

A STUDY ON RAINWATER COLLECTION IN BUILT ENVIRONMENT

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ABSTRACT

A STUDY ON RAINWATER COLLECTION IN BUILT ENVIRONMENT

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In the face of climate change and a growing global population, the decreasing availability of water highlights the urgency of effective water management. With the negative consequences in urban areas where rainwater cannot reach the ground due to the effect of concretion in the built environment, efforts to obtain, protect, and use water have become increasingly vital. Within the scope of this study, it is aimed first to classify roof types in the built environment and then conduct comprehensive research on how to increase the potential amount of rainwater that can be collected from different roof types at the building scale. After urban-scale analysis, a decision support mechanism was developed by recommending different roof types and heights to improve the rain collection capacity of any building from its roof surface. Although this study focuses on collecting rainwater, it is also possible to use the developed method in solving different problems related to determining the effective surface area.

Keywords: Rainwater Harvesting, Roof Typologies, Built Environment, Roof Detection

ÖZ

YAPILI ÇEVREDE YAĞMUR SUYU TOPLAMAK ÜZERİNE BİR ÇALIŞMA

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İklim değışikliğı ve artan küresel nüfus karşısında, suyun azalan mevcudiyeti, etkili su yönetiminin aciliyetini vurgulamaktadır. Yapılı çevrede betonlaşmanın etkisiyle yağmur suyunun yer altına ulaşmadığı kentsel alanlardaki olumsuz sonuçlarla birlikte, suyun elde edilmesi, korunması ve kullanılmasına yönelik çalışmalar giderek daha hayati hale gelmiştir. Bu çalışma kapsamında öncelikle çatı tiplerinin kentsel ölçekte sınıflandırılması, ardından bina ölçeğinde farklı çatı tipleri için toplanabilecek potansiyel yağmur suyu miktarının nasıl artırılabilceğine dair kapsamlı bir araştırma amaçlanmıştır. Şehir ölçeğinde yapılan analizler sonrasında, herhangi bir binanın, çatı yüzeyinden yağmur toplama kapasitesinin iyileştirilebilmesi için farklı çatı tipleri ve yükseklikleri önerilerek bir karar destek mekanizması geliştirilmiştir. Bu çalışma kapsamında yağmur suyunun toplanılmasına odaklanılmakla birlikte, geliştirilen metodun etkili yüzey alanının saptanmasına yönelik farklı problemlerin çözümünde de kullanılması mümkündür.

Anahtar Kelimeler: Yağmur Suyu Hasadı, Çatı Tipolojileri, Yapılı Çevre, Çatı Tespiti



To my family

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LIST OF ABBREVIATIONS

ABBREVIATIONS

C	Runoff Coefficient
ECA	Effective Catchment Area
EN	European Standard
ML	Machine Learning
RW	Rainwater
RWH	Rainwater Harvesting
TS	Turkish Standard



CHAPTER 1

INTRODUCTION

Water, an indispensable element in the life of all living things, has become one of the biggest problems in the world today, both with its absence and presence, due to wrong practices and unconscious use. While one part of the world is suffering from water scarcity, another part is dealing with flood disasters. Of course, climate change also plays a major role in this. However, not paying due attention to water management practices, which include many aspects of water collection, storage, and cleaning, increases the negative consequences of this situation. Population growth and unsustainable water use practices cause water scarcity in arid climates. At the same time, flood disasters continue to increase in regions with abundant rainfall due to the lack of proper water control in the built environment. However, ironically, some water-scarce regions of the world are also experiencing floods, as seen in Figure 1.1. Unfortunately, such scenes are inevitable when water is not properly collected and controlled.



Figure 1.1 Flooding has hit at least 33 of Kenya's counties (Luis Tato/AFP, 2023)
<https://www.aljazeera.com/gallery/2023/11/23/from-drought-to-deluge-kenyan-villagers-reel-from-floods>

Architecture has a great influence on water-related practices. It is thought that architectural implementations can be significant in collecting water more effectively, utilizing it without wasting it, and controlling the water reaching underground at the urban and building scales.

In this study, the importance of water, water collection, and management strategies in the world today, the interaction of architecture with water from past to present, different water sources and how water can be obtained from these sources, the importance of rain as one of the most effective water sources are discussed. Firstly, water supply, collection, and control in the built environment and its different components in the built environment have been investigated. Then, how rainwater is collected on various roof types at the building scale was examined.

Many different and effective methods are known for collecting rainwater at the building scale. Building-scale facades create a large catchment area, especially in high-rise buildings. However, collecting rainwater is of great importance not only in small and large buildings but also in smaller structures such as residences, which comprise a large part of the city. Therefore, the focus of this study is on roofs, which are the first surface that meets rain at the building scale in the built environment. The role of different roof types in collecting, directing, and controlling rainwater is discussed in depth in the following sections. The scope of the study is as seen in Figure 1.2.

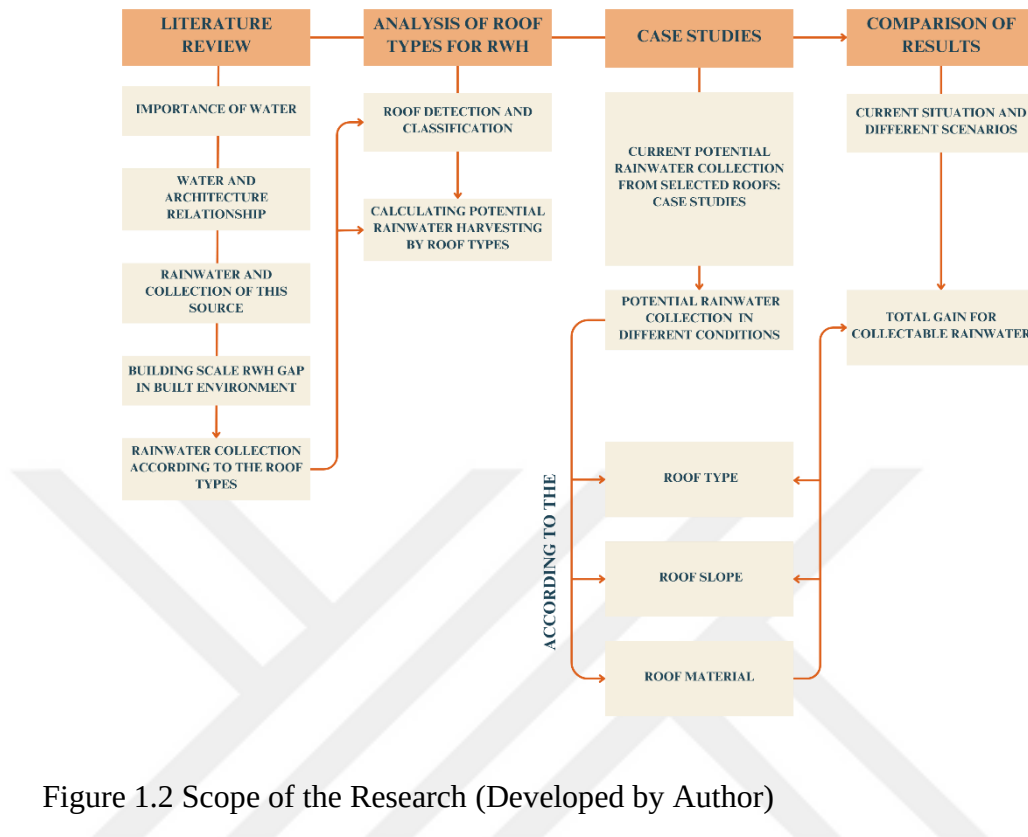


Figure 1.2 Scope of the Research (Developed by Author)

1.1 Problem Definition

The global need for water preservation, and as a part of it, rainwater collection and management practices, has intensified with water scarcity and floods resulting from environmental degradation due to rainwater not reaching the ground. Effective water collection at both urban and building scales has great importance today. Although roofs are the first surfaces exposed to rainwater at the building scale, rainwater collection systems of different roof typologies are not clearly discussed in line with environmental factors in the existing literature. There are examples of initiatives to optimize rainwater harvesting on an individual building basis, particularly in large and specialized buildings. However, at the urban scale, in current practices in smaller structures (e.g., residential buildings), which comprise the majority of buildings, decisions regarding rainwater collection are often not consciously planned. Current

strategies are often unable to collect rainwater at the maximum level and get more efficiency from the water that can be collected.

Rainfall patterns and climatic conditions directly influence rainwater harvesting efficiency. The key issue is a lack of holistic understanding of how various roof designs also affect the potential rainwater harvesting with those factors. Current literature has gaps in addressing this important issue, which requires extensive research to optimize different roof types. Therefore, the effects of varying roof types on the potential rainwater that can be collected should be examined in further studies.

1.2 Hypothesis

This research hypothesis suggests that since different roof types have crucial roles in rainwater collection, appropriate roof types should be provided in the built environment to maximize the gain of rainwater at both individual buildings and urban scales. Thus, practical implementation challenges can be addressed, and overall efficiency can be increased by integrating improved rainwater harvesting strategies into specific geographical and climatic contexts by considering different roof types. This hypothesis forms the basis of comprehensive research into the improvement of rainwater harvesting on common building roofs.

1.3 Objectives of the Research

This study aims to conduct comprehensive research on increasing the efficiency of the collection of rainwater on the roof at the building scale by identifying and classifying roofs at the urban and any built environment scale. After the classification of roofs, it is aimed to calculate the effective surface areas and the maximum amount of rainwater that can be collected for different roof types and to recommend different roof types and heights for the optimum amount of rainwater that any building can collect if the rainfall data and the projected area information where the building interacts with rain are known. In this context, the main aims of this study are:

- Research and review of roof designs: Conducting a comprehensive analysis of various roof designs affected by environmental factors such as climatic conditions and rainfall patterns and identifying gaps in the existing literature regarding the impact of roof design on the quantity of rainwater runoff,
- Analysis of roofs in the built environment: Evaluation of the performance of existing roof detection models in accurately identifying and classifying various roof types in the built environment.
- Analysis of different roof types: Discussion of different roof types and designs to obtain the maximum amount of rainwater possible to be collected through the roof surface.
- Quantitative Analysis: Calculating the potential amount of rainwater that can be collected for different roof types and roof slopes and comparing it with the current amount.
- Providing appropriate roof type: Evaluation of the results for different roof types with geographical and climatic contexts and selecting the proper roof for specific building(s).

In line with these purposes, it is aimed to develop a decision support mechanism. In this way, it is thought that it is possible to create a method that can be used not only in collecting rainwater but also in situations that require determining the effective surface area in different studies (such as the placement of solar panels).

1.4 Research Questions

This study is centered around exploring the following research questions:

1. What are the rainwater collection and management mechanisms for different roof typologies affected by climatic conditions and rainfall patterns?
2. What gaps exist in the literature regarding the impact of roof design on rainwater collection efficiency, and how can these gaps be addressed?

3. What is the performance of current roof detection models in accurately identifying and classifying various roof designs, and how can technological advances in this field contribute to rainwater harvesting research?
4. How possible is it to integrate rainwater harvesting strategies that aim to increase the potential amount that can be collected into specific geographical and climatic conditions?

1.5 Scope and Significance

This research focuses on the multifaceted examination of rainwater harvesting on building roofs, highlighting the impact of various roof designs on efficiency. The scope includes an in-depth examination of the impact of rainwater harvesting systems on different roof designs, first at the urban and then at the building scale and identifying gaps in the existing literature. Studies evaluating the performance of roof detection models and their contribution to research on various roof designs form an important part of the methodology of this research.

This study aims to contribute to the literature on the effective collection of rainwater, one of the most valuable resources. Addressing the gaps identified in the literature, this study provides a mechanism for efficiency-targeted decisions regarding the improvement of rainwater harvesting practices in terms of roof typologies in the built environment. It is thought that this mechanism can be used not only within the scope of this study, but also in solving different problems where the evaluation of effective surface areas is important, such as the placement of solar panels.

In addition, within the scope of this research, it was aimed to provide a method to accelerate and facilitate the applications of different disciplines in terms of maximizing rainwater collection for the roof in any location. This approach has been developed as a method that can be used to harvest rainwater, also at urban scale. Thus, it can also be considered as a starting point for studies that evaluate building heights in terms of rainwater harvesting in built environment. In other words, the

method of this research could serve as an initial reference for future studies that focus on how the height of buildings impacts rainwater harvesting practices within urban or constructed areas. Overall, the importance of this research is that it has the potential to provide a new perspective on architectural practices in terms of rainwater harvesting systems and to promote more efficient use of rainwater resources on a global scale.



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A comprehensive literature review was conducted within the scope of this study. In the literature review, the importance of water, the world's water collection and management strategies today, and the interaction of architecture with water from the past to the present were investigated. Then, water collection methods from different sources and the advantages and disadvantages of these methods were evaluated. The literature review continued with research covering system components and architectural implementations on how rainwater is collected in the built environment. The scope of the research was narrowed to evaluate the architectural elements that are first exposed to rain, namely the roofs, at the building scale. Different roof types that collect rainwater and roof examples in different climates of the world were analyzed, and common design decisions were evaluated.

In summary, this literature review has investigated the historical development of the connection between water and architecture, various water harvesting methods, and their effects. Based on a comprehensive review of rainwater harvesting systems at both building and urban scales, focusing specifically on roof typologies, this research aimed to understand the relationship between rainwater harvesting and roof typologies, underlining the need for improvement of rainwater harvesting practices in contemporary applications.

Access to water has become one of the biggest problems in the world. Since the late 1980s, water scarcity has started to attract attention in public and politics (Liu et al., 2017). According to Liu et al. (2017), studies on future water scarcity show that with the rapid increase in the world population, the number of people who can access water will decrease, as seen in Figure 2.1.

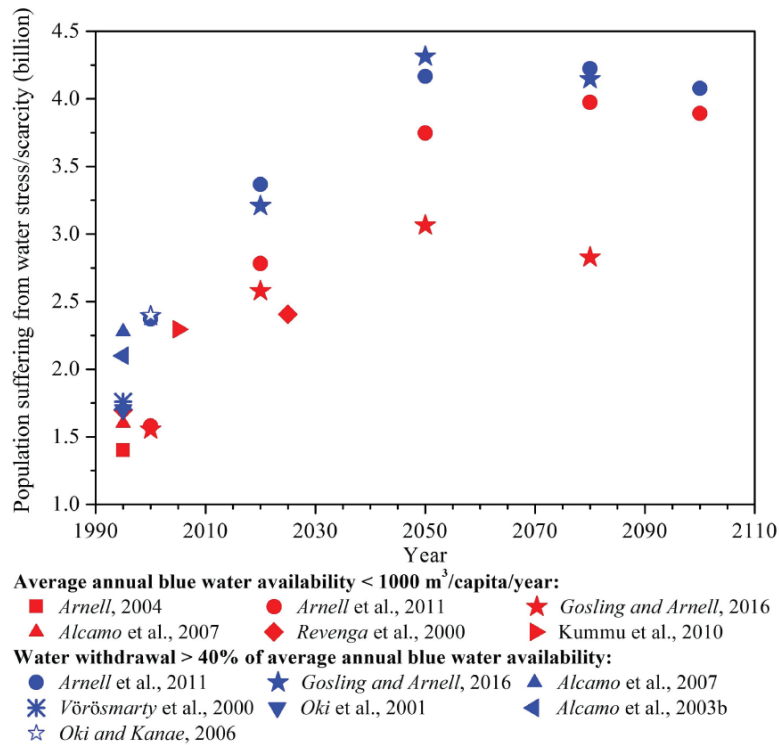


Figure 2.1 Yearly water availability and rates per person (Liu et al., 2017)

There is no specific definition regarding water scarcity; instead, it might be defined in terms of what people and nature require or in terms of how much of the source could be used to meet these demands. Although there are many water scarcity indicators, some of these indicators evaluate only quantity, quality, or green water, while others evaluate more than one feature, as seen in Table 2.1.

