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Assessing the vulnerability of cities to climate change: A new index proposal for Türkiye cities

Hale Öncel*

Abstract

On a global scale, as cities continue to grow and climate change brings increasing hazards, the vulnerability and risk levels for cities are also rising. Assessing the risk and vulnerability of urban areas has become more vital now than in previous decades. In this context, the climate–adaptive city approach is gaining importance alongside sustainable development. Türkiye's geographical location is considered one of the most vulnerable regions in terms of climate change, due to decreasing precipitation and rising temperatures. In the literature, some studies primarily evaluate the full range of risks associated with climate change, while others develop a climate–adaptive city approach that focuses on a single risk. However, the consequences of climate change vary across regions and countries. In this study, the vulnerability of cities to climate change is discussed separately for each risk. Vulnerability criteria are considered separately for drought, sea-level rise, heavy rainfall, and extreme heat. For each risk, indicators of the impact, pressure, vulnerability, resistance, and adaptive capacity that contribute to the risk are identified. Methodologically, relevant studies in the literature were compiled, previous studies were utilized in determining the indicator, and new indicators were developed. As a result, a holistic approach has been developed to assess the vulnerability of cities to climate change across all risks. This makes it possible to identify both how cities remain unprepared for the consequences and risks of climate change and, on the other hand, the climate–adaptive aspects of cities. This study is intended to contribute to researchers working on urban resilience as well as to urban municipalities. In conclusion, a guiding index has been put forward to inform planning and decision-making processes for the creation of a climate–adaptive city.

Keywords: climate–adaptive city, climate change, resilient city, vulnerability assessment index, Türkiye

1. Introduction

UNDESA (2012) projected that 75 percent of an estimated global population of 9 billion will live in urban areas in 2050. Urban areas (with at least 50,000 residents) account for 71% of carbon emissions, even though they cover less than 3% of the Earth's surface (IPCC, 2007). Therefore, cities play a critical role in making the world a more sustainable place. On the other hand, environmental changes such as unpreventable global warming affect cities more severely than rural areas. Urban resilience has become a prominent concept as cities continue to grow (Carmin et al., 2012; Leichenko, 2011). Most reports (UNEP, 2012; Franklin & Andrews, 2012) highlight the challenges facing cities in this century. The need for adaptation is evident across cities of all sizes and climates, particularly in the rapidly growing cities of developing countries (Greenwalt et al., 2018). According to the Regional Climate Change Index (RCCI), the Mediterranean Region, along with the Northeastern European regions, is considered a 'primary hot-spot region'. Türkiye, located in the Eastern Mediterranean Basin, is recognized as one of the regions most threatened by climate change (IPCC, 2007; Giorgi, 2006). The vulnerability of the Mediterranean Region stems from its position in the transition zone between the North African Climate and that of Central Europe. Consequently, it is influenced by interactions between these two zones, hence even minor changes

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*(Corresponding author), Assist. Prof. Dr., Konya Technical University, Türkiye ✉honcel@ktun.edu.tr

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in air circulation can result in significant changes of the Mediterranean Climate (Giorgi & Lionello, 2008).

Vulnerability is defined as the degree of susceptibility of a city or community to the consequences of hazards or stress (Turner et al., 2003). Stress develops gradually but with steadily increasing pressure (e.g., climate change, drought). Pelling (2003) points out the system of weakness as the inability to avoid or absorb potential harm. Hazards are classified as natural (e.g., earthquake, volcanic eruption, hurricane), social (e.g., civil riot, terrorist attack), or technological (e.g., spill, explosion, release of toxic chemical). In recent decades, a new class of hazard has emerged, known as socio-natural, which results from human action, such as climate change. Vulnerability increases in direct proportion to exposure and susceptibility and is inversely related to coping capacity (Villagrán de León, 2006). Chambers (1989) submitted the external and internal sides of vulnerability:

- External: related to exposure to external shocks and stresses; and
- Internal: associated with defencelessness, incapacity to cope without damaging losses.

Vulnerability can be defined as a combination of damage potential, resilience, and resistance. Bogardi (2006) clarified resistance as related to the capacity of the system to remain unchanged for an interval of time following a disruptive event. In contrast to resistance, resilience refers to the system's capacity to return to its pre-disaster state. Coping capacity is defined as a combination of resistance and resilience (Villagrán de León, 2006).

Resilience denotes the natural, built, social, and economic capacities of an urban system to manage change and to respond after experiencing disaster, stress, or shock (Newton & Doherty, 2014). Urban resilience includes strengthening the resistance of cities to natural disasters such as earthquakes or floods, as well as to risks such as human-induced global warming or terrorist attacks. Moreover, the focus of resilience is not only reducing losses in the face of a risk, but rather on improving the overall performance of a system when confronted with threats. Cities should have key attributes that enable them to be reactive, adaptable, recoverable, regenerative, and transformable in the face of risks and hazards (Dincer & Yalçıner Ercoşkun, 2024). Urban planning is critical to achieving resilient cities by incorporating climate change into urban planning, analyzing high-risk areas, preventing urban areas, developing climate adaptation plans, and determining building codes related to climate change. Vulnerability assessments can be regarded as the first step in achieving adaptation-planning integration (Sılaydın Aydın, 2021). Climate adaptation is defined as the adjustment of natural or human systems to potential climate stimuli or their effects, which involves mitigating damages, taking advantage of opportunities, and ultimately preventing or reducing vulnerability to climate change. Climate-adaptive cities' characteristics are: effective resource management, stakeholder participation, a low-carbon economy, decentralized climate change management, innovation in governance and industry, utilizing knowledge, education-focused, and foresight in planning (Yari et al., 2024).

