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Evaluation of the Transportation Infrastructure Vulnerability in Kaynarca, Sakarya Basin from a Flood Spread Risk Perspective

Umut Erol[1*], Yiğit Kızmaz[2], Abdulkadir Özden[1], Ahmet İyad Ceyhunlu[1]

[1]*Civil Engineering Department, Sakarya University of Applied Sciences, Sakarya, Türkiye*
[2]*32. District, Directorate General for State Hydraulic Works, Sakarya, Türkiye*

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Abstract

Natural, technological or man-made disasters caused social, economic and environmental losses in history. These devastating events affect communities by stopping or interrupting normal life and usual daily activities, and the affected community cannot cope by using local opportunities and resources. The topographic, climatic and seismic structure of Turkey allows disasters to be seen frequently in the region. Disasters such as floods, landslides-rock fall and fires are experienced almost all year round in its seasons, including medium-scale earthquakes (with an average magnitude of 5 to 6). Furthermore, transportation infrastructure has been a critical asset in all stages and time frames including mitigation, preparedness, response and recovery in disasters. In this study, the Kaynarca district of Sakarya has been evaluated based on its flood flow recurrence modelling with its effect on transportation infrastructure. With a range between 25-year and 500-year recurrence scenarios, it is found that the local roads and streets are vulnerable in all different cases, while major collectors are significantly affected by flooding in the 500-year recurrence scenario. Major collectors are the transportation infrastructure carrying the transit passengers and loads, as well as emergency aids from disaster logistic centres in case of need; therefore, less disruption increases the resiliency of the infrastructure. On the other hand, local emergency management agencies should prepare a contingency plan for local roads and streets for pinpointing the possible gridlocks, accessibility of critical infrastructure in rural areas, and robustness of major collectors.

Key words: Transportation, Resilience, Flood risk, Disaster management

1. Introduction

Transportation is both the driving force of economic and social development with the mobility it provides, and is one of the most important causes of global warming, increasing carbon footprint and other harmful environmental effects. In this dilemma, meeting the needs of mobility and minimizing the environmental effects have long been a discussion in the research community. On the other hand, investment in transport infrastructure aims to improve the quality of transport services, increase travel safety and create additional capacity for moving people and goods. In addition to reducing transportation costs and adverse environmental effects in general, this may lead to shorter travel times and ease of accessibility in case of need such as emergency situations [1], [2].

It has been proven by years of experience that natural and man-made disasters cause serious problems in transportation infrastructure and other interconnected critical substructures due to

* Corresponding author e-mail: g180904074@subu.edu.tr

their unpredictable and destructive features. From a disaster management perspective, transportation infrastructure has been a critical asset in all stages and time frames including mitigation, preparedness, response and recovery in disasters. At the same time, transportation infrastructure itself is also open to damage (vulnerability of the infrastructure) during disasters, which may cause further complications, including social and economic, as it was a fundamental measure of accessibility [1], [3]. One of the means for measuring vulnerability is resilience, the "Ability to resist, absorb and adapt to disruptions and return to normal functionality" [1], [3]. Enhancing the transportation resiliency and reliability requires the quantification of resilience to be able to assess and pinpoint the weaknesses, thus prioritizing recovery activities and necessary precautions [3], [4]. Although confusion on the terminology has been declining recently, transportation resilience in disasters has not been well studied in the literature [3]. Faturechi and Miller-Hooks [1] covered the related definitions for further readings in transportation infrastructure from a disaster management perspective.

Table 1. Common definitions of common performance metrics in disasters (adopted from [1])

Measure	General Definition
Risk	Combination of probability of an event and its consequences in terms of system performance
Vulnerability	Susceptibility of the system to threats and incidents causing operational degradation
Reliability	Probability that a system remains operative at a satisfactory level post-disaster
Robustness	Ability to withstand or absorb disturbances and remain intact when exposed to disruptions
Flexibility	Ability to adapt and adjust to changes through contingency planning in the aftermath of disruptions
Survivability	Ability to withstand sudden disturbances to functionality while meeting original demand
Resilience	Ability to resist, absorb and adapt to disruptions and return to normal functionality

In addition, climate change, which is one of the results of Global Warming, has increased its severity in recent years. This change in climate parameters causes changes in meteorological data such as seasonal temperatures, precipitation seasons and precipitation intensities [5]. As a result of these changes, some areas are exposed to severe rains and play a major role in the formation of floods, while some areas are exposed to drought and high temperatures [6].

