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Structural and non-structural measures to mitigate the impact of climate change on civil engineering structures: A review

İnşaat mühendisliği yapıları üzerinde iklim değişikliğinin etkisini hafifletmek için yapısal ve yapısal olmayan önlemler: Bir inceleme

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Abstract

This paper deals with some structural and non-structural measures that should be taken for civil engineering structures to be adaptable to climate change. Various measures to be taken to mitigate the impact of climate change in different civil engineering implements are presented from a broad perspective. The service life of existing structures is shortened by increasing temperature differences due to climate change, changing precipitation regimes, and rising sea levels. In addition, climate change will complicate the planning, design, calculation, and implementation stages of new structures for engineers in the long term. The aim of this study is to present measures to adapt infrastructure and superstructures to the effects of climate change. In the study, mitigation measures against factors such as changing climate parameters, floods, overflows, rising sea levels, and CO_2 reduction measures in construction activities are explained for existing or new buildings. In addition, the role of civil engineers in reducing the effects of climate change is also discussed in the study. Additionally, this study explains how civil engineers can guide decision makers in strategies to mitigate the effects of climate change. As a result, when different literature studies are examined, measures such as the use of waste materials in the production of construction materials, constructing drainage systems, using long-term precipitation forecasts, elevating infrastructure and structures, re-analyzing the dimensions of the bearing elements of the structures, building barrier systems, reorganizing existing water and marine structures, updating design standards, and preparing risk maps in river and coastal areas have been identified. In addition, it is understood that civil engineers have an important role in determining adaptation strategies against climate change in coastal areas and cities.

Keywords: Climate change, Adaptation measures, Design, Structures, Flood and overflood, Rising sea level.

Öz

Bu makale, inşaat mühendisliği yapılarının iklim değişikliğine karşı uyumlu olması için alınması gereken yapısal ve yapısal olmayan önlemler ile ilgilidir. Farklı inşaat mühendisliği uygulamalarında iklim değişikliğinin etkisinin hafifletilmesi için alınması gereken çeşitli önlemler geniş bir bakış açısı ile sunulmuştur. Mevcut yapıların hizmet ömrünü iklim değişikliği sebebiyle artan sıcaklık farkı, değişen yağış rejimi ve artan deniz seviyesi kısaltmaktadır. Ayrıca, iklim değişikliği uzun dönemde yeni yapıların planlama, tasarım, hesaplama ve uygulama aşamalarını mühendisler açısından zorlaştırmaktadır. Bu çalışmanın amacı, altyapı ve üst yapıların iklim değişikliğinin etkilerine karşı uyum sağlanmasına yönelik önlemleri ortaya koymaktır. Çalışmada, mevcut veya yeni yapıların değişen iklim parametreleri, sel, taşkın, yükselen deniz seviyesine karşı hafifletici önlemler ile inşaat faaliyetlerinde CO_2 miktarı azaltma önlemleri belirtilmektedir. Bunun yanı sıra çalışmada, iklim değişikliğinin etkilerinin azaltılmasında inşaat mühendislerinin rolü de tartışılmıştır. Ayrıca bu çalışmada inşaat mühendislerinin iklim değişikliğinin etkilerini azaltma stratejileri konusunda karar vericilere nasıl rehberlik edebileceği açıklanmaktadır. Sonuç olarak farklı literatür çalışmaları incelendiğinde, atık malzemelerin kullanılması, drenaj sistemlerinin inşa edilmesi, uzun süreli yağış tahminlerinin kullanılması, altyapı/üstyapıların yükseltilmesi, taşıyıcı sistemlerin boyutlarının yeniden analiz edilmesi, bariyer sistemlerinin inşa edilmesi, mevcut su ve deniz yapılarının yeniden düzenlenmesi, tasarım standartlarının güncellenmesi, nehir ve kıyı bölgelerinde risk haritalarının hazırlanması gibi önlemler öne çıkmaktadır. Ayrıca, kıyı bölgelerinde ve kentlerde iklim değişikliğine karşı uyum stratejilerinin belirlenmesinde inşaat mühendislerinin önemli bir rolünün olduğu anlaşılmaktadır.

Anahtar kelimeler: İklim değişikliği, Uyum önlemleri, Tasarım, Yapılar, Sel ve taşkın, Yükselen deniz seviyesi.

1 Introduction

The climate system is an interactive system consisting of the atmosphere (gas and vapor layer), hydrosphere (ocean and other water bodies), cryosphere (glacial layers and snow cover), land surface, and biosphere (habitat) [1]. This system is subject to constant change due to external factors such as solar radiation emission or internal factors such as atmosphere-ocean circulation and land surface-atmosphere interaction [2]. Global warming is the increase in the average earth's surface temperature due to the increase in the concentration of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor in the atmosphere caused by human activities [3]. This increase

in the earth's surface temperature brings about some changes in the climate system. For this reason, global warming and climate change are defined as different terms [4]. The first climate modeling and greenhouse gas effects were quantitatively determined by Svante Arrhenius in 1896 using the air balloon method [5]. The first scientific reports on climate change and global warming were published by Massachusetts Institute of Technology (MIT) in 1970. In the

