water

MDPI

Article

A Proposed Method for Calculating the Rainfall Threshold Based on the Multi-Method to Provide Heavy Rain Disaster Impact Information

Dong Ho Kang [1], Dong Ho Nam [2], Young Seok Song [3] and Byung Sik Kim [4,*]

[1] Department of Urban and Environmental Disaster Prevention Engineering, Kangwon National University, Samcheok-si 25913, Republic of Korea; kdh@kangwon.ac.kr
[2] Department of Land, Water and Environment Research, Korea Institute of Civil Engineering and Building Technology, Goyang-si 10223, Republic of Korea; ndh1228@kict.re.kr
[3] Department of Fire and Disaster Prevention, Konkuk University, Chungju-si 27478, Republic of Korea; yssong@kku.ac.kr
[4] Department of Artificial Intelligence & Software, Kangwon National University, Samcheok-si 25913, Republic of Korea
* Correspondence: hydrokbs@kangwon.ac.kr; Tel.: +82-33-570-6819

Abstract: Recently, Korea has been affected by various disasters caused by climate change and the resulting changes in weather, which have been taking an increasing toll on the country. A review of weather phenomena and their socioeconomic impact identified weather disasters as one of the most damaging categories of disasters. As such, this study suggests a method for calculating the rainfall threshold to predict the impact of heavy rain. In order to calculate the rainfall threshold based on the multi-method, the entire territory of South Korea was divided into 1 km by 1 km grids, and a method for calculating the rainfall threshold was proposed by grouping them into four categories: standard watershed, urban areas, rivers, and inundation traces. This study attempted to verify the results of the rainfall threshold in standard watersheds and urban areas. The results were verified using the data from events during the heavy rain in Seoul in 2022 and 2018, the heavy rain in Busan in 2020, and Typhoon Mitag in October 2019. As a result of the verification and calculation, a rainfall threshold was found on the grid where the actual flooding damage occurred in Busan, where heavy rain caused a large amount of urban flooding in July 2020. The application of the rainfall threshold on the grid caused enough damage to flood vehicles. After this application, it was found that flooding of more than 0.2 m affected vehicles. During early September in the Gangneung grid, flooding damage was caused by Typhoon Haishen, which affected traffic. In this damaged grid, it was also found that flooding of more than 0.2 m occurred according to the rainfall impact limit. In this study, since there were no quantitative data, verification was performed using qualitative data such as news and SNS. Therefore, quantitative verification methods using flooding sensors and CCTVs need to be carried out in the future. After verification using qualitative data, we found that the time when the actual flooding damage occurred and the flooding patterns were well ascertained. The rainfall threshold calculation method and the rainfall prediction information developed in this study are expected to be applicable to impact forecasting, which can provide people affected by heavy rainfall with information on how the rainfall will affect them, as well as simple rainfall forecasts.

Keywords: impact forecast; threshold rainfall; multi-method; G2G (grid to grid)

Citation: Kang, D.H.; Nam, D.H.; Song, Y.S.; Kim, B.S. A Proposed Method for Calculating the Rainfall Threshold Based on the Multi-Method to Provide Heavy Rain Disaster Impact Information. *Water* **2023**, *15*, 3366. https://doi.org/10.3390/w15193366

Academic Editor: Gwo-Fong Lin

Received: 9 August 2023
Revised: 19 September 2023
Accepted: 20 September 2023
Published: 25 September 2023

1. Introduction

A review of the correlation between weather events and their socioeconomic impact shows that weather disasters inflict the largest and most frequent damage among all disasters. Among all weather disasters, heavy rain and typhoons are the most damaging [1]. Korea is surrounded by the sea on three sides. Due to the effect of the oceanic atmosphere, heavy rain accounts for the largest percentage of damage caused by weather disasters. The damage caused by these disasters can be minimized by predicting rainfall. The Korea Meteorological Administration (KMA) uses the ensemble prediction method to predict future rainfalls [2]. Ensemble prediction addresses the limitations of deterministic prediction, which uses single-number quantities to probabilistically predict the future by analyzing several models with different initial conditions, physical processes, and boundary conditions [3]. The KMA uses these data to provide rainfall forecasts in various forms including short-term, medium-term, long-term, and neighborhood forecasts. However, the technique has a major drawback: its predictions do not consider local and social characteristics because they only provide information on rainfalls. While the system does provide forecasts for facilities, flooding, and inundation, it does not offer quantitative information about them.

To address this issue, the World Meteorological Organization (WMO) studied the impact of various disasters and developed guidelines for weather forecast services, emphasizing the importance of an 'impact forecast' [2]. Meteorological leaders such as the United States and the United Kingdom have already partially adopted impact forecasts [4]. The United Kingdom Flood Forecasting Centre (FFC) published a manual for flood impact forecasts and built a flood risk matrix that distinguishes between four risk levels [5]. The FFC also provides grid-by-grid flood impact forecasts and uses grid-to-grid (G2G) models to forecast the impact of a flood on each grid [6–8]. Ref. [9] analyzed the relationship between vegetation cover and urbanization using an urban heat island (UHI) analysis. Ref. [10] conducted a study on rainfall prediction using a neural network for accurate streamflow and flash flood prediction. Ref. [11] presented a proof of concept for an impact-based forecasting system for pluvial floods. In addition, the authors used a model chain consisting of a rainfall forecast, inundation, and contaminant transport and a damage model, which provided predictions for expected rainfall, inundated areas, the spreading of potential contamination, and the expected damage to residential buildings. Ref. [12] conducted research based on the MIKE model, which is a numerical simulation from the perspective of the impact of different rain patterns on waterlogging. Ref. [13] presented a case study on a pilot project that aimed to establish impact-based flood monitoring and an early warning and decision support system for the Vaisigano River, which flows through Apia, the capital of Samoa. Ref. [14] proposed an automated warning message based on color codes to trigger risk mitigation actions at the local level in flood-exposed communities of the Kelantan River basin, Malaysia. Ref. [15] qualitatively tested whether a warning message based on color codes is understandable and useful for triggering risk mitigation actions at the local level in flood-exposed communities of Rajapur and Ghorjan unions in Sirajganj District, Bangladesh.

In addition, research related to rainfall thresholds has been actively conducted. Ref. [16] conducted a very precise estimation of daily design rainfall depth for various return periods. The approach was not based on the commonly used annual maxima (AM) method but on the peak over threshold (POT) method with the use of Hill statistics. Ref. [17] proposed a method for applying web crawlers to identify waterlogging rainfall in cities lacking waterlogging observation data and classifying them using rainfall intensity–duration curves. Ref. [18] developed a quick pluvial flood warning system using rainfall thresholds for central Taipei. A tabu search algorithm was implemented with hydrological analysis-based initial boundary conditions to optimize rainfall thresholds. Ref. [19] proposed improving the warning effectiveness of the rainfall threshold method for urban areas using deterministic–stochastic modeling without sacrificing simplicity and efficiency.

Many researchers in Korea have also touched on the issue of impact forecasting. Ref. [20] described the characteristics of impact forecasting and analyzed the current status and experiences regarding impact forecasting in leading countries. The Ministry of Land, Infrastructure and Transport (MOLIT) adopted the United Kingdom's flood risk matrix method to improve public safety during floods and enhance the country's disaster response capabilities. Ref. [21] estimated rainfall thresholds that cause flooding damage by analyzing the inundation damage caused to the Gangnam area in Seoul. Ref. [22] established a database of rainfall inundation areas by rainfall scenarios and conducted a real-time prediction for urban flood mitigation. Ref. [23] established quantitative standards for conducting impact forecasts on heavy rains with k-means cluster analysis using weather data and past damage data. Ref. [24] used big data from media articles to extract and analyze more specific and practical damage information from past disaster weather information. The authors also presented a plan to subdivide the existing special report stage into four risk levels to preemptively respond to and reduce damage caused by disaster weather. Ref. [25] developed a model forecasting the impact of rainfall on riverside flood risks in the Busan Metropolitan. Critical rainfall was determined based on the endpoint of the river and the discharge–water level relationship between design flood discharge and design flood level by analyzing water rainfall during a 3-h critical rainfall.

