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Mega Flood Inundation Analysis and the Selection of Optimal Shelters

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Abstract: In recent decades, extreme storm events due to climate change have frequently occurred worldwide, a few of which have even occurred consecutively; we class such rainfall events as mega events. That is to say, if the inter-arrival time between rainfall events with a 100-year frequency is less than the IETD (Inter-Event Time Definition), the event can be considered a mega event. Therefore, the aim of this study was to implement flood inundation analysis using the hypothetical mega event from two consecutively occurring events of 100-year frequency, and select the optimal shelters using a developed method for minimizing casualties from floods. The Gyeongan stream basin, which is a tributary of the Namhan River in Korea, was selected as the study area. This study calculates mega flood discharge using the SSARR (Stream Synthesis and Reservoir Regulation) model, and conducts a flood inundation analysis of mega floods via the level pool method and the HEC-GeoRAS model. An inundation map was constructed, and the inundated area was classified into three zones and five administrative districts. Sixteen shelters were selected as candidates based on the criteria of the local government safety management plans and the Guidelines for Establishing the Disaster Relief Plan of 2013. To evaluate the candidates for evacuation in each district, we selected seven evaluation indicators from the shelter criteria of several countries, and calculated the weights of the indicators using the Analytic Hierarchy Process (AHP) method. As a result, four optimal shelters were selected in the study area. The results of the study can be used as the basic information for analyzing mega natural disaster events and inundation, and for establishing evacuation shelters, which are one of the non-structural flood protection measures.

Keywords: mega rainfall; mega flood; flood inundation map; evacuation shelter



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1. Introduction

The frequency of extreme events is increasing worldwide due to climate change [1]. Similarly, the damage caused by rainfall, especially localized intensive rainfall, is also increasing on a scale not observed in previous data [2]. Moreover, there is an ongoing increase in flood damage caused either by storm events that continuously overlap with each other over a short period of time, or those that persist for a relatively longer period of time [3]. In April and May 2011, torrential rains continuously poured for over a month in the United States, resulting in floods along the Mississippi River. There were approximately 20 human casualties and over 16,000 evacuees. Furthermore, in South Korea, three typhoons (Bolaven, Tembin, and Sanba) consecutively occurred in 2012, and resulted in seven deaths and power outages in 520,000 homes caused by rainfall and wind. When two rainfall events consecutively occur, such that one rainfall event overlaps with the other event before the impact of the first event subsides, two peak flood runoff discharges at the

outlet of the watershed may arise. The same thing occurs when a rainfall event persists for a relatively long time period. The rainfall events of the above-mentioned examples can result in major flood damage; therefore, we class these events as “mega floods”. We class the two consecutive events used in this study as a mega rainfall and mega flood, respectively. Mega rainfall events cause damage to the social infrastructures along rivers and riversides, as well as socioeconomic damage and the significant loss of lives, due to urban flood inundation. Therefore, it is necessary to prepare for evacuation and establish flood protection measures in advance, through the analysis of the inundation caused by actual and hypothetical mega rainfall events and mega floods. For establishing flood protection measures, an accurate rainfall–runoff analysis is first required. However, rainfall–runoff analyses are affected by various parameters such as rainfall, infiltration, soil characteristics, and evapotranspiration; therefore, different results are obtained according to the differences in each parameter. In particular, as we need to calculate the flood discharge due to consecutive storm events in the case of a mega flood, we must conduct rainfall–runoff analyses through a rational method of parameter estimation. Additionally, in the case of a mega flood, the ground is weakened due to the consecutive storm events, thereby limiting the effectiveness of the extant structural flood protection measures established through design flood estimation [1]. Hence, we may need to establish non-structural flood protection measures, such as flood forecasting, and optimal shelters where local residents can be evacuated in the event of a mega flood.

Regarding the studies on the efficient estimation of the parameters of runoff, Mohan (1997) used a Genetic Algorithm (GA) approach to estimate the parameters, with the aim of calibrating non-linear Muskingum models [4]. Kim et al. (2008) estimated the parameters using an optimization method in rainfall–runoff models, such as the Storage Function Model (SFM), TANK model, and Streamflow Synthesis and Reservoir Regulation (SSARR) model [5]. In addition to these studies, various other studies have employed auto-calibration methods, such as GA and the Shuffled Complex Evolution method, developed at The University of Arizona (SCE-UA), to estimate parameters for the purpose of calibrating rainfall–runoff models [6–12]. To conduct a flood inundation analysis, many hydraulic–hydrodynamic models have been developed, and are categorized into one-dimensional (1D) models, two-dimensional (2D) models, and one-dimensional river flow models coupled with two-dimensional floodplain flow (1D–2D) models. In the case of one-dimensional models, MIKE11, FLDWAV, and HEC-RAS are widely used [13,14]. The 1D models are simple to use and provide information on bulk flow characteristics, but they fail to provide detailed information regarding the flow field. Regarding the two-dimensional models, FLUMEN, MIKE-FLOOD, FFC-5, FLO-2D, and HEC-RAS are the most famous models [15–18]. Although the 2D models require substantial computing times, they can provide better results than the 1D models when analyzing bays and estuaries, braided streams, and so on [17]. Because of the defects of 1D and 2D models, many researchers have tried to couple 1D river flow models with 2D models. The 1D–2D models have the advantage of providing real time simulations of flood events [16].

With regards to selecting shelters to minimize human casualties, previous studies have assessed the selection and suitability of optimal shelters using location–allocation models based on GIS [19–21]. Subsequently, the most suitable locations are identified on a network in terms of the capacity of evacuation shelters, shortest distance, minimum evacuation time, etc., [22–24]. In these previous studies, the rainfall–runoff analysis was performed by estimating the parameters for single storm events. As mentioned above, rainfall–runoff analysis is affected by various parameters; thus, different analysis results can be obtained when the analysis is performed on consecutive storm events.

Therefore, in this study, we used the SCE-UA method to estimate the parameters for consecutive storm events. We estimated the optimal parameters for simulating consecutive storm events by assessing two objective functions, namely the Sum of Squared Residuals (SSR) and the Weighted Sum of Squared Residuals (WSSR) [25], based on their suitability for auto-calibrating the target model, thereby aiming to derive more rational rainfall–runoff

analysis results [26]. To conduct a flood inundation analysis for mega floods, firstly we extended river cross section data to riverside area using a HEC-GeoRAS model for the extension of the section area, and the data for the extended area were obtained using a Digital Elevation Model (DEM). If the analysis is performed without extension, the water level can only be calculated for the river cross section area surveyed, and the depth of flooding cannot be estimated for the riverside area. Moreover, to aid the decision-making of residents that need to evacuate in the event of a mega flood, we used the Analytic Hierarchy Process (AHP) to rank the priority of shelters based on their evaluation scores. Through this process, we sought to identify optimal shelters, thereby minimizing the casualties caused by mega floods.

2. Study Area

We selected the Gyeongan stream basin, a tributary of the Namhan River, Korea, as the study area (Figure 1). The Gyeongan stream has a length of 49.5 km and a basin area of 558.2 km². In addition, the population density is relatively high, and the area has witnessed rapid urbanization. Flood damage in the Gyeongan stream basin will lead to human casualties because the waterfront area and ecological wetlands have been intensively developed around the Gwangju urban area, leading to greater utilization of the stream by local residents. Moreover, in 2011, floods occurred in seven towns, including Chowol-eup and Jiwol-ri, isolating 760 residents and resulting in four deaths. One person died owing to a sudden rainstorm on 16 May 2018. Thus, measures need to be taken to prevent the loss of human lives. For this reason, we estimated the mega flood discharge for the Gyeongan stream basin, and constructed a corresponding flood inundation map at the eup, myeon, and dong (administrative districts of town, township, and neighborhood) levels. Based on this map, we selected optimal shelters to minimize the loss of lives in the event of inundation due to a mega flood in the stream basin. There are four Automated Synoptic Observing System (ASOS) weather stations (Seoul, Suwon, Icheon, and Yangpyeong). To calculate areal rainfall at the Gyeongan stream basin, we collected hourly rainfall data from the surrounding weather stations, and used the Thiessen method.