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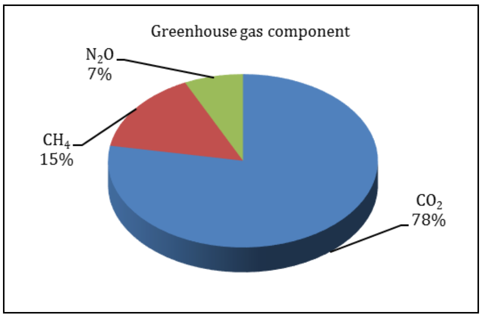
MIT reports, the causes of global warming and the human factor's effect on this warming are not fully explained. However, as global climate models have evolved, uncertainty regarding the processes influencing climate change has decreased over time. For example, the temperature change estimates in these climate models resulting from a two-fold increase in CO_2 are close to the temperature change values derived from real model results [6]. In recent years, climate science has developed further, and long observational records and advanced climate models have been used instead of geographical limitations and limited time data. Human activities are responsible for a ~1.2 °C increase in global average temperature and climate change, according to the findings of a vast majority of scientists [7]. Greenhouse gases cause rapid climate change and create a greenhouse effect in the atmospheric environment by keeping heat in the atmosphere. The captured heat energy is absorbed by the land surface, and then some of this heat energy is reflected back to the atmosphere. Reflected heat energy is absorbed by greenhouse gas molecules or emitted back to the earth's surface or space [8],[9]. Greenhouse gases contain ~77% carbon dioxide (CO_2), ~15% methane (CH_4), and ~7% nitrous oxide (N_2O) [10]. In addition, greenhouse gases are caused of ~46% of the energy and industry sectors, ~25% of agricultural practices, ~14% of the transportation sector, and ~6% of the construction sector [11]. CO_2 gas mainly originates from 34% of the energy sector, 22% of the industry sector, and 18% of households. CH_4 gas is mainly emitted in the waste (~44%) and agriculture sectors (~39%). ~65% of N_2O gas is emitted in the agricultural sector [10]. Figure 1 shows the ratios of greenhouse gas components and the distribution of sectors where greenhouse gases occur. When Figure 1 is examined, it is understood that the gases emerging in electricity and heat production and in the industry and agriculture sectors account for 70% of greenhouse gas emissions. On the other hand, it is seen that CO_2 gas, which has the largest share of greenhouse gas emissions, is an important factor in the occurrence of the greenhouse effect.



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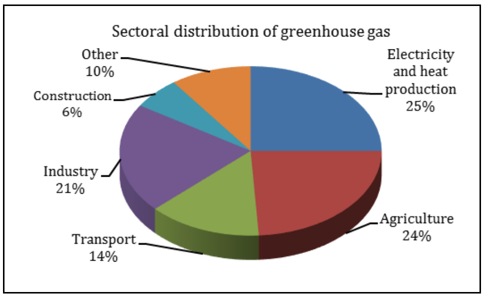
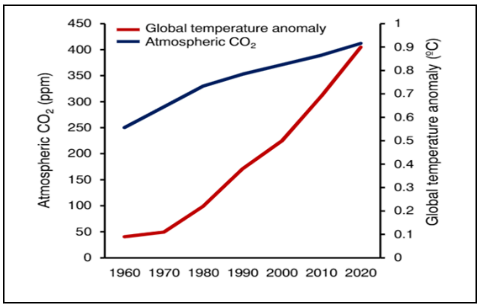


(b)

Figure 1(a): Greenhouse gas component ratios (%) [10] and b) Sectoral distribution of greenhouse gas emissions (%) [11].

Figure 2 shows the relationship between the amount of CO_2 and global temperature and the estimated amount of CO_2 for the year 2100.



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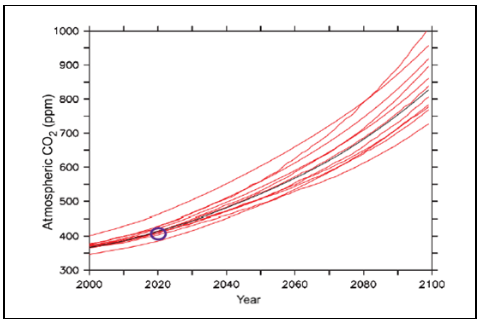

(b)

Figure 2(a): Relationship between amount of CO_2 and global temperature [12] and b) Estimated amount of CO_2 in 2100 [13].

As shown in Figure 2(a), CO_2 accumulated in the atmospheric environment seems to trigger a continuous increase in the average global surface temperature [12]. In addition, it is estimated that CO_2 emissions will increase until the 2100s Figure 2(b) [13]. In different scientific studies, it is explained that CO_2 emissions and the average global temperature will increase until the 2100s [14]-[16]. In the 2100s, it is predicted that the atmospheric temperature will increase by ~4 °C in the coastal areas and ~7 °C in the interior regions [16]. In 2016, the Paris Agreement was signed by 195 member states of the United Nations in order to prevent irreversible disasters by reducing CO_2 emissions. Within the framework of this agreement, a program with an annual budget of 100 billion dollars has been proposed in order to implement the necessary projects to reduce carbon emissions in developing countries [14]. Various studies and developed forecasting models show that an extra 1.5~2 °C increase in the average global temperature can lead to potential disasters [17]. Some of the disasters and extreme weather events that can be caused by global warming are hurricanes, tornadoes, rising sea levels, melting glaciers and ice sheets, increases in ocean temperature and ocean acidification, tsunamis, precipitation regimes, and flood disasters [19]-[24].

Figure 3 graphically shows the number of floods, extreme weather events, wildfires, extreme temperatures, and glacier eruptions reported globally between 1960 and 2022. When Figure 3 is examined, it is seen that there has been a serious increase in the number of some disasters and extreme weather events in the last 60 years all over the world. According to statistical values and historical observations, global warming and climate change have a great impact on human life and our environment [18],[26].