While the actual amount of rain from the sky is essential for calculating rainfall, rain runoff may vary depending on topographical characteristics (standard watersheds, urban areas, and rivers) as well as land use and conditions. In addition, depending on the drainage system of the affected area, rainfall may cause secondary damages due to urban inundation, landslides, and river flooding. The same amount of runoff may have a different impact on different regions at different times. In other words, the same amount of rainfall causes disasters of significantly different types and scales depending on the topographical characteristics of the affected area. As such, by identifying the characteristics of secondary and tertiary disasters caused by rainfall, we can expect to provide specific forecasts for the affected areas, vis-à-vis, rainfall-centered forecasts.

This study is distinguished from the previous literature in that it developed a multi-method algorithm to estimate threshold rainfall for each receptor. The method considers non-urban area areas, urban areas, and rivers that pose inconvenience or risk to people's daily routines in areas affected by heavy rain, focusing on inundation damages caused by heavy rain. 'Threshold rainfall' means the rainfall that causes inundation that affects the receptors. In this study, the affected receptors consist of people, traffic, and buildings. For each receptor, we sought to calculate rainfall that caused 0.1 m, 0.2 m, and 0.5 m inundation, respectively.

Due to the limitations in collecting past flooding damaged data, this study analyzed and verified the grid-based threshold rainfalls in standard watersheds and grid-based threshold rainfall for urban areas using the G2G.

We verified the threshold rainfalls calculated in this study using rainfall events in July 2020 and Typhoon Haishen during September of the same year. Figure 1 shows a flowchart of threshold rainfall calculation using the multi-method approach. Table 1 provides a description of the terms used in this study.

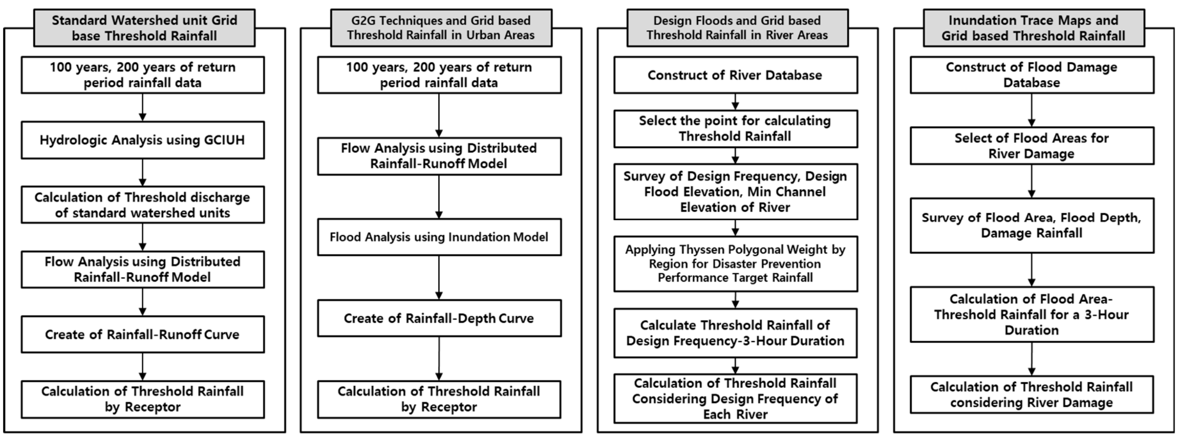


Figure 1. Flowchart Showing the Design of this Study.

Table 1. Key Term Definitions.

Term	Description
Threshold discharge	When analyzing a standard watershed unit, which is a non-urban area analysis method, threshold discharge refers to the maximum outflow of the relevant basin. If the rainfall exceeds the marginal outflow, damage occurs in the relevant basin.
Rainfall–runoff curve	A curve showing the relationship between rainfall and runoff.
Receptor	In this study, receptors are people, vehicles, and facilities were selected as objects, and the impacts of each object correspond to walking, traffic, and buildings.
Threshold rainfall	Rainfall that causes inconvenience to the daily life of a receptor due to rainfall.
Rainfall–depth curve	The amount of rainfall that causes the depth of flooding that affects an object due to rainfall. The depth of flooding for each object is assumed for walking (0.1 m), traffic (0.2 m), and building (0.5 m).
Design flood	Flood volume used in the design of water structures such as dams and river structures.

The paper is arranged as follows: Section 2 introduces the methods for calculating threshold rainfall. Section 3 describes an application to past flood damage cases using the calculated threshold rainfall. Section 4 presents the conclusions.

2. Theoretical Background

2.1. Threshold Rainfall Calculation Based on the Multi-Method

In order to calculate the threshold rainfall based on the multi-method, the entire territory of South Korea was divided into 1 km by 1 km grids, with a total number of grids of 104,197 EA. To compensate for the limitations of the existing underestimated rainfall information, a study was conducted to correct the amount of rainfall so that it reflected the peak value hydrologically. Ref. [26] also produced rainfall information in a 1 km/1 km grid unit from corrected predicted rainfall information, and this study also conducted an analysis with a 1 km grid to link it with this rainfall information. These data will be available for integration with radar rainfall data produced for each grid in the future.

Figure 2 shows the threshold rainfall calculation algorithm based on the multi-method that is capable of analyzing grids across the country. The threshold rainfall calculations for standard watersheds are obtained from grids across the country. For urban areas, the G2G-based, grid-specific threshold rainfall calculations are overlapped. For grids with rivers, the threshold rainfall calculations considering the rivers' design rainfalls are overlapped. Lastly, for grids previously affected by rainfall, threshold rainfalls based on the inundation trace map are overlapped. Thus, we calculated the nationwide threshold rainfalls considering the characteristics of different grids.

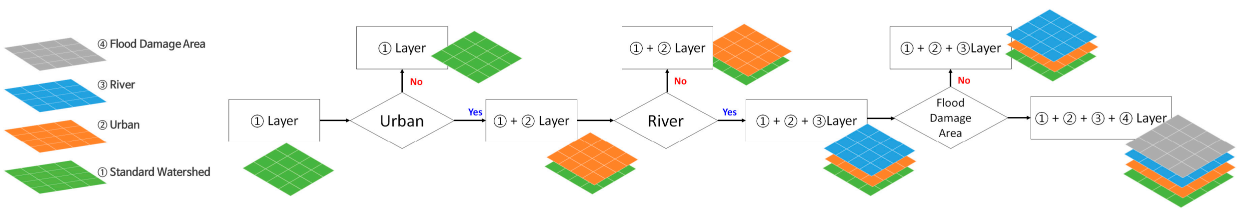


Figure 2. The Multi-Method Algorithm.

