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Estimation of Sediment Yield in Madawaki Watershed Using GeoWEPP Model

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Abstract

Erosion is a recurrent challenge in the Madawaki watershed widely affecting farming techniques, water quality, and soil fertility. The study portrays a novel use of geographical interface of the WEPP (Water Erosion Prediction Project) model, known as GeoWEPP to estimate sediment yield in the unique agro-ecological region. Leveraging ArcGIS 10.2, detailed maps were generated to support the modeling process, signifying a high-resolution analysis of the watershed activities.The result shows an average annual sediment yield of 219 ton/ha. Among the evaluated management practice, forest perennial emerged as the most effective in reducing the sediment yield by 78.3% (47.6 tons/ha). The analysis contains a critical idea into the efficacy of GeoWEPP model in estimating and managing watershed challenges. By showing the model ability to integrate GIS mapping techniques and assess forest perennials as a sustainable management practice. It also offers an important advancement in soil and water conservation strategies. These findings proffer critical gaps in sediment yield estimation and watershed management, demonstrating the study to be a valuable contribution to the field of watershed development planning.

Key words: Sediment yield, GIS, GeoWEPP, Madawaki, Gusau

1. Introduction

Despite scientific studies and conservation efforts, soil erosion remains a significant global issue, driving land degradation and threatening ecosystems [1]. It is widely regarded as the greatest ecological danger to the survival of both animal and plant life on Earth. Erosion, caused primarily by wind or water, depletes soil by transferring sediment from one area to another. Assessments indicate that approximately 65 percent of the planet's soil has degraded due to erosion, salinity, and desertification [2].

Soil is one of Earth's most critical ecosystems, providing habitat for living organisms, supporting biodiversity, and anchoring human-made developments. Damage to soil directly endangers life by reducing its fertility, productivity, and ability to sustain vegetation. Soil erosion, primarily driven by destructive forces such as water, wind, gravity, and human interference, accelerates the depletion of organic matter and vital nutrients, undermining global food production and biodiversity [3]. Global food production is being negatively impacted by soil loss, which is currently an important ecological problem**.** This has profound environmental and economic consequences, particularly in developing nations where farming communities

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often lack resources to restore lost soil and nutrients. The ongoing imbalance, where the rate of soil loss exceeds the natural regeneration of soil, continues to reshape the environment and exacerbates the challenges of sustaining life on Earth [5].

A modified version of the Water Erosion Prediction Project (WEPP) hillslope model, the WEPP watershed model is a process-oriented, continual simulation erosion forecasting framework that may be used to calculate watershed runoff and sediment production [6]. The process of infiltration hypothesis, hydrology, soil science, plant science, hydraulics, and erosion dynamics are the foundations of the WEPP model. The creation of the climate, the cold-season process, irrigation, hydrology, soils, plant development, breakdown of residues, downstream hydraulics, erosion, and deposition are its nine components [6].

GeoWEPP had been the name of the geographic interface for the WEPP model that was initially proposed [7]. After being developed as an ArcView 3.2 extension, it is now compatible with ArcGIS. The National Soil Erosion Research Laboratory (NSERL) of the USDA-ARS and Purdue University developed the program first currently, it is updated often via the University at Buffalo's Environmental System Analysis and Modeling lab, which may be found at https://lesami.geog.buffalo.edu/projects/active/geowepp [8]. The GeoWEPP ArcGIS extension allows users to obtain and import readily available topographic, soil, and land use/land cover data layers for preparing model input and executing WEPP model scenario simulations when used in conjunction with the ArcGIS software and the independent WEPP Windows interface [8].

The study aims to estimate the sediment yield using GeoWEPP a spatial interface of the WEPP model in the Madawaki watershed of Gusau Local government, Zamfara state, Nigeria. The availability of data on sediment yield is limited in the study area and there is also limited research using the GeoWEPP model in Nigeria, therefore, the result will be validated with research conducted at different locations of the world.

2. Materials and Methods

2.1. Description of the study area

The research was carried out in the Sudan Savannah of Nigeria (Figure 1) at a height of 429 meters above sea level in Gusau (latitudes $12^0\ 11'\ 72^{"} to 12^0\ 11'\ 28^{"}$ N and longitudes $6^0\ 37'\ 17.04^{"} to 6^0\ 37'\ 17.84^{"}$ E) and a total area of 1600ha. Two seasons are different in the region's climate: the rainy season (May - October) and the dry season (November - April). Additionally, it experiences a monomodal cycle of rainfall, with a yearly average of 875 mm and a range of 750 to 1000 mm. Temperatures are 30 degrees Celsius on average every year. The short grasses that make up the landscape act as a framework for the prickly plants. River Sokoto drains and affects the Gusau area, while a few tiny river and stream systems pass through the uplands [9].

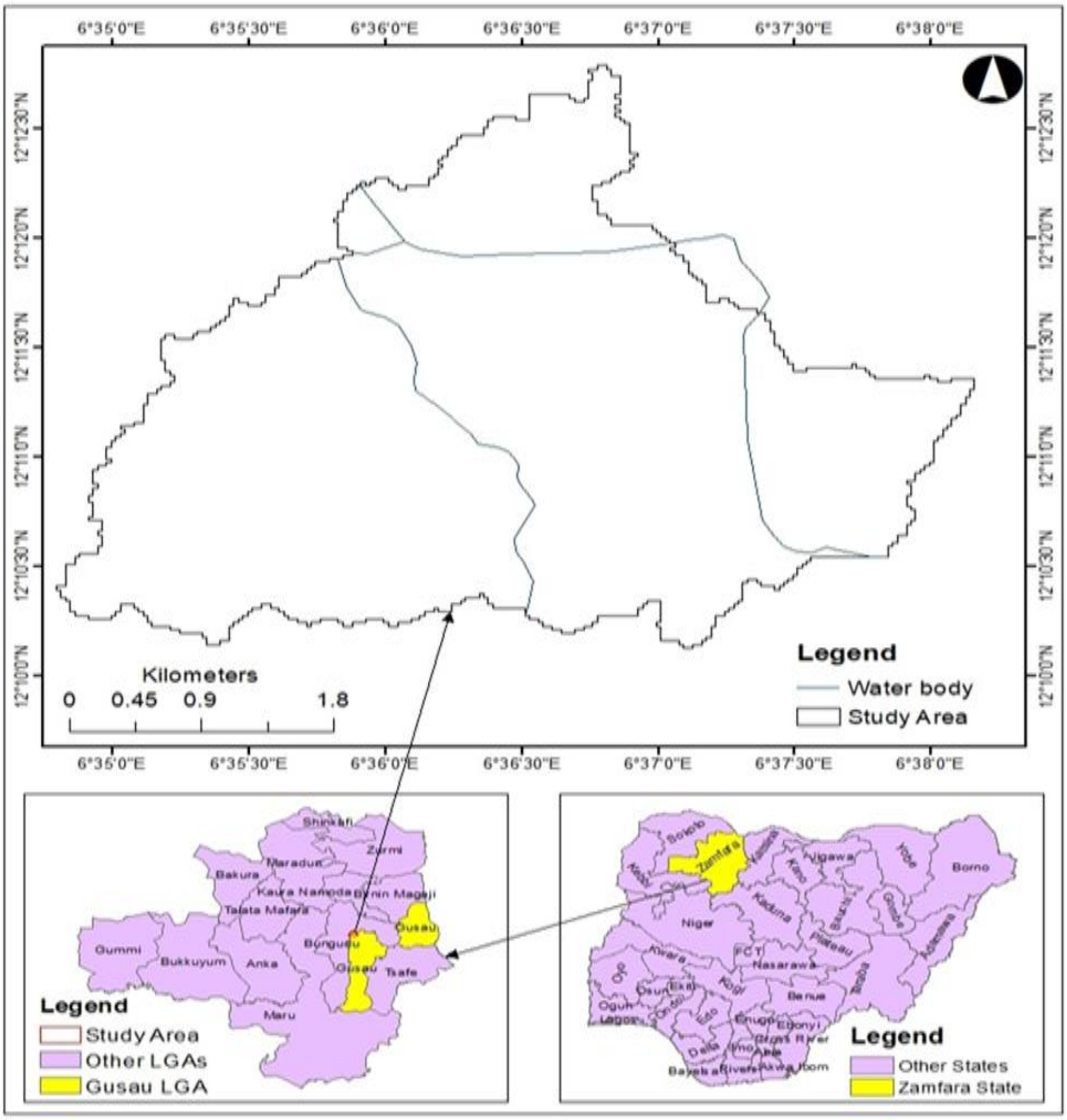

Figure 1. Study area (Madawaki Watershed)

2.2. Meteorological data

Climate data from 1992 to 2022 were obtained from the Nigerian Metrological Agency (NIMET) in Gusau, Zamfara State. Rainfall, maximum and lowest temperatures, wind direction and speed, relative humidity, and dew point are among the data. The first necessary element in the equation is rainfall erosivity. The R factor evaluates the amount and speed of runoff, which are directly related to a certain precipitation event, and is dependent on rainfall intensity in the sense of kinetic energy [10].

The rainfall data for the 30 years' time were used to obtain the rainfall erosivity in line with the formula:

$$R = \sum_{i=1}^{12} 1.735 \left[1.5 \times \log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right] \quad (1)$$

Where R is the rainfall erosivity factor (MJ.mm.$ha^{-1}.h^{-1}.y^{-1}$) and P is the mean annual rainfall (mm) [11].

2.3. Soil data

Ten different points of soil samples were obtained from the watershed [12]. Particle size distribution analysis was carried out on the soil at the study area in the Department of Soil Science, Soil Survey Laboratory, Ahmadu Bello University Zaria, to ascertain the textural classification of the area.

2.4. Satellite data

2.4.1. Digital Elevation Model

The United States Geological Survey (USGS) Earth Explorer was used to obtain Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM). The slope of the image was produced as a result of processing it in the ArcGIS program. Figure 2 shows the elevation of the study area, ranging from the high, which is orange (444m) above mean sea level, to the low, which is dark blue (360m).

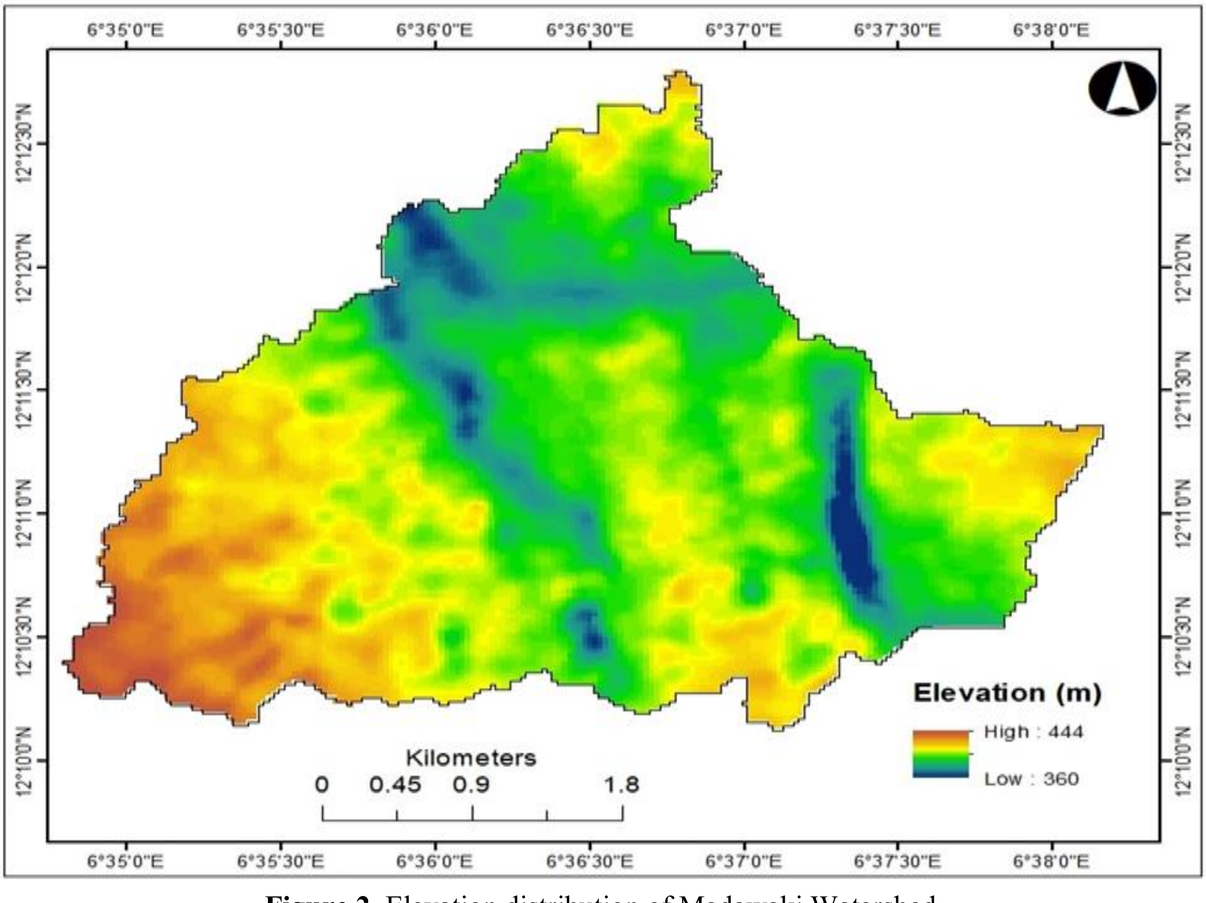

Figure 2. Elevation distribution of Madawaki Watershed

2.4.2. Remote Sensing

Remote sensing data was also downloaded from the United States Geological Survey (USGS) Earth Explorer. Data from remote sensing was used to generate land use and cover. Using maximum likelihood classification and supervised classification, the LC08_L2SP190052 satellite image from 1992–2022 was categorized using ArcGIS software.

2.5. Best Management Practices (BMPs)

When used in physically based model applications, BMP can enhance watershed planning and effectively reduce sediment yield, and its effects [13]. Many cropping and tillage options are accessible in the WEPP database to be considered to lessen the effects of sediment yield. Therefore, the conventional tillage was taken as the baseline. At the same time, the forest perennial, corn, soybean no-till, corn, soybean-fall mulch till, and corn fall mulch till were used as the four scenarios in testing the best management practice in the watershed [14].

2.6. Model input parameters

2.6.1. Model calibration

The DEM, land use/cover, and soil map were uploaded into the Geospatial interface of the WEPP model (GeoWEPP) add-in in the ArcGIS 10.2 environment, while the climate, soil, and land cover files from WEPP were inputted for simulation. The climate data of 2001 and 2011 were used to calibrate the model using a trial-and-error method.

2.6.2. Climate data

The WEPP model's climate (.cli) file was imported from the Breakpoint Climate Data Generator (BPCDG) aggregated climate data.

2.6.3. Slope

The TOPAZ interface generated the slope from the DEM and the channel network delineation.

2.6.4. Soil data

The converted ASCII soil file generated from GIS was used in the simulation.

2.6.5. Management file

Corn, soybean, spring chisel plow WEPP inbuilt file was adapted, and the same farming practice was used in the study area.

2.7. Channel Network Delineation

To define the drainage pattern and watershed with sub-watershed, the wizard was determined, and the channel parameters and the watershed outlet cell. The wizard integrates Topography Parameterization (TOPAZ), a program for topographic analysis. To determine the channel network, TOPAZ needs a minimum source channel length (MSCL) and a critical source area (CSA). The wizard provides a tool to set the outflow for the watershed of interest once the network outline satisfies the outline seen in the area [7].

Channel parameters and watershed outlet were set and the drainage pattern was delineated by Topography Parameterization (TOPAZ). The critical source area (CSA) of (20ha) and the minimum source channel length (MSCL) of (300m) was set for the channel network delineation [7]**.** The allowable soil loss tolerance limit will be 1.5ton/ha [15].

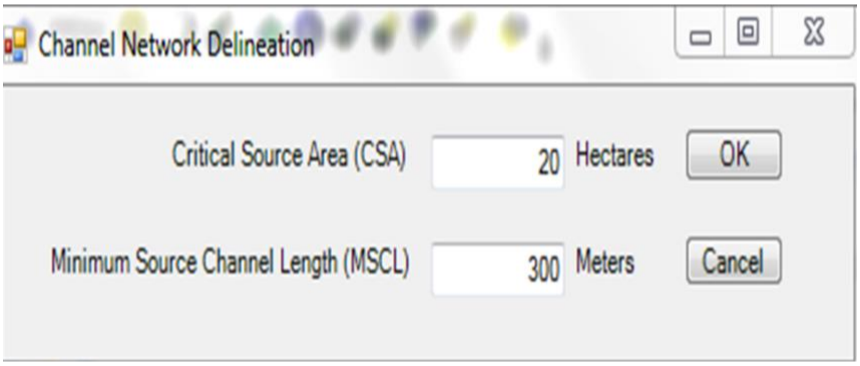

Figure 3. Channel Network Delineation setup from TOPAZ of Madawaki Watershed

2.8. WEPP Equations

The WEPP model calculates the soil erosion and deposition processes using the steady-state sediment continuity equation [16]. Erosion prediction in the WEPP model starts with detailing soil parameterization. Some mathematical equations are used for computing soil detachment and subsequent sediment deposition processes. Soil detachment by prevailing driving forces can be obtained using this equation, expressed as:

$$\frac{dG}{dx} = D_f + D_i \tag{2}$$

Where x = distance downslope (m), G = sediment load (kg/s/m^2), D_i = interrill erosion rate (kg/s/m^2), and D_f = rill erosion rate (kg/s/m^2).

Hence, the soil sediment capacity by concentrated flow process is expressed as:

$$T_c = K_{tr} q_w S \tag{3}$$

Where K_{tr} = constant rill erodibility parameter, q_w = flow discharge per unit width (m^2/s), S = slope (%).

In a situation where the soil sediment load exceeds its transportation capacity, a net deposit occurs and it is calculated using the equation:

$$D_f = \left[\frac{V_f}{q}\right][T_c - G] \tag{4}$$

Where V_f = the sediment's effective fall velocity (m/s), and q = the flow discharge per unit width (m/s^2).

As a process, the climate generator (CLIGEN) component of WEPP generates the rainfall intensity, while the hydrologic component of the WEPP computes the runoff peak and duration. The effective runoff duration is obtained using the equation:

$$t_r = \frac{V_r}{P_r} \tag{5}$$

Where t_r = length of the effective runoff (s), V_t = total volume for rainfall event (m), and P_r = peak runoff per unit area (m/s) [17].

The motion of suspended sediment in rill, interill, and channel flow zones is found by applying a steady-state erosion model to solve the sediment continuity equation. The values for detachment, transport, and deposition are obtained from the steady-state solution of the sediment continuity equation [18].

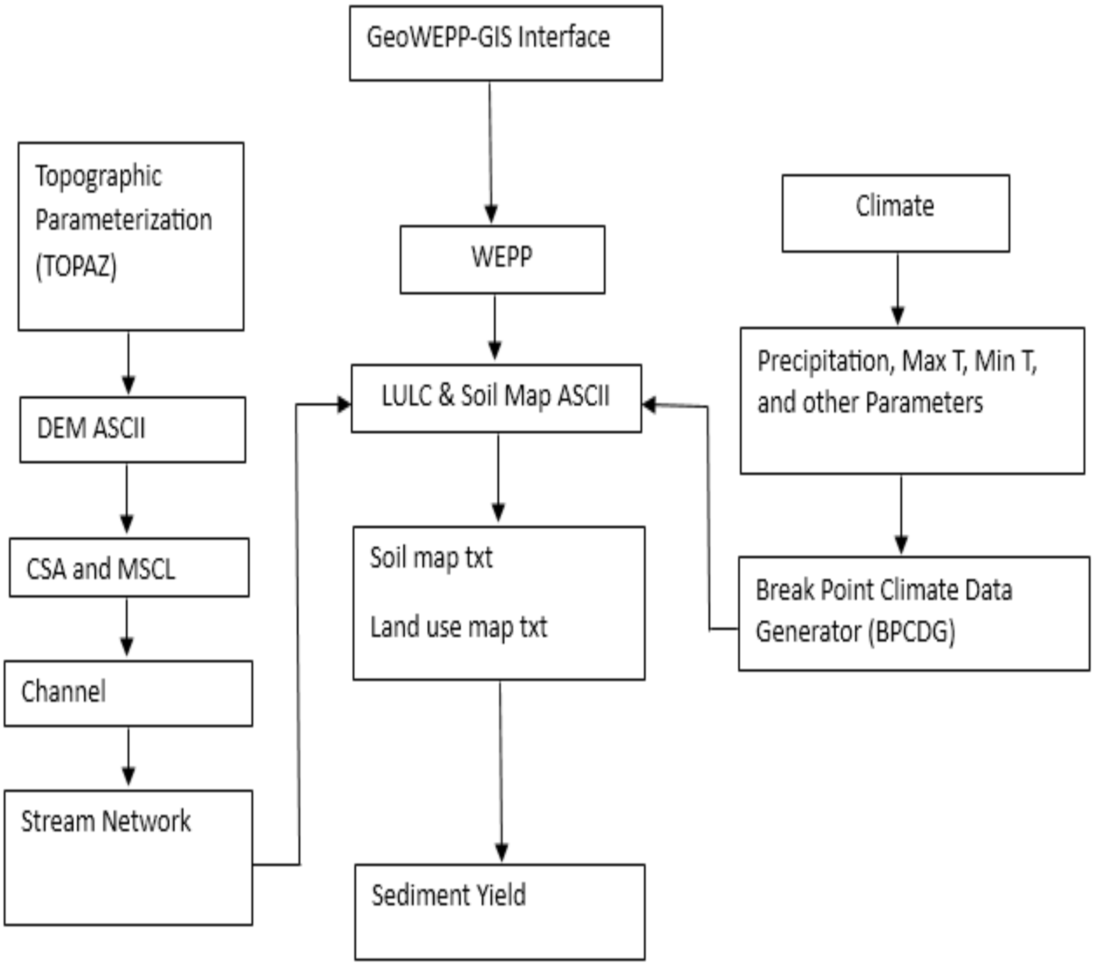

Figure 4. Flow chart for simulation

3. Results and Discussion

Figures 5 and 6 below, show the rainfall map and the rainfall erosivity factor map. The map in Figure 5 shows areas in the watershed where rain was high and low while in Figure 6, the map shows areas where the erosivity factor is high and low.