There are many studies in the literature on assessing urban vulnerability to global warming. Xie and Zheng (2017) examined the evaluation indicator system for climate-adaptive cities. Balica et al. (2012) developed a Coastal City Flood Vulnerability Index based on exposure, susceptibility, and resilience to coastal flooding. This study demonstrated the most vulnerable cities through an analysis of nine coastal cities around the world. Binita et al. (2015) conducted vulnerability analyses by combining climatic, social, land cover, and hydrological components into a unified vulnerability assessment. Kim et al. (2016) assessed the vulnerability of Korea and identified key municipalities at risk to support the national adaptation plan. Zanetti et al. (2016) developed the socio-environmental vulnerability index for coastal areas in the context of climate change and applied it to the city of Santos, Brazil. Jubeh and Mimi (2012) developed the Governance and Climate Vulnerability Index, which measures the vulnerability of five countries (Israel, Jordan, Lebanon, Palestine, and Syria) to water-related issues, taking into account governance and climatic indicators. Menezes et al. (2018) developed a Municipal Vulnerability Index and evaluated the factors that make the municipalities in the state of Amazonas, Brazil, vulnerable to climate change in the context of the world's largest tropical forest, as well as regions of the State are the most susceptible. Feindouno et al. (2020) proposed an index of exogenous vulnerability that can be used to identify countries that are more susceptible in terms of structural and physical reasons.

Studies conducted for Turkish cities: Sılaydın Aydın et al. (2017) identified the primary spatial factors that increase vulnerability to excessive precipitation and sea-level rise and determined the zones at risk in İzmir (Türkiye) based on building characteristics and development. Sılaydın Aydın (2021) sought to develop a framework on how vulnerability analysis should be handled at different scales. Akbulut Başar (2023) proposed a spatial multi-criteria analysis of the physical environment. This study aims to analyze the vulnerability of the Niğde city center. Salata et al. (2022) studied the sponge district concept in İzmir (Türkiye), one of Europe's most vulnerable areas to pluvial flooding. They employed a composite index to determine potential areas of intervention for nature-based solutions. Toy and Eren (2023), proposed suggestions for Türkiye concerning the classification and parameterization of urban characteristics that affect climate elements, the conversion of these parameters into data, and the monitoring and evaluation of meteorological parameters alongside these data. Gülpınar Sekban and Acar (2024) aimed to illustrate how spatial solutions can be developed by integrating climate change adaptation strategies into the redesign of urban open green areas, thereby enhancing ecosystem services and reducing the carbon footprint of the designs by embedding these strategies into the design process.

There are two theses in the YÖK Theses database on global warming and cities: Hajibayov (2017) prepared a thesis entitled: 'Evaluating the impact of floods on planning in Edirne city in terms of global climate change'; and Çimen (2023) completed a thesis entitled: 'The relationship between megacities and global warming: a comparison between Kocaeli and Şanlıurfa'. In addition to these valuable studies, there is no comprehensive research addressing all the risks of climate change in Türkiye, nor is there any study analyzing urban vulnerability separately for all risks.

1.1. Aim and Objectives

1.1.1. Aim

The study aims to develop an index to measure the vulnerability of cities in Türkiye, not to a single consequence of climate change, but to all possible consequences.

1.1.2. Objectives

The following objectives have been outlined to develop the index:

a. To identify criteria for assessing the vulnerability of cities to climate change in terms of drought, sea-level rise, extreme heat, and extreme heavy rainfall
b. To develop new criteria
c. To identify cities that are more vulnerable to different risks and to contribute to the necessary policies and preparations

1.2. Research Questions

a. Which cities are at risk and have more vulnerability to the various consequences of climate change?

2. Literature Review

2.1. Climate Change

The cause of climate change is the significant increase in greenhouse gas emissions on a global scale. This also leads to changes in exposure to climate hazards, with the impacts depending to a certain degree on social, economic, and governance factors that determine both sensitivities and their capacities (Leary et al., 2008). Climate change causes unpredictable weather events, an increased incidence of both extreme heat and cold, rainfall instability, rising sea levels, and the melting of land-based ice masses. Other concerns include the impacts of food production and low-lying human settlements. While impacts of climate change will vary regionally, they can be summarized as follows (Change, I. P. O. C., 2001):

Freshwater resources: By mid-century, annual average river runoff and water availability are projected to decrease by 10-30% in some dry regions at mid-latitudes; however, they are expected to rise by 10-40% at high latitudes and in some wet tropical areas. Water supplies stored in glaciers and snow cover are projected to decline, which is expected to increase drought-affected areas. Heavy precipitation events will heighten flood risk.

