was analyzed considering the increase in torrential rain associated with climate change, and the resulting probability of flooding was calculated accordingly. The numbers of rainfall events for the 2-h and 3-h durations were calculated using rainfall data collected from 26 rainfall observation stations. There were a total of 2912 rainfall events over the course of 2 h, and 3517 rainfall events over the course of 3 h. The rainfall potentially causing flooding between underground spaces in the case of standard rainfall causing a flooding depth of 11 cm or more was 134 times for 2 h (Figure 7a) and 292 times for 3 h (Figure 7b). The probability was calculated accordingly, which was 4.6% for 2 h and 8.3% for 3 h.

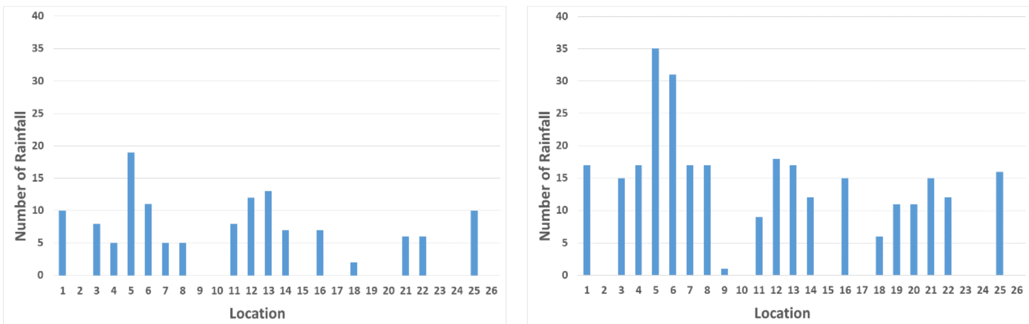


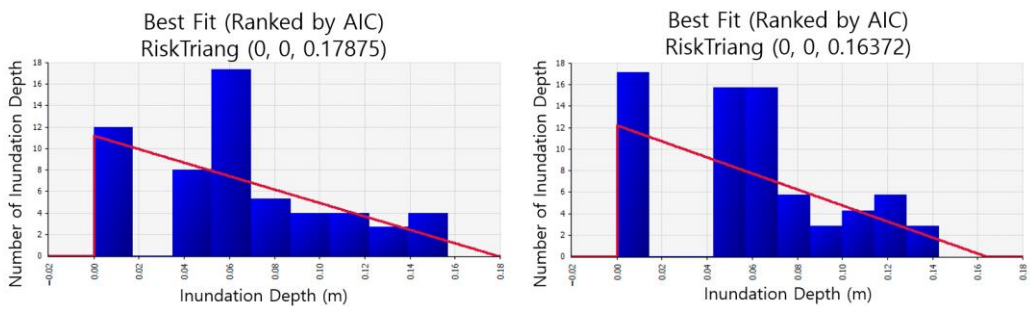
Figure 7. Number of Rainfall Occurrences: (**a**) 2 h; (**b**) 3 h.

5. Quantitative Evaluation of Underground Floods

5.1. Selection of Probability Distribution

To analyze the probability of flooding in underground spaces, a probability distribution for the flooding depths must be selected using a database of pre-submerging depths. The probability distribution for the inundation depth was selected using the commercial statistical software @Risk [16]. To determine the distribution, flood depth data were classified in the flood depth database when rainfall exceeded 113 mm (2 h) and 131.5 mm (3 h). @Risk's batch fit function was used to determine the distribution of the classified flooding depth data. At this point, the data type was determined as continuous, and the standard for the information quantity was used in conjunction with the adjustment decision coefficient to determine the degree of fitting. The information quantity standard enables a comparison and determination of whether the coefficient of determination (R2) value increases owing to the model's improved performance or simply as a result of the increase in the variable. The Akaike information criterion (AIC) and Bayesian information criterion are distinguished by the method used to calculate the weights lost in the information volume standard. The AIC method was used in this study. After estimating the model for various distributions, the distribution with the smallest standard information quantity was selected.

The overall average AIC for 2 h is −143.4, and the lowest even distribution is −154.6936. The maximum and minimum values were 0.1788 and 0.0524, respectively, with a standard deviation of 0.0421. The average AIC for 3 h was −1700.208, and the lowest even distribution was −185.569. At this time, the maximum was 0.1637, minimum was 0, average value was 0.048, and standard deviation was 0.0386 (Figure 8). There are numerous probability distribution types provided by @Risk Tool; however, after conducting a suitability analysis for the flooded depths, the "Pert" distribution type was selected and applied to the probabilistic analysis.



