Heliyon 9 (2023) e22695

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Analysis of the impact and moderating effect of high-density development on urban flooding

Cheol Hee Son, Chang Hwan Lee, Yong Un Ban *

Department of Urban Engineering, Chungbuk National University Cheongju, 28644, South Korea

ARTICLE INFO

Keywords:
urban flooding
High-density development
Land use
Moderation effects
Tobit model

ABSTRACT

Although previous studies have posited that the high-density development of urban buildings and infrastructure contributes to urban flooding, empirical analyses and in-depth investigations into the interaction factors have remained limited. This study aims to analyze the influence and moderating effect of high-density development on urban flooding. Thus far, various land-use and interaction factors related to urban development density have been explored. Subsequently, the urban watershed was selected, utilizing panel data 2002 to 2017, and employing the Tobit model for analysis. The analysis revealed that high-density development had an adverse effect on urban flooding and that the runoff characteristics of high-density development were not limited to those of impervious surfaces. The horizontal and vertical aspects of dense buildings and structures acted as sub-watersheds that increased the time to reach peak flow. Moreover, high-density development had a moderating effect in low-lying areas. The results of this study underscore the necessity of urban disaster prevention planning to consider the direct and indirect effects, as well as the runoff characteristics, of high-density development on urban flooding.

1. Introduction

The process of urbanization has brought about significant alterations to watershed and water quality dynamics within urban areas, thereby influencing hydrological systems at the watershed scale [1]. Given the concentration of both population and critical infrastructure in cities, the risks to human health and property from urban flooding are substantial. Moreover, owing to frequent abnormal weather and accelerated urbanization in most cities, this phenomenon is poised to worsen in the future [2]. Therefore, identifying the factors that increase the risk of urban flooding due to torrential rain has become imperative for cities.

The study of factors contributing to urban flooding in cities has traditionally centered on impervious surfaces, with practical evidence and research indicating that these impervious areas play a role in shortening the time it takes for peak flow to occur [3]. However, while existing literature emphasizes minimizing runoff and shortening the arrival time of flow, the impact of land use and the high-density development of urban buildings and infrastructure on flooding has received relatively less attention. It is important to consider the effectiveness of high-density development in reducing or increasing urban flooding. Previous studies have indicated that high-density development areas as highly vulnerable to flood damage [4,5]. However, the concept of vulnerability indicates that areas with high development densities possess a large population and considerable social and economic assets; thus making them more susceptible to substantial damage in the event of urban flooding. However, this does not necessarily imply that urban flooding will

* Corresponding author.
E-mail addresses: chuleeson@nate.com (C.H. Son), lch4580@chungbuk.ac.kr (C.H. Lee), byubyu@chungbuk.ac.kr (Y.U. Ban).

https://doi.org/10.1016/j.heliyon.2023.e22695
Received 26 September 2023; Received in revised form 16 November 2023; Accepted 16 November 2023
Available online 22 November 2023

occur more frequently or produce higher runoff.

Excluding the vulnerability aspect, previous studies have explained the runoff characteristics of high-density development based on an increase in impervious land surfaces [6]. Therefore, when analyzing the impact of high-density development on urban flooding, impervious land surface was used as a proxy variable for high-density development. However, this approach does not completely consider the characteristics of the three-dimensional (3D) drying environment. In architectural engineering, the runoff path of an urban watershed can get complicated due the density of buildings [7]. The space occupied by the walls and roofs of tall buildings can affect the peak flow by blocking the horizontal and vertical outflow [8]. This implies that the runoff characteristics of high-density development, that is, the size of the walls and roofs, serve as a type of sub-watershed, which distinctly differs from the runoff caused by impervious surfaces. Therefore, the first step in verifying this phenomenon is to define high-density development, which is distinguished from imperviousness, and use it as a variable to analyze its independent effect and influence on urban flooding.

Second, if the primary direct effect of high-density development on urban flooding is considered in the first step, it becomes imperative to explore its indirect effects through interactions with other contributing factors. Previous studies have stated that densely developed areas act as triggers and wield a significant effect on runoff [9]. However, these studies were not interested in identifying the most important mediator [10]. If a densely developed area affects the peak flow as a sub-watershed, it can have an indirect effect, either positively or negatively, by interacting with other factors affecting runoff. Therefore, the phenomenon of advancing or delaying the time to reach peak flow can explain this regulating effect.

Based on the above information, the following research questions were posed.

(1) Do densely developed areas with controlled runoff effects from impervious surfaces have an impact on urban flooding?
(2) Do high-density developed areas moderate the occurrence of urban flooding?

To answer these research questions, the impact and moderating effect of high-density development on urban flooding were analyzed in this study.

2. Literature review

2.1. Urban flooding

Floods are classified according to their cause and location, with main categories being river, urban, flash, and coastal flooding. Urban flooding is defined as flooding that occurs in urban watersheds and accumulates in one place because water cannot penetrate or drain owing to the obstacles caused by urban development [11]. Therefore, urban flooding is closely related to urban land use and,

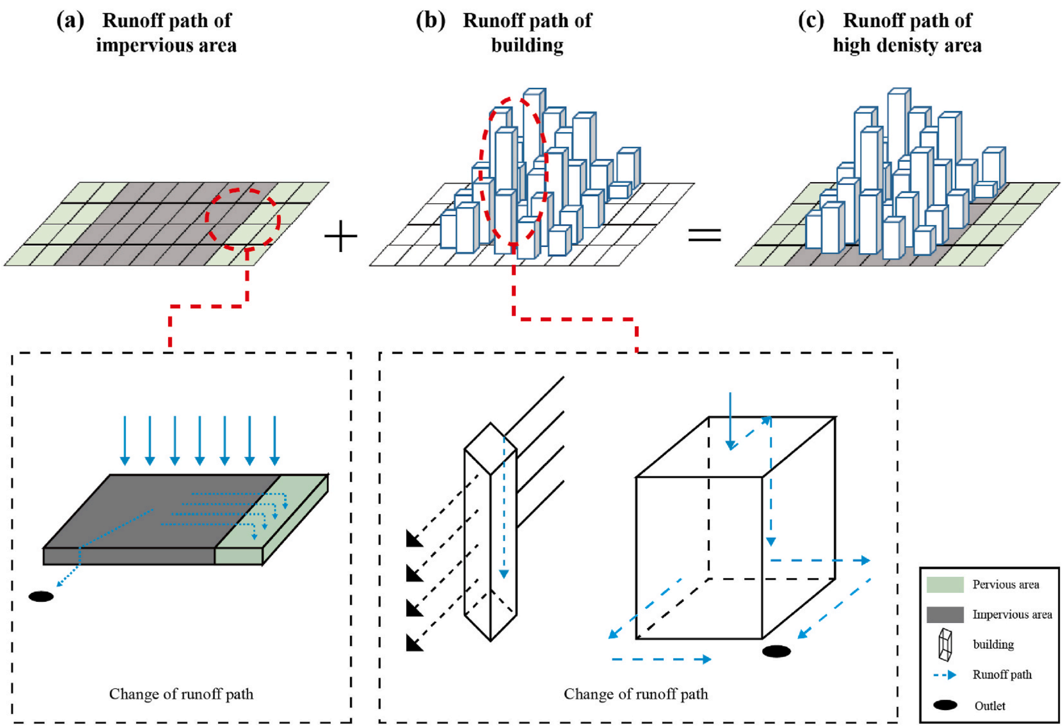

Fig. 1. High-density development definition. (a) and (b): Definition of high-density development in previous study; (c): Definition of high-denisty development in this study.

unlike other types of flooding, it occurs locally and inconsistently in the lowlands [12]. In addition, it is characterized by a complex occurrence of various physical factors and infrastructure, such as the built environment and rainwater drainage facilities.

Another aspect to consider is that since urban flooding usually leads to damage, the concepts of urban flooding and urban flood damage are not properly distinguished. If a flood is the movement of a large amount of water that causes inundation, then according to Fleming's [13] definition, urban flooding can represent an outflow process. Therefore, urban flood damage represents the outcome. Here, the term "damage" refers to the demographic, social, and economic loss. Therefore, to analyze the impact of high-density development on urban flooding, the scope of the study should be limited to urban flooding. Since social and economic factors are not considered, urban flooding is more suitable than urban flood damage, which only represents vulnerability.