Ecosystems: Many ecosystems are likely to be affected by land-use change, overconsumption of resources, flooding, drought, wildfire, insect outbreaks, and ocean acidification. If the global average temperature exceeds 1.5-2.5°C, the functions and structures of ecosystems, ecological interactions, and the geographic ranges of species are expected to change. The increasing atmospheric carbon dioxide causes ocean acidification and affects marine shell-forming organisms, such as corals and other species that depend on them.

Food and forest products: At lower latitudes, especially in tropical and seasonally dry regions, crop productivity is expected to decrease. In addition, fish species are projected to experience regional shifts in production.

Coastal systems and low-lying areas: Coasts may be among the highest-risk areas due to sea-level rise. Dense urbanization in low-lying areas will face challenges such as tropical storms or local coastal subsidence. If the global average temperature increases by 1-4°C, partial deglaciation of the Greenland and West Antarctic ice sheets could cause sea levels to rise by 4-6 m or more. If the Greenland and West Antarctic ice sheets melt completely, sea-level rise will reach 7 m and about 5 m, respectively.

Industry, settlement and society: Economies are closely linked to climate-sensitive resources, and industries and settlements experiencing rapid urbanisation in areas prone to extreme weather events or located in coastal and river floodplains are among the most vulnerable. Extreme weather events are expected to cause economic and social losses. Moreover, climate change and its associated exposures are likely to impact human health.

Both rural and urban areas are confronted with climate change through a complex feedback mechanism that affects entire systems. To set an example, while extreme precipitation increases flood risks, it can also facilitate the spread of vector-borne microbes. Urban areas are at greater risk of floods because most changes in the hydrology and geomorphology of rivers and drainage basins occur in these areas. The most vulnerable social group consists of poor households that lack insurance coverage to recover and rebuild their homes. In addition, the urban heat island (UHI) effect makes urban areas more vulnerable to the heat-related manifestations of climate change. UHI, together with heat waves, has particularly detrimental effects on low-income populations, as these residents are less likely to afford health insurance or air conditioning. Moreover, resource-based industries, which are highly sensitive to changes in temperature and precipitation, can lead to a ‘socio-economic drought’. Elderly populations will also be affected by heat waves and extreme weather conditions (Binita et al., 2015). Consequently, elderly and lower-income populations are more vulnerable to the consequences of climate change.

Solutions vary by country, region, and city. In high-income countries, improving urban spaces is critical for reducing greenhouse gas emissions. In developing countries, different solutions should be implemented (Greenwalt et al., 2018). Cities around the world need to implement planning and practices that will increase urban resilience against climate change (Balica et al., 2012). The World Bank (2021) suggests that nature-based solutions beneficial for urban resilience include wetlands, salt marshes, river floodplains, sandy shores, forests, river and stream renaturation, open green spaces, urban agriculture, and building solutions. These solutions make important contributions, such as mitigating heat stress, reducing flood risk, and storing carbon.

As a preliminary step, vulnerability analysis is essential for assessing the resilience and vulnerability of cities. Only after this step is it possible to determine adaptation policies. In addition, the vulnerability levels of cities vary according to many factors, such as their physical, geographical, infrastructural, and building conditions. In addition, many social and economic factors, such as the level of development, unemployment rates, the proportion of the population living alone, the proportion of children, the elderly, women, and disabled people, increase the vulnerability of the city (Sılaydın Aydın, 2021; Dincer & Yalçıner Ercoşkun, 2024).

As cities continue to grow and become more complex, poor urban design and management have unintended consequences (Pickett et al., 1997). Because the dynamics of cities are non-linear, we have to change traditional linear planning methodologies. Urban ecosystem services need to be sustainable, and new means of planning have to deal with the complexity of urban areas (Wilkinson, 2011). Evidently, we need to integrate governance systems with stakeholder participation for improving adaptive and transformative capacities of cities (Barthel et al., 2010).

3. Methods and Materials

Different methods are used to assess vulnerability on different scales. At the national scale, various tools are used to assess the vulnerability of countries, including the disaster-risk index (BCDR-UNDP), the hot-spots model (World Bank), the composite vulnerability index, natural disaster vulnerability indicators, the social vulnerability index, and disaster-risk indices (IADB-ECLAC-IES) (Villagrán de León, 2006). These models typically draw on data from past disasters and related losses, make predictions for the future, and identify the most vulnerable countries.

Munich Re Group (2003) developed a method to assess the vulnerability of megacities around the world, using three parameters: structural vulnerability, standard of preparedness/safeguards, and overall quality of construction and building density. The index is built on a foundation of information on the current status of the cities, rather than on the historical outcomes of previous disasters. Many studies assessing vulnerability at the local level have developed methods within the framework of various criteria according to the type of disaster (Villagrán de León, 2006). Most indices are based on metrics, mainly the arithmetic or weighted mean of factors.