Global statistics shows that nearly 50% of the world's population lives near rivers or coasts [7]. In addition, the fact that 1 million people live in floodplains increases the importance of the measures taken against natural disasters such as floods and tsunamis [8]. According to studies, the areas exposed to floods in Europe have increased by 1000% in the last 150 years [9]. In the last 30 years, about 3 million people have been affected by the flood in the world, about 600,000 people have died and 400,000 people have been injured [10]. In addition, recent studies estimate that the world population is expected to reach 9.3 billion by 2050 [11], and is predicted that this increase will cause the proliferation of urban areas. Accordingly, it is inevitable to have new structural expansion and impermeable surfaces including roads and buildings as it will escalate the risks of floods and other environmental disasters [12], [13].

On the other hand, disaster logistics covers a variety of activities at different times, depending on the type of disaster, in order to respond quickly and efficiently. Moreover, the common goal is to save human lives and reduce the disaster impact by delivering the proper material to the right person, in the right amount, at the right time and at the right place [14], [15]. Furthermore, recovery time for a transportation network can vary due to the size of the impact (from a few days to even months) and significantly affect the accessibility of the disaster location, reaching the affected areas and people. Likewise, possible damage to the highways or rail network may even increase the time needed for the recovery of transportation infrastructure [16].

Hurricane Sandy (2012), the Japanese Tsunami (2011) and its nuclear effects, the Marmara Earthquake (1999), Nepal Earthquake (2015), the Minneapolis I-35W bridge collapse in the U.S. (2007), Bozkurt-Kastamonu Flooding in Turkey (2021), Northern California Wildfires (2017), Marmaris Wildfires in Turkey (2021) are the few examples of devastating events in the last two decades. The impacts of these events proved how critical and vulnerable transportation systems are in such disasters.

Hurricane Irene affected more than 2500 miles of roadways in addition to 200 miles of railways, and 300 bridges of various sizes in Vermont [17]. The collapse of the I-35W Bridge over the Mississippi River imposed over $0.4 million in costs on daily passenger trips alone due to traffic rerouting [18]. 1999 Marmara Earthquake reports of the State Planning Organization of Turkey revealed that the amount of financing that should be allocated to compensate for the losses in the energy, transportation and communication sectors was determined as approximately 320 million dollars in the short term and 960 million dollars in the long term (adjusted to 2021 values). The share of highways and roadway infrastructure is nearly 391 million dollars and is in the first place [19].

In the Bozkurt-Kastamonu flood in 2021, the settlement area was established on both sides of the Ezine stream and in the flood zone, and it is obvious that this contradictory residential plan was effective in increasing the dimension of the impact. Torrential rain triggering the severe flooding and mudslides caused the demolition of some bridges that enable the movement between the two sides of the district and making others unfunctional, the collapse of the stream side retaining walls, and the damage to the streets and local roads; creating a significant disruptions in both rescue activities and the delivery of emergency aids [20]. In another study, Alkayis et. al. [21] investigated and mapped the fire risk potential in the south-western part of the Turkey (Menteşe Region, Muğla - which is a critical location that hosted almost half of the total fires that occurred in the region) and emphasized the closeness to the roads and residential areas both from the viewpoint of the risks and the rescue activities. Furthermore, there are a few studies focuses on the impact of see-level rise on transportation network, specifically on pedestrian and bicycle facilities [22], [23]. There are many studies on flood modelling and flood analysis in the literature [24]–[27].

In this perspective, considering the increasing disaster risks due to global warming and other destructive environmental effects and the significance of transportation infrastructure; there is a need for a) developing a systematical infrastructure resiliency approaches for disaster management and preparedness and b) site-specific studies for pinpointing the weaknesses and improving the resiliency of the transportation infrastructure. This study focuses on the latter case, focusing on a high-risk location in the Sakarya-Kaynarca district by integrating the flood risk areas prepared by Kizmaz [28] and the current transportation infrastructure. The study is expected to identify the vulnerable regions in the area for possible flooding events and help responsible stakeholders to make preventive decisions.