2.2. High-density development

In this study, high-density development is defined as the practice of constructing numerous buildings within confined urban areas by increasing the floor area ratio and building-to-land ratio. This definition allows us to consider the impact of 3D buildings on flooding. Therefore, the runoff characteristics of high-density development (Fig. 1(c)) are determined by changes in the runoff path due to impervious surfaces (Fig. 1(a)) and the three-dimensional area of buildings and infrastructure (Fig. 1(b)).

2.3. Factors causing urban flooding

Urban flooding begins with rainfall on urban watersheds and rivers. The amount and concentration of rainfall over time influence the occurrence of floods [14]. Urban watersheds serve as reservoirs that collect rainfall, and their response, particularly the flow, to rainfall varies depending on local topographical conditions. Previous studies have reported that the lower the elevation [15], the lower the slope [16–18], and the higher the water system density [15,19], the more likely urban flooding is to occur. In addition, the degree of rainfall infiltration or runoff varies depending on the urban land use. Impervious surfaces have been shown to reduce infiltration and increase rainfall-runoff [20]; this increase in surface runoff leads to a faster flow peak time [21]. Rainwater that flows along a surface without penetrating, flows into rainwater drainage facilities including rainwater pipes (including sewage pipes), drainage pumps, and reservoirs (or reservoir facilities). South Korean cities are mainly dependent on rainwater drainage systems, which handle approximately 68 % of rainwater runoff [12]. Stormwater drainage facilities are connected to rivers; therefore, the riverbed coefficient increases during the rainy season, and when the water level of the tributary river is higher than that of the rainwater drainage facility, the rainwater cannot be discharged into the river and flows backward. In addition, the water level of a river is affected by water structures, such as dams, river embankments, and spillways, which protect against flooding. Therefore, to analyze urban floods, regions containing rivers and flood defense facilities must be considered [22].

Although few empirical studies have analyzed the relationship between high-density development and urban flooding in terms of rainfall runoff, land-use conditions, such as residential and commercial areas, can be considered characteristics of high-density developed areas [23]. This is because restrictions on the floor-area ratio differ depending on area use. Additionally, the floor-area ratio of buildings can be used to directly measure the degree of high-density development [24]. However, the location and disposition owing to floodplain development are important land-use drivers of flooding, and alterations in these components can lead to corresponding changes in flood risk [25,26].

2.4. Factors that interact with high-density development

We summarize the factors that interact with high-density development from the following three perspectives: First, when impervious surfaces affect urban flooding, urban development leads to a relationship between the two. Brody et al. [27] stated that high-density development induces urban flooding, whereas Brody and Highfield [14] reported that it has a suppressing effect. Regarding their contradictory results, Lee and Brody [6] explained that even in densely developed regions, the impact of impervious areas on urban flooding can vary. In addition, Wijayawardana et al. (2023) argued that urban development density increases urban flooding by influencing the runoff of impervious surfaces. Although these studies did not consider the characteristics of sub-watershed runoff during high-density development, they indicated that development density is related to impervious surfaces and runoff.

Second, the impact of high-density development on urban flooding can be considered in relation to the availability of stormwater drainage facilities, such as sewer pipes. In general, urban areas with high development densities are likely to have infrastructure systems capable of adequately handling large amounts of surface runoff [27]. Rainwater drainage facilities are effective in reducing the impact of floods [15], but results differ from expectations in highly developed cities. For example, in Seoul, one of the most overcrowded cities in the world, Son and Ban [12] found that flood damage was significant in areas with a high density of rainwater drainage facilities. In addition, Brody and Highfield [14] stated that despite the presence of drainage infrastructure, high-density development trends increase flood damage. Therefore, it is necessary to clarify whether urban density exerts pressure on the drainage system when stormwater drainage facilities affect urban flooding.

Third, the influence of urban density on urban flooding can be considered in relation to the existence of developmental activities in low-lying areas. Low-lying areas have good conditions for urban development due to their gentle gradients [28]. Therefore, numerous studies have provided evidence that development within urban areas has occurred in low-lying areas [29,30]. In addition, some studies, such as Mazzoleni et al. [31] and Kuenzer et al. [32], have discovered that urban density is higher in low-lying areas close to rivers. However, few studies have explained or verified the role of urban density in the relationship between urban flooding and low-lying development. Nevertheless, low-lying areas are places in which water accumulates, where impervious surfaces increase due to development, there is a lack of water flow capacity, and flood levels accordingly increase. Therefore, stormwater backflow occurs frequently, and these areas can be easily affected by urban density.

2.5. Statistical Reliability of urban flooding analysis

Prior studies have frequently made errors when conducting data collection and analysis methods. Ford et al. [33] stated that unreliable conclusions can be obtained if a broad generalization is performed using the results of a few individual flood events. This is because, similar to climate change, floods have a large range of temporal and spatial variability. Thus far, reliable results must be obtained by statistically analyzing changes in long-term data averages.

In addition, Carvalho et al. [34] and Son [12] mentioned the modifiable areal unit problem (MAUP), which transpires when urban flooding occurs locally in densely developed cities, requiring a significantly larger spatial scope for data collection (the spatial unit). Representative evidence of the MAUP indicates that the sign of a variable changes as the spatial unit increases or decreases. The MAUP can be mitigated by minimizing the spatial units of the collected data [35]. In addition, because water problems such as urban flooding have complex causes and large financial costs, the government and authorities solve them. This also identifies those responsible for disaster prevention. Accordingly, in numerous countries, statistical data related to urban flooding are collected by administrative districts (si/gun/gu in South Korea) and used for analysis. However, a problem arises due to the spatial mismatch between the watershed unit, where rainfall is collected, and the administrative district unit (see Fig. 3(c)). Data collected by administrative districts can be easily obtained, but the analyzed results could lead to errors in interpreting the urban flood process. Therefore, to obtain consistent and reliable results, empirical studies should use long-term data [36], and the spatial unit and size of urban flood characteristics should be considered.

