Flood vulnerability characteristics considering environmental justice and urban disaster prevention plan in Seoul, Korea

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Abstract
This study aimed to evaluate environmental injustice and analyze flood vulnerability characteristics in consideration of environmental justice and urban flood disaster prevention planning. We investigated various physical and non-physical urban disaster prevention factors to prevent urban flooding and applied them to the urban development process in Seoul from an environmental justice perspective. Flood risk areas were identified, and flood damage data from 2000 to 2018 were collected. Furthermore, a panel analysis was performed and the final model was selected. The flood vulnerability characteristics were found to be detached houses having basements, aged detached houses, land area for detached houses, public assistance recipients, and population aged 65 years or above, which had impact factors of 8.323, 3.781, -2.877, 3.257, and 2.637, respectively. The results indicate that not only the socially vulnerable population lacked the ability to respond to floods, but buildings and areas with poor residential environments also suffered from flood damage. This implies that there was socioeconomically disproportionate exposure (termed as environmental injustice) in the process of urban flood prevention planning and urban development. Our results can contribute qualitatively and quantitatively to preparing a flood prevention plan based on environmental justice paradigm.

Keywords Flood vulnerability characteristics · Environmental justice · Socially vulnerable population · Urban disaster prevention plan

1 Introduction

Flood damage results in not only recovery costs but also indirect costs, such as economic downturn, health problems, and emotional distress (Lee and Brody 2018; Wang et al. 2017). If an urban area packed with residential and commercial facilities and social
infrastructure is flooded by heavy rains, physical and personal damage increase due to the area’s vulnerability to disaster (Eini et al. 2020). Accordingly, it is critical to determine the flood vulnerability characteristics of a city as they influence the level of flood damages (Chen et al. 2019).

It is known that socially and economically disadvantaged people are highly vulnerable to natural disasters because of their limited ability to manage disasters (Morse 2008); this is called social vulnerability (Rolfe et al. 2020). Notably, these underprivileged populations often reside in areas vulnerable to floods (Morse 2008). Hurricane Katrina, which occurred in 2005, is a representative case that demonstrates how modern society can be unjust from the perspective of natural disasters (Allen 2007). In this case, public rental housing for communities of color and low-income families was built in lowlands that were vulnerable to flooding, thereby causing great damage to a particular part of the society (Bullard and Wright 2009). Such problem that results in the disproportionate exposure of specific communities with color and socioeconomic status is called “environmental injustice,” whereas the solution to this problem is called “environmental justice” (Ban 2007; Bullard 2007).

An urban disaster prevention plan is a management and mitigation policy that protects people’s lives and properties from the risks caused by intensive land use and social conditions, and it is very important for realizing environmental justice. To manage and reduce urban flooding, infrastructure strategies such as sewerage systems and rainwater drainage facilities, land use strategies such as reducing impervious areas or building houses in safe places, and architectural adaptation strategies such as installing disaster prevention facilities around houses are used (Creach et al. 2019). These physical factors can determine the scale of flood damage as part of the urban built environment (England and Knox 2015). If an urban disaster prevention plan is intentionally and excessively concentrated for specific population or regions and causes irrational discrimination without considering fairness, it cannot guarantee minimum environmental rights for certain population or regions.

As such, there is a need to analyze flood vulnerability characteristics from the perspectives of urban disaster prevention planning and environmental justice (Hughes et al. 2021). However, only a few studies have integrated and analyzed both perspectives. Specifically, although studies related to urban disaster prevention plan have demonstrated that urban flooding is caused by natural factors (e.g., rainfall, topography) as well as anthropogenic factors (e.g., rainfall pipes, green spaces, impermeable spaces) (Lin et al. 2021), much less effort has been put into examining factors relevant to environmental justice (in particular, variables closely related to social factors such as building composition or land use). Research on environmental justice has focused on investigating the degree of disproportionate exposure of racial, ethnic, and socioeconomic groups to certain risk (Collins et al. 2018). For example, studies by Alejandra Maldonado (2016), Neil Debbage (2019), Maantay and Maroko (2009) quantified the degree of disproportionate exposure of vulnerable populations to flood risk across various socio-economic characteristics, but did not consider urban disaster prevention factors. Nevertheless, these studies suggest that the inequality suffered by the vulnerable in common may differ depending on the situational factors (water infrastructure, dry environment, etc.) caused by development, and that the inequality may differ in accordance with spatial scale. In addition, Walker and Burningham (2011), Faber (2008) and others argued that it is necessary to focus on process and production issues. For example, Walker and Burningham (2011) showed a pattern of exposure to coastal flooding among the wealthy population in the UK; however, the use of coastal amenities and scenery is voluntary for the rich. Furthermore, they argued that this is not an environmental injustice because the rich have the insurance and the economic power to reduce their risks.
These findings have helped us understand that flood vulnerability needs to be analyzed in consideration of both urban disaster prevention factors and environmental justice factors such as socio-economic status and spatial scale of communities susceptible to flood disaster. Thus, based on the above literature review, we have drawn the following research questions: First, what are the flood vulnerability characteristics considering environmental justice and urban disaster prevention plans? This question would help us understand the causes and effects of urban disaster from the perspective of environmental justice. Second, are the flood vulnerability characteristics the results of the flood disaster prevention plan being unfairly distributed in the process of urbanization? It is intended to assess environmental injustice by focusing on process and consequences.