Table 2.1 Water Scarcity Indicators (Liu et al., 2017)

Indicator Name	Measurement	Water Quantity (Blue Water)	Green Water	Water Quality	EFR	Main References
Falkenmark indicator (water shortage)	Per capita water availability	Y	N	N	N	<i>Falkenmark et al. [1989]; Ohlsson and Appelgren [1998]; Falkenmark et al. [2009]</i>
Criticality ratio (water stress)	Ratio of water use to availability	Y	N	N	Y ^b	<i>Falkenmark [1997]; Raskin et al. [1997]; Alcamo et al. [2000]; Vörösmarty et al. [2000]; Oki and Kanae [2006]</i>
IWMI indicator (physical and economic water scarcity)	Proportion of water supply that is water availability, accounting for water infrastructure	Y	N	N	N	<i>Seckler et al. [1998]</i>
Water poverty index	Weighted average of five components (water availability, access, capacity, use, and environment)	Y	N	N	Y	<i>Sullivan [2002]; Sullivan et al. [2003]</i>
Green-blue water scarcity	Requirement versus availability of green-blue water resources	Y	Y	N	Y ^b	<i>Rockström et al. [2009]; Gerten et al. [2011]</i>
Water footprint-based assessment	The ratio of water footprint to water availability	Y	Y	N	Y	<i>Hoekstra et al. [2011]</i>
Cumulative abstraction to demand ratio	Cumulative abstraction to demand ratio	Y	N	N	N	<i>Hanasaki et al. [2008]</i>
LCA-based water stress indicator	The ratio of water use of water footprint to availability	Y	Y	Y	N	<i>Frischknecht et al. [2009]; Pfister et al. [2009]</i>
Quantity–quality–environmental flow requirement (QQE) indicator	Incorporating water quantity, quality, and EFR	Y	N	Y	Y	<i>Zeng et al. [2013]; Liu et al. [2016]</i>

EFR, environmental flow requirements; IWMI, International Water Management Institute; LCA, life cycle assessment.

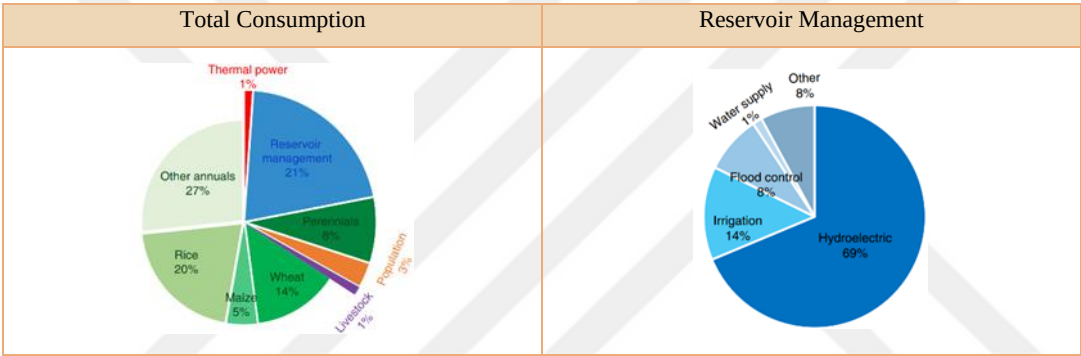
^bEFR is included but constant 30% requirement assumed.

While research on water scarcity initially focused only on groundwater and surface water, over time, various indicators such as water quality, water consumption, and water stress have been included in water scarcity indicators. Thus, research on water scarcity has become more detailed (Liu et al., 2017). Nowadays, it is possible to

contribute to studies that can solve water scarcity by collecting rainwater and using it effectively.

Additionally, when water is mentioned, it is impossible to think of only drinking water. When viewed from the perspective of all sectors, the bad consequences of unconscious use and waste of water also remind that all types of water should be used efficiently. Moreover, savings are possible by utilizing non-potable water in different areas, especially with rainwater collection. In Table 2.2, total consumption and reservoir management of water graphics were given.

Table 2.2 Water Consumption and Reservoir Management (Qin et al., 2019)



As seen in the graphs, reservoir management has a large share in total consumption. Proper use of water resources and not wasting them is of great importance for the water scarcity expected to be faced in the future. Rainwater, which is the most prominent water resource in the built environment, should be considered as an important water resource and should be used in a planned and conscious manner, just like other water resources.

Unconscious misuse of water resources in every field plays a major role in bringing the world to its current state. Problems related to water scarcity, which has been one of the most important problems in the world from the past to the present, are becoming quite serious today. Global freshwater demand is estimated to be in excess of supply by 40 percent by 2030 (World Economic Forum, 2023). According to the World Economic Forum's 2023 Global Risks Report, environmental risks include

natural resource crises, including increasing climate change, biodiversity loss and ecosystem degradation, and water crisis. There is a strong relationship between them and the risks in the other fields, as seen in Figure 2.2. If necessary measures are not taken in a short time, it is expected that the world will be damaged irreversibly.

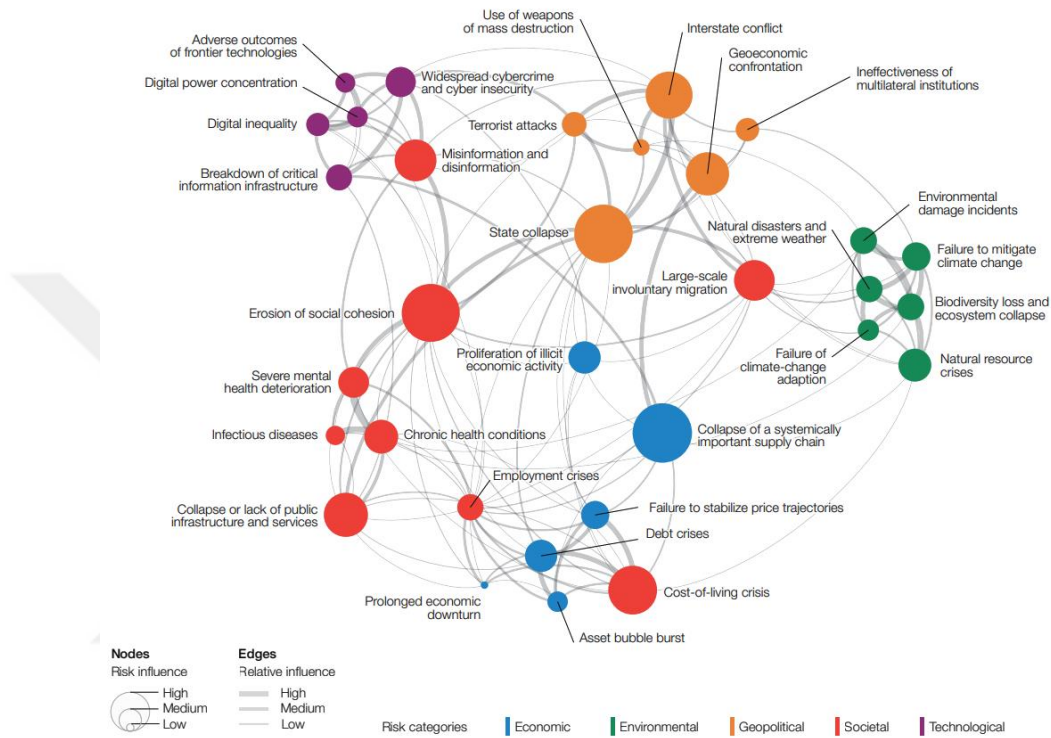


Figure 2.2 Global Risks 2022-2023. (The Global Risks Report, 2023)

In addition to water scarcity, in some parts of the world, different disasters, such as floods, occur because of improper control of water sources. In other words, not only the need for water but also the need for proper control and consumption of water as a resource attracts attention among the most necessary applications for the whole world today. With increasing population growth and urbanization, architecture will play an important role in water management. Therefore, research on the acquisition, use, and conservation of water in built environments is of great importance. For this reason, as a water source that plays a major role in the built environment, the collection and control of rainwater should be done more consciously through architecture, thus increasing water gain.

2.2 Designing for Water: Incorporating Water Harvesting Systems in Architectural Practice

Water and architecture have had a very strong relationship throughout history. This relationship gained a different dimension when people settled down. After settled life, the need to control water for agriculture through the construction of dams and canals arose. Evidence of water networks can be found even in the cities of the first ancient civilizations. Rainwater and drainage systems, wells and water pipes, and sewer systems were already used by early civilizations, as seen in Figure 2.3. (Juuti et al., 2007).

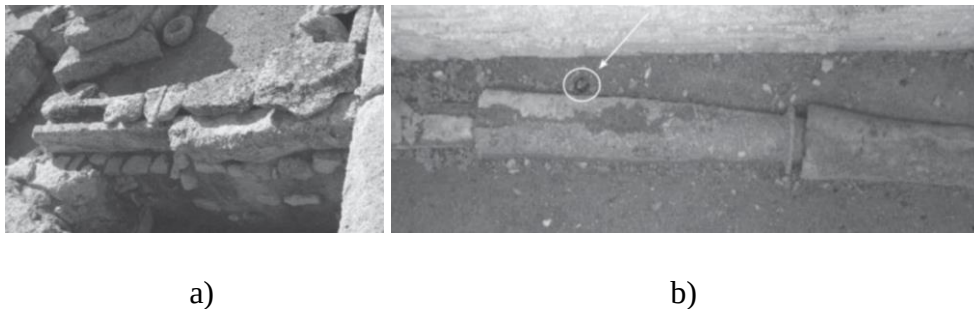


Figure 2.3 (a) Minoans' separate sewer systems in Knossos (Photo: Elsi Maijala-Juuti), (b) Old and new technology together in Knossos (Photo: Petri Juuti) (Juuti et al., 2007)

Obtaining and storing rainwater, which has been one of the most important water resources throughout history, is one of the practices that have continued for many years with the techniques developed by different civilizations for themselves. It has been collecting and using rainwater for about 4000 years in especially arid and semi-arid areas (Kinkade-Levario, 2007, pp. 6-9). Rainwater has historically been collected, often through roofs, artificial ponds, or other structures specifically built to collect water. Rainwater harvesting has been used in various parts of the world, including the Middle East, Asia, ancient Rome, and Mexico. India has a long history of using simple stone structures to capture rainwater. In Rome, rainwater was collected from covered walkways and used in small pools in gardens for both irrigation and decorative purposes. The Romans designed their villas and cities with

rainwater collection in mind, using it as their main source of drinking water and for other domestic uses. In central Mexico, rainwater collected from plazas and rooftops was stored in underground cisterns for use as both drinking water and irrigation (Kinkade-Levario, 2007, p.7).

Dams, water channels, and cisterns built by different civilizations in different periods served to meet the increasing water needs of each period. Some examples of buildings built throughout history are included in a timeline in Figure 2.4.

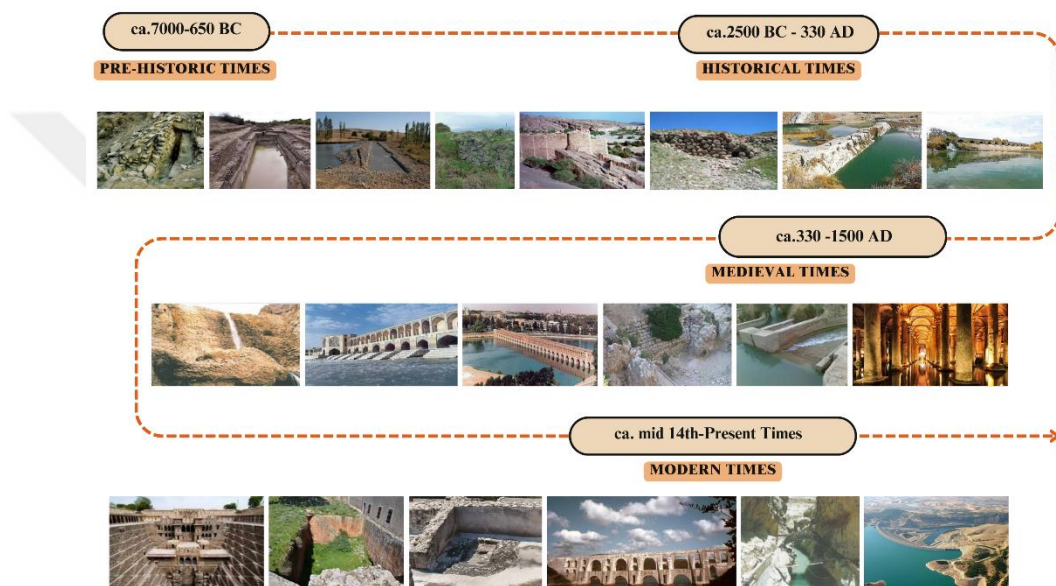


Figure 2.4 Timeline of Rainwater Structure Examples (Baba et al., 2018)
(Developed by Author)

These examples mostly include dams, water channels, and cisterns rather than specialized small-scale structures. Table 2.3 lists the most common techniques and specialized structures to collect rainwater, which have been used by different civilizations throughout history.

Table 2.3 Some of the Traditional Rainwater Harvesting Techniques (Adapted from Aslan et al., 2022)

	STRUCTURE	METHOD
Tanka		Rainwater is collected through roofs and stored in water tanks.
Kund/Tanka		Rainwater is collected through special water structures and collected from holes in the tank or through ground openings.
Talab		Rainwater is gathered and stored in artificial ponds.
Berkad		Rainwater flow on sloped ground is typically regulated by channels, collected in a man-made pond, and then stored.
Khadin		Rainwater gathered on the ground will be planted by either channeling it through canals or the slope of the land.

Water harvesting methods in the built environment have differed from past to present depending on variables such as water usage area, land, culture, and technology. The type of water harvesting structure used also depends on the source of the water being collected, such as surface water, rainwater, stormwater, or groundwater (Baba et al., 2018). Several types of water harvesting structures have been identified, including individual domestic rainwater tanks and large-scale collection, reuse systems for industrial or agricultural sites, and aquifer recharge systems. Socioeconomic factors have impacted the progress of water resource management in different parts of the world, both in ancient and modern times. While some areas have made significant advances in water collection, others are still in the early stages of developing effective solutions to satisfy their water needs. The ancient Egyptian civilization developed dams, canals, and irrigation systems to control the flow of the Nile River. These same techniques are still used today in some parts of the world. Other ancient technologies, such as pools, rainwater storage systems, underground water tanks, and dockyards, also continue to be used in modern times. However, there are still many underdeveloped countries that lack modern hydraulic engineering, rainwater harvesting, drainage, and sanitation systems (Baba et al., 2018).

Water also shaped the settlement of temples, terraced garden designs with its landscape effect, and the design of walking paths. Thus, cities gained a different character in history (Wylson, 2013). The use of water as an architectural element is still quite common today, developing technology can support the contribution of water to architecture. Although it plays a major role in many areas of architecture, the focus of our age is on obtaining, managing, and cleaning water. Certainly, obtaining water has been among the greatest goals of humanity throughout the ages, but the increasing population and climate changes have been the factors that have pushed humanity to seek ways other than traditional methods to obtain water with the contributions of technology.

Although rainwater harvesting was the most common method used after open water sources to obtain water in ancient times, the methods of obtaining water have increased with the development of technology. As the need for water has reached serious levels today, different methods of obtaining water continue to be used. These methods continue to be developed using very different techniques, such as the use of different technologies, chemical methods, and methods learned from nature. Thus, the relationship of architecture with water has also developed by transforming. Water harvesting strategies, which are still being researched all over the world, can be divided into four groups in general: seawater harvesting (desalination), groundwater harvesting, atmospheric water harvesting, and rainwater harvesting (Kinkade-Levario, 2007).

Firstly, about seawater harvesting, Xevgenos et al. (2016) explained that desalination is becoming increasingly important to address water needs, but it is expensive and requires much energy. This can strain the environment by using up fossil fuels and releasing greenhouse gases during the process of generating the necessary energy. Additionally, the wastewater produced during desalination (called brine) can harm the local marine environment when it is discharged. For desalination to be considered sustainable, these issues must be addressed. On the other hand, seawater desalination processes continue today.

Secondly, one technique utilized in areas where there are not enough readily available water resources is groundwater harvesting. Groundwater is the water that fills the spaces in the soil. It can be thought of as a hidden treasure because it is one of the most reliable sources of potable water, making up about 94% of the world's freshwater. Groundwater is found in aquifers, which are connected by semi-permeable layers of rock or soil. These aquifers form a groundwater basin, which acts as a unit with interconnected aquifers that all flow to a common outlet. Groundwater is always moving from areas of recharge, where it is replenished, to its natural outlet. There has been a shift towards using groundwater for irrigation instead of surface water because groundwater is easier to access through pumps and does not require costly transportation through canals (Mohan & Kuipally, 2021, pp.735-

775). However, long-term usage of this approach is not advised because it is thought to be disruptive to the ecological balance by resulting in irreparable harm to the natural water cycle (Bradshaw, 2016).

As a third technique, the technique of condensing water from airborne water particles is known as atmospheric water harvesting. This technique has led to the development of numerous designs and equipment. For instance, Dr. Cristian Suau created a fog-catching network system in South America termed the "foghive" (Suau, 2010). According to the systematic reviews, passive atmospheric water harvesting methods are generally categorized as fog, dew, or air humidity (Brambilla et al., 2022). The biggest problem encountered when harvesting fog with traditional methods is optimizing the thickness of the mesh structure used to harvest fog. Mesh components that trap small droplets cannot hold water when the mesh is too thick and can become clogged when thin. Compared to fog harvesting methods, dew harvesting methods require complex technologies as they are performed according to thermodynamic laws.