Figure 1. Gyeongan stream basin in Namhan river, Korea; broken lines mark the Thiessen network.

3. Methodology

3.1. Mega Flood Scenario

3.1.1. Definition of Mega Rainfall and Mega Flood

In recent years, there has been an increase in the damage caused by single, as well as consecutive, storm events. In 2014, the 18th typhoon Phanfone, and the 19th typhoon Vongfong, hit Japan consecutively in the span of two weeks, resulting in extensive damage. Similarly, in Korea, for the first time since weather observations began, three typhoons successively hit the Korean peninsula in 2012, causing significant property loss and human casualties. There is a growing number of such cases worldwide, where the second rainfall event occurs before the impact of the preceding rainfall event has subsided. Accordingly, in this study, we define a mega rainfall as the sequence of events, and a mega flood refers to the situation caused by mega rainfall. As mentioned above, this refers to the situation where a major flood occurs due to a rainfall event that takes place before the effects of flood damage due to extreme storm events, such as heavy rain, typhoon, abnormal flood, and flash flood, subside.

3.1.2. Mega Rainfall Scenario and Mega Flood

This study defines mega rainfall as the occurrence of consecutive storm events. However, if the non-rainfall duration between two storm events is long enough, then the combined impact of the two events will be less than that of a mega rainfall event that has a shorter non-rainfall duration. Therefore, in this study, we ensured that the two storm events in question could be considered as one mega rainfall event. That is, if the non-rainfall duration between two storm events is less than the Inter-Event Time Definition (IETD), the two events were considered as one mega rainfall event (Figure 2). The Coefficient of Variation (CV) was used to calculate the IETD, as shown in Figure 3. In the CV method for IETD, all rainfall events were distinguished by given non-rainfall period, and then used to calculate the coefficient of variation. The IETD is the point where the coefficient of variation is 1.

In addition, we set up a scenario for the occurrence of a mega rainfall event. In this scenario, design rainfall events with a duration of 24 h and a 100-year recurrence interval, occur consecutively. That is, we generated the scenario by supposing that the design rainfall events occurred consecutively within the bounds of Probable Maximum Precipitation (PMP). The procedure for working out the scenario was as follows.

1. Estimating the Frequency-Based Rainfall in the Target Basin

The frequency-based rainfall, with respect to period and duration, was estimated by selecting meteorological stations that have at least 30 years of rainfall data, obtaining statistical significance, conducting preliminary analysis, fitting probability distributions, estimating parameters, performing goodness-of-fit tests, and selecting the optimal probability distribution.

2. Calculating the Minimum Non-Rainfall Duration

The rainfall time series data are presented in a continuous format. Thus, we calculated the minimum non-rainfall duration to partition consecutive storm events into single storm events. Thereafter, the consecutive storm event scenario was generated by causing the subsequent storm event to occur within that duration, after the occurrence of the preceding storm event. We simulated hypothetical rainfall events, and if two rainfall events consecutively occurred within the IETD, it was regarded as one event. Alternatively, if the non-rainfall period between two events was greater than the IETD, it was regarded as two separate events.

3. Estimating Probable Maximum Precipitation

PMP refers to the greatest depth of precipitation that is physically possible at a particular time and location. Therefore, the mega flood scenario must also be generated such that it does not exceed the PMP.

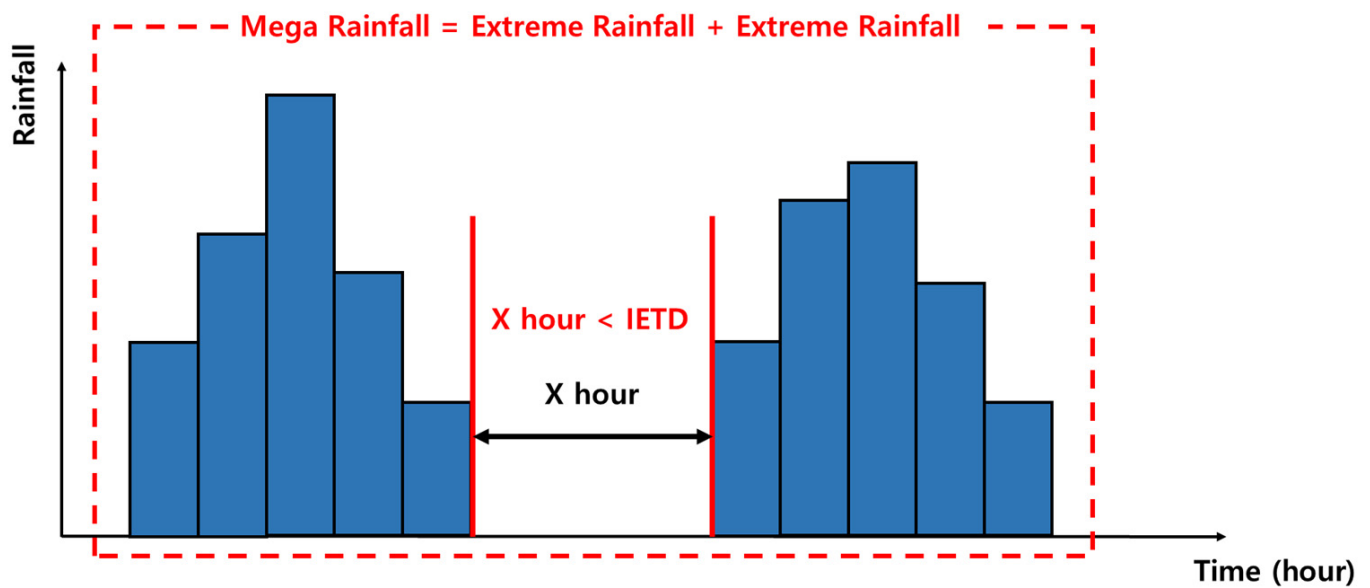


Figure 2. Definition of mega rainfall event using IETD; mega rainfall event consists of two extreme rainfall events that have an inter-arrival time less than IETD.

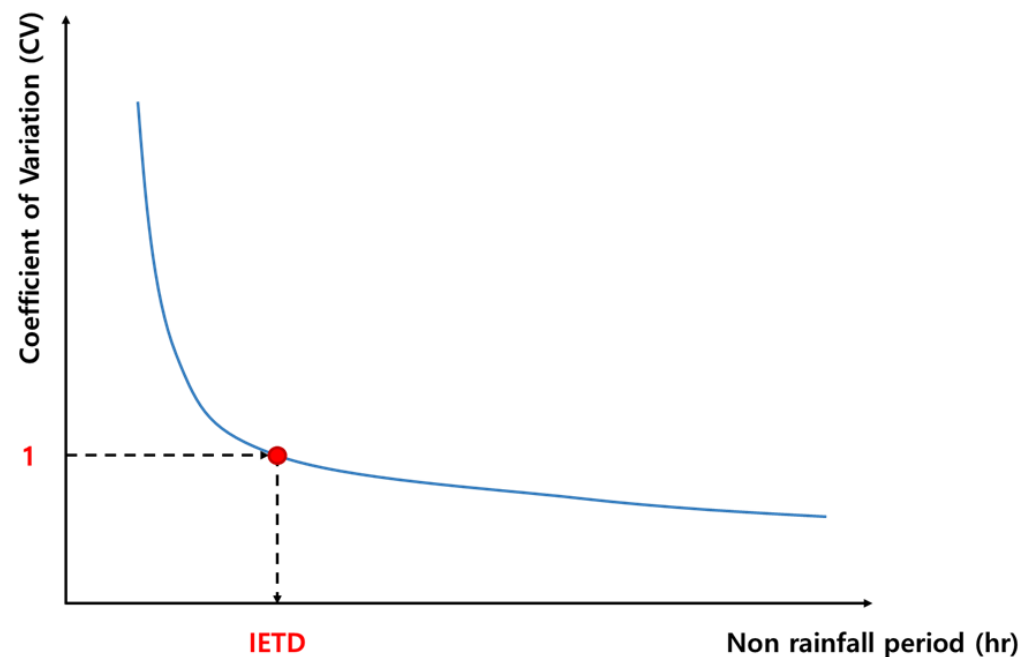


Figure 3. Coefficient of Variation (CV) method for calculating IETD; when the value of CV is 1, the corresponding y coordinate is the non-rainfall period, which is the IETD.