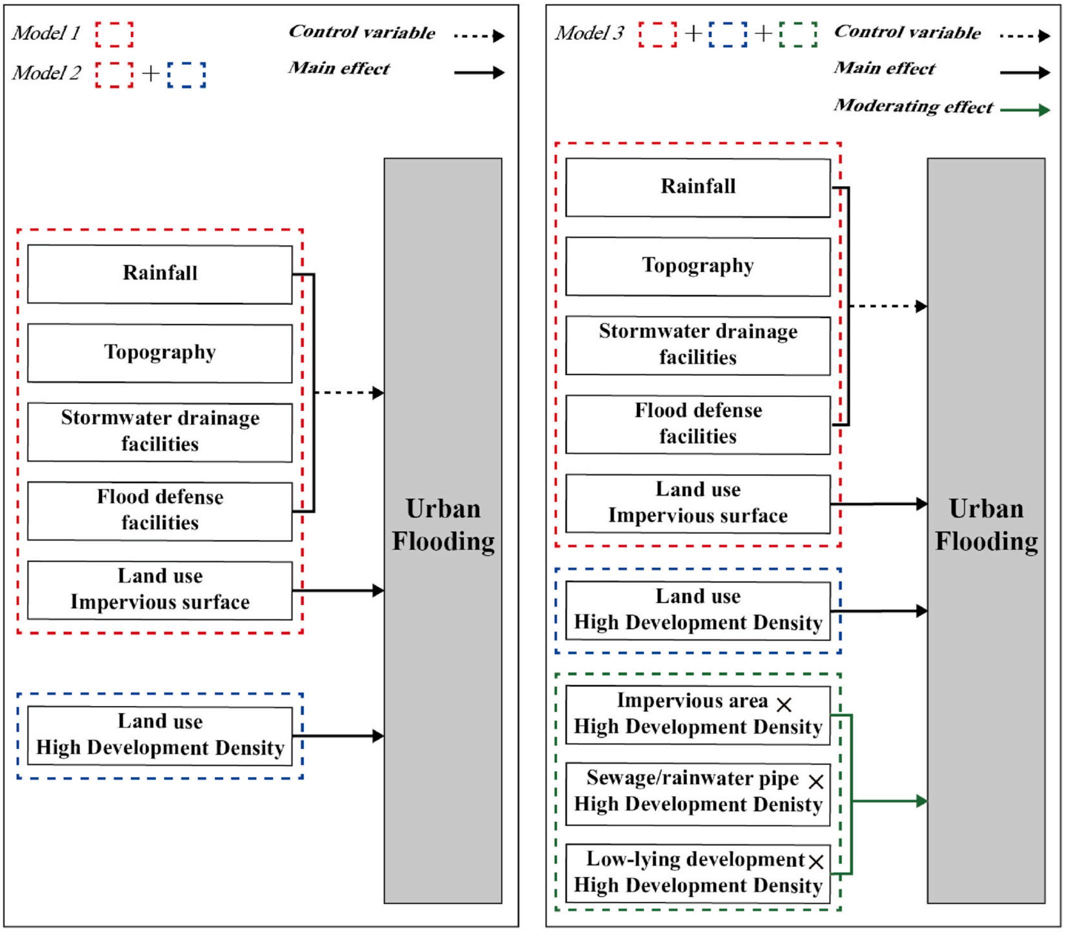

Fig. 2. Research concepts: Models 1 and 2 (left), Model 3 (right).

3. Methods

3.1. Research concept

Models 1 and 2 in Fig. 2 present the concepts used to answer the first research question. Model 1 includes the factors identified in previous studies as the control group. The runoff impact of impervious areas is better understood when considering a combination of factors such as rainfall, terrain, stormwater drainage, and flood defense facilities. In Model 2, factors related to urban development density are added to Model 1. The independent effect of urban development density can be demonstrated by Model 2, as the factors used in Model 1, particularly those related to impervious surfaces, were controlled. The stability of the model can be assessed by

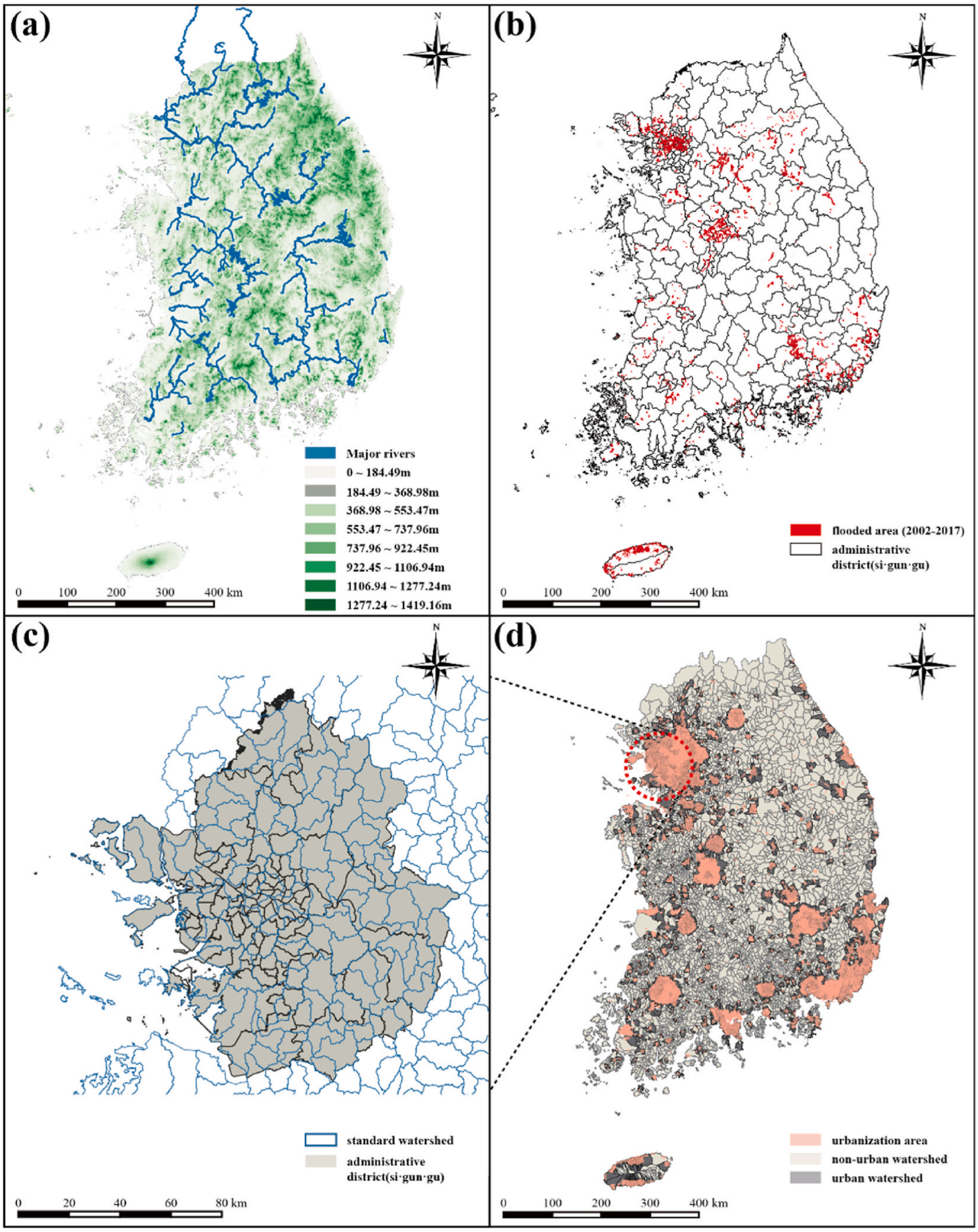

Fig. 3. Study area. (a): Mountains and rivers in Korea; (b): Flooded area characteristics; (c): Different spatial unit (standard watershed and administrative district); (d): Distinction between urban and non-urban watersheds.

determining the significance and sign direction of the urban development density factors and analyzing whether the sign and direction of all factors in Models 1 and 2 are the same. The specific variables used in Models 1 and 2 are provided in Table 1 based on Section 2.3. Model 3 addresses the second research question. If Models 1 and 2 can identify the main (direct) effect of urban development density, Model 3 can identify the moderating effect. Model 3 includes variables from both Models 1 and 2. The moderating effect can be measured by multiplying the two factors, a and b, which are predicted to interact to create a new variable, c (c = a * b), and considering a, b, and c simultaneously. The new variable, c (represented by the green dotted line), is based on section 2.4. Therefore, it is possible to analyze whether the urban development density advances or delays the time of peak flow in combination with impervious surfaces, rainwater drainage facilities, and lowland development area factors.

3.2. Study area

The target area for this study was an urban watershed in South Korea. As of 2022, the population was approximately 51.55 million, the area was 100,412 km^2, and the population density was 515.2 people/km^2. The waterways of South Korea include 62 national rivers (2979 km) and 3773 local rivers (26,860 km) (Fig. 3 (a)). Owing to the influence of the Asian monsoon climate, the rainy season and heavy rains occur from June to August. The amount of rainfall at this time is approximately two-thirds of the annual total of 1263 mm [37]. In Korea, most floods occur during this period (Fig. 3 (b)).

A standard watershed was used as the data collection unit to mitigate the MAUP and spatially consider the characteristics of urban flooding. The standard watershed consisted of 850 common watershed roads established by the government for the creation and management of water-related data. This was also the smallest watershed unit that reflected natural conditions and drainage

Table 1
Selected variables and Explanations.