As a result, architecture has had a very close relationship with water throughout history. Strategies initially developed to benefit from open water resources and rain have made it possible to benefit from different water resources with the advancement of technology. However, today, rain is still the primary source of the built environment. The technologies required to obtain water from other sources do not seem applicable under all conditions. However, it is notable for being the conscious collection and use of rainwater in the built environment is of great importance and is easier and more applicable in many parts of the world than other technologies.

2.3 From Drops to Systems: Comprehensive Study of Rainwater Harvesting Methods and Their Practical Applications

Rainwater, which is often overlooked as a valuable resource, is the primary source of water in many places. Rainwater catchment systems aim to make the most efficient use of this primary source of water by capturing and storing it where it falls.

When the literature was examined, an analysis was created by evaluating the keywords in studies on rainwater harvesting in built environments. In the search conducted with the keyword "rainwater harvesting" using only the Web of Science database, 436 results were found (see Figure 2.5).

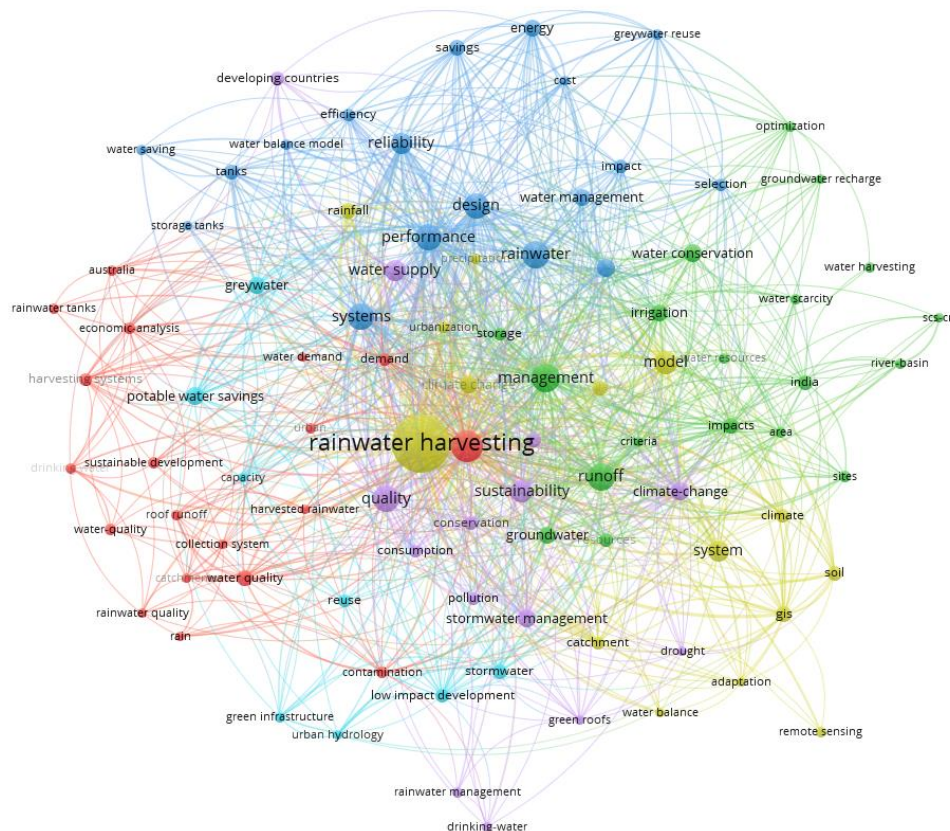


Figure 2.5 Keyword Analysis of Rainwater Harvesting (Developed by Author)

When the keyword analysis shown in Figure 2.5 is examined, management, quality, performance, and runoff keywords attract attention. However, when looking at the

building and urban scale, not many studies have been found on the relationship between the built environment and rainwater harvesting. When the keyword was changed to "rainwater harvesting" AND "roof," 76 results were obtained. When the relationship between the built environment and rainwater harvesting was searched, only 11 results were found. The relationship between rainwater harvesting and roofs is commonly expressed in studies with the keywords "roof runoff," "quality," "performance," "systems," "design," "reliability," and "water." Common keywords for the relationship between rainwater harvesting and built environment are "green infrastructure," "quality," and "cost-benefit analysis." When analyzing the research results, it can be predicted that the number of studies found through searches in different databases other than the Web of Science will be higher. However, in general, a comment can be made that the keywords associated with rainwater harvesting are similar in literature reviews.

The benefits of rainwater harvesting are mostly greatly exemplified in literature. For instance, rainwater is high-quality water with low minerals. It is also low-cost when compared to other water sources. Additionally, it is easy to construct a rainwater harvesting system. As an example of the benefits of the rainwater catchment system, Abdulla and Al-Shareef (2009) stated that according to some studies, thanks to rainwater harvesting, 30% to 90% of the water is provided in different countries. In the study, it is also explained that urbanization and rising demand are straining the available water supplies. It is also stated that alternatives like rainwater collecting systems and additional water sources with multiple uses are now the center of attention (Abdulla & Al-Shareef, 2009).

2.3.1 System Components

Depending on the level of water quality required, rainwater harvesting, and stormwater collection, required components change. These components are generally catchment area, conveyance, filtration, storage, distribution, and purification. The most used design parameters in rainwater harvesting design are

precipitation and storage. The least considered parameters in RWHS are building structure, appearance, environmental concerns, social policy, and owner preference, as seen in Figure 2.6 (Adnan et al., 2023).

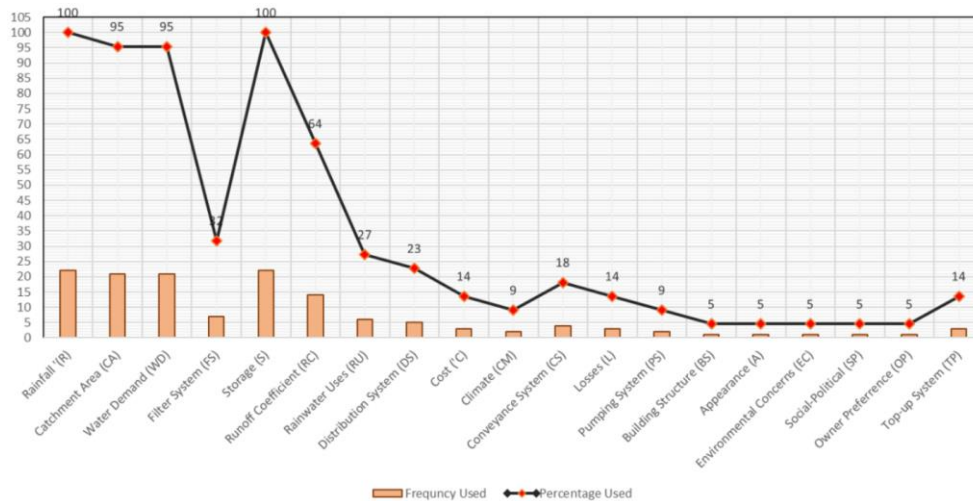


Figure 2.6 Rainwater Harvesting Design Parameters (Adnan et al., 2023)

The catchment area, in addition to being the first component required for rainwater harvesting, is an element of the rainwater collection system that significantly affects the amount of rainwater collected, its quality, the cost of the rainwater collection system, and how the collected rainwater will be directed. Capturing rainwater from the roof is the most common and easiest method of harvesting rainwater. However, it is also possible to collect rainwater from other hard surfaces, such as concrete patios, stone surfaces, and asphalt parking lots. Usually, rain is referred to as stormwater once it has reached the ground. Stormwater runoff can also be captured by contouring landscapes. The catchment area, surface porosity, surface texture, and slope conditions all affect how much water is collected. The catchment area can also consist of different areas, such as pavements apart from rooftops (Kinkade-Levario, 2007). However, rooftops are preferred unless there is a purification system for potable use of water. The pattern and frequency of rainfall also affect the quality of rainwater that is captured. The extent of the storm event, or the amount of rain that falls, as well as the frequency of storms, have an impact on how clean the catchment

region is. Fewer contaminants will be transported to the first flush device or the storage unit by higher rainfall volumes and frequency.

Regarding conveyance, it is stated that there are two different types of wet and dry systems. In a wet system, the downspouts go down the wall, underground, and then up into the tank, where they are maintained as a storage system for standing water. A dry system eliminates standing water in the conveyance system after a rain event by having the downspouts drain into the storage system (Kinkade-Levario, 2007, pp. 18-20).

Since most houses and businesses are not initially equipped with a storage system, the cisterns or storage tanks represent the largest investment in a rainwater harvesting system. Storage cisterns can be divided into three classes: Cisterns on the surface, at grade, or above ground, below-grade, underground (including partially underground) tanks, and integral cisterns or tanks built into a dwelling or commercial building (Kinkade-Levario, 2007, pp. 25-28). On the other hand, most problems with rainwater harvesting systems seem to be related to tanks when the literature is reviewed. Storage areas take up too much space, and they can pose a risk to children if they are not well protected; rainwater tanks should be cleaned regularly against the risk of debris and dust, or very effective filtration methods should be used (Gibberd, 2015). The way rainwater is collected also varies depending on the location of storage areas. Advantages and disadvantages vary depending on whether it is inside or outside the building and depending on the floor it is located on. Factors such as the area covered by the storage areas, access to the storage areas, extra load on the building if it is inside the building, cleaning, and exposure to sunlight or not also affect design decisions such as the number, dimensions, and placement of rainwater collection system elements (Younesi et al., 2013).

Lastly, distribution systems that direct rainwater can be very simple systems, such as sloping pavements, or they can consist of complex collection and distribution systems (Kinkade-Levario, 2007, pp. 29-30).

In designing a rainwater harvesting system, the selection of the above-mentioned system components, such as conveyance, purifying, etc., based on the character of the surface where the water is collected, is crucial to contribute positively to increasing the efficiency of this sustainable water resource.

When all components are evaluated, it is possible to make the conclusion that, although rainwater is mostly used for non-potable purposes such as irrigation and toilet flushing, its filtering is of great importance. In addition, the characteristics of the locations where rainwater is stored are also very important in terms of the quality and quantity of rainwater. However, as seen in Figure 2.7, when the design parameters are evaluated among the components in a rainwater collection system, it can be said that the impact of the catchment area is much higher than the other components. For this reason, studies on catchment areas that first come into contact with rain in the built environment are of great importance. In the following sections, the effect of the roofs that form these areas on the building scale in collecting rainwater is discussed in detail.

2.3.2 Building Level Implementations

After a thorough analysis of the literature, it was discovered that rainwater harvesting is one of the most used types of water harvesting techniques being used in built environments (Aslan & Selçuk, 2018). In this study, after obtaining general information about rainwater harvesting systems, more detailed research on the use of these systems and the water obtained was directed, and some studies on the world were examined.

In the study of Abdulla and Al-Shareef (2009), roof rainwater harvesting systems in Jordan were specifically investigated. Although not widely used, rainwater collection technology was present in much of Jordan. Abdulla and Al-Shareef (2009) stated that water collection from roof systems can be utilized for drinking, according to samples.

Ward et al. (2012) explained that in an office building, an RWH system significantly increased water efficiency for WC flushing. Pumping the collected rainwater into an office building required very little energy. However, concerns about energy consumption could be allayed further by encouraging innovation in RWH system design, for instance, in relation to gravity-based systems. When predicting demand, the design occupancy of a proposed building was used, which resulted in an oversizing of the storage tank even though the structure's actual occupancy was far lower. It could be helpful to do a sensitivity analysis when designing the system for commercial and office buildings with potentially varied occupancies in order to determine the range of tank sizes that should be taken into account.

Additionally, Şahin and Manioğlu (2019) stated that the findings of studies indicate that because different building types can result in varied rainfall catchment areas in housing developments with the same number of units, residents, and land area but distinct building types, the amount of rainwater harvest also varies. The amount of rainwater captured in horizontally built projects may rise even higher than in vertically formed projects, depending on the roof catchment area, yield coefficient of the surface, and annual precipitation. As a result, projects with architectural forms that are climate-independent should also be assessed in terms of rainwater harvesting and water conservation in their work on water conservation through rainwater harvesting using different building forms in different climatic regions.

In another study, Yannopoulos et al. (2019) explained that water cannot be provided for all domestic applications by RWH systems, and it is nearly difficult to make households independent of traditional water delivery systems. RWH systems, however, can act as the primary water source in rural areas where the availability of water resources is a major concern. They can also function as a supplemental water supply in urbanized areas if they are connected to the already existing conventional water supply systems.

Teston et al. (2022) stated, as a result of the literature research, that the use of rainwater for non-potable purposes has a great contribution to the environment in

terms of sustainability. It is stated that using collected rainwater for non-potable purposes will make a great contribution to saving drinking water. It was argued that economic factors also play an important role in rainwater management, and the amount of water consumed should be investigated for different buildings, such as commercial and public buildings. It was concluded that separate applications are made at both building and city scales, but larger scale and more efficient results can be obtained with the integration of these applications (Teston et al., 2022).

Lastly, in the modern rainwater harvested methods section, Aslan et al. (2022) exemplified some buildings, and most of them harvested rainwater through their roofs, while some of them were designed with special architectural elements, in similar usage areas, such as firefighting systems, WC, cleaning service, landscape, and garden irrigation, air conditioning, animal husbandry, and domestic uses. When observing these practices of rainwater harvesting methods, it can be concluded that the form of the catchment areas on a building scale is as important as the design of the rainwater system components in terms of types of water collection and storage.

Rainwater collection targets and strategies also vary depending on the purpose of use of buildings, climatic conditions, and economic factors. In line with these strategies, architectural design decisions also vary. For example, in some buildings, wide openings on the roofs serve as funnels to collect water, while in some buildings, it is aimed to collect rainwater effectively with the help of channels and gutters. However, globally, buildings that aim to collect rainwater effectively are in the minority. The next section serves to exemplify the theoretical constructs articulated earlier through the examination of real-world architectural applications. To illuminate the practical realization of the concepts of roof types and rainwater harvesting, a series of case studies are presented that examine the subtle interplay between various roofing structures and their consequent effects on rainwater harvesting. These studies include roofs of different building types, on which the components that contribute to rainwater harvesting are labeled and explained in Table 2.4.

Table 2.4 Some Building Scale Implementations from Different Climate (Developed by Author)

FORM	BUILDING	OPENINGS	CHANNELS	DOWNPIPES/ UNDERGR. PIPES	GUTTERS
 https://www.greenroofs.com/projects/gard	Super Tree Towers, Singapore, 2012	×	×	✓	✓
 https://www.dezeen.com/2016/06/16/rua-arquitetos-golf-course-rio-2016-olympic-games-brazil/	Olympic Golf Club House, Brazil, 2015	✓	×	✓	×
 https://www.archdaily.cl/cl/972114/mercado-publico-matamoros-c733	Matamoros Market, Mexico, 2019	✓	×	×	×
 https://www.archdaily.com/941560/waterhall-project-orient-occident-atelier	Water Hall Community Center, Cambodia, 2019	✓	×	✓	×
 https://architizer.com/projects/pylonesque/	Pylonesque, Thai, 2019	✓	×	✓	×
 https://www.archdaily.com/972835/stormwater-facility-gh3	Stormwater Facility, Toronto, 2021	×	✓	×	✓
 https://www.archdaily.com/999139/people-tree-house-archiptyx	People Tree House, India, 2022	×	×	✓	×

As seen in Table 2.4, there are many ways to collect rainwater. Many factors, such as the type of building, climate conditions, and rainfall amount, affect the decision on how to collect rainwater. Successful rainwater collection mechanisms in architectural applications have great value both in terms of meeting needs and raising awareness. However, these examples, whose rainwater collection mechanisms are examined, are in the minority in number, and when looking at built environments, most buildings do not have a well-planned rainwater collection system. When sample buildings are examined, it is seen that most of them are built in large areas, use high technologies, or are specialized only for collecting, storing, and filtering rainwater. Although these buildings are few in number in the built environment, they are large-scale structures compared to other structures that make up a much larger part of the urban areas. Today, where rainwater collection has great importance, utilizing not only single and large buildings but also other structures within the urban will significantly affect the amount of rainwater collected. Strategies applied solely in buildings are not sufficient to effectively collect and control rainwater. This is why urban-scale applications have great importance.

