Flood Vulnerability Characteristics Considering Environmental Justice and Urban Disaster Prevention Plan in Seoul, Korea

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Research Article

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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 urban disaster prevention factors applied to the urban development process in Seoul from the perspective of environmental justice. 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 lacks the ability to respond to floods, but buildings and areas with poor residential environments also suffer from flood damage. This implies that there is 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 prepare a flood prevention plan based on environmental justice paradigm.

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 they have a low capacity to handle disasters (Morse 2008); this is called social vulnerability (Rolfe et al. 2020). Notably, these disadvantaged people are deliberately driven into areas that are 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. Such problems that result in the disproportionate exposure of specific communities of color and socioeconomic status is called "environmental injustice," whereas the solution to this problem is called "environmental justice" (Ban 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 can not 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 the two 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 is 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 risk (Collins et al. 2018). However, only the unbalanced distribution was confirmed, but it did not identify the degree by which different characteristics were affected (Walker and Burningham 2011). In addition, Walker and Burningham (2011), Faber (2008) and others have found that focusing on process and production problems is also has argued strongly that it is necessary. 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, Walker argued that it was not environmental injustice because the rich had the insurance the economic power to reduce their risk.

Therefore, our first research question is—what is the flood vulnerability characteristics considering environmental justice and urban disaster prevention plans? Through this, we can identify various flood vulnerability characteristics and the magnitude of their impacts, and understand them from the perspective of environmental justice. The second research question is—whether the flood vulnerability characteristics are 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 production issues.

The purpose of this study is to analyze the flood vulnerability characteristics in consideration of environmental justice and urban flood disaster prevention plan and to evaluate 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 km^2, 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 occurs 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 km^2 (Fig. 1 a). It has small basins centered on the Hangang River, along with four other rivers (Cheongyecheon, Jungrangcheon, Tancheon, and Anyangcheon), and is also surrounded by mountains (Fig. 1 b). The lowlands (with an elevation lower than the flood level) 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).

2.2 Seoul's urbanization process

The population of Seoul has rapidly increased since the Korean War. According to Statistics Korea, the 1955 census indicated a population level breakthrough 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[1]. 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 Seoul's urban disaster prevention plan

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 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- and low-income citizen 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, respecively (Chancel et al. 2021). Chancel et al. (2021) pointed out, “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 OECD countries, and by the 2050s it will be the oldest country in the OECD (OECD 2019).

Footnote:

[1] 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㎡ according to the Korean Building Act.

3. Materials And Methods

3.1 Research concept and design

Fig. 2 schematically illustrates the concept of the present study on urban flooding. Urban flooding are not simply floods that occur in urban areas. It does not happen when the river crosses the embankment (river flooding) or when a storm surge (coast flooding) comes. 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).

Fig. 2(a) path 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. Fig. 2(b) path is a concept of resource allocation that affects the reduction/increase of flood risk in the urbanization process. This is expressed as a flood vulnerable area. Fig. 2(c) path shows the relationship between the flood vulnerable population due to Fig. 2(a) and the flood vulnerable area due to Fig. 2(b). This relationship represents environmental injustice and is revealed through the distribution pattern of flood vulnerability characteristics Fig. 2(a) and (b) and the justification of Fig. 2(c).

In this study, appropriate variables for Fig. 2(a) and (b) paths are selected and data are collected. After that, an environment prone to flooding is identified and a model that considers temporal and spatial effects is selected and analyzed. Finally, we discuss environmental injustice from the results.

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 following variables were selected in consideration of the disaster prevention plan elements applied to Seoul and environmental justice.

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, 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.

3.3 Data Construction

The unit of analysis for the study is gu, administrative districts under the Seoul Metropolitan Government (Lee and Brody 2018). From 2000 to 2018, 475 samples were obtained from 25 gu in Seoul (25 × 19). The detailed construction process of the variables determined using ArcMap 10.4 is explained below:

2.3.1 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, e).

2.3.2 Variable data construction

The flood damage data of Seoul was collected from the Water Resources Management Information System (WRMIS), 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 system (ASOS) and automatic weather system (AWS) locations, and then, the 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.