3.2. Mega Flood Estimation Method

The Streamflow Synthesis and Reservoir Regulation (SSARR) model was used to estimate the flood discharge of mega floods. SSARR model was developed by the U.S. Army Corps of Engineers in 1956 to provide mathematical, hydrologic simulations required for the planning, design, and operation of water control works. It is widely used for operational river forecasting and management in many countries, including Korea. Korean government used the SSARR model as an official rainfall–runoff model that comprised the Integrated Water Resources Management System of the Korea Water Resources Corporation, i.e., K-water [27,28]. The optimized 24 parameters of the SSARR model can be found by the trial-and-error method, and this could be more suitable for the simulation of runoff

from consecutive rainfall events than that from a single rainfall event. Many researchers have used the SSARR model to calculate flood discharge. Moreover, to simulate the flood discharge rationally, the Shuffled Complex Evolution method, developed at the University of Arizona (SCE-UA), was applied for the estimation of parameters. Subsequently, the optimal parameters for simulating the mega flood were estimated by assessing the suitability of the two objective functions for auto-calibrating the model, namely, SSR and WSSR. These are described in detail in the following subsections.

3.2.1. Mega Flood Simulation Model

The SSARR model was used for the mega flood runoff simulation. The SSARR is a lumped parameter model, and it uses the trial-and-error method to determine optimum values for 24 or more parameters. Therefore, when simulating consecutive storm events instead of the usual single storm events, the SSARR model serves as a more rational means of simulating a mega flood by estimating various parameters.

3.2.2. Parameter Estimation Method

As mentioned above, different parameters can lead to different results in the rainfall-runoff analysis. Therefore, it is important to estimate the optimal parameter values. Parameter estimation can be performed using methods such as GA [29], pattern search [30], and SCE-UA [25,31]. SCE-UA is a hybrid optimization method that introduces the new concept of complex shuffling to the existing search methods, such as GA, the simplex method, the Controlled Random Search (CRS) method, and competitive evolution [32]. In particular, the SCE-UA method can be used to determine the overall optimal solution over an extensive domain. If the convergence criteria are provided, this increases the probability of determining the overall optimal solution. In this study, we employed a global optimal solution method, known as SCE-UA, to estimate the parameters. If the SSARR model is auto-calibrated through SCE-UA, it is possible to simulate mega floods more accurately by determining the optimal parameters for the model [11].

3.2.3. Objective Function

When auto-calibrating a model, an objective function serves as a measure of the behavior of the model, and its values represent the proximity of the estimated values to the actual values. However, because the estimation of parameters varies according to the different objective functions, there can be no definitive answer as to which objective function is more suitable. Therefore, to auto-calibrate the model parameters, it is necessary to select an appropriate objective function. In this study, we applied two objective functions: SSR, which is the sum of the squared deviations between the observed runoff and simulated runoff, and WSSR, which was proposed by Kim et al. [33]. After assessing the suitability of these objective functions, we selected a function that was optimal for auto-calibrating the parameters.

SSR is the sum of the squared deviations between the observed runoff and simulated runoff, and its objective function is shown in Equation (1). WSSR is an objective function that assigns weights related to peak flow and the time of peak flow to SSR, and it is expressed in Equation (2). As shown in Equation (3), WSSR applies the relative error of peak flow as a weight to prevent the under- and overestimation of peak flow. In addition, as shown in Equation (4), WSSR applies the percentage error of the time of peak flow as a weight to reduce errors in lag times in flood runoff hydrographs [14].

$$\text{Min} = \sum_{i=1}^n [Q_{obs}(i) - Q_{sim}(i)]^2 \quad (1)$$

$$F = \left[\sum_{i=1}^n (Q_{obs}(i) - Q_{sim}(i))^2 \right] \times W_1 \times W_2 \quad (2)$$

$$W_1 = 1 + \frac{|Q_{obs,peak} - Q_{sim,peak}|}{Q_{obs,peak}} \quad (3)$$

$$W_2 = 1 + \frac{|T_{obs,peak} - T_{sim,peak}|}{T_{obs,peak}} \quad (4)$$

Here, n represents the number of data points, i is the number of observed data points, Q_{obs} is the observed runoff, Q_{sim} is the simulated runoff, $Q_{obs, peak}$ is the observed peak flow, $Q_{sim, peak}$ is the simulated peak flow, $T_{obs, peak}$ is the time of the observed peak flow, and $T_{sim, peak}$ is the time of the simulated peak flow.

3.2.4. Evaluation Criteria for Selection of Objective Function

To auto-calibrate the model parameters, it is necessary to select an appropriate objective function by evaluating the functions of SSR and WSSR. Such an evaluation can help in determining which objective function is more suitable. In this study, we used the three evaluation criteria shown in Equations (5)–(7) below, to compare and analyze the differences between the simulated runoff obtained by SSR and WSSR and the observed runoff. Based on these results, we selected the more suitable objective function.

- Non-dimensional Root Mean Square Error (NRMSE)

$$NRMSE = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^n [Q_{obs}(i) - Q_{sim}(i)]^2}}{Q_{obs,peak}} \quad (5)$$

Here, n is the number of data points, Q_{obs} is the observed runoff, Q_{sim} is the simulated runoff, and $Q_{obs, peak}$ is the observed peak flow. When the NRMSE value is close to 0, the simulation may be judged to have a high efficiency.

- Relative Error of Peak Flow (RE)

$$RE = \frac{|Q_{sim,peak} - Q_{obs,peak}|}{Q_{obs,peak}} \quad (6)$$

Here, RE represents the relative error of peak flow, Q_{sim} represents the peak of the simulated peak flow, and Q_{obs} represents the peak of the observed peak flow. In this case, when the RE value is close to 0, the simulation may be judged to have high efficiency.

- Coefficient of Determination (R^2)

$$R^2 = \frac{\sum_{j=1}^n (Q_{obs}(i) - Q_{obs,ave})(Q_{sim}(i) - Q_{sim,ave})}{\sqrt{\sum_{i=1}^n (Q_{obs}(i) - Q_{obs,ave})^2} \sqrt{\sum_{i=1}^n (Q_{sim}(i) - Q_{sim,ave})^2}} \quad (7)$$

Here, $Q_{obs}(i)$ is the observed runoff at time (i), $Q_{sim}(i)$ is the simulated runoff at time (i), n is the number of observed data points, $Q_{obs,ave}$ is the average observed runoff, and $Q_{sim,ave}$ is the average simulated runoff. The value of R^2 ranges from 0 to 1, and when it has a value close to 1, the simulation may be judged to have high efficiency.

3.3. Method of Flood Inundation Analysis for Mega Flood

As mentioned in the introduction, various hydraulic–hydrodynamic models (1D, 2D, and 1D–2D models) were developed for conducting flood inundation analysis. In this study, we used the level pool method and HEC-GeoRAS model. The level pool method is a method used to obtain the flood inundation range by estimating the overflow volume according to the inundation depth. However, when using the level pool method with only river cross section data, water level is only calculated in the range of the river cross section data, and is thus overestimated. To overcome this problem, we applied a HEC-GeoRAS

model. Using the HEC-GeoRAS model, we extended the river cross sections to input location information from topological data, and then estimated the runoff to inland areas to minimize uncertainty regarding flood area when making flood inundation maps for mega floods.

3.4. Selection of Optimal Shelters According to Flood

To select optimal shelters in the event of flood, first, the areas where human casualties are expected to occur must be located on the basis of flood inundation analysis. Then, appropriate shelters that can minimize casualties in the identified regions must be identified, and they should be evaluated to select optimal shelters.