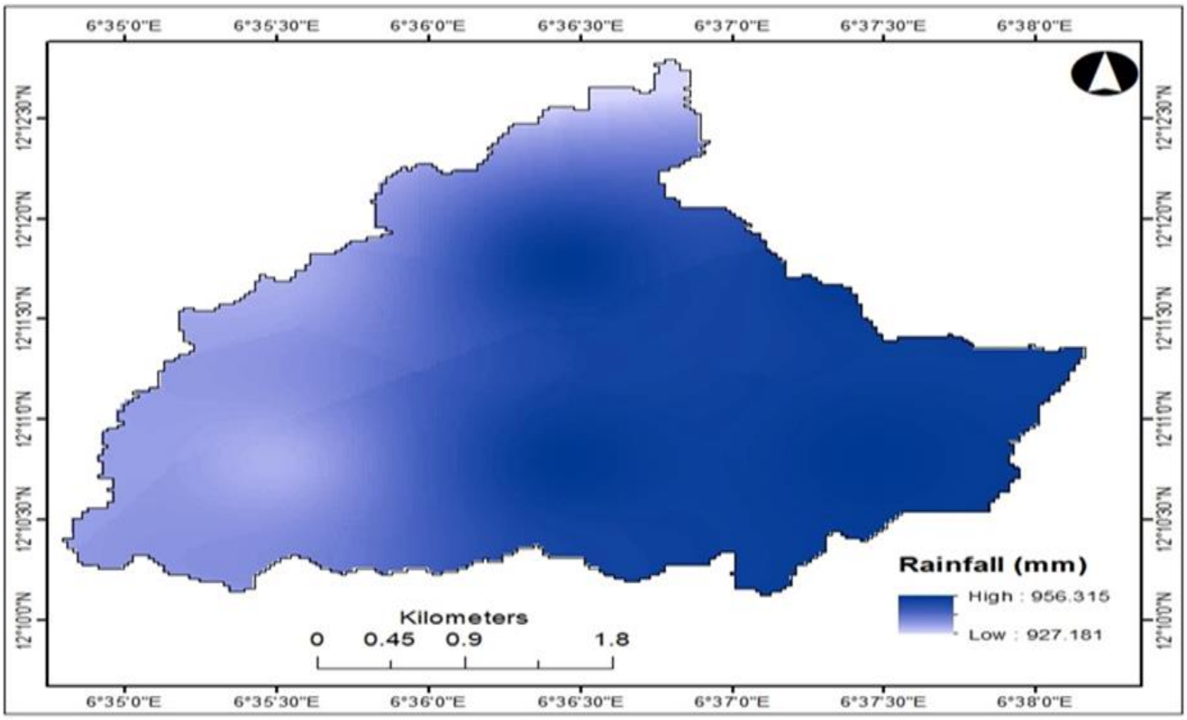

Figure 5. Rainfall map of Madawaki Watershed

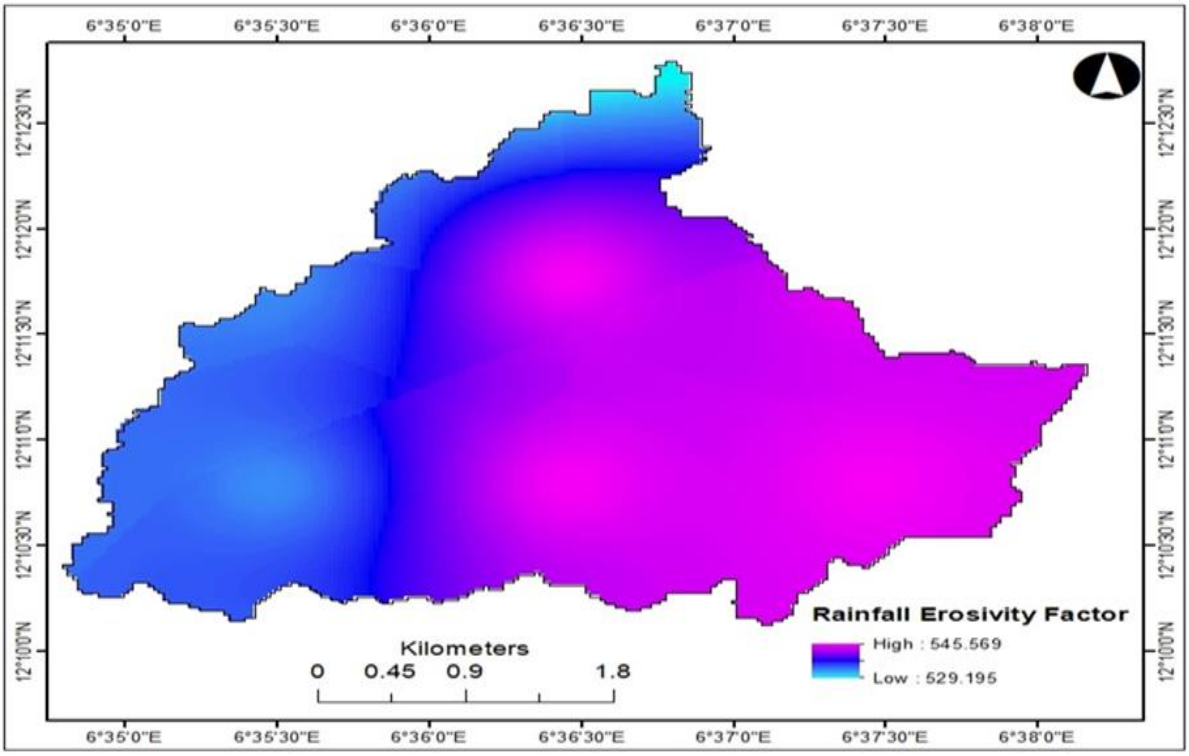

Figure 6. Rainfall erosivity map of Madawaki Watershed

Thirty years' worth of rainfall records are used to calculate the R factor, which indicates the erosive potential of rainfall. Volume, intensity, length, and pattern of rainfall all have a significant impact on how erosive a downpour is. The result shows that the mean annual rainfall ranges from 927.2mm north to 956.3mm southeastern part of the area and mean annual R factor values range from 529.2MJmm/ha/yr north to 545.6 MJ mm/ha/yr in the southeastern part of the study area.

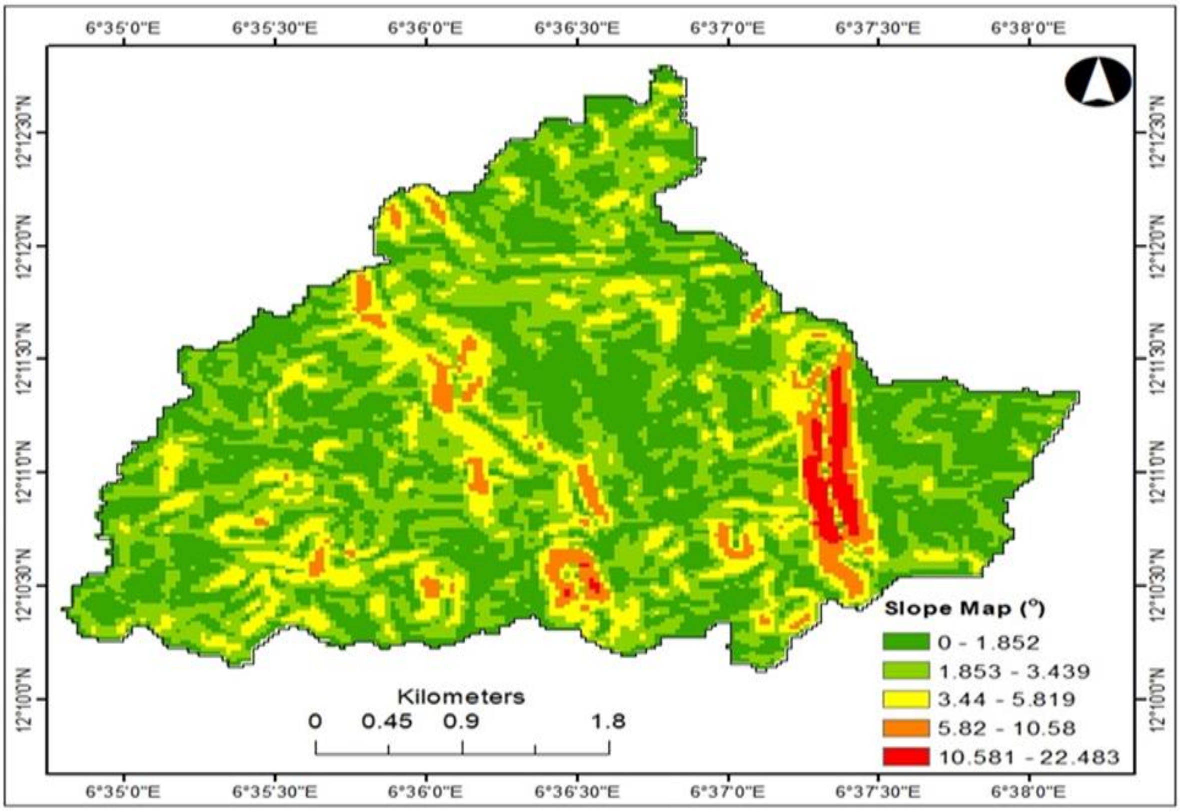

Figure 7. Slope map of Madawaki Watershed

As a result, the study area constitutes different classifications ranging from normal zone to productive zone to sensitive zone and their various slope percentages. The slope of 5^0 and above shows sensitive areas in the study area. Figure 8 shows different classifications of land cover in the study area, which include: bare land, build-up, vegetation, and water bodies. İt also shows the land use/cover map of the Madawaki watershed with ground points superimposed to the map generated from ArcGIS 10.2 which validated the classification. Ten (10) points were obtained from each class to check for the agreement between the map and the points.

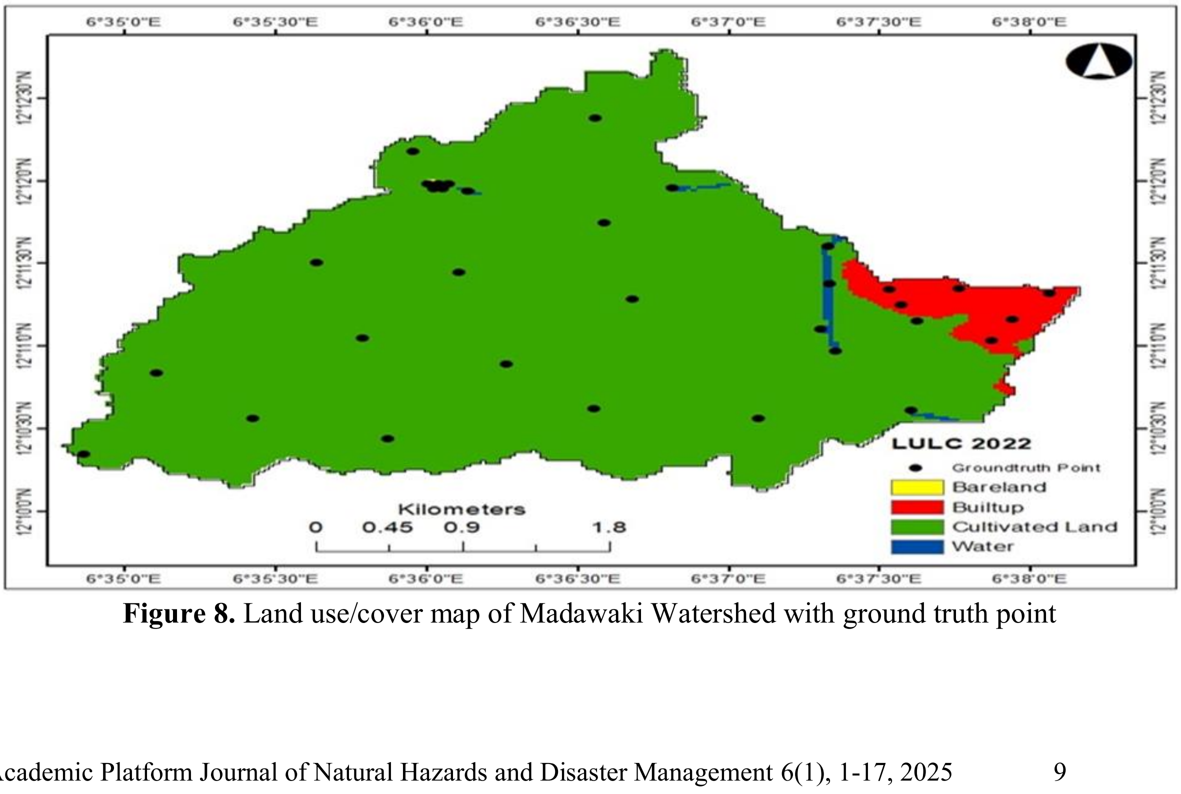

Figure 8. Land use/cover map of Madawaki Watershed with ground truth point

Table 1 shows the classes of land use in the Madawaki watershed, the area they cover and the percentage of the area covered. A confusion matrix analysis was performed using a Microsoft Excel sheet to evaluate the precision of the ground truth points superimposed on the geographical representation of land use and cover in Table 2 above to show agreement between the ground truth points and the map. The kappa value obtained was 0.72, which shows a substantial agreement with the map. Figure 9 shows the soil map of the study area obtained from ArcGIS 10.2. It clearly shows different textures from sandy clay loam, loam, and silty loam to sandy loam.

Table 1. Classes of land use/cover with the areas and percentages

Name	Area (ha)	Percentage (%)
Water	10.44	0.65
Built-up	66.15	4.10
Bare land	1.17	0.07
Farmland	1537.56	95.15
Total	1615.32	100

Table 2. Confusion matrix of the land use/cover

Class name	Water	Built-up	Bare land	Cultivated Land	Total	User Acc.	Kappa
Water	4	0	0	1	5	0.80	
Built-up	0	5	0	1	6	0.83	
Bare land	0	0	4	1	5	0.80	
Cultivated Land	1	1	1	14	17	0.82	
Total	5	6	5	17	33	0.00	
Producer Acc.	0.80	0.83	0.8	0.82	0	0.82	
Kappa							0.72

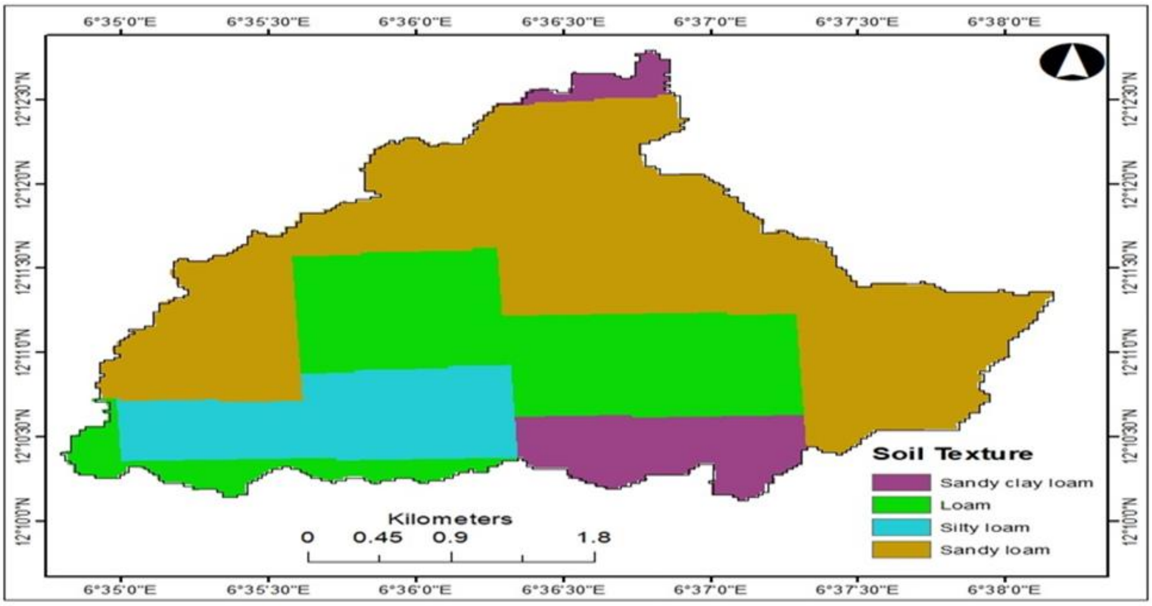

Figure 9. Soil map of Madawaki Watershed

Validation of soil map by conducting physical test as seen above in Table 3, shows textural classes of soil obtained. Sandy loam predominantly covers the watershed. The watershed was divided into four (4) different sub-watersheds for easy delineation then the sediment yield was simulated. The WEPP model yielded the average annual outcome for each sub-watershed.

Table 3. Particle size distribution analysis results: The research area's results were used as the validation of the soil map

S/N	BLK	(DT*0.36)	40SECS R	2 HRS R	% CLAY	% SILT	% SAND	TEXTURAL CLASS
1	0	2	21	2	8	38	54	Sandy Loam
2	0	2	15	8	20	14	66	Sandy Loam
3	0	2	12	2	8	20	72	Sandy Loam
4	0	2	8	1	6	14	80	Loamy Sand
5	0	2	18	5	14	26	60	Sandy Loam
6	0	2	32	6	16	52	32	Silt Loam
7	0	2	12	4	12	16	72	Sandy Loam
8	0	2	28	8	20	40	40	Loamy Sand
9	0	2	18	2	8	32	60	Loam
10	0	2	17	2	8	30	62	Sandy Loam

3.1. Sediment Yield

The average annual sediment yield of the erosion site is $219 tons/ha$. These findings (219tons/ha) are comparable with the findings of [18].

Table 4. Sediment yield obtained from GeoWEPP model

Sub-watershed	Average Annual Sediment Yield(ton/ha)	Sediment Delivery Ratio
SW1	150	0.32
SW2	20	0.48
SW3	36.1	0.88
SW4	12.8	0.21

3.2. Spatial distribution

This section demonstrates the spatial distribution of the sediment yield in Madawaki watershed. It portrays the channel network delineation followed by the spatial distribution maps (Figure 10). Figure 11 displays the spatial distribution of sediment yield at the watershed. The sediment yield ranges from light greenish, which signifies a low amount of sediment deposition to pinkish which signifies the highest level of sediment deposition. The map shows critical areas that require urgent attention for effective soil and water conservation management.