3.4 Data Analysis

To determine the impact 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):

$$Y_{it} = \alpha + \beta X_{it} + \epsilon_{it}(but, \epsilon_{it} = \mu_i + \lambda_t + v_{it})$$

where, Y_{it} represents the dependent variable, a is the Y-intercept, β is the slope, X_{it} represents the independent variable, ϵ_{it} is the error term, i represents the individual (1,2, 3, etc.), t is time (1,2,3, etc.), λ_t is the unobserved time effect, and v_{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 damages in lowlands. Setting the model in the panel model is the most important aspect in the process of setting the panel model and estimating the parameter using the data.

In this study, we conducted the Chow, Breusch–Pagan Lagrange Multiplier (Breusch–Pagan LM), and Hausman tests, 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. Notably, we found no variables that would cause significant problems, such as those that cause the standard deviation to become excessively large or relatively small.

In Seoul, large and small-scaled flood damage occurred every year during the observation period. The average flood damage density was 10636 (won/m^2). 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 X^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 X^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 Prob > X^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 Diagnosis of Analysis Model Assumption

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 heteroscedasticity results indicated a value of $p < 0.001$, indicating heteroscedasticity between the regions. 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.

4.4 Selection of Final Analysis Model

In the fixed effect and random effect, they portrayed consistent direction in terms of variables. Considering the model description and the reality of the assumption, as well as the significance of the coefficients, this study concludes that the FGLS model is the most appropriate.

4.5 Flood Vulnerability Characteristics Compared to previous studies

Table 5 portrays the analysis models used in our study and their findings. 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 damages 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 a result contrary to the previous study that the more rainfall discharge facilities there are, the less the flood damage is (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 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 Figure 1, this chapter discusses the policy implications of flood vulnerability and evaluates environmental injustice. The impact factor values shown in Table 5 are the standardized coefficients.

Analysis of the path in Fig. 2(a) 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 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 in Fig. 2(b), 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, it indicates that reviewing flood protection facilities for buildings is more effective than anything in terms of prevention. 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.

By analyzing the pathways in Fig. 2(c), the inequality patterns in the flood-vulnerable population Fig. 2(a) and flood-vulnerable areas Fig. 2(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 have 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 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 purpose of this study is to analyze the flood vulnerability characteristics in consideration of environmental justice and 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 10636 (won/m^2) 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 includes the flood vulnerable population that has suffered flood damage, and in particular, it is necessary to pay attention to the possibility of being exposed to flood risk in the future and that the damage will increase.

Second, low-density residential areas with old and underground floors are flood vulnerable areas. Further, it is necessary to discuss the qualitative performance of the drainage system. Otherwise, it may not be appropriate as a variable. Additionally, in high-density cities, building considerations are more effective at preventing flood damage than traditional stormwater drainage methods such as infrastructure. In particular, because residential environment factors, including land use vulnerable to flooding and 3D building composition, are clearly related to the socially vulnerable, policies that take this into account 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 occurs in areas with weak flood disaster prevention plans and in the socially vulnerable population lacking flood response capacity, is not justified when focusing on process and production issues. The reason for such environmental injustice is 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 example, 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.

Declarations

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Tables

Table 1. Disaster Prevention Plan Elements of Seoul's Lowland Urban Development Plan

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 hazardous areas due to low-lying location and layout	• 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)	• Very high land-use density	