3.4.1. Flood Inundation Map

We performed a flood inundation analysis of a mega flood and developed a flood inundation map for Gyeongan stream basin. Figure 4 explains the procedure for flood inundation map construction. We used Digital Elevation model (DEM) data from the National Spatial Data infrastructure portal, which has $30\text{ m} \times 30\text{ m}$ resolution for South Korea. First, we clipped DEM data located within the shape of the Gyeongan stream basin, and increased the number of river cross sections and data. We added 16 cross section data by DEM, and obtained total 136 cross section data points for the Gyeongan stream. This helped to analyze the protected lowland or inland areas in the river basin. Flood level estimated from mega flood runoff discharge was used as input data into river cross sections, then analysis of grid and Triangular Irregular Networks (TIN) was performed. Finally, the flood inundation map was obtained using elevation difference between flood level and DEM.

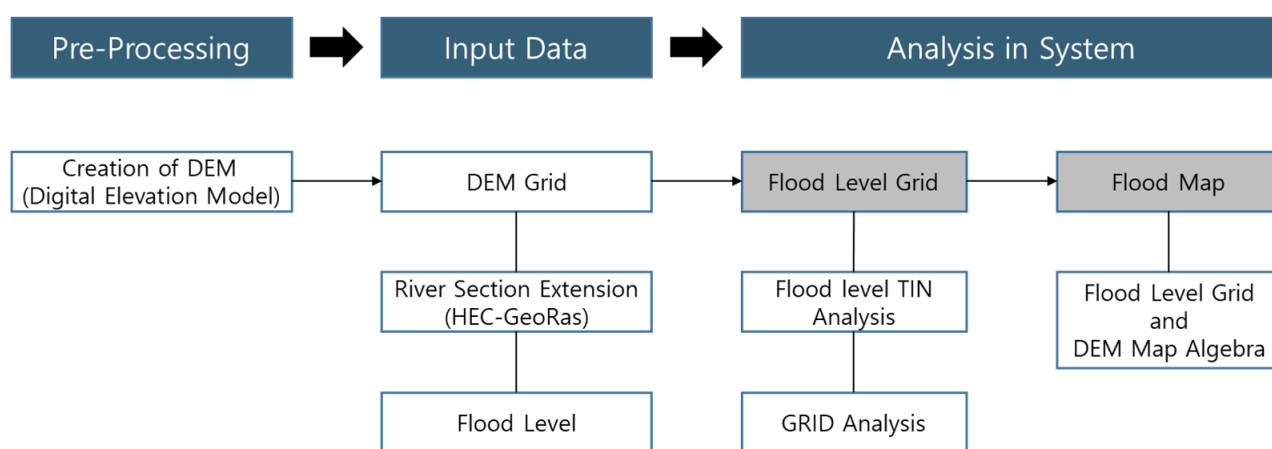


Figure 4. Procedure for flood inundation map construction.

3.4.2. Adoption of an Evaluation Indicator for Selecting Optimal Shelters

To select optimal shelters from the shelters identified by the administrative district, one must use appropriate evaluation indicators. Therefore, we examined the shelter selection criteria in several countries and adopted a set of evaluation indicators to evaluate the shelter alternatives.

- Shelter Selection Criteria in Korea

According to the Guidelines for Establishing the Disaster Relief Plan, a designated shelter should be within walking distance from the area to be evacuated [34]. Flood inundation area, flood inundation depth, accommodation area, capacity of evacuation shelters, evacuation route, distance, etc., should be considered when selecting shelters. In general, a shelter should be easily accessible from the main evacuation routes. Regarding the size of the shelter zone, the designated facility must adhere to the capacity of evacuation shelters, which is usually 1000 persons at most.

- Shelter Selection Criteria in the United States

The Standards for Hurricane Evacuation Shelter Selection of the American Red Cross (ARC 4496) provide the shelter selection criteria used in the United States [34]. Here, the criteria for selecting a flood shelter include selecting a facility outside the 100-year predicted flood area, and avoiding the selection of a shelter within the 500-year predicted flood area. The distance between the flood inundation zone and the shelter must be considered, and zones that can become isolated due to inundation must be avoided. A building may be designated as a shelter if the first-floor level is the same, or higher than, the standard flood level.

- Shelter Selection Criteria in Japan

In Japan, shelters are selected in accordance with the Shelter Management and Operation Guidelines, which are based on the Disaster Control Measures of Japan [35]. Shelters are designated at the council or district level, and they must be public buildings of earthquake-proof and rebar structure. Moreover, the number of victims accommodated at a shelter is limited to two persons per 3.3 m².

- Shelter Selection Criteria in the United Kingdom

In the United Kingdom, shelters are selected based on the Evacuation and Shelter Guidance regulations [36]. For short-term evacuation, instead of moving to a shelter, evacuees are advised to move to a safe area in close proximity to their location, such as a higher floor in the same building. For mid-term evacuation, shelters must be located near the evacuees' place of residence.

By examining the shelter selection criteria of various countries, it can be seen that there are minor differences; however, in the final analysis, public buildings are recommended as shelters wherever possible, considering their scale of accommodation and geographical conditions. Therefore, to evaluate the shelter alternatives identified earlier, we adopted three general, and seven specific, evaluation indicators as the basic features that a shelter must possess (Table 1).

Table 1. Optimal shelter evaluation indicators.

General	Specific Evaluation Indicators
Scale accommodation	Adequate accommodation of evacuees Height of shelter building
Geographical conditions	Ease of access from evacuation route Distance of shelter from stream/river Time taken to evacuate to shelter
Type	Public buildings Private institutions

3.4.3. Assignment of Weights to the Evaluation Indicators Using AHP

The AHP analysis is designed for the decision-making of many agents using a di-verse array of evaluative criteria. It is a multi-criteria decision-making method that arranges the relevant evaluative criteria in a hierarchy, and assigns weights to them according to their place in the hierarchy [37]. This provides a comprehensive framework for solving decision-making problems by considering both quantitative and qualitative factors based on intuitive, rational, or irrational judgments of the decision makers. AHP analyzes a multi-criteria decision-making problem in terms of the hierarchical structure, and determines the importance of each property by comparing them through an expert survey. Thus, it can be used to provide quantitative results for evaluating which shelter alternative is optimal in the event of a mega flood.

4. Result and Discussion

4.1. Generation of the Mega Rainfall Scenario

To simulate a mega rainfall scenario using the IETD, it is necessary to first calculate the non-rainfall duration for the rainfall time series of each meteorological station in the study basin. There are methods, such as gamma distribution, exponential distribution, and CV, to calculate the IETD. This study used the CV method for the calculation of the IETD because we can select the IETD by intuition. As we can see in Figure 5, the IETD is obtained at the point where CV is 1. The hourly rainfall data for the rainy season of June to September over 30 years were obtained from the stations in the Gyeongang stream basin, and the IETDs were calculated.