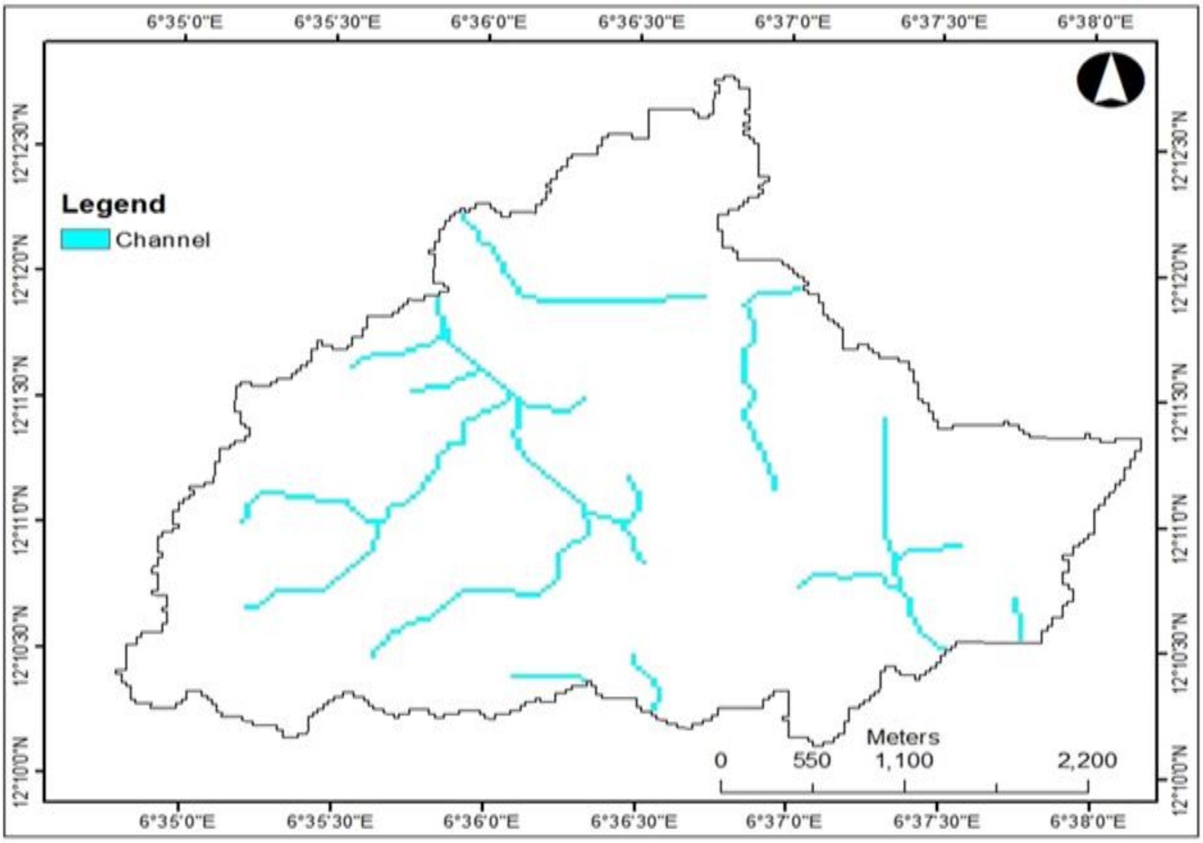

Figure 10. Channel network delineation in the Madawaki Watershed

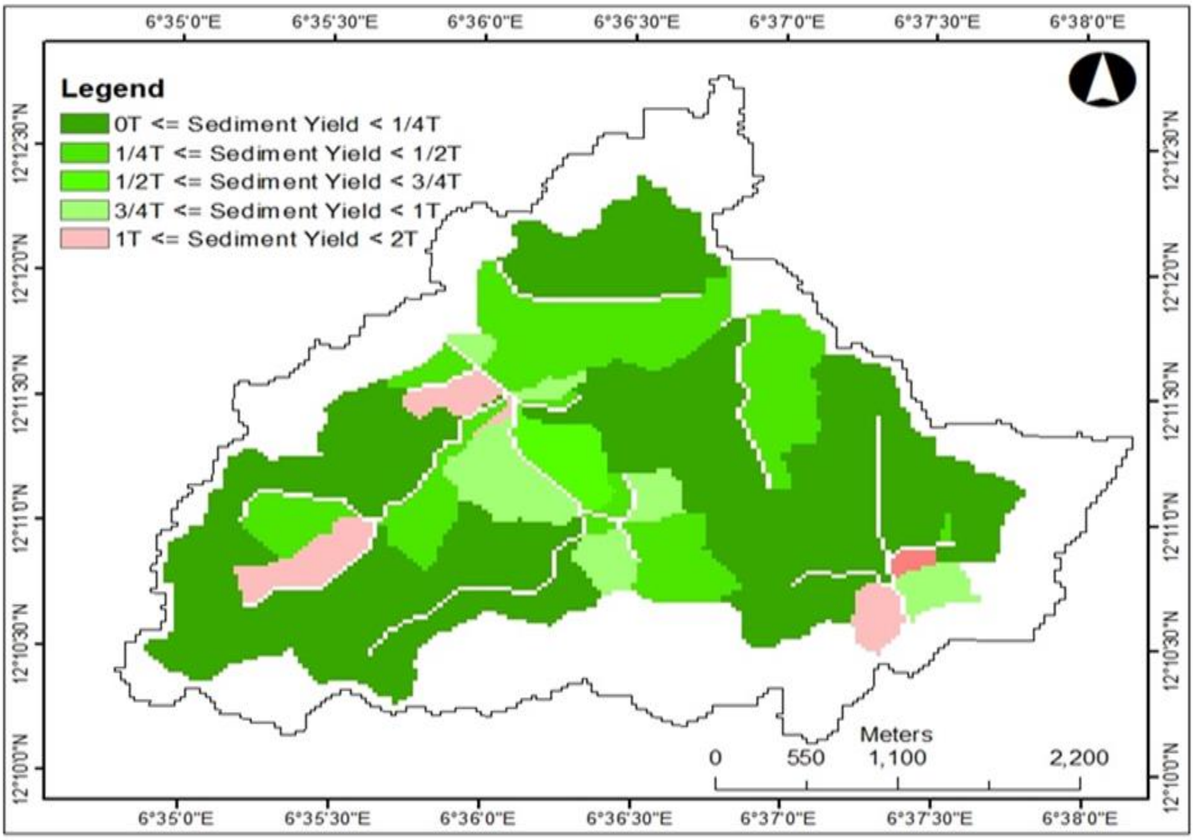

Figure 11. Spatial distribution of sediment yield in the Madawaki Watershed

3.3. Best Management Practices (BMPs)

Recognizing the critical areas, there is a need to provide solutions for water and soil conservation management. To do that, baseline (conventional tillage) and four different scenarios were analyzed to effectively reduce sediment yield. The scenarios are forest perennial (S1), corn, soybean no-till (S2), corn, soybean fall mulch till (S3), and corn fall mulch till (S4).

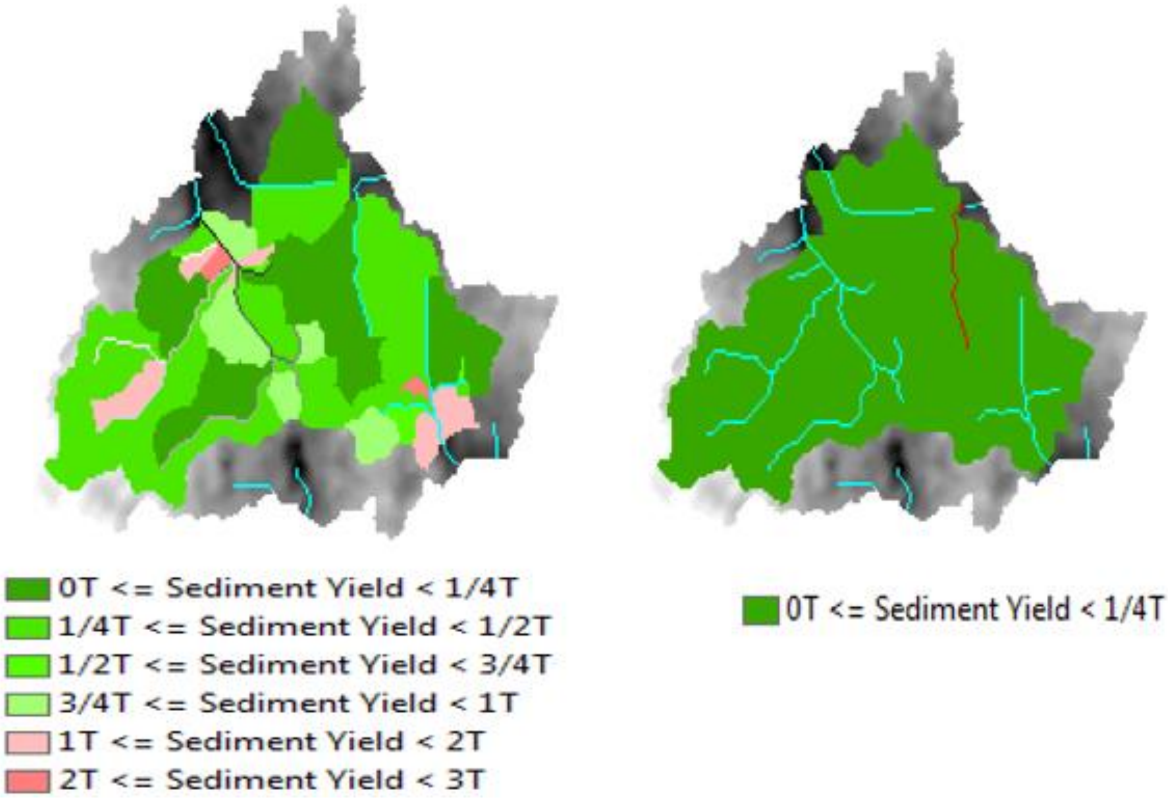

Figure 12. Conventional tillage (baseline) and forest perennial (Scinario1)

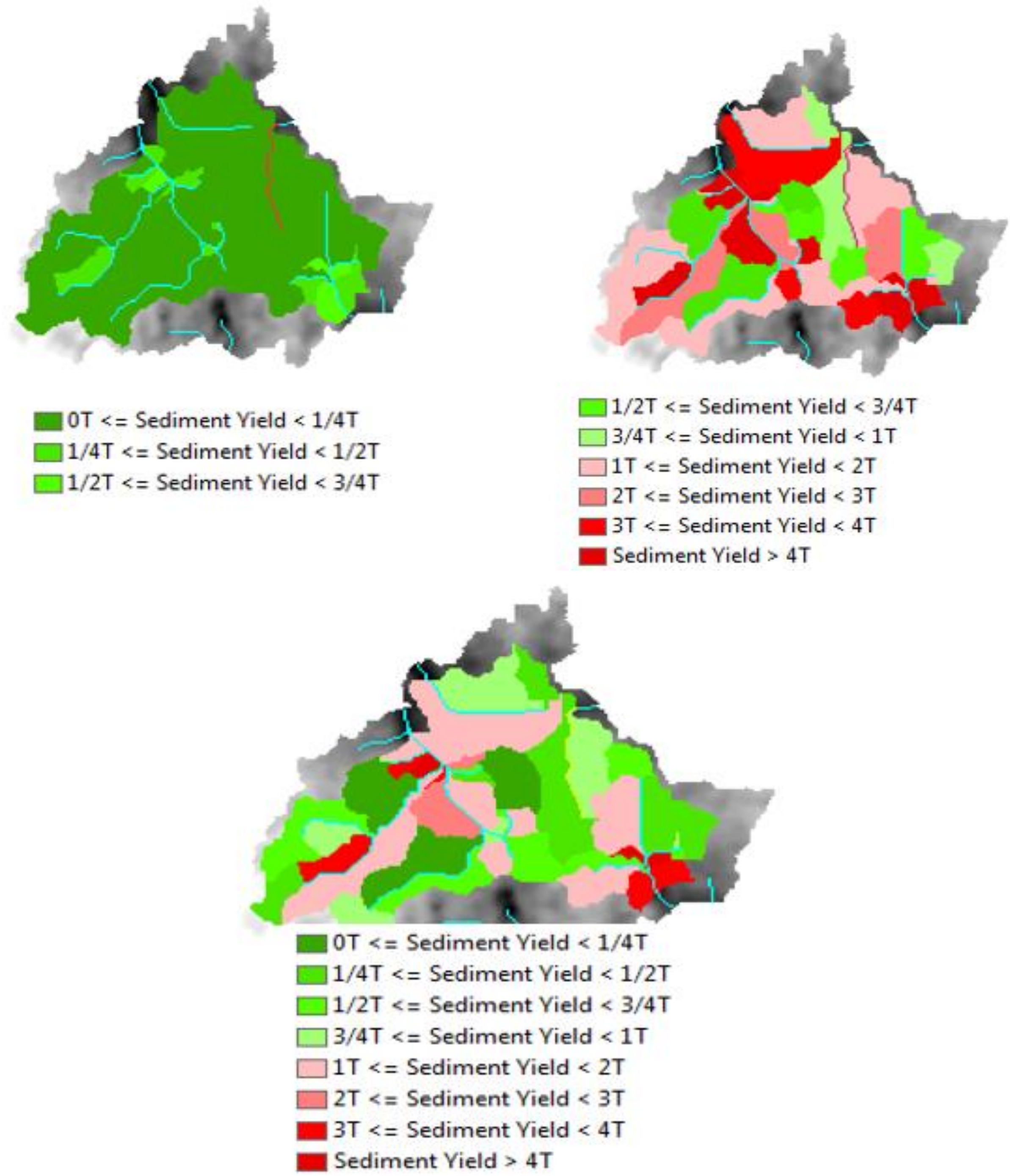

Figure 13. Corn, soybean no-till (S2), corn, soybean fall mulch till (S3), and corn fall mulch till (S4)

Upon the application of the management practices, there is a reduction in sediment yield which ranges from 36.3% to 78.3%. Analyzing the baseline and the other four scenarios, the scenario forest perennial (S1) appears to be the most effective management practice in reducing with a percentage reduction of 78.3% (47.6 tons/ha) of sediment yield (Table 5). This result is comparable with the findings of [18].

Table 5. Sediment yield management scenarios in the Madawaki Watershed

Scenario	Sediment Yield(ton/ha)
Conconventional tillage (Baseline)	272.9
Forest Perennial (S1)	47.6
Corn, Soybean no-till (S2)	139.4
Corn, Soybean-fall mulch till (S3)	1601.8
Corn fall mulch till (S4)	617

4. Conclusion

In this study, WEPP model efficacy was tested to predict sediment yield and runoff at Madawaki watershed. Based on the research, the following conclusions were drawn:

- The study's findings have demonstrated that the Madawaki watershed was affected by a sediment yield of (219ton/ha) 30% less than a study by [19].
- The scenario forest perennial has shown to be the best management practice in the Madawaki watershed with a percentage reduction of sediment yield of 78.3%. The scenario corn and soybean no-till is the least with a percentage reduction of 36.3%. Scenario corn, soybean-fall mulch till, and, corn fall mulch till have shown an increase in the sediment yield with 86% and 64.5%.
- The Madawaki watershed can benefit greatly from these discoveries in terms of land management, conservation, and sustainable development, to reduce sediment yield, and so also preserve the health of ecosystems.

Then, it is recommended that:

- Researchers should use the GeoWEPP model to estimate sediment yield and to provide necessary measures to curtail the increase.
- It is anticipated that GeoWEPP users will increase in Nigeria as GIS techniques and computer-based methods are widely used across the globe for erosion prediction.
- The effectiveness of the model needs to be evaluated across larger areas. More research and focused actions are needed.

Conflict of Interest

No potential conflicts of interest were reported by the author.

Author Contribution

I. A. led the conceptualization, data collection, analysis, and initial drafting of the manuscript. J. O. contributed to the literature review and research design, and assisted in revising the manuscript. M.A. supervised the overall research process, provided insights, and supported the final editing.

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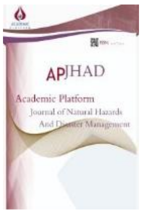

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Effective Distribution of Primary Relief Supplies in Post-Disaster Scenarios

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Abstract

The frequency, severity, and impact of natural disasters are increasing globally, posing significant risks to both human lives and economic systems. Rising population density and the expansion of high-risk areas have further exacerbated the destructive consequences of these events. Earthquakes, in particular, represent a critical threat to densely populated regions, requiring the development of effective disaster response strategies. In this study, an optimization model was developed to ensure the fastest and most efficient delivery of aid materials stored in AFAD warehouses to the affected regions of Bingöl. In order to better represent local aid demands, Bingöl province was divided into 52 regions based on neighborhood proximity and population density. To avoid logistical complexity, the model ensures that each region receives aid from a single warehouse. It optimizes the timely and accurate distribution of five aid types (tents, beds, bed sets, heaters, and kitchen sets) by considering warehouse capacities, locations, available resources, geographical accessibility, and road conditions. The model was tested under two different scenarios to determine optimal warehouse-to-region assignments and was solved using IBM ILOG CPLEX software. According to the results, a total of 470,271 aid items were delivered using 525 vehicles, with each vehicle serving an average of 377 people. In this context, the model aims to accelerate post-disaster response, prevent potential complexity in aid distribution, and minimize human losses.

Key words: Disaster management, AFAD warehouses, emergency logistics, humanitarian logistics, optimization.

1. Introduction

Rapid and effective distribution of aid during disasters is crucial for meeting the basic needs of affected individuals. The success of post-disaster aid distribution depends not only on having sufficient resources but also on the swift delivery of these resources to the areas in need. In this context, the location, capacity, and logistics strategies of the warehouses used in the distribution process play a key role in managing the disaster effectively.

Delivering aid to victims is one of the fundamental response activities after a disaster. Alongside aid materials pre-stocked by governments and non-governmental organizations (NGOs) or procured after the disaster, individuals also provide in-kind donations to support those affected. However, only a portion of these donations is suitable for meeting urgent needs [1, 2].

When disasters occur—whether natural or industrial in nature—humanitarian aid operations are promptly initiated to remove the deceased, rescue the injured, distribute supplies, and provide shelter and medical assistance. Delays in the delivery of supplies or the provision of aid in such

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situations can result in loss of life. Thus, humanitarian logistics is vital for the effectiveness of a relief effort, as it ensures the flow of goods and services in the supply chain [3].

Aid distribution is a core task during the post-disaster response phase, addressing the needs of affected areas and mitigating the impact of disasters [4]. The efficiency of aid distribution is influenced by two main factors [5], the pre-positioning location and quantity of emergency supplies, and operational efficiency in establishing distribution centers and conducting sorting, collection, loading, and unloading activities. As the location and quantity of emergency supplies are predetermined, establishing temporary cross-docking centers to expedite sorting, collection, loading, and unloading processes is critical for enhancing the efficiency of aid distribution [6].

Additionally, disruptions in communication and transportation infrastructure will make accessing information more challenging; hence, decisions made post-disaster will be built upon uncertainties, such as the extent of emergency aid required and the time it will take for aid to reach the affected areas [7]. This highlights the increased importance of strategic planning under uncertain conditions for post-disaster aid distribution.

Infrastructure networks, including the affected areas, shelters, warehouses, centers, and distribution points, play a vital role in delivering humanitarian aid to demand points [8-10]. These networks facilitate the connection between government and non-governmental organizations, enabling the mobility of resources and access to critical facilities during times of need [11, 12].

Another significant concern in post-disaster humanitarian logistics is the ability to sustain operations under conditions of scarcity. Disasters can devastate materials and resources within affected communities, and the flow of critical supplies from external sources may be delayed. This leads to survivors being deprived of critical materials that would ordinarily be readily available [13]. Therefore, ensuring rapid and sufficient access to resources under scarcity conditions is a critical factor for the success of relief efforts.

This study focuses on matching the regions in need with provinces providing aid in the case of Bingöl Province. It aims to propose a planning model for directing post-earthquake aid to ensure the appropriate quantity of aid is delivered to the right locations at the right time. Through the proposed mathematical model, the study seeks to facilitate the delivery of post-disaster aid to the regions in need, minimizing the impacts of the emergencies brought by disasters. Comprehensive analyses are conducted to determine the affected regions, prioritize their needs, and match them with donor provinces. Key steps in this process include identifying the impacted areas, ensuring the accessibility of aid, determining the priority of needs, and considering geographical and logistical factors.

The rest of the paper is structured as follows: Section 2 reviews the literature on post-disaster humanitarian logistics, with a focus on emergency logistics and the methodological approaches commonly adopted in this field. Section 3 outlines the problem definition, the data required for the mathematical model and the model itself. Section 4 presents the implementation results of the proposed model. Finally, Section 5 provides conclusions, managerial implications for decision-makers and directions for future research.

2. Literature Review

To position this study and highlight its contribution, we review the literature on humanitarian aid logistics management, addressing logistical system design issues and related methodological approaches explicitly.

Several studies have been conducted to solve models under uncertainty. For instance, [14] developed mathematical models for scheduling and routing land and air vehicles with a dual objective of efficiently providing telecommunications capabilities and emergency supplies. They found that the column generation (CG)-based computational approach outperformed exact methods in solving the MILP model proposed for the two-stage decision framework. [15] presented a comprehensive mixed-integer linear programming (MILP) model to integrate pre- and post-disaster decisions in humanitarian supply chain (HSC) design, considering quantitative flexibility contracts and equitable distribution of aid materials under uncertainty for potential disasters like floods and earthquakes. [16] addressed disaster relief logistics (DRL), providing adequate aid materials to disaster victims. They explicitly considered supplier selection and inventory, corresponding to static preparedness decisions and dynamic post-disaster purchasing and delivery, formulating a risk-averse two-stage distributional optimization (DO) model to tackle uncertain dynamic DRL with incomplete distribution data. [17] examined a highly integrated humanitarian aid network design problem under the adverse effects of disasters, where network reinforcement planning and inventory prepositioning arrangements are optimized collaboratively. Based on problem structure and decomposition optimization, they proposed both exact and heuristic approaches to solve bilinear subproblems. Taking into account hybrid uncertainties in demand and travel time, [6] developed two mathematical models to optimize post-disaster relief kit assembly and distribution, aiming to minimize total cost and maximize demand satisfaction.

Emergency management has always been a prominent topic for researchers, as it is a discipline that prepares for, responds to, and aids in the reconstruction of communities after disasters. For example, [18] developed a resilient aid supply plan by creating an integrated supply-storage model, specifically designed to determine the integrated aid supply-storage plan using a portfolio of supply sources. [19] evaluated aid centers for flexibility and efficiency in housing the injured and sick under disaster and pandemic conditions by applying Geographic Information Systems (GIS) and multi-criteria decision-making (MCDM) according to standard criteria. [20] developed an integrated decision-support framework containing a model-based data propagation component to coordinate damage assessment, road repair, and aid distribution in real time during the disaster response phase. [21] proposed a dynamic prepositioning strategy to efficiently meet the needs of victims under uncertain and dynamic demands within the humanitarian aid context. [22] contributed to a better understanding of disasters, disaster preparedness, post-disaster recovery, and production efficiency in Caribbean firms, examining the impact of a firm’s disaster preparedness and post-disaster recovery strategies on technical efficiency using Stochastic Frontier Analysis (SFA). [23] presented a technique for extracting information from primary social media sources to find and distribute critical aid needed in emergencies and disaster situations. [24] examined emergency resource allocation and vehicle routing in post-disaster emergency management, which are the fundamental and inseparable response actions. They proposed individual and joint chance-constrained programming DSO models for multi-period emergency resource allocation and vehicle routing under demand distribution uncertainty, uncovering managerial insights that could be valuable for disaster response operations. [25] focused on the three-dimensional objectives of efficiency, effectiveness, and equity in humanitarian logistics. They proposed an emergency material allocation model with multiple rescue sites, affected sites, and periods, meeting the requirement for timely emergency distribution and providing decision-makers with a rapid distribution plan.