Classification	Variable (unit)	Reference	Source
Urban flooding	Flooded area (m^2)	Wang, Du [15]	Land and Geospatial Informatix Corporation, flood trace map (data.go.kr)
Rainfall characteristics	Maximum hourly precipitation (mm)	Brody and Highfield [14]	Korea Meteorological Administration, Meteorological Data Open Portal (data.kma.go.kr)
	Maximum daily precipitation (mm)	Piyumi, Abenayake [39]	
	Maximum monthly precipitation (mm)	Brody and Highfield [14]	
Topography characteristics	Average elevation (m)	Wang, Du [15]	National Geographic Information Institute, Digital Elevation Model (data.nsdi.go.kr)
	Average slope (%)	Bradshaw, Sodhi [16], Kropp [17]	
	Average curvature (mm)	Li, Kitsikoudis [40]	
	River system density (%)	Lee and Chung [19]	Map of the Flood Control Minor Water Resources Unit of the Han River (data.nsdi.go.kr)
Stormwater drainage facility characteristics	Sewage or rainwater pipe length (m/km^2)	Son and Ban [12], Shin and Park [23]	Ministry of Environment, Sewerage Statistics (me.go.kr)
	Rainwater management facility capacity (m^3/km^2)	Burns, Schubert [41]	
	Rainwater storage facility capacity (m^3/km^2)	Son and Ban [12],	
	Rainwater utilization facility capacity (m^3/km^2)	Burns, Schubert [41]	
Flood defense facility characteristics	River maintenance basic plan establishment rate (%)	Lee and Brody [6]	List of rivers in Korea (river.go.kr)
	River improvement completion rate[a] (%)	Lechowska [42]	
	Design flood level (EL.m)	Son and Ban [12]	
Land-use characteristics	Impervious surfaces (km^2)	Brody and Highfield [14], Lee and Brody [6], Wijayawardana, Abenayake [9]	Statistical Yearbook of Local Governments (data.go.kr)
	Agricultural area (km^2)	Lee and Brody [6]	
	Forest area (km^2)	Shin and Park [23]	
	Net population density (people/km^2)	Kang, Yeom [43]	Statistical Geographic Information Service, census data (sgis.kostat.go.kr)
	Net development density (m^2/km^2)	Stevens, Song [5]	E-architecture information system, building ledger(open.eais.go.kr)
	Ratio of detached houses (%)	Shin and Park [23], Harcourt [44]	
	Ratio of apartment complexes (%)	Shin and Park [23]	
	Ratio of commercial and business facilities (%)	Lee and Brody [6], Shin and Park [23]	
	Ratio of development and use of low-lying areas (%)	Stevens, Song [5], Miguez, Veról [45]	

[a] River improvement refers to the increased water capacity.

management systems for rainwater runoff.

However, it is difficult to separate the standard watersheds into urban and non-urban watersheds, we have classified them according to the following criteria. 1) watersheds that include residential, commercial, industrial, and green areas corresponding to urban areas, 2) those with a stormwater drainage management system, and 3) those with a population density of over 150 people per square kilometer (The OECD classifies areas with scores below 150 as rural local units) [38]. There were 327 urban watersheds that satisfied all of the above conditions, with a total area of 35,843 km^2, accounting for 33.4 % of the total area of South Korea (Fig. 3 (d)). Moreover, the average area of the urban watershed is 109.61 km^2. This is smaller than the average area of 389.64 km^2 for municipalities units (si, gun, gu) used for collecting flood data in previous studies.

3.3. Variable selection

Table 1 lists the variables selected through a review of previous studies that cause urban flooding. Factors were selected and grouped into several characteristics in a series of urban runoff processes that lead to flooding: blocking, infiltration, retention, and drainage of rainfall and runoff. The flooded area was selected as the dependent variable. Because the flooded area data collected by the Korea Land and Geospatial Information Corporation was collected consistently across the country, it could be used as a direct variable to determine the scale of urban flooding.

3.4. Data processing

The variable processing is presented as follows. All variables were processed using ArcGIS software. The data collection period was from 2002 to 2017. The spatial unit was 327, corresponding to urban watersheds from the 850 standard watersheds. Therefore, the sample of collected data is 5232 (327 urban watersheds × 16 years). The urban watershed, which was the basis of data processing, was classified by overlapping the urban area spatial data provided by the Ministry of Land, Infrastructure, and Transport with the standard watershed provided by the National Water Resources Management Information System. The flooded area acting as the dependent variable was calculated using a flood trace map provided by the Korea Land and Geospatial Information Corporation. Among the characteristics of rainwater drainage facilities, the lengths of sewage and rainwater pipes were obtained from sewage statistics published by the Ministry of the Environment and divided by the area of the urban watershed. To determine the characteristics of flood defense facilities, the Korea River List data provided by the River Management Geographic Information System were used. Data on land-use characteristics were obtained from the annual statistical yearbooks of the local governments. The urbanized area was calculated as the sum of the land, school, and road areas; the agricultural area as the sum of the fields and paddy fields; and the forest area as the total area of forests. Development density-related variables that measured high-density development were calculated using the building ledger provided by the Building Data Private Open System. The total floor area was calculated using information on the total floor area of buildings in the building register, and the net development density was established by dividing the total floor area by the urbanized area. For net population density, census data from the Statistical Geographic Information Service were used.

3.5. Analysis methods

We constructed panel data to consider flood variability and analyzed them using a panel model. The panel model was used to increase the accuracy of the estimation because there were many more observations than cross-sectional data. In addition, panel models can estimate parameters more efficiently and accurately by assuming heterogeneity between individuals and controlling for them [12].

$$y_{it} = \alpha + \beta X_{it} + \epsilon_{it}, \left(\epsilon_{it} = \mu_i + \lambda_t + v_{it}\right)$$

where μ_i represents the unobserved individual effect, λ_t represents the unobserved time effect, and v_{it} represents the remainder of the stochastic disturbance term.

However, data such as floods have a censored feature because the dependent variable is not observed when floods do not occur; therefore, the Tobit model was used as a representative model to analyze the panel data. The advantage of the Tobit model is that an independent variable is observed even when the value of the dependent variable is zero. This assumes that the factors that affect an event occurring or otherwise are the same and have an effect in the same direction.

$$y_i = X_i^{'} + \epsilon_i, \epsilon_i \sim N\left(0, \sigma^2\right),$$

$$f\left(y_i \middle| \beta, \sigma^2\right) = \begin{cases} P\left(y_i^* < 0\right), if\ y_i = 0 \\ f\left(y_i \middle| \beta, \sigma^2\right), if\ y_i > 0 \end{cases}$$

when X_i is a $k \times 1$ explanatory variable vector, β is a $k \times 1$ parameter vector. ϵ/σ follows a symmetric standard normal distribution; therefore, $P(y_i^* < 0) = \Phi(-X_i^{'}\beta/\sigma)$.

Moreover, the moderating effect was analyzed to discern whether high-density development interacts with other factors in the urban flooding relationship. The method analyzed whether each independent variable had an independent influence on the dependent variable or whether changes in the dependent variable were caused by other independent variables. In this case, multicollinearity occurred. To address this issue, mean centering was performed.

3.6. Model test

The Tobit panel model proceeds in the order of goodness of fit and model stability, marginal effects, and hypothesis verification using the likelihood ratio (LR) Chi-square test. Model selection from panel models is an important part of parameter estimation (see Fig. 4). The validation process selects the most appropriate model from several effect models such as mixed, fixed, and random effects. The Baron and Kenny's [46] method was used to test the moderating effects. The effect of the independent variable, moderating variable, and interaction term on the dependent variable was determined by adding the product of the independent and moderating variables (interaction term). We then verified whether the interaction term significantly affected the dependent variable. Through the simple slope experiment proposed by Aiken et al. [47], the direction of the sign of the interaction variable was identified to determine