To answer those research questions, this study has intended to analyze the flood vulnerability characteristics in consideration of environmental justice and urban flood disaster prevention plan, and to find relationship between process and consequence of flood disaster prevention focusing on environmental injustice. The target area for this study was Seoul, South Korea. Seoul is one of the cities that achieved rapid economic growth in a very short period compared to other major cities in the world. In 2020, the population density of the city was 15,865 / km², which is higher than that of Tokyo, New York, and Paris. In Seoul, urban functions, such as economy, politics, and buildings are highly integrated, and underground spaces are also used on a large scale. In particular, it is easy to collect flood damage data in Seoul due to the high frequency of urban flooding that has occurred in the city.

2 Floods in Seoul, Korea

2.1 Study area

Seoul is located at 37°34’ N 126°59’ E, with a total area of 605.41 km² (Fig. 1 a). It has small basins centered on the Hangang River, along with four other rivers (Cheonggyecheon,
Jungrangcheon, Tancheon, and Anyangcheon), and is also surrounded by mountains (Fig. 1b). The lowlands (with an elevation lower than the flood level\(^1\)) correspond to 30.75% of the area of Seoul (Koh 2013). There are 36 rivers and streams in the Seoul area, and their total extended lengths are 242.11 km. The average annual precipitation for 30 years from 1981 to 2010 was 1450 mm (KMA 2021). Floods generally occurred in the summer (July–August), and precipitation during this period accounted for two-thirds of the annual precipitation (Son et al. 2015). There are two reasons for the heavy rainfall in summer. One is concentrated torrential rain that occurs during the rainy season in summer when atmospheric pressure is unstable, and the other reason is the localized heavy rains caused by typhoons crossing the Korean Peninsula between July and September (KMA 2021).

### 2.2 Process of urbanization in Seoul

The population of Seoul has rapidly increased since the Korean War. According to Statistics Korea, the 1955 census indicated a population level of 1.57 million, while the 1960 census revealed a population level of 2.44 million. As of 2019, Seoul’s population is around 10.05 million. To meet the increasing housing demand caused by the population explosion, a large-scale land readjustment project was started in the undeveloped lowlands in the 1960s. After the land was cleared, the private sector led the supply of detached houses.\(^2\) However, the government decided that it was difficult to solve the housing problem in Seoul with single-family houses alone, and in the 1970s, the government promoted a policy of mass supply through public development. As 70–80% of new houses were supplied as apartments, the proportion of apartments, which accounted for only 0.8% of the total housing stock in 1970, increased to 53.0% in 2005 (Seoul Solution 2015).

The land readjustment project developed 58 zones, with the related area reaching 140.0 km\(^2\), thereby changing as much as 40% of Seoul into an urbanized area over a short period of 30 years (Koh 2013). Many buildings were built during this development-intensive period, and the current state of deterioration in the city is serious. According to the Seoul Building Register, 49.5% of approximately 610,000 buildings have exceeded the service life of 30 years, and this percentage is expected to reach 65.8% within the next five years (Seoul Data 2019).

### 2.3 Urban disaster prevention plan in Seoul

The elements of urban disaster prevention planning applied in the urban development process of Seoul are summarized in Table 1 with reference to the studies of Institute (2015), Koh (2013), Lee and Brody (2018), and Son et al. (2015). In the 1960s, the undeveloped lowlands were vulnerable to river flooding. Even before the 1960s, projects such as the construction of dams, embankments, and embankment roads were promoted to transform the lowlands into residential areas that are safe from river floods. In other words, the land readjustment project was carried out as the risk of river flooding disappeared. The drainage system was designed with an average design frequency of 5–10 years (65–75 mm/hr). In addition, most of the detached houses have basements, which were intended to be used as

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\(^1\) National rivers: 100-year flood frequency, Local rivers: 50–80-year flood frequency.

\(^2\) A detached house refers to a row house with three stories or less and a multi-family house with total floor area of less than 660 m\(^2\) according to the Korean Building Act.
| Building | Land use | Infrastructure |
|----------|----------|----------------|
| Encourage the construction of basement buildings as shelters and air-raid shelters | Elevation of the ground level through the public water reclamation project | Establishment of infrastructure (dams and levees) that protects the Seoul basin |
| Structural weakness due to an aging building | Exposure to flood risk by developing lowland areas near rivers (requires development restriction policy in hazardous areas) | Establishment of infrastructure (rainwater exclusion facilities) quantitatively, without a plan |
| Private company led detached house development to cover development costs (disaster prevention facilities are lacking) | Lack of permeable area due to high land-use density (requires limited development density) | |
an air-raid shelter when the north and the south, which are currently at a ceasefire, fought again. However, a growing population has used basements as living spaces, making them vulnerable to flooding. As of 2015, 228,467 (65.5%) of the 384,782 semi-basement households nationwide were in Seoul.