2.3.3 Urban Scale Applications

As mentioned earlier, it is as important to manage rainwater at the urban scale as it is to collect it at the building scale. Controlled management of collected rainwater can prevent flooding and water wastage. In addition to the applications made at the building scale, many new measures have been taken at the urban scale, and concepts have been developed in line with the importance of the use of rainwater. The most popular one is the “Sponge City Concept”. The term “Sponge City” describes the urban planning concept. This concept has the potential to be helpful in supplying water and increasing the availability and security of water. There are many different names for Sponge City Concepts worldwide, such as “blue-green city,” “water-wise city,” “water-sensitive city,” etc. It includes a blue-green infrastructure to collect, treat, release, and store the water for later use. To strengthen the natural urban water

cycle, strategies are green roofs and facades and urban gardening at the household scale; at the public scale, strategies are complex bio-retention, urban lakes, artificial wetlands, multifunctional areas, low elevation green belt, infiltration ditch, and reactivation of former water bodies (Thoms & Köster, 2022).

Additionally, conveyance infrastructure in urban areas is also quite significant. Combined sewer systems that contain wastewater and stormwater in the same pipe network are currently used in most of the city. However, there are many disadvantages to these systems. One of the most important of them is these systems do not have good effects on public health. Lund et al. (2019) stated that flash flooding could destroy the significant functions of cities due to intense, short-term rainfalls. Thus, solutions are required for existing urban infrastructure problems. It was aimed that the proposed combined systems, which consist of a smart city concept and integrated infrastructure, be placed in the urban landscape to control stormwater flow. In the proposed concept, the main goal is to use a real-time control system that allows entering the stormwater runoff into a combined sewer system when it is necessary or storing the aboveground in green infrastructure elements. It was also emphasized that if catchment areas, such as roofs or pavements, can also be controlled, control systems would be important to optimize the sewer system (Lund et al., 2019).

According to the systematic reviews, green roofs and rain gardens, living walls, built wetlands, bioswales, ponds, and planted permeable pavements are the types of nature-based solutions systems for circular urban water systems. Tsatsou et al. (2023) stated that the most dominant term is “water-sensitive urban design” in the literature about nature-based solutions.

As other parts of the urban, green roofs provide drought resilience, biodiversity, climate change mitigation, urban cooling, and many more benefits with absorbing and regulating water flows, capturing, filtering, and storing rainwater, living walls on building façade provide regulation of the urban micro-climate, reducing the

greenhouse effects, food production by purification of rainwater, greywater, and blackwater.

Also, permeable pavements reduce the risk of urban flooding while pavement structure infiltrates the runoff; thus, it serves to harvest and store the filtered water and transfer the infiltrated water. Tree pits, on the other hand, are also noticeable systems for the improvement of urban green areas by harvesting, infiltration, and reuse of water. Thus, runoff is collected and stored within the underlying structure. In the same way, rain gardens, constructed wetlands, and bioswale also provide enhancements of greenery at the urban scale and biodiversity, which also have many positive impacts on physical and mental health by filtering and storing water (Tsatsou et al., 2023).

In China, one of the leading countries in the world with a crowded population, detailed plans have been made to collect and utilize rainwater. Zhou et al. (2023) stated that national seminars, regulations, and standards on this subject have been organized in detail at the urban scale, as seen in Figure 2.7, and there have been three stages of urban-scale rainwater harvesting strategies, which are initial development, rapid development, and sponge city construction phases.



Figure 2.7 Policy Evolution of Urban Rainwater Harvesting in China (Zhou et al., 2023)

As seen in Figure 2.7, China has taken precautions for rainwater harvesting applications from the early periods. This is due to the increasing need for water with the dense population. Although China is one of the world's leading countries in this regard, since as the need for water increases, awareness in the world has also begun to increase, these measures and regulations to collect and utilize rainwater more efficiently can be applied all over the world. Rainwater harvesting techniques vary depending on urban scale, land use, collection methods, storage location, and reuse ways. Different methods have been developed according to the surfaces on which rain will collect in the urban areas, as seen in Figure 2.8.

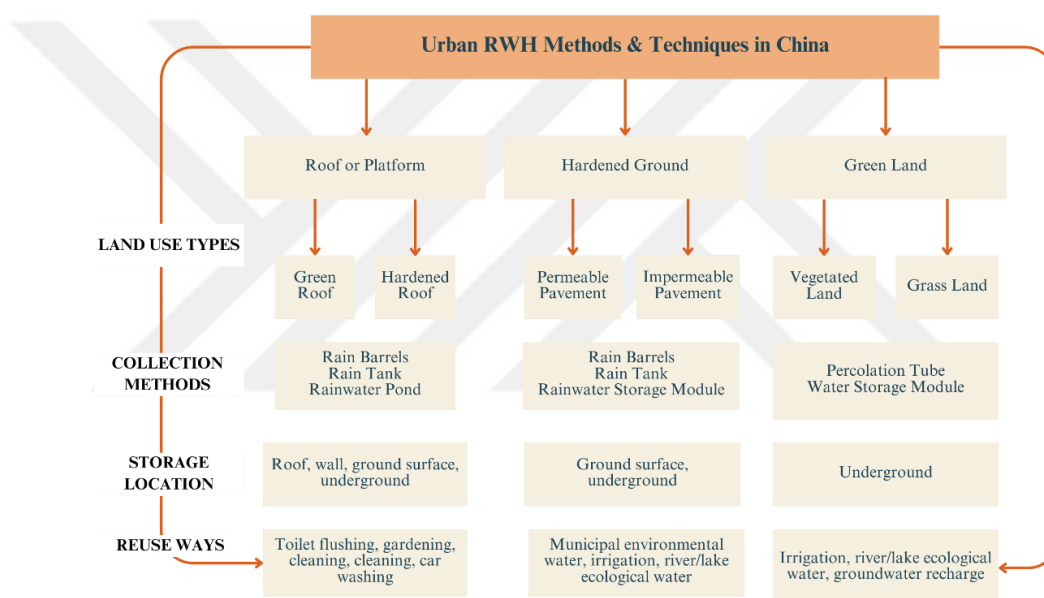


Figure 2.8 Classification of RWH Methods (Adapted from Zhou et al., 2023)

These methods, their equivalents in architectural applications, rainwater collection techniques, the amount of rainwater that can be collected, and the areas of use of the collected rainwater are explained and listed in Table 2.5.

Table 2.5 Implementation Cases of RWH Methods (Adapted from Zhou et al., 2023)

RWH Method	Project Name	Water Collecting Area (m ²)	RWH Capacity (m ³)	RWH Technique	Water Use
Hardened Roof RWH	Water Cube (Zuo et al., 2009)	29,000	10,500	Scattered collection and centralized processing	Vegetation, irrigation, landscape water, toilet flushing
Green Roof RWH	Tianxiu Garden Community (Chiu, 2012)	23,900	5,600	Centralized collection and centralized processing	Vegetation, irrigation, landscape water
Permeable Pavement RWH	Bird's Nest Square (Liu et al., 2015)	220,000	67,000	Scattered collection and centralized processing	Vegetation, irrigation, landscape water, toilet flushing, washing of park lots, runways, and roads
Impermeable Pavement RWH	Lotus Bridge Reservoir (Wang et al., 2021a, 2021b, 2021c)	136,000	12,000	Scattered collection and centralized processing	Vegetation, irrigation, river supplement water
Green Land RWH	Olympic Sunken Garden (Li et al., 2017a, 2017b)	45,000	26,325	Scattered collection and scattered processing	Landscape water, ecological water

When the studies and measures taken around the world at the urban scale are examined, it is seen how critical water management and rainwater collection are with the increasing population. Collecting rainwater effectively in any built environment, not only in the world's leading countries in technology but also throughout the world, has become of great importance, especially in recent years. Therefore, all kinds of permeable and impermeable surfaces, pavements, roads, green areas, and roofs that can be considered catchment areas on a city scale should be considered as part of a planned system. Thus, the amount of rainwater to be collected will increase significantly, and although it is not potable, it will serve different purposes, such as irrigation and toilet flushing, and will be an effective solution to water scarcity in the future by reducing the pressure on potable water. Directing the collected rainwater to the areas where it will be stored with the right techniques, performing the necessary filtering processes, and then recycling it to serve buildings and green areas, as well as preventing environmental degradation by reaching the underground, should be among the applications aimed to be realized in the built environment.

2.4 Green Building Certification Systems and Rainwater Harvesting

Since rainwater harvesting plays a sustainable role in building design, it is also a factor that should be taken into consideration in green building rating systems. Green building certification systems, which are particularly meticulous about energy saving, aim for a sustainable environment by evaluating different criteria. Although there are many green building certification systems today, the first green building rating system was the Building Research Establishment's Environmental Assessment Method (BREEAM) in the 1990s. After that, the U.S. Green Building Council (USGBC) and Leadership in Energy and Environmental Design (LEED) rating system emerged. While green building certification systems can be a good marketing tool, they also lead to setting goals for a more sustainable world (Vierra, 2016).

Different green building certification systems use different rating criteria for 11 different categories, such as energy efficiency and waste management. (Vyas and Jha, 2016). Water use criteria are basically water use reduction, cooling, water consumption, water monitoring, water leak detection, water-efficient equipment, potable water, water saving, rainwater, and greywater use in different green building certification systems, which are LEED, BREEAM, Green Star, CASBEE. Water resources, water saving, rainwater, and graywater criteria are included in the CASBEE certification system (Alwisy et al., 2018).

As a practice of green building certificate systems, a map was developed to analyze the location of the green buildings and identify the potential areas for green buildings in the city. BREEAM is one of the most popular multi-criteria assessment systems in Poland. There are many versions of BREEAM according to the different factors such as countries, type of function of the buildings, etc. It analyzed the impacts of the location of the green buildings on rainwater management, urban heat islands, and air quality. Since generally there are common sewage systems in city centers, it is important to promote distinct solutions for rainwater management at the place of the buildings in the certification process. So, the location of the buildings is important in terms of the certification systems in the aspect of rainwater management on an

urban scale. In the BREEAM certification system, credits can be taken in the areas in which tap water is not needed for not only irrigation but also other usage of water (Bak et al., 2019).

Also, Fowler and Rauch (2006) stated that there had been many certification systems, but LEED is one of the most dominant ones and has been adopted worldwide. LEED certification systems were formed to provide reliable standards to the building industry in terms of green building descriptions.

Assessment categories of water are water conservation, innovative water technologies, water use, and water-efficient landscape. It is stated that there are common concerns in terms of water efficiency among different rating systems, which are LEED, BREEAM, CASBEE, SABA, and GB Tool (Ali & Al Nsairat, 2009). However, when the evaluation criteria of green building certification systems are examined, it is seen that the efficiency and correct evaluation of water are evaluated at a very low percentage, as seen in Figure 2.9.

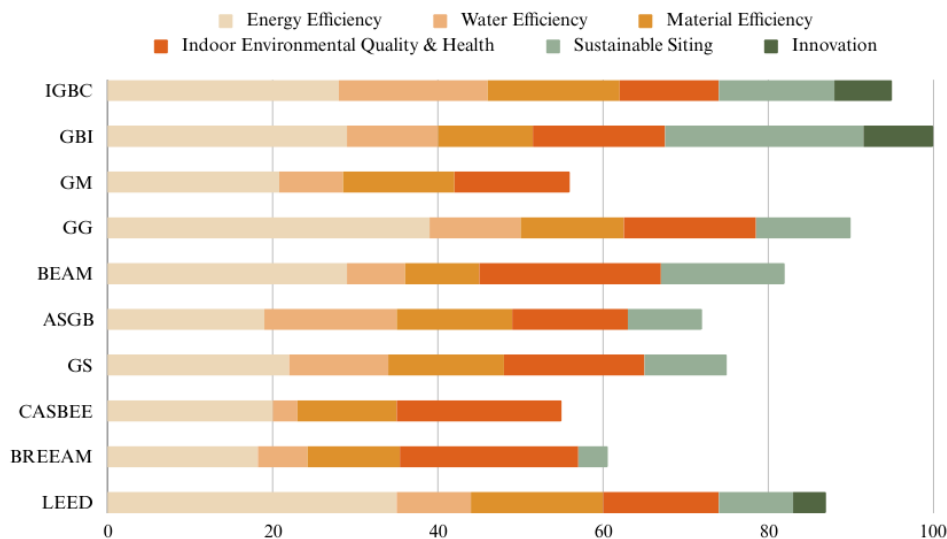


Figure 2.9 Comparison of Different Green Building Rating Systems (Adapted from Tang et al., 2020)

In addition, although the water efficiency criterion includes many separate factors, such as water consumption, evaluations regarding rainwater collection or rainwater

management are either absent or at a very low percentage. For example, for LEED, water efficiency is evaluated with a maximum of 11 points out of 110 points, while rainwater management is worth only 3 points (Vierra, 2016).

Although green building certification systems are systems that are thought to evaluate the contributions of buildings to a sustainable world, the evaluation of design decisions regarding water resource insufficiency, one of the biggest problems in the world, has a very low share compared to the general evaluation criteria. In particular, evaluation criteria can be provided to encourage more careful planning for rainwater collection and control. In this way, it can be aimed at preventing water waste in the built environment, increasing the amount of rainwater collected, and using the rainwater collected more effectively.

2.5 From Top to Tap: How Roofs Serve as Catchment Areas for Rainwater Harvesting

As explained in detail in the previous sections and examined through examples, there are many ways to collect rainwater at three different scales: building, cluster, and urban scale. For example, in high-rise buildings, it is possible to collect an effective amount of water from the building facade, depending on the material properties, technology used, and climatic conditions. Al-Kodmany (2022) stated that while every arrangement to be made in high-rise buildings will have great effects, improvements in their design, construction, and engineering will provide great savings in areas such as energy saving and potable water savings. Additionally, it is possible to collect rainwater from green lands, pavements, roads, and any surface that can be considered as a catchment area. However, roofs, which are the catchment areas that first come into contact with rain at the building scale in the built environment, constitute effective surfaces to collect rainwater not only in large-scale but minority buildings that specialize in harvesting rainwater but also in architectural structures such as small-scale residences that make up the built environment in

general. For this reason, research on roofs that should be considered as effective catchment areas has guided this study.

The location and climatic conditions of the building, the purpose of use of the building, and environmental factors cause changes in the roof design. These changes also manifest themselves in rainwater collection mechanisms, sometimes with green roof applications and sometimes with innovative applications (such as water collection from the atrium), thereby increasing the amount and quality of rainwater collected or contributing to the city by managing rainwater after heavy rains. Although collected rainwater is often not potable, recycling the collected rainwater as gray water after being filtered increases potable water saving. Of course, structures that can collect large amounts of rainwater contribute greatly to sustainability and increasing water needs. However, factors such as materials and technologies used and building height are just a few of the design decisions that are not valid for most buildings in the built environment. In this study, which is based on the idea that collecting rainwater is of great importance for smaller, ordinary buildings that already exist in urban, the method of increasing the amount of rainwater that can be applied to every building on an urban scale will be to focus on roofs. Thus, by including a large portion of the buildings in the city, the amount of rainwater collected can be increased, and the control of the collected rainwater can be achieved more easily.

In the next section, architectural implementation examples that include different roof types are examined in terms of rainwater collection systems, as seen in Table 2.6. In the buildings examined, rainwater collection and drainage elements that can be observed on the roof are expressed in different colors on the roof visuals. Detailed explanations of these expressions are given in Table 2.7. When roof designs affected by different climatic conditions and architectural decisions are examined, different slope angles attract attention. The buildings use different slopes, roof types, and materials. Since the buildings are mostly designed with the aim of rainwater harvesting, large-volume cisterns, and water tanks are included, and the locations of these elements vary depending on the building characteristics. Although different

design decisions for transferring collected rainwater to tanks attract attention, it is clear that these decisions were made in a planned manner.