Table 2. Setting and Description of Variables

Classification		Variables (unit)	Description of variables	Data source
Flood damage		Flood damage density (won/ m^2)	Total amount/area	wamis.go.kr
Natural characteristics		Maximum monthly precipitation (mm)	Maximum precipitation value for one hour	data.kma.go.kr
		Maximum hourly precipitation (mm)	Maximum precipitation value for a day	
		Total annual precipitation (mm)	Total annual precipitation	
		Average surface elevation (m)	Average surface elevation	ngii.go.kr
Economic characteristics		Average public land price (won/m^2)	Public land price/ area	data.seoul.go.kr
		Financial independence (%)	Financial independence	
Characteristics of vulnerable area	Infrastructural facility	Density of sewage and rainfall pipes (km^2)	Length/area of sewage and rainfall pipes	me.go.kr
		Density of rainfall discharge facilities (m^3/day/km^2)	Capacity/area of rainfall reserve facilities	
	Buildings	Rate of detached houses having basements (%)	(Houses having basements/ total buildings) x 100	cloud.eais.go.kr
		Rate of aged detached houses (%)	(Houses constructed before 1979/total buildings) x 100	
		Rate of commercial and office facilities having basements (%)	(Commercial and office facilities having basements) x 100	
	Land use	Average land area for detached house (m^2)	Average land area for detached house	
		Housing density (house/m^2)	Units/area of houses	
Characteristics of Vulnerable Population	Inter-generations	Rate of public assistance recipients (%)	(Population of public assistance recipients/total population) x 1,000	sgis.kostat.go.kr
	Intra-generation	Rate of vulnerable population (population aged 65 years or above) (%)	(Population aged 65 years or above /total population) x 100	

Table 3. Descriptive Statistics Table

Classification				Obs.	Mean	Std. Dev.	Minimum	Maximum
Dependent Variable	Flood damage density (won/ m^2)			475	10636.84	41702.13	0	604338.9
Independent Variables	Natural characteristics	Maximum monthly precipitation (mm)		475	143.4272	57.05289	43.74315	301.717
		Maximum hourly precipitation (mm)		475	43.89188	13.10828	21.19491	90.17009
		Total annual precipitation (mm)		475	1227.806	365.5045	351.0723	2015.54
		Average surface elevation (m)		475	57.98456	42.35409	10.86577	157.0912
	Economic characteristics	Average public land price (won/m^2)		475	3230092	1580629	1403536	9326551
		Financial independence (%)		475	45.21403	18.42749	15.641	95.3
	Characteristics of vulnerable areas	Infrastructural facility	Density of sewage and rainfall pipes (km^2)	475	16025.27	4080.04	7670.53	28836.19
			Density of rainfall discharge facilities (m^3/day/km^2)	475	7198.935	8644.417	0	33192.41
		Buildings	Rate of detached houses having basements (%)	475	40.3642	11.67039	12.93693	69.97075
			Rate of aged detached houses (%)	475	14.91072	7.583604	1.47316	29.3681
			Rate of commercial and office facilities having basements (%)	475	16.17292	5.522781	8.96623	35.61539
		Land use	Average land area for detached house (m^2)	475	43.29645	12.30788	23.54663	71.46151
			Housing density (house/ m^2)	475	9.233622	4.042441	2.642455	19.56126
	Characteristics of vulnerable people	Inter-generations	Rate of public assistance recipients (%)	475	20.20431	8.277147	6.176449	50.09058
		Intra-generation	Rate of vulnerable population aged 65 years or above (%)	475	9.56547	3.070755	4.472259	18.02208

*Note: Obs- Observation; Std. Dev.- Standard Deviation

Table 4. Descriptive Statistics Table

Classification		One-way error model				Two-way error model		
		Region specifics		Time specifics		Consideration of both region and time specifics at the same time		
		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 ()		8.352	.3829	2.325		5.064	0.528	
sigma_e ()		2.823	2.823	2.376		2.33	2.333	
rho ( )		.897	.018	.489		0.824	0.048	
	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	
-value		1.11		11.73		1.64		
Prob >		0.3278		< 0.001		0.0206		
Wald			260.50		75.08		585.12	270.68
Prob >			< 0.001		< 0.001		< 0.001	< 0.001
Breusch–Pagan LM			2.43		112.58		0.79	12.43
	Prob >		0.0594		< 0.001		0.1876	0.0114

Table 5. Analysis Models with Results

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	.805
		Maximum hourly precipitation (mm)	9.142* **	7.109* **	9.135* **	9.731* **
		Total annual precipitation (mm)	1.225*	-2.006	1.243*	.725
		Average surface elevation (m)	-.0651	-0.245	-0.007	-.397
Economic Characteristics		Average public land price (won/ m^2)	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 (km^2)	.988	0.546	0.987	.359
		Density of rainfall discharge facilities (m^3/day/ km^2)	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 (%)	.688	0.472	0.579	1.287
	Land Use	Average land area for detached houses (m^2)	-2.365* *	-1.605* *	-2.475* *	-2.887* **
		Housing density (house/□)	-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* *