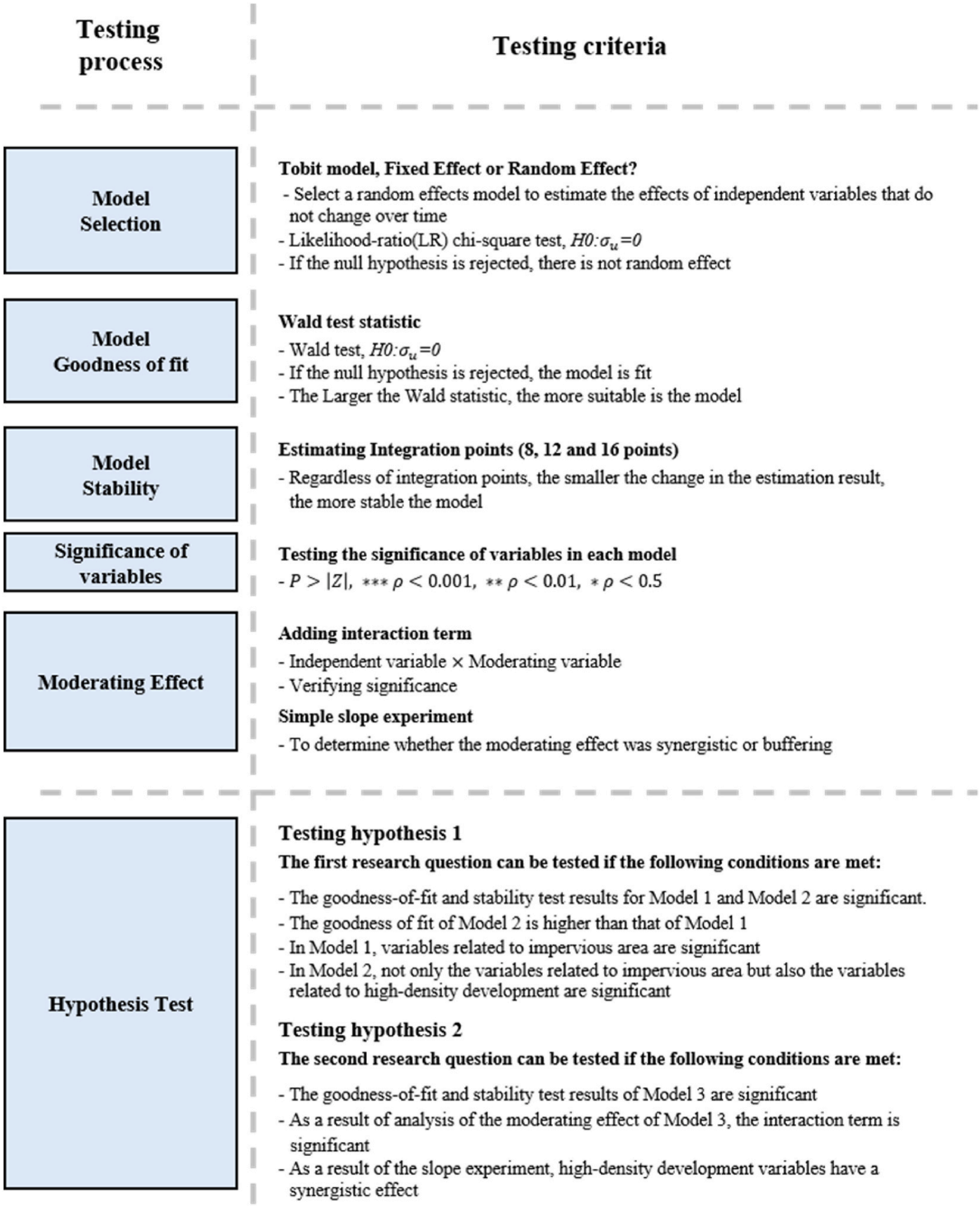

Fig. 4. Analysis process.

whether the moderating effect was synergistic or buffering. This method estimates the regression equation of the independent variable X and dependent variable Y between 0, and 1, and +1 standard deviations of the moderating variable.

4. Results

4.1. Descriptive statistical analysis

The results of the descriptive statistical analysis of the variables are shown in Table 2. There were 5232 observations, and all variables were built as balanced data. No significant problematic variables were identified, such as an excessively large mean and standard deviation, or relatively small observations. The skewness and kurtosis of all the factors did not exceed the absolute values of three and eight, which are the criteria for normality verification proposed by West et al. [48]. Therefore, all the factors satisfied the condition of normality for further parametric statistics.

4.2. Goodness of fit and stability

Before interpreting the results, it was necessary to verify whether the estimated model was significant. The results are presented in Table 3. The LR chi-square statistic of the Tobit model was used to test the null hypothesis, $H_0 : \sigma_u = 0$. As the results of the test were extremely small, the null hypothesis was rejected, confirming that the estimated models were statistically significant. In addition, because Models 1, 2, and 3 rejected the null hypothesis among the coefficients, all models in this study were selected as random-effect models.

For the test statistics of the model, the smaller the LR and larger the Wald statistic, the more suitable the model. To examine the stability of the estimation results, integration points were estimated by dividing them into 8, 12, and 16 points. As a result of the estimation, the log-likelihood of the fitted quadrature 12 point was −537.4, the comparison quadrature 8 point was −537.4875, and the comparison quadrature 16 point was −537.4876, confirming that the estimation result was very stable regardless of integration points.

Table 2
Descriptive statistics from observations.

Variables			Mean	Standard deviation	Minimum	Maximum
Dependent variable	Flooded area (m^2)		43,968	344,570	0	8,276,320
Independent variable	Rainfall characteristics	Maximum precipitation per month (mm)	419	176	46	1376
		Maximum precipitation per hour (mm)	45	12	15	106
		Maximum daily precipitation (mm)	145	53	38	805
	Topography characteristics	Average elevation (m)	126	106	6	939
		Average slope (%)	8	4	1	20
		Average curvature (mm)	−0.001	0.006	−0.052	0.019
		River system density (%)	2	1	0	4
	Stormwater drainage facility characteristics	Sewage or rainwater pipe length (m/km^2)	0.003	0.005	0	0.033
		Rainwater management facility capacity (m^3/km^2)	1067	3958	0	33,515
		Rainwater storage facility capacity (m^3/km^2)	29,434	121,760	0	1,142,266
		Rainwater utilization facility capacity (m^3/km^2)	5168	46,000	0	714,000
	Flood defense facility characteristics	River maintenance plan establishment rate (%)	12	20	0	100
		Complete river improvement rate (%)	7	15	0	100
		Design flood level (EL.m)	1	5	0	76
	Land-use characteristics	Impervious surfaces (km^2)	0.108	0.096	0.011	0.634
		Agricultural area (km^2)	0.243	0.307	0.001	8.720
		Forest area (km^2)	0.521	0.343	0.029	10.928
		Net population density (people/km^2)	201	285	0.444	2543
		Net development density (m^2/km^2)	576,852	788,832	2009	7,763,163
		Ratio of detached houses (%)	53	13	9	86
		Ratio of apartment complexes (%)	4	6	0	36
		Ratio of commercial and business facilities (%)	40	11	14	81
		Ratio of development and use of low-lying areas (%)	69	18	12	100

Table 3
Significance test results for the models.
$***\rho < 0.001$, $**\rho < 0.01$, $*\rho < 0.05$

Variables		Model 1	Model 2	Model 3
Statistical results	Constant	−0.629***	−0.552***	−0.560***
	Number of observations	5232	5232	5232
	Number of groups	327	327	327
	σ_u	0.065	0.064	0.064
	σ_e	0.176	0.1759	0.175
	ρ	0.121	0.1193	0.119
Test results	Likelihood-ratio test	26.43***	24.22***	24.86***
	Wald test statistic	285.84***	290.71***	290.86***

4.3. Significance of variables by model

Table 4 shows the results of the comparison of the coefficient values and ρ-values for each model. In particular, Model 3 has a low LR, and large Wald statistic compared to those of other models, indicating that the remaining models may underestimate the coefficients. Thus, Model 3 best explains the factors affecting urban flooding.

Based on Model 3, the higher the maximum monthly rainfall ($\rho < 0.001$), maximum hourly rainfall ($\rho < 0.001$), and maximum daily rainfall ($\rho < 0.001$), the higher the urban flooding rate. In addition, the lower the average elevation ($\rho < 0.01$) and the higher the river system density ($\rho < 0.01$), the higher the risk of urban flooding. These results agree with the conclusions of previous studies that mentioned rainfall and terrain characteristics [15,19]. The longer the sewage or rainwater pipe lengths ($\rho < 0.01$) and greater the rainwater utilization facility capacity ($\rho < 0.001$), the greater is the likelihood of urban flooding. This result is contrary to that of Wang et al. (2017). Our results indicate that areas in which sewerage and stormwater drainage facilities are concentrated are places where urban floods occur frequently, and stormwater drainage facilities have insufficient water flow capacity. Urban flooding increases as the river maintenance basic plan establishment rate ($\rho < 0.05$) and design flood levels increase ($\rho < 0.05$). Therefore, urban floods frequently occur in well-maintained areas, such as embankments and river structures, examining flood characteristics in South Korea. Considering that flood patterns have changed from river to urban floods along with South Korea's flood defense measures [37], urban floods now occur more frequently in floodplains closer to rivers.

