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Assessing the Impact of Urbanization on Flood Risk by RS and GIS: A Case Study on Istanbul-Esenyurt

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ABSTRACT

Floods, exacerbated by escalating urbanization, pose significant threats to life and property globally. Over the past decade, the Esenyurt district in Istanbul has witnessed a series of floods, highlighting existing flood risks. Rapid population growth in this area and dense urbanization caused by intensive construction increase flood risks. Given these factors, the study focuses on examining the historical impact of urbanization on flood risks, considering spatial and temporal changes. Landsat-8 satellite data, specifically examining NDVI, NDBI, and BU, was employed to detect building imprints and reveal their historical backgrounds for temporal risk calculations. The analysis showed a sudden increase in urbanization rates in 2016, 2017, and 2021. In the flood risk calculations, 2014 data for a return period of 100 years were used and flood inundation depth, economic damages, affected population and depth-damage function were taken into consideration. The results indicate that from 2014 to 2022, increasing urbanization led to a 32.9% increase in the population affected by floods, a 22.3% rise in potential economic damage, and a 13.6% increase in total flood risk. The relationship between flood risks, contemporary urbanization, and its economic dimensions has been evaluated to reduce risks and achieve sustainable cities.

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Highlights:	**Contribution to the field statement:**
- Utilizes Landsat-8 satellite data within the HVE (Hazard, Vulnerability, Exposure) framework to evaluate the impact of urbanization on flood risk in Istanbul's Esenyurt district. - Employs remote sensing and GIS technologies for a detailed historical analysis of urban development and its correlation with increased flood vulnerability. - Highlights the critical role of urban planning in mitigating flood risks, emphasizing the need for sustainable urban development strategies. - Provides a comprehensive data-driven approach, underlining the socio-economic consequences of rapid urbanization on flood risk management.	The study uniquely combines remote sensing (RS) and geographic information systems (GIS) to explore the relationship between urbanization and flood risk in Istanbul's Esenyurt district. Using Landsat-8 satellite data within the HVE (Hazard, Vulnerability, Exposure) framework, it documents the significant impact of urban expansion on increasing flood risk, evidenced by a considerable rise in the affected population and potential economic damages between 2014 and 2022. This work not only sheds light on the historical development and flood vulnerability nexus but also serves as a critical reference for formulating urban planning and flood mitigation strategies, contributing significantly to the discourse on economic dimensions of sustainable urban development.

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1. Introduction

Over time, the correlation between rainfall and water flow has undergone extensive changes, mainly due to the increase in urbanization. The effects of urbanization result in anomalies in the urban water cycle, influencing various factors and causing urban floods. The Emergency Events Database reveals that the averages for flood occurrences, loss of life, and economic damage from 2002 to 2021 were significantly lower than those recorded in 2022. This change suggests an increase in the frequency and severity of floods from 2022 onwards. The trend of rising flood incidence across the globe is notable, and Turkey is no exception to this trend. According to the 2017 data from the General Directorate of Water Management, Republic of Turkey Ministry of Agriculture and Forestry, the comparison between the periods 1975-2002 and 2003-2015 demonstrates a 1.5 times rise in flood incidences (General Directorate of Water Management, 2017:25).

Metropolitan areas with high population densities are particularly vulnerable to increased flood risk because floods have significant and complex consequences in terms of damage and loss of life. In this context, the increasing flood risk associated with expanding urbanization and rapid development has become a significant concern for cities. Therefore, this study aims to evaluate the flood risk due to urbanization historically. Thus, the effects of increasing urbanization on flood risk were evaluated in the framework of economic damage and population affected by floods.

Population growth in urban areas has led to an increase in natural disasters, with floods being the most frequent occurrence (Li et al., 2022). The primary cause of flood is a significant change in the water cycle within cities, which has been exacerbated by urban expansion, a rise in population density and the prevalence of artificial surfaces. This situation can lead to flood depending on various factors in the water cycle, which is a highly complex system.

Urbanization has a complex impact on a range of factors that influence the water cycle, resulting in intricate relationships. For example, a study conducted by Verbeiren et al. (2013) demonstrates that increased impervious surfaces lead to higher peak discharges. Additionally, Huang's (2019) study highlights that urbanization not only raises flow volume but also accelerates flow velocity, reaching its peak more rapidly. Impermeable surfaces have significant effects on crucial hydrological parameters including surface runoff velocity, magnitude, and volume as evidenced by the studies conducted by Salvadore et al. (2015), Walsh et al. (2005), and Dams et al. (2013).

Figure 1 shows a hydrograph that demonstrates changes in discharge over time as a result of urbanization. The process of urbanization involves a change in land use, in particular an increase in impervious surfaces such as built-up areas and asphalt roads. These surfaces replace natural and green spaces, leading to decreased permeability. Residential areas often have over 50% impermeable surface, whereas industrial areas can reach 70-80% (Salvadore et al., 2015). The composition and extent of such impermeable surfaces have a significant impact. This change leads to a decrease in evapotranspiration and an increase in soil infiltration, causing precipitation to convert into surface runoff. As a result, the runoff rates, volume of surface runoff (Salman and Li, 2018; Chen, Xie, and Xu, 2019), and peak flow due to urbanization intensify (Huang, 2019; Miller et al., 2014; Du et al., 2012; Li and Wang, 2009).

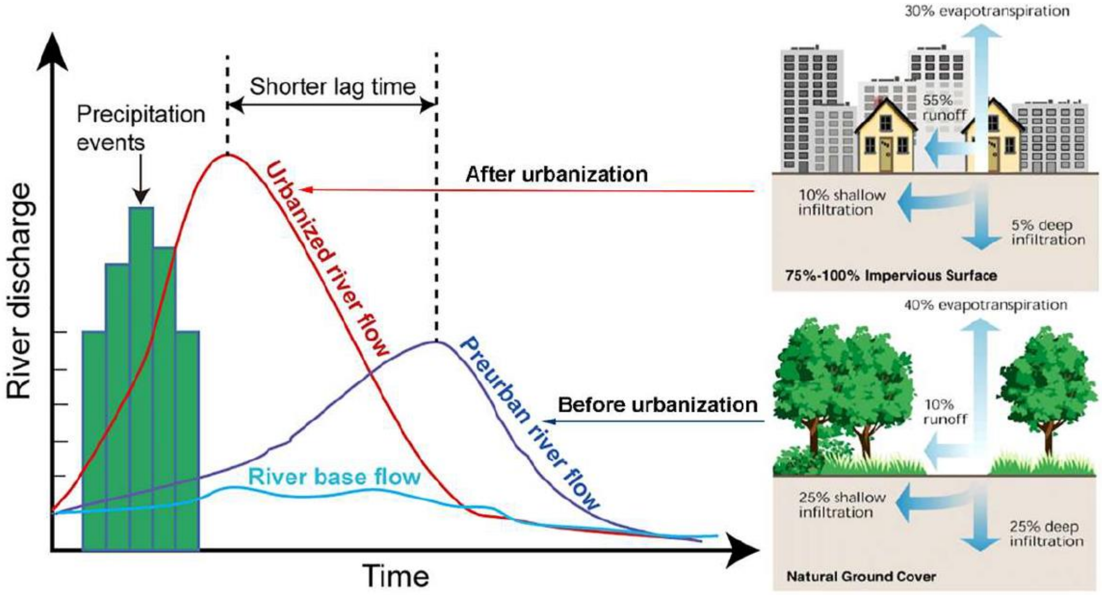

Figure 1. Impacts of urbanization on the surface on hydrological parameters (Ding, Wu, Tang, Chen, and Xu, 2022).

The imbalance created by all interrelated parameters causes a flood. Flood risk analysis is necessary to identify these relationships, but there are differences between flood risk analysis studies conducted in the context of urbanisation due to the framework, scale, method or components of flood risk.