2.2. Threshold Rainfalls in Standard Watershed Units

Figure 3 shows a flowchart indicating the steps used to calculate threshold rainfalls in standard watershed unit grids. We use a hydrological model [27] for standard watersheds across Korea to calculate these threshold rainfalls, which are runoffs exceeding the 100-year frequency for three hours of duration in each watershed. Then, we use a rainfall–runoff model [28] to draw rainfall–runoff curves for different frequency levels at a 10% interval. These curves were used to calculate the threshold rainfalls for standard watershed unit grids that exceed the threshold rainfall drawn from the hydrological model. See Ref. [29] for more details about the calculation of threshold rainfalls for standard watershed unit grids.

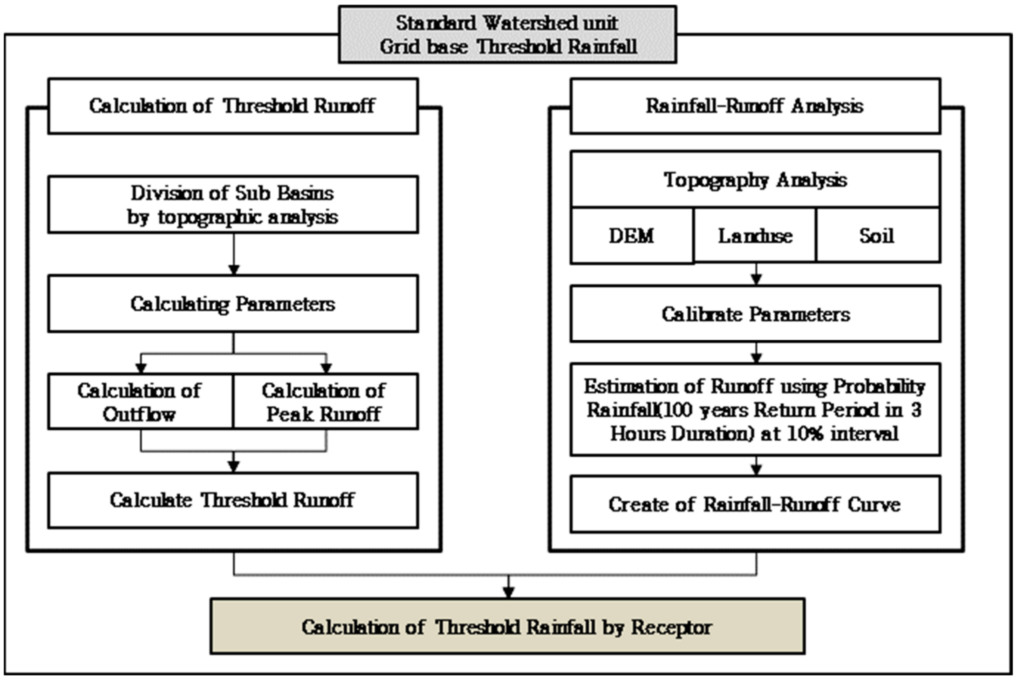


Figure 3. Steps to Calculate Threshold Rainfalls for Standard Watershed Unit Grids.

2.3. Grid-Based Threshold Rainfalls in Urban Areas Using the G2G Method

To calculate grid-based threshold rainfalls in urban areas, we use the G2G method to calculate threshold rainfalls of grids classified as urban areas on the land use map for Korean cities with populations of 100,000 or larger. The reason for calculating threshold rainfall using the G2G technique is that the grid-based distributed model was used for the same level of analysis as the predicted rainfall information generated based on the grid. There are practical limitations in building data to estimate G2G-based physical models by applying nationwide pipeline data to urban area grids across the country. Therefore, in this study, runoff was calculated by subtracting the runoff in the frequency of 5 to 10 years, which is the general flood protection capability in urban areas, from the runoff results analyzed using the rainfall–runoff model (S-RAT). The calculated runoff was used as input data for the inundation model (Flo-2D) [30]. Figure 4 shows a flowchart indicating the steps used to calculate the threshold rainfalls in urban areas. We used the inundation runoff model to calculate 100-year frequency rainfall data (runoff and flood peak) at a three-hour duration for each area at a 10% interval. Then, we used the runoff data as the input data for the flood model to calculate the inundation depth of each grid and then used these findings to draw the rainfall–depth curves, as shown in the right-side image in Figure 4, to calculate threshold rainfalls.

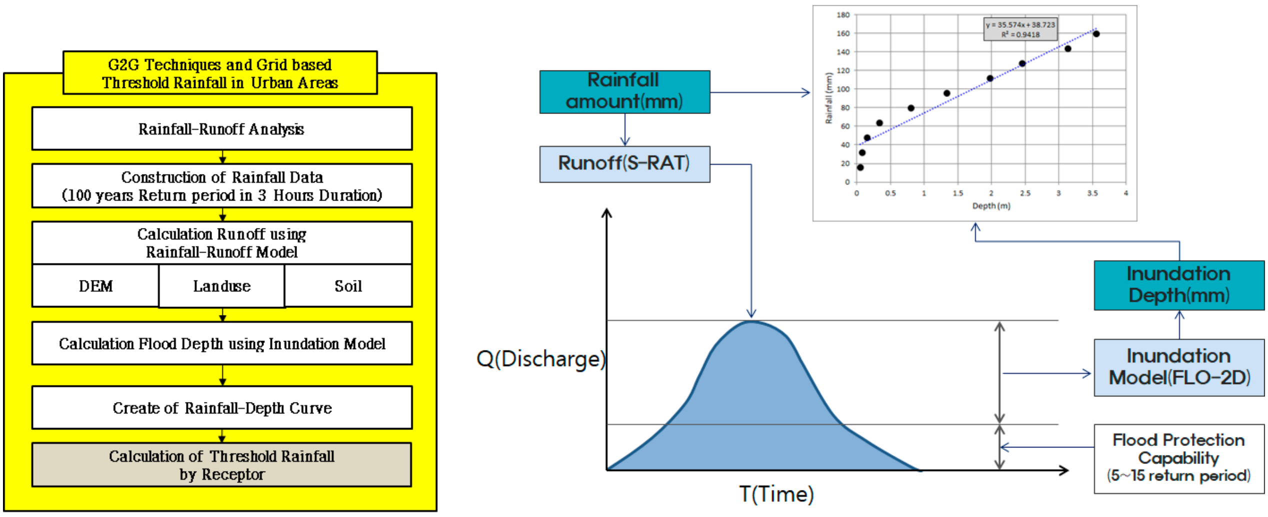


Figure 4. The G2G Technique and Grid-Based Threshold Rainfall Calculations for Urban Areas.

3. Calculation and Verification of Threshold Rainfalls

3.1. Results of Threshold Rainfall Calculation for Standard Watershed Units

Watersheds in Korea are divided into large watersheds, medium watersheds, and standard watersheds in order to carry out water resource development, planning, and management tasks. Based on the river map of watersheds, large watersheds are divided into 21 regions, medium watersheds are divided into 117 regions, and standard watersheds are divided into 792 regions. In this study, the rainfall–runoff curve for the impact limit rainfall was analyzed for 792 standard watersheds nationwide. Figure 5 shows a part of the rainfall–runoff curves for 792 standard watersheds calculated using the methods proposed in 2.2.

3.2. Grid-Based Threshold Rainfall Calculation for Urban Areas Using the G2G Method

There are 63 cities in Korea with populations of 100,000 or larger. Among these 63 cities, we selected areas classified as urbanized on the land use map to apply the G2G model (rainfall–runoff model, inundation model) and calculate threshold rainfalls. Figure 6 shows the rainfall–depth curves based on the analysis findings for one of the grids in Busan and Gangneung, which we used to verify the threshold rainfall calculations.