On the other hand, the apartments supply is supervised by public institutions, and development profits was used to construct infrastructure or convenience facilities. There was still no comprehensive plan for the entire city, but in preparation for urban flooding, the first floor was formed higher than the flood level, the ground was raised, and the structure of the pilotis were designed.

2.4 Social and economic inequality and increase in vulnerable populations

Due to the high inflation rate and worsening income distribution since the 1970s, the gap between high-income and low-income citizens has emerged as one of the most critical social issues in South Korea. According to the World Inequality Report, the wealth of the top 10% of South Korea is 52 times greater than that of the bottom 50%, and 14 times as much in terms of income (Chancel et al. 2021). Korea’s income level is similar to that of developed countries in Western Europe, but the wealth inequality is nine and ten times more severe than that of Britain and Germany, respectively (Chancel et al. 2021). Chancel et al. (2021) pointed out that “in the 1960s and 1990s, when the Korean economy did not build a social safety net, inequality worsened as regulations were eased and rapid growth occurred.”

The 2019 census indicated that the aging population exceeded 1.41 million, accounting for 14.4% of the total population. However, the speed of transformation of an aged society gradually increases the number of problems to be solved by the society. Korea’s population is aging faster than other Organization for Economic Cooperation and Development (OECD) countries, and by the 2050s it will be the oldest country in the OECD (OECD 2019).

3 Materials and methods

3.1 Research concept and design

Figure 2 schematically illustrates the concept of the present study on urban flooding. Urban flooding is not floods that occur in urban areas. This does not happen when the river crosses the embankment (river flooding) or when a storm surge (coastal flooding) occurs. It is caused by excessive runoff from developed watersheds that has nowhere to go. Additionally, coastal and river flooding occur over large areas, whereas urban flooding is fragmented and localized (Fig. 1c).

The concept of research is illustrated in Fig. 2 based on paths A, B, and C. The path A is a concept in which socioeconomic disparities and the vulnerable population increase as a side effect of rapid economic development. This is expressed as the flood-vulnerable population. The path B is a concept of resource allocation that affects the decrease or increase of flood risk in the urbanization process. This is expressed as a flood vulnerable area. Thus, the answer to the first research question can be obtained by deriving path A and path B factors and statistically verifying them using models that considers spatiotemporal effects. This is provided in Sect. 4.6. Path C represents the relationship between the flood-prone
population due to path A and the flood-prone area due to path B. The answer to the second research question can be obtained by discussing whether this relationship is unjust. This is provided in Sect. 5.

3.2 Variable Selection

As a dependent variable, the flooded area, human casualties, and flood damage density were considered. The flooded area oversimplifies the damage, and human casualties have hardly occurred in Korea since 1990 (Son et al. 2015). Therefore, the flood damage density was selected. Natural characteristics, such as rainfall (Highfield and Brody 2013), rainfall intensity (Brody and Highfield 2013; Highfield and Brody 2013), and elevation (Wang et al. 2017), can be assumed to affect flooding. Notably, economic characteristic variables are closely related to flood damage. These factors are statistically significant, because the amount of damage to a land or building varies according to its value, irrespective of whether they have the same area (Rufat et al. 2015). Therefore, these factors were used as control variables in previous empirical studies to determine the effects of floods (Brody and Highfield 2013; Highfield and Brody 2013; Lee and Brody 2018). The location and structure of detached houses (Creach et al. 2020), basements and semi-basements (Forrest et al. 2020), aged and poorly built houses (Brody et al. 2011) and type of house (Ketteridge and Fordham 1998) are related to flood damage and social vulnerability, and they may be considered as variables. Even for land use, if development is carried out in an area that is vulnerable to flooding, in addition to land coverage (Burby et al. 2001; Stevens et al. 2010), it is imperative to impose a limit (Berke et al. 2009; Stevens et al. 2010) for the development density. In addition, land use may be related to vulnerable population. Most of the residential areas in Seoul where low-rise houses are characterized by a small housing area, a large proportion of the elderly and single-person households, and no significant change in infrastructure (Maeng et al. 2016). Therefore, the average land area of detached houses is used as a variable representing land use in the area where the vulnerable population lives.
Notably, we did not select the race variable because Korea is a single nation with no serious racial conflict problems. In addition, Korea’s higher education completion rate is 10.4% higher than the OECD average in terms of adults, so it belongs to the top group. Therefore, the education level variable was excluded because it had no discriminatory power (Indicators 2020). To consider the increase in the population that is vulnerable to flooding and economic inequality, we selected the ratios of the elderly population (Cutter et al. 2003; Parker et al. 2005) and recipients of public assistance (Cutter et al. 2003; Rufat et al. 2015) as variables in our study (see Table 2).

3.3 Data construction

The unit of analysis for the study was gu, administrative districts under the Seoul Metropolitan Government (Lee and Brody 2018). The analysis needs to be addressed Modifiable Areal Unit Problem because the changes in the scale of analysis lead to debates about environmental justice, yielding different outcomes (Baden et al. 2007). Carvalho (2022) had noted that the environmental definition results for river flooding were different at the scale of large cities and autonomous districts. In the case of urban flooding, it is important to set a spatial scale that can reflect this characteristic. As flood damage occurs locally in densely populated large cities and varies depending on the dry environment (England and Knox, 2016), a small unit that can understand the impact of the dry environment is appropriate for the spatial scale. Thus, the scale of our analysis is autonomous districts. Additionally, since the results can vary depending on the size of the area, it was constructed using a ratio.