Flood risk is generally expressed in the literature as "Risk = Hazard×Vulnerability×Exposure". Studies adopting the Hazard, Vulnerability and Exposure (HVE) framework highlight the significance of incorporating exposure into flood risk assessments (Aerts et al., 2018; Kron, 2005; Field et al., 2012). The main focus of exposure analysis is to evaluate individuals and property (Field et al., 2012), which have a critical impact on flood risk. Díez-Herrero and Garrote (2020) conducted a bibliometric analysis using the main keywords ‘flood risk analysis and assessment’ and showed that population and land use were the factors frequently considered in exposure analysis in the studies reviewed. This is because the effect on population and assets depends on land use trends. Therefore, exposure analysis is particularly important in urban areas with high population densities and rapid land use alterations. This framework provides a comprehensive and systematic approach to understanding and addressing flood-related issues, hence the use of the HVE framework in this study.

Flood risk analysis studies within the scope of urbanization were examined in the literature. The study by Luino et al. (2012) focused on the town of Alba in Italy, known for its industrial areas along a river. Despite structural measures, flood risk increased from 4% to 48% between 1852 and 1994, indicating a correlation between historical development, urbanization, and flood risk. Urbanization-induced changes in Land Use/Land Cover (LULC) were found to elevate flood risk, as shown by studies in Surat City, India, and East Ern Jeddah, Saudi Arabia (Waghwala & Agnihotri, 2019; Bahrawi et al., 2020). Changes in city density, LULC, and urban area alterations impact the water cycle, necessitating a combined assessment of hydrological processes and land use. Because the study concluded that changes in LULC caused by rapid urbanization increase the risk of flood. Studies, such as Nguyen et al. (2021), analysing the Tra Khuc River basin in Vietnam, integrated urban flood risk, land use, and hydraulic modelling. The Analytic Hierarchy Process method assisted in building-based flood risk evaluation, providing spatially detailed risk maps. Zope et al. (2016) observed a 6% increase in flood-prone areas in a Mumbai urban basin due to rapid urbanization between 1966, 2001 and 2009. Mustafa et al. (2018) projected a 5.5% to 11% increase in flood risk every decade from 2030 to 2100 in Belgium, factoring in 24 urbanization scenarios. In northern Vietnam, Do et al. (2022) used remote sensing and GIS to identify a 43% urban intensity increase over 35 years. Flood risk assessment demonstrated higher risk in intensely urbanized areas, emphasizing the importance of the extent and intensity of urbanisation. Research in Istanbul's Esenler district by Nigussie and Altunkaynak (2019) utilized the SLEUTH (Slope, Landuse, Excluded area, Urban extent, Transportation and Hillshade) model for urbanization modelling. Dense development scenarios resulted in increased flood areas and, consequently, heightened risk. Yu et al. (2021) applied the HVE perspective to flood risk in Ulsan Metropolitan City, Korea. They conducted a high-resolution building-based flood risk assessment, emphasizing the importance of facility use and concentrations in risk calculations. It was determined that the risk is high especially when urban development is rapid around the river, but there is no risk in planned settlements. Handayani et al. (2020) highlighted that poorly planned urbanization contributes to increased flood-prone areas in Indonesia, emphasizing the need for urban plans considering flood risk amid population and infrastructure growth (Mustafa et al., 2018).

Changes in land use and rapid urbanisation have an impact on the water cycle, leading to research that examines both hydrological processes and urbanisation simultaneously. Diverse investigations conducted in Vietnam, India, Indonesia, and Belgium have examined the consequences of urbanization scenarios on flood risk, revealing a progressive rise in risk levels. Case studies in Northern Vietnam and Istanbul have demonstrated the manner in which the degree of urban expansion influences flood risk. The incorporation of remote sensing and geographic information technologies has provided valuable insights into evaluating flood risk in urban areas. In brief, urbanization without adequate attention to flood risk leads to the expansion of flood-vulnerable regions and emphasises the critical importance of urban planning in mitigating flood risks and economic damages.

Urbanization, flooding and the economic impact of flooding are three important interrelated factors. Understanding these relationships is critical for the creation of sustainable and resilient cities. Although the economic evaluations vary according to the aim, the damage to settlements in urban floods causes economic damage (Merz et al., 2010). This damage may occur in residential areas, commercial areas, infrastructure and other urban function areas. When urban planning is used effectively, loss of life, physical damage and economic damage arising from possible floods are minimized. In addition, after urban floods occur, improvement and risk reduction efforts for future floods have an economic impact. These efforts may include various measures such as infrastructure projects, water management plans and emergency preparations. Thus, ensuring the balance between urbanization and flood risk and managing the economic relationship is critical to ensure sustainable urban development.

In this study, a site-specific methodology was applied in order to present the flood risk historically. This methodology includes elements such as analyzing past flood events, determining economic damage, and analyzing the affected population. This process aims to show how flood risk evolves and increases in the process of urbanization, highlighting the importance of urban planning. The economic perspective emphasises that urban planning strategies should address not only the physical infrastructure but also the sustainability and resilience of the economy. The findings suggest that urban planning plays a critical role in determining strategies to cope with flood risk. Consequently, this study emphasises the importance of urban planning as a key component to understanding flood risk in urban areas from a historical perspective and to effectively mitigate these risks.

2. Materials and Methods

The research methodology comprises two interconnected components for calculating flood risk that centres around buildings over time (Figure 2). The first step is to identify buildings that have been affected by floods. The second step is to determine the flood risk by following the methodology used in Flood Management Plans using the identified buildings. These components are not isolated, but rather they are interlinked and reinforce each other. The two components of the methodology are described in detail in sections "2.1.2 Background Analysis of Buildings" and "2.1.3 Flood Risk Methodology".

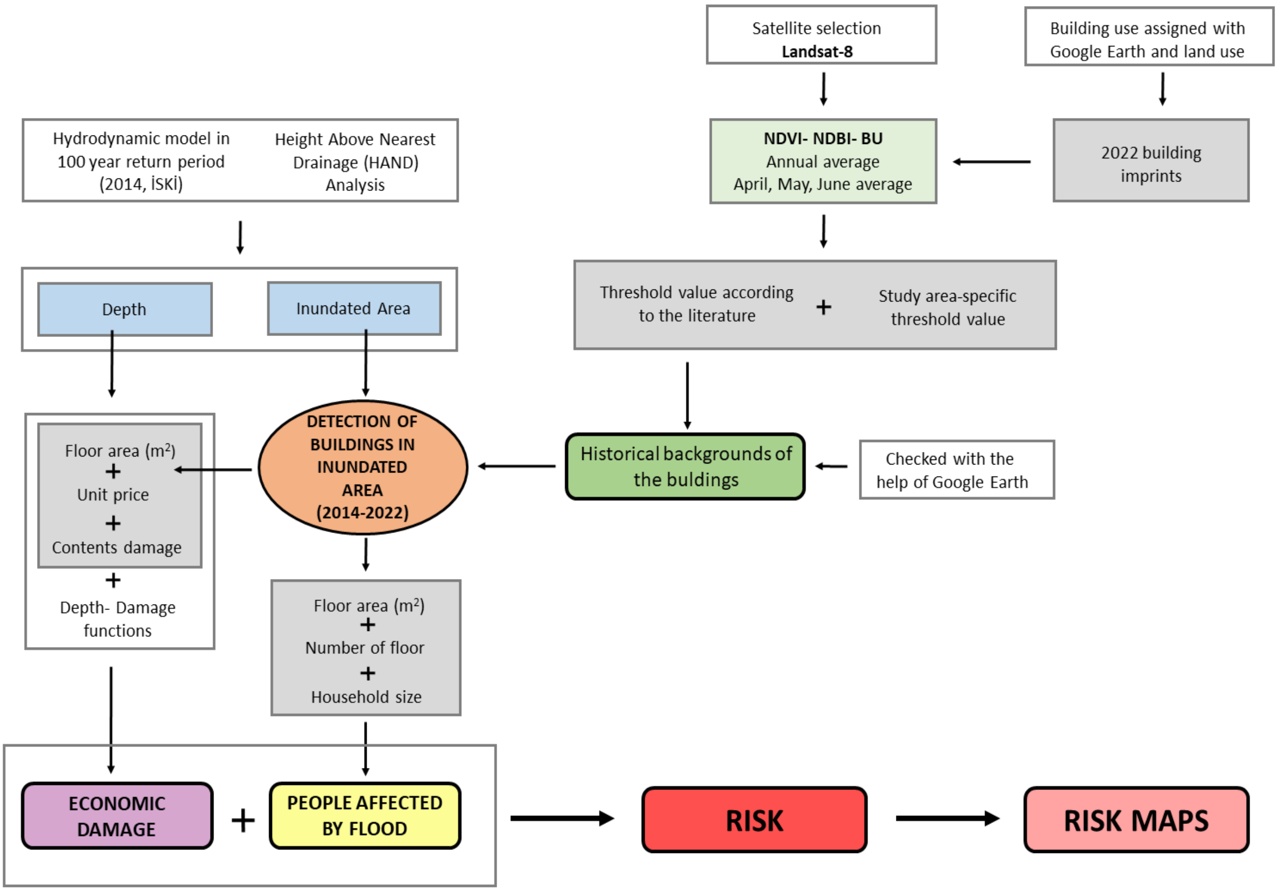

Figure 2. Study methodology flow diagram.