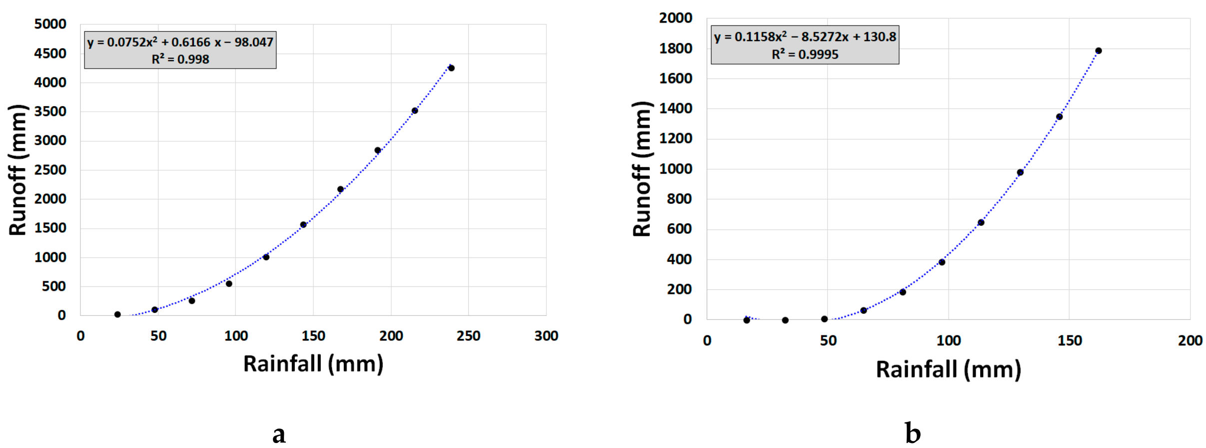


Figure 5. *Cont.*

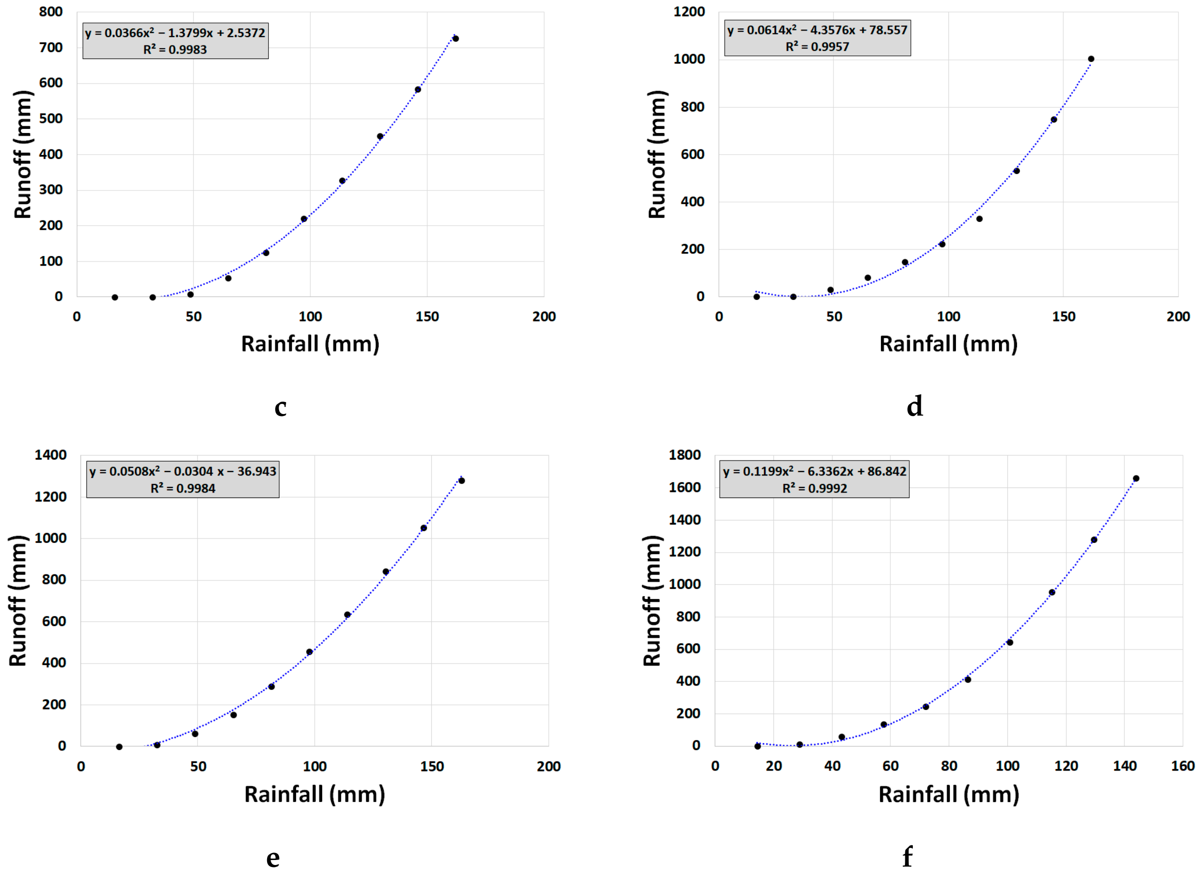


Figure 5. Rainfall–Runoff Curve Results in Standard Watershed Areas. (**a**) The upper reaches of the Imjin River; (**b**) Yongjicheon; (**c**) Namdaecheon; (**d**) Suipcheon; (**e**) Ssangyongcheon; (**f**) Gamcheon.

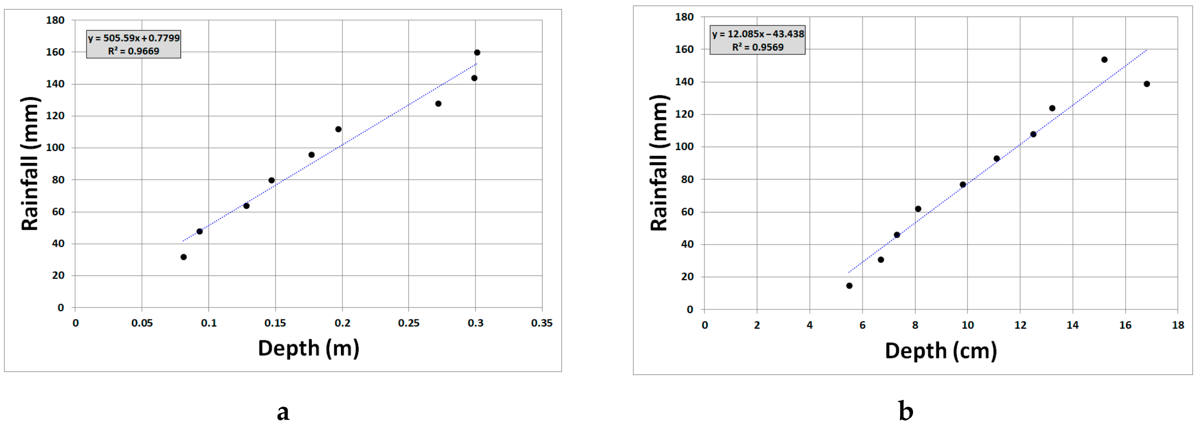
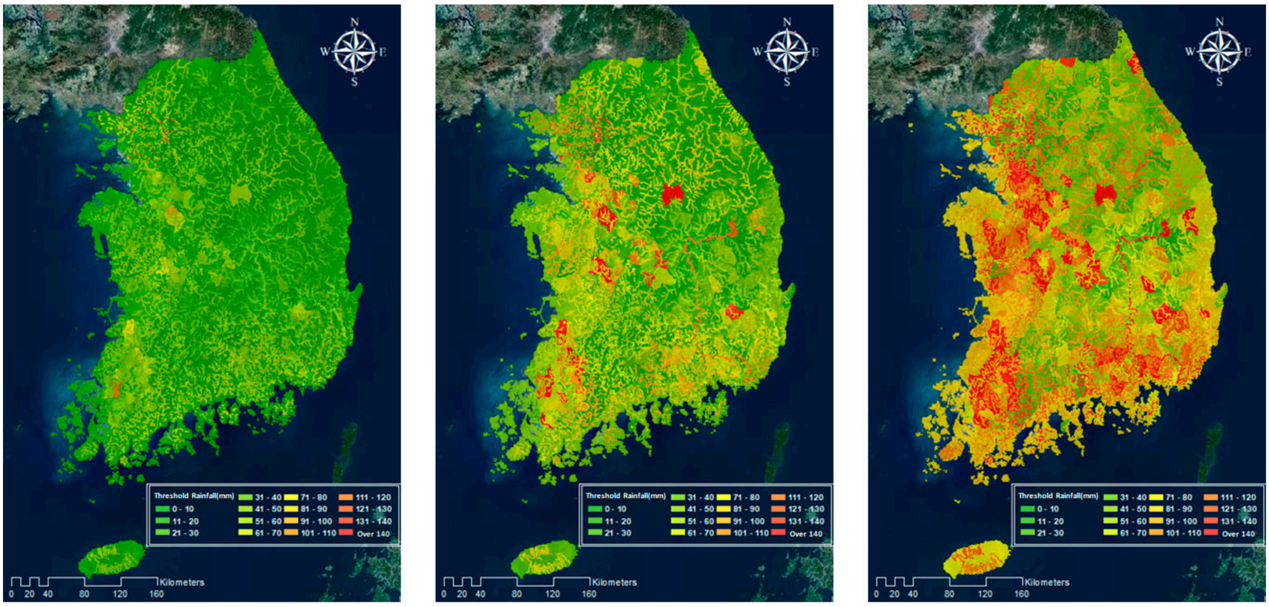