The average area of an autonomous district in Seoul is 24.21km², with an average of 173,104 residents. From 2000 to 2018, 475 samples were obtained from 25 gu in Seoul (25 × 19). The detailed construction process of the variables determined using GIS is explained below in subsections.

3.3.1 Derivation of flood risk areas

Analyzing the entire Seoul area may have the disadvantage of overestimating/underestimating the flood vulnerability characteristics because the scope of the study is broad. Therefore, flood risk areas are selected for analysis. First, consider the topographical factors. This is because factors such as elevation, slope, and relative relief directly affect urban flooding. The design flood level is also very important. This is because, for water to be drained, it is affected by the design flood level of each river along with the topographical factors. Lastly, even if the stream does not overflow, the water in the urban watershed is discharged into the stream, so water may accumulate around the stream when the flood level rises. The River Act stipulates that the area affected by flooding is within 500 m from the river boundary. For this reason, flood risk areas were selected according to the following criteria. (1) the areas with an elevation of 30 m or lower, slope of 7° or lower, and relative relief of 20 m or lower (2) the areas lower than the design flood level of each river (3) the areas located 500 m away from the river boundary (Fig. 1 d).

3.3.2 Variable data construction

The flood damage data of Seoul were collected from the Water Resources Management Information System (WWMIS), and the inflation was adjusted as of 2018. The total annual precipitation (mm) was acquired by first obtaining the data on the automated synoptic observing
| Classification | Variables (unit) | Description of variables | Data source |
|----------------|------------------|--------------------------|-------------|
| Flood damage  | Flood damage density (won/m²) | Total amount/area | https://wamis.go.kr/ |
| Natural characteristics | Maximum monthly precipitation (mm) | Maximum precipitation value for one hour | https://data.kma.go.kr/cmmn/main.do |
| | Maximum annual precipitation (mm) | Total annual precipitation | https://angii.go.kr/ |
| | Average surface elevation | Public land price / area | https://data.seoul.go.kr/ |
| Economic characteristics | Average public land price (won/m²) | Financial independence | https://me.go.kr/ |
| | Density of sewage and rainfall pipes (km²) | Length/area of sewage and rainfall pipes | https://cloud.eais.go.kr/ |
| | Capacity/area of rainfall reserve facilities (m³/day/km²) | Capacity/area of rainfall reserve facilities | https://sgis.kostat.go.kr/ |
| Infrastructure facility | Rate of detached houses having basements (%) | Rate of aged detached houses (%) | https://sgis.kostat.go.kr/ |
| | Rate of commercial and office facilities having basements (%) | Rate of commercial and office facilities having basements (%) | https://sgis.kostat.go.kr/ |
| Buildings | Average land area for detached house (m²) | Average land area for detached house (m²) | https://sgis.kostat.go.kr/ |
| Land use | Housing density (houses/m²) | Rate of public assistance recipients (%) | https://sgis.kostat.go.kr/ |
| Characteristics of vulnerable population | Inter-generations | Rate of vulnerable population (population aged 65 years or above / total population) × 100 |
| Characteristics of vulnerable population | Intra-generation | Rate of vulnerable population (population aged 65 years or above / total population) × 100 |
system (ASOS) and automatic weather system (AWS) locations, and then, calculating the average values by assigning the distance adjusted weight to inverse distance weighted (IDW) interpolation. Because the maximum one-hour precipitation (mm) and maximum daily precipitation (mm) do not provide the AWS data, only the ASOS was used. For the average surface elevation, the average data were acquired from the digital elevation model (DEM) data from the National Geographic Information Institute for regional statistics. The map scale was 1:5000, and the average cell size was 90 m. The data on rainwater discharge facilities were acquired from sewage statistics published by the Ministry of Environment. The total length was calculated by summing the length of the sewage pipes and rainwater pipes. Building-related variables were acquired from the building registry provided by the civilian opening system of the architectural data. The property data were combined into the building database (DB) provided at the new road address. The average public land price, financial independence, and ratio of public assistance recipients were constructed based on data provided by Seoul City. The average public land price was reflected in the inflation and was constructed in connection with the variables related to the building and the parcel number (PNU) code. The vulnerable population density for people aged 65 years or above was used from the census date of the Statistical Geographic Information Service (SGIS). Table 2 shows the variable descriptions and sources. The “gu” as a unit was used to combine the data with different resolutions, and then the statistical analysis was performed (Fig. 1c).

3.4 Data analysis

To verify the significance of flood vulnerability characteristics on flood damage, we applied a panel model. Pielke and Downton (2000) argued that because natural disasters occur in a very complicated way according to regional characteristics and policies, the limited independent variables cannot explain all the damages from a natural disaster. The panel model can take into account unobserved time and individual effects. The panel model can be expressed using a regression model, as follows (Hsiao 2014):

$$Y_{it} = \alpha + \beta X_{it} + \mu_i + \lambda_t + \nu_{it}$$

where $Y_{it}$ represents the dependent variable, $\alpha$ is the $Y$-intercept, $\beta$ is the slope, $X_{it}$ represents the independent variable, $\epsilon_{it}$ is the error term, $i$ represents the individual (1,2, 3, etc.), $t$ is time (1,2,3, etc.), $\lambda_t$ is the unobserved time effect, and $\nu_{it}$ is the remaining stochastic disturbance term.