Table 2.6 Case Studies (Developed by Author)

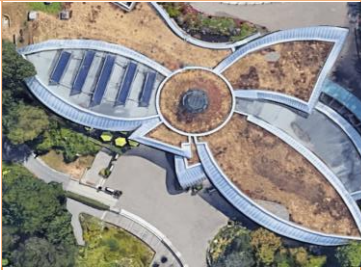
Building	Form	Roof
VanDusen Botanical Gardens Visitor Center Institutional Canada Temperate Climate		
Government Canyon Visitor Center Educational Texas Hot Semi-Arid Climate		
Poquoson Elementary School Educational USA Temperate Climate		
Swenson Civil Engineering Building Institutional Minnesota Humid Climate		

Table 2.7 Rainwater Collection Mechanisms of Different Roof Types (Developed by Author)

Building	VanDusen Botanical Gardens Visitor Center	Government Canyon Visitor Center	Poquoson Elementary School	Swenson Civil Engineering Building
Roof Type	Sloped (5% - 50%)	Sloped	Butterfly/Folded Sloped, Flat	Flat, intensive vegetative roofs (23%) are represented in the Table 2.7 with a green color.
Roof Material	Metal, Green Roof	Metal	Metal	In the roof design, materials found in the region were transformed and used, and the concrete roof was painted with white paint
Roof Area	1858 m ²	725 m ²	7600 m ²	3080 m ²
Gutters	The form of the roof merges with the garden and directs rainwater, reaching all the way to the ground in some areas, and the gravel coating on the inside of the roof parapets continues along the parapets.	There are 3 metal gutters on the building's roof.	There are 16 metal gutters on the building's roof (Red lines represent the gutters in Table 2.7). On sloping roofs, gutters are placed in the direction where rainwater flows.	No typical gutter was found in the design of the building. Rainwater is stored by scuppers (which are represented in the Table 2.7 with red colors) and transferred to large French drains.
Downspouts/Downpipe(s)	There are no downspouts visible in the building.	Rain chain downspouts are located at the ends of the gutters.	The number of rainwater downpipes varies depending on the size of the surfaces where the gutters are located. There are 21 rainwater downpipes on the building (green circles show the location of rainwater pipes in Table 2.7). Rainwater downpipes are positioned at the ends and middle parts of the gutters.	No typical downspouts or pipes were found in the building.
Cistern(s)	One cistern is located under the north roof petal. 125 m ³ of water is collected in the cistern.	There are five cisterns in the visitor center. Two of them are located aboveground (12113.31 L), and 3 of them are located belowground (14384.56 L).	Although there is no information about the area where water is stored in the building, gravel was applied to the ground in the parts where rainwater flows.	There is an underground system to hold water, in addition to French drains which are represented in the Table 2.7, with an orange color.
Rainwater Roof Outlet(s)	Rainwater is collected from a single point on the part where the cistern is located and directed to the cistern	No rainwater outlet was found on the roof surface.	There are rainwater outlets on the flat roofs of the building, in line with the rainwater pipes.	No typical rainwater roof outlets were found in the building.

Different inferences were made when interpreting the results obtained when buildings with different roof types, which use various strategies to collect rainwater from different climatic regions, were examined. First of all, the effectiveness of green roofs in retaining rainwater is one of the prominent elements in the analysis of sample buildings. Green roof designs show themselves at different slopes in the examples examined.

Additionally, a conscious design approach emerges when the location of rainwater collection elements is examined. Depending on the roof size, symmetrical layouts are usually located near the corners or in the center. This deliberate positioning and the size and number of components of the rainwater harvesting system aim to increase the amount of rainwater to be collected.

In the examples examined, it is noteworthy that more than one rainwater outlet is provided to reduce water accumulation on flat roofs. The strategic placement of rainwater outlets aims to prevent the possibility of ponding and related structural problems by providing efficient drainage. Additionally, placing rainwater outlets away from possible obstacles, such as chimneys and skylights, ensures that the flow of water is not blocked. When architectural implementation examples are examined, the locations of rainwater storage tanks also vary. Where rainwater storage tanks are located outside, or their location can be predicted, the strategic design of gutters aims to shorten the distance for collected rainwater to reach the storage area. Thus, potential losses in collected rainwater were tried to be minimized.

The common feature of these examples, which aim to collect rainwater effectively, is that they are mostly buildings that are a minority in number in the city. However, a conscious approach has been taken to increase the rainwater collection capacity of all these examples, and most of them are specialized for this task or are large buildings. However, when we look at the buildings that make up an urban area in general, it is seen that there is no strategic planning of rainwater collection systems, and conscious and well-planned choices are not made other than very general principles regarding material selection, roof type selection, and placement of

rainwater outlets. For example, in Table 2.8, photographs of rainwater collection elements taken from different parts of the world are shown. Photos were taken from cities in different climate zones randomly selected in Google Earth.

Table 2.8 Implementations of Roofs and Other Components in Built Environment
(Developed by Author)

Country	Roofs in Built Environment	Roofs as Catchment Areas	Details
Turkey			
Kenya			
Spain			
India			
Italy			
Mongolia			
Uganda			

As seen in Table 2.9, even the connections between the components used by many buildings in the city to drain rainwater are not checked. Different strategies are not developed according to roof types, and some buildings do not even have rainwater pipes. These and similar examples are quite common in built environments. In addition, the situation seems to be similar all over the world under different climatic conditions. For this reason, determining the roof types and making the right design decisions according to their types is very important to collecting and directing rainwater effectively. Also, the placement of gutters, rainwater outlets, and rainwater downpipes should be planned for each building and checked regularly after the applications. Thus, for any location, an improvement in the built environment can be highly effective in terms of rainwater harvesting efficiency.

In the scope of the literature review, after a comprehensive literature review on the importance of water, strategies to protect and manage water on a global scale, the relationship between architecture and water, the importance of rainwater as the primary water source in the built environment, and how to collect rainwater from rooftops in the built environment at the building scale is discussed. Case studies on collecting rainwater on roofs were examined.

As a result of these studies, it was determined that the buildings designed to direct the rainwater on the roofs to the rainwater outlets in a controlled manner and from there to the area where it will be stored in a very small minority compared to the buildings in the city. Fields. Issues such as material selection for rainwater collection, roof typologies, and placement of rainwater outlets are not clearly discussed in the literature. Buildings that effectively collect and direct rainwater are in the minority. For this reason, in order to increase the amount of rainwater collected in the built environment, improvements in rainwater collection in buildings that constitute a large part of urban areas and are not taken into account are of great importance. One of the most important steps for these improvements is to effectively evaluate the roofs that form catchment areas and to make different strategies and design decisions for different roof types.

CHAPTER 3

METHODOLOGY

The scope of this study is primarily aimed at detecting and classifying roofs in the built environments to calculate the amount of collectible rainwater from the roof surface, which is the first building element exposed to rain on a building scale. Projected areas of roofs were calculated at the urban scale, and the maximum amount of rainwater that could be collected for each roof was calculated by taking into account the rainfall data in the region where the buildings are located. Then, effective catchment area and quantity of rainwater runoff formulas were calculated for each different roof type, referring to the standards (EN 12056-3) and calculations in the literature. Then, the amount of rain that could be collected from the roof of a randomly selected building in its current state was calculated and compared with the maximum values. Thus, by targeting any building with a certain roof type and area in the built environment, it is aimed to increase the quantity of rainwater that can be harvested from the roof at the building scale. The scope of the methodology of this study is included in Figure 3.1.

After a comprehensive literature review, it was concluded that different calculations should be made for each roof at the building scale in order to increase the amount of rain collected from the roof surface in ordinary and small-scale buildings that are located in the built environment and make up a large part of the city. Therefore, to solve the problem, the first step was to detect the roofs of the surrounding buildings. In the second stage, the classification of roofs is of great importance. Thus, an effective catchment area can be found in line with the calculations developed for different roof types. In the third stage, the aim was to find the projected areas and side lengths of the detected roofs. By finding the side lengths, it is aimed to calculate the potential amount of rainwater that can be collected, which varies for different slope values. By including the runoff coefficient values of roof materials in the calculation, which is another important factor in rainwater collection, the values calculated for different material types can be compared. All these steps are discussed and explained in detail in the following sections of the study, as shown in Figure 3.1.

3.1 Machine Learning Task-1

This chapter of the thesis aims to explain the first machine learning task performed for the detection and classification of roofs in the built environment, which is the first stage of solving the research problem. The diagram of this chapter, which clarifies the data collection, analysis, and interpretation, is shown in Figure 3.2. In the following sections, all the parts included in Figure 3.2. are explained in detail.

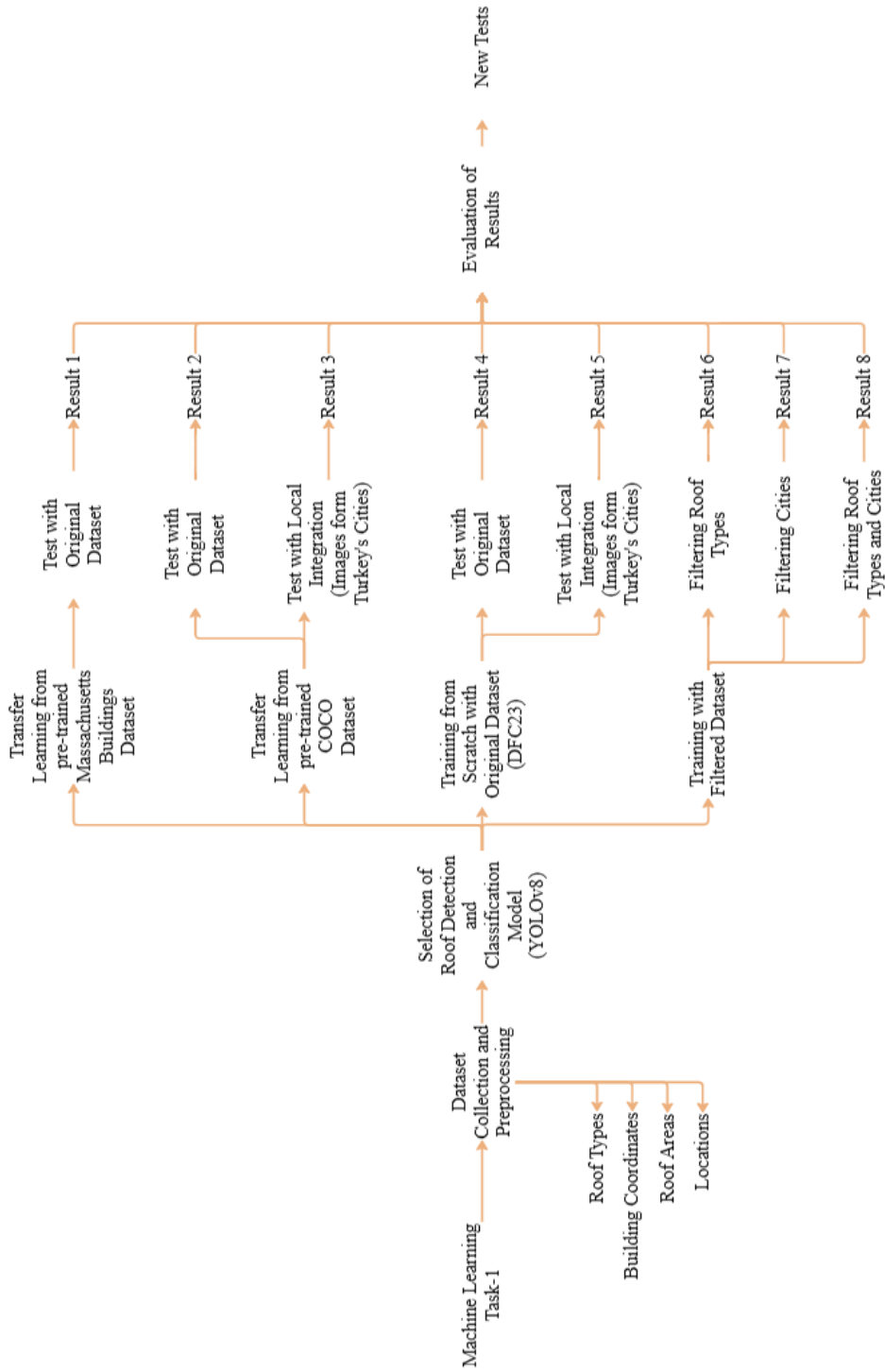


Figure 3.2 Machine Learning Task-1 Outline (Developed by Author)

3.1.1 Dataset Collection and Preprocessing

There is a notable gap in determining the roof types of buildings. Especially in urban scale applications, since roofs are the only components that can be interpreted about buildings in aerial photographs, the classification of roofs is of great importance for various analyses in the following stages. Classifying building roof types from satellite images poses a challenge primarily due to the unclear visual characteristics inherent in such images.

In this study, in order to find solutions to the above-mentioned problems, for the 2023 IEEE GRSS Data Fusion Competition organized by the Image Analysis and Data Fusion Technical Committee (IADF TC) of the IEEE Geoscience and Remote Sensing Society (GRSS), affiliated with the Chinese Academy of Sciences. Aerospace Information Research Institute, Universität der Bundeswehr München and GEOVIS Earth Technology Co., Ltd, specifically prepared the DFC23 dataset.

The dataset leveraged in this study, known as DFC23, is a new large-scale urban structure classification dataset. The DFC23 dataset covers urban buildings distributed across seventeen cities spanning six continents. Buildings in the dataset are labeled with a fine-grained classification of roof types. This comprehensive classification comprises 12 distinct roof types, each annotated with corresponding numerical identifiers:

- 1-gable roof
- 2-gambrel roof
- 3-row roof
- 4-multiple eave roof
- 5-hipped roof V1
- 6-hipped roof V2
- 7-mansard roof
- 8-pyramid roof
- 9-arched roof

- 10-dome
- 11-other

Containing approximately 300,000 examples, the DFC23 dataset includes twelve different roof types. The dataset includes not only optical images but also Synthetic Aperture Radar (SAR) images. This combination of different methods aims to improve the accuracy of building extraction and classification models. However, since SAR images are not easily accessible, these images were not included in this study.

Images in the DFC23 dataset were collected from the SuperView-1 (or "GaoJing" in Chinese), Gaofen-2 and Gaofen-3 satellites. These satellites provide optical images with spatial resolutions of 0.5 m, 0.8 m, and 1 m, respectively. Additionally, the dataset is divided into three sets: training set, validation set, and test set.

Overall, the DFC23 dataset provides a rich collection of data from various geographical locations and architectural applications.

3.1.2 Models: Object Detection for Roof Classification

It was aimed to perform the object detection task for the detection and classification of roofs as the first step of the methodology. Object detection is of great importance for computer vision and involves identifying instances belonging to certain classes. The main purpose of object detection is to determine the existence and location of objects. The evolution of object detection is broadly categorized into two periods: the "traditional object detection period (pre-2014)" and the "deep learning-based detection period (post-2014)". A significant advancement in the latter period is the introduction of You Only Look Once (YOLO) by Joseph et al. in 2015, as seen in Figure 3.3.

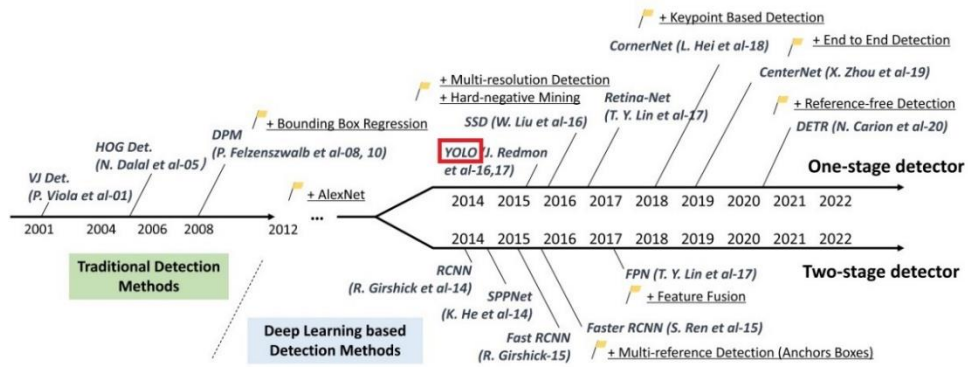


Figure 3.3 Road Map of Object Detection (Zou et al., 2023)

YOLO stands out as the first one-stage detector in the deep learning era, as outlined by Redmon et al. (2016). Unlike traditional detectors, YOLO uses a single neural network to analyze the entire image. For this analysis, it divides the image into regions and simultaneously estimates the bounding boxes and probabilities for each region. Since a single neural network is used at this stage, the object detection task can be completed faster compared to traditional methods.

This approach results in a significant improvement in detection speed (Zou et al., 2023). YOLO represents a paradigm shift in object detection methodologies, providing both accuracy and speed, and its introduction has had a profound impact on the landscape of computer vision applications. In January 2023, Ultralytics, the developer of YOLOv5, released YOLOv8. YOLOv8 introduced five scaled versions: YOLOv8n (nano), YOLOv8s (small), YOLOv8m (medium), YOLOv8l (large), and YOLOv8x (extra-large). These versions of YOLO encompass diverse functionalities; it is capable of performing multiple vision tasks, including object detection, segmentation, and classification. (Sirisha et al., 2023).

This study aimed to employ the YOLOv8x (You Only Look Once, version 8) model for roof detection and classification. The methodology involves utilizing the YOLOv8 model by transfer learning from pre-trained COCO dataset, transfer learning from pre-trained Massachusetts Buildings Dataset, and subsequently training a YOLOv8 model from scratch using a dedicated roof dataset.

The COCO (Common Objects in Context) dataset is a comprehensive resource for advancing research in computer vision, particularly in the domains of object detection, segmentation, and captioning. Featuring 330,000 images, with annotations for 200,000 images, it encompasses 80 diverse object categories, ranging from common items like cars and animals to specific objects like umbrellas and handbags (Lin et al., 2014). The COCO dataset is a tool also used by popular models such as YOLO.

On the other hand, Massachusetts Buildings Dataset includes 151 images of suburban and urban areas with buildings which have different dimensions. Resolution of all the aerial images is 1 (Mnih,2013).