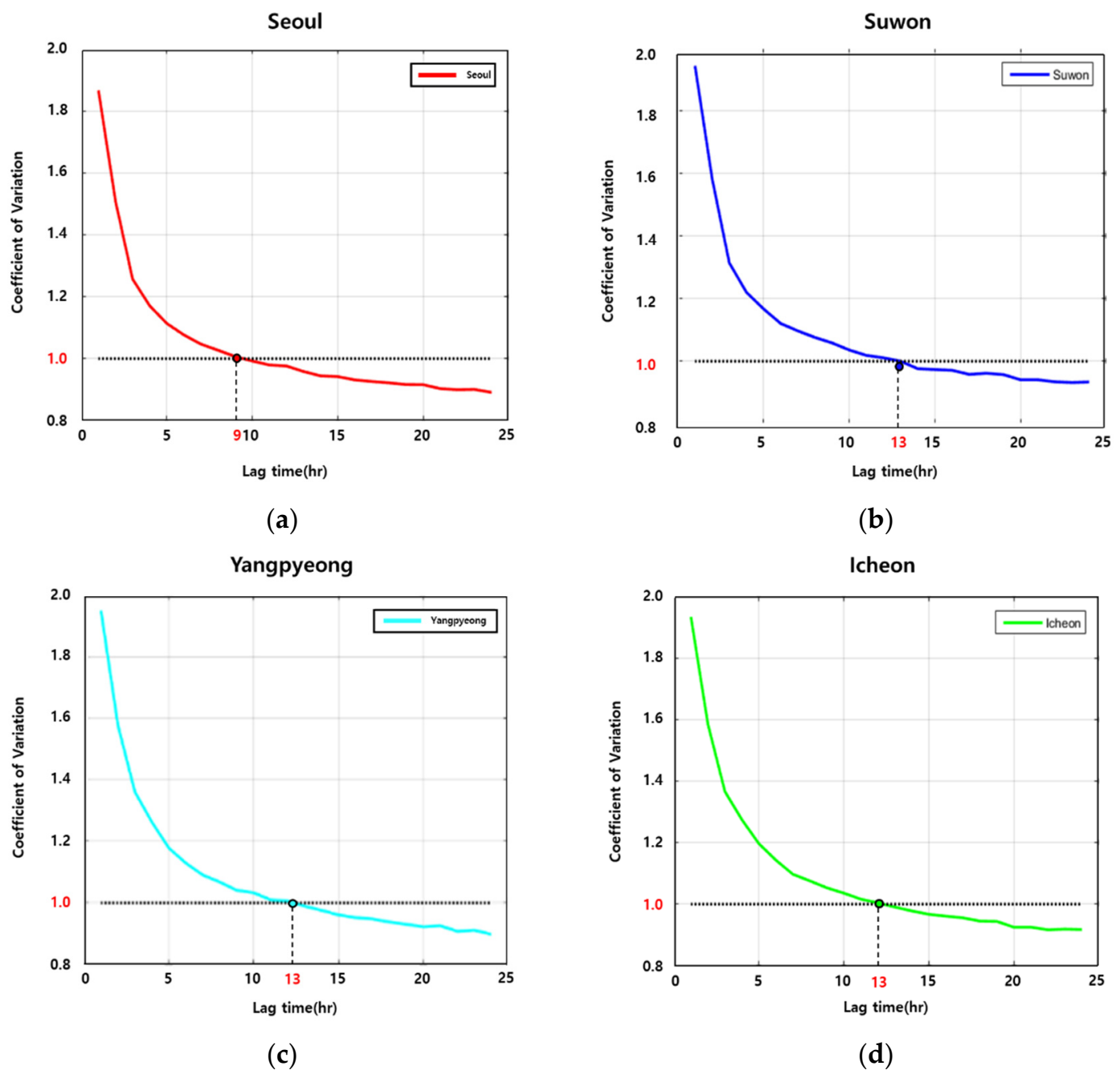


Figure 5. Selection of IETD from the coefficient of variation; (a) Seoul station (9 h), (b) Suwon station (13 h), (c) Yangpyeong station (13 h), (d) Icheon station (13 h).

Accordingly, the minimum non-rainfall duration was calculated for the meteorological stations in the Gyeongang stream basin, i.e., Seoul, Icheon, Suwon, and Yangpyeong meteorological stations, as shown in Figure 5. The IETD calculated for each meteorological station was 9 h for Seoul, 12 h for Icheon, 13 h for Suwon, and 12 h for Yangpyeong. Because conversion rainfall must be implemented when applying rainfall to each subbasin, the minimum non-rainfall duration was selected as 9 h, based on the smallest IETD value, i.e., the value for the Seoul meteorological station. Lastly, we applied the IETD (Figure 6) to produce consecutive 100-year frequency-based rainfall events, as suggested in the report of the Channel Improvement Plan of the Gyeongang stream [38]. That is, a 100-year frequency was the design storm event for the Gyeongang stream basin.

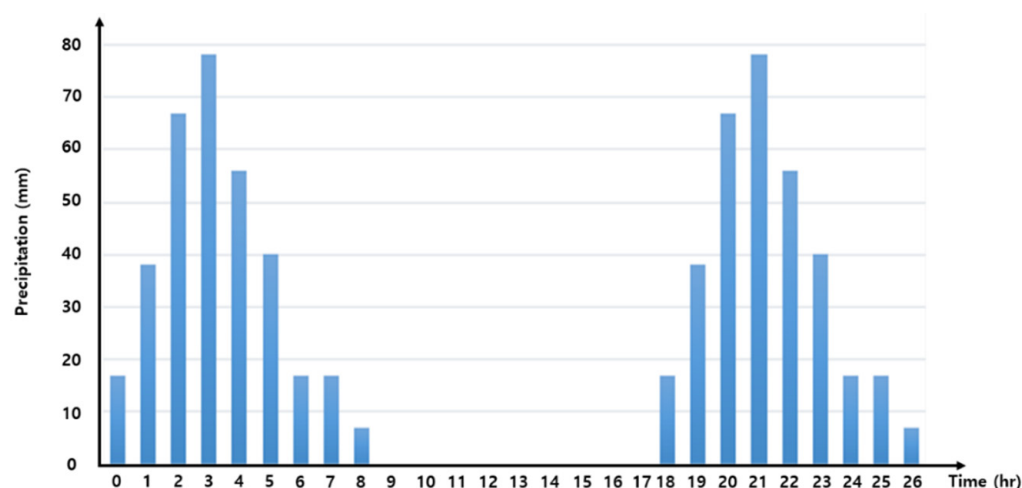


Figure 6. Mega rainfall event scenario using IETD; two 100-year frequency-based rainfall events exist within IETD (9 h).

4.2. Calibration and Validation of the Model Using the Objective Function

The model was calibrated using SSR, WSSR, and rainfall events in the Gyeongang stream basin. We selected the events that consisted of two peak discharges. We used four events during 2002 to 2018. One of the event was from 9 to 12 July 2009 (Table 2). The suitability of the objective functions was assessed by R^2 , NRMSE, and RE. As listed in Table 1, the results indicated that WSSR is a more suitable objective function. Moreover, as listed in Table 3, when we validated the model using rainfall events from 1 to 31 August 2002, from 1 to 31 July 2006, and from 1 to 31 July 2008, WSSR was again found to be more suitable than SSR. Therefore, the objective function WSSR was found to be more appropriate for simulating mega flood runoff discharge from consecutive storm events.

Table 2. Calibration of the model using objective functions.

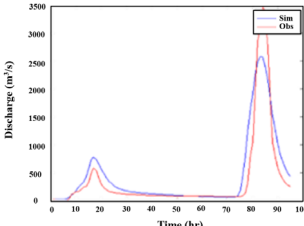
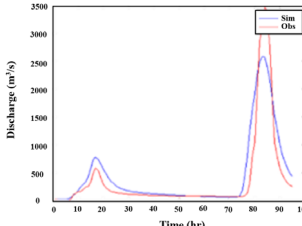
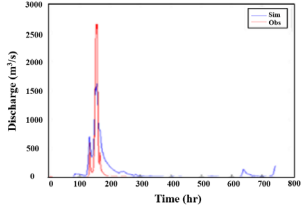
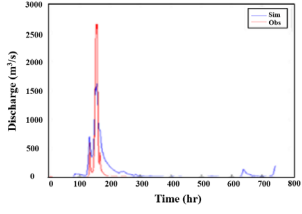
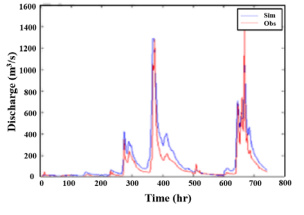
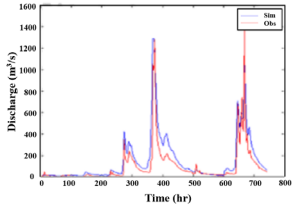
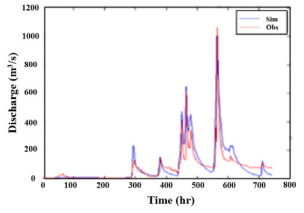
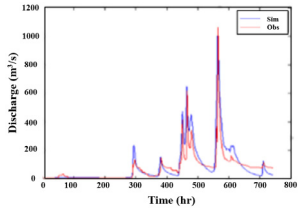
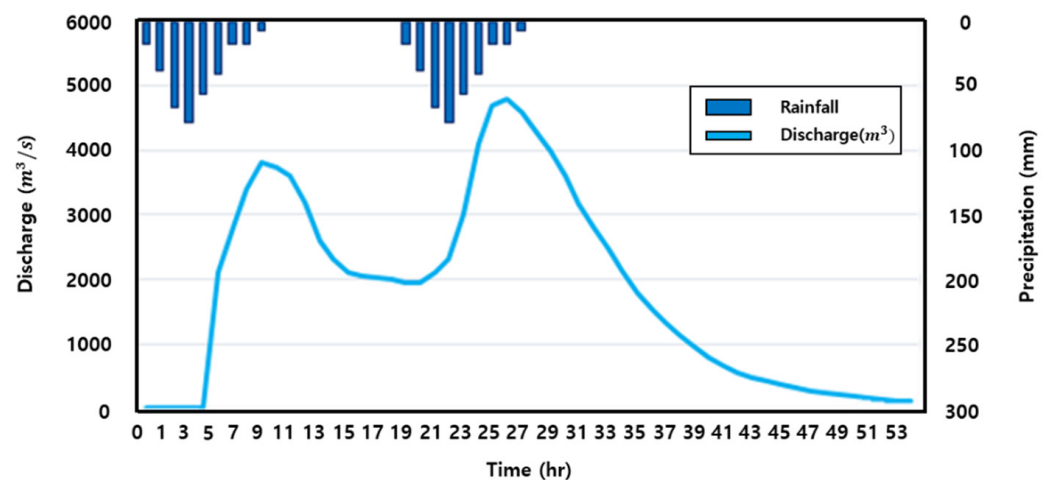
Calibrating Events	Evaluative Indicator	SCE-UA	SSR	WSSR
9 July 2009–12 July 2009	R^2	0.8670		
	SSR	0.1063		
	RE	0.2583		
	R^2	0.8694		
	WSSR	0.1024		
	RE	0.2241		