2. Materials and Method

2.1. Study Area

Kaynarca district, located in the Northern part of Sakarya province, has an average altitude of 50m and presents traditional Black Sea climate, where high precipitation and moisture is common, including short and heavy rains that may cause flooding (Figure 1). The Seyren

Stream, which passes through this region, has a basin area of 10.78 km^2 and a main stream length of 6.37 km, but has a narrow and meandering structure. Kaynarca district has a population of approximately 25 thousand, consisting 19% elderly, 34% young and 47% of them are middle-aged. There is an average of 3.58 people per household in this region. In terms of socio-economic status[1], 13% of the population is classified in A (upper-middle class), 19% in B (middle-middle class), and 68% in C and D (Lower-middle and working class) [29].

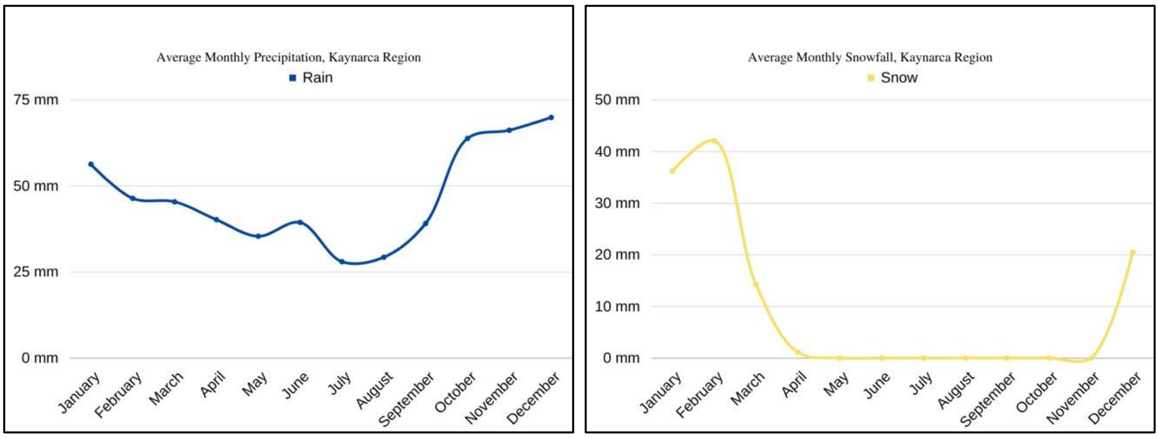

Figure 1. Seasonal climate trend of the Kaynarca region

There are few major connections between the Kocaeli-Sakarya region and northern coastal areas and Kaynarca is one of the hubs in this direction. Coastal regions (Karasu, Kefken, Cebeci, etc.) are attracting visitors for both residents of these two cities (Kocaeli and Sakarya) and other locations including Ankara, Eskişehir, Bursa and Istanbul. At the same time, the coastal area has been serving as a freight transportation hub with ports of a variety of sizes. Furthermore, recent off-shore gas drilling activities increased the importance of transportation infrastructure in the region (Figure 2). Therefore, a disruption during a natural and/or man-made disaster not only affects the local accessibility but regional transportation activity.

Figure 2. Study area – Kaynarca province in Sakarya

[1] Endeksa.com

2.2. Recurrent Flood Flow Calculation and Hydrological Modelling

The Kaynarca region does not have any flow monitoring stations in the study area, thus restricting the calculation of recurrent flood flows by using observed flows of Seyren Stream. Kizmaz [28] used 15-years of precipitation data from Sakarya State Meteorological Service (SMS) station and 5-years of precipitation data from Kaynarca SMS station since Kaynarca station was only active after 2014. Additionally, in order to calculate the extreme distribution of daily maximum precipitation, various methods were tested via the Kolmogorov-Smirnov method, and the Log-Pearson Type III method was determined as the distribution type with the most optimum results. Recurrent flood flow calculation has been performed by using a deterministic method, the non-superposed Mockus Method [28]. Flood recurrence rates of 5, 10, 50, 100 and 500 years were calculated and flood hazard maps were created based on depth and velocity parameters [Figure 3 and Figure 4].