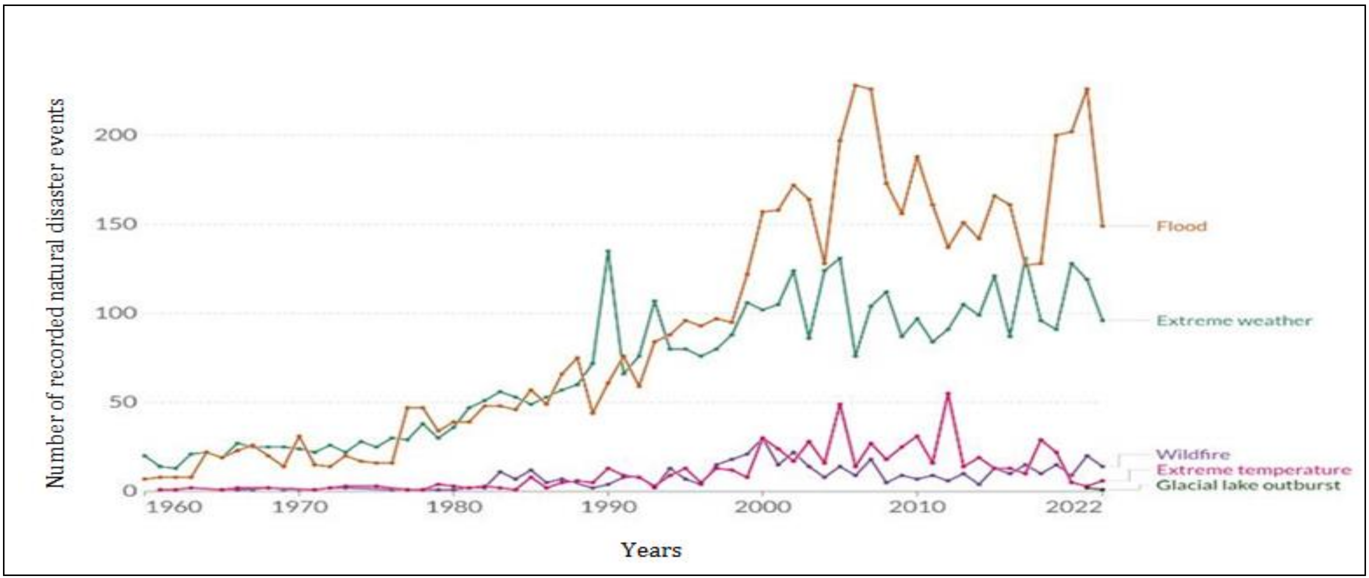

Figure 3. Number of disasters and extreme weather events between 1960 and 2022 [25].

These disasters and extreme events (flood, extreme weather etc.) have caused the deaths of many people, and it is estimated that the frequency, duration, and intensity of these disasters and extreme events will increase over time [27]. It is expected that climate change will cause less human loss in some regions of the world, while risk perception will change and human loss will be high in some regions. For example, in the Caribbean region, a linear increase in the number of hurricanes was detected according to wind speed data from 1970 to 2021. The change in hurricane frequency and duration could potentially result in large human losses in the Caribbean [28]. Different research studies and various climate models reveal that the damage of global warming and climate change to our world will increase exponentially. Some of the difficulties that will be caused by climate change will create new problems and impose new tasks on civil engineers. Civil engineers play an important role in industries that affect or are affected by climate change, such as construction, transportation, electricity, drainage, and flood defense. Climate change is predicted to have a negative impact, especially on undeveloped or developing countries with weak infrastructure [29].

The aim of this study is to identify structural and non-structural measures to mitigate the effects of some problems caused by global warming and climate change. For this purpose, in civil engineering structures, some structural and non-structural measures have been specified for flood and overflow extreme events, the effect of rising sea level, and adaptation of structures to climate change, reducing the value of CO_2 emissions. It is also understood that civil engineers have an important role in mitigating the negative effects of climate change. Differently from other literature studies, the issue of how to prepare for the changing climate change parameters in the coming years with civil engineering implements has been examined from a broad perspective. In addition, in our study, various literature studies including mitigation of the effects of climate change in different implements such as infrastructure, superstructure, water structures, and construction processes are presented together. On the other hand, it is emphasized that civil engineers can guide decision-makers in mitigating the effects of climate change. Thanks to the implementation of the specified mitigation measures, economic damages and risks to life and property safety caused by climate change can be reduced.

2 Methodology

In this study, it is explained that the land surface temperature and CO_2 value will increase in the future according to the predictions of various climate models. The construction industry also causes an increase in greenhouse gas emissions. Accordingly, for this literature study, various articles on building materials, construction techniques, and site management were examined first. According to these articles, measures to reduce the amount of CO_2 have been determined in terms of the construction industry and civil engineers. Secondly, various articles on infrastructure design, water management planning, and flood risk management have been searched for the adaptation of structures to extreme events such as increased floods and overfloods due to climate change. In these studies, structural and non-structural measures to be taken against the flood risk caused by climate change were determined. Thirdly, articles on the protection of marine structures and coastal areas against the effects of rising sea levels were examined, and measures that could be taken by civil engineers for the protection of coastal areas were identified. Fourthly, different articles examining the effects of changing climate parameters on structures were searched. According to these researched articles, the design, analysis, and planning measures for the adaptation of structures to climate change were examined. All the examined articles were categorized and presented on specific sub-topics.

3 Results and discussion

3.1 CO_2 emission reduction measures

Cement production accounts for about 5~7% of global CO_2 emissions. The use of industrial wastes such as fly ash and blast furnace slag as raw materials in the production of cement clinker and the use of blended cement produced from these industrial wastes in the construction sector considerably reduces CO_2 emissions [30]. In addition, the use of artificial raw material-based construction materials or construction materials made from recycled materials instead of natural-sourced raw materials in the construction sector decreases CO_2 emissions [31]. On the other hand, preferring to use machinery and equipment with high efficiency and low CO_2 emissions during construction time is very effective in reducing greenhouse gas emissions [29]. In addition, changes in construction techniques and the use of advanced construction technologies also reduce greenhouse gas emissions. For example, it has been determined that the amount of CO_2 emissions during the construction of the structures produced using 3D printed concretes (Contour Crafting Method) is ~86% less than the amount of CO_2 emissions that occur during the construction of the structures built with traditional methods [32]. Construction activities such as demolition works, excavation, drilling, mounting, loading and unloading of rubble, road construction, road maintenance and repair, mixing, and the movement of construction equipment in and around the construction site produce CO_2, dust, and particles [33]. As a result of these construction activities, dust and particles emitted into the environment cause air pollution [34]. Some measures can be taken to reduce CO_2 emissions in and around the construction site. Norway has aimed to reduce gas emissions at the construction site by implementing zero-emission construction site projects [35]. A zero-emission construction site can be defined as providing energy savings at the construction site, reducing the amount of construction waste, reducing environmental pollution, using renewable energy, and taking necessary measures to reduce CO_2 emissions [36],[37]. Some of the measures to be taken to reduce CO_2 emissions at the zero-emission construction site are listed below [35],[36],[38];

- Using electrical work machines,
- Preferring to use biodiesel-powered work machines on construction sites where there is no electrical installation,
- Reducing the use of fossil fuels or electricity by using solar or wind energy,
- Pre-planning of the most suitable alternative transportation route to reduce the number of transports of both personnel and construction materials,
- Reducing the construction time by choosing easy-to-assemble construction materials,
- Ensuring that construction materials are stored in the most suitable conditions,
- Using sensor lighting,
- Reducing the amount of construction and demolition waste.