Although the issues related to undesired materials or material convergence post-disaster and the challenges caused by useless donations are strongly emphasized in the literature, only a few studies address how to tackle these issues. For instance, [2] proposed a classification process as an intermediate step in the flow of donated aid, in addition to suggesting a greening strategy for needed materials to be sent to aid organization warehouses for later use in other disaster situations. In this context, they focused on the economic and environmental dimensions of sustainability among the three pillars of sustainability: economic, environmental, and social. [26] developed a two-stage stochastic programming model and solution method to assist decision-makers in preparing for and addressing the logistics of aid material distribution after a major earthquake. [27] focused on the design of a three-layered network to support short-term recovery under demand and capacity uncertainty, aiming for the distribution of critical materials to affected populations post-disaster. [28] presented disaster conditions where multilevel networks support aid mode strategies based on predicted demand, focusing on an analytical solution to determine if these strategies contribute to providing aid based on forecasted demand. [29] proposed a five-step procedure to generate and analyze earthquake disaster scenarios at the block level in urban areas, allowing for rapid response planning by estimating the amount and location of aid demand for each scenario. [30] introduced the socially costly vehicle routing problem: a mathematical optimization model that considers social costs to determine the right mix for transporting, routing, and delivering critical material. Due to the NP-hard nature of the problem, they developed a hybrid metaheuristic algorithm with a novel local search to solve it. [31] a distributionally robust optimization model (DROM) is developed to optimize relief distribution and facility locations while minimizing costs and addressing uncertainties.

Makes a significant contribution to the existing literature by introducing a novel model that optimizes post-disaster humanitarian logistics. While various optimization models for disaster aid distribution exist in the literature, the proposed model is uniquely developed based on AFAD warehouses, presenting an original application within the context of disaster management in Türkiye. Unlike most existing studies that focus on general humanitarian logistics, this model optimizes aid distribution processes for a specific region in detail, simplifying logistical coordination by ensuring that each region receives aid from only one warehouse, considering the worst-case scenario. Additionally, it integrates critical factors such as geographical accessibility, road conditions, and warehouse capacities directly into the modeling process, providing a realistic and practical solution. The most significant innovation of this study is its flexible structure, which is tested under different scenarios to adapt to varying disaster conditions. With these features, the model offers strategic insights for decision-makers in disaster management, contributing to the acceleration of post-disaster aid distribution, the minimization of victimization, and the more efficient management of logistical processes.

The studies reviewed in the literature are summarized in Table 1, organized by disaster phase—pre-disaster (PreD) and post-disaster (PoD)—and types of aid provided.

Table 1. Summary of humanitarian aid logistics optimization models

Author(s)	Phase		Type of Aid											
	PreD	PoD	Water	Food	Aid Kit	Hygiene Kit	Shelter	Tent	Clothing	Blanket	Bed	Bed Set	Heater	Kitchen Set
Faiz et al. [14]		✓	✓	✓	✓									
Modarresi and Maleki [15]	✓	✓	✓	✓	✓			✓		✓				
Wang et al. [16]		✓	✓	✓	✓			✓		✓				
Zhang et al. [17]	✓	✓	✓	✓	✓			✓	✓					
Zhang et al. [6]		✓			✓									
Aghajani et al. [18]	✓	✓	✓	✓										
Choukolaei et al. [19]		✓		Location of Aid Centers										
Farzaneh et al. [20]		✓		✓	✓		✓							
Hu et al. [21]		✓	✓	✓	✓									
Mohan [22]	✓	✓		Unspecified										
Vishwanath et al. [23]		✓		Unspecified										
Wang et al. [24]		✓	✓	✓	✓	✓	✓	✓	✓	✓				
Wang and Sun [25]		✓	✓	✓				✓		✓				
Alegoz et al. [2]		✓		High-Priority Items										
Chang et al. [26]		✓	✓	✓						✓				
Daneshvar et al. [27]		✓		✓		✓	✓							
Kawase and Iryo [28]		✓		Unspecified										
Mota-Santiago et al. [29]		✓		Unspecified										
Sadeghi et al. [30]		✓	✓											
Wang et al. [31]		✓		Unspecified										
This paper		✓						✓		✓	✓	✓	✓	✓

3. Materials and Method

In this study, a mathematical optimization model has been developed to ensure the effective and timely distribution of relief materials stored in AFAD warehouses to the disaster-affected regions of Bingöl province. In the initial phase of the study, data on the locations, storage capacities, and types of relief supplies available in AFAD warehouses were collected. This data formed the foundation for constructing the optimization model. The primary objective of the model is to assign each region to a single AFAD warehouse, taking into account warehouse capacities, geographic proximity, and the diversity of aid materials (tent, bed, bed set, heater, kitchen set).

The problem was formulated as a deterministic linear optimization model with binary decision variables that indicate whether a region is assigned to a specific warehouse. The model was solved using IBM ILOG CPLEX Optimization Studio version 22.11.

Additionally, the study considers the possibility that some warehouses may become inoperable due to damage during a disaster, and an alternative scenario was developed to prevent potential disruptions in aid delivery and minimize victim impact.

3.1. Problem definition

This study was developed in response to the challenges encountered during the distribution of relief supplies following the most recent major earthquake in Türkiye, and it was applied specifically to Bingöl province, which is classified as a high-risk earthquake zone. In this context, a mathematical optimization model was developed to ensure the effective and timely distribution of relief materials stored in AFAD warehouses to the disaster-affected regions of Bingöl. The model was solved using IBM ILOG CPLEX Optimization Studio. IBM ILOG CPLEX is an optimization software designed to solve linear, integer, and quadratic programming problems.

The primary objective of the model is to assign each region to a single AFAD warehouse while determining the most appropriate distribution plan by considering various factors such as the diversity of aid types (tent, bed, bed set, heater, kitchen set), warehouse capacities, geographical distances, and transportation constraints. The model minimizes the total transportation distance while ensuring that the aid demands of all regions are fully met without exceeding the warehouse capacities.

During the modeling process, logistical constraints were also taken into account. These include the limited number of available vehicles, road distances calculated using GIS data, and the volume of each type of aid item. Each vehicle is assumed to have a maximum carrying capacity of 90 m^3. The volume of aid items was estimated based on average packaging dimensions used in previous earthquake relief operations.

To evaluate the robustness and practical applicability of the model, two different scenarios were analyzed:

Scenario 1: A scenario in which all 22 AFAD warehouses are actively involved in the distribution of aid.

Scenario 2: A scenario in which the warehouses located in provinces expected to be affected by the earthquake (Elazığ, Erzincan, Erzurum, and Muş), as identified in the AFAD Provincial Risk Reduction Plan (IRAP) [32], are excluded from the aid distribution process.

3.2. Data collection

In this study, data required to optimize aid distribution to Bingöl province were carefully selected and collected from various sources. These data enabled the accurate determination of the model's parameters and constraints. Below, the types of data used and the process of obtaining them are detailed:

Annexes 1 and 2 analyze the most affected provinces for Scenarios 1 and 2.

AFAD Warehouse Data: The data regarding the locations, capacities, and types of aid stored in AFAD warehouses, which will be used in aid distribution, were obtained from AFAD's official resources and sources identified through a literature review. These sources provide detailed information on the types of aid available at each warehouse and their respective capacities. The collected data were utilized in forming the model's "warehouse capacities" and "aid types" constraints.

AFAD has established 27 logistics warehouses across Türkiye. Table 2 shows the quantities of disaster relief aid materials stored in warehouses located in 22 provinces [33, 34].

Table 2. AFAD Warehouse capacity information [33, 34]

Province	Number of Container	Tent	Bed	Bed Set	Heater	Kitchen Set
Adana	96	48000	115200	192000	69120	138240
Adıyaman	48	24000	57600	96000	34560	69120
Afyonkarahisar	96	48000	115200	192000	69120	138240
Balıkesir	48	24000	57600	96000	34560	69120
Bursa	48	24000	57600	96000	34560	69120
Denizli	96	48000	115200	192000	69120	138240
Diyarbakır	48	24000	57600	96000	34560	69120
Elazığ	48	24000	57600	96000	34560	69120
Erzincan	48	24000	57600	96000	34560	69120
Erzurum	96	48000	115200	192000	69120	138240
Kastamonu	48	24000	57600	96000	34560	69120
Manisa	96	48000	115200	192000	69120	138240
Kahramanmaraş	96	48000	115200	192000	69120	138240
Muğla	48	24000	57600	96000	34560	69120
Muş	96	48000	115200	192000	69120	138240
Samsun	96	48000	115200	192000	69120	138240
Sivas	48	24000	57600	96000	34560	69120
Tekirdağ	96	48000	115200	192000	69120	138240
Aksaray	48	24000	57600	96000	34560	69120
Kırıkkale	48	24000	57600	96000	34560	69120
Yalova	48	24000	57600	96000	34560	69120
Düzce	48	24000	57600	96000	34560	69120

Regional Aid Needs: The population density, demographic characteristics, and potential post-disaster aid needs of Bingöl's districts were extracted from official reports provided by the Turkish Statistical Institute (TÜİK) and local administrations. The needs for different types of aid for each region (B) were analyzed and used as the "regional needs" parameter in the model. The demand quantities required by the regions were determined based on the per-household aid distribution rates announced by AFAD during the last major earthquake, which were then scaled according to the demographic structure of Bingöl province. Additionally, considering the possibility of extraordinary situations, estimated demand values were calculated with a safety margin. Warehouse capacities were planned to meet demand even in worst-case scenarios and were modeled with a capacity exceeding normal demand levels. Furthermore, regional demand calculations were proportioned to the population and set at approximately twice the estimated need, creating an additional safety margin to accommodate sudden increases. As a result, the dataset was structured to ensure that aid is delivered in a timely and sufficient manner. Table 3 presents the needs of the regions.

Table 3. Need capacity of the regions

	Tent	Bed	Bed set	Heater	Kitchen set		Tent	Bed	Bed set	Heater	Kitchen set
B1	458	3666	3666	458	458	**B27**	630	5040	5040	630	630
B2	424	3390	3390	424	424	**B28**	536	4286	4286	536	536
B3	623	4980	4980	623	623	**B29**	536	4286	4286	536	536
B4	623	4980	4980	623	623	**B30**	536	4287	4287	536	536
B5	438	3501	3501	438	438	**B31**	536	4287	4287	536	536
B6	438	3501	3501	438	438	**B32**	536	4287	4287	536	536
B7	454	3634	3634	454	454	**B33**	507	4055	4055	507	507
B8	471	3766	3766	471	471	**B34**	507	4055	4055	507	507
B9	356	2844	2844	356	356	**B35**	507	4055	4055	507	507
B10	465	3720	3720	465	465	**B36**	507	4055	4055	507	507
B11	465	3720	3720	465	465	**B37**	404	3230	3230	404	404
B12	483	3863	3863	483	483	**B38**	404	3230	3230	404	404

B13	460	3678	3678	460	460	**B39**	382	3052	3052	382	382
B14	460	3678	3678	460	460	**B40**	382	3052	3052	382	382
B15	460	3678	3678	460	460	**B41**	523	4182	4182	523	523
B16	690	5521	5521	690	690	**B42**	523	4182	4182	523	523
B17	509	4075	4075	509	509	**B43**	408	3262	3262	408	408
B18	528	4223	4223	528	528	**B44**	331	2648	2648	331	331
B19	528	4223	4223	528	528	**B45**	335	2683	2683	335	335
B20	528	4223	4223	528	528	**B46**	332	2654	2654	332	332
B21	528	4223	4223	528	528	**B47**	401	3207	3207	401	401
B22	528	4223	4223	528	528	**B48**	665	5317	5317	665	665
B23	552	4419	4419	552	552	**B49**	665	5317	5317	665	665
B24	478	3826	3826	478	478	**B50**	463	3704	3704	463	463
B25	478	3826	3826	478	478	**B51**	124	991	991	124	124
B26	478	3826	3826	478	478	**B52**	174	1389	1389	174	174

Geographical and Distance Data: The road distances between AFAD warehouses and regions in Bingöl were calculated using GIS and mapping services. Due to unpredictable traffic conditions following a disaster, it is not possible to determine exact travel times. In the dataset, the preferred routes are main roads, while roads with a higher risk of damage, such as mountain roads and single-lane roads, have been excluded from consideration. These data were used to develop the “distance” parameters in the model by accounting for actual road distances. The distances between regions (B) and warehouses (D) play a critical role in determining which warehouse should supply aid to a specific region.

Number of Vehicles: Based on research in the literature, the capacity of a single vehicle is assumed to be 90 m³. Additionally, the model determines the number of vehicles required when a warehouse dispatches aid to a region.

The dimensions of the relief materials were calculated based on the data from [35]. The volume of each type of relief material is as follows:

$\alpha_1 = 0.464$ $\alpha_2 = 0.137$ $\alpha_3 = 0.020$ $\alpha_4 = 0.048$ $\alpha_5 = 0.029$

The collected data were preprocessed for use in the model and optimized using IBM ILOG CPLEX 22.11 software. The reliability and currency of the data were meticulously assessed to enhance the model’s accuracy. This ensured that the theoretical foundation of the model was grounded in realistic conditions, thereby contributing to the effective planning of aid distribution for Bingöl province.

3.3. Mathematical Model

The goal is to optimally distribute aid from AFAD warehouses to the regions of Bingöl province. The constraints and variables used in the model aim to ensure that each region is assigned only one warehouse, while optimizing the capacities of the warehouses and the needs of the regions. The mathematical model in this study is developed based on the vehicle routing problem for humanitarian logistics, as considered in the work of [36].

Notation:

Indices	
i	Set of demand regions.
j	Set of AFAD warehouses.
t	Set of aid types. (1 = Tent, 2 = Bed, 3 = Bed Set, 4 = Heater, 5 = Kitchen Set)
Parameters	
d_{ij}	Road distance between region i and warehouse j.
c_{jt}	Capacity of warehouse j for aid type t.
r_{it}	Need of region i for aid type t.
M	A sufficiently large positive number (e.g., $M = 10^6$).
h	Set of warehouses to be excluded (h = {2, 3, 4, 5}).
α_t	Unit volume for aid type t (m^3)
V_{max}	Maximum transport capacity per vehicle (90 units)

Decision Variables	
x_{ij}	Binary variable 1, if aid is sent to region i from warehouse j, and otherwise, 0
y_{ijt}	Quantity of aid type t sent from warehouse j to region i.
z_{ij}	Number of transport vehicles between region i and warehouse j.

Objective function (1) minimizes the distance required to deliver relief supplies between the region and the warehouse.

$$\min Z = \sum_{i\epsilon I}\sum_{j\epsilon J} d_{ij}z_{ij} \tag{1}$$

Constraints:

$$\sum_{j\epsilon J} y_{ijt} = r_{it} \qquad \forall i \in I,\ \forall t \epsilon T \tag{2}$$

$$\sum_{i\epsilon I} y_{ijt} \leq c_{jt} \qquad \forall j \in J,\ \forall t \epsilon T \tag{3}$$

$$y_{ijt} = 0 \qquad \forall i \in I,\ \forall j \epsilon h, \forall t \epsilon T \tag{4}$$

$$y_{ijt} \leq M.x_{ij} \qquad \forall i \in I, \forall j \epsilon J, \forall t \epsilon T \tag{5}$$

$$\sum_{j\epsilon J} x_{ij} = 1 \qquad \forall i \in I \tag{6}$$

$$\sum_{t\epsilon T} \alpha_t y_{ijt} \leq V_{max} z_{ij} \qquad \forall i \in I, \forall j \in J \tag{7}$$

$$x_{ij} \epsilon \{0,1\} \qquad \forall i \in I, \forall j \in J \qquad (8)$$

$$y_{ijt} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall t \in T$$
$$z_{ij} \geq 0 \qquad \forall i \in I, \forall j \in J \text{ and } z_{ij} \in \mathbb{Z}^{+} \qquad (9)$$

If aid types are available in varying amounts in the warehouses, separate capacity and demand constraints are applied for each aid type, as shown in Constraint (2). The model ensures that the quantity of each aid type dispatched from each warehouse does not exceed its capacity Constraint (3). Warehouses that are most likely to be affected during a disaster are prohibited from sending aid to any region Constraint (4). To ensures logical consistency, the quantity y_{ijt} is positive if aid type t is sent from warehouse j to region i, otherwise it must be zero Constraint (5). For a specific region and aid type, assistance must be supplied from only one warehouse Constraint (6). The total volume of relief materials delivered to each region must not exceed the capacity of the transportation vehicles Constraint (7). A binary decision variable constraint is implemented to ensure that x_{ij} is binary (0 or 1) Constraint (8). Finally, the quantity of relief materials delivered to each region and the capacity of transportation vehicles cannot be negative Constraint (9).

4. Discussion

This section presents the results of the model analysis conducted under two different scenarios. In the first scenario, all warehouses participate in the aid distribution process, providing a broader range of resources and access. In the second scenario, the effects of excluding the warehouses from the regions predicted to be affected by the earthquake are analyzed. The results of both scenarios are compared, particularly in terms of resource capacity, distribution speed, and aid accessibility rates.

The model was formulated and solved using IBM ILOG CPLEX Optimization Studio version 22.11 on a MacBook equipped with an Apple M2 chip and 8 GB of RAM. It consists of 8,008 decision variables, including 1,144 binary and 6,864 integer variables, and 7,286 constraints. The scenarios were solved in 00:00:47 (47 seconds), demonstrating that the model is computationally tractable.

4.1. First Scenario: Situation with All Warehouses Participating

With the participation of all warehouses, the available aid materials had a wide resource capacity. This resulted in greater flexibility and inclusiveness in the types of aid provided to the regions. The geographical spread of the resources shortened the distances to the regions, enabling a faster distribution process. This is particularly advantageous in situations requiring quick intervention immediately after the disaster. With the participation of all warehouses, distance were reduced, and the distribution process became more efficient, as the broader distribution of resources lowered transportation distance. When the model was solved using IBM ILOG CPLEX 22.11, the objective value obtained was 71,762 and the quantities of aid types sent are shown in Table 4.

4.2. Second Scenario: Situation with the Exclusion of Provinces Affected by the Earthquake

In the second scenario, a situation was examined where the provinces predicted to be affected by the earthquake did not participate in the aid distribution process. In this case:

The reduction in the number of warehouses limited the resource capacity. This, particularly in the distribution of aid over large areas, led to longer access times for some regions. The decrease in the number of warehouses resulted in increased transportation times to specific regions. For geographically distant regions, the aid process had to be spread over a longer time frame. When the model was solved using IBM ILOG CPLEX 22.11, the objective value obtained was 130,572 and the quantities of aid types sent are shown in Table 5.

This notation is used in Table 4 and Table 5: W denotes warehouses, A represents aid types, R refers to regions, V indicates the number of vehicles used for transportation, and To stands for the total amount of aid delivered.

Table 4. Region-warehouse matching according to Scenario 1

W	2					4					5					12					
A	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	V
R																					
1											458	3666	3666	458	458						10
2																424	3390	3390	424	424	9
3																623	4980	4980	623	623	13
4																623	4980	4980	623	623	13
5																438	3501	3501	438	438	9
6																438	3501	3501	438	438	9
7						454	3634	3634	454	454											10
8						471	3766	3766	471	471											10
9											356	2844	2844	356	356						8
10	465	3720	3720	465	465																10
11	465	3720	3720	465	465																10
12																483	3863	3863	483	483	10
13											460	3678	3678	460	460						10
14											460	3678	3678	460	460						10
15	460	3678	3678	460	460																10
16																690	5521	5521	690	690	14
17	509	4075	4075	509	509																11
18																528	4223	4223	528	528	11
19	528	4223	4223	528	528																11
20	528	4223	4223	528	528																11
21	528	4223	4223	528	528																11
22	528	4223	4223	528	528																11
23											552	4419	4419	552	552						12
24																478	3826	3826	478	478	10
25																478	3826	3826	478	478	10
26	478	3826	3826	478	478																10
27																630	5040	5040	630	630	13
28																536	4286	4286	536	536	11
29																536	4286	4286	536	536	11
30																536	4287	4287	536	536	11
31																536	4287	4287	536	536	11
32																536	4287	4287	536	536	11
33	507	4055	4055	507	507																11
34	507	4055	4055	507	507																11
35											507	4055	4055	507	507						11
36	507	4055	4055	507	507																11
37											404	3230	3230	404	404						9
38											404	3230	3230	404	404						9
39																382	3052	3052	382	382	8
40																382	3052	3052	382	382	8
41	523	4182	4182	523	523																11
42	523	4182	4182	523	523																11
43											408	3262	3262	408	408						9
44											331	2648	2648	331	331						7
45											335	2683	2683	335	335						7
46											332	2654	2654	332	332						7
47											401	3207	3207	401	401						9
48											665	5317	5317	665	665						14
49											665	5317	5317	665	665						14
50											463	3704	3704	463	463						10
51	124	991	991	124	124																3
52						174	1389	1389	174	174											4
To	7180	57431	57431	7180	7180	1099	8789	8789	1099	1099	7201	57592	57592	7201	7201	9277	74188	74188	9277	9277	525

Table 5. Region-warehouse matching according to Scenario 2

W	6					7					12					
A	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	V
R																
1											458	3666	3666	458	458	10
2											424	3390	3390	424	424	9
3											623	4980	4980	623	623	13
4											623	4980	4980	623	623	13
5						438	3501	3501	438	438						9
6											438	3501	3501	438	438	9
7											454	3634	3634	454	454	10
8	471	3766	3766	471	471											10
9	356	2844	2844	356	356											8
10											465	3720	3720	465	465	10
11											465	3720	3720	465	465	10
12	483	3863	3863	483	483											10
13											460	3678	3678	460	460	10
14											460	3678	3678	460	460	10
15											460	3678	3678	460	460	10
16						690	5521	5521	690	690						14
17											509	4075	4075	509	509	11
18						528	4223	4223	528	528						11
19						528	4223	4223	528	528						11
20						528	4223	4223	528	528						11
21						528	4223	4223	528	528						11
22						528	4223	4223	528	528						11
23											552	4419	4419	552	552	12
24						478	3826	3826	478	478						10
25						478	3826	3826	478	478						10
26											478	3826	3826	478	478	10
27	630	5040	5040	630	630											13
28	536	4286	4286	536	536											11
29						536	4286	4286	536	536						11
30						536	4287	4287	536	536						11
31						536	4287	4287	536	536						11
32						536	4287	4287	536	536						11
33											507	4055	4055	507	507	11
34											507	4055	4055	507	507	11
35											507	4055	4055	507	507	11
36											507	4055	4055	507	507	11
37											404	3230	3230	404	404	9
38											404	3230	3230	404	404	9
39											382	3052	3052	382	382	8
40	382	3052	3052	382	382											8
41											523	4182	4182	523	523	11
42											523	4182	4182	523	523	11
43											408	3262	3262	408	408	9
44						331	2648	2648	331	331						7
45											335	2683	2683	335	335	7
46											332	2654	2654	332	332	7
47											401	3207	3207	401	401	9
48											665	5317	5317	665	665	14
49											665	5317	5317	665	665	14
50											463	3704	3704	463	463	10
51	124	991	991	124	124											3
52	174	1389	1389	174	174											4
To	3156	25231	25231	3156	3156	7199	57584	57584	7199	7199	14402	115185	115185	14402	14402	525

4.3. Numerical results

As a result of the implementation of our model, a plan was obtained that optimizes the distribution of aid materials from warehouses to 52 regions. This plan ensures that all five different types of aid (tents, beds, bed sets, heaters, and kitchen sets) required by each region are fully met while minimizing the total transportation distance.