Among the land-use characteristics, urban flooding increased as the impervious surfaces increased ($\rho < 0.01$). However, the

Table 4
Significance and coefficient values of variables for each model.
$***\rho < 0.001$, $**\rho < 0.01$, $*\rho < 0.05$

Variable	Model 1	Model 2	Model 3
Maximum monthly precipitation (mm)	0.419***	0.415***	0.414***
Maximum hourly precipitation (mm)	0.271***	0.269***	0.268***
Maximum daily precipitation (mm)	0.441***	0.435***	0.432***
Average elevation (m)	−0.238**	−0.278**	−0.273**
Average slope (%)	−0.108*	0.078	0.072
Average curvature (mm)	−0.005	−0.010	−0.011
River system density (%)	0.125**	0.112**	0.109**
Sewage or rainwater pipe length (m/km^2)	0.138***	0.127**	0.154**
Rainwater management facility capacity (m^3/km^2)	0.087	0.097	0.111
Rainwater storage facility capacity (m^3/km^2)	−0.122	−0.173**	−0.174
Rainwater utilization facility capacity (m^3/km^2)	0.230***	0.232***	0.233***
River maintenance basic plan establishment rate (%)	0.093**	0.088**	0.088*
River improvement completion rate (%)	0.007	−0.009	−0.011
Design flood level (EL.m)	−0.466**	−0.384*	−0.374*
Impervious surfaces (km^2)	0.137**	0.203**	0.217**
Agricultural area (km^2)	0.136	0.151	0.150
Forest area (km^2)	−0.361	−0.333	−0.335
Net population density ($people/km^2$)		−0.083	0.126
Net development density (%)		0.145**	0.238**
Ratio of detached houses (%)		−0.275***	−0.279**
Ratio of apartment complexes (%)		−0.142	−0.132*
Ratio of commercial and business facilities (%)		−0.155	−0.155
Ratio of development and use of low-lying areas (%)		0.140**	0.145**
Sewage or rainwater pipe length × net development density			0.244
Impervious surfaces × net development density			0.182
Ratio of development and use of low-lying areas × net development density			0.263*

relationship between agricultural and forested areas and floods was found to be insignificant. Since the urbanization area is a representative factor of the impermeability of urban watersheds [20], this result was judged to have been analyzed appropriately. In contrast, agricultural and forest areas can be considered variables for non-urban watersheds. As net development density increases, urban flooding increases; as the proportion of detached residential areas decreases, urban flooding increases; as the development and utilization of low-lying areas increases, urban flooding increases. This indicates that densely developed areas contribute positively to the occurrence of urban flooding.

4.4. The independent runoff effects of high-density development

In Model 1, the significance ($\rho < 0.01$) of the impervious area variable was confirmed. In Model 2, the significance ($\rho < 0.01$) of the impervious area and high-density development variables was confirmed. The Wald value indicating goodness of fit was 285.84 for Model 1 and 290.71 for Model 2, showing that Model 2 was higher. In Model 2, there was no significant change in influence and sign of impervious area-related variables compared to Model 1, even though variables were added. This indicates that Model 2 is stable, and the coefficients are well estimated. In addition, as mentioned in 4.3, the results of variables that can indirectly measure impervious areas and high-density development (proportion of single-family residential areas, agricultural land, forest land, etc.) can be interpreted as meaningful results. Overall, Model 2, which simultaneously considers impervious areas and high-density development variables, explains flood runoff better than Model 1, which only considers impervious areas. Additionally, through a comparison of Models 1 and 2, it can be said that independent outflow characteristics of high-density development exist.

4.5. The moderating effects of high-density development

The moderating effect analysis revealed that high-density development had no moderating effect when impervious surfaces and sewage or rainwater facilities had a positive effect on urban flooding ($\rho > 0.05$) (see Table 4 Model 3). However, high-density development had a moderating effect on the relationship between the ratio of low-lying area development and urban flooding ($\rho < 0.05$) (see Table 4 Model 3). The simple slope experiment analysis showed that the independent variable, ratio of development and use of low-lying area, had a positive sign, and the interaction variable, ratio of low-lying area development × urban development density, also had a positive sign, which was analyzed as a synergistic effect (see Fig. 5(a)). This suggests that the impact on flooding varies based on the combination of city location and development density. Specifically, low-lying and highly developed areas have a greater positive impact on urban flooding. The results and coefficients of the moderating effects are shown in Fig. 6.

5. Discussion

This section establishes the relationship between high-density development and urban flooding and discusses sustainable cities. First, it is necessary to consider runoff characteristics to determine the contribution of high-density development to urban flooding. The findings in Section 4.3 indicate that urban flooding occurs frequently in densely developed urban watersheds. Most notably, the runoff characteristics of high-density development were not caused by an increase in impervious land surfaces, as claimed in previous studies. Models 2 and 3 found that net development density positively affected urban flooding, even when the impervious surface variables were controlled for, and other variables related to urban development density varied in the magnitude and sign of the effect according to the degree of development density. Therefore, densely developed areas in urban watersheds have independent runoff characteristics other than those owing to impervious surfaces. Based on the literature review in Section 2.2, this runoff characteristic can be considered to distort the flow path of stormwater because urban buildings and structures are densely located. For this reason, a rainfall-runoff analysis process that considers vertical and horizontal paths on the roof and walls of a building is necessary [8]. In this regard, Cho and Yoo [49] confirmed through simulation that peak runoff can increase by up to 22.2 % owing to the roof and walls of a high-rise building. In addition, Kim and Jun [50] confirmed that as the flow of rainfall is blocked by buildings, the flow rate around the building and depth of flooding increase.

Another factor that should be considered is the moderating effect of high-density development in low-lying regions. The

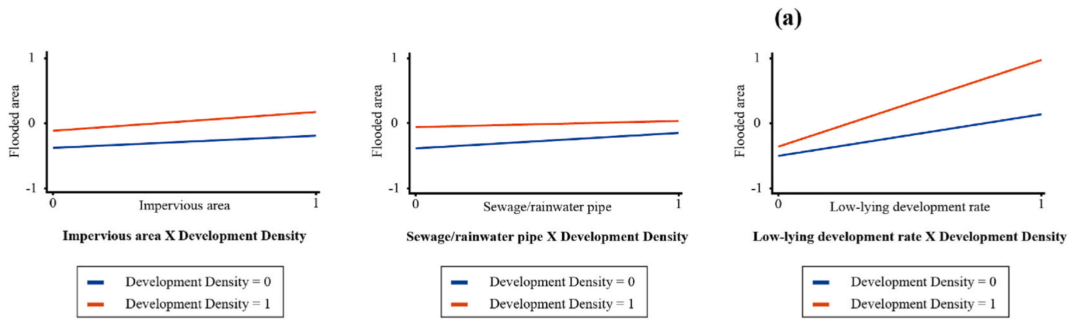

Fig. 5. A simple slope to analyze the moderating effect. (a): A synergistic effect with low-lying development and high-denisty development.

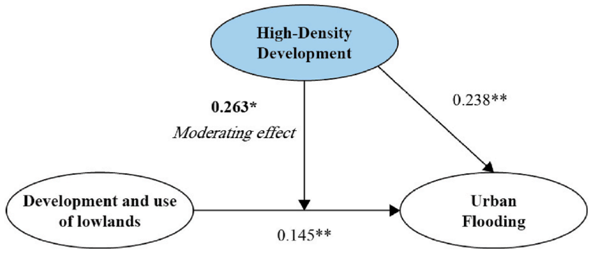

Fig. 6. Moderating effect of high-density development. Note: $**\rho < \mathbf{0.01}, *\rho < \mathbf{0.05}$.

development or use of low-lying areas often causes urban flooding because surface runoff is concentrated owing to the increase in the runoff coefficient and low elevation. If buildings and structures are densely built, the flow rate increases, inflow time to the rainwater drainage facility is shortened, and time to reach the peak flow rate is shortened because the waterway network is effectively maintained in these areas [8,49]. Ultimately, the moderating effect of high-density development acts as a factor that causes urban flooding to occur more quickly and frequently in low-lying developed areas (see Fig. 7). In conclusion, this suggests that areas in which these two factors are combined require differentiated efforts to eliminate the risk of urban flooding compared to other areas.