This study proposes a strongly balanced data structure based on the region and time to determine the fixed and random effects of floods on damage in lowlands. Selecting the model in the panel model was the most important aspect in estimating the parameter. The Chow, Breusch–Pagan Lagrange multiplier (Breusch–Pagan LM) and Hausman tests were conducted along with autocorrelation and heteroscedasticity tests, to select the most suitable model for the panel model analysis from the mixed, fixed effect, random effect, and feasible generalized least squares models (FGLS).
4 Results

The descriptive statistics of the variables for the analysis of the effects of urban flood damage are described in Table 3. The variables in Table 3 are suitable for panel analysis because no variables that cause serious problems such as excessively large or relatively small standard deviations were found. In Seoul, large- and small-scaled flood damage occurred every year during the observation period. The average flood damage density was 10,636 (won/m²). Table 4 shows the statistics of the various models analyzed in the study.

4.1 Testing significance of one-way error component model

To test the significance of the one-way error component model, we first conducted a test to investigate whether the regional fixed effect was statistically significant. The $F$ statistic was 1.11 ($p > 0.05$), which is not significant. Therefore, the null hypothesis was not rejected. Next, the regional random effect was checked. Because the testing results indicated that the $\chi^2$ statistic was 2.43 ($p > 0.05$), the null hypothesis could not be rejected. However, in the one-way error component model, a model in which the time effect is controlled (instead of the area effect), may be considered. The results indicated that the $F$ statistic was 11.73 ($p < 0.001$). Therefore, the null hypothesis was again rejected. To investigate whether the time random effect was statistically significant, the Breusch–Pagan LM test was conducted. The $\chi^2$ statistic was 112.58 ($p < 0.001$). Therefore, the null hypothesis that “there is no time random effect” was rejected. To determine which model was more appropriate between the time fixed effect model and the random effect model, the Hausman test was conducted. The results indicated that $p = 0.4762$, indicating that the random effect model in which the explanatory variable and region-specific effect were independent from each other and not correlated, was not rejected at the significance levels of 1% and 5%.

4.2 Testing significance of two-way error component model

The estimation results indicated that the region and time fixed effects were statistically significant when the region effect and time effect were all controlled for using an F-testing value of 0.0206 and a 5% significance level. However, a model, in which there was a random effect for region specifics, and another model, in which there was a fixed effect for time specifics, could be estimated. The Breusch–Pagan LM test results rejected the null hypothesis, which states that there is no time random effect associated with $p < 0.001$. Finally, we applied a two-way random effect model that considered region and time specifics as random variables. The test results showed a very small p-value, that supported the existence of region and time random effects. The results indicated $\text{Prob} > \chi^2 = 0.3631$ so that the random effect model was not rejected at both significance levels of 1% and 5%, arguing that the explanatory variable and region-specific effects are independent from each other.

4.3 Testing Significance of heteroscedasticity and autocorrelation

Because the autocorrelation test indicated a value of $p < 0.001$, the null hypothesis was rejected, portraying that the panel model had AR1 autocorrelation. The test of
Table 3  Descriptive statistics table

| Classification | Obs | Mean  | Std. Dev | Minimum | Maximum |
|----------------|-----|-------|----------|---------|---------|
| **Dependent Variable** | Flood damage density (won/m²) | 475 | 10,636.84 | 41,702.13 | 0 | 604,338.9 |
| **Independent Variables** | Natural characteristics | 475 | 143.4272 | 57.05289 | 43.74315 | 301.717 |
| | Maximum monthly precipitation (mm) | 475 | 13.10828 | 21.19491 | 90.17009 |
| | Total annual precipitation (mm) | 475 | 365.5045 | 351.0723 | 2015.54 |
| | Average surface elevation (m) | 475 | 57.98456 | 42.35409 | 10.86577 | 157.0912 |
| | Economic characteristics | 475 | 1,580.629 | 1,403,536 | 9,326,551 |
| | Average public land price (won/m²) | 475 | 3,230.092 | 1,403,536 | 9,326,551 |
| | Financial independence (%) | 475 | 45.21403 | 15.641 | 95.3 |
| **Characteristics of vulnerable areas** | Infrastructural facility | 475 | 16,025.27 | 28,836.19 |
| | Density of sewage and rainfall pipes (km²) | 475 | 4080.04 | 7670.53 |
| | Density of rainfall discharge facilities (m³/day/km²) | 475 | 8644.417 | 0 | 33,192.41 |
| | Buildings | 475 | 11,670.39 | 12,936.93 | 69.97075 |
| | Rate of detached houses having basements (%) | 475 | 14.91072 | 1.47316 | 29.3681 |
| | Rate of aged detached houses (%) | 475 | 16.17292 | 5,522,781 | 35.61539 |
| | Rate of commercial and office facilities having basements (%) | 475 | 16.42364 | 8.96623 | 71.46151 |
| | Land use | 475 | 43.29645 | 23.54663 | 71.46151 |
| | Average land area for detached house (m²) | 475 | 12,307.88 | 23.54663 | 71.46151 |
| | Housing density (house/m²) | 475 | 9.233622 | 4.042441 | 2.642455 | 19.56126 |
| **Characteristics of vulnerable people** | Inter-generations | 475 | 20.20431 | 8.277147 | 6.176449 | 50.09058 |
| | Rate of public assistance recipients (%) | 475 | 20.20431 | 8.277147 | 6.176449 | 50.09058 |
| | Intra-generation | 475 | 9.56547 | 3.070755 | 4.472259 | 18.02208 |