On the other hand, Lim and Kim compared the amount of CO_2 emissions that occur during the production of precast concrete elements in the construction site with the amount of CO_2 emissions that occur during the production of precast concrete elements in the plant. In their studies, it is stated that less fuel, electricity, materials, and transportation equipment are used due to the production of precast concrete elements in the construction site. Accordingly, it has been calculated that the CO_2 emissions resulting from the production of precast concrete elements in the construction site instead of at the plant have decreased by ~15%. As a result, it has been determined that CO_2 emissions can be reduced by producing precast concrete elements in the construction site [39].

In the transportation sector, ~20% of the global CO_2 emissions occur, and the majority of the CO_2 gas emitted in this sector is caused by road transport [40]. Accordingly, transportation systems should be planned not only in terms of movement and safety but also in terms of the environment and climate change's impact [41]. Transportation is one of the most important branches of civil engineering [42]. Accordingly, in order to reduce CO_2 emissions in transportation planning, traffic flow should be facilitated by taking measures to reduce traffic bottlenecks at railway and highway junctions. In addition, fuel consumption should be reduced by using intelligent transportation systems (ITS) on highways, and the use of energy-saving technology in transportation facilities should be encouraged [29],[43]. In addition, the road structure or pavement is deteriorated by factors such as suddenly rises in traffic loading, improperly designed drainage systems, high temperature changes, and improper soil compaction. These deteriorations increase the number of road maintenance/repair works and cause an increase in greenhouse gas emissions [40],[44]. Accordingly, greenhouse gas emissions can be reduced by road construction with a durable and long service life. On the other hand, the type of pavement material is effective in reducing CO_2 emissions. When asphalt pavement and concrete pavement are compared, the CO_2 emission amount of the asphalt pavement type is higher due to the short service life of the asphalt material and the use of high heat in the production of asphalt mixture [45],[46]. On the other hand, CO_2 emissions can be reduced by modifying asphalt mixtures with waste plastic. For example, Yao et al. calculated in their experimental study that the service life of the asphalt pavement increased and CO_2 emissions decreased by ~29% when asphalt mixtures were modified with recycled asphalt and Polyethylene Terephthalate (PET) plastic waste [47]. Similarly, in another study, it was stated that CO_2 emissions can be considerably reduced by using high-density polyethylene (HDPE) waste plastic material as aggregate in asphalt mixtures ~5% by weight [48]. On the other hand, according to Vasudevan et al. found that 1 ton of waste plastic material can be used for the construction of a single-lane plastic road with a length of ~1 km. Thus, it has been stated that the amount of CO_2 can be reduced by ~3 tons by preventing the burning of ~1 ton of waste plastic [49].

When different literature studies are examined, civil engineers can contribute to reducing CO_2 emissions by using waste or recycling-based building materials in construction, planning site management with zero carbon emissions, choosing electric or high-efficiency work machines, applying new construction techniques, and designing the most appropriate intelligent transportation systems. Therefore, the decisions of civil engineers during construction are very important in reducing the impact of global warming and climate change.

3.2 Mitigation measures for flood and overflow events

Flood is defined as an extreme natural event in which a dry area is covered by a large body of water as a result of complex hydrological events [50]. Generally, flood disasters are classified in three different ways according to meteorological events. This classification of floods includes flash floods, river floods, and coastal floods. 1) Flash floods are defined as a rainy flood caused by heavy rainfall that is not caused by a body of water. 2) River floods are the rising of the river's water level and covering the adjacent lands with water due to reasons such as heavy rainfall or snowmelt. 3) Coastal floods can be explained as the submersion of low-lying areas when the water level of the sea or a lake rises [51]. There is a linear relationship between the air temperature value and the saturated vapor pressure value. Accordingly, the amount of atmospheric precipitation is also increasing due to the increase in global temperature. This situation causes a flood disaster by increasing the average precipitation value and the peak precipitation value [52]. In different literature studies, it is stated that global warming and climate change cause excessive precipitation and flood disasters [53]-[55]. Figure 3 shows an increase in the number of extreme flood events in the world between 1960 and 2022. Flood disasters cause a significant negative impact on society and the environment [56]. Cities with high population densities and significant infrastructure/superstructure facilities are highly vulnerable to flooding, and these cities may suffer serious economic losses as a result of flooding [57]. Bacanlı and Tuğrul observed in different analysis methods that global climate change affects the Mediterranean climate and that the maximum precipitation value, minimum precipitation value, and average temperature values increase [58]. Zeybekoğlu and Karahan stated that irregularities in rainfall due to climate change negatively affect existing and planned water structures [59]. Since global warming changes the precipitation regime and increases the risk of flooding, infrastructure designs and plans, as well as water management plans need to be changed or rearranged [52]. Accordingly, the negative effects of flood disasters that may be caused by global warming can be reduced by taking some structural and non-structural measures by civil engineers. Çelik et al. examined the flash flood event that occurred in Türkiye/Hopa Region in 2015 and some measures to be taken to reduce the damages of flash flood were determined. Accordingly, closed canals should be converted into open canals, canal dimensions should be reconstructed according to 500-year precipitation regime estimates, and drainage systems should be constructed. In addition, according to 100-year flood height estimates, roads and buildings should be built on high areas, the basement floor of existing buildings in lowlands should be raised, and building reinforcements should be made. In addition, it was stated that construction standards and regulations should be updated for flood risk measures [60]. Gupta investigated the flood risk management and measures taken to reduce the flood risk that may be caused by the change in monsoon rain regime due to climate change in several cities in India (Mumbai, Chennai, Surat, and Hyderabad). In these cities, the rain drainage system and the sewage system were separated from each other, the canals were widened, flood walls were built along the canal, and water pools were built in Mumbai. In addition, it was stated that drainage systems and flood storage areas should be established against excessive precipitation in urban areas [61]. In another study, the risks of global warming and adaptive measures against these risks were investigated. In the study, it is recommended to increase the capacities of dams and levees against the increasing flood risk and to divide the flood-risky areas into sections to prevent the spread of flood water. In addition, it was mentioned that the effects of flood risk could be reduced by establishing a disaster management system and developing a disaster management network [29]. The increased risk of flash floods related to climate change causes great damage, especially to cities. In cities, in order to reduce the impact of floods and the peak flow value, permeable/porous pavement roads, infiltration trenches, and drainage systems should be built instead of traditional impermeable concrete or asphalt pavement roads around parks, gardens, schools, mass housing, and streets. Thus, the peak flow value can be reduced by ensuring rainwater leaks into the ground [62]. In addition, supportive policies and technical regulations are required for measures to reduce the risk of floods in cities [63]. In Figure 4, the Kapisre Deresi (Artvin/Türkiye) stream bed was expanded to prevent floods in 2017.