Second, it is necessary to consider the rationale behind urban flooding continuing despite the continued growth of cities and the gradual stabilization of drainage systems. First, the continuous growth of cities is related to urban densification. Although the population is flocking toward jobs, education, and infrastructure, high-density development within the city is inevitable because land is limited. Importantly, areas with high building densities are usually located in lowlands or floodplains [31]. Several factors have contributed to the dense development of lowland floodplains. As vacant land becomes scarce to meet growing populations and housing needs, flood-prone land may be a viable asset or be attractively priced [51]. In addition, facilities to protect cities from external water (or river flooding), such as dams and levees, encourage low-lying development by making it appear as if the risk of flooding around rivers is reduced [52]. The lack of urban disaster prevention plans and institutional laws or regulations, and the development method of private companies focusing their energy on passing regulatory standards without taking responsibility for solving flood risks have led to frequent urban flooding in these areas.

Third, should high-density development be avoided because it adversely affects urban flooding? We do not believe so. Although the impact of high-density development on the environment in terms of urban planning is a major debate [53], it has benefits, such as job creation, reduced commuting time, and high-quality amenities. In addition, the prevailing argument is that high-density development is advantageous for sustainable development by minimizing environmental problems, such as energy and air quality [54]. In terms of urban flood prevention, from a cost-benefit perspective, it is better to increase the level of flood protection in areas with high development density and economic power [55]. Therefore, based on the results of this study, we emphasize that an urban disaster prevention plan that considers the outflow characteristics of urban development density in lowland development areas is essential for reducing urban floods. For example, by designating low-lying areas with high-rise buildings as special planning zones, it could become mandatory to install storage facilities, secure permeability in open spaces, and create water barriers. Simultaneously, the joint

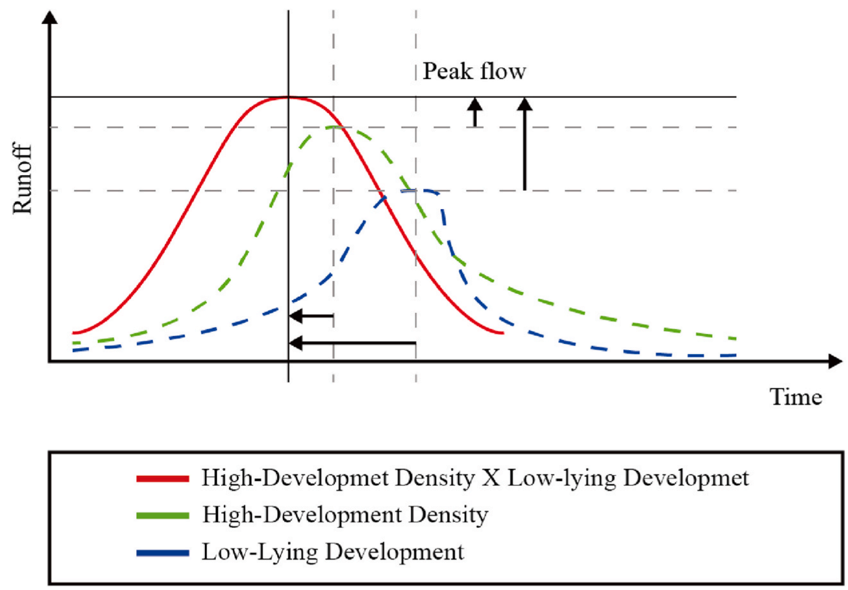

Fig. 7. Changes in peak flow due to the moderating effect of high-density development.

development of land led by the public should be considered. By promoting building floor area ratio incentives for low-impact development, the outflow characteristics of the density can be considered.

6. Conclusion

In summary, considerable attention must be paid to urban land use to prevent urban flooding. This study aimed to analyze the influence and moderating effects of high-density development on urban flooding.

The first research question of this study is: Does dense development affect urban flooding when the runoff effect of impervious surfaces is controlled? We found that the runoff characteristics of the variables related to high-density development are independently valid. In Model 2, where the runoff effect of impervious surface is controlled, the high-density development variable is significant ($\rho < 0.01$), and the goodness of fit of Model 2 (The Wald value is 290.71) compared to Model 1 (The Wald value is 285.84) explains flood runoff better.

The runoff characteristics of high-density development are to act as sub-watersheds that advance the time for the horizontal and vertical areas of dense buildings and structures to reach peak flow. This indicates that the runoff characteristics of high-density developments reported in previous studies were not based on impervious surfaces. Therefore, in urban flooding, it is necessary to manage runoff based on impervious surfaces in urban watersheds but also to manage runoff in sub-watersheds based on building density.

The second research question of this study is: do high-density developed areas moderate the occurrence of urban flooding? We created an interaction variable to confirm that there is a moderating effect of high-density development. The model is stable (The Wald value is 290.86). Specifically, urban flood risk factors in low-lying developed areas were moderated by high-density development, which had a more significant impact on urban flooding ($\rho < 0.05$). However, high-density development had no moderating effect on rainwater drainage facilities or impervious areas ($\rho > 0.05$).

In addition, the characteristics of urban watersheds in which urban flooding frequently occurs, include high urban development density ($\rho < 0.01$), low-lying areas ($\rho < 0.01$) with well-maintained levees and river structures ($\rho < 0.05$), areas with high imperviousness ($\rho < 0.01$), and areas with a high density of sewer pipes ($\rho < 0.01$). We discovered that urban flooding has occurred frequently in high-density development areas in urban watersheds in South Korea over the past 20 years, and there is a high possibility that this will reoccur. This indicates that high-density development is a factor that causes urban flooding and that considering this factor in future urban disaster prevention plans is as important as the variables identified in previous studies (such as impervious areas and rainwater drainage facilities).

While this study found that high-density development negatively affects urban flooding, some researchers who oppose urban sprawl for environmental reasons argue that high-density areas are more resilient to risks like disasters. Our findings emphasize the importance of decision-makers considering various runoff characteristics associated with urban density to effectively mitigate urban flooding resulting from urban development.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Cheol Hee Son: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Chang Hwan Lee:** Visualization, Resources, Data curation. **Yong Un Ban:** Supervision, Project administration, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2021R1I1A1A01058138).

References

[1] R.R. Brown, N. Keath, T.H. Wong, Urban water management in cities: historical, current and future regimes, Water Sci. Technol. 59 (5) (2009) 847–855.
[2] Y. Zang, et al., Study on urban flood early warning system considering flood loss, Int. J. Disaster Risk Reduc. 77 (2022), 103042.
[3] J. Wang, S. Zhang, Y. Guo, Analyzing the impact of impervious area disconnection on urban runoff control using an analytical probabilistic model, Water Resour. Manag. 33 (2019) 1753–1768.
[4] S. Deepak, G. Rajan, P. Jairaj, Geospatial approach for assessment of vulnerability to flood in local self governments, Geoenvironmental Disasters 7 (2020) 1–19.
[5] M.R. Stevens, Y. Song, P.R. Berke, New Urbanist developments in flood-prone areas: safe development, or safe development paradox? Nat. Hazards 53 (2010) 605–629.
[6] Y. Lee, S.D. Brody, Examining the impact of land use on flood losses in Seoul, Korea, Land Use Pol. 70 (2018) 500–509.
[7] E. Cho, et al., Experiment of wind-driven-rain measurement on building walls and its in-situ validation, Build. Environ. 185 (2020), 107269.