(**a**) (**b**)

Figure 8. Distribution Estimation: (**a**) 2 h; (**b**) 3 h.

As mentioned above, based on the preliminary flooding depth data, the Pert probability distribution type was selected. Considering only the flooding depth, the minimum, mode, and maximum values were selected as probability variables for the probability distribution type; the selections were 0.144, 0.15, and 0.22 for 2 h and 0.125, 0.165, and 0.208 for 3 h, respectively, as the input data. When the maximum inundation depths at 2 h and 3 h were compared, the inundation depth at 2 h was greater than that at 3 h. At 2 h, the increase in the Huff rainfall distribution over 10 min was also high. The x-axis of the graphs in Figures 9 and 10 indicates the depth of the flooding.

5.2. Evaluation of Underground Inundation Probability

The probability of flooding at the entrance of the underground space was analyzed as the surface flooding occurred and flooding depth increased in urban areas owing to heavy rains. To address the inherent uncertainty in the inundation depth, a probability distribution was defined, and the statistical package @RISK [16] was used to estimate the probability variables of the probability distribution type using the inundation depth. Figures 11 and 12 show the results of the probabilistic analysis conducted by generating random numbers 10,000 times using Monte Carlo simulation. The x-axis represents the flooding depth, and the results for the probability of becoming 0.11 m (11 cm) or greater are shown.

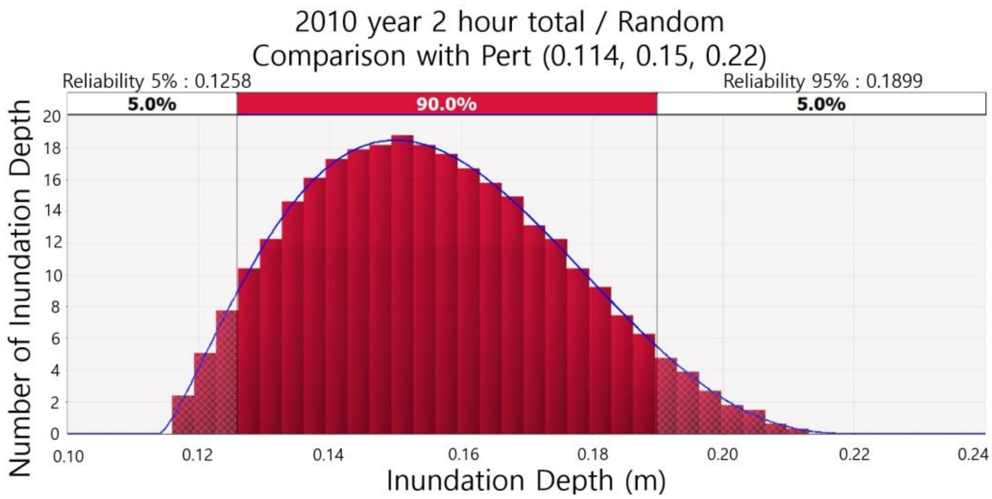


Figure 9. Probability Distribution for Flood Depth (2 h).

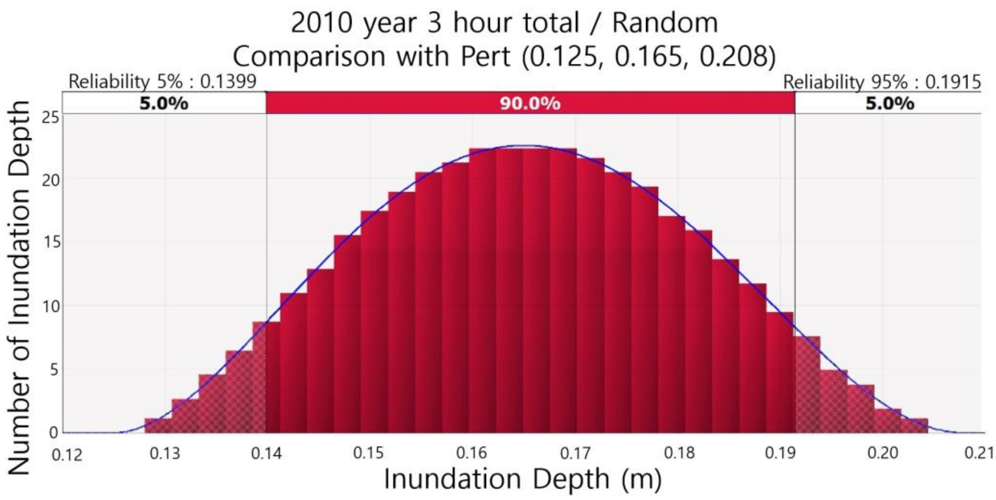


Figure 10. Probability Distribution for Flood Depth (3 h).