In addition to physical and structural vulnerability, social and economic vulnerability is equally important. A combination of biophysical and social processes generates vulnerability (Tonmoy et al., 2014). In the literature, various criteria such as age, personal wealth, single-sector economic dependence, poverty, unemployment, renter population, immigrants, race, income, gender, inmate population, female-headed household, and occupation are used to measure social vulnerability (Zanetti et al., 2016; Binita et al., 2015). In this study, social and economic vulnerabilities are assumed to remain constant across all risks and are therefore not included in the criteria set.

The method is based on the information about the current status rather than previous disasters. The first reason for this is that the effects of climate change on the atmosphere and ecosystems are only beginning to be observed. The second reason is the view that the effects of climate change will manifest very rapidly over the next century. The impacts of climate change are discussed under four headings: Drought, Sea-Level Rise, Heavy Rainfall, and Extreme Heat. For these headings, factors were determined according to the criteria of effect, pressure, vulnerability, resistance, and adaptive capacity. All factors are presented without weighting. The first type of indicator, *effect*, describes the criteria that reveal the risk. The second criterion, *pressure*, includes indicators that increase the vulnerability of the city and have a negative impact. The third indicator, *vulnerability*, shows the dimensions of the city’s existing structural, natural, economic, and geographical characteristics that have the potential to increase risk. The *resistance* criterion has a positive effect. It includes indicators that the city has and that increase its resilience. Finally, the *adaptive capacity* criterion shows the indicators that have the potential to be developed for the city.

Extreme weather events, as one of the consequences of climate change, are not analyzed under a distinct heading. This is because extreme heat and extreme precipitation were addressed separately, while hurricane risk was not considered. The first reason for this is that, in the studies in the literature, the methodologies for determining the storm risk are largely predicated on whether a settlement has previously experienced a storm disaster. However, hurricane risk may apply to all settlements, not only to those with a history of hurricanes. It was excluded from the scope as it was a disaster that developed outside the physical, structural, and spatial characteristics of the city. The second reason is that Türkiye has never experienced a hurricane disaster to date.

One of the difficult aspects of identifying risk is that it requires a large amount of local data, which is often unavailable for extended areas (Zanetti et al., 2016). In many studies, the choice of method depends on the objectives of the study and the availability of data (Feindouno et al., 2020). In this study, factors were formed on the basis of the available data.

4. Results and Findings

4.1. Indicators Determining Urban Vulnerability to Climate Change

Studies show that the consequences of climate change differ for each region and city. While some regions will face drought, some regions will face sudden heavy rainfall or extreme heat (Figure 1). In order to create climate-adaptive cities, it is initially necessary to determine the vulnerability of each city.

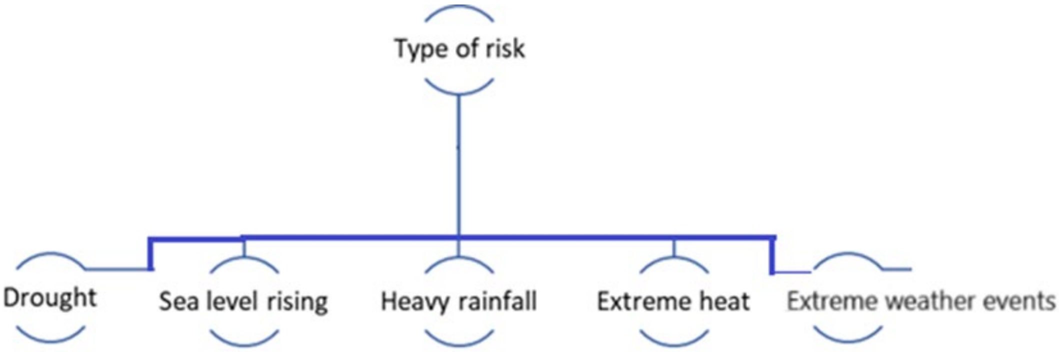

Figure 1 Type of risk due to climate change (Prepared by the author)

In this study, an index has been developed to assess urban vulnerability to climate change across different dimensions. In this way, it will be possible to more effectively manage the resources allocated to countries' resilience. Through this comprehensive method, both the vulnerability of cities and their resilience can be determined. In addition, it will help reveal the deficient dimensions in order to increase adaptation in a city. Thus, an assessment template will be established to measure the vulnerability of cities. The necessity of such a method arises from the fact that no country has sufficient resources to make all cities climate-adapted to all risks simultaneously. Therefore, countries need to implement a climate-adaptive approach in stages, beginning with high-risk cities. The identification of risk types and indicator types is as follows:

Table 1 Drought Risk Indicators and Impact

Risk	Indicator types	Effect	Indicators	Impact	References
DROUGHT	Effect	Negative	Temperature level	Average annual air temperature affects the amount of precipitation. Studies accepted a lower limit of -4,7 and an upper limit of 28.4.	Adapted from Feindouno et al., 2020
			Rainfall level	Drought risk increases if annual rainfall is low. Studies accepted a lower limit of 33.5 and an upper limit of 3792.4.	Adapted from Feindouno et al., 2020
	Pressure		Trend in temperature instability	As air temperature increases and humidity decreases, precipitation may decline. Studies accepted a lower limit	Adapted from Feindouno et al., 2020

				of -0.07 and an upper limit of 0.02 for annual average temperature change.	
			Trend in rainfall instability	Decreases in the rainfall regime increase the risk of drought. Studies accepted a lower limit of -287 and an upper limit of 202 for changes in rainfall instability.	Adapted from Feindouno et al., 2020
			Consecutive dry days	The climate parameter that indicates a greater propensity for dry periods. The higher the average CDD, vulnerability increases.	Adapted from Menezes et al., 2018
			Records of water supply decrease due to drought	Vulnerability is considered very high if the annual reduction in water resources is over 50%.	Adapted from Kim et al., 2016
			Urban population	As the population grows, vulnerability increases because of rising water and food demand.	Adapted from Sılaydın Aydın, 2021; Villagrán de León, 2006
			Rate of population growth	Vulnerability increases in cities with annual population growth rates above 4%.	Adapted from Sılaydın Aydın, 2021
			Distance to the water supplies (km)	Distant water sources contribute to increased vulnerability.	Adapted from Jubeh and Mimi, 2012
			The presence of forest areas near settlements due to forest fires	The risk of forest fires increases, especially in summer, in areas where rainfall decreases and temperatures rise.	Elaborated by the author
			Proportion of urban population living from agriculture	Vulnerability rises as the proportion of the population dependent solely on agriculture increases.	Elaborated by the author
			Water consumption per capita	Pressure increases as per capita water consumption rises.	Adapted from Xie and Zheng, 2017
	Vulnerability		Amount of agricultural area	Vulnerability increases as the amount of agricultural land and the share of the agriculture sector in the city's economy.	Elaborated by the author
	Resistance	Positive	Water potential	Resistance increases when the annual per capita availability of water resources is high.	Adapted from Sılaydın Aydın, 2021
			Greywater recycling systems	The reuse of treated wastewater and the rate of wastewater recycling reduce water demand.	Adapted from Jubeh and Mimi, 2012; Xie and Zheng, 2017
			Dry farming practices	Dry farming practices reduce water demand in the agricultural sector (the sector with the highest water consumption).	Elaborated by the author
			Rainwater harvesting systems	The collection rate of rainwater falling on building roofs and asphalt surfaces, the presence of rainwater collection systems in buildings, and the incentives applied reduce water demand.	Adapted from Freni and Liuzzo, 2019
			Drought-resistant planting and green areas	Drought-tolerant landscaping in yards and parks increases the resilience of urban greenery.	Elaborated by the author
			Efficient household water use strategies	Efficient household water use strategies reduce water demand.	Adapted by Leary et al., 2008
			Drought-resistant agricultural practices	Drought-resistant crop varieties and efficient irrigation systems reduce water demand.	Rezvani et al., 2023
	Adaptive capacity		Forest cover, reforestation and afforestation	The amount of forest land and trees to reduce greenhouse gas emissions and fight drought by increasing atmospheric humidity. On the other hand, drought can also lead to forest fires. Therefore, precautions can be taken for forest areas close to settlements.	Rezvani et al., 2023 and Sılaydın Aydın, 2021

The drought risk depends on the current levels of temperature and rainfall, as well as on the trends over time. Green spaces play a key role in stormwater management, and raingardens are shallow vegetated areas that help to collect and treat the stormwater runoff from the surrounding impermeable surfaces (Croce & Vettorato, 2021). Greywater recycling helps to reduce freshwater demand (Rezvani et al., 2023). The indicators of drought risk are presented in Table 1.

Table 2 Sea Level Rise, Risk Indicators, and Impact

Risk	Indicator types	Effect	Indicators	Impact	References
SEA LEVEL RISE	Effect	Negative	Sea level rise	Vulnerability increases as the sea level rises. Studies reported sea level rise values from the most vulnerable to the most resilient: 0.9 m, 0.7 m, 0.5 m, 0.3 m, 0 m.	Adapted from Zanetti et al., 2016 and Tallis et al., 2011
	Pressure		Altitude	Positive effect if the altitude of the city is high.	Adapted from Sılaydın Aydın et al., 2017
			Distance to the coast	Should be evaluated together with altitude: If the altitude of the area between the settlement and the coast lies at or below sea level, being far from the coast has less positive impact. However, if the settlement itself is located at sea level or below, and there are high-altitude areas between it and the coast, it can be considered more resilient. In addition, cities situated on cliffed shores and at high altitudes have high resistance, even when they are close to the coast.	Adapted from Zanetti et al., 2016 and Anazawa et al., 2013
			The ratio of built-up area at low altitude	The risk increases as the proportion of built-up areas in low-altitude coastal areas increases.	Adapted by Ercanlı, 2024, Balica et al., 2012, Kahraman and Aydın, 2016
			The length of the coastline	The risk increases as the length of the built-up area along the coast increases.	Adapted by Ercanlı, 2024, Balica et al., 2012, Kahraman and Aydın, 2016
			Population at risk	The percentage of the total population living in areas of high and very high risk for landslides and hydrological events of the total population.	Adapted from Menezes et al., 2018
			Rate of population growth	Cities with positive annual population growth rates are more vulnerable.	Elaborated by the author
			Irrigation and freshwater systems close to the sea	The risk increases if such systems are located both close to the coast and at low altitude due to the salinization risk.	Adapted by Leary et al., 2008; Balica et al., 2012
			Costs of coastal protection versus the costs of land use relocation	Coastal uses with high relocation costs, such as industrial and technology centers, increase vulnerability.	Adapted from IPCC, 2007