When comparing the two scenarios, notable differences emerge:

In the first scenario, the participation of all warehouses facilitated rapid and widespread access to aid, while in the second scenario, the limited number of warehouses decreased the speed of access. The first scenario offers an advantage in terms of logistical distances, whereas in the second scenario, a significant increase in distances was observed. The reduction in the number of warehouses increased the operational burden on the remaining ones, leading to longer travel distances and less efficient distribution.

A total of 525 vehicles were used to deliver 470.271 aid items to the affected regions. Within this distribution plan, each vehicle was assigned to deliver aid to an average of 377 people. These results demonstrate the operational feasibility of the system and its ability to reach a large number of individuals effectively during post-disaster relief operations.

5. Conclusion

Effective planning of aid distribution is of vital importance in disaster situations. In this study, the aid distribution process for Bingöl province was examined through two different scenarios.

In the first scenario, all 22 AFAD warehouses were included in the distribution process. According to the model results, a total of 470.271 relief items would be delivered to Bingöl from the warehouses located in Elazığ, Erzurum, Muş, and Diyarbakır. This scenario offered advantages in terms of accessibility and logistical efficiency; since the total transportation distance was reduced, aid was delivered more quickly and warehouse workloads were balanced.

In the second scenario, warehouses in high-risk provinces expected to be affected by the disaster—namely Elazığ, Erzincan, Erzurum, and Muş—were excluded from the distribution process. In this case, aid to Bingöl was supplied from warehouses in Sivas, Adıyaman, and Diyarbakır, and again a total of 470.271 relief items were delivered. However, this scenario led to increased operational burden on the remaining warehouses and longer transportation distances.

A total of 525 vehicles were used to deliver aid to the disaster-affected areas, with each vehicle serving an average of 377 people.

Accordingly, this study assumes a worst-case scenario and develops a model based on data specific to Bingöl, a province with a high risk of earthquakes. To represent local aid needs more accurately and in greater detail, Bingöl was divided into 52 regions based on neighborhood proximity and population density. This regional division allows the model to balance geographical accessibility and population demand more precisely in the aid distribution process. As a result, the model is able to produce more accurate assignment decisions by taking into account the varying logistical conditions of each region. Official and up-to-date data from AFAD warehouses—such as aid types and storage capacities—were directly incorporated into the model. In addition, the scenarios consider the possibility that certain warehouses may become inoperable during a disaster. By ensuring that each region receives aid from a single warehouse, the model prevents logistical complexity in the distribution process. All components were formulated as an optimization model and solved to demonstrate its operational feasibility.

In future studies, aid distribution models can be further improved by addressing different regional conditions, alternative warehouse strategies, and transportation options through more detailed analyses.

Authorship Contributions

T. D. and H. M. A. collected the data, designed the models, contributed to the research's design, implementation, analysis, and evaluation of the results, and wrote the manuscript.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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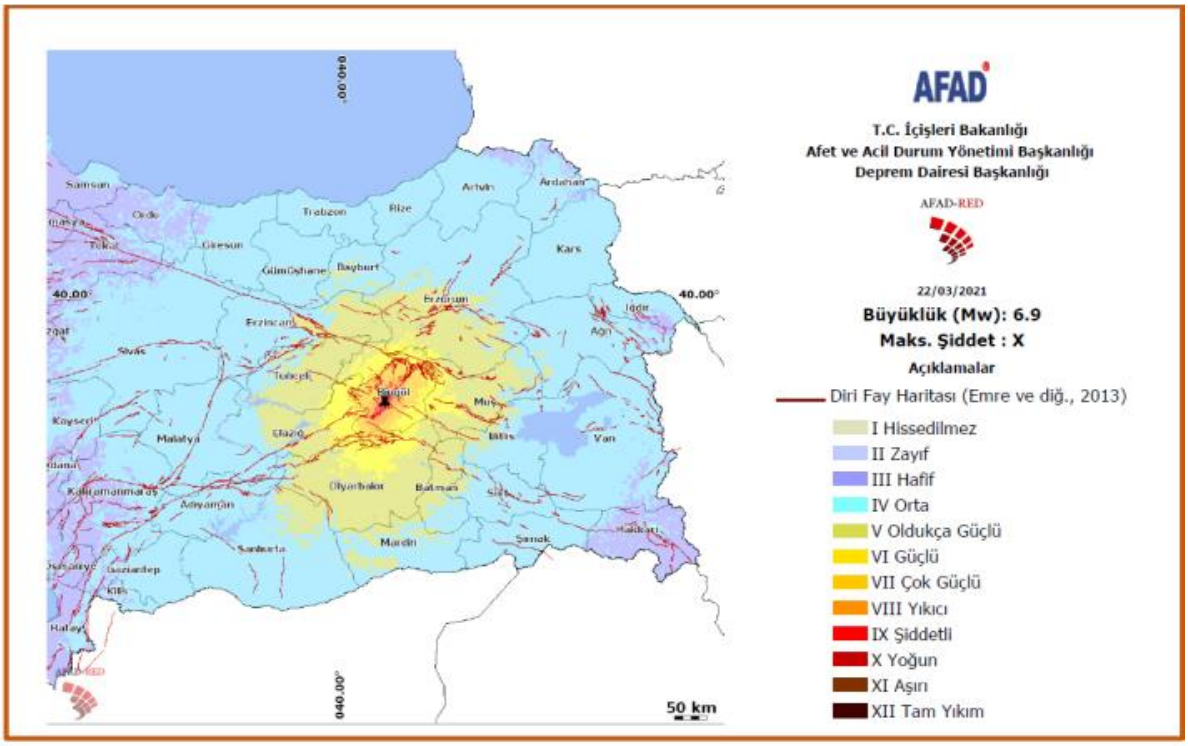
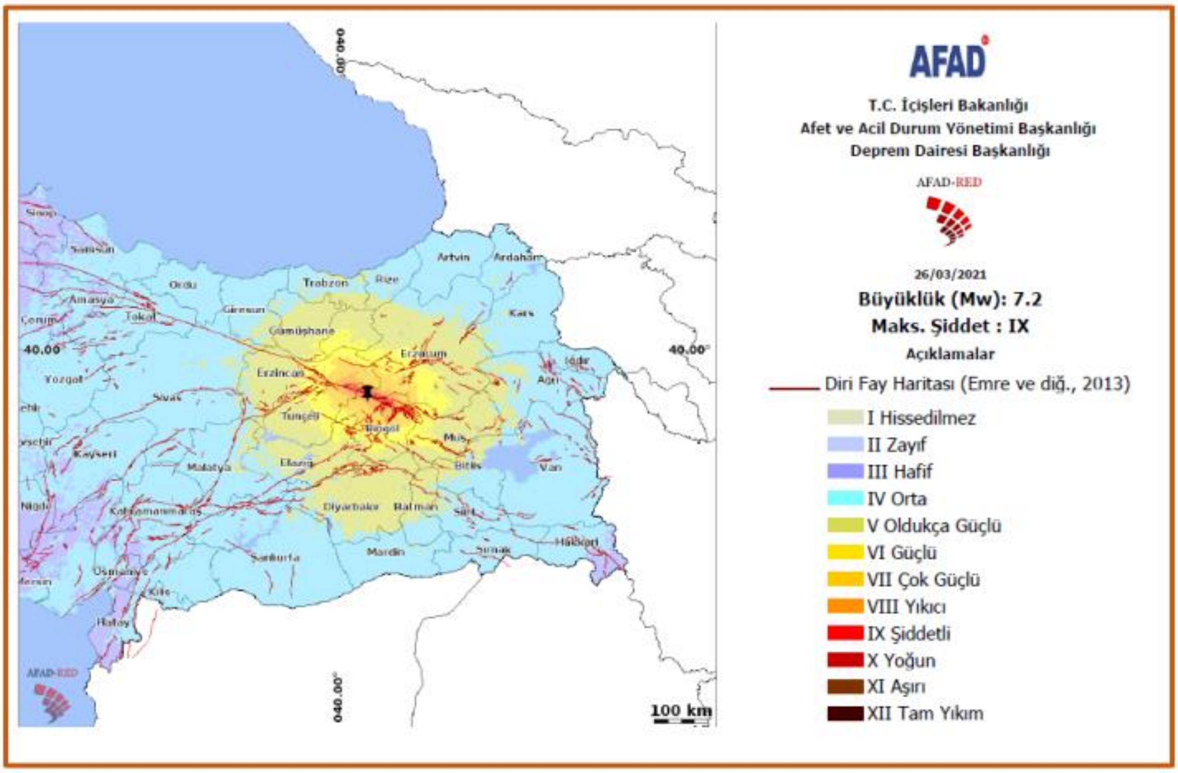
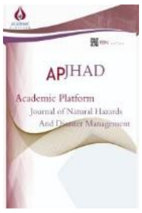
ANNEX

Annex 1. The intensity distribution map generated by AFAD's RED analysis for a magnitude 6.9 earthquake [32]



Annex 2. The intensity distribution map generated by AFAD's RED analysis for a magnitude 7.2 earthquake [32]





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A Look at the Leadership Management of Chernobyl and Fukushima Nuclear Accidents

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Abstract

This article aims to analyze the role of leadership in the context of the Chernobyl and Fukushima nuclear accidents. The study begins with the definition of basic concepts such as nuclear energy, nuclear accidents and leadership. It also attempts to examine how leaders behaved in managing disasters and crises in these two major nuclear accidents and their behaviors such as effective communication, decisive action and adaptation to rapidly changing situations during crises. It also attempts to understand the behavioral patterns and effects of different types of leadership on individuals in crisis management. The study also aims to provide insight into the critical role of leadership in managing complex emergencies and preventing similar disasters in the future, while trying to understand which type of leadership is more effective in reducing the impact of disasters, especially in the context of nuclear accidents. The study attempted to synthesize previous studies in these areas using the literature review method. Finally, the research concluded that strong leadership is necessary in ensuring safety and security

Key words: Chernobyl, Fukushima, Nuclear accident, Leadership

1. Introduction

"Nuclear energy" is high energy generated by the splitting of atoms. This energy is produced in a controlled manner in nuclear power plants. When nuclear energy or its waste goes out of control and harms the facility workers, the public and the environment, this is called a "nuclear accident" [1]. As seen in the Fukushima nuclear accident; natural disasters such as earthquakes, floods, storms and forest fires pose serious risks to nuclear power plants [2]. Both the Chernobyl and Fukushima accidents were classified as Level-7, the worst level on the International Nuclear Event Scale (INES) [3]. The Chernobyl nuclear accident occurred on April 26, 1986, at the Chernobyl Nuclear Power Plant near the town of Pripyat in the Ukrainian Soviet Socialist Republic. The radiation leak caused by this accident is one of the worst nuclear accidents in history [4]. The Fukushima Daiichi nuclear disaster occurred in Japan on March 11, 2011, and is one of the major events following a nuclear disaster such as the Chernobyl disaster. In Fukushima (March 2011, Japan), an earthquake occurred, followed by tsunami. When the coolant pumps were submerged in water and did not work, the reactors overheated, leading to hydrogen explosions in the spent fuel pool, which caused fires. Tons of water contaminated with radiation were released into the sea [5].

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Table 1. General Comparison of Fukushima and Chernobyl Accidents [5]

Accident Features	Fukushima Accident	Chernobyl Accident
Accident Date	March 11, 2011	April 26, 1986
Accident Level According to Ines Scale	7. Level- Important Accident	7. Level- Important Accident
Number of Reactors	There are six reactors, three reactors are in use	There are four reactors and the accident occurred in a reactor.
Reactor Type	It is a boiling water reactor (BWR).	It is a boiling water reactor with graphite moderator.
Summary of Accidents	The 8.9 magnitude earthquake and tsunami damaged the power plant's electrical system, collapsed the cooling system, causing a hydrogen haze explosion.	As a result of the sudden power fluctuation that occurred during the system test of the reactor, the reactor pressure vessel was damaged and this was followed by a series of explosions. The fire in the reactor lasted for 10 days.
Affected Area	60 km in the northwest direction of the power plant and 40 km in the south-southwest direction, the radiation limit was measured above the values.	According to the UN notification, radiation emissions have reached 500 km away from the power plant.
Evacuated Area	It is a region where 20-30 km of people were voluntarily evacuated, and people from five different regions were evacuated.	30 km area has been evacuated.
Number of People Evacuated	78,000 people have been evacuated from the region.	In 1986, 115 thousand people were evacuated, then about 220 thousand people were transported from various regions.
Accidental Deaths	No deaths caused by radiation were found	In the UN report, 64 cases of death due to radiation were reported as of 2008.
Current Status	Protective structures are being built around the reactors to prevent radioactive leakage. The reactors are still cooling.	The damaged reactor was completely covered with a concrete coating sarcophagus to prevent leakage.

Nuclear accidents are complex and potentially destructive events that create significant challenges for leadership. Leaders in nuclear energy facilities must make decisions during a crisis, inform the public, take emergency measures and effectively manage the effects of the disaster. Conceptually, it was seen that leadership began to attract attention and research in the early 1800s [6]. After the middle of the 19th century, the concept of leadership was discussed more theoretically and today, with its emergence in many fields, it has become a subject that has attracted the attention of both management and organizational theorists and practitioners [7]. Leadership is one of the most complex and multifaceted phenomena. Leadership has ancient origins, evolving from authoritarian styles focused on tasks to participative styles centered on people. This shift has created more supportive and empowering work environments. Today, leadership continues to advance, with a particular focus on service leadership, reflecting ongoing progress in personal and professional development within organizations [8].

The study of leadership has been extensive over the years and has become even more critical in today’s fast-paced and increasingly globalized world. However, leadership continues to create fascinating and confusing discussions due to the complexity of the subject. Bennis stated that "leadership is the most studied and least understood topic in social sciences" and that "never have so many worked so long to say so little." Leadership is fundamentally a social influence process involving both leaders and followers [9].

In this study, 3 types of leadership theories will be discussed; such as Transformational Leadership, Transactional Leadership, or Complexity Leadership. These theories were explained in relation to crisis management and tried to be associated with the behaviors observed in both accidents. The types of leadership mentioned are:

1. Transformational Leader: When we look at the dictionary meaning of transformation, we see that it is written "to transform into a different form, change shape, transformation, revolution, change", but it can also be expressed as increasing or decreasing the level of something, that is, to bring it to a different level [10]. James V. Downtown’s mentioned the concept of transformational leadership for the first time in book "Rebel Leadership". It was James McGregor Burns in 1978 with his book "Leadership" who brought this concept to the literature. The concept of transformational leadership has also been included in Turkish sources as a reformist, transformational, transformative leader [11].

2. Transactional Leadership: The transactional leader focuses on the subordinate-superior relationship with the employees, formal reward system and control based on structure and performance attaches importance to its activities, influences its employees by using official authority, He is a person who avoids risks and leads and guides communication. Transactional leadership, characterized by a strong emphasis on protocols, rules, and predefined roles, could have contributed to the rigid adherence to procedures that limited flexibility during the crises [12]. To protect his own interests and current situation, the leader fulfills the material and physical needs of his followers. Conditional reward, which is clearly communicated by the leader what is the reward, appreciation and promise to receive in the face of the audience's effort, is an important dimension of the interactive leader [13].

It is important to determine the objectives, business standards and the machinery and equipment to be used in the work to be done in this form of leadership. Active management with exceptions, which is the second dimension of interactive leadership, is the way the leader controls the performance of the audience and takes the right action in the mistakes formed by comparing it with the standards [14].

3. Complexity Leadership: Given the dynamic and unpredictable nature of nuclear accidents, illustrate how this leadership style, which focuses on adaptability and emergent problem-solving, could have helped manage the crises more effectively [12]. The nuclear accidents at Chernobyl and Fukushima nuclear disasters underscore the paramount importance of strong and effective leadership during crises. These incidents highlight several vital lessons, including the necessity of timely decision-making, the value of transparent and clear communication, and the role of international collaboration in managing such complex events. For leaders, the focus must be on prioritizing emergency preparedness, fostering transparency, and building and maintaining public trust. By doing so, they can significantly enhance safety measures and more efficiently mitigate the risks associated with nuclear energy, ensuring better outcomes in future crises.

Additionally, when the literature is scanned, many studies are found about the Fukushima and Chernobyl nuclear accidents. Likewise, many studies have been conducted on leadership and leadership types. However, no study combining these two topics has been found. After describing the previous studies on this subject, the article explains the gap in the literature and aims to contribute by filling this gap.

2. Materials and Method

The Fukushima nuclear power plant accident is a natural disaster, caused by a tsunami caused by a magnitude 9.0 earthquake. The Chernobyl nuclear power plant accident, on the other hand, can be considered a disaster, although it is not natural, although it is caused by human error. As stated in the Disaster and Emergency Regulation of the Ministry of Internal Affairs of the Republic of Turkey, disasters are “natural, technological or human-induced events that cause physical, economic and social losses for the whole society or certain segments of society, stop or interrupt normal life and human activities, and for which the affected society does not have sufficient capacity to cope” [15]. Leadership and relationships are difficult concepts. In fact, it has been stated that there are more than 650 definitions of leadership in the literature [16]. Leadership can generally be achieved through long and difficult work. Leadership requires having certain characteristics. Although there is a lot of research on effective leaders and their specific qualities, there is no common list of their characteristics. However, it is suggested that all successful leaders have three basic characteristics. These are; character, management and experience [17].

This study focuses on the behavior of leaders in the Chernobyl and Fukushima nuclear accidents in disaster situations, focusing on their effects on risk management, which has been studied in various academic platforms. While conducting the research, keywords such as "Chernobyl", "Fukushima", "nuclear accident" and "leadership" were used extensively in Web of Science, Cambridge Core, Project Muse, Pub Med, Dergi Park and Research Gate. The research used mostly academic articles and, in some cases, relevant research sections published in books. Initially, article titles and abstracts were scanned, excluding those that were irrelevant or lacking in depth. Then, the selected studies were examined in detail. While the review included peer-reviewed journal articles and relevant books, these and other comprehensive documents were excluded due to their broad scope. The study also took into account factors such as national and international security regulations. A total of approximately 800 research articles were found during the keyword search. The most cited and directly related to the subject and content were selected and used, and their languages were English and Turkish.

In this study where the examinations were made, answers were sought to the following three questions;

1- How did the Fukushima and Chernobyl nuclear power plant accidents occur?
2- How were the crisis environment that resulted from the Fukushima and Chernobyl nuclear power plant accidents managed?
3- What are the definitions and types of leadership?
4- What are the crisis management styles of leaders in large-scale disasters?

3. Results

Actionable strategies that leaders in the nuclear industry or other high-risk sectors can adopt based on the lessons learned from these two accidents may be:

3.1. Lessons Learned in the Chernobyl Nuclear Disaster and Their Practical Effects:

1. The first prominent problem about leadership in the Chernobyl accident is communication errors. In such major disasters, it is very important that the leaders correctly convey the seriousness of the event and its potential effects to the public and other leaders. Thus, the necessary precautions can be taken faster.
2. Leaders responsible for managing the event must be willing to take responsibility. The authorities should not underestimate the scale and danger of the incident and should not cause delays in taking the necessary emergency measures.
3. Information about the disaster should be shared transparently and honestly with the public and employees, and trust should be provided.
4. Personnel should receive all the necessary training and have the competence related to their work. Training the personnel working in the reactor on emergency plans and procedures will make it easier to control the disaster.
5. Effective cooperation and coordination between different organizations and levels of leadership will ensure effective use of the resources and expertise necessary for better crisis management.

Leadership management in Chernobyl has enabled various courses to be taken not only in the nuclear energy industry, but also in leadership and crisis management in general.

3.2. Lessons Learned in the Fukushima Nuclear Disaster and Their Practical Effects:

1. The first notable leadership lesson in Fukushima was about communication. We have understood how important it is to fully convey the seriousness of the disaster to the public and other leaders.
2. The importance of taking responsibility has emerged. It is very important to take responsibility and convey the real situation to the public by considering the principle of transparency and quickly.
3. Long-term preparation for such disasters should be made. Nuclear facilities must be made sufficiently resistant to earthquakes and tsunamis. This long-term preparation will allow to control and reduce disaster.
4. Making emergency plans in the right ways and paying attention to the completeness of trainings in this area will facilitate crisis management. Emergency measures should be implemented quickly and effectively.

Finally, we can say that the most important actionable strategies that leaders in the nuclear industry or other high-risk sectors can adopt based on the lessons learned from these two accidents are proactive crisis communication and emergency preparedness training. It has been seen that the importance of transparent communication and the fact that leaders communicate correctly with the public and employees during a crisis will be of great benefit. It may also be recommended that leaders focus on regular training and simulation exercises to better prepare for possible disasters. The following two tables show the successful aspects of leadership theories and their role in managing crises.