Within the scope of this study, both pre-trained models and trained from scratch DFC23 dataset were tested and compared. The results of the tests are explained in detail in the following sections.

3.1.3 Strategies for Selection of Data to Utilize

The data set includes satellite photographs taken from cities with a wide variety of roof types and different climate zones. However, when the common roof types used in the built environment were evaluated, a filtering process was performed, and selection strategies were determined for the data to be prepared for training. Thus, it was possible to compare the models trained with the datasets created by filtering and without filtering. Figure 3.4 shows the table of different trainings done before moving on to the testing phase.

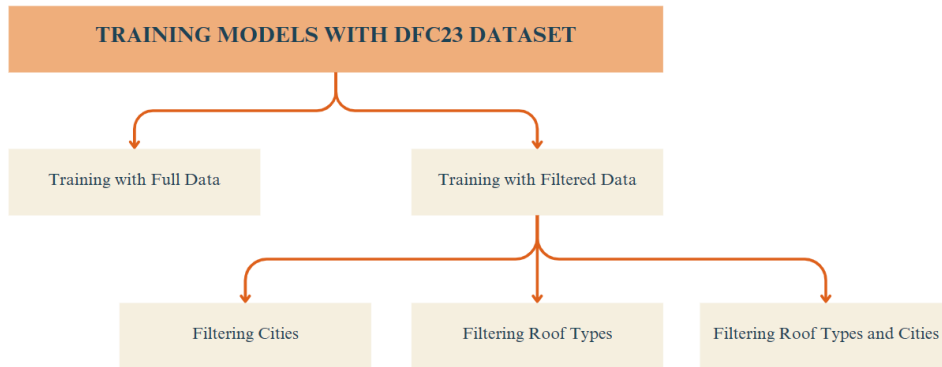


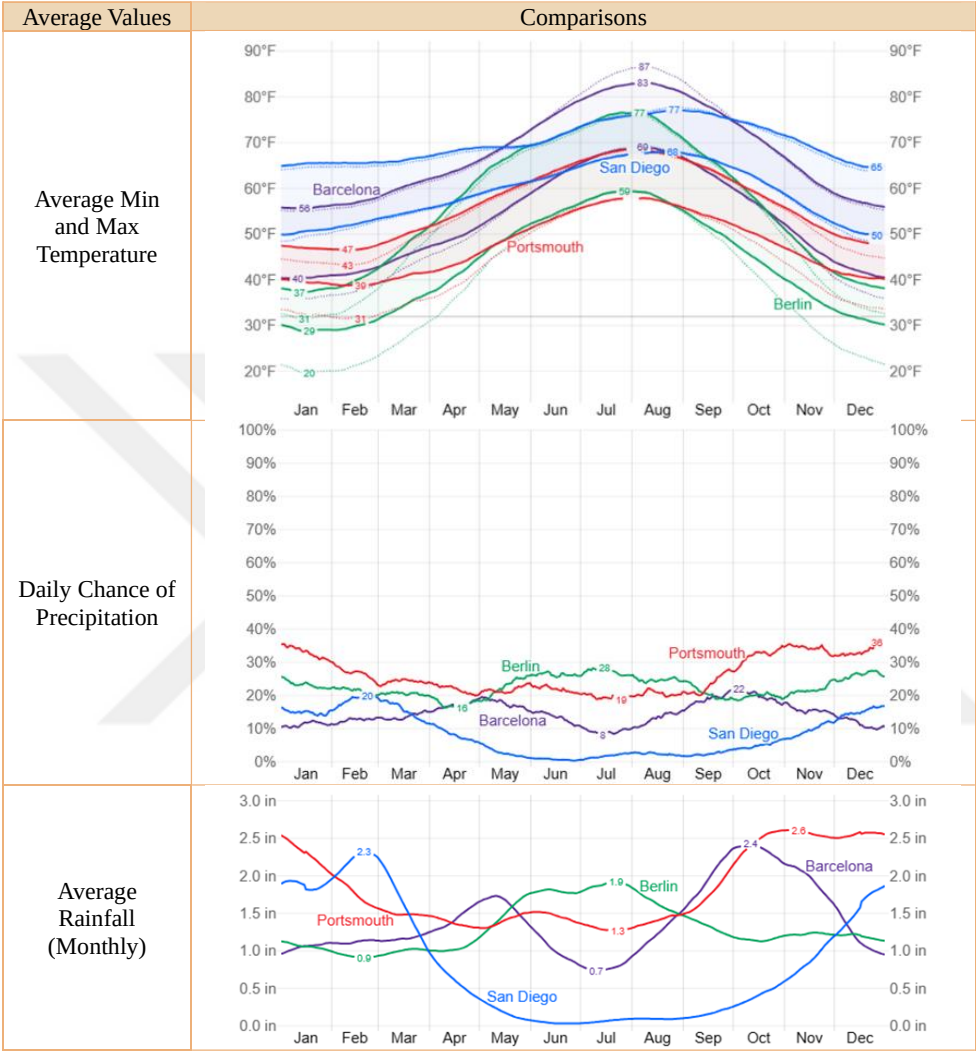
Figure 3.4 Training Strategies (Developed by Author)

Given the significant size of the dataset of 300,000 samples, the aim was to improve the training results through a systematic filtering procedure.

To achieve a variety of results, the dataset went through a rigorous filtering process based on two different parameters. This aims to divide the dataset into subsets, each trained independently, thus facilitating comparative analysis of the results.

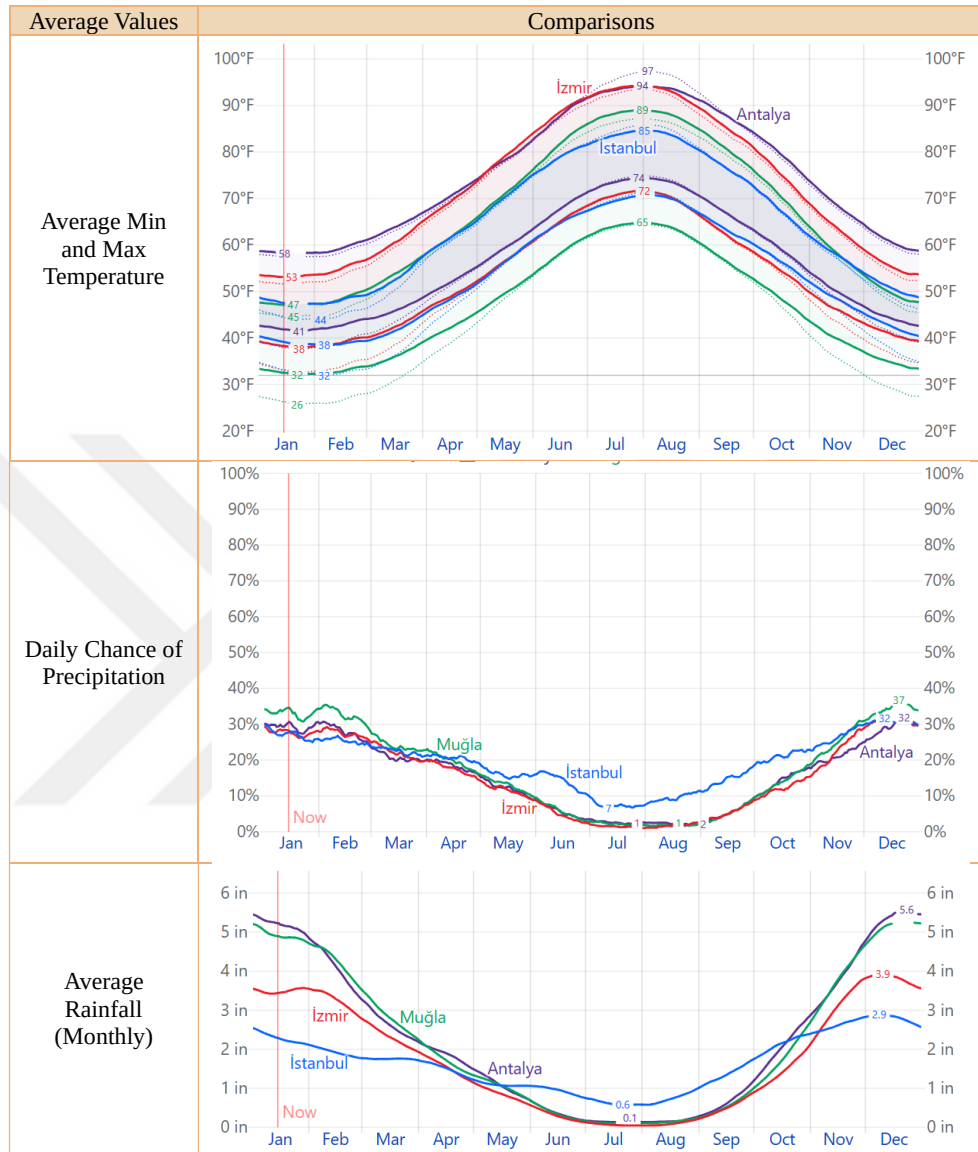
The first filtering criterion focused on selecting regions that exhibit similar climatic conditions. In regions where climatic conditions and average rainfall amounts are similar, roof types are expected to be similar. For this reason, Barcelona, Portsmouth, Berlin, and San Diego, which are included in the dataset and have similar temperature and precipitation values, were selected, and a dataset was created based only on the data of these cities. The relationship between the climates of the selected cities is visually represented in Table 3.1.

Table 3.1 Comparison of Selected Cities in Dataset for Filtering (<https://weatherspark.com/compare>) (Developed by Author)



It is aimed to increase the detection and classification performance of roofs in cities with similar climatic conditions in different locations taken from Google Earth, which will be used in the later testing phase of the selected cities. These locations for Turkey are Izmir, Istanbul, Muğla, and Antalya, as seen in Table 3.2.

Table 3.2 Comparison of Selected Cities in Turkey
(<https://weatherspark.com/compare>) (Developed by Author)



Then, the second criterion for dataset filtering revolved around the selection of three completely different roof types: flat, gable, and hipped roof. The reason behind this selection was the prevalence of these roof types in Turkey. The main purpose of this filtering step is to evaluate the effectiveness of the model in local contexts and to measure its adaptability to dominant architectural features.

Finally, a new model was trained with a new filtering to evaluate both the specified cities and the specified roof types together.

By using these three different filtering strategies, the performance of the model and its suitability for specific regional conditions were increased. The results obtained from these filtered datasets were then compared in terms of the adaptability and effectiveness of the model in various scenarios.

3.1.4 Testing Phase

After the models were trained, new strategies were determined for the testing phase. As seen in Figure 3.5, these strategies include a comparison of the images in the dataset and images taken from Google Earth and comparisons made with different strategies to test the model for different locations.

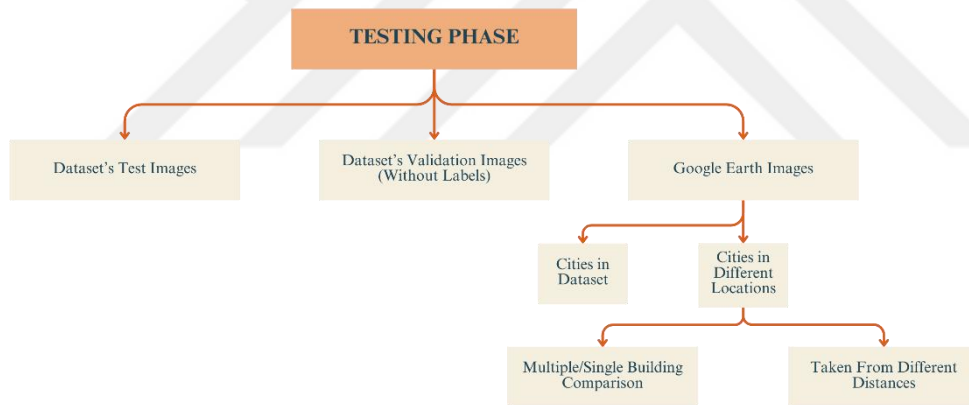


Figure 3.5 Testing Phase Strategies (Developed by Author)

At this stage, although the images in the dataset are satellite photographs, since the images used to test the models, other than those in the dataset, will be images taken from Google Earth, images taken from different distances and with different numbers of buildings/roofs in the same image were preferred. The results of the study are described in detail in the following sections.

3.2 Machine Learning Task-2

Thanks to the model trained with the DFC23 dataset with Machine Learning Task-1, it is possible to detect and classify roofs in any location. However, although there is data for the images in the dataset, the necessary data (projected area and side lengths) to find the potential RWH amount for different roof types in the images taken from Google Earth cannot be calculated. Therefore, the necessary data for calculations were obtained by using a new machine-learning model. To perform Machine Learning Task-2, the steps in Figure 3.6 were applied respectively.

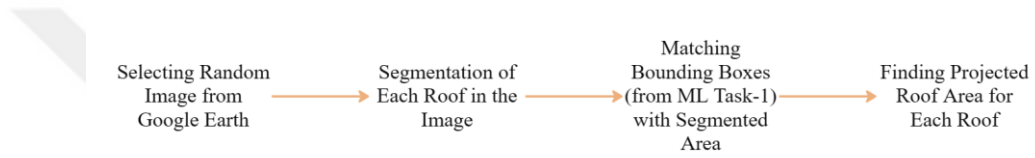


Figure 3.6 ML Task-2 Process (Developed by Author)

A pre-trained model was used for the second machine-learning task. This model aims to segment roofs in an image given as input. Thus, the roof areas that could not be calculated in the first machine-learning task were calculated. After each roof was divided into segments, the bounding boxes obtained by the first machine-learning task were matched with the segments; thus, the roof area was calculated. Since this task aims to calculate the projected area of the roofs in any location, photos taken from Google Earth of randomly selected areas for Ankara, Bursa, Aydın, Mersin, Trabzon, Diyarbakır, and Erzurum were used as input images.

After selecting random images from Google Earth, the segmentation of roofs was aimed at the ML task-2 model, which was developed to calculate the projected area of each roof. Thus, by obtaining the mask of the roofs in the image, the areas detected as roofs were separated from the areas without roofs. Then, the roofs that were detected and classified in ML Task-1 were matched with their masks obtained after segmentation. Thus, the roof areas within each bounding box were obtained. As a

last step of ML Task-2, the corner points of the determined roof areas were determined from the segmentation map. Then, to find the edge lengths of the roofs, the image resolution was multiplied by the length between two corner points.

3.3 Rooftop Rainwater Collection

As mentioned in the previous parts of the study, many different techniques are used for water harvesting. However, within the scope of this study, the focus is on collecting rainwater from the roof surface. Since the roof generally is the first surface area of a building exposed to rain, the types of roofs and materials used to collect rainwater have great importance in addition to factors such as the location and climate of the building and the frequency and amount of the rain. When the literature and recent applications are examined, roof types are broadly defined and classified in different ways. Roof types are generally divided into two groups in different sources: flat roofs and pitched/sloping roofs. Flat roofs are defined as roofs with a slope of less than 10° (Wilkinson & Dixon, 2016). Flat roofs are renowned for being relatively easy to install for rainwater collection systems. Their vast horizontal surface area makes rainwater collection effective. Although the classification of roofs is made according to the materials used, flat roofs can be grouped as cold roofs, warm roofs, inverted roofs, walk-on roofs, green roofs, deck-type or industrial roofs, flooded roofs, and parking roofs (Younesi et al., 2013). Flat roofs, which are more common in high-rise buildings, provide large surfaces to manage rainwater and reduce urban flooding. The factor that determines the type of flat roof often depends on the materials used, the layers, and their location. For instance, a warm roof is a type of roof in which the insulation layer is placed on top of the roof structure on flat roofs, as opposed to a cold roof, which is a type of roof in which the thermal insulation layer is placed just above or between the ceiling joists, that is, everything is above the insulation (Syed Azizul Haq, 2016).

Green roof applications, on the other hand, which have been very popular recently, are a generally type of flat roof that improves urban sustainability and has benefits

in many areas, such as energy, ecosystem, aesthetics, and air and water quality (Mihalakakou et al., 2023). Although green roof is an application mostly seen on flat roofs, retrofit applications can also be made on sloping roofs. On sloping roofs, green roof application can be done at maximum slopes of 32 or 35 degrees. Sloping roofs are frequently equipped with broad, low-maintenance green roofs. On sloping roofs, the number of substrates is increased because rainwater will take in faster (Wilkinson & Dixon, 2016). Studies conducted as a result of combining green roofs and rainwater harvesting applications in different climatic conditions have concluded that great efficiency is achieved in terms of potable water savings (Almeida et al., 2023).