*Note: OLS- ordinary least squares; FGLS- feasible generalized least squares models

Figures

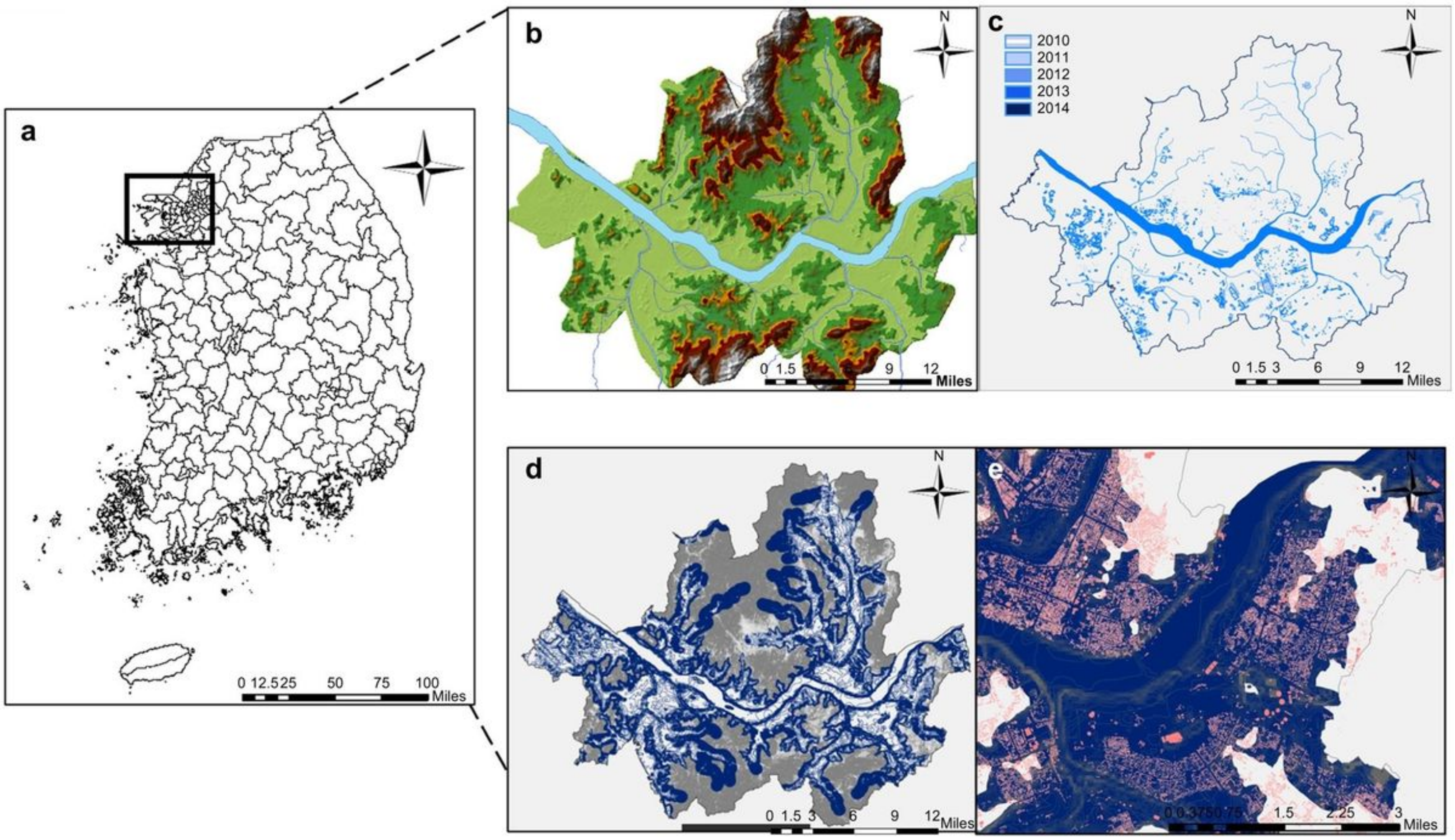

Figure 1

Legend not included with this version.