Figure 4. Expansion activities of the stream bed (Kapisre Deresi/Türkiye).

Şen stated that both traditionally designed water structures and planned water structures should be adaptable to climate change. In addition, it was stated in the study that water structures (dams, weirs, aqueducts, culverts, treatment plants, channels, etc.) in which the effect of climate change is neglected may cause drought and flood disasters. On the other hand, in order to reduce the impact of climate change on water structures, it is recommended to construct settling basins on the incoming route of the dam water, to increase the size of the spillway, to revise the water management system, and to prepare flood hazard maps against the flood risk in order to prevent sediments from being brought by the flood waters [64]. In Tai et al. studies, it is recommended to construct dry dams to adapt to climate change [65]. A dry dam is a without sliding gate dam built for flood control [66]. Thanks to the dry dam, flood water can be controlled in cases of excessive precipitation and flood disasters. In addition, dry dams can be used as water reservoirs in drought periods to provide agricultural irrigation and drinking water [65]. Changes in precipitation regimes and increased flood risk negatively affect transportation infrastructure. Flood waters can cause bridges to be submerged. Especially on single-span bridges, bridge spans should be re-evaluated in terms of increased flood and overflow risk [67],[68].

In different studies in the literature, it has been stated that drainage systems should be built in order to reduce the risk of flooding in areas where there may be flood risk, such as settlements, buildings, roads, factories, important facilities, water structures, and river sides [69]-[71]. There are many calculation methods for designing drainage systems and rainwater storage plants. Among these calculation methods, the most known is the Rational Formula Method. The Rational Formula Method determines the relationship between rainfall amount and peak runoff [72],[73]. The Rational Formula equation;

$$Q = C\ I\ A \qquad (1)$$

Q: peak discharge (m^3/sec); C: runoff coefficient (mm/h); I: runoff intensity; A: drainage area [72],[73].

However, it is understood in this our study that the design of drainage systems becomes difficult because climate change changes the runoff intensity (I). If the changing rainfall intensity cannot be predicted correctly, drainage systems may be inadequate. In this state, inadequate drainage systems increase the risk of floods. Accordingly, in our study, it is recommended to use longer-term precipitation forecast data in designing drainage systems for climate change adaptation and determining rainfall intensity. On the other hand, existing drainage systems or drainage system projections should be controlled and re-designed every 5 or 10 years. Civil engineers can be pioneers in taking some structural or non-structural measures to mitigate the damage of flood disasters on structures. In light of the studies investigated, civil engineers can take precautions such as preparing flood hazard maps for flood-risk areas, updating construction regulations, producing policies to reduce flood risk, using long-term precipitation forecasts in water structure design, controlling existing infrastructure/superstructures, re-designing water management, and establishing a disaster management system. In addition, measures can be taken such as increasing the capacity of water structures, constructing structures in high areas, expanding river beds, constructing drainage systems, and constructing permeable roads to reduce peak precipitation in urban areas.

3.3 Mitigation measures against rising sea levels effects

Climate-related factors such as the melting of glaciers and ice sheets, the thermal expansion of the oceans in Greenland and Antarctica, structural factors, and human activities are very effective in raising sea level. Especially climate-related factors cause about 80% of the rising sea level. In this case, due to the increase in global temperature and CO_2 emissions, especially the melting of glaciers and ice sheets, raises the sea level considerably [74].

Figure 5 shows the mass change of Antarctica, the change in the area covered by the ice sheets, the increase in ocean temperature, and the change in sea level rise according to NASA data.

In Figure 5, it is seen that the mass of Antarctica and the areas covered by the ice sheets are decreasing. On the other hand, it is stated in Figure 5 that the ocean temperature and sea level are increasing. Similarly, satellite images show that the areas covered by the Arctic sea ice sheets have decreased (Figure 6). While the area covered by the Arctic sea glaciers in 1979 was ~7 million km^2, in 2022 this ice sheet area was ~5 million km^2. According to NASA satellite observation data, sea level rose by ~103 mm between 1993 and 2022 [75].

By the 2100s, it is estimated that sea level rise will increase. Figure 7 shows the estimated amount of global mean sea level rise from 1995 to 2100. In addition, it is stated in different climate models in the literature that the sea level will increase until 2100 [76],[77]. Sea level rise will most affect coastal areas and the 600 million people living in coastal areas. It is estimated that the affected population will cause large migration movements due to sea level rise [79],[80]. Moreover, about a billion people will be at danger from coastland-specific climatic risks due to urbanization and population growth in low-lying coastal areas by 2050 [81]. Decision-makers such as the government, municipalities, non-governmental organizations, and technical experts should take the necessary measures against the risk of rising sea levels. Civil engineers can provide solutions with infrastructure and superstructure applications to reduce the effects of climate change in cities and coastal areas and to protect coastal areas [82].