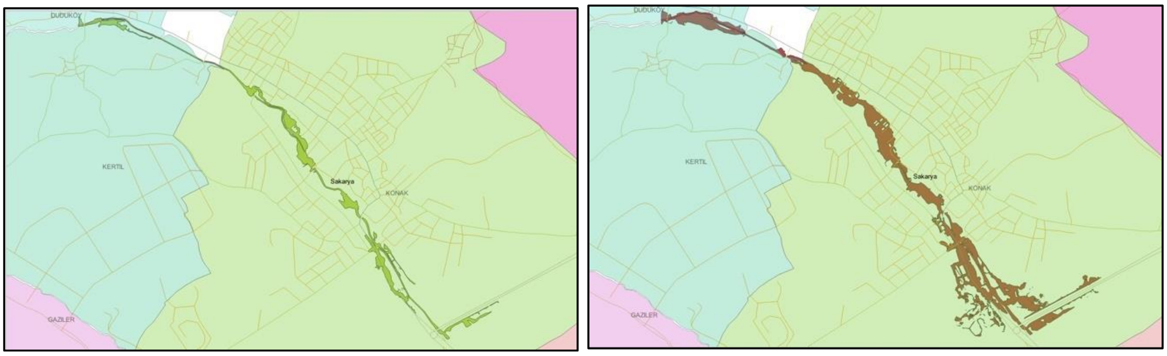

Figure 3. 25-year (left) and 50-year (right) flood risk area [26]

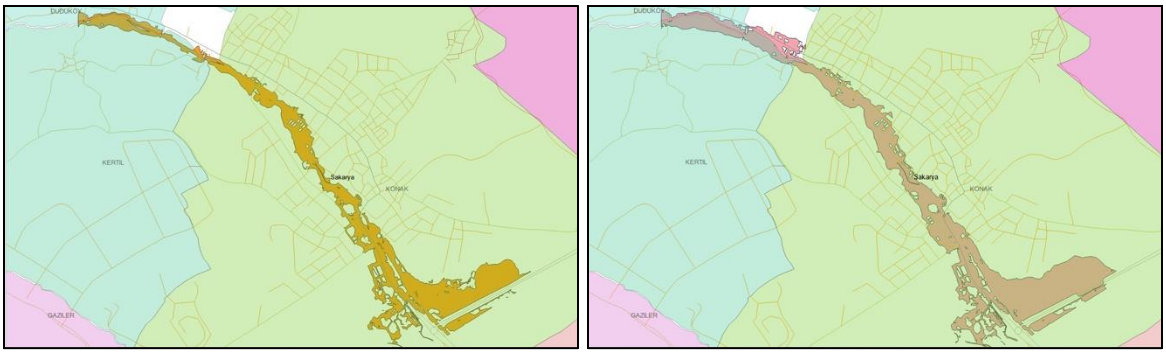

Figure 4. 100-year (left) and 500-year (right) flood risk area [26]

2.3. Transportation Network in the Region

The roads are first evaluated based on the classification of the General Directorate of Highways in order to understand the uses and priorities. In most cases, even in large-scale cities in Turkey, there are solid evacuation or disaster management plan during disasters that focuses on the use of transportation infrastructure. Thus, the classification of roads as major collectors, rural roads, streets and local roads facilitated quantifying the amount of network in each class that may have possible damage.

Figure 5. Roadway transportation infrastructure near Kaynarca province

3. Results

Based on the recurrent flood flow calculations and determination of flood risk areas, Kizmaz [28] revealed that the Seyren Stream in the region does not overflow at Q5 and Q10 annual flow rates. Thus, Q25, Q50, Q100 and Q500 annual flow rates had been studied in detail and the generated flood propagation models are presented above in Figure 3 and Figure 4. It is seen that the flood spread is notably increased in 100-year and 500-year models. Since the spread and the depth of the spreading water in the region are the primary indicators of the size and the extent of the damage to the transportation infrastructure, these models are found enlightening for the resilience of the transportation infrastructure.
Integrating the flood risk areas with the current roadway network layer revealed the possible affected roads in the flood propagation area. Following Figures 6-9 present the affected roadway infrastructure based on different frequency models. The figures highlight the increase in length and coverage of the transportation infrastructure as the flood propagation recurrence moves from 25-year to 500-year.

According to the 25-year recurrence modelling, 738.3 m of roadways are affected in the flooding region including approximately 30 m of major collectors, 157 m of local roads, 68 m of rural roads, and 466 m of streets. Similarly, based on 50-year recurrence modelling, 1794.34 m of roadways are affected in the flooding region including approximately 42 m of major collectors, 737 m of local roads, 395 m of rural roads, and 552 m of streets.