2.1.1 Study Area

The Esenyurt district of Istanbul province was chosen for the purpose of the study. The reasons for the selection of this study area are as follows:

- It is the most populous district of Turkey with a population of approximately 1 million.
- When the population changes in the past years are examined, rapid population increases have been observed.
- There is a dense coexistence of industrial and residential areas.
- In 2022, the flood disaster that occurred in Esenyurt caused a loss of life.

The study area, Esenyurt, is located on the European side of Istanbul and is bordered by the Trans-European Motorway (TEM) and D-100 highway, which are major transport arteries (Figure 3).

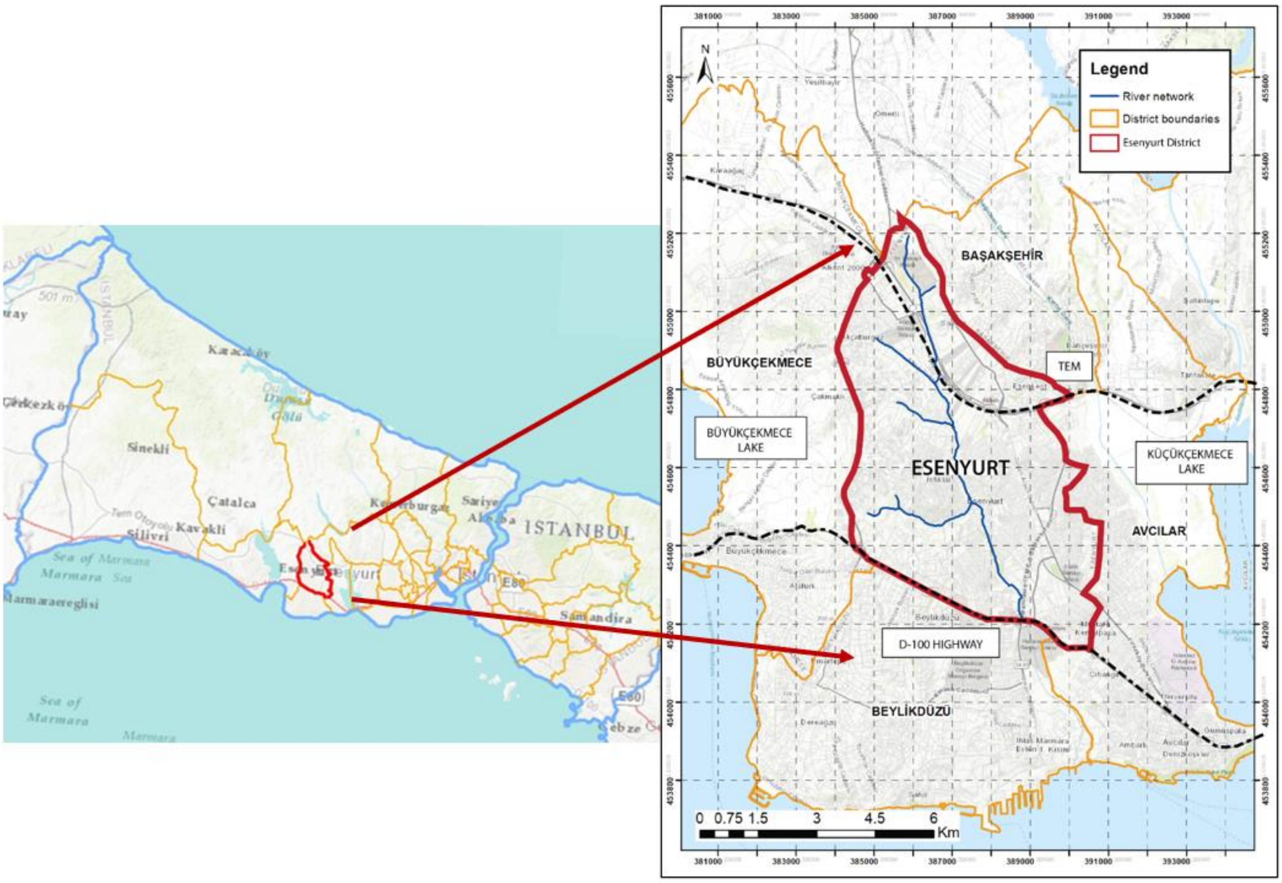

Figure 3. Esenyurt district in Istanbul.

In 1970, Esenyurt was a village with a population of 2,066, dominated by agriculture and livestock (URL-5). According to Ayhan's (2019) research into the population growth of Esenyurt, the strategic location of the area in Istanbul led to the development of industrial zones in the 1980s. Accordingly, the population increased and reached 7,180 in 1980 (URL-5). Within 10 years, mass housing constructions started, and the population of the district became 72,519 due to cheap land prices and the relocation of industrial facilities outside the city (URL-5). In the 2000s, rapid and unplanned settlement was experienced, and the population was 173,198 in 2000 (URL-5). In 2008, it gained district status, and in these years, both industrialisation and vertical construction accelerated. After 2008, although the population growth rate in the district varied, it continued to show a continuous upward trend. Today, it is the most populous district of Turkey and Istanbul with a population of approximately 1 million. The population of the district was 983,571 in 2022, constituting 6.18% of Istanbul's population (URL-2). While it was a village dominated by the agriculture and livestock sector with a population of 2,066 approximately 50 years ago, today it has turned into a district with high density consisting of industrial and residential areas.

Another important feature of Esenyurt district is the Haramidere River passing through the centre of the district. Haramidere is a river that originates in Esenyurt district and forms a catchment of approximately 47.5 km^2. The river passes through important main arteries (TEM and D-100 highway), densely populated residential areas and industrial zones. Esenyurt district constitutes the majority of the basin (74.1%) and when the floods occurring in this river were analysed, it was seen that all of them occurred in Esenyurt district. For these reasons, the part of the Esenyurt district affected by the Haramidere River was determined as the study area (Figure 4). In addition, the presence of both industrial and residential areas in the study area was useful in determining the risk change in areas with different characteristics.