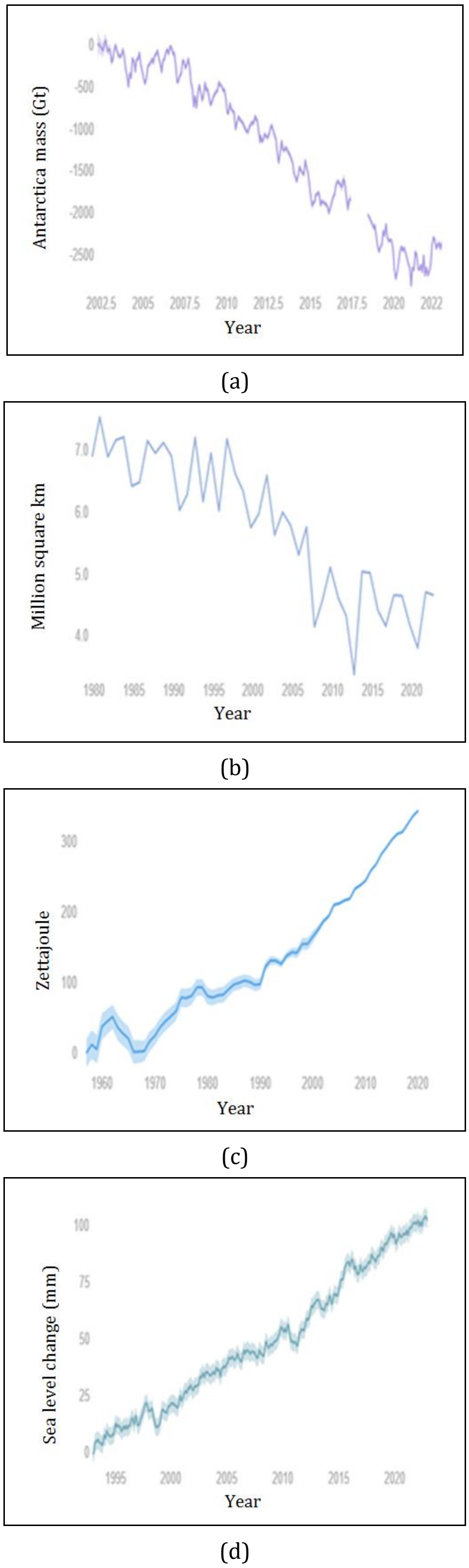

Figure 5(a): Mass change of Antarctica (thousands of gigatons). (b): Change of ice sheet area (million square km). (c): Ocean temperature change (zettajoule). (d): Sea level change (mm) [75].

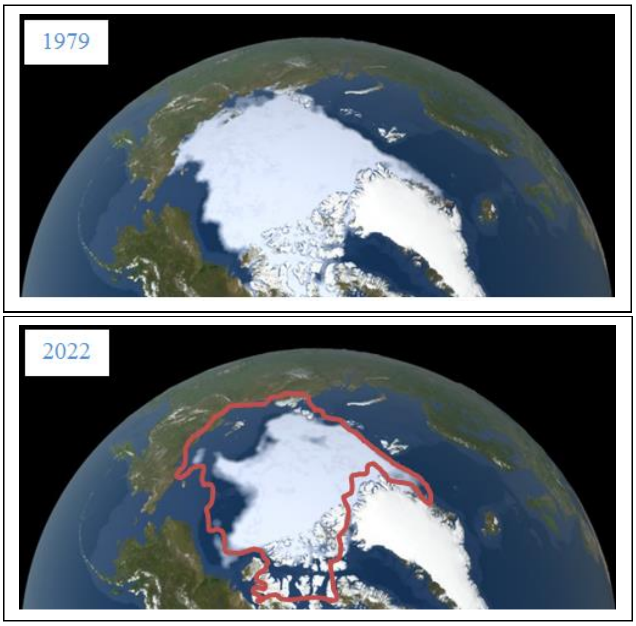

Figure 6. Satellite images of glaciers from 1979 and 2022 [75].

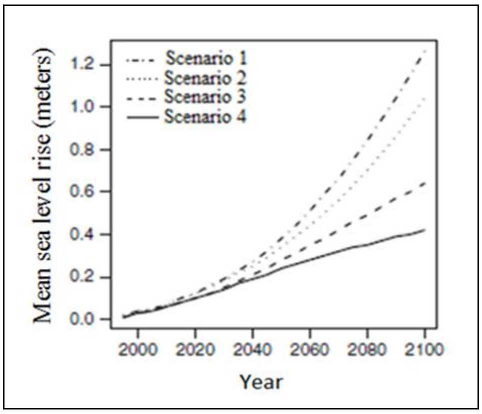

Figure 7. Estimated global mean sea level rise (meters) [78].

Accordingly, civil engineers play an important role in protecting coastal areas against rising sea level risks. Rising sea level increases coastal erosion, saltwater intrusion into coastal regions, and the risk of coastal floods. In addition, the traditional design standards used to construct marine structures fall short due to changing climatic parameters.

Therefore, design standards for coastal and marine structures must be continuously updated in response to the risk of rising sea levels [83]. Bulkheads, dikes, sea gates, and pump systems should be constructed and alternative water sources identified to reduce the impact of saltwater intrusion in coastal regions [84]. Also, it is widely accepted that structures such as breakwaters, rock walls, and sea barriers in coastal areas mitigate the effects of sea level rise. Accordingly, sea barriers and slope paving should be built in coastal areas, and existing breakwaters and rock walls should be continuously maintained [79]. In addition, the angle and height of seawalls should be updated periodically to reduce the impact of coastal floods and increased wave height [85]. Moreover, in coastal regions, roads and ports should be raised according to the estimated sea level, and infrastructure such as existing cables and pipelines should be moved to higher areas [86]. Rising sea levels also raise the groundwater level along the coastline. This state causes the risk of liquefaction in coastal areas. In structures such as buildings and bridges in coastal regions, measures should be taken against the risk of liquefaction in case of earthquakes, and land use should be limited by preparing a risk map for geotechnical hazardous areas. Geotechnical engineering is one of the most important branches of civil engineering. Accordingly, geotechnical engineers can rehabilitate building foundations and bridge piers against the risk of liquefaction [53],[87]. In addition, in the studies of Matanle et al. it is stated that rising sea levels increase the tsunami risk. In the study, it was emphasized that in coastal regions, measures such as structurally concrete seawalls, forested embankments, and manmade channels should be taken to reduce coastal erosion and mitigate the tsunami effect [88]. In the research of Dedekorkut-Howes et al. some structural measures are suggested for the structures to adapt to the sea level. These structural measures include the elevating of infrastructure and buildings, developing drainage systems, and the construction of structures such as floating houses, breakwaters, dikes, gabion baskets, and piers. In addition, it is stated in the research that these structural measures can have high costs and significant negative environmental consequences [89]. Munaretto et al. investigated the measures to be taken in response to the rising sea level effect in the city of Venice. Accordingly, in Venice, it is recommended to install mobile barrier systems at lagoon entrances, re-planning water networks, and strengthening breakwaters as structural measures [90]. Mohamed Rashidi et al. stated that in coastal areas, hard structural measures such as tidal barriers, armor rocks, temporary sandbags, wave breakers, and submerged dikes should be taken to mitigate the effects of rising sea levels. Another study explains that in coastal areas, seawalls and embankments should be built to protect existing lands and strategic structures in order to reduce the negative effects of sea level rise [91]. In their study, it is also recommended to construct emergency flood shelters in coastal areas [92]. Figure 8 shows a modern seawall built to reduce the impact of rising sea levels and floods on the Isle of Wight, England.