Table 2. Comparison of Achievements Aspects of Leadership Theories and Their Role in Crisis Management [7], [12], [18]

Leadership Theories	Core Achievements	Crisis Management Roles
Transformational Leadership	**Long-term trust-building** through consistent communication and accountability. **Visionary planning** for post-crisis recovery (e.g., community resettlement, radiation monitoring). **Stakeholder alignment** among government scientists and NGOs.	**Motivating teams** under extreme stress (e.g., keeping workers engaged during prolonged containment efforts). **Transparency** in risk communication (critical for public compliance with safety measures). **Ethical responsibility** (owning mistakes to rebuild trust, as seen in post-Fukushima apologies).
Transactional Leadership:	**Short-term order** via clear chains of command (e.g., Chernobyl firefighters ' immediate response). **Task efficiency** through rewards/punishments (e.g., bonuses for risk-taking liquidators). **Structured protocols** (e.g., Fukushima's initial evacuation drills).	**Rapid decisions** under time pressure (e.g., Chernobyl's sand-dropping helicopter missions). **Procedural compliance** (e.g., enforcing radiation exposure limits). **Accountability enforcement** (e.g., disciplining TEPCO for negligence).
Complexity Leadership:	**Adaptive learning** (e.g., real-time adjustments to radiation thresholds). **Networked collaboration** (e.g., integrating IAEA experts post-Chernobyl). **Innovative problem-solving** (e.g., Fukushima's improvised cooling methods).	**Decentralized decision-making** (e.g., local teams prioritizing evacuation routes). **Cross-sector coordination** (e.g., joint government-private sector task forces). **Resilience-building** (e.g., redundant systems for future disasters).

4. Discussion

As a result of the study, it was seen that the Chernobyl and Fukushima nuclear accidents contained a number of similarities and differences in terms of leadership. These nuclear accidents provide various global learning opportunities related to nuclear accident management, crisis communication and energy policies. These events underline the importance of leaders being prepared for crisis situations, communicating effectively and gaining public trust. To summarize the factors that affect leadership in nuclear accidents: first, the ability to make quick and accurate decisions is crucial because nuclear accidents require immediate intervention. Leaders must be well organized, understand the scope of the event, and make quick and effective decisions. Second, effective communication is vital. It is critical to communicate openly and transparently with the public, staff and other authorities. Immediate sharing of reliable information can prevent panic and gain people's trust. Third, international cooperation is important. Nuclear accidents often have cross-border effects. Leaders should collaborate with the international community to use experts and resources effectively. Necessary attention should be given to the effectiveness of emergency plans. Leaders in nuclear power plants should create emergency plans for possible accidents and test them regularly. The effectiveness of these plans provides a quick response in a crisis. In addition, community participation and awareness are important. Leaders must educate and inform the public living near nuclear power plants. Public awareness and preparedness in crisis situations is very important to minimize the impact of disasters. Leaders should also regularly review and improve safety standards to ensure the long-term security of nuclear power facilities. Finally, in this context, facility personnel and crisis management teams should be trained regularly and exercises that simulate crisis situations should be carried out.

This study has also limitations due to the lack of sufficient articles and research on the management of nuclear accidents. I hope that new studies will be carried out in this matter in the future.

5. Conclusions

The comparative analysis of the Chernobyl and Fukushima accidents reveals a critical paradigm: effective crisis leadership is not about rigid adherence to a single theory, but about adaptive integration of transactional, transformational, and complexity approaches across disaster phases. Three universal lessons emerge: Transactional leadership's structured protocols proved vital for Chernobyl's initial firefighting (saving lives) but failed in Fukushima's cascading failures due to inflexibility. Transformational leadership's trust-building was absent in both cases when most needed (Chernobyl's secrecy; Fukushima's delayed transparency), exacerbating long-term consequences. Complexity leadership's adaptive capacity—though theoretically ideal for unprecedented scenarios—was hindered by cultural and institutional rigidities. As Table 3 illustrates, organizational culture dictated leadership effectiveness more than theoretical models: The Soviet "zero-mistakes" culture suppressed early warnings at Chernobyl, while Japan's "safety myth" blinded TEPCO to station blackout risks. Hierarchical structures in both contexts delayed bottom-up innovation, underscoring the need for decentralized decision-making in complex crises. The Chernobyl-Fukushima comparison reveals a critical institutional paradox: the very leadership models most capable of preventing catastrophic failures—namely, transformational and complexity-based approaches—are systematically disregarded until crises become inevitable. To break this cycle, adaptive leadership must be embedded into the core of nuclear safety governance, not as a reactive measure but as an intrinsic design principle that shapes organizational culture and decision-making processes from the outset. The following table provides a summary of the topic.

Table 3. Leadership in Crisis Management: Chernobyl vs. Fukushima Nuclear Accidents

Aspect	Chernobyl (1986)	Fukushima (2011)	Key Lessons for Crisis Leadership
Initial Response	- Heroic but disorganized liquidator efforts - Military-style command structure - Immediate denial then delayed disclosure	-Protocol-driven but slow response - Over-reliance on emergency manuals - Early evacuation but poor communication	Transactional leadership works for immediate response but requires flexibility
Communication	-State secrecy and misinformation - Delayed international notification (3 days) - Downplayed radiation risks	- Corporate hesitancy (TEPCO) - Conflicting government messages - Delayed severity acknowledgment	Transformational leadership's transparency is crucial for public trust
Decision- Making	-Centralized Soviet bureaucracy - Local commanders improvising solutions - Scientific input ignored initially	- Hierarchical Japanese culture hindered quick decisions - Excessive procedural adherence - Late expert consultation	Complexity leadership enables adaptive solutions in unprecedented crises
Long-Term Management	-600,000+ liquidators with inadequate protection - Permanent sarcophagus took 8 months - Lasting environmental impact	- 30km exclusion zone established quickly - Ongoing decommissioning (30-40-year estimate) - Water contamination issues	Mixed leadership approach needed for different crisis phases
Cultural Factors	-Soviet "no mistakes" culture prevented early admission - Priority on saving face internationally	- Japanese hierarchical norms slowed local initiatives - "Safety myth" blinded risk preparedness	Organizational culture shapes crisis response effectiveness
International Impact	-Accelerated Glasnost reforms - Created IAEA emergency protocols - Changed global nuclear safety standards	- Revised "defense in depth" requirements - New focus on station blackout scenarios - Stricter regulatory independence	Effective crisis leadership has global safety implications

Conflict of Interest

Authors declare no conflict of interest.

Author Contribution

S.D. led the research design, data collection, analysis, and manuscript writing. M.E.Ö. supervised the study, provided critical feedback throughout the research process, and contributed to the refinement of the manuscript.

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Examining the Potential of Micromobility to Reduce Urban Air Pollution and Associated Health Hazards

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Abstract

This study examines the relationship between micro-mobility usage and air quality across six major cities in Turkey, highlighting the environmental benefits of sustainable transportation systems. Micro-mobility, including e-scooters and bicycles, has emerged as a promising alternative to traditional fossil fuel-dependent modes of transport. To quantify the adoption of micro-mobility, a Micro-Mobility Usage Index (MMUI) was developed, using data on user frequency from the Moovit platform. Air quality indicators, PM2.5 and PM10, were derived from the World Air Pollution platform. Among the cities studied, Antalya displayed the highest MMUI score (61.4) and the lowest PM2.5 (54.7) and PM10 (51.2) levels, suggesting a strong link between high micro-mobility adoption and improved air quality. In contrast, Ankara had the highest PM2.5 concentration (99.2) and a lower MMUI (20.3). The Pearson correlation coefficients indicated a strong negative relationship between MMUI and air pollution levels, with values of -0.8932 for PM2.5 and -0.8364 for PM10. These findings underscore the potential of micro-mobility systems to mitigate urban air pollution, though challenges such as infrastructure and cultural acceptance remain critical.

Key words: Sustainable transportation, Health hazards, Air quality

1. Introduction

Worldwide, increasing environmental problems cause serious problems on human health. Especially air and water pollution, which are essential elements for human life, have an important place among these situations [1]. Air pollution, which occurs as a result of changes in the natural composition of the air, occurs with the increase of solid, liquid and gaseous foreign substances in the atmosphere. Air pollution, which increases with factors such as population growth, energy consumption, industrial development and urbanization, can harm human health, natural life, ecological balance and the environment.

The causes of air pollution include meteorological factors, location and topographical structure as well as foreign substances entering the atmosphere. Unplanned urbanization, lack of green areas and the use of fossil fuels are also among the important factors affecting air pollution. Air pollution causes problems at local, regional and global levels. In particular, climate change is an important global consequence of air pollution. A large proportion of human activities accelerate climate change by causing an increase in greenhouse gases [2].

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Excessive use of fossil fuels, deforestation and polluting habits pose a serious threat to the world. Although various measures have been taken to protect forest areas, adequate measures have not yet been taken regarding the use of petroleum products. The rapid increase in the number of motor vehicles based on petroleum products in the transportation sector also increases air pollution [3].

In recent years, economic and incentive measures have been taken to reduce the reliance on petroleum products and to move towards environmentally friendly transportation systems. In this framework, alternative transportation methods such as electric vehicles or public transportation systems, walking and cycling are encouraged instead of individual cars. These policies, referred to as sustainable transportation policies, adopt the main objective of discouraging the use of motor vehicles and increasing the use of more environmentally friendly modes of transportation [4].

There are many studies in the literature that address air pollution from transportation and examine the impact of sustainable transportation systems applied to reduce this pollution. Looking at the content of the studies, it is seen that studies on electric vehicles, pedestrian transportation, public transportation and micro mobility vehicles stand out [5-7]. Thanks to these studies, the environmental damage caused by fossil fuel-consuming vehicles is more clearly revealed, while the environmental advantages of alternative transportation sources are also revealed [8, 9].

In one of the studies, Bikis and Pandey conducted air quality measurements at public transportation stations in order to reveal the air pollution caused by public transportation systems. As a result of the measurements, it was determined that the PM2.5 value was quite high. In addition, it was determined that approximately 45% of the people living around the public transportation stations faced diseases related to air quality. As a result of the study, it was revealed that air pollution is higher at public transportation stations and people living in areas close to these stations have a higher risk of disease [10].

In a study examining the impact of electric vehicles on air pollution, Ferrero et al. conducted some experiments on a highway section in Milan, Italy. In these experiments, traffic emissions, meteorological parameters and chemical concentrations were measured. By simulating the measurement results with various scenarios, it was found that electric vehicles significantly reduce air pollution. In addition, even if the rate of electric vehicle use is low, it is determined that the preference of these vehicles during periods of intense air pollution will be significant in improving air quality [11].

The widespread use of pedestrian transportation not only has significant positive impacts on air pollution but also provides economic gains. In their study, revealed the distribution of harmful gases emitted by road transportation in Erzurum province of Turkey in a year according to vehicle types. The amount of fuel consumed annually was also determined according to the specified vehicle types and fuel type. As a result of the results obtained, it has been revealed that encouraging pedestrian transportation will provide significant advantages in terms of both air pollution and fuel consumption [12].

The effects of micro-mobility vehicles (such as bicycles and electric scooters) on air pollution and human health have been examined in various studies in recent years. For example, a health impact assessment study conducted in Barcelona found that increased use of e-scooters and e-bikes increased physical activity and contributed to preventing premature deaths. The same study also reported that the use of these vehicles reduced air pollution exposure and lowered risks related to traffic accidents [13]. Similarly, a study in Taipei showed that bicycle and e-scooter users are exposed to lower levels of air pollutants compared to vehicle commuters [14]. These findings highlight the role of micromobility tools in sustainable transport systems and their potential health benefits, but also suggest that their environmental impacts should be carefully considered.

Although micro-mobility solutions offer many advantages in terms of sustainable transportation, the potential negative impacts of these vehicles must be assessed in a more comprehensive and multidimensional manner. In particular, the production processes of electric scooters and bicycles raise questions about environmental sustainability in terms of battery-related carbon footprints and supply chain emissions. Additionally, the random abandonment or improper use of these vehicles within cities can lead service providers to use fossil fuel-powered vehicles to reposition them, thereby increasing local traffic congestion and emissions. The frequency of these redistribution processes varies depending on the type of vehicle used and logistics strategies, but it can lead to outcomes that contradict carbon-neutral goals, especially during periods of high demand. Additionally, the unplanned integration of micro-mobility infrastructure can lead to issues such as sidewalk obstruction, reduced pedestrian safety, and conflicts with other modes of transportation. As this mode of transportation becomes more widespread in the future, it is crucial for policymakers to address the aforementioned issues more clearly.

Existing studies in the literature reveal the importance of sustainable transportation systems in reducing air pollution. When the studies are examined, there is no study that clearly demonstrates the effect of the frequency of use of sustainable transportation modes on air quality in cities. It is especially important to reveal the extent to which the frequency of micro-mobility use contributes to sustainable transportation systems and thus to the reduction of air pollution. In this study, it is aimed to clearly reveal the relationship between the frequency of micro-mobility use and air quality in different cities in order to make an important contribution to the literature.

2. Materials and Method

2.1. Case study

The cities of Adana, Ankara, Antalya, Bursa, Bursa, Istanbul and Izmir in Turkey were selected as the study area. These cities are among the most populous cities in the country. Another common feature is that they have data on both the frequency of micro-mobility use and air quality indices. The diversity of the data distribution of these cities is very important in order to interpret the results of the study more efficiently. The population and locations of the cities in the study area are given in Table 1 [15].

Table 1. List of cities

No	City	Population (Million)	Latitude/longitude
1	Adana	2.270	36.59◦ N / 35.19◦ E
2	Ankara	5.803	39.56◦ N / 32.50◦ E
3	Antalya	2.696	36.54◦ N / 30.43◦ E
4	Bursa	3.250	40.11◦ N / 29.40◦ E
5	İstanbul	15.656	41.01◦ N / 29.00◦ E
6	İzmir	4.479	38.24◦ N / 27.10◦ W

Turkey, situated between Europe and Asia, has a highly developed road transportation network due to its strategic location on major trade routes. However, the cities within the country differ in terms of climate, economic activities, and transportation infrastructure.

Adana is located in the southern part of Turkey and has a hot Mediterranean climate. The average annual temperature is around 20°C, with heavy rainfall in December and January. The city is predominantly known for its agricultural production. Adana’s transportation system is well-structured, with a developed road network supporting intra-city and regional travel.

Ankara, the capital city, plays a key role as an administrative center. It has a continental climate, characterized by snowy winters and rainy spring months, with an average annual temperature of 11°C. The city's transportation system is well developed, particularly in terms of road and rail networks. Traffic congestion often occurs in areas close to government institutions.

Antalya, like Adana, is located in the south and lies on the Mediterranean coast. It is a major tourism destination, with a population that increases significantly in the summer months. The city has an average temperature of 20°C and receives winter rainfall. While road transportation dominates, its overall transportation network is less developed compared to cities of similar size.

Bursa, situated in the Marmara Region, experiences a generally mild climate with an annual average temperature of 15°C. Rainfall is more frequent in the winter months. The city is a hub for industrial activities, particularly in automotive, textile, and furniture sectors. In addition to road transport, a light rail system is actively used within the city.

Istanbul is Turkey’s most populous city and a major global center, especially in trade. The city has a 14°C average annual temperature and significant rainfall in December and January. Divided by the Marmara Strait, Istanbul connects the continents via bridges, tunnels, and maritime transport. Although it has an extensive transportation network including road, rail, and sea routes, traffic congestion remains a major issue due to the high number of vehicles.

Izmir, located on the Aegean coast in the western part of the country, is an important city for trade and tourism. Its port plays a key role in commercial activities, and the population rises during the summer months due to tourism. The city has an average temperature of 18°C and receives rainfall mostly in the winter. Transportation modes including highways, railways, and maritime lines are all well developed. Figure 1 illustrates the geographical locations of the cities discussed.

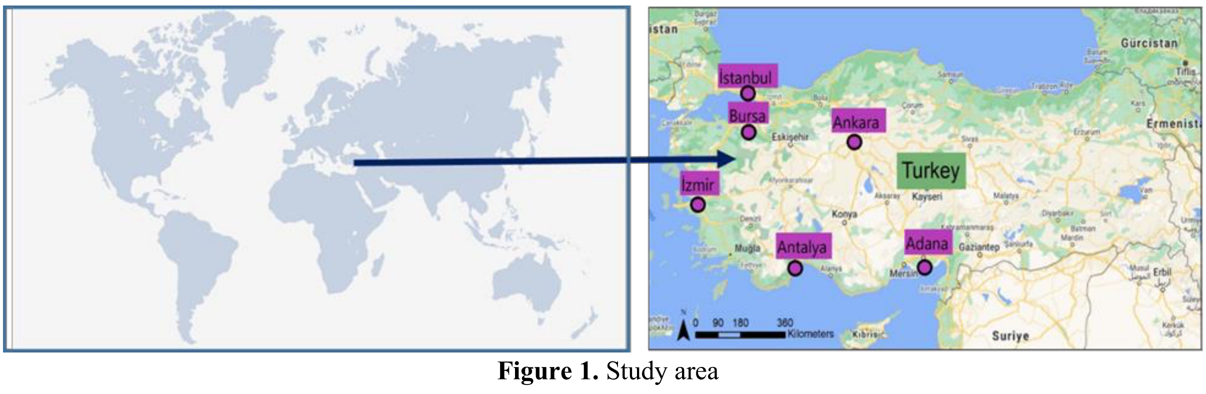

Figure 1. Study area

2.2. Method

In order to determine the relationship between the frequency of micro-mobility use and air quality, the study needed the frequency of use of micro-mobility vehicles in each city and the PM10 and PM2.5 levels measured in these cities. Data on the frequency of use of micro mobility vehicles was obtained from the Moovit platform. As a result of its investigations in the study area, this platform has proportionally revealed the frequency of bicycle and e-scooter use by people in 2022. The PM10 and PM2.5 values, which are the most prominent pollutants among the daily air quality indices for 2022, were obtained from the World Air Pollution platform. Particulate matter, known as PM10 and PM2.5, remain suspended in the air and can reach the lungs through inhalation. These two pollutants are very dangerous for human health. The air quality index value in a region is calculated using Equations 1 and 2.

$$AQI = \max\ (IAQI_1\,, IAQI_2, \ldots \ldots . . IAQI_n) \tag{1}$$

$$I_{AQI} = \frac{I_h - I_l}{C_h - C_l} \times (C - C_l) + I_l \tag{2}$$

Where I_{AQI} = the Individual Air Quality Index, n=the pollution project (PM2.5 and PM10), I_h *and* I_l = AQI limits, C_h *and* C_l = the pollutant concentration limits, C = the input value, the pollutant concentration [16]. Table 2 shows PM2.5 and PM10 air pollutant concentration limits.

Table 2. PM2.5 and PM10 air pollutants concentration limits [17]

AQI value of index	PM2.5 concentration (µg/m3)	PM10 concentration (µg/m3)	Air pollution level
0–50	0–12	0–54	Level 1
51–100	12.1–35.4	55–154	Level 2
101–150	35.5–55.4	155–254	Level 3
151–200	55.5–150.4	255–354	Level 4
201–300	150.5–250.4	355–424	Level 5
301 and Higher	250.5–Higher	425–Higher	Level 6

The Pearson correlation coefficient is a statistical measure used to assess both the direction and the magnitude of the linear association between two variables. It is commonly applied to evaluate how a variation in one variable may be associated with changes in another. This coefficient ranges from −1 to +1, where positive values indicate a direct (positive) linear relationship, and negative values signify an inverse (negative) linear relationship. Values approaching +1 or −1 suggest a stronger correlation. The formula for Pearson's correlation coefficient is given below in Equations 3.

$$r = \frac{\sum_{i=1}^{n}[(x_i - \bar{x}) \times (y_i - \bar{y})]}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \times \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{3}$$

In this context, x_i and y_i correspond to the low-frequency impedance at 0.01 Hz ($|Z|_{0.01}$Hz) and the phase angle (θ), respectively. For interpreting the correlation strength, the criteria outlined in Table 3 are typically considered.

Table 3. Interpreting Correlation Coefficient [18]

Absolute Magnitude of the Observed Correlation Coefficient	Interpretation
0.00–0.10	Negligible correlation
0.10–0.39	Weak correlation
0.40–0.69	Moderate correlation
0.70–0.89	Strong correlation
0.90–1.00	Very strong correlation

3. Results

Urban areas have increasingly embraced micro-mobility solutions such as e-scooters, bicycles, and shared mobility systems as sustainable alternatives to traditional transportation. Moovit, a leading mobility platform, has categorized micro-mobility usage into five distinct frequency levels to better understand user behavior: "Daily," "Frequently," "Occasionally," "Rarely," and "Never." These categories provide a comprehensive perspective on how residents in different cities utilize micro-mobility options, reflecting variations in infrastructure availability, cultural attitudes, and commuting habits. For instance, individuals categorized as "Daily" users heavily rely on these solutions as part of their routine, whereas "Occasionally" and "Rarely" users might consider these options situationally or as backups to other transportation methods.

In the article titled An Assessment of the Relationship Between Micro-Mobility Use and Air Quality in Selected Cities, a detailed index—known as the Micro-Mobility Usage Index (MMUI)—was developed to quantify the extent of micro-mobility adoption in urban environments [19]. This formula aggregates usage frequency across populations by assigning weighted values to each frequency category:

$$MMUI=(365\times N_D)+(156\times N_F)+(60\times N_O)+(4\times N_R)+(0\times N_N)$$

Here, N_D, N_F, N_O, N_R, and N_N represent the number of individuals in the categories "Daily," "Frequently," "Occasionally," "Rarely," and "Never," respectively. This weighted approach allows for the translation of qualitative frequency data into a quantitative measure that can be compared across different urban areas, providing insights into how intensively cities embrace micro-mobility. Figure 2 shows the micro-mobility usage frequency by cities.