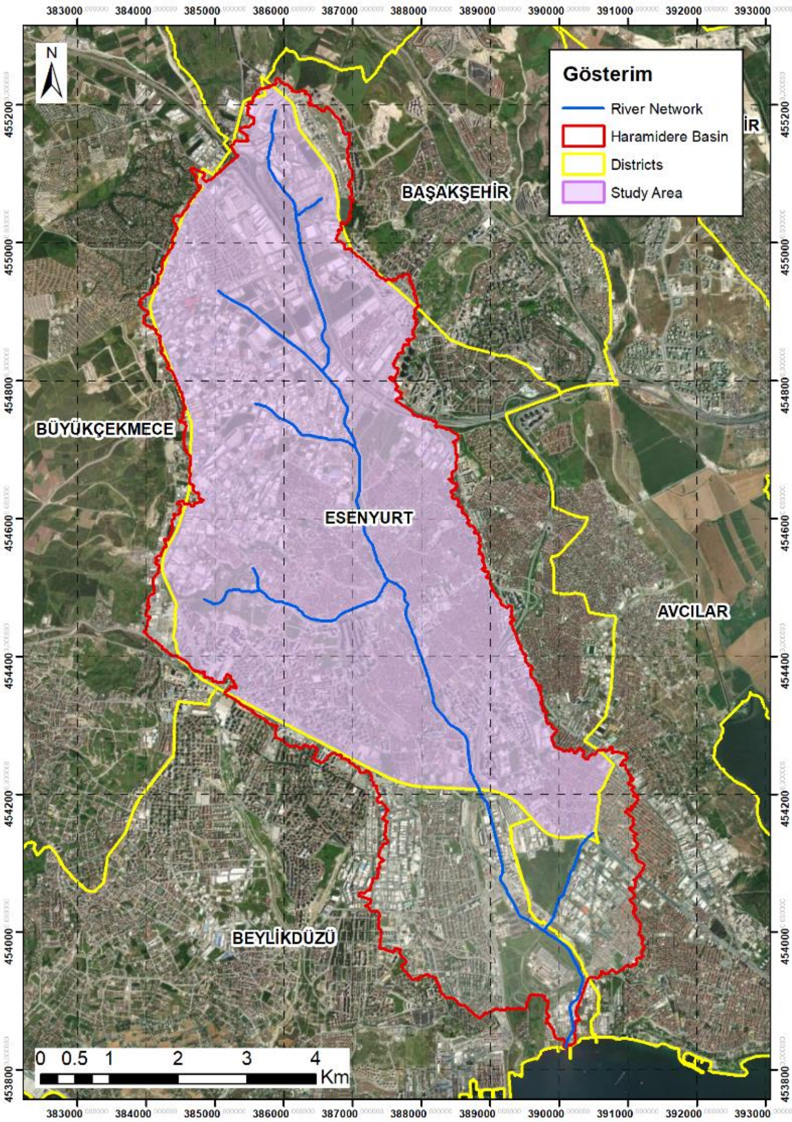

Figure 4. Study area.

2.1.2 Background Analysis of Buildings

To carry out the flood risk on a building-specific and historical basis, it is necessary to identify the buildings in different years. For this reason, in this study, the past conditions of the buildings were determined by remote sensing techniques. The following criteria were determined for the use of these techniques:

- Satellite data should be compatible with the historical time range (2014-2022).
- It should take measurements at least once a month in terms of temporal resolution.
- It should have bands that allow water, green areas, and soil to be distinguished.
- It should have the highest possible spatial resolution (<30m).

There are several methods in the literature to distinguish between water, vegetation and soil, which is one of the basic requirements. One of these methods is the separation of different wavelengths. The NDVI, NDBI and BU indices were used in this study to distinguish wavelengths from each other and to distinguish buildings from other components. NDVI is assumed to decrease when a previously vegetated area becomes a built-up area, while the other two indices, NDBI and BU, are assumed to increase in the opposite way. In order to calculate the indices, satellites with bands for Visible Red, Near Infrared (NIR) and Short-Wave Infrared (SWIR) wavelengths are needed. The selection of satellites was made according to the criteria established for the indices, and as a result of the comparison of satellites, the Landsat-8 satellite was considered to be the most suitable satellite.

The vegetation and construction of the buildings in the flooded area were analysed. The aim was to retrospectively determine the years of construction of the buildings. The aim was to determine the values used in the classification of these indices in relation to the years of construction of the buildings. For this purpose, the thresholds of the indices were determined that would distinguish the buildings from the ground and green areas.

Google Earth Engine (GEE) scripts were used to process the Landsat-8 library in this study. Instead of downloading each data individually, all analyses were conducted on the GEE platform. The dataset used is specifically named "LANDSAT/LC08/C02/T1_L2" and provides atmospherically corrected surface reflectance and land surface temperature derived from Landsat 8 OLI/TIRS sensors (Google-GEE, 2023). Images with more than 20% cloud cover were excluded from the study. In addition to annual averages, three-month averages for April, May and June, representing periods of dense vegetation, were examined to eliminate the influence of snow or ice. NDVI, NDBI and BU calculations were performed on 1,051 building polygons within the 2022 flood zone. For each building, both annual and three-month (April, May, June) averages of NDVI, NDBI and BU were calculated for the years 2014-2022. The calculations were carried out in four basic stages:

1. Identification of the years with breaks in the index values using the cumulative percentage of the annual averages and the months covering April-May-June for the respective year in the time series.
2. Subsequently, thresholds for buildings based on the NDVI classification obtained from the literature were examined.
3. Considering possible variations in the dynamics of the study area, specific building thresholds for the area were determined. This involved taking the lower and upper index values (NDVI, NDBI and BU) calculated for all buildings in the study area since 2014 as the building threshold. The years outside these values were then identified for buildings constructed after 2014.
4. Validate the results for some buildings within the inundated area using historical Google Earth imagery and compare with the results from the first three steps to determine the most appropriate method.

As a result, years of construction were determined for buildings within the inundated area that were classified into three main categories: “residential, commercial and industrial”. In this way, the buildings in the study area and the construction thresholds for each of these buildings were determined (Figure 5).

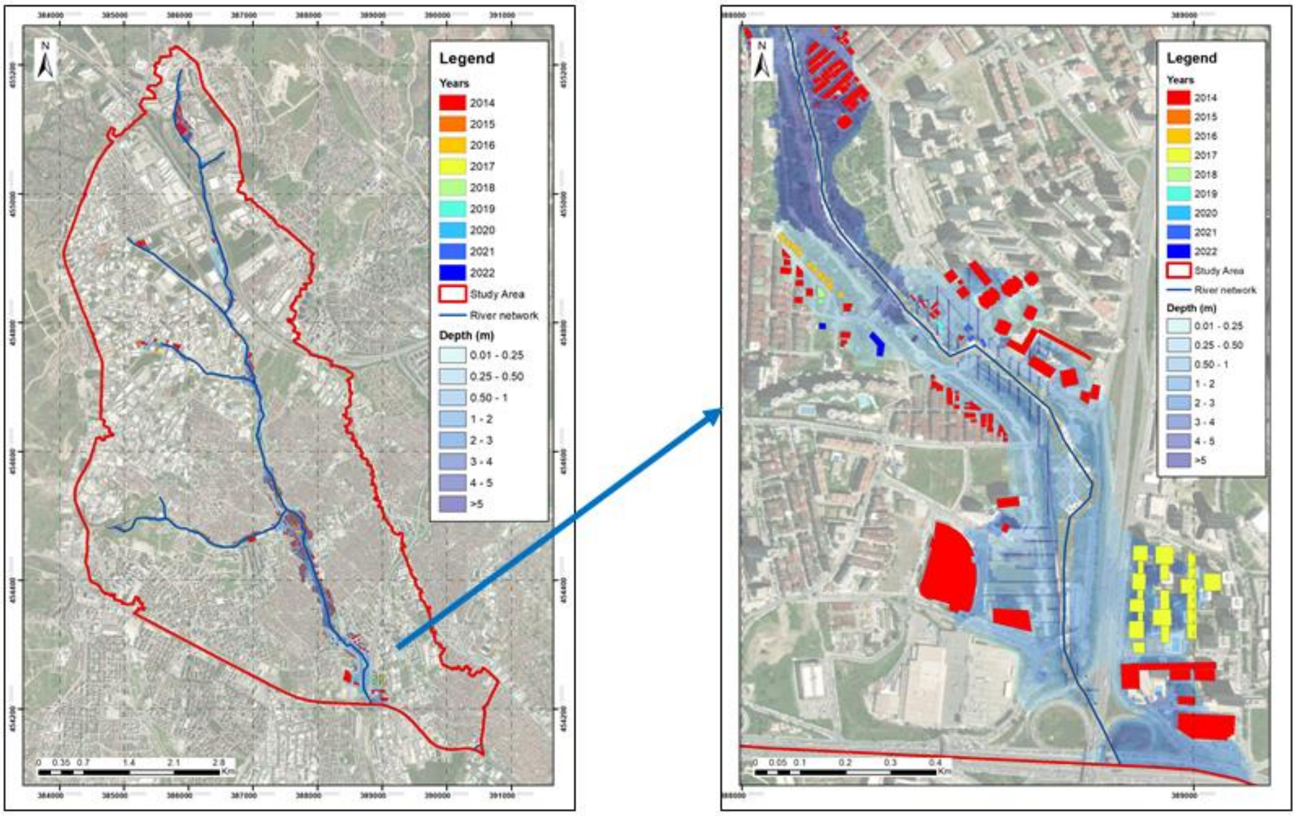

Figure 5. Construction years of the buildings.