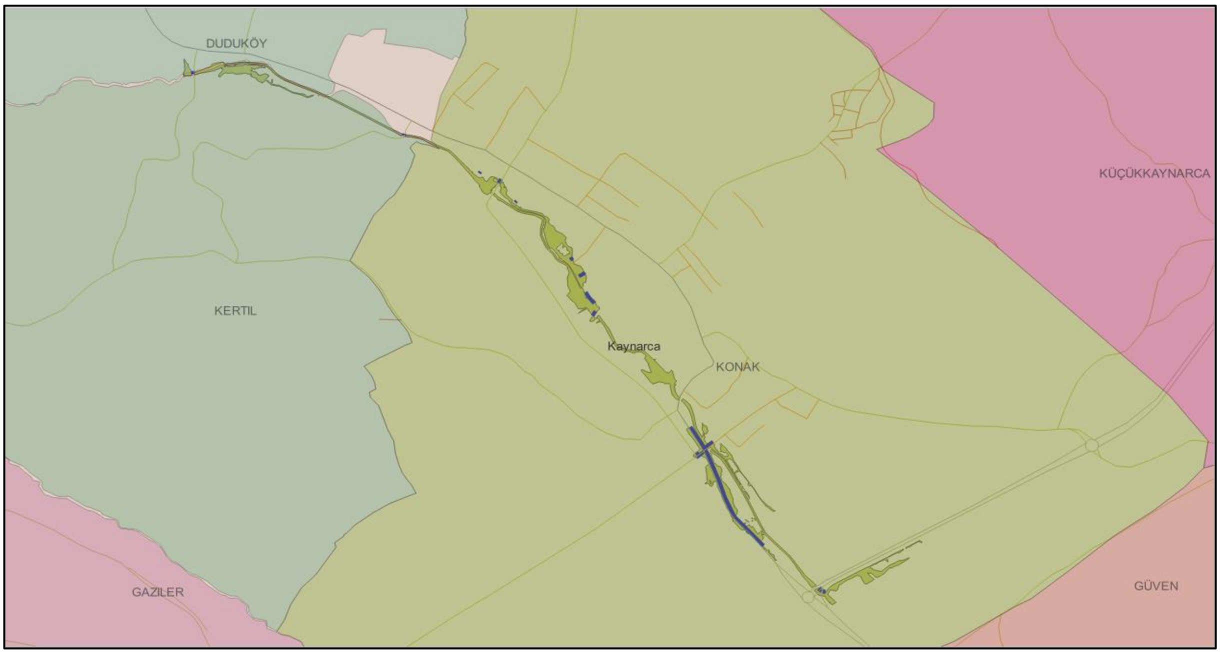

Figure 6. Identification of affected roads in the 25-year flood risk area

Figure 7. Identification of affected roads in the 50-year flood risk area

In 100-year and 500-year scenarios, the length of the affected major roads rises significantly from nearly 44 m to 371 m, almost 8 times. Other road types increase substantially between 8% to 26%. The total length of the affected roads increased by almost 50.5% from 2416.4 m to 3638.35 m. Following Table 2 presents a summary of the length of the affected roadways in varying categories and Figure 10 visualize the change.