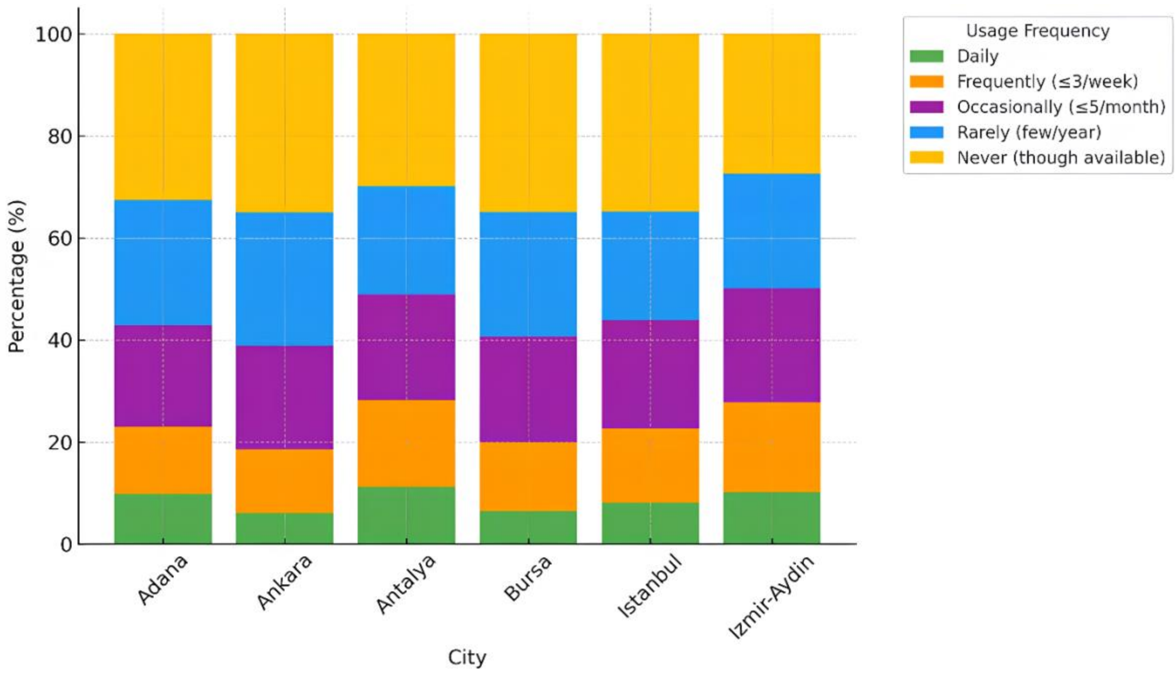

Figure 2. Micro-mobility usage frequency by cities

The chart illustrates the frequency of micro-mobility usage across six major cities in Turkey. Antalya stands out with the highest percentage of "Daily" users at 10.4%, reflecting a stronger integration of micro-mobility into daily routines compared to other cities. Similarly, the city also has a higher percentage of "Frequently" (10.4%) and "Occasionally" (10.45%) users, suggesting a broader acceptance and accessibility of micro-mobility solutions. In contrast, cities like Bursa and Adana have the largest proportions of "Never" users, at 63.4% and 63.2% respectively, indicating potential barriers such as lack of infrastructure or cultural reluctance to adopt such modes of transport.

Interestingly, Izmir exhibits a relatively balanced distribution across the categories, with significant usage even among the "Occasionally" (10.35%) and "Rarely" (35.8%) groups. This distribution may point to growing interest but insufficient adoption for daily use. Istanbul, despite being Turkey's largest city, has a notable proportion of "Rarely" (26.7%) and "Never" (58.1%) users, reflecting possible limitations in integrating micro-mobility into a complex urban environment. Overall, the data highlights significant regional disparities in micro-mobility adoption, shaped by factors such as infrastructure availability, cultural preferences, and urban planning.

The relationship between micro-mobility use and air quality has been a subject of growing interest. Increased adoption of micro-mobility solutions can potentially lead to reduced dependence on fossil fuel-based vehicles, thereby lowering urban air pollution levels. Cities with higher MMUI scores may exhibit improved air quality, as micro-mobility options provide an eco-friendly alternative for short-distance commutes. However, the impact is not universally positive; shared e-scooters and bicycles, if not well-integrated into urban planning, might contribute indirectly to traffic congestion or emissions during their production and maintenance cycles. Further research is essential to fully understand this dynamic and optimize the integration of micro-mobility systems for both environmental and social benefits. Figure 3 shows the relationship between micro-mobility usage frequencies and air quality indices for cities.

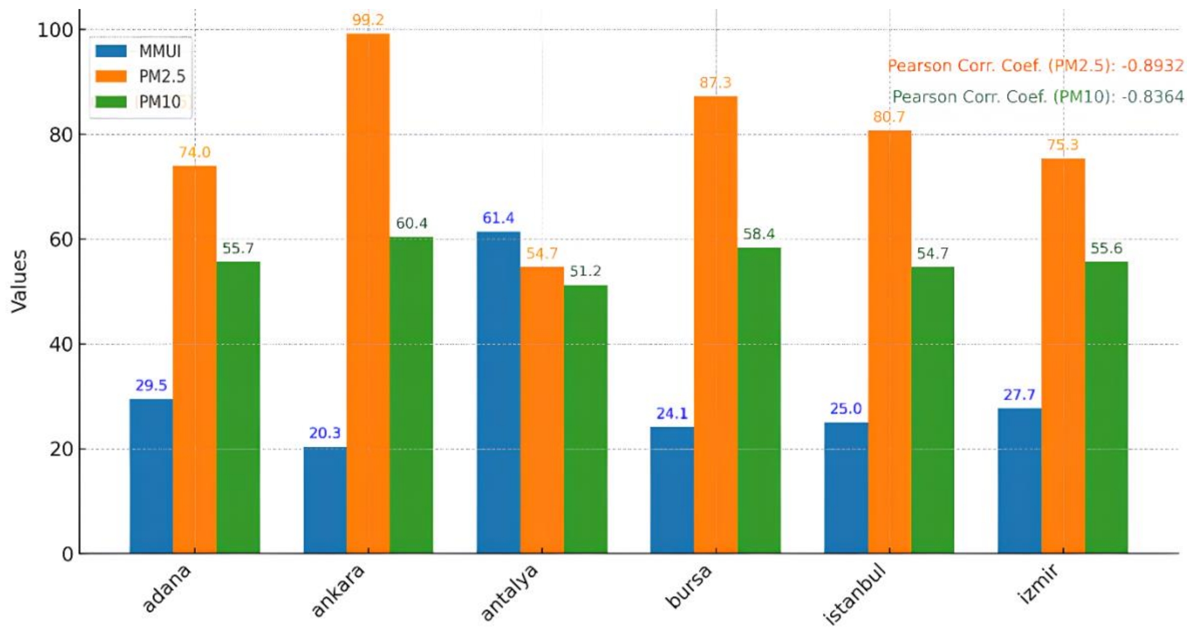

Figure 3. Air Quality and MMUI analysis

The provided chart illustrates the relationship between micro-mobility usage intensity (MMUI) and air quality indicators (PM2.5 and PM10 levels) across six cities in Turkey: Adana, Ankara, Antalya, Bursa, Istanbul, and Izmir. The MMUI values, represented by blue bars, indicate the extent of micro-mobility adoption, while orange and green bars correspond to air pollution levels of PM2.5 and PM10, respectively.

Ankara stands out with the highest PM2.5 concentration (99.2) and relatively low MMUI (20.3). Similarly, Bursa has high PM2.5 (87.3) but a low MMUI (24.1), suggesting that these cities might rely more on traditional transportation modes, contributing to higher pollution. Conversely, Antalya, with the highest MMUI (61.4), shows significantly lower PM2.5 (54.7) and PM10 (51.2) levels, indicating a possible positive impact of micro-mobility on air quality. Adana and Izmir exhibit moderate MMUI and pollution levels, while Istanbul, despite its dense urban population, maintains mid-range pollution levels with relatively low MMUI.

The Pearson correlation coefficients reveal a strong negative relationship between MMUI and both PM2.5 (-0.8932) and PM10 (-0.8364). These coefficients suggest that increased micro-mobility use is associated with reduced particulate matter levels, emphasizing the potential role of sustainable transportation in mitigating urban air pollution.

4. Discussion

This analysis highlights significant urban variations in micro-mobility usage and air quality, underscoring the complex interplay between transportation modes and environmental factors. The strong negative correlation between MMUI and particulate matter levels suggests that promoting micro-mobility can be an effective strategy for improving air quality. Cities like Antalya demonstrate the potential benefits of integrating micro-mobility into urban transport systems, as reflected in lower pollution levels and higher MMUI.

However, cities such as Ankara and Bursa, with high PM2.5 and PM10 levels, illustrate the challenges of reducing air pollution in urban areas heavily dependent on conventional transport. These findings emphasize the importance of policy interventions, such as infrastructure development, subsidies for micro-mobility services, and public awareness campaigns, to encourage the adoption of sustainable transport solutions. Additionally, air quality improvement initiatives must address other sources of pollution, such as industrial emissions and energy production, to achieve comprehensive results.

One important limitation of the study is related to the data source used for estimating micromobility usage. The Moovit app data may not fully represent the entire population, especially in cities where app usage is low or unevenly distributed among different socioeconomic groups. Therefore, the MMUI values should be interpreted with caution, as they may reflect app user behavior rather than the general population's actual micromobility usage. Future studies may consider combining multiple data sources to increase representativeness.

Future research should explore the causal mechanisms linking micro-mobility adoption to air quality improvements. Longitudinal studies could help determine whether increasing MMUI directly leads to reduced pollution or if other factors, such as city-specific policies and infrastructure investments, play a more significant role. Moreover, qualitative research could provide insights into user behavior and barriers to adoption, enabling cities to tailor interventions effectively.

This study underscores the critical role of sustainable transportation in achieving urban environmental goals. While the data shows promising trends, addressing systemic challenges and ensuring equitable access to micro-mobility services are key to maximizing their environmental benefits.

5. Conclusions

This study emphasizes the critical role of micro-mobility in reducing urban air pollution. The findings highlight significant variations among the six studied cities in Turkey, illustrating the environmental advantages of adopting sustainable transportation systems. Antalya, with the highest MMUI score, stands out as a model city, demonstrating the potential benefits of widespread micro-mobility use. The significant negative correlation between MMUI and air pollution levels reveals the effectiveness of micro-mobility in reducing harmful particulate matter concentrations.

The results suggest that cities with higher micro-mobility adoption rates tend to experience better air quality, as evidenced by lower PM2.5 and PM10 levels. This relationship underscores the importance of investing in infrastructure to support micro-mobility, such as dedicated bike lanes and e-scooter parking areas. Additionally, public awareness campaigns and incentives can play a pivotal role in encouraging greater adoption of sustainable transportation modes.

To strengthen the policy implications of this study, city-specific recommendations should be considered in alignment with the existing infrastructure and socio-cultural context of each urban area. For instance, Adana, with its relatively flat topography and wide roads, is well-suited for the rapid deployment of protected bike lanes and shared e-scooter networks, particularly in central business districts. In Ankara, where micro-mobility usage remains limited due to steep gradients and car-centric planning, investment should prioritize multimodal integration—such as secure e-bike parking at metro stations and subsidized transfers between modes—to enhance usability. Antalya, already performing well in micro-mobility adoption, can serve as a pilot site for smart mobility innovations like geofenced zones and dynamic pricing to manage usage and prevent sidewalk clutter. Bursa, with its industrial layout and dispersed settlement structure, would benefit from establishing inter-district micro-mobility corridors and targeted awareness campaigns to shift perceptions about vehicle alternatives. In Istanbul, given its population density and traffic congestion, a zoning-based regulatory framework that limits private car access and prioritizes micro-mobility in selected areas (e.g., historic districts, coastal promenades) could yield significant environmental gains. Lastly, Izmir should capitalize on its ongoing sustainable transport initiatives by expanding its existing bike-sharing system to underserved neighborhoods and integrating it with real-time transit apps to facilitate journey planning. These localized strategies provide a more actionable roadmap for advancing urban air quality goals through micro-mobility integration.

Future research should explore the causal mechanisms behind the observed correlations, focusing on longitudinal analyses to determine the direct impact of micro-mobility on air quality. Furthermore, qualitative studies could provide valuable insights into user behavior and barriers to adoption, helping policymakers design more effective strategies. Overall, this study contributes to the growing body of evidence supporting the integration of sustainable transportation systems into urban planning to combat air pollution and promote healthier living environments.

Conflict of Interest

No conflict of interest declared by the Author.

Author Contribution

The whole paper is prepared by one Author.

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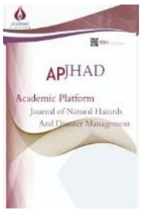

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Design and Cost Comparison of Reinforced Concrete Structures Modeled According to TBDY 2018 in Terms of Earthquake Soil Motion

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Abstract

Türkiye is located in an active earthquake zone. Therefore, it has been exposed to large-scale earthquakes dating back to a long history. Major earthquakes in the past have caused thousands of casualties and damage to structures. For example, events such as the 1939 Erzincan Earthquake, the 1943 Samsun Earthquake and the 1999 Kocaeli Earthquake deeply affected the country. However, two earthquakes on 6 February 2023 were recorded as the largest earthquakes of the last century. These earthquakes occurred on the Eastern Anatolia Fault and directly affected 11 provinces. In terms of loss of life and property, it caused three times more damage than the 1999 Marmara Earthquake. Reinforced concrete structures in Türkiye are built in accordance with defined standards. The construction criteria of buildings in earthquake zones are determined by regulations. The current regulation, which entered into force in 2018, involves classifications according to earthquake levels. These classifications vary between earthquake soil motion Level-1 (DD-1) and earthquake soil motion Level-4 (DD-4). As a minimum criterion for the design of reinforced concrete structures, DD-2 soil motion with a probability of 10% in 50 years is taken into consideration.

However, in this study, a reinforced concrete structure to be constructed in Sakarya province will be modelled according to both DD-1 and DD-2 levels. Studies related to building cost analysis generally focus on several basic areas. These include comparative analyses of different earthquake regulations and cost differences between steel and reinforced concrete building systems. The effect of soil types on the cost of reinforced concrete superstructures is also under investigation. In addition, there are studies investigating the cost of retrofitting existing reinforced concrete buildings. These studies highlight the importance of cost in building construction and many researches have been carried out in this field. However, the effects of earthquake levels on cost have not been sufficiently studied. This study will fill the gap in the literature and examine the effects of earthquake levels on cost. The differences between these two approaches will be analyzed and the losses and additional costs that will arise if DD-1 is taken into account in the design will be evaluated.

Key words: Earthquake, IdeCAD, Numerical Analysis, Reinforced Concrete Structure, Cost Estimation

1. Introduction

Türkiye, located on active earthquake zones, has been exposed to large-scale earthquakes for generations. Türkiye has experienced several large-scale earthquakes in recent history. The 1939 Erzincan Earthquake (Ms=7.9) resulted in 32,968 deaths and damage to 116,720

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structures. The 1943 Samsun Earthquake (Ms=7.2) caused 4,000 deaths and damaged 40,000 structures. The 1999 Kocaeli Earthquake (Ms=7.8) led to 17,480 deaths and damage to 73,342 structures [1]. On February 6, 2023, two major earthquakes occurred, resulting in 50,783 deaths and damage to 1,929,312 residential and industrial buildings. The earthquakes, which occurred 9 hours apart, were recorded as the largest earthquake of the last century [2]. The 6 February earthquakes occurred on the Eastern Anatolian Fault (EAF), an important tectonic structure in the Eastern Mediterranean, separating the Arabian and Anatolian tectonic plates along a 600 km boundary [3]. These earthquakes, which directly affected 11 provinces in Anatolia, caused approximately 3 times more loss of life and property than the 1999 Marmara Earthquake [4]. The magnitude of the earthquake varied between Mw 7.7-7.95 for Pazarcık and Mw 7.5-7.86 for Elbistan according to different sources [5]-[7].

Reinforced concrete structures in Türkiye, which is located on active earthquake zones, are constructed according to certain rules. These rules are collected as a whole in the regulation containing the construction criteria of the buildings to be constructed in earthquake zones.

The current regulation was published in 2018. In the current regulation, classifications have been made regarding earthquake levels. These classifications are Earthquake Motion Level-1 (DD-1), Earthquake Motion Level-2 (DD-2), Earthquake Motion Level-3 (DD-3) and Earthquake Motion Level-4 (DD-4). Of these, DD-1 characterizes very infrequent earthquake motion, where the probability of exceeding the spectral magnitudes in 50 years is 2% and the recurrence period is 2475 years. DD-2 characterizes the rare earthquake activity where the probability of exceeding the spectral magnitudes in 50 years is 10% and the corresponding recurrence period is 475 years. DD-3 characterizes frequent earthquake activity where the probability of exceeding the spectral magnitude in 50 years is 50% and the corresponding recurrence period is 72 years. DD-4 characterizes very frequent earthquake activity where the probability of exceeding the spectral magnitudes in 50 years is 68% (50% probability of exceeding in 30 years) and the corresponding recurrence period is 43 years [8].

DD-2 soil motion in the design of reinforced concrete structures is taken into consideration. This earth movement with 10% probability of occurrence in 50 years determines the limits of the measures to be taken. However, DD-1 soil motion with a probability of occurrence of 2% in 50 years is not taken as a reference as it has a very weak probability of occurrence.

If a reinforced concrete structure is designed according to DD-1, the structure directly becomes more reliable since a low probability earthquake case will be taken into account. Since the design considering such a small probability will make a significant contribution to the behavior in case of DD-2, the topic becomes even more important. In this study, a reinforced concrete structure is designed to be built in Sakarya Province, which is located in an active seismic zone. The structure will be modelled using the IdeCAD software according to DD-1 and DD-2 earthquake design levels. The quantity and area changes between the two approaches are calculated. It is analyzed what kind of losses and additional costs occur when DD-1 is considered in the design. The results obtained are analyzed and interpreted as a whole.

Sakarya is located on one of the active earthquake zones of Türkiye, which significantly affects the structural design criteria in the city. The effects of soil movements on the design of structural and reinforced concrete structures in Sakarya City should be considered in detail. Since Sakarya is located near the North Anatolian Fault Line, the region experiences frequent earthquakes. Historical data show how large-scale earthquakes around Sakarya have affected the structural safety in the city. Therefore, special design criteria have been developed to improve the earthquake resistance of structures in the city. Surface movements observed in Sakarya are intense and variable, especially in the regions near fault lines. Among the main characteristics of soil movements, fault line activities and soil types are decisive. Among these concepts, fault line activity, the activity of fault lines around Sakarya has a direct effect on the frequency and intensity of earthquakes. Soil types can increase or decrease the effects of earthquakes. It is known that seismic frequencies spread more especially in soft soils.

Structural and reinforced concrete designs in Sakarya, concepts and methods such as structural design, seismic isolation, vertical and horizontal stability have been developed to minimize earthquake risk. The most common type of structure that is widely used and sustainable is reinforced concrete structures. Reinforced concrete structures should be built according to certain design standards to be resistant to earthquakes. Reinforced concrete structures behave with the principle of using concrete and reinforcement in a composite form in the carrier system. The correct placement and proper diameter of the reinforcements in reinforced concrete structures increase the durability of the structure during earthquakes. The quality of concrete is an important factor affecting the performance of the structure under seismic loads. The use of high-quality concrete increases the safety of the structure. Understanding the effects of soil movements and earthquake risk on structural designs in City of Sakarya is critical for the construction of safe and durable structures. Structural engineering and reinforced concrete design considerations should be optimized in accordance with the seismic conditions of Sakarya. In addition, the earthquake resistance of structures should be continuously increased by following current research and technologies. In some studies, on cost analyses of structures, comparisons were made between earthquake codes [9], [10]. In some academic studies, the cost values of steel and reinforced concrete structural systems were compared with each other [11], [12]. In some of the studies, the effects of soil classes on the cost of reinforced concrete superstructure were investigated [13], [14]. There are also cost studies on the situation regarding the reinforcement of reinforced concrete structures [15]. As can be understood from these studies and the fact that many studies have been and are being carried out on the subject, cost is a very important parameter in the construction of structures. Therefore, many studies have been carried out in this field [9]-[15]. These studies can form groups within themselves. However, while these studies have focused on many areas, the effects of differentiation on earthquake levels on cost have not been sufficiently investigated. With the realization of this study, it is aimed to contribute to filling the gap in the literature.

In this study, a reinforced concrete structure modelled to be constructed in Sakarya province, which is located in the Active Earthquake Zone, will be modelled according to DD-1 and DD-2 using IdeCAD package program. The quantity and area changes between the two approaches are calculated. It is analyzed what kind of losses and additional costs occur when DD-1 is considered in the design. The results obtained are analyzed and interpreted as a whole.

2. Numerical Model: Identification of Loads, Design Criteria and Modelling Stages of the Structure in IdeCAD

2.1. Identification of Loads

IdeCAD is a software used in civil engineering and architectural applications and the definition of loads is one of the basic functions of this software. Loads are defined as forces and moments acting on the structural system of a structure and are generally classified as follows:

2.1.1. Vertical Loads

These loads are the forces applied perpendicular to the floor of the structure. Vertical loads are divided into two main groups: fixed loads and live loads.

- Constant Loads (Dead Loads): It is caused by the structure's own weight and permanent structural elements (walls, floors, roof coverings, etc.). Constant loads are usually calculated by considering the material densities and dimensions of the structural elements.
- Live Loads: These are loads that can vary during use and are temporary. People, furniture, vehicles and other moving loads fall into this category.