Table 3. Validation of the model using objective functions.

Validating Events		Evaluation Indicator		SCE-UA SSR	WSSR
1 August 2002–31 August 2002	SSR	R^2	0.8751		
		NRMSE	0.0724		
		RE	0.1613		
	WSSR	R^2	0.8787		
		NRMSE	0.0715		
		RE	0.1349		
1 July 2006–31 July 2006	SSR	R^2	0.8670		
		NRMSE	0.1063		
		RE	0.2583		
	WSSR	R^2	0.8694		
		NRMSE	0.1024		
		RE	0.2241		
1 July 2008–31 July 2008	SSR	R^2	0.8516		
		NRMSE	0.0627		
		RE	0.0394		
	WSSR	R^2	0.8534		
		NRMSE	0.0627		
		RE	0.0122		

4.3. Mega Flood Runoff Simulation Using the Mega Rainfall Scenario

The results derived from simulating a mega flood runoff according to the mega rainfall scenario generated using WSSR, are shown in Figure 7. The estimated mega flood runoff discharge was 4802 m³/s, representing an increase of 992 m³/s over the 100-year design flood of 3810 m³/s, which was estimated in the report of the Improvement Plan of the Gyeongan stream [38]. This increase in runoff due to consecutive storm events, as compared with the runoff due to single storm events, can be explained by the saturation of the soil caused by consecutive storm events.

**Figure 7.** Mega flood runoff discharge simulation using the mega rainfall scenario.

4.4. Making a Flood Inundation Map for the Mega Flood Runoff Discharges

We developed a flood inundation map for a mega flood in the Gyeongan stream basin, as shown in Figure 8. As for the mega flood inundation area in the Gyeongan stream basin, it was found that mainly three zones would be inundated by the mega flood, as shown in Figure 8. Therefore, we separated the flood inundation area into three zones, as shown in Figure 8b,c.

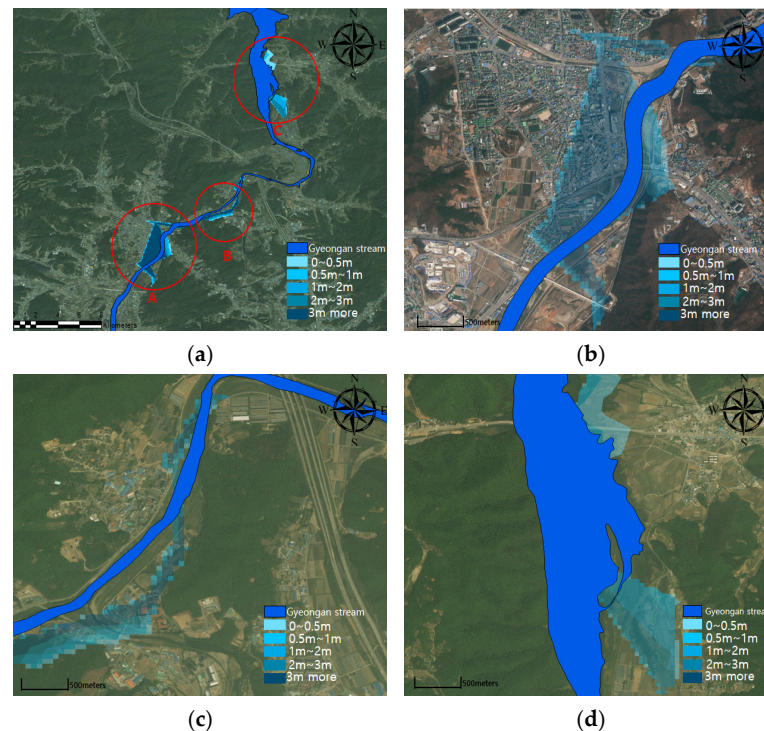


Figure 8. Flood inundation maps for a mega flood: (a) flood inundation map for a mega flood in the Gyeongan stream basin; (b) flood inundation map at area A in (a); (c) flood inundation map at area B in (a); (d) flood inundation map at area C in (a).

Then, we overlaid the flood inundation map for the mega flood with the administrative district map of the Gyeongan stream basin to identify the administrative districts that would be inundated by the mega flood (Figure 9).

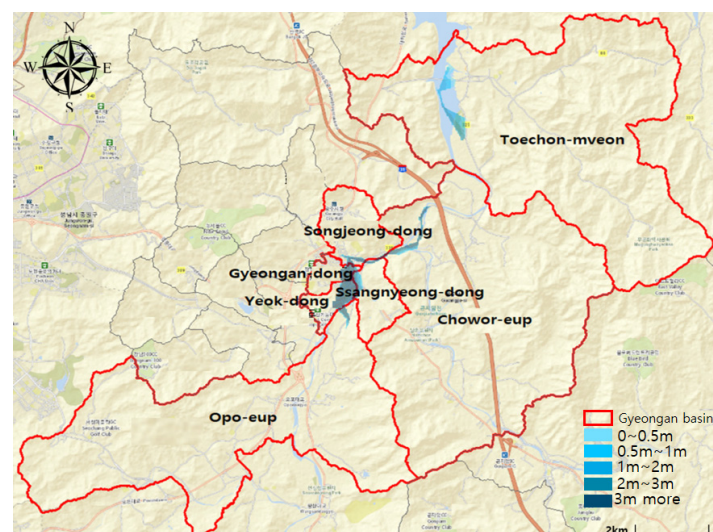


Figure 9. Administrative district map of the Gyeongan stream basin inundated by a mega flood.

4.5. Identification of Shelters through the Mega Flood Inundation Map

We identified shelters in each administrative district in the Gyeongan stream basin that would be inundated according to the above analysis. We identified shelters by referring to the shelter designation criteria provided in the local government safety management plans and the Guidelines for Establishing the Disaster Relief Plan [35]. According to the shelter designation criteria, the disaster history of the target area must be reviewed to determine whether a shelter can be designated in this area. Moreover, a shelter's accommodation area must be at least 3.3 m² per person, and the shelter building should accommodate people easily and should be structurally safe, such as public buildings, schools, churches, or village halls. Considering the shelter designation criteria, we identified shelter alternatives in each administrative district that would be inundated by the mega flood in the Gyeongan stream basin (Table 4). We selected five shelter alternatives in Gyeongan-dong, five in Songjeong-dong, four in Yeok-dong, and two in Chowol-eup. However, because there were no shelters that satisfied the above-mentioned designation criteria in Ssangnyeong-dong, Opo-eup, and Toechon-myeon (township), we excluded them from the analysis. We selected public buildings such as welfare centers, libraries, schools, and churches.