Figure 6. Rainfall–Runoff Curve Results in Urban Areas. (**a**) Busan; (**b**) Gangneung.

3.3. Result of the National Threshold Rainfall Estimation

Figure 7 shows the results of calculating the threshold rainfall on walking, traffic, and buildings using the rainfall-depth curve calculated in Sections 3.1 and 3.2.

As can be seen in the figure, the threshold rainfall on walking, traffic, and buildings is different. The applicability was evaluated by applying it to past damage cases.



a. Walking(0.1m) b. Traffic(0.2m) c. Building(0.5m)

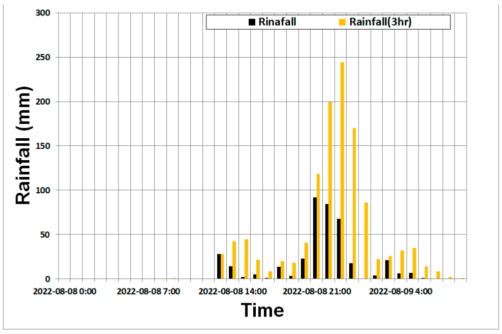
Figure 7. Results of Threshold Rainfall.

3.4. Selection of Events for Threshold Rainfall Verification

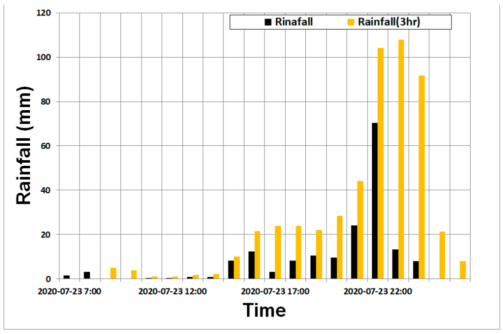
Verification of the threshold rainfall calculations requires the selection of previous rainfall events that inflicted damages. As such, we chose the heavy rainfall in Seoul in August 2022 and August 2018 (Figure 8), the heavy rainfall in Busan in July 2020, and the Typhoon Mitak event in Gangneung in September 2019 for verification. In addition, in the case of rainfall data, observed rainfall data provided by KMA were used.

Figure 8. Selection of Regions for Verification.

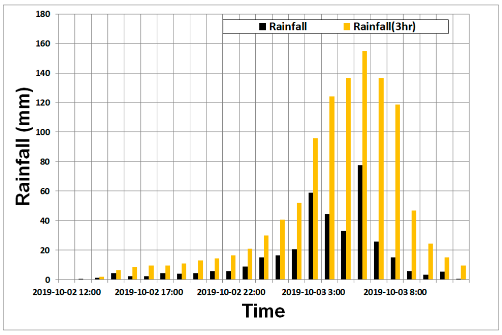
The August 2023 heavy rainfall caused inundation in many urban areas across Seoul. As shown in Figure 9a, the daily rainfall on 8 August reached 396.5 mm, with a maximum 3-h rainfall of 244 mm. Figure 9b shows a hyetograph of heavy rainfall in Busan. The total rainfall was 176.3 mm, and the maximum 3-h rainfall was 107.8 mm. Typhoon Mitak landed in Korea in October 2020, causing significant inundation damage in the city of Gangneung. The total rainfall on 6 and 7 September reached 368.5 mm, and the maximum 3-h rainfall was 155 mm, as shown in Figure 9c.



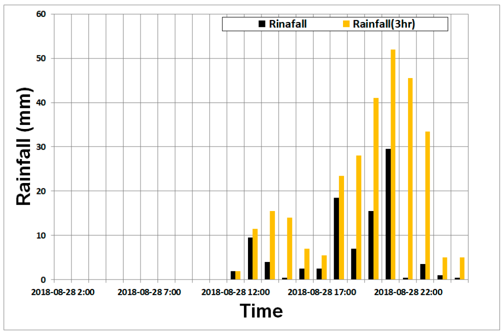
a. August 8, 2022, Heavy Rain in Seoul



b. July 23, 2020, Heavy Rain in Busan



c. October 2, 2019, Typhoon Mitkg in Gangneung



d. August 28, 2018, Heavy Rain in Seoul

Figure 9. Rainfall Events for Threshold Rainfall Verification.

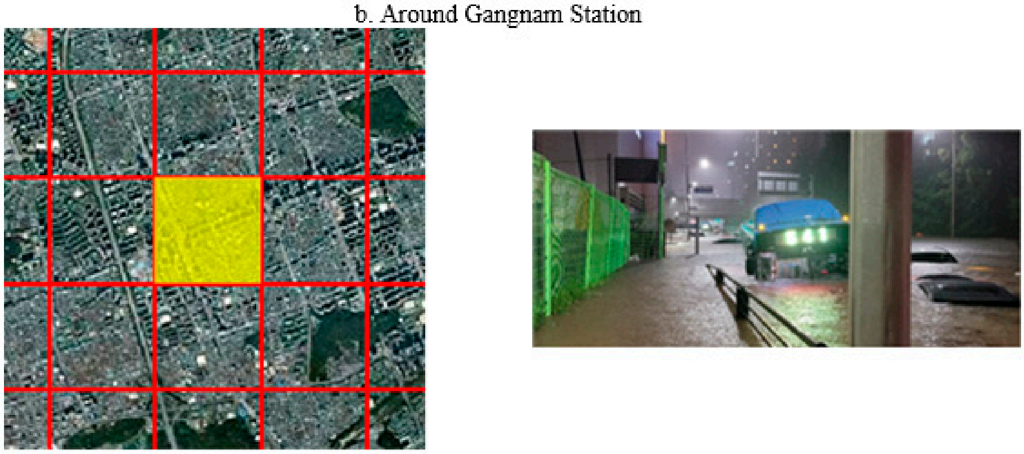
3.5. Verification of Threshold Rainfalls Using Actual Damage Data

To verify the threshold rainfall calculations, we obtained actual inundation damages in Seoul, Busan, and Gangneung by reviewing social media posts and news reports. Figure 10 shows inundation events in Seoul, Busan, and Gangneung (Figures 11–13). Here, the yellow and red boxes on the left side of the figure represent the grid where the damage occurred, and the right side shows a photograph of the actual damage.