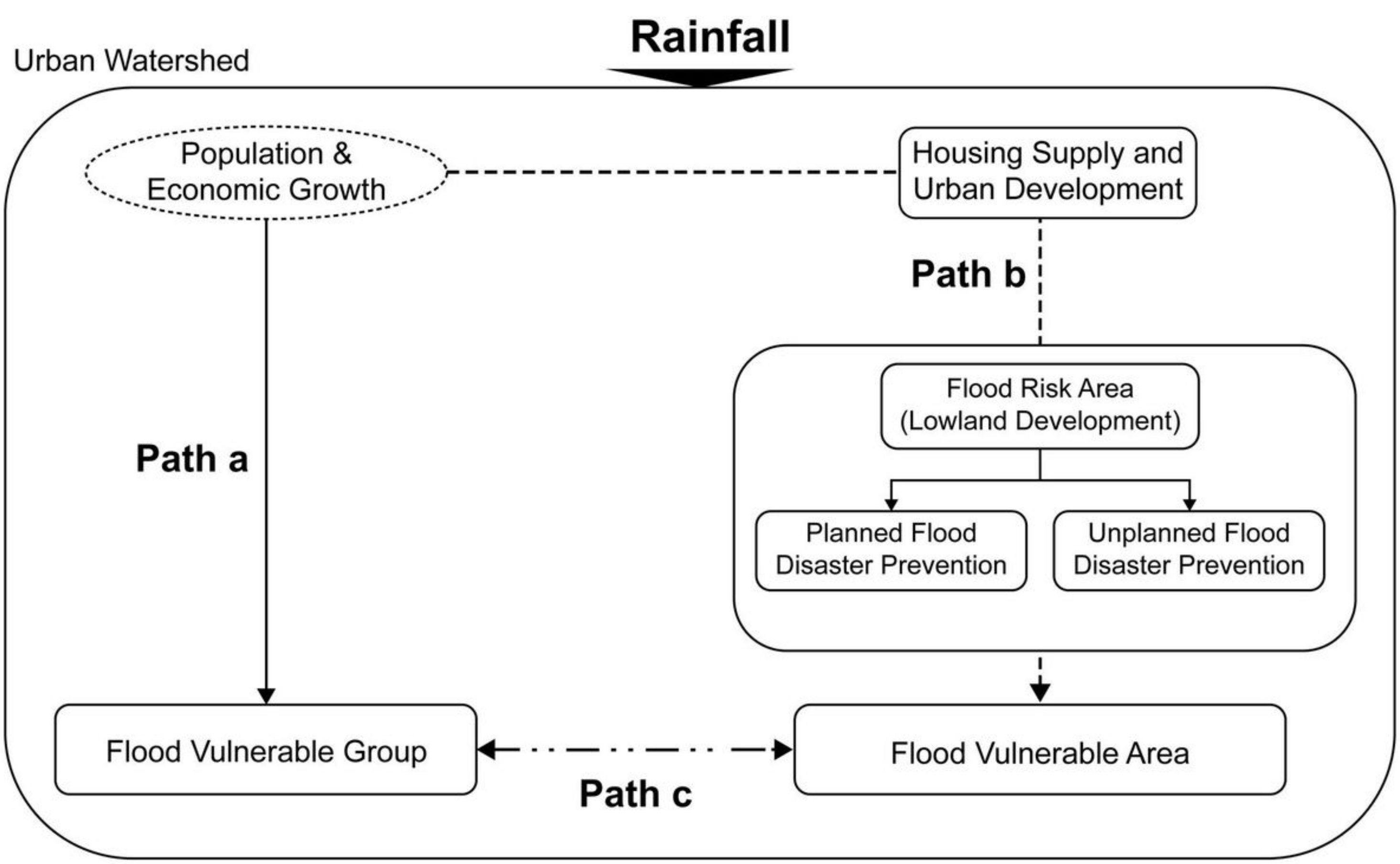

Figure 2

Legend not included with this version.