[8] B. Blocken, J. Carmeliet, A simplified numerical model for rainwater runoff on building facades: possibilities and limitations, Build. Environ. 53 (2012) 59–73.
[9] N. Wijayawardana, et al., An urban density-based runoff simulation framework to envisage flood resilience of cities, Urban Science 7 (1) (2023) 17.
[10] S. Madusanka, et al., A decision-making tool for urban planners: a framework to model the interdependency among land use, accessibility, density, and surface runoff in urban areas, Sustainability 14 (1) (2022) 522.
[11] T. Tingsanchali, Urban flood disaster management, Procedia Eng. 32 (2012) 25–37.
[12] C.H. Son, Y.U. Ban, Flood vulnerability characteristics considering environmental justice and urban disaster prevention plan in Seoul, Korea, Nat. Hazards 114 (3) (2022) 3185–3204.
[13] G. Fleming, How can we learn to live with rivers? The findings of the Institution of Civil Engineers Presidential Commission on flood-risk management, Philos. Trans. R. Soc. London, Ser. A: Math. Phys. Eng. Sci. 360 (2002) 1527–1530.
[14] S.D. Brody, W.E. Highfield, Open space protection and flood mitigation: a national study, Land Use Pol. 32 (2013) 89–95.
[15] C. Wang, et al., Analyzing explanatory factors of urban pluvial floods in Shanghai using geographically weighted regression, Stoch. Environ. Res. Risk Assess. 31 (2017) 1777–1790.
[16] C.J. Bradshaw, et al., Global evidence that deforestation amplifies flood risk and severity in the developing world, Global Change Biol. 13 (11) (2007) 2379–2395.
[17] S. Kropp, The influence of flooding on the value of real estate, J. Build. Surv. Apprais. Valuat. 1 (4) (2012) 318–324.
[18] M. Vera Pérez, J. López Blanco, Evaluación de amenazas por inundaciones en el centro de México: el caso de Iztapalapa, Distrito Federal (1998-2005), Investigaciones geográficas (73) (2010) 22–40.
[19] J. Lee, G. Chung, Analysis of runoff speed depending on the structure of stormwater pipe networks, J. Korea Water Resour. Assoc. 51 (2) (2018) 121–129.
[20] S.J. Wenger, et al., Twenty-six key research questions in urban stream ecology: an assessment of the state of the science, J. North Am. Benthol. Soc. 28 (4) (2009) 1080–1098.
[21] B. Feng, Y. Zhang, R. Bourke, Urbanization impacts on flood risks based on urban growth data and coupled flood models, Nat. Hazards 106 (2021) 613–627.
[22] J. Schwab, et al., Planning for Post-disaster Recovery and Reconstruction, American Planning Association Chicago, IL, 1998.
[23] s. Shin, c. Park, Analyzing relationships between land use characteristics and flood damage areas: the case of Seoul, The Korea Spatial Planning Review 81 (2014) 3–20.
[24] M. Cheng, et al., Can floor-area-ratio incentive promote low impact development in a highly urbanized area?—a case study in Changzhou City, China, Front. Environ. Sci. Eng. 12 (2018) 1–9.
[25] H. De Moel, J.C. Aerts, E. Koomen, Development of flood exposure in The Netherlands during the 20th and 21st century, Global Environ. Change 21 (2) (2011) 620–627.
[26] B. Güneralp, İ. Güneralp, Y. Liu, Changing global patterns of urban exposure to flood and drought hazards, Global Environ. Change 31 (2015) 217–225.
[27] S.D. Brody, et al., Examining the influence of development patterns on flood damages along the Gulf of Mexico, J. Plann. Educ. Res. 31 (4) (2011) 438–448.
[28] J. Borowski, et al., Conditions for the effective development and protection of the resources of urban green infrastructure, in: E3S Web of Conferences, EDP Sciences, 2018.
[29] S. Du, et al., How did the urban land in floodplains distribute and expand in China from 1992–2015? Environ. Res. Lett. 13 (3) (2018), 034018.
[30] A. Früh-Müller, M. Wegmann, T. Koellner, Flood exposure and settlement expansion since pre-industrial times in 1850 until 2011 in north Bavaria, Germany, Reg. Environ. Change 15 (2015) 183–193.
[31] M. Mazzoleni, et al., Deciphering human influence on annual maximum flood extent at the global level, Communications Earth & Environment 3 (1) (2022) 262.
[32] C. Kuenzer, et al., Varying scale and capability of envisat ASAR-WSM, TerraSAR-X Scansar and TerraSAR-X Stripmap data to assess urban flood situations: a case study of the Mekong delta in Can Tho province, Rem. Sens. 5 (10) (2013) 5122–5142.
[33] J.D. Ford, et al., Case study and analogue methodologies in climate change vulnerability research, Wiley Interdisciplinary Reviews: Clim. Change 1 (3) (2010) 374–392.
[34] C. Carvalho, A.G. Del Campo, D. de Carvalho Cabral, Scales of inequality: the role of spatial extent in environmental justice analysis, Landsc. Urban Plann. 221 (2022), 104369.
[35] M. Su, M.-C. Lin, T. Wen, Spatial Mapping and Environmental Risk Identification, 2011.
[36] S. Rufat, et al., Social vulnerability to floods: review of case studies and implications for measurement, Int. J. Disaster Risk Reduc. 14 (2015) 470–486.
[37] C.-H. Son, et al., The effects of mitigation measures on flood damage prevention in Korea, Sustainability 7 (12) (2015) 16866–16884.
[38] M. Brezzi, L. Dijkstra, V. Ruiz, OECD Extended Regional Typology: the Economic Performance of Remote Rural Regions, 2011.
[39] M. Piyumi, et al., Urban flood modeling application: assess the effectiveness of building regulation in coping with urban flooding under precipitation uncertainty, Sustain. Cities Soc. 75 (2021), 103294.
[40] X. Li, et al., Experimental and numerical study of the effect of model geometric distortion on laboratory modeling of urban flooding, Water resources research 57 (10) (2021).
[41] M.J. Burns, et al., Testing the impact of at-source stormwater management on urban flooding through a coupling of network and overland flow models, Wiley Interdisciplinary Reviews: Water 2 (4) (2015) 291–300.
[42] E. Lechowska, The impact of embankment construction on floodplain land use in the context of its influence on the environment: a case study of selected cities in Poland, Pol. J. Environ. Stud. 26 (2) (2017).
[43] S. Kang, J. Yeom, J. Jung, Urban form and natural hazards: exploring the dual aspect concept of urban forms on flood damage, Sustainability 13 (16) (2021) 9007.
[44] P. Harcourt, Impacts of urban land use changes on flood events in warri, delta state Nigeria, ISOR Journal of environmental science, toxicology and flood technology (IOSR-JESTFT) 8 (10) (2014) 37–45.
[45] M.G. Miguez, et al., Urban floods in lowlands—levee systems, unplanned urban growth and river restoration alternative: a case study in Brazil, Sustainability 7 (8) (2015) 11068–11097.
[46] R.M. Baron, D.A. Kenny, The moderator–mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations, Journal of personality and social psychology 51 (6) (1986) 1173.
[47] L.S. Aiken, S.G. West, R.R. Reno, Multiple Regression: Testing and Interpreting Interactions, sage, 1991.
[48] S.G. West, J.F. Finch, P.J. Curran, Structural Equation Models with Nonnormal Variables: Problems and Remedies, 1995.
[49] E. Cho, C. Yoo, Rainfall-runoff analysis method considering the effect of high-rise buildings, Journal of the Korean Society of Hazard Mitigation 20 (6) (2020) 407–420.
[50] s. Kim, k. Jun, Analysis of the impact of building congested area for urban flood analysis 15, Korean Society of Disaster & Security, 2022, pp. 41–46. Journal of Korean Society of Disaster & Security), 3.
[51] R.J. Burby, et al., Urban containment policy and exposure to natural hazards: is there a connection? J. Environ. Plann. Manag. 44 (4) (2001) 475–490.
[52] G.A. Tobin, The levee love affair: a stormy relationship? 1, JAWRA Journal of the American Water Resources Association 31 (3) (1995) 359–367.
[53] A.M. Hassan, H. Lee, The paradox of the sustainable city: definitions and examples, Environ. Dev. Sustain. 17 (2015) 1267–1285.
[54] C.H. Son, J.I. Baek, Y.U. Ban, Structural impact relationships between urban development intensity characteristics and carbon dioxide emissions in Korea, Sustainability 10 (6) (2018) 1838.
[55] D. Wang, P. Scussolini, S. Du, Assessing Chinese flood protection and its social divergence, Nat. Hazards Earth Syst. Sci. 21 (2) (2021) 743–755.