We analyzed whether the threshold rainfall results represent the actual damage caused by the rainfall. When applying three-hour rainfalls to the calculated threshold rainfalls, in Seoul, the deepest inundation (0.7 m) occurred around Daechi Station, as shown in Table 2. A 1.7 m inundation depth also occurred around Gangnam Station and Jinheung apartment. In Busan, the deepest inundation (1.2 m) occurred in the Gaya Underpass area, as shown in Table 3. The inundation depth exceeded 0.5 m, which is the threshold depth for the flooding of buildings. In fact, a large SUV was flooded, as shown in the photograph. An inundation event with a depth of 35 cm was predicted in the Hadan Station area, causing damage to pedestrians and traffic. Inundation depths of 0.7 m and 0.25 m were predicted for the Oncheoncheon and Yeonsan-dong areas, which well-represent the actual damages caused. In Gangneung, a 1.1-m-deep inundation event was predicted for the Ojukheon area, as shown in Table 4. A comparison with the actual photograph shows possible impact on traffic. In Seoul in 2018, inundation occurred around Yeonnam-Dong and Sangam-Dong. This event also indicated that the results of calculating the threshold rainfall well reflect the actual damage, as shown in Table 5.

a. Around Daechi Station

b. Around Gangnam Station



c. Around Jinheung Apartment

Figure 10. Grid of Flood and Article (in Seoul, 2022).

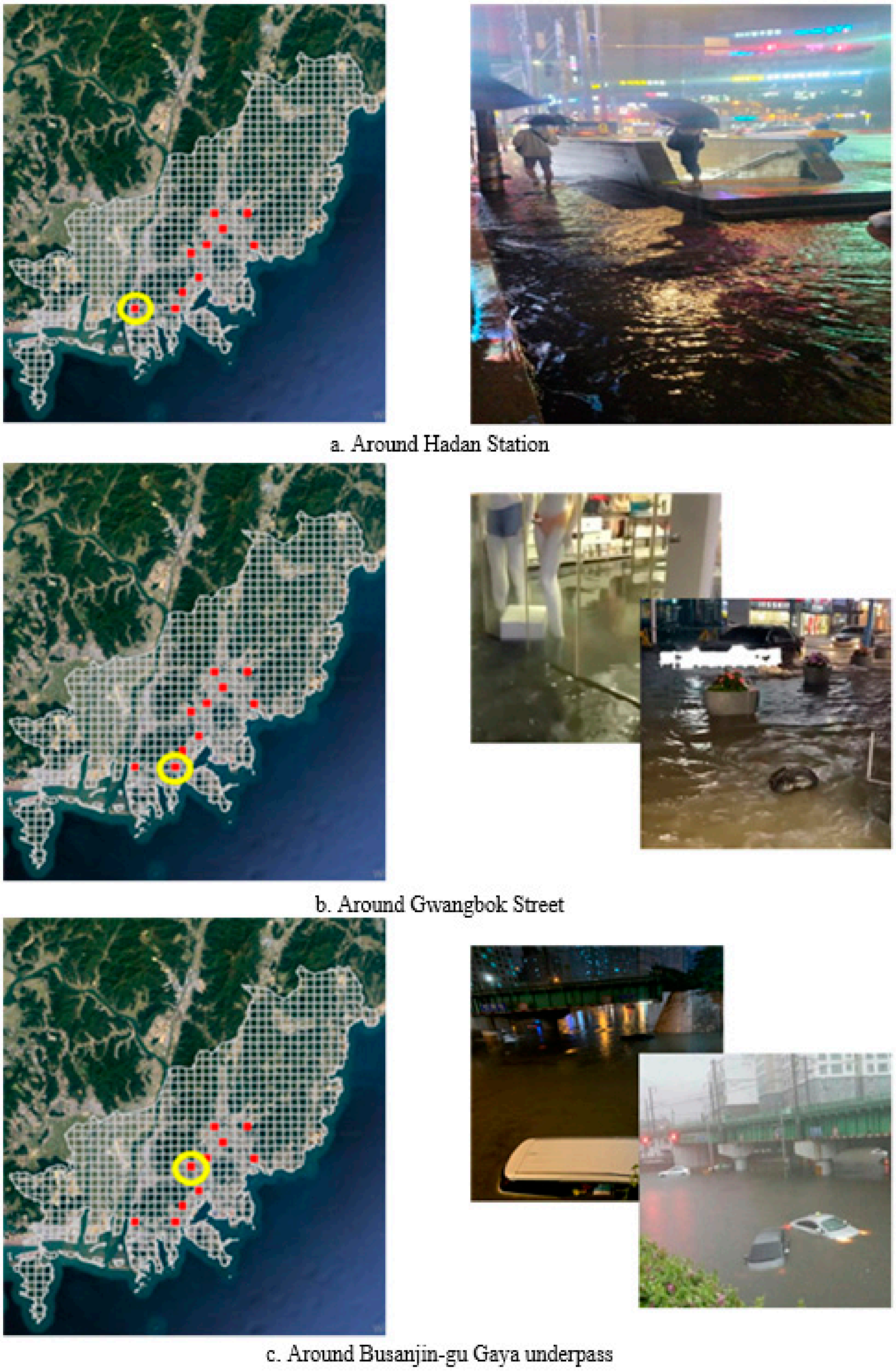


Figure 11. Grid of Flood and Article (in Busan, 2020).

Figure 12. Grid of Flood and Article (in Gangneung, 2019).

a. Around Yeonnam-dong, Mapo-gu

b. Around Sangam-dong, Mapo-gu

Figure 13. Grid of Flood and Article (in Seoul, 2018).

Table 2. Verification Results for Threshold Rainfall in Seoul (2022).

Around Daechi Station								
Time	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Accumulated rainfall (mm/3 h)	0	28	42.5	45	22	8.5	20	18.5
Flood depth (m)	0	0	0.1	0.1	0	0	0	0
Time	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00

Table 2. *Cont.*

Accumulated rainfall (mm/3 h)	40.5	118.5	199.5	244	170	86	22.5	26
Flood depth (m)	0.1	0.3	0.6	0.7	0.5	0.2	0	0
Around Gangnam Station								
Time	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Accumulated rainfall (mm/3 h)	0	28	42.5	45	22	8.5	20	18.5
Flood depth (m)	0	0	0.1	0.1	0	0	0	0
Time	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00
Accumulated rainfall (mm/3 h)	40.5	118.5	199.5	244	170	86	22.5	26
Flood depth (m)	0	0.7	1.3	1.7	1.1	0.4	0	0
Around Jinheung Apartment								
Time	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Accumulated rainfall (mm/3 h)	0	28	42.5	45	22	8.5	20	18.5
Flood depth (m)	0	0	0.1	0.1	0	0	0	0
Time	20:00	21:00	22:00	23:00	00:00	01:00	02:00	03:00
Accumulated rainfall (mm/3 h)	40.5	118.5	199.5	244	170	86	22.5	26
Flood depth (m)	0	0.7	1.3	1.7	1.1	0.4	0	0

Table 3. Verification Results for Threshold Rainfall in Busan (2020).