2.1.3 Flood Risk Methodology

For flood risk assessment, the primary focus was on hazard analysis, determining the inundated area and inundation depth. The flood modelling project conducted by İSKİ (Istanbul Water and Sewerage Administration General Directorate) in 2014 in the Haramidere Basin served as the basis for identifying flood areas. This project used 1 and 2-dimensional hydrodynamic models for flood simulations. Hydrological and hydrodynamic studies were carried out for return periods of 25, 100, and 500 years, calculating the maximum discharge (Qmax) for each return period. The results of these studies provided information on flood-inundated areas and inundation depths for each return period. Inundation depth and inundated area results of the 100-year return period were used since the use of the 100-year return period would give more realistic results in risk calculations.

This study is based on the inundated area and inundation depth corresponding to the 100-year return period in the project carried out in 2014. It is assumed that no rehabilitation works have been carried out in the stream since 2014 and that the inundated areas and inundation depths have remained constant. The inundated areas (1.54 km^2 in total) and depths of inundation have been digitised for use in the risk calculation. For these reasons, historical risk assessments were made from 2014 to 2020.

In this study, the methodology applied in the Flood Management Plans by the General Directorate of Water Management, Republic of Turkey Ministry of Agriculture and Forestry was used for risk analyses.

The number of people affected by the flood was calculated based on the buildings identified in the "Background analysis of buildings" section. One of the important assumptions is that everyone in the inundation area will be affected regardless of the water depth. While calculating the affected population risk, household size of 3.43 people and night population were taken as basis (URL-10). When economic damage is analysed, it is seen that the methodology emphasises that economic damage has a linear relationship with depth damage. Traditionally in the literature, damage is associated with the depth of flood. It is based on the linear relationship between depth and damage (Chinh, Dung, Gain, & Kreibich, 2017; Pistrika, 2010). It is assumed that damage is greater in areas with greater depth. In this sense, the methodology and literature are compatible with each other.

To determine the economic damage, the following formula was calculated separately for each building.

$Z = DR \times A \times BF \times 0.6 \times 0.5 \times 1.18$………………………………………………………………...(i)

Z: Economic damage value (TL)

DR: Depth- damage function value

A: Floor area of building (m^2)

BF: Unit price of building (TL/m^2)

To compute flood risk using the provided formula, the initial step involves establishing the depth-damage relationship. This relationship is derived from flood data, specifically inundation depth, and economic damage data from historical events. However, due to the limited availability of comprehensive flood-related data in Turkey, the methodology referred to as "Global flood depth-damage functions," outlined by the Joint Research Center (JRC) in 2017, was adopted (Huizinga et al., 2017). These depth-damage functions were formulated separately for each continent, and the values designated for Europe were applied within the methodology. Consequently, the value of damage function value was determined for each building type and corresponding depth.

In the formula, the parameter called "BF", which represents the building unit cost, plays a crucial role in determining economic damages. This signifies the economic valuation of one square meter of building. The building costs used were taken from the publication "Announcement on Building Approximate Unit Costs to be Used in the Calculation of Architecture and Engineering Service Fees for the Year 2022/3", issued by the Ministry of Environment, Urbanization and Climate Change. The values have been specifically chosen to suit the context of our country (URL-11). This document was used to determine construction costs, which vary according to factors such as the type of residential building, the number of floors, the height of the building, the number of floors in industrial buildings and the type of production. In order to prevent the risk value from being affected by inflation, the values for 2022 are taken as fixed for the cost of each year.

The majority of depth-damage curves are reported to approach a value of 0.60. Irrespective of the water height, 40% of structures remain undamaged by the flood, and this portion should be excluded from maximum damage calculations (Huizinga et al., 2017: 55). Consequently, the undamaged segment of buildings was taken into account in damage calculations and adjusted by a factor of 0.60.

It is recommended to include a depreciation factor in damage assessments, considering the reduction in the value of buildings over time (Huizinga et al., 2017: 54). Different countries have modified the maximum damage value of buildings by introducing coefficients ranging from 0.50 to 0.63 in these assessments. In the methodology used, this coefficient is fixed at 0.50. In the methodology used, this coefficient is fixed at 0.50. As the approximate unit cost of buildings does not include VAT, the calculated damage value has been adjusted by multiplying it by 1.18.

The economic damage values discussed earlier specifically concern damage to buildings and do not encompass damage to contents. The computation of contents damage adheres to the approach outlined by Huizinga et al. (2017), linking contents damage to building damage. To be precise, contents damage is calculated as 50% of building damage for residential areas, 100% for commercial areas, and 150% for industrial areas.

In accordance with the methodology, the calculation of the total flood risk is based on normalized values for economic damages and affected population. The provided formula was used to normalize the data. As a result, the economic damage and affected population values for each building were transformed to be in the range of 0 to 1.

Total Risk = 0.5 × Economic Risk (0-1) + 0.5 × Population Risk (0-1)……………………………..(ii)

Once the calculation has been performed, the final flood risk is determined for each building. The overall risk assessment takes into account both economic and population factors. As a result, the resulting risk assessments provide a holistic result by considering not only physical damage but also the population.

3. Results and Discussion

The building-based risk analysis under high urbanization was carried out in two steps: background analysis and risk analysis of buildings from satellite imagery. Together with the background analysis of buildings, buildings were analysed historically according to their type of use (Table 1). When analysing the change from 2014 to 2022, the number of buildings increased continuously; residential buildings increased by 12.9%, commercial buildings by 8.6%, industrial buildings by 32.2% and total buildings by 13.9%.

Table 1. Buildings in the flood-inundated area.

Years	Number of buildings						
	Residential		Commercial		Industrial		Total Building
	Building	%	Building	%	Building	%	
2022	935	89.0	78	7.4	38	3.6	1,051
2021	929	88.4	75	7.1	38	3.6	1,042
2020	929	884	71	6.8	38	3.6	1,038
2019	927	88.2	71	6.8	38	3.6	1,036
2018	927	88.2	70	6.7	38	3.6	1,035
2017	918	87.3	69	6.6	38	3.6	1,025
2016	867	82.5	65	6.2	36	3.4	968
2015	835	79.4	61	5.8	36	3.4	932
2014	828	78.8	59	5.6	35	3.3	922

The economic damage and the population affected by the flood were calculated for each building. The population affected was calculated on the basis of the use of the building, the number of floors and the floor area of the buildings, determined by years. Based on the results, the number of individuals affected in 2022 is 50,407 (Table 2). This represents an increase of 12,471 people and an increase of 32.9% compared to the 2014 figures. Although there is a steady increase in the number of people affected by floods until 2022, it is seen that the growth rate decreases when compared to the total population of Esenyurt district. This is due to the significantly higher population growth rate in the Esenyurt district.

Table 2. People affected by flood.