Figure 8. An example of a modern seawall on England's Isle of Wight [93].

Sheet piles are used to prevent leakage in the foundations of hydraulic structures such as dams [94]. In our study, it is recommended to use steel sheet piling in the foundations of infrastructure and strategic structures to mitigate the negative effects of rising sea levels. For example, sheet-pile seawalls have been constructed around San Francisco Airport to protect against extreme events such as continuously rising water levels or storm surges. Thus, the construction of the sheet pile against rising water levels is planned to protect the San Francisco Airport until 2085 [95].

In the coming years, rising sea levels will cause loss of life and property, especially in coastal regions. It is very important to adapt marine structures to climate change in coastal areas. Infrastructure and structures in risky coastal areas should be moved to higher areas, taking into account the rising sea level-time relationship. When different literature studies are examined, it is understood that it is inevitable to construct new dams, seawalls, pump systems, and breakwaters and adapt existing sea structures to climate change in the light of new design standards in response to sea level rise in coastal areas. In addition, disaster scenarios should be prepared to reduce the risk of life and property security from rising sea level. Policymakers, decision-makers, the public, and civil engineers should support prepared disaster scenarios.

3.4 Adaptation of civil engineering structures to climate change

Depending on climate change, especially the change of temperature and precipitation regime parameters, causes some risks in civil engineering infrastructure (tunnels, transmission lines, dams, etc.) and superstructures (bridges, roads, etc.) [96]. Changing environmental conditions make engineering solutions very difficult. Particularly since the 1700s, civil engineering constructions such as railways, sewerage systems, waterway structures, energy transmission lines, roads, and channels have been constructed using enormous financial investments. It is very important to transform these civil engineering constructions to adapt to the increasing population, urbanization, energy needs, and changing climate conditions [97]. As climate change changes the temperature, precipitation regime, and moisture, factors such as corrosion, carbonation, aging, and deterioration that negatively affect structures occur. These factors shorten the service life of existing structures [98]. In addition, due to climate change, increasing floods, landslides, storms, snow loads, freeze-thaw frequency, the ultraviolet (UV) effect, foundation problems caused by liquefaction, and increased wind effects reduce the durability of existing structures and complicate the design conditions of infrastructure/superstructure for civil engineers and technical experts [98]-[100]. In the study of Swarna and Hossain explained that increasing temperatures, changing precipitation regimes, and moisture imbalances caused by global warming cause the deterioration of asphalt pavement material. In addition, it has been stated that the number of road pavement works will increase with climate change. Accordingly, in their studies, it was recommended to increase the thickness of the asphalt pavement and use a modified hot asphalt mixture to prevent deterioration of the asphalt pavement [101]. Yassaghi and Hoque stated that in order to reduce the impact of climate change on buildings and save energy, buildings should be constructed with a low window-wall ratio and covered with thermal insulation materials [102]. In the study of Nogal assessed that changing environmental conditions due to climate change may increase the corrosion of reinforced concrete buildings and decrease their service lives. In the study, it was recommended to use stainless or galvanized steel rebar, polymer rebar, and slag cement in reinforced concrete structures and to apply thicker concrete cover in order to adapt the reinforced concrete structures to climate change and to increase the corrosion resistance of these structures [103]. In another study, Eisenbarth et al. explained that by covering the surfaces of high-rise buildings with a light membrane facade material, the formation of potential urban heat islands can be prevented and rainwater harvesting can be done [104]. Mondoro et al. proposed some measures to increase the service life of bridge structures against hurricanes and changing wind forces within the scope of adaptation to climate change. Accordingly, in existing bridges or new bridge designs, it has been suggested to raise the bridge deck, insert holes in the bridge deck, manufacture the bridge decks from concrete material, place concrete ripraps on the bridge piers, and use toe nails and epoxy-bonded wooden blocks for bridge deck coverings [105]. In another similar study, it was recommended to re-evaluate the locations of existing bridges and to insert storm surge barriers in the near fields of existing bridges in order to adapt the bridge structures to climate change [106]. In addition to existing structures, historical buildings should be protected against climate change. The change in temperature and precipitation regime due to climate change can also affect the indoor climate and indoor moisture balance in historic buildings. In addition, high temperature differences and moisture changes can cause damage to historical buildings. In order to protect historical buildings against changing climatic conditions, natural ventilation scenarios should be prepared, historical exterior and interior walls should be insulated against moisture and evaporation, and reinforcing works should be carried out in buildings [107]. For historical buildings, it is very important to select the most suitable insulation materials and to apply these materials correctly [108]. In a similar study, it was stated that it is difficult to adapt heritage buildings to the negative effects of climate change without losing their traditional aesthetics [109]. Due to the fact that climate change changes environmental conditions, the design standards of buildings should be updated periodically [98]. For example, Xu et al. estimated that climate change will increase wind speed according to the climate models used in their research. According to the climate model analysis, the calculated design wind speeds in the building codes and standards should be taken into account in order to protect the buildings from extreme wind load effects [110]. On the other hand, if the changing wind speed is applied to new construction designs, it is calculated that the construction cost increases by ~1.4% [111]. In addition, depending on climate change, it is estimated that the snow load will increase in cold regions and decrease in warm regions [112]. In another study, it was stated that the roofs of ~200 buildings collapsed due to the increased snow loads on the roofs as a result of climate change in the winter season of 2005-2006 in Central Europe. In the research, it was recommended to update the changing snow load and snow melting times in the existing design standards and to prepare national snow maps [113]. Kozak and Liel found that there are significant differences in the safety of roofs designed according to 50 years of snow load and snow accumulation of existing structures in different geographies and climates, and that larger load-bearing element dimensions should be used for these existing roofs. It is possible that the structures built according to existing design standards in accordance with climate change may be insufficient in the future [114]. Furthermore, in order to adapt to climate change in existing buildings, the load-bearing elements should be altered, some parts of the structure should be reinforced, and the static analysis of the structure should be reanalyzed due to the change in the load-bearing system [99]. Nikolis et al. stated that in the long term, global climate change will most affect the infrastructure facilities in the Middle East and North Africa Regions. In the study, the design of the Doha Metro, which was built in the Middle East-Qatar, to be resilient to climate change was investigated. The service life of the design of Doha Metro is planned as ~120 years. During this service life, drainage systems have been designed to protect the metro against the increased risk of flooding. In addition, it was stated that stainless steel fiber and sulfate-resistant cement would be used as the most suitable building materials to prevent deterioration in the metro structure [115].