			Urban densities on the coast	Ratio of neighborhood population size to neighborhood area in the coast.	Elaborated by the author
			Share of territory 1 m below sea level	The risk may increase if the altitude in some areas of the settlement reaches sea level or falls below it. In some studies, the lower limit is defined as 0 and the upper limit as -93.5 cm.	Adapted from Feindouno et al., 2020 and Sılaydın Aydın, 2021
	Vulnerability		Loss of tourism-related income	Proportion of the population living in the tourism zone if tourism areas are on the coast.	Adapted from Leary et al., 2008
	Resistance	Positive	High altitude	The risk decreases as the altitude increases	Adapted from Ercanlı, 2024
			Open space ratio of coastal and low-altitude areas	The risk decreases as the open space distance between the coast and the building areas increases.	Adapted from Ercanlı, 2024, Balica et al., 2012, Cowell et. al, 2003
	Adaptive capacity		Implementation of trench and seawall	Topographic redesign of the space between the coastline and building blocks according to risk (e.g., slope) will decrease risk	Adapted from Ercanlı, 2024, Rezvani et al., 2023
			Implementation of new architectural systems	Flexible living spaces with floating architectural systems, designing structural systems that can rise with the water level, will decrease risk.	Adapted from Ercanlı, 2024

Due to climate change, coastal communities are expected to be increasingly affected by floods and sea-level rise. 21% of the world's population lives within coastal zones, and under current conditions, 46 million people experience storm-surge flooding per year. Moreover, the potential impacts of sea-level rise pose a risk for the broader coastal ecosystem and urban areas (Balica et al., 2012). According to modelling studies of thermal expansion, glaciers, and ice-sheets, the estimated rate of sea-level rise from 1910 to 1990 ranges from 0.3 to 0.8 mm per year (Church et al., 2001). After the 1990s, the rate of global mean sea-level rise has reached 3.3 mm per year, nearly twice that of the previous decades (Cazenave & Cozannet, 2014). It has been suggested that sea-level rise could exceed 1 m during this century (Feindouno et al., 2020). Climate change is expected to impact tourism by accelerating beach erosion, inundating and degrading coral reefs, threatening hotels, damaging other tourism-related infrastructure, and discouraging tourists from visiting the affected areas (Leary, 2008). Indicators of sea-level rise risk are presented in Table 2.

Another consequence of global climate change is sudden rainfall, which increases the risk of flooding. The impermeable surfaces in urban areas increase the risk of flooding. In addition, technological developments contribute to the creation of climate-adapted cities. Indicators of heavy rainfall risk are presented in Table 3.

Table 3 Heavy Rainfall, Risk Indicators and Impact

Risk	Indicator types	Effect	Indicators	Impact	References
HEAVY RAINFALL	Effect	Negative	Rainfall level	High precipitation level increases the risk. The accepted rainfall range is 3792,4 mm (upper limit) and 33,5 mm (lower limit)	Adapted from Feindouno et al., 2020
	Pressure		Trend in rainfall instability	Flood risk increases as changes in precipitation trends go to up levels, negative levels, and drought risk increases as they go to negative levels. The accepted	Adapted from Feindouno et al., 2020

				range is -287 (lower limit) to 202 (upper limit).	
			Urban population	As the population increases, the risk increases as the urban area expands and the proportion of impermeable surface increases.	Elaborated by the author
			Rate of population growth	Vulnerability increases for cities with annual population growth rates above 4%.	Adapted from Sılaydın Aydın, 2021
			Size of built-up area	As urban areas expand, vulnerability rises due to increased impermeable surfaces and a higher population exposed to potential disasters.	Adapted from Sılaydın Aydın, 2021; Villagrán de León, 2006
			Footprint ratio	As the footprint ratio (floor area of the building on the parcel) increases, the proportion of impermeable surface and flood risk increases.	Adapted from Sılaydın Aydın, 2021
			Slope	In flat areas, the risk of flooding increases, while in areas with high slopes, severe runoff situations are experienced (with slopes above 80% and below 20% most risky)	Adapted from Sılaydın Aydın et al., 2017 and Zanetti et al., 2016
			Water body proximity (WBP)	Flood risk increases in settlements close to water bodies such as lakes and dams.	Adapted from Anazawa et al., 2013
			The rate of impermeable surface	Impermeable surfaces such as roads, highways, building footprints, and parking lots increase flood risk.	Elaborated by the author
	Vulnerability		Geotechnical classification of soil (GCS)	From the most vulnerable to the most resilient: 1. Colluvium and talus body, expansive soils 2. Alluvial, fractured rock with clean raptures filled with clays 3. Laterite soils, sandy soil 4. Tertiary non-expansive soil, fractured rock with rugose surface 5. Bedrock	Zanetti et al., 2016
			Urbanization close by rivers and natural drainage areas	Drainage areas in and near the city increase vulnerability.	Adapted from Sılaydın Aydın et al., 2017
	Resistance	Positive	Flood barriers, trenches and levees in flood-prone areas	Topographic redesign according to risk (slope, etc.) will decrease risk.	Adapted by Ercanlı, 2024, Rezvani et al., 2023
			High open space ratio, natural and green areas	Increasing the proportion of permeable surfaces that allow rainwater to reach the soil increases urban resilience.	Adapted from Sılaydın Aydın et al., 2017, Xie