Years	People affected by flood	Population of Esenyurt district	The ratio of the population affected by the flood to the district population (%)
2022	50,407	983,571	5.1
2021	49,646	977,489	5.1
2020	49,646	957,398	5.2
2019	48,521	954,579	5.1
2018	48,521	891,120	5.4
2017	48,198	846,492	5.7
2016	40,282	795,010	5.1
2015	38,677	742,810	5.2
2014	37,936	686,968	5.5

At the end of the applied process, the economic loss of each building was calculated by taking into account the number of floors, building height, floor area and unit cost according to the building use. These calculations for all years are given in Table 3. Between 2014 and 2022, there was a significant increase in economic damage to residential buildings, reaching around 90 million TL and contributing 11.6% more to the total damage. Commercial buildings experienced an increase in economic damages of around 30 million TL, increasing their share of total damages by 4.2%. For industrial buildings, it increased by approximately 18 million TL, up by 2.4%. The total damage during the period 2014-2022 showed an increase of approximately 143 million TL. Specifically, the economic damage in 2022 showed a notable increase of 22.3% compared to the figures recorded in 2014. It was found that the majority of the economic damage occurred in residential buildings. The reasons for the damage to houses are as follows:

- Increased urbanization and the establishment of residential areas close to riverbeds.
- Increase in the density of residential areas in existing settlements.
- High-rise buildings and therefore high unit costs of residential buildings constructed in recent years.

Although the number of industrial buildings is high, the economic damage caused by them is less than that caused by commercial buildings. The reason for this is that industrial buildings tend to be single-storey and have relatively low approximate unit costs, whereas commercial buildings tend to be multi-storey and have high approximate unit costs.

Table 3. Economic damage values (2014 - 2022).

Years	**Economic Damage (TL)**						
	Residential		**Commercial**		**Industrial**		**Total**
	TL	%	TL	%	TL	%	
2022	434,488,988	55.6	202,981,662	26.0	144,573,498	18.5	782,044,148
2021	431,715,832	55.2	202,981,662	26.0	142,358,106	18.2	777,055,600
2020	431,715,832	55.2	202,981,662	26.0	140,802,139	18.0	775,499,633
2019	427,128,864	54.6	202,981,662	26.0	140,802,139	18.0	770,912,665
2018	427,128,864	54.6	202,981,662	26.0	140,288,118	17.9	770,398,644
2017	422,935,273	54.1	202,981,662	26.0	135,598,661	17.3	761,515,596
2016	370,137,872	47.3	182,956,149	23.4	133,669,714	17.1	686,763,735
2015	352,077,976	45.0	182,956,149	23.4	130,919,358	16.7	665,953,484
2014	343,124,144	43.9	170,183,638	21.8	126,089,445	16.1	639,397,227

For each building, flood risk from both damage and population was calculated and risk maps were created at five risk levels (very low, low, low, medium, high and very high) in ArcGIS program. Within the scope of the study, the risk of all buildings was calculated and divided into zones (Figure 6). Maps of prominent examples within these zones were given (Figure 7, Figure 8, Figure 9, Figure 10).

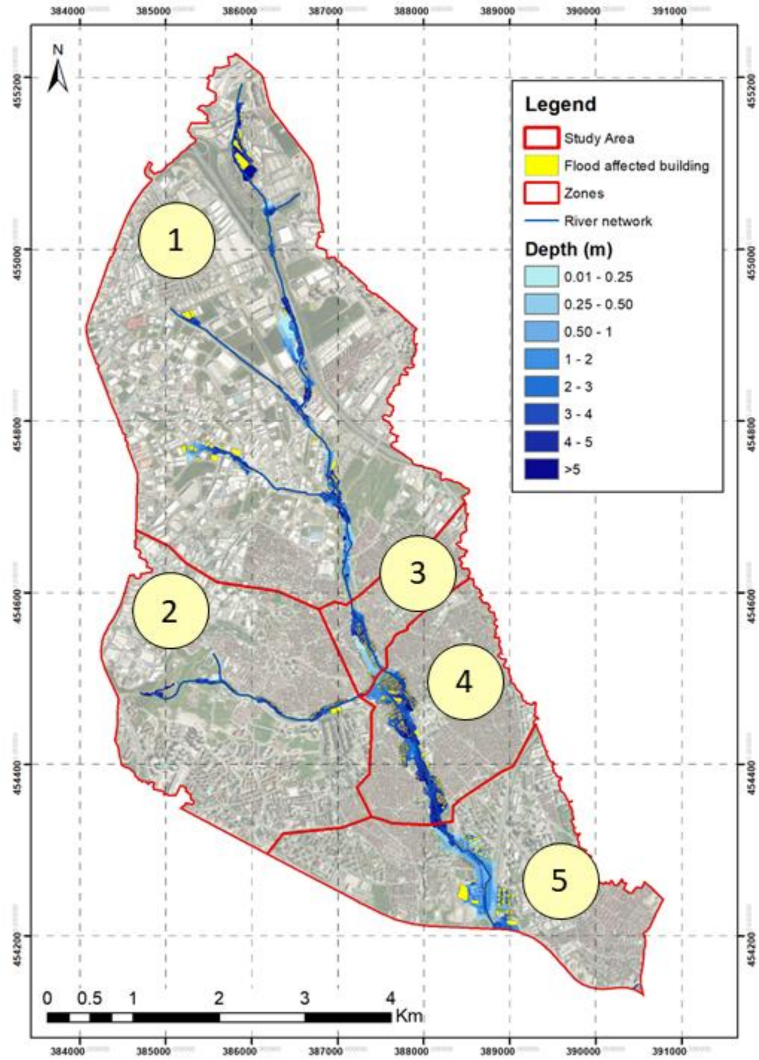

Figure 6. Study area zones.

According to the given maps, in Zone-2 (Figure 7 and Figure 8) residential buildings were constructed after 2014 at a distance of about 20 meters from the river and are classified in the "medium" risk category. In Figure 7 and Figure 8, there are 2 industrial buildings in the "high" risk category and both of them are single-storey buildings. Except for these industrial buildings, all other buildings are residential and categorised as "low" and "very low" risk. Therefore, depending on the depth of the risk classes, the importance of floor area, number of storeys and building use in risk classification becomes prominent. It also occurred in Zone-4 given in Figure 9 and Figure 10. After 2014, residential buildings were constructed approximately 50 meters from the river and were categorised as "very high" risk depending on the number of storeys and floor area of the building.

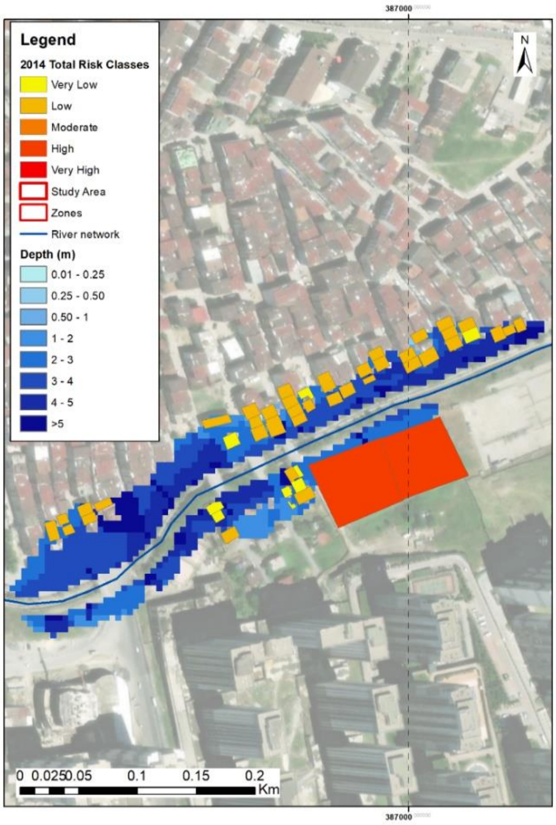

Figure 7. Flood risk map for Zone-2, 2014.