*Obs- Observation; Std. Dev.- Standard Deviation*
Table 4  Statistical significance test of panel models used in the analysis

| Classification | One-way error model | | | Two-way error model | Consideration of both region and time specifics at the same time |
|---|---|---|---|---|---|
| | Region specifics | Time specifics | | Fixed effect | Random effect | Fixed effect | Random effect |
| | Fixed effect | Random effect | Fixed effect | Random effect | Fixed effect | Pooled model (region random, time fixed) | Random effect |
| Constant term | 19.805 | -12.019*** | -4.359* | -6.557*** | 20.677* | -2.632 | -12.027*** |
| sigma_u (σ_u) | 8.352 | .3829 | 2.325 | 2.325 | 5.064 | 0.528 |
| sigma_e (σ_e) | 2.823 | 2.823 | 2.376 | 2.376 | 2.33 | 2.33 |
| rho (ρ) | .897 | .18 | .489 | .489 | 0.824 | 0.048 |
| R² | within | 0.3756 | 0.3580 | 0.1166 | 0.5911 | 0.5728 |
| | between | 0.0083 | 0.5227 | 0.2023 | 0.0030 | 0.5182 |
| | overall | 0.0276 | 0.3648 | 0.1582 | 0.1314 | 0.5700 |
| F-value | 1.11 | 11.73 | 1.64 |
| Prob > F | 0.3278 | <0.001 | 0.0206 |
| Wald χ² | 260.50 | 75.08 | 585.12 | 270.68 |
| Prob > χ² | <0.001 | <0.001 | <0.001 | <0.001 |
| Breusch–Pagan LM χ² | 2.43 | 112.58 | 0.79 | 12.43 |
| Prob > F | 0.0594 | <0.001 | 0.1876 | 0.0114 |

*Statistically significant at the 5% level; ** 1% level; *** 0.1% level
heteroscedasticity results indicated a value of \( p < 0.001 \), indicating heteroscedasticity between the regions and spatial dependence. Because both autocorrelation and heteroscedasticity existed in the panel data, the variance of the error term was estimated and the FGLS regression model was employed, which enabled the application of the weighted least square (WLS) model. The Wald statistic of the FGLS model was 292, which was found to be significant at the level of \( p < 0.001 \).

### 4.4 Describing the overall model performance and selection of the final model

In summary, the time random effect model of one-way error, the random effect of two-way error, and the FGLS model considering heteroscedasticity and autocorrelation were found to be suitable. Table 5 shows that the direction of the coefficients is consistent in all of the pooled OLS, one-way error model, two-way error model, and FGLS model, indicating that the model has high stability. Compared to other models, the FGLS model has the highest Wald statistic, high estimation coefficient, and many significant variables, so it is possible that the remaining models underestimate the coefficients. Consequently, this study concluded that the FGLS model was the most appropriate.

### 4.5 Flood Vulnerability Characteristics

From the FGLS model in Table 5, we observed that the more the maximum one-hour precipitation, the bigger the urban flood damage (\( p < 0.001 \)). This means that there was no dispute on the conclusion that precipitation intensity increased flooding (Brody and Highfield 2013). However, the total precipitation did not have any impact on flooding. Considering that the precipitation intensity is the product of precipitation volume by time, we found that the precipitation intensity was the more influential variable than the precipitation volume because it enhanced the peak flow. Additionally, we observed that the average surface elevation did not have any impact on flooding (\( p > 0.05 \)). In previous studies, low elevation is an important variable affecting flooding (Wang et al. 2017), but in this study, it is not a significant variable. This is a reasonable result because the derived flood risk area is a low-altitude topography (see 3.3.1).

Notably, the average public land price (\( p < 0.001 \)) had an effect on the increase in flood damages. We could deduce that flood damage is the absolute cost affected by the economic value. Therefore, it is expected that economic damages caused by floods will be large in areas with high economic value; however, it cannot be said whether the damage intensity is large (Rufat et al. 2015).

It was found that the higher the density of rainfall discharge facilities, the more the urban flood damage (\( p < 0.01 \)). This is contrary to the previous studies, according to which the more rainfall discharge facilities there are, the less damage will be caused by flooding (Abi Aad et al. 2010; Zachary Bean et al. 2007). Nevertheless, we found that the claims of previous studies may not be appropriate in high-density urban areas such as Seoul. This is because, for the rainfall discharge facilities or sewage and rainfall pipes to be considered as variables, it is necessary to discuss whether the flood reduction effect is qualitatively sufficient. Seoul has designed rainfall discharge facilities that focus on quantity at a frequency of 5 to 10 years in flood-risk areas, but this is insufficient to prevent heavy rain of more than 75 mm/hr.