					and Zheng, 2017
			Implementation of floating or stilted structures	Initiatives and regulations for the development of floating or stilted structures increase resilience.	Adapted from Huebner, 2025
			Subbasement	Proportion of buildings with subbasement strengthened resistance.	Adapted from Sılaydın Aydın, 2021
			Rainwater and sewage systems	The installation of rainwater harvesting tanks with a capacity higher than 5 m³ will reduce risk.	Adapted from Freni and Liuzzo, 2019
			Green roofs and walls	For moderate rainfall events, if at least 50% of the surrounding area has green roofs, and for strong rainfall events 60% to 95% of green roofs could prevent flooding.	Adapted from Mora-Melià et al., 2018
			River basin management, restoration of natural water bodies and wetland restoration	River and wetland restoration will reduce flood risk.	Adapted from Wharton and Gilvear, 2007
			Permeable pavements	Technological applications such as porous asphalt and the use of pervious concrete in the landscape structures, such as parking areas, bicycle roads, and walkways, allow rainwater to be delivered to the underground effectively	Adapted from Tokgöz et. al., 2022
	Adaptive capacity		Presence of unused land	Planning urban gaps as open and green spaces can reduce flood risk.	Adapted from Sılaydın Aydın, 2021

It is to be expected that heat waves due to global climate change will pose a greater problem closer to the equator. However, studies indicate that the impacts will also be significant at higher latitudes. Because of albedo feedback and ocean current heat transport, surface temperature will strongly alter by about 5-12 °C in polar regions, while it is expected to be 2-3 °C in the low and mid-latitudes. High latitudes will be more vulnerable to alteration by changes in climate, through changes in sea ice, permafrost, river flow, or weather conditions (Roots, 1989), whereas heat waves are expected to pose a more severe problem at low latitudes. The World Meteorological Organization (WMO) defines a heat wave as five or more consecutive days of prolonged heat during which the daily maximum temperature exceeds the average maximum temperature by at least 5 °C (9 °F). Heat waves exacerbate air pollution, increase fire risk, cause heat- and drought-induced crop failures, and pose a significant risk to human health (Zeder & Fischer, 2023). Total urban warming refers to the combined increase of extreme heat in urban settlements from both the UHI effect and anthropogenic climate change. Studies indicate that at latitudes closer to the equator, the increase in the annual number of days with temperatures above 30°C is more pronounced (Tuholske et al., 2021). Some studies also suggest that wind speeds can decrease up to 22% under extremely high temperatures and severe drought conditions (Jiménez et al., 2011). But dense high-rise buildings in urban areas weakened wind speeds, and rapid urbanization has intensified the UHI effect and increased the frequency of urban heat wave events (Zong et al., 2021). On the other hand, strong winds can have detrimental effects on infrastructure, forests, and fires (Gliksman et al., 2023).

Urban design and urban surfaces play a key role in fostering the consequences of climate change. Urban surfaces can be divided into two main categories: ground and building surfaces. Ground surfaces include road networks and urban open spaces, while building surfaces comprise façades and rooftops. Cool materials can help maintain lower surface temperatures and mitigate the UHI effect. Green spaces improve thermal comfort, while green building elements ensure indoor and outdoor climatic comfort and energy efficiency. Building roofs account for approximately 20-25% of the total urban surface (Croce & Vettorato, 2021). Therefore, green roof applications are of considerable importance. In addition, urban tree planting provides localized cooling effects (Rezvani et al., 2023). Extreme heat risk indicators are presented in Table 4.