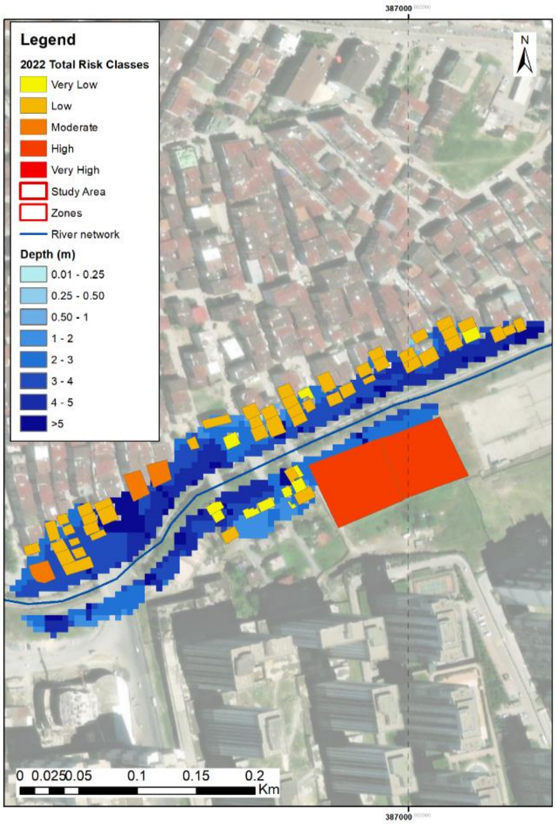

Figure 8. Flood risk map for Zone-2, 2022.

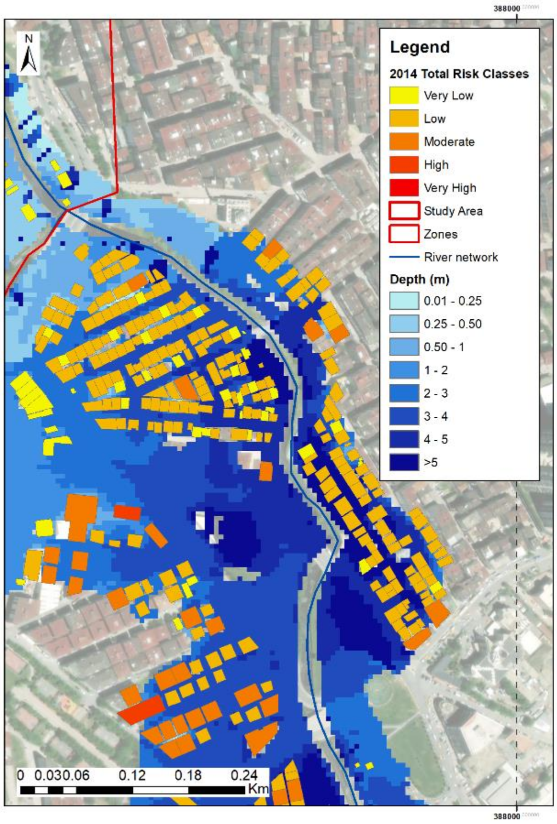

Figure 9. Flood risk map for Zone-4, 2014.

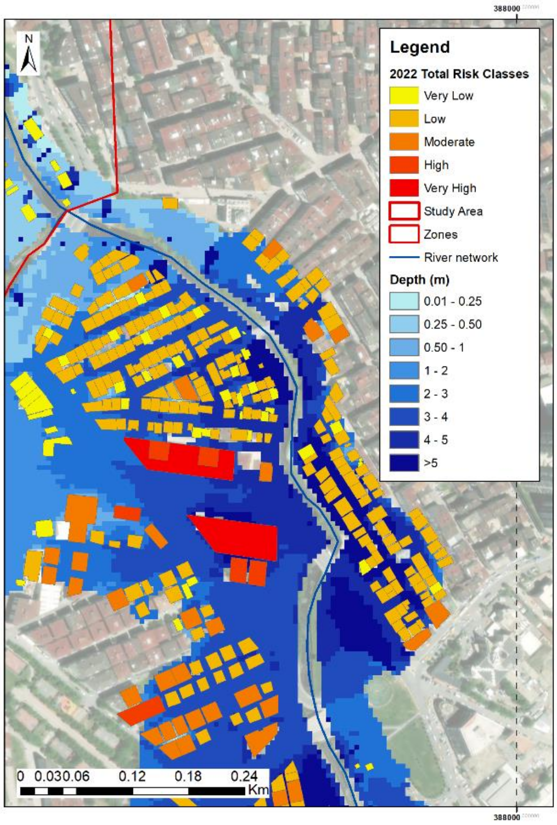

Figure 10. Flood risk map for Zone-4, 2022.

The results of the building-specific risk analysis were examined. The risk for residential buildings increased by 16.6%, the risk for commercial buildings increased by 9.9% and the risk for industrial buildings decreased by 13.3% (Table 4). The reduction in the average floor area of industrial buildings towards 2022 was identified as the main factor contributing to the decrease in their risk. After a comprehensive examination of the entire study area, there was a 13.7% increase in the average total risk from 2014 to 2022.

Table 4. Risk averages of building use by years.

Years	Residential Risk	Industrial Risk	Commercial Risk	Total Risk
2014	0.0314	0.0319	0.0728	0.0330
2015	0.0318	0.0321	0.0760	0.0335
2016	0.0319	0.0307	0.0760	0.0335
2017	0.0358	0.0293	0.0799	0.0370
2018	0.0357	0.0299	0.0799	0.0369
2019	0.0357	0.0296	0.0799	0.0369
2020	0.0364	0.0296	0.0799	0.0375
2021	0.0364	0.0283	0.0799	0.0374
2022	0.0366	0.0277	0.0799	0.0375

When analysing all the results together, it was determined that the increase in the number of buildings, particularly in 2017, had an impact on the overall risk. In addition, it was found that the general trend of "number of floors" and "building area" is compatible with the change in risk. However, it should not be forgotten that the water depth in which the buildings are located is the most important factor in determining the risk.

In 2019, there was an above-trend increase in the population, which led to an increase in residential risk and total risk in the subsequent years. As a result, high urbanization has increased the number of people affected by flood by 32.9%, the economic damage in case of flood by 22.3% and the total flood risk by 13.6% from 2014 to 2022. In this case, 5,1% of the population of Esenyurt became vulnerable to the flood. All results show that the flood risk has increased significantly over the last 9 years. The most effective reasons for the increase in risk are:

- sudden population growth,
- increase in urbanization and settlements close to riverbeds,
- increase in settlement density in existing settlement areas
- increase in storey height of residential buildings constructed in recent years (Özer, 2023).

The main reason for their occurrence is that urban planning is not carried out effectively and in accordance with the study area.

Urban planning emerges as a key tool for flood risk reduction, facilitating the implementation of strategies, especially for current and future flood scenarios. In new settlements, the distance to riverbeds needs to be considered and in existing settlements, structural measures can be implemented where there is a risk of flooding. These measures are designed to divert flow away from flood-prone areas during flood events. Examples include the construction of reservoirs to mitigate downstream flows, the widening of canals to increase capacity, the implementation of diversions to reduce flows in main channels, and the construction of embankments to protect areas adjacent to canals (de Andrade Cruz et al., 2023). In 2020, the Istanbul Metropolitan Municipality initiated infrastructure and rehabilitation efforts for the study area. Infrastructure and rehabilitation works, including widening the channel section and strengthening the infrastructure to separate rainwater and wastewater, have not yet been completed. However, these measures remain incomplete and successive floods, particularly in 2022, have continued during these efforts.

Complementing structural measures are non-structural and nature-based solutions aimed at flood prevention and mitigation (Conitz et al., 2021). Non-structural measures aim to minimise flood risks, reduce damage and increase community resilience without relying on physical alterations. Examples include urban planning and its enforcement, the formulation of flood management and mitigation plans, the establishment of floodplain zoning regulations to limit development in high-risk areas, the implementation of flood early warning systems, and public education on flood risks and preparedness measures.

The lack of adequate urbanization planning and the non-implementation of non-structural measures have led to an escalation of risk levels over time. As a result, changes in flood-risk areas have increased the potential losses in terms of human life and property (Şenol Balaban, 2016). In addition to the economic damages quantified in this study, the structural measures commonly used in Turkey to prevent floods entail additional costs. Embankments, rehabilitation, and other structural measures may not be sufficient to address various parameters such as flood frequency, velocity, and depth (Bruwier et al., 2015).