Detached houses having basements (Forrest et al. 2020; Ketteridge and Fordham 1998) (\( p < 0.001 \)) and aged detached houses (Brody et al. 2011) (\( p < 0.001 \)) had a positive impact
Table 5  Test results for each variables of panel models tested for significance

| Classification                              | OLS               | One-way time random model | Two-way random model | FGLS   |
|---------------------------------------------|-------------------|----------------------------|----------------------|--------|
| Constant                                    | -11.837***        | -6.557***                  | -12.027***           | -12.587*** |
| Natural Characteristics                      |                   |                            |                      |        |
| Maximum monthly precipitation (mm)          | 1.282             | 2.895*                     | 1.273                | 0.805  |
| Maximum hourly precipitation (mm)           | 9.142***          | 7.109***                   | 9.135***             | 9.731***|
| Total annual precipitation (mm)             | 1.225*            | -2.006                     | 1.243*               | 0.725  |
| Average surface elevation (m)               | -0.0651           | -0.245                     | -0.007               | -0.397 |
| Maximum hourly precipitation (mm)           | 9.142***          | 7.109***                   | 9.135***             | 9.731***|
| Total annual precipitation (mm)             | 1.225*            | -2.006                     | 1.243*               | 0.725  |
| Average surface elevation (m)               | -0.0651           | -0.245                     | -0.007               | -0.397 |
| Average public land price (won/ m²)         | 5.561***          | 4.803***                   | 5.546***             | 5.211***|
| Financial independence (%)                  | 1.163             | -0.389                     | 1.483                | 1.951  |
| Characteristics of Vulnerable Areas         |                   |                            |                      |        |
| Infrastructural Facility                    | Density of sewage and rainfall pipes (km²) | 0.988 | 0.546 | 0.987 | 0.359 |
|                                            | Density of rainfall discharge facilities (m³/day/ km²) | 1.691* | 1.206* | 1.789* | 1.907** |
| Buildings                                   | Rate of detached houses having basements (%) | 7.545*** | 4.895*** | 7.761*** | 8.323*** |
|                                            | Rate of aged detached houses (%) | 3.606*** | 2.709*** | 3.557*** | 3.781*** |
|                                            | Rate of commercial and office facilities having basements (%) | 0.688 | 0.472 | 0.579 | 1.287 |
| Land Use                                    | Average land area for detached houses (m²) | -2.365** | -1.605** | -2.475** | -2.887*** |
|                                            | Housing density (house/m²) | -1.776 | -1.181 | -1.787 | -1.293 |
| Characteristics of vulnerable Population     |                   |                            |                      |        |
| Inter-generations                           | Rate of public assistance recipients (%) | 2.720** | 1.340 | 2.976** | 3.257*** |
| Intra-generation                            | Rate of vulnerable population (population aged 65 or above) (%) | 1.811 | 1.343 | 1.929 | 2.637** |

*Statistically significant at the 5% level; ** 1% level; *** 0.1% level

*Dependent variables were converted to logarithms for data stabilization, and independent variables were normalized to change to a common scale without distorting the difference in ranges
on increasing flood damage. The larger the average land area of detached houses, the higher the impact of flood damage ($p < 0.01$). Therefore, we deduced that such flood-vulnerable areas suffer more damage.

In addition, we deduced that the rate of public assistance recipients (Cutter et al. 2003; Rufat et al. 2015) had a significant effect on flood damage ($p < 0.001$). The rate of vulnerable population (population aged 65 years or above) (Cutter et al. 2003; Parker et al. 2005) also had a positive effect on the flood damage in the city ($p < 0.01$). Therefore, it can be said that these flood-vulnerable population have experienced more flood damage.

5 Discussion

In this study, we revealed the flood vulnerability characteristics in consideration of environmental justice and urban disaster prevention plans. Based on Fig. 1, this chapter discusses the policy implications of flood vulnerability and evaluates environmental injustice.

Analysis of the path A in Fig. 2 reveals that the socially vulnerable population, which lack the ability to respond to floods, has suffered flood damage. The impact factor of the rate of public assistance recipients is 3.257, and the rate of vulnerable population aged 65 or above is 2.637. In particular, as the number of socially vulnerable population in Korea is rapidly increasing (see subsect. 2.4), it should be noted that this group will be exposed to flood risk in the future and will not be protected and the damage will be large. The current relief and recovery support system executed by the central government or local government does not consider social equity. For example, in case of flood damage, financial support is provided according to the “Framework Act On The Management Of Disasters And Safety,” but the same is paid without considering social group and individual abilities (30 million won for home loss). Therefore, a relative standard for the socially disadvantaged rather than an absolute standard should be prepared.