Table 4. Identification of shelter alternatives by administrative district.

Administrative District	Alternatives	
Gyeongan-dong (Neighborhood)	Ga1	Gyeongan-dong Administrative Welfare Center
	Ga2	Gwangju Library
	Ga3	Gwangju Church
	Ga4	Gwangju Elementary School gymnasium
	Ga5	Gwangju Catholic Church
Songjeong-dong (Neighborhood)	Sj1	Gwangju High school
	Sj2	Gwangju Youth Counseling & Welfare Center
	Sj3	Songjeong-dong Village Hall
	Sj4	New Life Church
	Sj5	First Methodist Church
Yeok-dong (Neighborhood)	Y1	Whole Heart Church
	Y2	Yeok-dong Village Hall
	Y3	Yeok-dong village New Village Hall
	Y4	Podowon Church
Chowol-eup (Town)	Cw1	Jiwol-5 village Senior Center
	Cw2	Jiwol-5 village Welfare Center

4.6. Evaluation Indicator Data Collection and Standardization

To evaluate shelter alternatives, we collected the evaluation indicator (Indic. Value) data for the alternatives, listed in Table 5. Because the data values for each evaluation indicator are measured in different statistical units, they must be converted to the same unit, or reasonable value, for direct comparison. To facilitate comparison between the data values, it is necessary to standardize them as dimensionless values so we can compare their relative magnitudes. There are various methods of indicator standardization; however, the Z-score method is commonly used [39]. This method takes a given set of data and assigns a score of 0 to the mean and 1 to the standard deviation, and represents a data point in the dataset in terms of how many standard deviations it is away from the mean, that is, as a standardized Z-score. Thus, it is a useful method for comparing data.

Table 5. Data collection and standardization of shelter evaluation indicators.

Evaluation Indicators		Scale of Accommodation				Geographical Conditions						Type			
		Adequate Accommodation of Evacuees (No. of Persons)		Height of Shelter Building (Floor)		Ease of Access from Evacuation Route (m)		Distance of Shelter from Stream/River (m)		Time Taken to Evacuate to Shelter (min.)		Public Buildings		Private Institutions	
		Indic. Value	Std. Value	Indic. Value	Std. Value	Indic. Value	Std. Value	Indic. Value	Std. Value	Indic. Value	Std. Value	Indic. Value	Std. Value	Indic. Value	Std. Value
Gyeongan-dong	Ga1	1225	0.38	4	1.00	30.15	0.99	497.51	0.20	11	0.25	1	1.00	0	0.00
	Ga2	1149	0.18	3	0.00	8.42	0.00	428.52	0.00	10	0.00	1	1.00	0	0.00
	Ga3	1410	0.40	3	0.00	30.31	1.00	780.53	1.00	11	0.25	1	1.00	0	0.00
	Ga4	408	0.00	4	1.00	10.92	0.11	661.13	0.66	14	1.00	1	1.00	0	0.00
	Ga5	1662	1.00	3	0.00	18.75	0.47	597.44	0.48	14	1.00	1	1.00	0	0.00
Songjeong-dong	Sj1	85	0.00	2	0.00	9.48	0.05	923.68	0.76	16	1.00	1	1.00	0	0.00
	Sj2	685	1.00	3	0.33	27.36	0.29	348.36	0.83	16	1.00	1	1.00	0	0.00
	Sj3	414	0.05	2	0.00	5.61	0.00	189.06	0.35	10	0.25	1	1.00	0	0.00
	Sj4	397	0.05	2	0.00	28.22	0.31	74.96	0.00	8	0.00	1	1.00	0	0.00
	Sj5	125	0.25	2	0.00	79.37	1.00	403.69	1.00	10	0.25	1	1.00	0	0.00
Yeok-dong	Y1	748	1.00	4	1.00	7.93	0.00	281.27	1.00	14	0.00	1	1.00	0	0.00
	Y2	346	0.31	2	0.00	11.47	1.00	616.88	0.99	11	0.00	1	1.00	0	0.00
	Y3	165	0.00	2	0.00	3.88	0.16	473.54	0.57	11	0.00	1	1.00	0	0.00
	Y4	208	0.07	3	0.50	2.4	0.00	619.85	1.00	13	0.67	1	1.00	0	0.00
Chowol-eup	Cw1	659	1.00	2	0.00	19	1.00	113.24	1.00	16	1.00	1	1.00	0	0.00
	Cw2	530	0.00	3	1.00	16.09	0.00	72.01	0.00	15	0.00	1	1.00	0	0.00

In this study, we used the Z-score method expressed in Equation (8) to standardize the evaluation indicator data.

$$Z_i = \frac{X_i - \mu}{\sigma} \quad (8)$$

Here, X_i is the value of a given indicator, μ is the mean value, and σ is the standard deviation.

4.7. Assignment of Weights to the Evaluation Indicators

To conduct a more rational evaluation of the shelter alternatives, we used the AHP method to calculate weights for each evaluation indicator.

We conducted an expert survey to assign more accurate weights to the evaluation indicator. A total of 53 people participated in the questionnaire for the AHP analysis, comprising 8 professors, 13 professional engineers, and 32 researchers from research institutes.

The results, after excluding inconsistent results and computing the weights, are summarized in Table 6. The calculation of weights for the general evaluation indicators through the AHP method revealed that the geographical conditions had the largest weight at 0.73. The calculation of weights for the specific evaluation indicators determined that the height of the shelter building had the largest weight at 0.83, among indicators for scale of accommodation. The distance of the shelter from a stream/river had the largest weight at 0.63, among indicators for geographical conditions. Finally, public buildings had the largest weight at 0.75, among specific evaluation indicators for type. In short, shelters are optimal if they are close to a stream or river, and are tall public buildings that receive support from the government.

Table 6. Assignment of weights through the AHP method.

General Evaluation Indicators	Weight	Specific Evaluation Indicators	Weight
Scale of Accommodation	0.19	Adequate accommodation of evacuees	0.17
		Height of shelter building	0.83
Geographical Conditions	0.73	Ease of access from evacuation route	0.18
		Distance of shelter from stream/river	0.63
		Time taken to evacuate to shelter	0.19
Type	0.08	Public buildings	0.72
		Civilian institutions	0.25

4.8. Selecting Optimal Shelters and Making a Shelter Map

Using the standardized evaluation indicator values and weights obtained through the AHP method, we evaluated the priorities of the flood shelters in the Gyeongan stream basin during a mega flood. These priorities are listed in Table 7. The evaluation score for each shelter was calculated by multiplying the specific and general evaluation indicator values by the weights obtained through the AHP method. In addition, because the shelter with the highest evaluation score is an optimal shelter, it will have the highest priority.

Table 7. Selection of optimal shelters by administrative district; the first priority shelter in each area is expressed in bold.

Administrative District	Alternative	Score	Priority
Gyeongan-dong	Ga1	0.49	4
	Ga2	0.07	5
	Ga3	0.70	1
	Ga4	0.67	2
	Ga5	0.51	3

Table 7. Cont.

Administrative District	Alternative	Score	Priority
Songjeong-dong	Sj1	0.55	3
	Sj2	0.70	1
	Sj3	0.26	4
	Sj4	0.10	5
	Sj5	0.69	2
Yeok-dong	Y1	0.71	1
	Y2	0.66	3
	Y3	0.34	4
	Y4	0.69	2
Chowol-eup	Cw1	0.82	1
	Cw2	0.22	2

Based on these priority results, we selected the optimal shelters by the administrative district, and used GIS to construct a shelter map by administrative district, shown in Figure 10.