In this case, effective solutions include model-based approaches like Green Infrastructures, such as rain gardens, green roofs, permeable pavements, and rainwater harvesting, alongside Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Sponge Cities, and Nature Based Solutions (NbS) (Qi et al., 2021). These approaches share the same objectives. Nature-based solutions are a concept inspired by nature, aiming to preserve the natural balance and include actions towards this (Cohen-Shacham, Walters, Janzen, and Maginnis, 2016; Huang et al., 2020). The objective of this approach to flood is to improve water retention capacity and minimise flood risk by addressing the ecosystem holistically. To realise these objectives, the following actions can be implemented in the study area:

- Rainwater harvesting, green roofs to slow down the flow processes in Haramidere River,
- Permeable pavements, infiltration trenches to increase the permeability of rainwater,
- Bioswales to increase the permeability of rainwater and provide ecological benefits,
- Retention ponds to reduce surface runoff.

These measures allow for water recycling, efficient utilization, economic advantages, and decreased flood risk. The prevention of flood risk is achievable through the reduction of numerous parameters that contribute to the formation of floods by implementing these measures. Previous research has extensively examined the efficacy of Nature-based Solutions (NbS) in mitigating flood risks. These studies primarily concentrate on various aspects, including decreasing peak flow (Jackisch and Weiler, 2017), minimizing runoff (Dreelin, Fowler, and Carroll, 2006), reducing flood volume (Mei et al., 2018), and decreasing flood inundated area and inundation depth (Costa et al., 2021). Investigating the suitability of these parameters for the specific study area is essential to effectively reduce flood risk. Consequently, spatial planning plays a crucial role, particularly during the implementation phase. Combining nature-based solutions with urban planning is a recommended approach to reduce flood risk in Esenyurt. Considering the historical floods in Esenyurt, it is concluded that more emphasis should be placed on urban planning and model-based approaches such as NbS rather than structural solutions for flood-resilient cities.

The study's findings highlight the complicated connection between urbanization, population growth, and flood risk. In Esenyurt, risk levels have increased significantly over time due to ineffective urban planning and a lack of implementation of non-structural measures. This study emphasizes the importance of structural measures while also highlighting limitations in addressing parameters such as flood frequency, velocity, and depth.

To address these limitations, a holistic approach that combines nature-based solutions (NbS) is advocated. These approaches aim to increase water retention capacity, minimize flood risk, and provide economic benefits. Additionally, they offer more sustainable economic contributions compared to structural solutions.

The proposed implementation of nature-based solutions for reducing flood risk in Esenyurt gains further significance when integrated with effective spatial planning and considering the urban economy. This study concludes that it is crucial to place greater emphasis on model-based approaches, such as urban planning and Nature-based Solutions (NbS), particularly in the face of increasing urbanization, to establish a sustainable and flood-resilient economic structure.

4. Conclusion

Floods are a widespread natural disaster causing significant economic damages and human losses. These losses are linked to rapid population growth and urbanization. Therefore, it is essential to assess flood risk and urbanization together. Accordingly, the flood risk caused by the frequently-flooded Haramidere River in the İstanbul district was analysed concerning urbanization. Esenyurt district was chosen due to its population of approximately 1 million and its dense construction in both industrial and residential areas.

The most important feature of this study is the combination of remote sensing and GIS in flood risk assessment and analysis. Using remote sensing, background analysis of buildings and their evolution over time were obtained. These data were processed with GIS and the areas exposed to flood risk were mapped by spatialising the degree of risk. These risk maps played a critical role in identifying high-risk areas, assessing potential flood impacts on the population, and informing urban planning decisions. While RS data provides temporal continuity of the data used in the study, GIS spatialises these data. GIS determines trends with analyses for temporal and spatial differences of the data provided by GIS and RS. The integration of RS and GIS creates a powerful whole for analysing and understanding spatial data. In summary, the research has provided a comprehensive and data-driven approach to understanding the complex interactions between urbanization and flood risks by developing remote sensing and GIS applications in flood risk assessment. Another important feature of this study is the introduction and comprehensive application of the HVE (Hazard, Vulnerability, Exposure) framework. With this framework, it has addressed multiple dimensions such as risk, economic damage (TL in 2023) and the number of people who will be affected by flood risk. It was determined that the flood risk has increased over the years, and this increase was caused by the rapid population growth and urbanization in the risky areas. It is concluded that population and risk increases are in parallel on an annual basis. In addition to its important features, it provides the information necessary to effectively target risk reduction and adaptation measures by identifying flood risk hotspots where hazards, vulnerabilities and exposures converge. Based on this information, it should be recommended to determine urban planning and model-based flood prevention and mitigation strategies such as nature-based solutions by analysing the basin in detail. While determining these solutions, urban density, population, and socio-economic status should be taken into consideration. The district is categorised as arid-semi-humid, but due to the decrease in precipitation in recent years, there is a possibility of transition to semi-arid status. For this reason, nature-based solutions such as plant-based green corridors, green roofs, bioswales, etc. cannot be implemented due to the characteristics of the area. Therefore, the study area should be investigated in detail and appropriate nature-based solutions should be implemented with the help of urban planning.

After the completion of the ongoing rehabilitation works in Esenyurt, it is predicted that the flood risk will decrease when the recommendations determined within the scope of the study are implemented. GIS plays a crucial role in assessing and managing flood risk, providing a versatile tool for analysis and implementation. It facilitates the simulation of a variety of scenarios related to the planning of nature-based solutions (NbS), including determining their location, size, and form. GIS helps urban planning by identifying the enduring consequences of climate change and urban development, improving adaptability to changing conditions. Before and after the implementation of Nature-based Solutions (NbS), Geographic Information Systems (GIS) assist in sustainable initiatives by facilitating the evaluation of possible consequences and tracking the efficiency of green infrastructure. By conducting consistent data collection and analysis, GIS guarantees the continued success of such features in mitigating the threat of floods. When GIS is combined with urban planning, it plays a crucial role in reducing flood risk through site-specific applications.

The study offered a practical solution to a serious problem related to the disclosure of flood risk associated with the rapid urbanization in Istanbul-Esenyurt. This study conducted an analysis of the historical flood risks between the years 2014 and 2022. It identified the susceptible areas and quantified the economic damages and the population affected by the flood. Furthermore, it provided a preliminary preparation for the potential applications to mitigate the flood risks and established a basis by assessing these risks. This study demonstrates that urbanization policies implemented without effective planning can result in economic losses. Settlements in high-risk areas and urbanization processes increase the impact of floods, leading to potential losses of infrastructure, property, and other economic assets. Therefore, it is important to have strict regulations on buildings in high-risk areas and to integrate contemporary planning processes to minimise the economic losses caused by floods. Urban planning has been proposed as a solution to the flood risk arising from urbanization and population growth. It is important to consider urban resilience to flooding and risk mitigation strategies in the design and implementation of urbanization policies. As a result, the study suggests that urban planning can be used to reduce flood risk and that local governments should consider the interaction between urbanization and flood risk when developing urban planning policies.

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Conflict of interests

The authors declared that there was no conflict of interest relating to the conduct, outcome, and publication of this study.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statements

Studies involving animal subjects: No animal studies are presented in this manuscript.
Studies involving human subjects: No human studies are presented in this manuscript.
Inclusion of identifiable human data: No potentially identifiable human images or data are presented in this study.

Institutional Review Board Statement

Not applicable.

CRediT author statement:

Buse Özer led the conceptualization, methodology, and investigation of the study, playing a crucial role in the formulation, planning, and execution of research activities. She was primarily responsible for writing the original draft of the manuscript and creating the visual materials to effectively represent the study's findings. Prof. Dr. Özge Yalçıner Ercoşkun provided critical supervision, contributing to the conceptual framework of the research and ensuring the project's direction and methodology were robust and reliable. She also played a key role in the validation of results, guaranteeing the accuracy and reliability of the findings, and was instrumental in reviewing and editing the manuscript, significantly enhancing its clarity and quality. Furthermore, Prof. Ercoşkun was responsible for acquiring the funding that supported the project, securing the necessary resources and materials for the research. Together, their combined efforts have significantly contributed to the advancement of the study, demonstrating a collaborative and comprehensive approach to research. All authors have read and agreed to the published version of the manuscript.

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