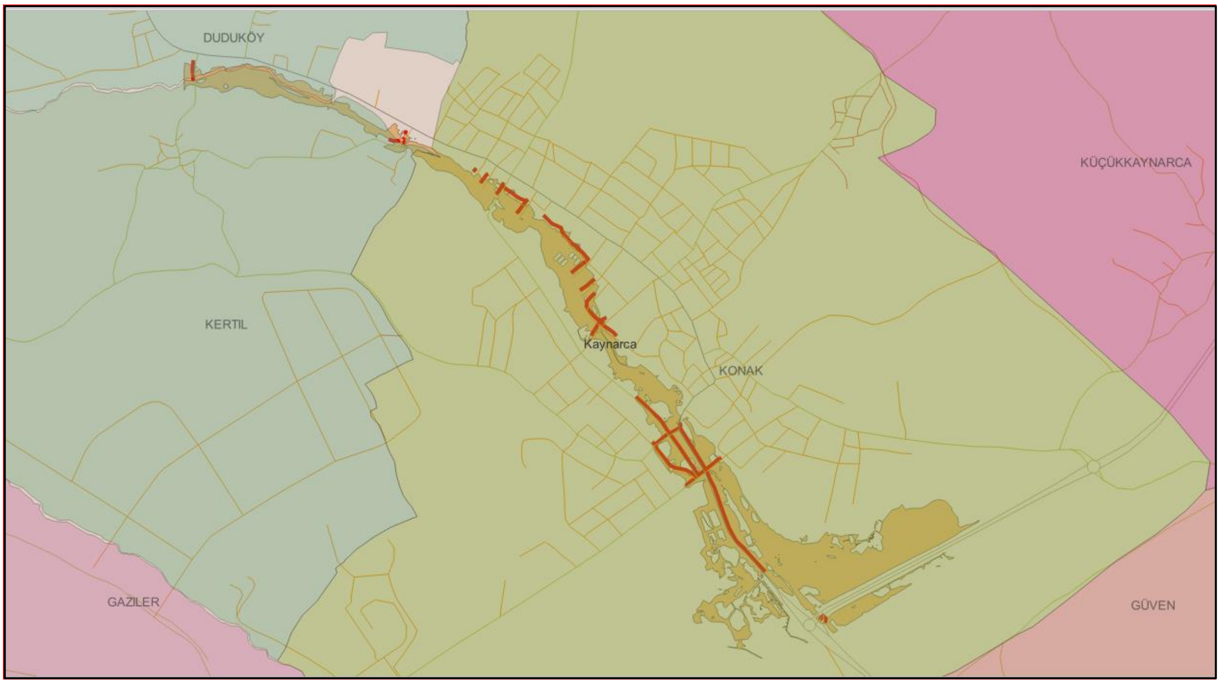

Figure 8. Identification of affected roads in the 100-year flood risk area

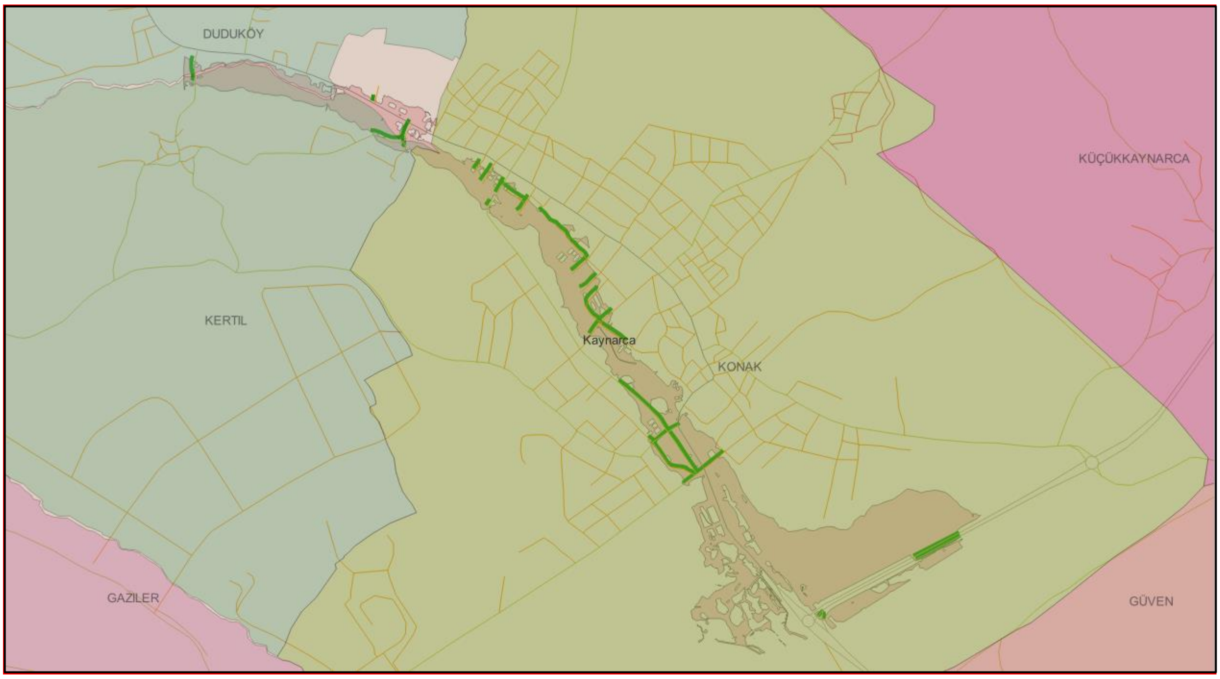

Figure 9. Identification of affected roads in the 500-year flood risk area

It is noted that streets are vulnerable to possible flooding, even in the 25-year recurrence scenario, and do not show a critical rise (36%) between the 25-year to 500-year scenario. On the other hand, the length of local roads that may have an impact during flooding is around 157.15 m in the 25-year scenario. However, it jumps to 736.75 m in the 50-year scenario (almost 5x) and continues increasing at a slow pace to 1279.23 m in the 500-year scenario. Both local roads and streets are critical transportation infrastructure in reaching the inner part of the residential areas, into the buildings, etc. Yet, alternative local roads and streets may usually be available since the town centres generally have a dense transportation network. However, the local emergency management agencies are required to prepare a contingency plan if a significant portion of the local roads and streets become inaccessible during flooding.