As a result of analyzing the path B in Fig. 2, flood damage occurred in the flood vulnerable areas to which the urban disaster prevention plan was not applied. In particular, the impact factor of rate of detached houses having basements was very high at 8.323, which is similar to the hourly rainfall intensity of 9.731, indicating that detached houses having basements are very important planning factor. The impact factor of rate of aged detached houses was 3.781 that also, appeared the second highest. These results support the latest research that building compositions and conditions are important for flood damage prevention (Lin et al. 2021). Furthermore, since cities such as Seoul have limitations (high construction cost, difficulty in installing underground piping and culverts, etc.) in preventing rainfall runoff due to the installation of infrastructure, that reviewing flood protection facilities in relation to the characteristics of aging buildings and buildings with basement levels may be helpful to reduce flood damage, if not the most effective. Therefore, policy makers should aim for construction activities such as removal of semi-basement through new construction/remodeling of vulnerable buildings, improvement of old houses, and installation of flood prevention facilities.

From the point of view of land use, the impact factor of the average area of a detached house is -2.887, and the smaller the site area, the higher the flood damage. In other words, flood damage occurred in low-rise residential clusters. Similar to the results of this study, in a study by Kong (2017) targeting Seoul, the area with a lot of flood damage was multi-family housing, and the average building-to-land ratio and green area ratio were 68.05% and 9.72%, respectively. On the other hand, the area with little damage from floods was
a high-end detached house, with an average building-to-land ratio of 36.67% and a green area ratio of 15.59%. These results indicate that land use vulnerable to flooding is clearly related to the socially vulnerable population. Therefore, it is necessary to consider the possibility that the socially vulnerable population will reside in these areas. Policy makers can contribute to flood reduction by providing infrastructure through residential environment improvement projects and increasing floor area ratio and reducing building-to-land ratio (Lin et al. 2021). It can also protect tenants by making the residence a long-term public lease.

In Fig. 2 by analyzing the path C, the inequality patterns in the flood-vulnerable population path A and flood-vulnerable areas path B were judged to be environmental injustice. The first reason lies in avoiding responsibility for flood risk. At the time of supplying detached houses in lowlands in the 1970s, the business entity was a private sector (Maeng et al. 2016). Private sector has avoided regulations to build housing that are safe from urban flooding because of their development interests (Son et al. 2017). In addition, the government was insufficient in management and supervision, and development was carried out without minimum disaster prevention measures (Koh 2013). Hong (1997) expressed the situation at the time as the deterioration of the residential environment due to the reckless development. There are advanced technologies for flood prevention today, but fundamentally institutional tools are important in flood control (Earles et al. 2009; Godwin et al. 2008).

The second reason is that the socially vulnerable population were not considered in the design of the urban disaster prevention plan. As can be seen from the review (see Sect. 2.3), apartments were the best means to prevent flood damage at that time. All the results of this study support this claim. However, as the supply of apartments proceeded without any measures for the socially vulnerable, it drove them into a more unfavorable environment, resulting in housing instability (Maeng et al. 2016). In Korea, especially in Seoul, housing prices and rents are high because apartments are more preferred than single-family houses or multi-family row houses (Maeng et al. 2016). As a result, the form in which the vulnerable live is an aged detached house or an underground detached house, and it is still a densely populated residential area with a high risk of flooding.

6 Conclusions

The objective of this study was to analyze the flood vulnerability characteristics, taking into account environmental justice and the urban flood disaster prevention plan and to evaluate environmental injustice. A panel analysis was conducted using flood damage data in Seoul from 2000 to 2018. During the observation period, an average of 10,636 (won/m²) of urban flood damage occurred in Seoul.

The rainfall discharge facilities (1.907), detached houses having basements (8.323), aged detached houses (3.781), land area for detached houses (-2.877), public assistance recipients (3.257), vulnerable population aged 65 or above (2.637) were significant flood vulnerability characteristics. What we found through this is that first, the socially vulnerable population was among those vulnerable to flood damage. Therefore, attention should be paid to these high-risk groups as threat of flooding and the resulting damage may increase in the future. Second, low-density residential areas with old and subterranean floors were susceptible to flooding. Further, there is a need to discuss the qualitative performance of the drainage system, or it may not be suitable as a variable. Additionally, it indicates that
reviewing flood protection facilities in relation to the characteristics of aging buildings and buildings with basement levels may be helpful to reduce flood damage, if not the most effective. As residential environment factors, including land use vulnerable to flooding and 3D building composition, were linked to socially vulnerable population, policies that address them should be implemented.

The evaluation of the environmental injustice of the flood vulnerable characteristics revealed that environmental injustice exists. The pattern of inequality, in which flood damage occurred in areas with weak flood disaster prevention plans and among socially vulnerable population lacking flood response capacity, is not justified when focusing on process and production issues. The reason for such environmental injustice was the evasion of responsibility for flood protection by the public and private sector in the process of urban development in Seoul and indifference to the socially vulnerable population.

Our results can contribute to the establishment of an urban disaster prevention plan for the realization of environmental justice by revealing the flood vulnerability characteristics and environmental injustice. For instance, it can provide a reference for building composition and development methods, and the impact factors will be useful in determining policy priorities through flood vulnerability assessment. In addition, it gives the legitimacy of legal and institutional arrangements to support the welfare of the underprivileged.

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Declarations

Conflict of interest The authors declare no competing interests.

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