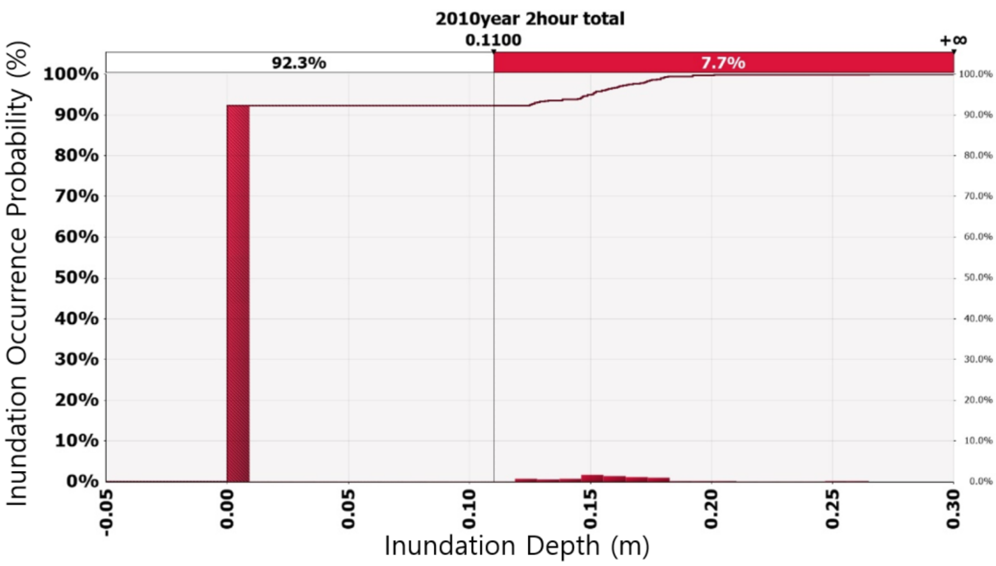


Figure 11. Evaluation of Underground Space Flooding (2 h).

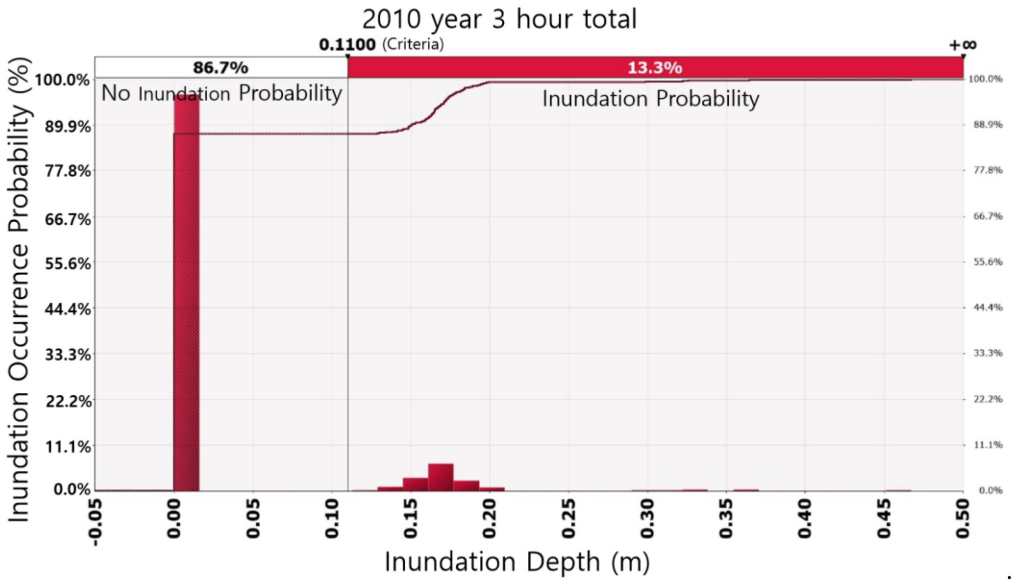


Figure 12. Evaluation of Underground Space Flooding (3 h).