Table 2. Flood-affected road lengths based on different annual flow data

	Q-25 Flood Propagation Risk Area				Q-50 Flood Propagation Risk Area			
Roadway Type	Konak Area (m)	Dudu Area (m)	Kertil Area (m)	Total Length (m)	Konak Area (m)	Dudu Area (m)	Kertil Area (m)	Total Length (m)
Major Collectors	30.05	0	0	30.05	41.81	0	0	**41.81**
Local Roads	157.15	0	0	**157.15**	736.75	0	0	**736.75**
Rural Roads	67.96	17.04	0	**85**	395.64	47.81	19.44	**462.89**
Streets	466.10	0	0	**466.10**	552.89	0	0	**552.89**
Total Length	**721.26**	**17.04**	**0**	**738.3**	**1727.09**	**47.81**	**19.44**	**1794.34**
	Q-100 Flood Propagation Risk Area				**Q-500 Flood Propagation Risk Area**			
Roadway Type	Konak Area (m)	Dudu Area (m)	Kertil Area (m)	Total Length (m)	Konak Area (m)	Dudu Area (m)	Kertil Area (m)	Total Length (m)
Major Collectors	44.79	0	0	**44.79**	371.26	0	0	**371.26**
Local Roads	1092.45	0	13.58	**1106.03**	1279.23	18.89	35.80	**1333.92**
Rural Roads	553.2	63.73	60.18	**676.93**	698.51	116.23	146.94	**961.68**
Streets	588.47	0	0	**588.47**	634.63	336.86	0	**971.49**
Total Length	**2278.91**	**63,73**	**73.76**	**2416.4**	**2983.63**	**471.98**	**182.74**	**3638.35**

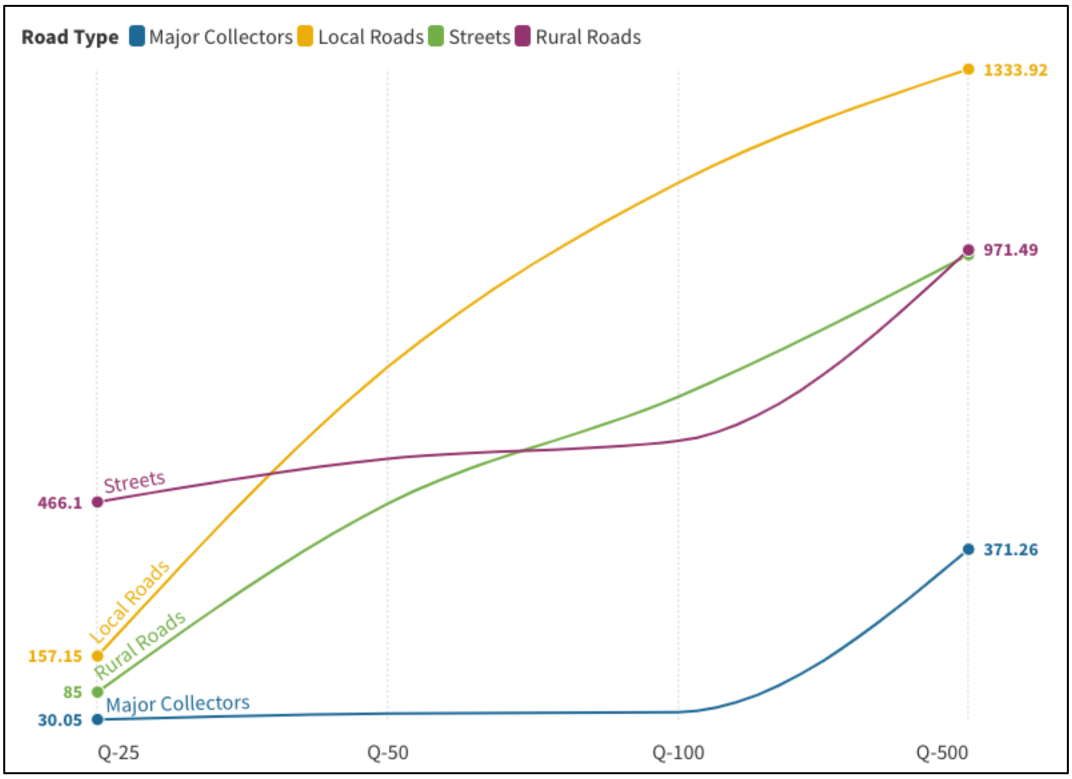

Figure 10. Change in the length of the affected-roads based on different flood risks (length in meters)