Although flat roofs are preferred because their applications are less costly and easier when looked at on a city scale, it is seen that the use of pitched roofs is common in many parts of the world. In this case, climatic conditions have a great impact. Pitched roofs, which can be grouped under many subheadings, have a great variety in terms of materials used and climatic conditions. All these choices affect rainwater harvesting efficiency.

The selection of materials used in different roof types is determined by factors such as economic factors and climatic conditions, as well as the purpose for which the collected rainwater will be used. For this reason, the materials used on the roof surfaces where rainwater is collected for potable and non-potable purposes also vary. Table 3.3 provides an overall comparison of roof designs and materials used in different climatic conditions.

Table 3.3 Roof Types, Materials, and Climates Relations
(<https://retipster.com/roofs/>) (Developed by Author)

Roof Type	Multiple Surface Roofs	Climate	Roof Materials
Hipped		Rainy, Snowy, Icy, Windy	asphalt shingles, standing seam metal, metal tiles, clay or concrete tiles
Pyramid		High windy, Heavy rainy	asphalt shingles, composite shingles, metal shingles, slate, clay or concrete tiles, or wooden shingles or shakes
Gable		Rainy, Snowy, Icy	all types of roofing materials
Mansard		Temperate	copper, zinc
Gambrel		Heavy Snowy, High windy	Wood shingles, asphalt shingles, or slate, metal roofing
Jerkinhead		Rainy, Snowy, Icy, Windy	asphalt or wood shingles, metal shingles, slate, composites
Saltbox		Rainy, Snowy, Icy, Windy	asphalt shingles, metal shingles, wooden or cedar shingles or shakes, slate, or composite shingles
Skillion		Heavy Snow, Rainy	Standing seam metal, PV solar panels
M-Shaped		Heavy Rainy	Asphalt shingles, wood shingles or shakes, metal, and slate
Butterfly		Arid	solid membranes (EPDM rubber, TPO, and PVC), metal roofing, organic materials

Table 3.3 (Continued)

Roof Type	Single Surface Roofs	Climate	Roof Materials
Shed		Moderate	asphalt shingles, wood shingles or shakes, metal, and slate.
Sawtooth		Not snowy/rainy	wood shingles, metal shingles, or reinforced concrete
Dome		All Type	Shingles, metal, glass
Curved		All Type	metal
Barrel Vaulted		Hot and Dry	Clay and Concrete Tile
Conical		Moderate, High Windy	Wood, asphalt shingles, and metal

While materials, with their different chemical properties, significantly affect the retention rate of rainwater in contact with the roof surface, they also affect the roof slopes. The same material can be used for different slopes in different applications.

To summarize, roof types vary in both the amount of rainwater collected and the way they collect rainwater. Although flat roofs are relatively more economical and easier to build, they can be difficult to use in areas with heavy rainfall. However, high-rise buildings such as skyscrapers are becoming important elements of the city in collecting and managing rainwater and providing a large surface area thanks to their flat roofs. When looking at modern high-rise buildings, most studies show that the use of green roofs is quite common, and recent studies in the literature indicate that the efficiency of rainwater collection increases with rainwater harvesting systems integrated into green roofs. Materials in roof types are also important in rainwater collection, both in terms of water quality and the amount of water collected depending on the surface properties of the material. However, when the literature is examined, research on collection mechanisms according to roof types is in the minority, and the number of studies on materials attracts attention. It is thought that research in this field will be very important for developing innovative solutions.

3.3.1 Calculations for Different Conditions

After the general examination of roof types, the differences in rainwater harvesting systems and their components between different roof types, which form the basis of this research, are examined. Rainwater collection methods vary depending on roof types. On flat roofs, rainwater is collected through numerous rainwater downpipes. In order to direct the rainwater collected on the roof surface to the inlets, another material is covered on the roof surface, and a low slope is given towards the inlets. Multiple entrances require more than one inclined surface, as seen in Figure 3.7.

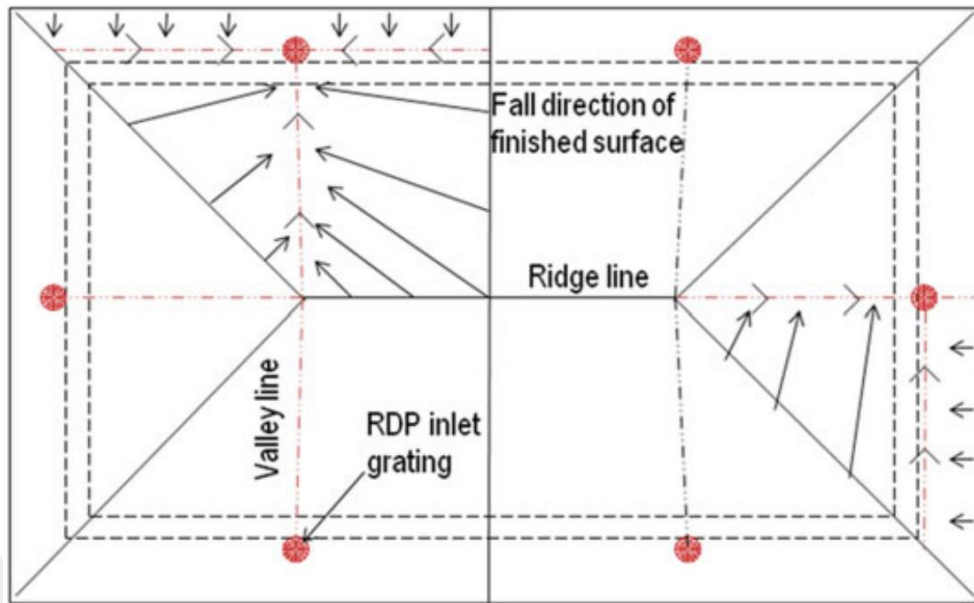


Figure 3.7 Rainwater inlets placement on a flat roof (Syed Azizul Haq, 2016)

The methods of collecting rainwater from different types of roofs also vary. Gutters are built under the sloping surfaces of pitched roofs. The required amount of rainwater inlets is calculated and placed. By creating a gutter section specifically for a particular inlet and installing it at the appropriate slope so that rainwater falls towards the inlet, the flow direction of rainwater in the gutter can be directed towards any inlet (Syed Azizul Haq, 2016).

The quantity of rainwater runoff depends on rainfall intensity, effective catchment area, and runoff coefficient. According to EN 12056-3, the calculation of the quantity of rainwater runoff is seen in Figure 3.8.

$$Q = r \times A \times C$$

Q represents the water flow rate, measured in liters per second (l/s).

r stands for rainfall intensity, measured in liters per second per square meter [$l/(s \times m^2)$].

A denotes the effective roof area, measured in square meters (m^2).

C is the runoff coefficient which is a dimensionless quantity.

Figure 3.8 Formula of Quantity of Rainwater Runoff

When calculating the quantity of rainwater runoff, the r value represents rainfall intensity, and its unit is $l/(s \times m^2)$. However, when the studies in the literature are examined, rainwater harvesting potential calculations are based on the average annual rainfall (mm) (Farreny et al., 2011; Hari et al., 2018; Mishra et al., 2020). Since rainwater harvesting potential will be calculated within the scope of this study, the r -value in mm is included in the calculations. Annual rainfall amounts were obtained by collecting historical weather data over a 15-year period. For this, the historical weather application "Open-meteo" was used.

One of the most important parts is the calculation of effective catchment area (A), and it is calculated in different ways for different types of roofs. For a flat roof, the calculation of the effective catchment area is given below (Syed Azizul Haq, 2016, p.84):

$$\text{Effective Catchment Area} = \text{Horizontal Plan Area} + 0.5 \times \text{Area of One Adjoining Vertical Wall}$$

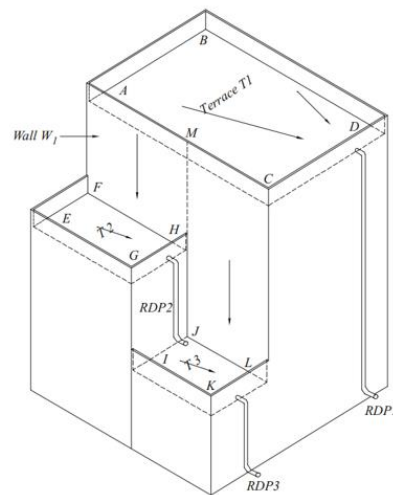


Figure 3.9 Example of Catchments of Flat-Roof Surfaces (Syed Azizul Haq, 2016)

For example, according to Figure 3.9,

$$\text{ECA for RDP2} = \text{Area of (EFGH)} + 0.5 \times \text{Area of (AFHM)},$$

$$\text{ECA for RDP3} = \text{Plan Area of Terraces at Level 2 and Level 3} + 0.5 \times (\text{Area of (AFHM)} + \text{Area of (MJLC)})$$

The area of the adjacent wall is also a factor affecting the catchment area on pitched roofs. An example of calculating the catchment area for a sloped surface is given in Figure 3.10. (Haq, 2016):

$$\begin{aligned}
 \text{Area} &= \text{roof plan } ABC'D' + \frac{1}{2} \text{ beveled surface } CDC'D' + \frac{1}{2} \text{ side wall } ADE \\
 A &= (25 \times 10) + (5 \times 25)/2 + (10 \times 5)/2 \\
 &= 250 + 62.50 + 12.50 \\
 &= 325 \text{ m}^2
 \end{aligned}$$

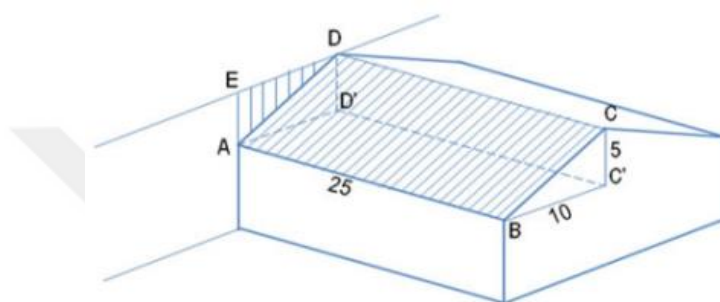


Figure 3.10 An example of Calculation Catchment Area (Syed Azizul Haq, 2016)

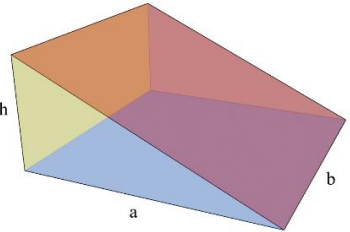
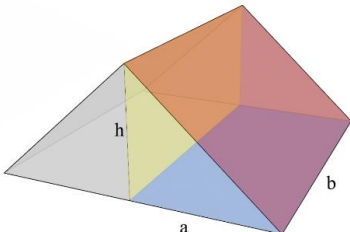
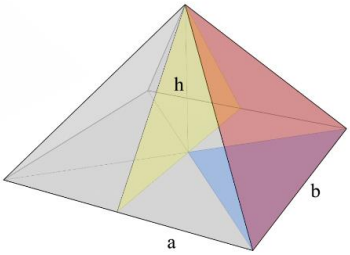
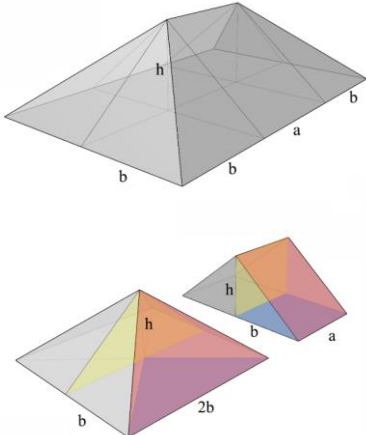
When TS EN 12056-3 standards and the sample calculations given above are examined, the effective catchment area for different roof pitches is calculated, as seen in Table 3.4.

Table 3.4 Calculation of Effective Catchment Area (The Building Regulations Document H, 2015)

Surface	Effective Catchment Area
Flat Roof	Plan area of the relevant portion
Pitched Roof at 30°	Plan area of portion x 1.29
Pitched Roof at 45°	Plan area of portion x 1.50
Pitched Roof at 60°	Plan area of portion x 1.87
Pitched Roof over 70° or any vertical wall	Elevational area x 0.5

These values seem to be valid for gable and shed roof. However, there is no calculation for a pyramid and a hipped roof. Therefore, effective water catchment areas (ECA) for different roof types have been calculated, as shown in Table 3.5. In these calculations, it is assumed that the slope of the adjacent surfaces for the hipped roof is the same.

Table 3.5 Calculations for Different Common Roof Types (Developed by Author)

Roof Type	Representative Image of The Roof	Effective Catchment Area
Shed		$(a \times b) + \frac{b \times h}{2}$
Gable		$2(a \times b) + (b \times h)$
Pyramid		$(b \times 2a) + \frac{(b \times h)}{2} + (a \times h)$
Hipped		$4b^2 + 2(b \times h) + 2(a \times b) + (a \times h)$

The covering material of the roof also greatly affects the amount of water that can be collected from the roof surface. Runoff coefficient (C) has different values for different materials. When the literature was examined, it was seen that the runoff coefficient values of roofing materials varied in different studies. These values also vary depending on whether the surface is flat or curved. In Table 3.6, runoff coefficient values are given for flat surfaces.

Table 3.6 Runoff Coefficient Values for Flat Surfaces (Syed Azizul Haq, 2016) (Developed by Author)

Material	Value	Reference
GI sheets, metals, glass, slate	0.9-1.0	Grundfos (2015)
Glazed tiles	0.6-0.9	Worm and Hattum (2006)
Clay tiles (handmade)	0.24-0.31	Zhu and Liu (1998)
Clay tiles (machine-made)	0.3-0.39	Zhu and Liu (1998)
Cement tile	0.62-0.69	Zhu and Liu (1998)
Aluminum sheets	0.8-0.9	Worm and Hattum (2006)
Flat cement roof	0.6-0.7	Worm and Hattum (2006)
Bituminous	0.7	Ward et al. (2010)
Corrugated Iron	0.8-0.85	Zhu and Liu (1998)
Thatched	0.2	Worm and Hattum (2006)
Plastic sheets	0.8-0.9	Khoury-Nolde (2016)
Gravel	0.7	Grundfos (2015)
	0.8-0.85	Lancaster (2006)
Green Roof	0.10-0.50	Haq (2017)

In Table 3.7, runoff coefficient values of different materials for sloped roofs are given.

Table 3.7 Runoff Coefficients of Materials for Sloped Roofs (Özeren Alkan and Hepcan, 2022) (Developed by Author)

Material	Value	Reference
Galvanized Sheets	0.90-0.95	Biswas and Mandal (2014)
	0.9	Dadhich and Mathur (2016)
Asphalt	0.9	Lancaster (2006)
Aluminum	0.7	Ward et al. (2010)
Tile	0.80-0.90	Biswas and Mandal (2014)
	0.75	Dadhich and Mathur (2016)
Concrete	0.70	Temizkan and Tuna Kayılı (2021)
	0.95	Hari et al. (2018)
Brick	0.50-0.60	Biswas and Mandal (2014)
	0.75	Temizkan and Tuna Kayılı (2021)
Corrugated Metal Sheet	0.70-0.90	Biswas and Mandal (2014)
PVC	0.98	Hari et al. (2018)
Soil	0.00-0.30	Biswas and Mandal (2014)
Bituminous	0.70	Ward et al. (2010)
Level Cement	0.81	Liaw and Tsai (2004)
Gravel	0.80-0.85	Lancaster (2006)
Asbestos	0.85	Hari et al. (2018)
	0.60-0.80	Biswas and Mandal (2014)
	0.8	Dadhich and Mathur (2016)

When the studies in the literature are examined, it has been seen that different roof materials can be applied at various slopes and that the selection of materials is affected by many different factors, such as the climatic conditions of the region, economic factors, and that there are no definitive acceptances other than general principles for certain roof slopes. The materials selected for the calculations made within the scope of this study were galvanized sheet, asphalt, aluminum, tile, concrete, corrugated metal, and bituminous for pitched roofs and metal, gravel, concrete, and green roofs for flat roofs. Calculations have been made for each of the minimum and maximum values determined in the literature for material runoff values.



CHAPTER 4

CASE STUDIES

After explaining the approaches on how to solve the research problem, this chapter includes the implementation of all stages listed in the methodology.

As stated in the methodology, first, the performances of the YOLOv8 model trained using the entire data in the DFC23 dataset, the YOLOv8 model trained with new filtered datasets, and the models created by transfer learning from the pre-trained YOLOv8 model using the COCO dataset were evaluated. Then, each of the created models was tested for different scenarios with selected input images, depending on different resolutions of the same location, depending on the number of buildings in an image of the same location, and depending on the source from which the image was taken (Google Earth and satellite photos in the dataset). According to the test results, Machine Learning Task-2 was carried out with the model that showed the best performance in detecting and classifying roofs. With ML Task-2, the areas and side lengths of the roofs were found, and then the potential amounts of rain that could be collected under different conditions were compared using them in the calculations recommended for each roof type.