Around Hadan Station							
Time	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Accumulated rainfall (mm/3 h)	1.8	2.2	10.1	21.6	24	24	22.1
Flood depth (m)	0	0	0	0	0	0	0
Time	20:00	21:00	22:00	23:00	00:00	01:00	02:00
Accumulated rainfall (mm/3 h)	28.4	44.2	104.1	107.8	91.7	21.4	8.1
Flood depth (m)	0	0	0.3	0.3	0.2	0	0
Around Gwangbok Street							
Time	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Accumulated rainfall (mm/3 h)	1.8	2.2	10.1	21.6	24	24	22.1
Flood depth (m)	0	0	0	0	0	0	0
Time	20:00	21:00	22:00	23:00	00:00	01:00	02:00
Accumulated rainfall (mm/3 h)	28.4	44.2	104.1	107.8	91.7	21.4	8.1
Flood depth (m)	0	0.1	0.3	0.3	0.2	0	0
Around Busanjin-gu Gaya Underpass							
Time	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Accumulated rainfall (mm/3 h)	1.8	2.2	10.1	21.6	24	24	22.1

Table 3. *Cont.*

Flood depth (m)	0	0	0	0	0	0	0
Time	20:00	21:00	22:00	23:00	00:00	01:00	02:00
Accumulated rainfall (mm/3 h)	28.4	44.2	104.1	107.8	91.7	21.4	8.1
Flood depth (m)	0	0	1.1	1.2	0.9	0	0

Table 4. Verification Results for Threshold Rainfall in Gangneung (2018).

Around Ojukheon							
Time	23:00	00:00	01:00	02:00	03:00	04:00	05:00
Accumulated rainfall (mm/3 h)	21	30	40.5	52	96	124	136.5
Flood depth (m)	0	0.1	0.2	0.3	0.6	0.8	0.9
Time	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Accumulated rainfall (mm/3 h)	155	136.5	118.5	47	24.5	15	9.5
Flood depth (m)	1.1	0.9	0.8	0.2	0.1	0	0

Table 5. Verification Results for Threshold Rainfall in Seoul (2018).

Around Yeonnam-dong, Mapo-gu							
Time	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Accumulated rainfall (mm/3 h)	2	11.5	15.5	14	7	5.5	23.5
Flood depth (m)	0	0	0	0	0	0	0.1
Time	19:00	20:00	21:00	22:00	23:00	00:00	01:00
Accumulated rainfall (mm/3 h)	28	41	52	45.5	33.5	5	5
Flood depth (m)	0.2	0.2	0.2	0.2	0.2	0	0
Around Sangam-dong, Mapo-gu							
Time	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Accumulated rainfall (mm/3 h)	2	11.5	15.5	14	7	5.5	23.5
Flood depth (m)	0	0	0	0	0	0	0
Time	19:00	20:00	21:00	22:00	23:00	00:00	01:00
Accumulated rainfall (mm/3 h)	28	41	52	45.5	33.5	5	5
Flood depth (m)	0	0.2	0.4	0.3	0.1	0	0

4. Conclusions

In this study, we proposed a method for calculating threshold rainfall based on the multi-method to provide heavy rain disaster impact information. The entire territory of South Korea was divided into 1 km by 1 km grids, and a threshold rainfall calculation method was proposed for standard watersheds, urban areas, rivers, and inundation traces. We also verified the threshold rainfall calculations for standard watersheds and urban areas using the inundation events in July 2020 in Busan and September 2020 in Gangneung. For standard watersheds, we calculated threshold runoffs for standard watershed units across South Korea and calculated three-hour 100-year frequency rainfalls using a grid-based distributive rainfall–runoff model, which identified rainfalls that exceeded the calculated threshold rainfalls. For grids classified as urban areas, we used a rainfall–runoff model to calculate threshold rainfalls using three-hour 100-year frequency rainfalls and G2G-based hydrological models. The duration was set at three hours to match the three-hour forecasts from the KMA. In addition, as there are physical limitations to building nationwide pipeline data for hydrological analysis, we calculated runoffs considering 5-year to 15-year drain capacity, which represents a city's ability to protect against inundation. For the threshold rainfall calculation, we calculated threshold rainfalls for 104,197 standard watershed grids and 2044 grids classified as urban areas.

We collected social media information and news articles to compare the calculations with actual inundation events in the past. We identified inundation events in Seoul caused by heavy rainfall in August 2022. When comparing the actual inundation photographs from Hadan Station and Gangnam Station, the result of calculating threshold rainfall indicated that inundation occurred in the evening hours. In addition, it was found that 1.7 m of flooding occurred in the area of Jinheung Apartment, and the actual flooding occurred to the extent that a bus was submerged.

For Busan rainfall events, the threshold rainfall calculation predicted the deepest inundation (1.2 m) around the Gaya Underpass. The actual photographs show the complete submersion of a vehicle. An actual inundation event occurred around Hadan Station, which affected road traffic in the area. The threshold rainfall calculation also showed a maximum inundation depth of 0.3 m. The threshold rainfall results were shown to well represent the actual damages. As for Gangneung, a region hit by Typhoon Mitak in October 2019, a maximum inundation depth of 1.1 m was predicted for the Ojukheon area. The actual photographs showed the impact on vehicle traffic. After applying a heavy rainfall event in Seoul in 2018, it was found that flooding occurred to the extent that could affect traffic in Yeonnam-dong and Sangam-dong, Mapo-gu, where the actual damage occurred.

We verified the threshold rainfall calculations using actual previous events, and the calculations were shown to represent actual damage. By applying the findings of this study along with radar-predicted rainfall information, we can preemptively prepare against inundation damages in areas where heavy rain is expected.

Since this study did not use quantitative data, qualitative data such as news and SNS were used to verify the calculations. In a future study, quantitative verification methods using flooding measurement sensors and CCTV need to be carried out.

In addition, it is expected that more specific impact information can be provided if a plan to utilize threshold rainfall is prepared and linked to the results of existing matrix-based impact forecasting studies. In particular, if impact information is provided considering the risk level for three categories including people, traffic, and buildings in urban areas, utilization will be higher. By applying the findings of this study along with radar-predicted rainfall information, we can preemptively prepare against inundation damages in areas where heavy rain is expected.

Author Contributions: D.H.K., D.H.N. and Y.S.S. carried out the survey of previous studies and created the graph of the data. B.S.K. suggested the idea of this study and contributed to writing the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by a grant (2021-MOIS37-001) from the Intelligent Technology Development Program on Disaster Response and Emergency Management funded by the Ministry of Interior and Safety of Korean government (MOIS, Korea).