2.1.2. Horizontal Loads

These loads are the forces that cause the structure to be affected horizontally. Horizontal loads include factors such as wind, earthquake and vehicle effects.

- Wind Loads: These are the forces applied to the surfaces of the structure under the influence of wind. These loads are calculated depending on the wind speed, direction and surface area of the structure.
- Earthquake Loads: These are the loads that occur due to the movements of the structure during the earthquake. These loads are determined according to the earthquake zone and seismic characteristics of the structure.

2.2. Identification of Loads

In building design, design criteria are rules set to ensure building safety, durability and performance. IdeCAD uses the following standards and parameters to design in accordance with these criteria:

- Standards and Regulations: In Turkiye, these standards are usually based on TS (Turkish Standard) and related regulations. For example, standards such as TS 500 [16], TS EN 1991 [17] and TBDY 2018 [8] are applied.
- Material Properties: The mechanical properties (e.g. tensile strength, compressive strength) of concrete, steel and other building materials are among the design criteria. IdeCAD stores these material properties in the programme database and uses them in the design process.
- Safety Coefficients: The coefficients used to ensure the safety of the structure are the coefficients in which loads and material strengths are evaluated with a certain safety margin. IdeCAD automatically applies these coefficients in accordance with the standards.

2.3. Modelling and Definition Phase of the Structure

The modelling and definition stages of the structure are the basic components of the design process and include the following steps:

- Geometric Modelling: It is the creation of a three-dimensional (3D) model of the structure. This stage includes all physical characteristics of the building (dimensions, shapes, locations, etc.) and usually includes building plans, sections and details.
- Material Identification: The material properties (density, strength, modulus of elasticity, etc.) of the building elements are defined. These material properties affect the load

carrying capacity and durability of the structure.

- Application of Loads: In the modelling phase, the vertical and horizontal loads mentioned above are assigned to the structural elements. The correct definition of these loads ensures that the structure is safe and stable.
- Determination of Boundary Conditions: Support points, connection elements and degrees of freedom are defined in the model of the structure. This affects the stress and deformation behaviour of the structure.
- Analysis and Simulation: Analyses are performed on the model of the structure under various load and boundary conditions. These analyses include various simulations to evaluate the performance of the structure (static, dynamic, seismic, etc.).

3. Widespread Use of IdeCAD in Sakarya Region

3.1. Standard Compliance and Regulatory Compliance

IdeCAD is designed to fully comply with the building standards and regulations in Turkiye. In projects implemented in the Sakarya region, this compliance ensures that the rules set by TS (Turkish Standard) and TSE (Turkish Standards Institute) are followed precisely. In particular, compliance with standards such as TS 500 [16], TS EN 1991 [17] and TBDY 2018 [8] is an important feature that ensures building safety and performance. Therefore, most of the construction projects in Sakarya are modeled using IdeCAD and files are submitted to municipalities through this software.

3.2. High Precision and Data Accuracy

IdeCAD has advanced calculation and modeling tools to ensure high precision and data accuracy in structural engineering. In the projects carried out in Sakarya region, static and dynamic analyzes of the structure must be performed accurately. IdeCAD minimizes the margin of error in the design of structural elements and load calculations by performing these analyzes with high accuracy.

3.3. Comprehensive Modeling Capability

IdeCAD offers a comprehensive design process with 2D and 3D modeling capabilities. In Sakarya projects, detailed modeling of all elements of the structure is critical for a realistic simulation of the project. The geometric details, material properties and load combinations of the building elements are integrated into IdeCAD's extensive database, allowing an accurate model to be created.

3.4. Interactive and Integrated Operation

The interactive design tools and integrated analysis modules offered by IdeCAD enable projects to be analyzed in a whole way. Thanks to these features, the design process is carried out more efficiently in engineering projects in Sakarya. In particular, accelerating the project process by ensuring coordination between civil engineers and architects is one of the important advantages of IdeCAD.

3.5. Municipality Approval Process and Standard File Formats

In projects submitted to municipalities in Sakarya, IdeCAD files are usually prepared in standard file formats. These formats contain all the data required for the municipality's project review processes and make the file approval processes easier. IdeCAD's support for such standard file formats makes it possible to work in line with municipalities and a fast approval process.

3.6. Training and Technical Support

The widespread use of IdeCAD in the Sakarya region encourages engineers and designers in the region to receive training and technical support on this software. IdeCAD's comprehensive user support and training materials ensure that local professionals can use the software effectively. This contributes to improving project quality and standardizing engineering practices.
The widespread use of IdeCAD software in the Sakarya region is an indication of the technical advantages it offers and its compatibility with regional construction practices. High accuracy, comprehensive modeling capabilities, compliance with standards and compliance with municipal approval processes are the main reasons why IdeCAD is preferred for projects in the region. This widespread use improves the quality and efficiency of construction projects in Sakarya, raising the region's standards in the construction and engineering sector.

4. Parametric Study

The structure analysed in this study belongs to a duplex type building planned to be constructed in Adapazarı District of Sakarya Province, which is located in the Active Earthquake Zone. The floor settlement of the dwelling measures 10.00m*9.50m and is 95 m^2 in size. The building is modelled as a duplex and the occupancy area is 190 m^2 in total on two floors.

The building is considered to be the same as a whole. C25 type concrete and B500 type reinforcing steel were used in the modeling of both buildings with the same residential and geometric structure. Since both structures are located on the same soil, all linear and non-linear parameters of the soil such as soil bearing capacity and cohesion etc. were considered to be the same. In order to make an evaluation within the scope of a study, the parameters selected as variables should be limited in number. Therefore, reinforced concrete structural system was chosen as the variable in this study. Reinforced concrete structural system is a whole consisting of shear walls, columns, beams, slabs, continuous beams and radial jeneral foundations. Since the building is considered as a whole, the structural system elements are not evaluated separately and are considered as a whole.

In this context, the structure was modeled considering DD-1 and DD-2 soil motion acceptance. Since DD-1 has a greater negative impact than DD-2, any structural system that satisfies DD-1 will also satisfy DD-2. For this reason, in order to understand the difference, the structure was first modeled to meet the criteria of DD-2. In the next step, behavioral improvements were provided by increasing the cross-section of structural system elements such as continuous beams and columns to meet DD-1. In this context, floor thicknesses, beam cross-sections and vertical load-bearing elements such as curtains were considered the same, and the structure was differentiated by making limited changes in column cross-sections and foundation beams. By choosing the same beams and slabs, the structure is ergonomically protected. As a result, the variables between the 2 models are limited only to the columns and continuous beams in terms of usage areas. The images of the structural mould plans of the numerical models of the building, DD-1 in Figure 1 and DD-2 in Figure 2, are given.

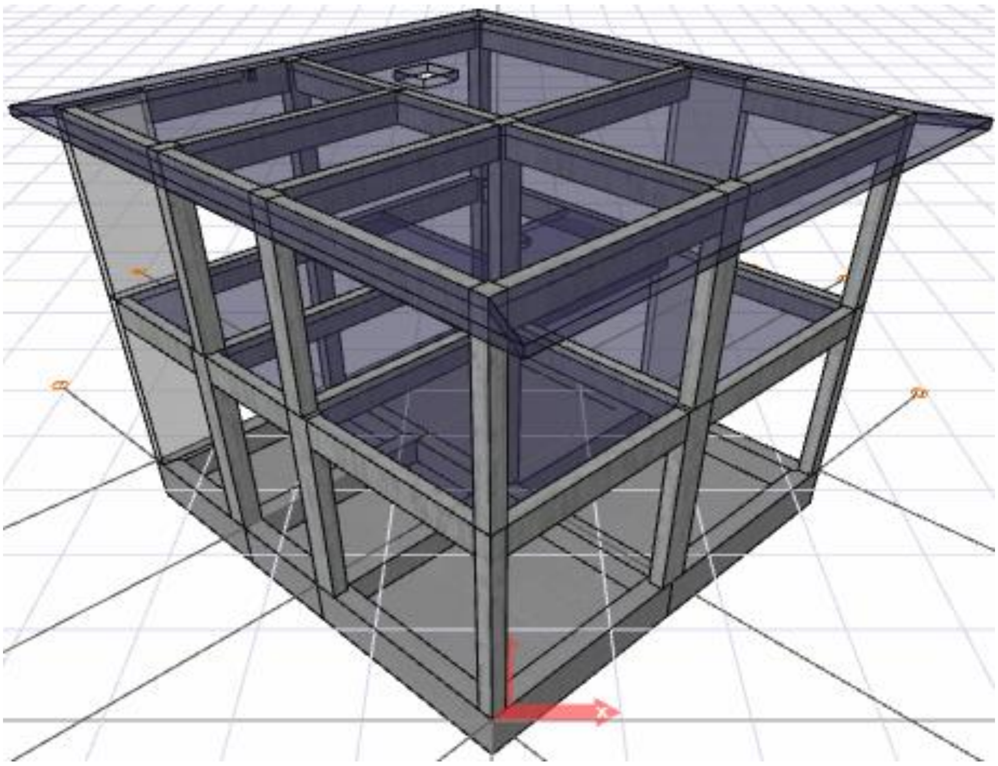

Figure 1. Solid model of the numerical model of the reinforced concrete structure according to DD-1

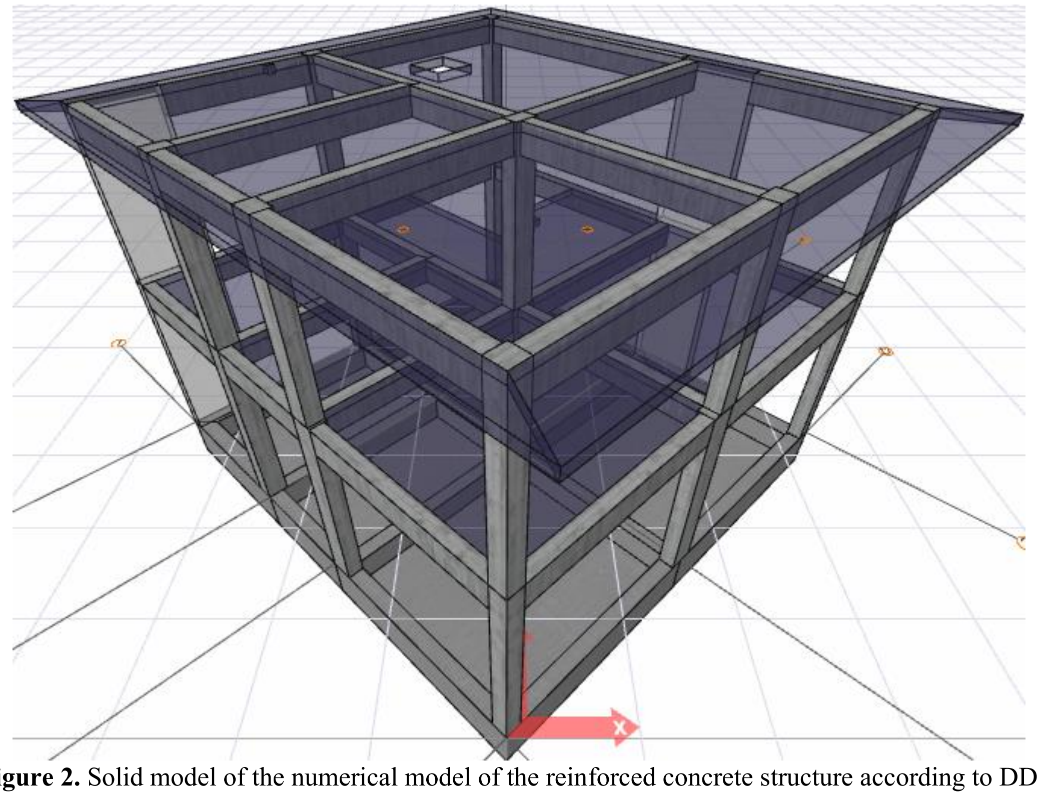

Figure 2. Solid model of the numerical model of the reinforced concrete structure according to DD-2

As a result of the reinforced concrete calculations performed in the design of the design, there have been changes in the reinforcements in the structural system elements. However, the increase in the reinforcement in the cross section does not cause any ergonomic problems. Column application plans of the numerical models are given in Figure 3 (DD-1) and Figure 4 (DD-2).

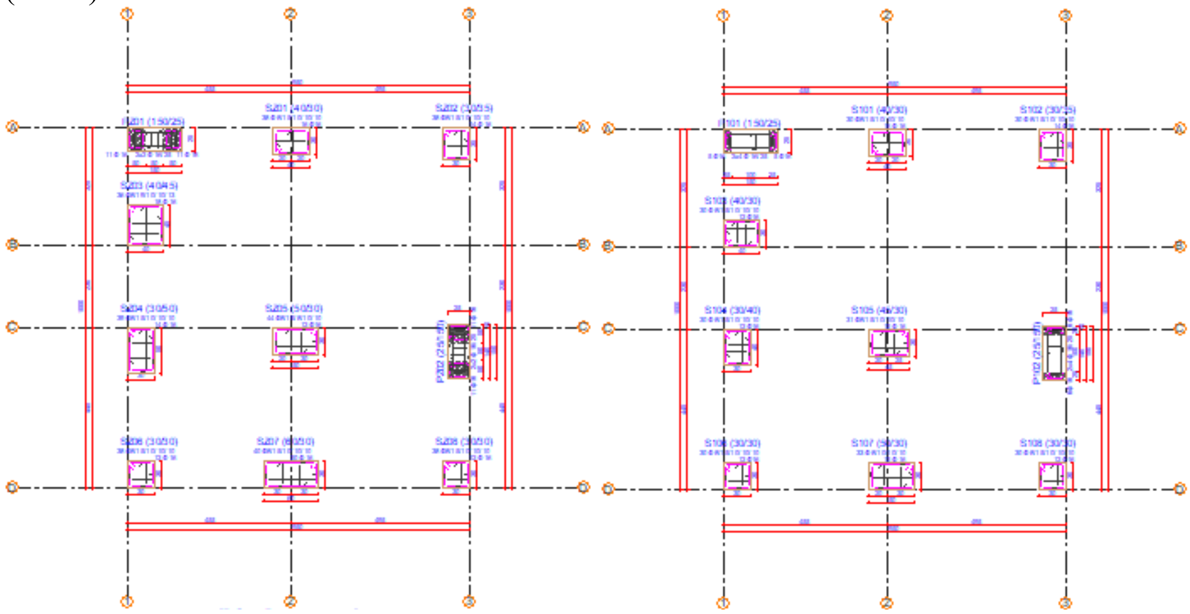

Figure 3. Column application plans of the structure modelled according to DD-1

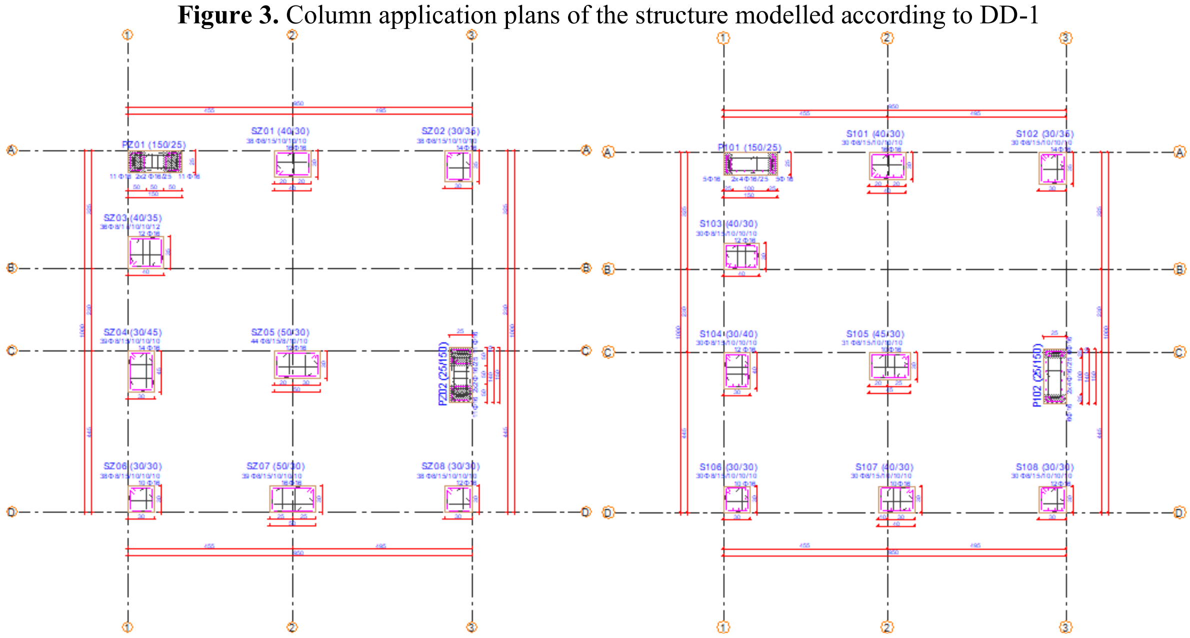

Figure 4. Column application plans of the structure modelled according to DD-2

In the foundation design, the structure modelled according to DD-1 includes foundation beams with dimensions of 40 cm*85 cm. In contrast, the structure modelled according to DD-2 includes two types of foundation beams: some are 30 cm*80 cm, while others are 35 cm*85 cm. Of course, these differences in cross-sectional dimensions caused differences in concrete and reinforcement quantities. The findings and differences obtained are analyzed in the conclusion section.

5. Conclusions

Both models have the same floor session area, the same site plan and the same floor structuring. As it is known, vertical structural elements in building design affect the usable areas. In other words, each structural element causes volume space loss in the volume in which it is located. Therefore, there is a limited amount of net usage area differences between these two models.

The examination within the scope of the study is not only limited to quantity calculations, but also takes into account the differences between the net usage areas. In this context, column cross-sectional areas were calculated. The total cross-sectional area of the vertical load-bearing elements was found to be 3.50 m^2 in the DD-1 model and 3.39 m^2 in the DD-2 model. Therefore, the difference between the 2 models was determined as 0.11m^2. Considering that the total construction area of the building is 190 m^2, it is clearly understood that the lost area is 0.058% and does not reach the levels to be taken into consideration.

When the difference is evaluated in terms of quantity and cost, the concrete quantity of the reinforced concrete structure modelled according to DD-1 is 102.55 m^3 and the concrete quantity of the reinforced concrete structure modelled according to DD-2 is 91.3 m^3. The concrete quantity difference between the two models was calculated to be 3.56%. A similar calculation was performed for reinforcement quantities. The total reinforcement in the DD-1 model was 9880 kg, while it was 9475 kg in the DD-2 model. The difference in concrete volume between the two models was calculated as 4.30% (Table 1).

Table 1. Quantity data of both structures

	Total Concrete Quantity (m^3)	**Total Reinforcement Quantity (kg)**
DD-1	102.55	10380
DD-2	91.33	9480
Difference	**11.23 (%12.29)**	**900 (%9.50)**

In the production of reinforced concrete structures, expenditures are made in 2 main items: materials and labor. The variables within the scope of this study do not cause any difference in terms of workers. For this reason, no calculation was made in terms of workers.

It is essential to identify the cost price units of the materials to be used in the cost calculations of both models. These data to be used within the scope of the study were determined by making use of the Construction and Installation Unit prices table for 2024 published by the Ministry of Environment, Urbanization and Climate Change. The results obtained from the lists show that as 2024, concrete price is 2300 TL/m^3 and reinforcement price is 33 TL/kg [18]. Considering the universality of the study, it was concluded that it is more appropriate to calculate the evaluation in US Dollars. For this reason, the cost obtained as a result of the evaluations is stated as 32 TL / Dollar. Total cost was calculated for both cases. The data obtained for concrete are given in Table 2 and the data obtained for reinforcement are given in Table 3.

Table 2. Cost calculation for the structure modelled according to DD1

	Total	**Unit Price (₺)**	**Total Amount (₺)**	**Dollar Value ($)**
Total Concrete (m^3)	102.55	2,300	235,865	7,371
Total Reinforcement (kg)	10,380	33	342,540	10,704
Total			**578,405**	**18,075**

Table 3. Cost calculation for the structure modelled according to DD2

	Total	**Unit Price (₺)**	**Total Amount (₺)**	**Dollar Value ($)**
Total Concrete (m^3)	91.33	2,300	210,059	6,564
Total Reinforcement (kg)	9,480	33	312,840	9,776
Total			473,910	16,340

Considering the construction unit costs published in the Official Gazette and market conditions, the cost of such a building was determined to be approximately 450 USD/m^2 [19]. Since the total construction area of the building is 190 m^2, its cost is determined as approximately 85500 USD. It is known from the field investigations that the structural system costs are approximately half of the total cost. Considering that half of the rough construction cost is material, it is understood that 25% of the total cost should be taken into consideration. Therefore, the cost to be considered is 21375 USD.

The cost difference between the two different design approaches remains at the level of 1735 USD. When this difference is calculated as a proportion of the total cost, a cost difference of 8.12% occurs.

In conclusion, although significant expenses have already been incurred for production and design features, it appears that the cost increase associated with designing a more durable structure is relatively limited. Prioritizing such structural improvements beyond the minimum code requirements will increase life and property safety. The fact that the building models within the scope of the study are 2 story-building and designed according to the minimum cross-section requirements of the regulation in force has caused the cost difference to be lower. Performing the same evaluations in the buildings called apartment buildings, which are designed with collective settlement facilities that allow 2 or more households to live under a single roof and contain multiple floors, will make an additional contribution to the literature.

Conflict of Interest

No potential conflicts of interest were reported by the Author.

Author Contribution

A. H. S. collected the data, designed the models and wrote the whole manuscript.

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