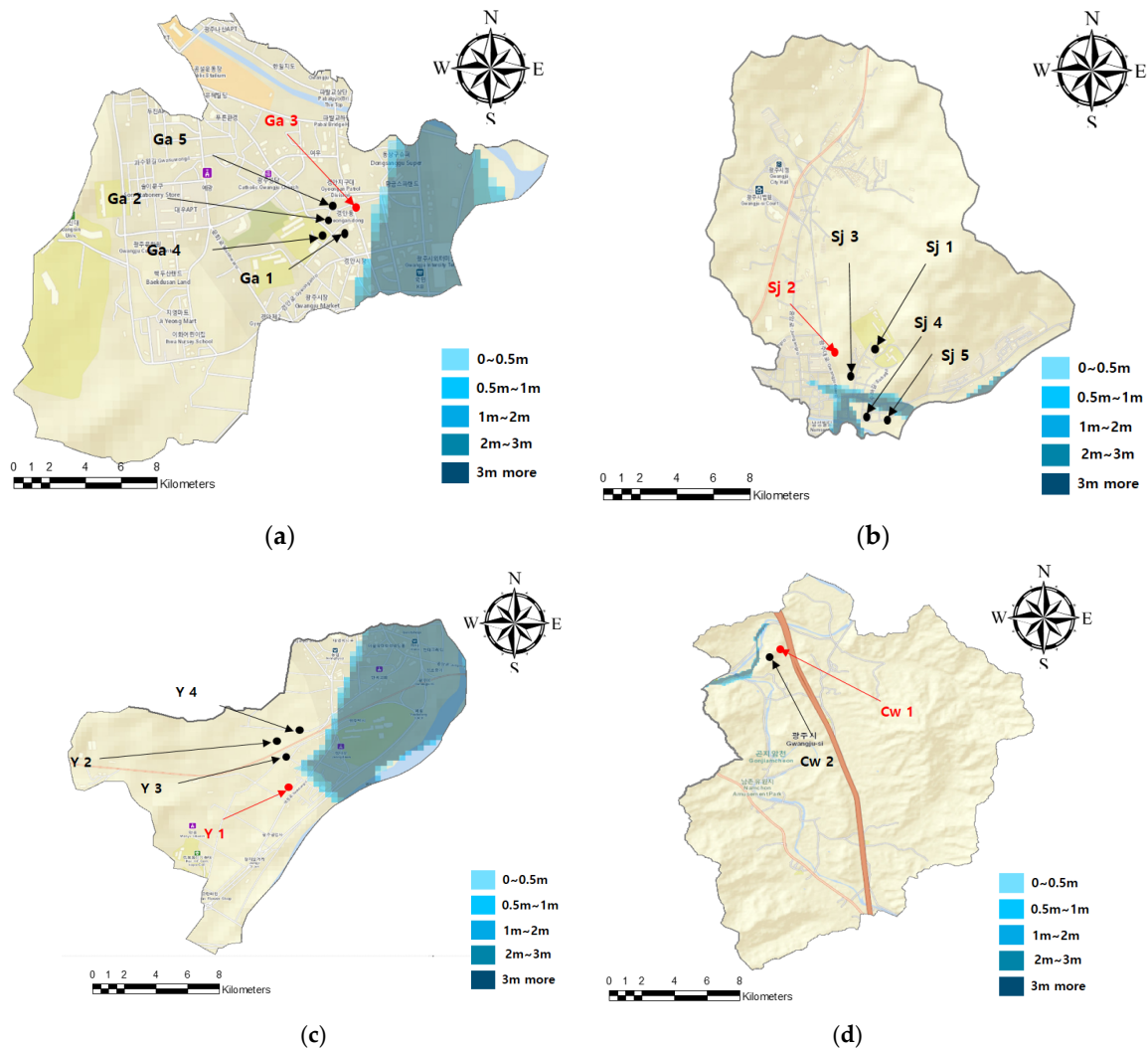


Figure 10. Optimal shelter map by administrative district in the event of a mega flood: (a) Gyeongang-dong; (b) Songjeong-dong; (c) Yeok-dong; (d) Chowol-eup; red dots are the priority shelters; black dots are the alternatives.

It was found that the optimal shelters in the Gyeongan stream basin in the event of a mega flood were Shelter Ga3 in Gyeongan-dong, Shelter Sj2 in Songjeong-dong, Shelter Y1 in Yeok-dong, and Shelter Cw1 in Chowol-eup.

4.9. Discussion

This study defined a mega flood as the flood discharge generated from consecutive rainfall events occurring within the IETD. To calculate the IETD of the Gyeongan stream, the coefficient of variation method was used. However, the CV method only considers characteristics of rainfall [40]. Therefore, there were some events in the Gyeongan stream that showed only one peak even when two rainfall events occurred within the IETD. In these cases, because of good weather conditions, i.e., high temperature for evapotranspiration, the soil moisture had already disappeared before the second rainfall event occurred. Thus, we need a new IETD calculation method that considers not only the rainfall characteristics, but also the soil conditions required to produce a mega rainfall event.

Rainfall–runoff models, such as the SSARR model, can reflect the soil moisture condition; this study used the SSARR model for the flood discharge simulation because the model contains the parameters related to the soil moisture. The SSARR model showed good performance for generating peak discharge, but it failed to simulate accurate discharge in the falling limb part after the peak flow. To solve this problem, we tried several runs with objective functions. The results still had the same problem. Although we thought the problem came from SSARR model, we could not find the reason. In a future study, we will analyze the SSARR model in order to find the reason for the problem, and then modify the model so that more accurate flow discharge calculations can be performed.

Based on the inundation analysis, we selected the proper shelter locations, by the GIS technique, to which people can evacuate. This study suggested the methodology for the selection of optimal shelters for evacuation using the proposed indicators and AHP method. The indicators were related to characteristics of the shelter. However, we may need more studies on evacuation plans and the selection of shelters using more various types of indices. For examples, we can consider alternative indices, such as emergency services (accessibility to police stations, fire stations, and paramedic bases), transportation considerations (distance to highways and major roads, access roads in flood zones), electricity and water supply access, land cost, population distribution, and so on [41–43]. These indicators can help to select more reasonable shelters and, therefore, we intend to use more indicators in the future study.

This study defined a mega flood, and then proposed the methodology for the simulation of mega flood discharge and the selection of optimal shelters. The study results will help us to understand the causes of major flood disasters, and help to establish non-structural flood mitigation measures. However, we only applied the methodology to Gyeongan stream. Therefore, we need to apply the same methodology to several other regions for the verification of the methodology.

5. Conclusions

Recently, mega floods caused by the unprecedented occurrence of consecutive storm events are becoming more frequent, and property damage and loss of lives caused by such floods are increasing. Therefore, this study defined a mega flood event, and proposed the methodology for mega flood discharge analysis. Furthermore, the study proposed the methodology for the selection of optimal shelters for mega flood events. We used the IETD and probable maximum precipitation for making a mega rainfall event. The SSARR model was used for calculating mega flood discharge with two objective functions (SSR and WSSR). We then constructed an inundation map with peak discharges of a mega flood and flood water level computation using the HEC-GeoRAS model. Based on the inundation map, we selected the optimal shelters for evacuation using the proposed indicators and AHP method. Although there are some limitations associated with the methodologies used, such as the IETD and the SSARR model, this study showed reliable results in terms of

analyzing mega flood events and selecting optimal shelter. We propose that the results of this study can provide the basic information for establishing non-structural measures for flood protection, in order to minimize human casualties in the event of a mega flood due to consecutive storm events.

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Data Availability Statement: Hourly rainfall data in Seoul, Suwon, Yangpyeong and Icheon station can be obtained from Korea Meteorological Administration (KMA) Weather Data Service (<https://data.kma.go.kr/resources/html/en/aowdp.html> accessed on 2 January 2022). Digital Elevation Model (DEM) is from National Territory Information Platform of Ministry of Land, Infrastructure and Transport (MOLIT) (<http://map.ngii.go.kr/mn/mainPage.do> accessed on 2 January 2022). Information of buildings in the study area is from National Spatial Data Infrastructure Portal of Ministry of Land, Infrastructure and Transport (MOLIT) (<http://www.nsdi.go.kr/lxportal/?menu=4074> accessed on 2 January 2022).

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

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