Data Availability Statement: The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Korean Meteorological Society. Planning Study on Introduction Plan of Influence Forecast. 2016. Available online: https://scienceon.kisti.re.kr/commons/util/originalView.do?cn=TRKO201800035577&dbt=TRKO&rn= (accessed on 20 March 2020).
2. Lee, S.-H.; Kang, D.-H.; Kim, B.-S. A Study on the Method of Calculating the Threshold Rainfall for Rainfall Impact Forecasting. *J. Korean Soc. Hazard Mitig.* **2018**, *18*, 93–102. [CrossRef]
3. KMA (Korea Meteorological Administration). A Study on the Construction of Integrated Data for Meteorological Disaster Impact Forecasting. 2012. Available online: https://www.kma.go.kr/kma/archive/pub.jsp#gal_cate14 (accessed on 20 March 2020).
4. Yeh, S.W. A suggestion for expanding impact prediction services. *Meteorol. Technol. Policy* **2017**, *10*, 6–17.
5. FFC. *Flood Guidance Statement User Guide*, 4th ed.; Flood Forecasting Centre: Devon, UK, 2017.
6. Cole, S. Flood Forecasting at national scales: Some UK experiences. In Proceedings of the National Flood Management Conference, Dublin, Ireland, 15 March 2018.
7. Price, D.; Hudson, K.; Boyce, G.; Schellekens, J.; Moore, R.J.; Clark, P.; Harrison, T.; Connolly, E.; Pilling, C. Operational use of a grid-based model for flood forecasting. *Water Manag.* **2012**, *165*, 65–77. [CrossRef]
8. Cranston, M.; Maxey, R.; Tavendale, A.; Buchanan, P.; Motion, A.; Cole, S.; Robson, A.; Moore, R.J.; Minett, A. Countrywide flood forecasting in Scotland: Challenges for hydrometeorological model uncertainty and prediction. In *Weather Radar and Hydrology, Proceedings of the Symposium, Exeter, UK, 18–21 April 2011*; Moore, R.J., Cole, S.J., Illingworth, A.J., Eds.; IAHS Publications: Wallingford, UK, 2012; Volume 351, pp. 538–543.
9. Liu, S.; Zang, Z.; Wang, W.; Wu, Y. Spatial-temporal evolution of urban heat Island in Xi'an from 2006 to 2016. *Phys. Chem. Earth* **2019**, *110*, 185–194. [CrossRef]
10. Wang, W.; Du, Y.; Chau, K.; Chen, H.; Liu, C.; Ma, Q. A Comparison of BPNN, and ARIMA for Monthly Rainfall Forecasting Based on Wavelet Packet Decomposition. *Water* **2021**, *13*, 2871. [CrossRef]
11. Rözer, V.; Peche, A.; Berkhahn, S.; Feng, Y.; Fuchs, L.; Graf, T.; Haberlandt, U.; Kreibich, H.; Sämann, R.; Sester, M.; et al. Impact-Based Forecasting for Pluvial Floods. *Earth's Future* **2021**, *9*, 2020EF001851. [CrossRef]
12. Chen, J.; Li, Y.; Zhang, S. Impact of Different Design Rainfall Pattern Peak Factors on Urban Flooding. *Water* **2023**, *15*, 2468. [CrossRef]
13. Williams, S.; Griffiths, J.; Miville, B.; Romeo, E.; Leiofi, M.; O'Driscoll, M.; Iakopo, M.; Mulitalo, S.; Ting, J.C.; Paulik, R.; et al. An Impacts-Based Flood Decision Support System for a Tropical Pacific Island Catchment with Short Warnings Lead Time. *Water* **2021**, *13*, 3371. [CrossRef]
14. Sidel, L.M.; Basri, H.; Mohammed, M.H.; Marufuzzaman, M.; Ishak, N.A.; Ishak, A.M.; Omar, B.Z.; Osman, S.; Ramly, S.; Hassan, M.H. Towards Impact-Based Flood Forecasting and Warning in Malaysia: A Case Study at Kelantan River. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *704*, 012001.
15. Fabio, S.; Lydia, C.; Albrecht, W.; Biswa, B.; Raihanul, H.K. Towards impact-basded flood forecasting and warning in Bangladesh: A case study oat the local level in Sirajganj district. *Nat. Hazards Earth Syst. Sci.* **2018**. [CrossRef]
16. Kołodziejczyk, K.; Rutkowska, A. Estimation of the Peak over Threshold-Based Design Rainfall and Its Spatial Variability in the Upper Vistula River Basin, Poland. *Water* **2023**, *15*, 1316. [CrossRef]
17. Ma, B.; Wu, Z.; Wang, H.; Guo, Y. Study on the Classification of Urban Waterlogging Rainstorms and Rainfall Thresholds in Cities Lacking Actual Data. *Water* **2020**, *12*, 3328. [CrossRef]
18. Liao, H.-Y.; Pan, T.-Y.; Chang, H.-K.; Hsieh, C.-T.; Lai, J.-S.; Tan, Y.-C.; Su, M.-D. Using Tabu Search Adjusted with Urban Sewer Flood Simulation to Improve Pluvial Flood Warning via Rainfall Thresholds. *Water* **2019**, *11*, 348. [CrossRef]
19. Jang, J.-H. An Advanced Method to Apply Multiple Rainfall Thresholds for Urban Flood Warnings. *Water* **2015**, *7*, 6056–6078. [CrossRef]
20. Kim, H.-M.; Min, K.-R.; Kim, I.-G.; Lim, B.-H.; Youn, M.-J.; Kim, S.-B. Paradigm shift to impact-based forecasting and warning services for natural hazard response. *Innov. Stud. Korea Soc. Innov.* **2017**, *12*, 161–178.
21. Lee, B.-J. Analysis on inundation characteristics for flood impact forecasting in Gangnam drainage basin. *Atmos. Korean Meteorol. Soc.* **2017**, *27*, 189–197.
22. Keum, H.-J.; Kim, H.-I.; Han, K.-Y. Real-Time Forecast of Rainfall Impact on Urban Inundation. *J. Korean Assoc. Geogr. Inf. Stud.* **2018**, *21*, 76–92.
23. Lee, S.-W.; Jung, S.-K. A Study on the Establishment of Quantitative Criteria for the Prediction Stage of Heavy Rainfall Impact-Based Forecasting Using k-means Clustering. *Crisisonomy* **2021**, *17*, 91–102. [CrossRef]
24. Lee, K.-K.; Shim, J.-K.; Cho, S.-J. Estimation of Risk Levels of Impact Forecast for Heavy Snow Event by Using Big Data of Media Articles. *e-Bus. Stud.* **2022**, *23*, 233–245. [CrossRef]
25. Song, Y.-S.; Lee, H.-S.; Kim, B.-S.; Park, M.-J. Developing a Rainfall Impact Forecasting Model for Disaster Mitigation around the River. *Crisisonomy* **2020**, *16*, 35–47. [CrossRef]
26. Ko, C.-M.; Jeong, Y.-Y.; Lee, Y.-M.; Kim, B.-S. The Development of a Quantitative Precipitation Forecast Correction Technique Based on Machine Learning for Hydrological Applications. *Atmosphere* **2020**, *11*, 111. [CrossRef]
27. Ministry of Construction & Transportation. High Spatiotemporal Resolution Flood Forecasting to Secure Enough Lead Time. 2016. Available online: https://www.kaia.re.kr/portal/landmark/readTskView.do?tskId=101706&yearCnt=1&menuNo=200060 (accessed on 20 March 2020).

28. Kim, H.-S.; Yoon, S.-K.; Yang, D.-M.; Kwon, H.-H. Development of Grid-Based Conceptual Hydrologic Model. *J. Korea Water Resour. Assoc.* **2010**, *43*, 667–679. [CrossRef]
29. Choo, K.-S.; Kang, D.-H.; Kim, B.-S. A Study on the Estimation of the Threshold Rainfall in Standard Watershed Units. *J. Korean Soc. Disaster Secur.* **2021**, *14*, 1–11.
30. Software Packages FLO-2D Manual. 2009. Available online: https://www.flo-2d.com/download/ (accessed on 20 March 2020).