Similar to local roads, rural roads that provide access to farms and villages nearby are affected after 50-year recurrence scenarios. However, accessing a village or farmland might not be possible or difficult to reach if there is only one road providing access. Thus, local agencies should evaluate if there is a critical infrastructure (energy lines, water pumps, etc.) that should be reached in the area in case of an emergency and make sure there are alternative accessibility options. Keeping the infrastructure in an unusable state may have social and economic costs to the region.

Last, major collectors are not significantly affected until the 500-year recurrence scenario, reaching 30.05 m to 44.79 m between 25-year and 100-year scenarios; and jumping to 371.26 m in the 500-year scenario. Functionality of major collectors is critical since this category of roads carry the major traffic in a region. However, the responsible agencies are required to further evaluate the 500-year scenario to create a resilient transportation infrastructure.

4. Conclusions

In this study, the Kaynarca region near Seyren Stream was determined as the study area. Kaynarca has been experiencing flooding in recent years due to excessive precipitation and is host to the critical transportation infrastructure between coastal areas and the major residential and industrial areas in the Eastern Marmara Region.

The study used Kizmaz [28] flood propagation models and integrated them with the current road network to identify the vulnerable areas in different flood propagation cases. First, classifying the roadway network in the region and combining the flood propagation models of 25, 50, 100 and 500-year in the Q-GIS platform, the vulnerable areas are highlighted. The total length of the vulnerable transportation infrastructure in different roadway categories based on various flood propagation risk areas is presented in Table 2 and the change visualized in Figure 10. It is clearly seen that the affected total roadway length increased from 738.3 m to 3638.35 m as the flood propagation increased from 25-year to 500-year recurrence scenarios.

It is also noticed that most streets and local roads are largely affected by possible flooding in contrast to major collectors and rural roads. This can be both beneficial and detrimental. Major collectors are the transportation infrastructure carrying the transit passengers and loads, as well as emergency aids from disaster logistic centres in case of need; therefore, less disruption increases the resiliency of the infrastructure. However, the affected length of the major collectors increases from 44.79m in 100-year to 371.26 m in 500-year recurrence. Considering the climate change effect and increasing sudden and heavy rains in the last decade, the responsible agencies should consider planning an alternative road to ensure the accessibility of the region in a major event.

On the other hand, local emergency management agencies should prepare a contingency plan for local roads and streets for pinpointing the possible gridlocks, accessibility of critical infrastructure in rural areas, and robustness of major collectors. Defining the critical buildings and/or infrastructure outside the town centre may help forecast the risk in these locations as the affected length of the rural roads increases from 157.15 m to 1333.92 m between 25-year and 500-year recurrence scenarios.

This study is expected to have two major contributions. First, shed a light on the critical transportation infrastructure that may have a high flood propagation risk and experienced flooding recently, which is unique for Kaynarca, Sakarya region. Highlighting the location of roads based on roadway categories enables related agencies to prepare contingency planning as well as first response and recovery routes in the area. This will have a direct impact on the disaster management activities and the resiliency of the infrastructure in addition to the high social contribution to the Kaynarca region. The second contribution is expected to be an example to other locations that may have a risk for any type of disaster. Integrating the critical buildings, transportation, energy, etc., into the contingency planning is expected to reduce the consequence of a possible disaster.

The limitation of the study is that the authors do not have relevant information regarding the locations of critical buildings and infrastructure to further narrow down conclusions. This case can be further studied with alternative accessibility options in a simulation environment.

Conflict of Interest
The authors have no conflicts of interest to declare that relevant to the content of this article and all authors confirm the final version of the study for publication.

Author Contribution
U.E. and A.Ö. conceptualized the framework and designed the study. Y. K. and A. İ. C. contributed to flood risk model. U. E. combined the flood spread risk model and transportation network, U. E. and A. Ö. evaluated the results. All authors contribute to writing the manuscript and approved its final form.

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