In advance, risky areas with critical infrastructure and facilities should be identified, and these risky areas should be announced to engineers, decision-makers, policymakers, and the public. Infrastructure and superstructure facilities in risky areas should be examined in terms of resistance to climate change and cost, and an engineering and economic evaluation of these facilities should be made [116]. Civil engineers have a great responsibility for adapting modern structures and existing buildings to climate change. In the future, due to the fact that the effects of climate change are not measurable, civil engineer's work and engineering projects will become more difficult. Technical experts such as civil engineers, meteorological engineers, and data science experts must work together to successfully adapt to climate change during the planning, design, and implementation stages of civil engineering structures. In addition, civil engineers can lead in the management of risks and uncertainties arising from natural disasters, in combining the public, private, and academic sectors in terms of technology and ideas, and in deciding environmental compliance and infrastructure regulations [117]. Table 1 summarizes the structural and non-structural measures that should be taken by decision-makers in civil engineering projects to mitigate reducing CO_2 emissions, the effects of increased flood and overflood extreme events, and the impacts of rising sea level disasters

Table 1. Some structural and non-structural measures to mitigate the impact of climate change.

State	CO_2 emission reduction	Reduction of the impact of floods and overflows	Mitigate the effect of rising sea level	Adaptation of structures
Structural measures	Using blended cement	Conversion of closed channels to open channels	Construction of bulkheads, sea gates, embankments, rock walls, breakwater, seawalls and pump systems in coastal areas	Increasing the asphalt pavement thickness and modifying the asphalt material
	Using artificial and recycled materials	Constructing drainage systems	Periodically updating of seawall heights and angles	Low window-wall ratio in buildings
	New construction techniques (Contour crafting method)	Using long-term precipitation forecasts	Transportation of roads, ports, cables and pipelines to high areas	Implementation of ventilation system and insulation in buildings
	Preferring prefabricated construction method (off-construction site production)	Elevating existing structures	Construction of forested embankments and manmade channels against tsunamis on the coastline	Using thick cover concrete, polymer or stainless steel in reinforced concrete structures
	Modification of asphalt mix material with waste materials	Expansion of channel beds	Construction of gabion baskets, and floating houses	Covering the building facade with membrane material
		Construction of flood storage areas	Using sheet piles on the foundation of strategic structures	Insulating the interior and exterior of historical buildings against heat and moisture
		Increasing the capacities of dams and levees		Reinforcing some parts of structures
		Construction of permeable/porous pavement roads in the city		Increasing the dimensions of the load-bearing elements for roofs
		Increasing the size of the spillway of the dams		
		Constructing dry dams		
Non-structural measures	Using of high-efficiency machinery	Construction of infrastructures/superstructures on high areas	Continuous updating of the building standards of coastal and marine structures	Placing storm surge barriers around the bridge pillar
	Zero emission construction management	Updating building standards and regulations	Preparing geological risk maps against liquefaction risk	Consideration of wind speeds in building standards and regulations
	Planning construction site	Establishing a disaster management system	Planning of low and high areas	Re-analyzed of static analysis of existing structures

Table 1. Continued.

Non-structural measures	Planning intelligent transportation systems for highways	Re-evaluated of existing single-span bridges against flood risk		Preparing snow maps
Decision-makers	Government Municipality Technical expert	Government Municipality Technical expert People Civil society organization	Government Municipality Technical expert People Civil society organization	Government Municipality Technical expert Civil society organization

4 Conclusions

This paper focuses on some structural and non-structural measures to mitigate the effects of global warming and climate change. These measures are summarized below:

- In order to reduce CO_2 emissions, the use of waste materials in the production of building materials, the production of building elements on the construction site, contour crafting, or prefabricated construction methods can be very effective,
- On the construction site, CO_2 emissions can be reduced by using electrical and highly efficient machinery, making the most suitable construction site planning, and applying zero-emission construction site management,
- Engineering solutions used now will be insufficient in the future due to global warming and climate change,
- Civil engineering projects should be designed with the cooperation of civil engineers and meteorological engineers, taking into account long-term (~500 years) precipitation regime values,
- Construction standards and regulations for water and marine structures should be continuously updated. Disaster management systems should be established for flood-risk areas and coastal areas,
- In flood-risky areas, the capacity and dimensions of existing water structures should be increased, drainage systems should be built, channel beds should be expanded, and infrastructure and superstructures should be built on high areas,
- Adaptation strategies for climate change in coastal areas and cities should be determined, existing marine structures should be updated and strategic facilities and infrastructure should be moved to high areas. In areas with a risk of liquefaction, the sheet pile method should be applied to the foundation of important structures,
- Existing structures should be reinforced against climate change, and the design parameters of the planned civil engineering structures should be increased,
- In order to increase design parameters and safety measures in climate change adaptation studies, supportive and regulatory changes should be made in cooperation with policymakers, decision-makers, municipalities, civil engineers, meteorological engineers, and data science experts.

5 Author contribution statements

Melih Şahinöz contributed to the design, analysis, research, literature review, editing, and put forward an idea. Ömer Şahinöz contributed to the evaluation of the results, research, methodology, literature review, writing work and visual design.

6 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared".

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