According to the results of the 2-h analysis, the probability of flooding in the underground space was 7.7% based on the frequency of occurrence, whereas the probability of no flooding was 92.3%. Form 3-h analysis, the probability of flooding in the underground space was 13.3%, and the probability of no flooding was 86.7%. The flooding depth distribution was defined and simulated for 2 h, with a minimum value of 0.114 m, maximum value of 0.22 m, standard deviation of 0.01957, distortion of 0.28966 m, and average flooding depth of 0.1557 m. In the case of the 3-h duration, the minimum, maximum, and average flooding depths were 0.125, 0.208, and 0.0156 m, respectively. The standard deviation was 0.0319, and the distortion was 0.1655 m. The calculated average flooding depth can be used to determine the need for structural reinforcements in existing underground spaces.

6. Discussion

The rainfall scenario was built using probability rainfall, and a total of 120 scenarios were created with durations of 1, 2, and 3 h in mind. A one-dimensional SWMM model was used as the input data, and the amount of overflow in the manhole was used to simulate a two-dimensional flooding analysis model. A total of 120 1-, 2-dimensional models were simulated, and a pre-invasive database was created by classifying them based on the coordinates of the flooding depth of the grid, as determined by a 2-dimensional analysis. The minimum flooding depth was 0.1 cm, and the maximum flooding depth was 22 cm based on the overall composition of the flooding depth data. The rainfall was determined to be 113 mm for 2 h and 131.5 mm for 3 h in order to generate flooding of 11 cm or more in the flood depth database, and the frequency of occurrence of this rainfall corresponded to a 10-year frequency.

The flooding rainfall in the underground space was analyzed 134 times in 2 h and 292 times in 3 h, and the probability was calculated based on this. The calculation yielded 4.6% for 2 h and 8.3% for 3 h. The number of rainfall occurrences by branch was schematized, and it was analyzed up to 124 times and at least 82 times in 2 h, and up to 156 times in 3 h. The maximum rainfall for 2 h was 171.0 mm at Gangdong AWS, and the maximum rainfall for 3 h was 232.5 mm.

According to the quantitative evaluation of the underground space, the probability of runoff inflow into the underground space due to flooding was 7.7% in the case of 2 h, and the probability of no flooding was 92.3%. The probability of flooding into the underground space was 13.3% in the case of 3 h, and the probability of no flooding was 86.7%. The distribution of the inundation depth was defined in the case of 2 h. The average inundation depth was calculated as 0.1557 m as a result of the simulation. The average depth of flooding after 3 h was 0.1655 m.

7. Conclusions

The probability of flooding in enclosed underground spaces was quantitatively analyzed in this study for improving water defense measures and water defense systems. Preliminary flooding depth data were generated using 1D and 2D models, and a statistical commercial program (@RISK) was used to analyze the probability of flooding in the urban underground spaces. To use @RISK, each variable was defined based on the flooding depth, and the results were analyzed through simulations.

The weather forecast is currently using rainfall forecasted 6 h ago. The decision maker of the underground space shall prepare a water barrier plate to prepare for a disaster if rain of 113 mm for two h is predicted and 131.5 mm or more is predicted for three h. Currently, there is a mandatory disaster prevention training regulation to prepare for flooding in the underground space, but due to the lack of customized actions such as guidelines, the operation timing of the water barrier plate depends on the decision maker judgment. This study can be used to suggest the operation timing.

The probability of flooding the entrance point of Gangnam Station No. 6 due to rainfall for two h was 4.6%. The expected flood height was 0.1557 m. Accordingly, a plan to increase the height of the underground space barrier bump by 0.1557 m and the water barrier plate shall be installed at least 0.1557 m. In the case of 3 h, the probability of flooding was 8.3%, and at this time, it was analyzed to be 0.1655 m. Therefore, it is considered appropriate to increase the height of the underground space barrier by 0.1655 m when establishing measures to prevent flooding in the underground space and to install it to be 0.1655 m or more when installing a water barrier plate.

As urban development continues to accelerate, urban problems such as lack of urban resources, infrastructure, and traffic congestion have become more prevalent. Therefore, this study is expected to help prioritize structural measures to prevent flooding, develop guidelines for structural measures, and establish institutional grounds based on quantitative evaluations of underground spaces vulnerable to damage from torrential rains. The purpose of this study is to quantitatively evaluate structural measures and investment priority calculations by analyzing the probability of flooding due to rainfall at the entrance of underground spaces. This is expected to help in prioritization as a quantitative indicator when developing measures to prevent flooding of existing underground facilities.

However, as a limitation of this study, a mutual comparative study could not be carried out by analyzing the probability of flooding in other underground spaces (other structures). Future research will examine the probability of flooding in other underground spaces using existing flooding probability analysis methods, as well as the inflow of underground spaces caused by floods using empirical formulas or simulations.

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