Table 4 Extreme Heat, Risk Indicators, and Impact

Risk	Indicator types	Effect	Indicators	Impact	References
EXTREME HEAT	Effect	Negative	Latitude	Vulnerability increases for cities located closer to the equator. Cities located at latitudes lower than 45 degrees North and South are more vulnerable.	Elaborated by the author
			Wind velocity and impact	Impact calculation based on the annual average number of windy days and wind intensity (Very low and very high wind impacts are negative, average values are positive). It positively affects thermal comfort at high temperatures, as the wind reduces the sensation of heat The number of days with a daily maximum wind speed exceeding 14 m/s is considered risky. Winds up to 10.8 m/s are considered "normal". Above 10.8 (10.8 * 3.6 = 38.8 km/h) is strong wind. Winds above 17.1 m/s (61.2 km/h) are storms.	Kim et al., 2016
	Pressure		Temperature	The number of days with over 33 °C of daily maximum temperature is considered risky.	Kim et al., 2016
			Urban density and urban area	Risk increases as urban densities rise, especially in megacities with a population density exceeding 3000 p/km², and urban areas reach 1000 p/km² or more.	Elaborated by the author
			Urban population	Although population growth does not have a direct impact, the urban heat island effect increases due to the demand for construction and the density required for the population. Megacities with populations in the millions are the most vulnerable cities.	Elaborated by the author
			Rate of population growth	Cities with positive annual population growth rates are more vulnerable.	Elaborated by the author
			Proportion of reflecting surface	The ratio of reflective surfaces, such as reinforced concrete, glass, and steel, in the city. Scoring of all surfaces should be recommended according to the albedo effect.	Elaborated by the author
			Road widths	As road widths increase, the urban heat island effect increases as the proportion of reflective surface increases.	Elaborated by the author
			Presence of forest areas near settlements due to forest fires	Forest areas near or within cities increase the risk of fire, especially in areas with drought and arid regions.	Elaborated by the author
	Vulnerability		Urban heat island effect	Urban heat island effect has a multiplier effect with global warming.	Elaborated by the author
			Proportion of elderly and child population	The percentage of the population that is elderly (60 years or older) and the projection of children aged 0 to 4 years for the coming or planned years constitute the vulnerable population.	Adapted from Menezes et al., 2018
	Resistance		Amount and proportion of absorbent surfaces that do not reflect sunlight and reduce local temperature	The proportion of surfaces such as forests, wooded areas, grass, green roofs, water bodies, and soil in and around the city reduces temperature (Maximum positive impact in forest areas, minimum positive impact in soil areas)	Croce and Vettorato, 2021
			Fire-resistant materials	The proportion of heat-resistant pavement materials and initiatives/regulations for the	Rezvani et al., 2023

				development of fire-resistant buildings encourages resilience.	
			Highly reflective and emissive materials	White or light-colored reflective materials, super-cool materials, and retroreflective materials increase resilience.	Croce and Vettorato, 2021
			Shading status of public areas	Ensuring climatic comfort, closed public space ratio, air-conditioned public space ratio, underground public space ratio, tree ratio in streets and pedestrian areas, shade-casting urban furniture, pavement shaded by buildings, etc.	Rezvani et al., 2023
			Cooling centers	Safe and air-conditioned environments protect from heat stress, and the number and size of air-conditioned buildings.	Rezvani et al., 2023
			Thermal comfort transportation	Air-conditioned public transport: vehicle ratio, metro line length, walkable green corridors	Elaborated by the author
			Green roofs and facade systems	Designing and building roofs and facades as absorbent surfaces instead of reflective surfaces has positive effects both in terms of the urban heat island effect and indoor thermal comfort.	Croce and Vettorato, 2021
			Building insulation	Proportion of buildings with insulation, and mandatory insulation requirements for new buildings.	Rezvani et al., 2023
			Hospital and health services	Health workers and health facilities per capita, enhanced emergency services, and infrastructure.	Rezvani et al., 2023
			Rescue and firefighting manpower	Strong firefighting manpower and infrastructure increase resilience against fire risk.	Adapted from Villagrán de León, 2006
			Existence of clean water resources	Increased water demand: Water consumption is expected to rise due to hot weather, affecting clean water resources.	Adapted from Change, I. P. O. C. (2001)
	Adaptive capacity		Presence of unused land	Mitigating the urban heat island effect by designating urban gaps in and around the city as green spaces.	Elaborated by the author

5. Conclusion

It is now well established that the effects of global climate change have different consequences for each region and city. In some regions, the risk of flooding increases due to irregular and excessive rainfall, whereas in others, the risk of drought increases. In addition, a climate-adaptive city approach is becoming increasingly important for protecting cities from potential future climate-related disasters. At this point, vulnerability assessments are among the first steps to be taken in order to identify the disasters that cities may face. In this study, all risks are considered separately in the vulnerability assessment of cities. Considering the limited resources of countries and urban municipalities, it is evident that taking precautions against all risks will be difficult. This study aims to provide a guiding index for both researchers working on urban resilience and city administrations. Thus, it seeks to contribute to the literature.

In addition, the incorporation of climate change into urban planning, zoning laws to prevent building in high-risk areas, the development of climate adaptation plans, and the development and enforcement of building codes related to climate change are key steps of the urban planning process for climate-adaptive cities. In future studies, a score-based index should be created by developing and weighting new criteria for vulnerability assessments.

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Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Ethics Committee Approval

Ethics committee decision is not necessary for this study.

Resume

Hale Öncel is an assistant professor in the Department of Urban and Regional Planning at Konya Technical University. She began her career in 2012 as a scholar in a Tübitak project focused on conservation-oriented rural planning. The following year, she became a research assistant at Selçuk University's City and Regional Planning department. Her research focuses on urban sprawl, sustainable urbanism, and urban design.