4.1 Machine Learning Implementations

As explained in the methodology, a total of 6 different models were trained. These models were:

1. Trained with transfer learning from pre-trained COCO dataset,
2. Trained with transfer learning from pre-trained Massachusetts Buildings Dataset,
3. Trained from scratch using all data in the DFC23 dataset,

4. Trained with the new dataset created by filtering the roof types,
5. Trained with the dataset obtained by filtering the cities and
6. Trained with the dataset filtered by only selected cities and roof types.

In training YOLOv8 models, resizing, color alteration, rotation, translation, changing perspective, flipping horizontally, and flipping vertically methods were applied for data augmentation. The purposes of each method are listed below:

- Resizing: It is aimed to develop a robust model for roof types of different sizes.
- Color Alteration: It is aimed to develop a robust model for roof materials of different colors.
- Rotation, Translation, and Flipping: Since the buildings in the built environment are not placed in a single way (in different rotations), it was aimed to develop a more robust model for the detection of roofs.
- Changing Perspective: Since aerial photographs are photographs taken from different perspectives, it is aimed to develop a more robust model for the images taken from Google Earth in the later stages of the study.

It is aimed to increase the performance of the models by increasing the number of images with data augmentation. Augmented data is shown in Figure 4.1. The city names seen in Figure 4.1 do not have any importance during the data augmentation stage. These cities only consist of randomly selected cities as examples for data augmentation.

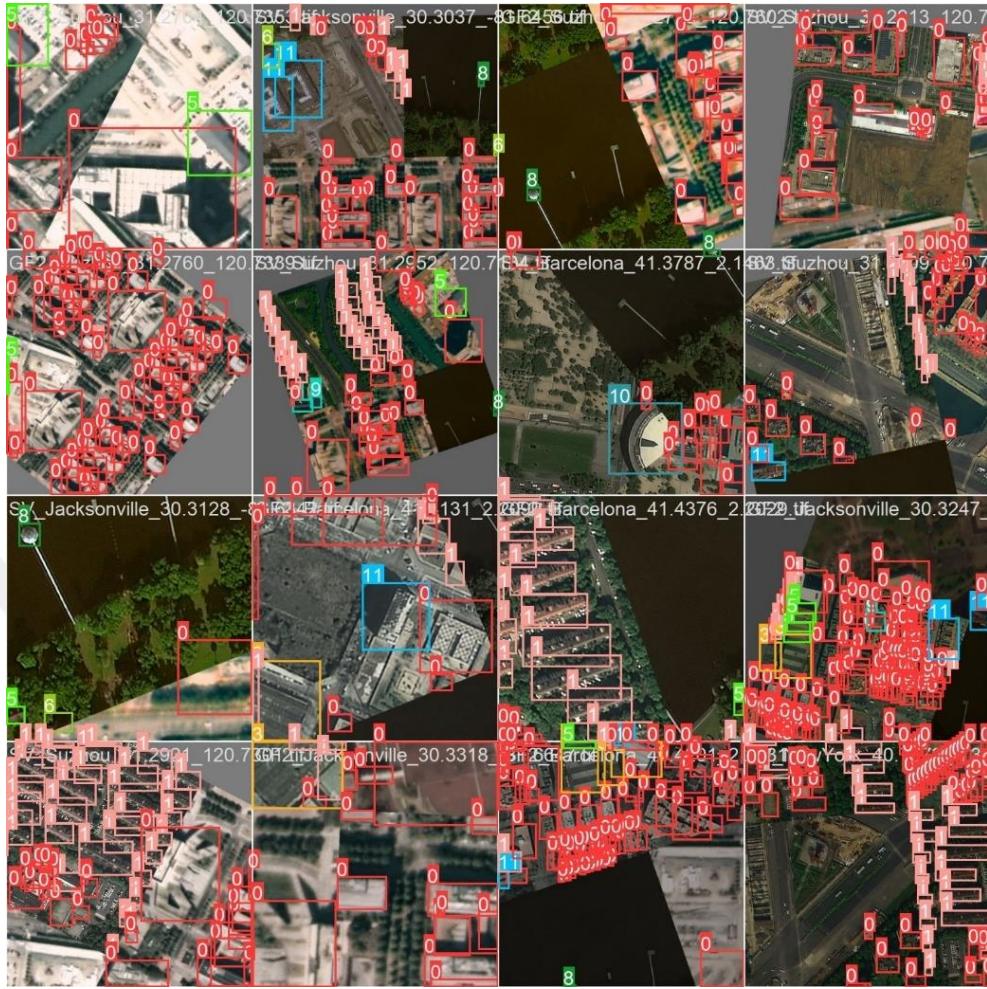
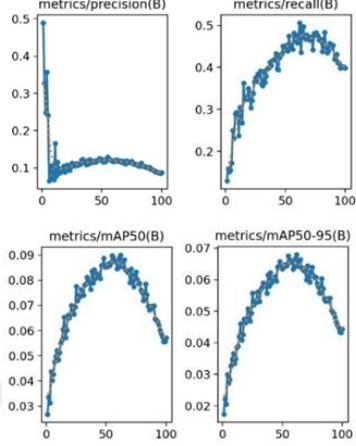
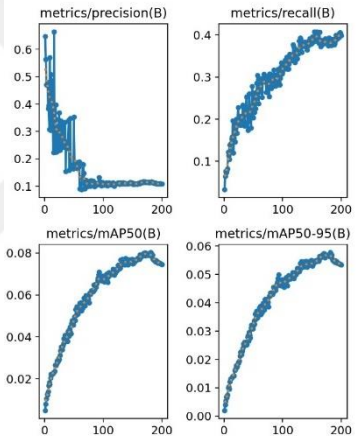
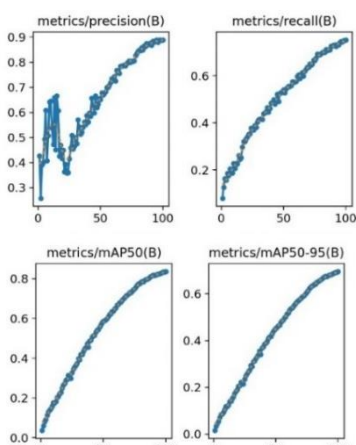


Figure 4.1 Augmented Data (Developed by Author)

The DFC23 dataset is divided into 80% for training and 20% for testing. The choices made for this process are random, and no strategy has been developed. Thus, it is aimed that the trained model does not show any bias towards data distribution.

First, tests were carried out on the trained model without any filtering on the dataset. The second training model is the model that is trained by taking only the data of the cities mentioned above and whose climate characteristics are given. When training the third model, data from only three different roof types (flat, gable, and hipped) were used, regardless of the cities. The final model was trained by filtering both cities and roof types. The results of all training models are given in Table 4.1.

Table 4.1 Comparison of Different YOLOv8 Models (1) (Developed by Author)

Model	Performance	Explanation
YOLOv8 Model, which is trained with Transfer Learning from pre-trained COCO dataset		Compared to the YOLOv8 model trained from scratch, a very low performance was observed in detecting and classifying the roofs in the input images tested with this model (0.09). In this performance, using objects from many different classes in the COCO dataset as data in training the model is effective. Although the COCO dataset is one of the most used datasets for object detection, it was not used in the later stages of the study because it was only aimed to detect and classify roofs within the scope of this study, and its performance was quite low.
YOLOv8 Model, which is Trained with Transfer Learning from pre-trained Massachusetts Buildings Dataset		This model, which has the lowest precision, recall, and mAP score (0.06) values compared to other models, was not used in the next stages as a result of the findings obtained after testing with the DFC23 dataset. The reason why its performance is so low can be interpreted as the fact that although it has the same type of data (aerial images) as the DFC23 dataset, its characteristics such as resolution and color are different.
YOLOv8 Model trained from scratch with the DFC23 dataset.		As clearly seen in the recall, precision, and mAP score metrics, the performance of this model is quite high (0.9) compared to others. The high performance of this shows that a large part of the roofs in the given input images were detected and classified correctly. For this reason, this model was used in subsequent interpretations within the scope of this study.

While evaluating the performance of roof detection models, the values of precision, recall, and mAP metrics were examined. In order to interpret Precision, Recall, and mAP score values, it is necessary to explain what they mean within a classification model. In a classification model, these measurements are obtained by comparing two sets of values, which are actual values and predicted values. This comparison is shown in Table 4.2.

Table 4.2 Comparison of Predicted and Actual Values (Adapted from Visa et al., 2011)

	Predicted Negative	Predicted Positive
Actual Negative	Number of correct negative predictions (a)	Number of incorrect positive predictions (b)
Actual Positive	Number of incorrect negative predictions (c)	Number of correct positive predictions (d)

In this comparison, the explanations of the values expressed as a, b, c, and d are as follows:

a = True Negative (TN); the number of predicted values as negative that are actually negative,

b = False Positive (FP); the number of predicted values as positive that are actually negative,

c = False Negative (FN); the number of predicted values as negative that are actually positive,

d = True Positive (TP); the number of predicted values as positive that are actually positive.

According to these explanations, accuracy, error, precision, and recall are expressed as seen in Figure 4.2:

$$precision = \frac{TP}{TP + FP}$$

$$recall = \frac{TP}{TP + FN}$$

Figure 4.2 Expression of Metrics Used for Evaluation of Results (Vanderbeck et al., 2011)

While precision measures how much of the predicted results are correct, recall expresses how much of the actually correct results can be predicted. mAP score expresses the average values for each class and is defined as "mean average precision". The AP metric is a graph showing the relationship of precision-recall values at different thresholds. The reason why the AP metric is also defined as the mAP score is that in object detection models, each of the AP values belonging to different categories is calculated separately, and their average values are taken (Terven et al., 2023).

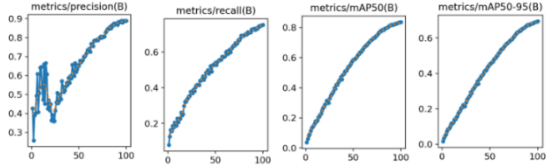
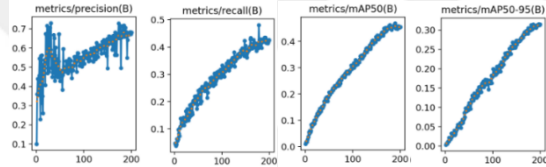
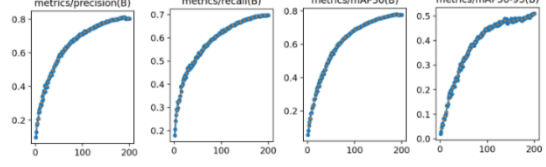
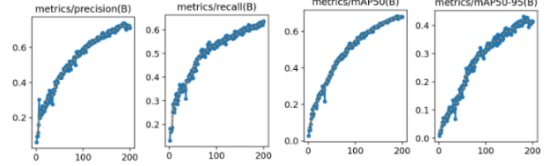
After evaluating the explained metrics for different models, it is seen that the mAP score in the model using the COCO dataset, and Massachusetts Buildings Dataset have very low values (0.09, and 0.06, respectively) compared to the YOLOv8 model trained from scratch with the DFC23 dataset. Additionally, the decrease in the mAP score metric is noteworthy. This decrease shows that the model stops learning after a while and memorizes the data. Likewise, a similar situation occurs when precision and recall values are compared. For this reason, a YOLOv8 model trained from scratch was used in all models to be trained with new datasets created by filtering the DFC23 dataset.

For the initial training phase, the model is trained on the roof dataset. The training is conducted for a set number of epochs, where each epoch represents a complete iteration through the entire training dataset. The model is trained in batches (e.g., batch size of 4), allowing for efficient optimization of the model parameters. Additionally, a specific image size (e.g., 640 pixels) is used during the training process.

In this study, all models were trained for 200 epochs, with each iteration containing a set of 4 examples. In the continuation of the study, the epoch and batch size are the same in other models trained using different filtering methods. A comparison of other YOLOv8 models were given in Table 4.3.



Table 4.3 Comparison of Different YOLOv8 Models (2) (Developed by Author)

Models	Performance	Explanation
Trained with Entire Data		This model has a higher performance than other models for recall, precision, and mAP values at different thresholds (between 0.5 and 0.95). Thus, it can be commented that there are fewer incorrect predictions in roof detection and classification. Especially a high mAP score is the most important factor in finding and correctly classifying bounding boxes for each roof.
Trained with Data Filtered by Cities		In this model, which shows a lower performance for all metrics compared to the model trained with the Entire dataset, the detection and classification of roofs has a relatively lower accuracy. This is because the dataset is narrowed down to only the four previously mentioned cities. Although the dataset is narrowed down, since there are 12 roof types expected to be predicted, it appears that this model cannot learn every roof type.
Trained with Data Filtered by Roofs		In this model, which shows the best performance after the model trained using the entire data set, a good performance is observed despite the narrowing of the data set, as the number of roofs expected to be predicted is reduced.
Trained with Data Filtered by Roofs and Cities		Although the performance of the model trained with a narrowed dataset in which both roof types and cities were filtered gave higher results than the performance of the model trained by filtering only cities, it has very low performance compared to other models.

When Table 4.3 is examined, it is seen that the models trained with filtered datasets show a lower performance compared to the model using the entire dataset. The reason for this can be interpreted as the lack of sufficient diversity in the filtered datasets. The results of different tests performed with these models are compared and interpreted in detail.

Qualitative analysis was performed with selected images for each model trained during the testing phase. As mentioned before, in these tests, the images in the dataset included photographs of the cities in the dataset and the cities in different climate zones in Turkey at different resolutions taken from Google Earth. Tables 4.4 and 4.5 contain qualitative analyses of the test results compared in different tasks. In Table 4.4, the comparison of tests was carried out for different models with the images in the dataset, images taken from Google Earth for the cities where the selected images are located, and Google Earth images taken from the locations (Turkey) where the cities not included in the dataset are shown. In Table 4.5, the outputs resulting from testing the photos taken from Google Earth at different resolutions with the models are given. The resolution values of the high-resolution image and the low-resolution image are 0.3 meter/pixel and 1 meter/pixel, respectively.

Table 4.4 Comparison of Different Tasks with Different Models (1) (Developed by Author)

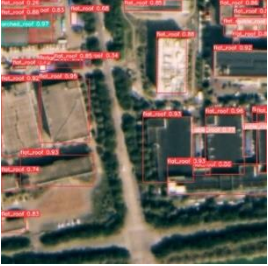
	Dataset's Test Images	Google Earth Images (From Cities in Dataset)	Google Earth Images from Turkey
Trained with Entire Dataset			
Trained with Dataset Filtered by Cities			
Trained with Dataset Filtered by Roof Types			
Trained with Dataset Filtered by Cities and Roof			

Table 4.5 Comparison of Different Tasks with Different Models (2) (Developed by Author)

	High Resolution	Low Resolution
Trained with Entire Dataset		
Trained with Dataset Filtered by Cities		
Trained with Dataset Filtered by Roof Types		
Trained with Dataset Filtered by Cities and Roof Types		

When the images in the dataset were evaluated, it was seen that more accurate predictions were made in terms of the detection and classification of roofs. In addition, considering that roof types vary depending on location, relatively superior performance can be mentioned when comparing Google Earth images taken from cities included in the dataset with images taken from Turkey, although they are not included in the dataset. Additionally, when images taken from different resolutions were evaluated, superior performance was observed in Google Earth images with resolutions close to the resolutions of the satellite images used in the preparation of the dataset. Based on this, the detection and classification performances of the models increase for features similar to the features of the images selected while preparing the dataset. These features can be evaluated within the scope of this study as roof type, material colors, roof dimensions, and resolution. Therefore, it can be expected that the results of a detection and classification task for residential buildings will not be the same for larger-scale structures. Although data augmentation aims to make the models robust, lower classification and detection performance is predicted because features such as color and perspective in the photographs taken from Google Earth are not the same as the satellite photographs used in the preparation of the dataset. Although the accuracy values of Google Earth images are open to discussion, the ability to make predictions for any location can be considered as a step to be taken in the built environment to improve rainwater collection from rooftops.

Based on the results of tests with different models, the YOLOv8 model, which used the entire dataset and was trained from scratch, became the preferred model for the continuation of the study. In the next stage, Machine Learning Task-2 was developed to calculate the projected roof area, which cannot be calculated using the dataset. For this task, a pre-trained model was used. Although there is no information about the performance of the model, it was carried out with the ML Task-2 pre-trained model because it showed a high performance compared to the projected roof area values given for certain coordinates in the dataset.

In the following section, the results will be examined through tests conducted with Google Earth images taken from different cities in Turkey. Since it was aimed to make calculations for locations belonging to different climate types, images taken from 7 randomly selected cities from different geographical regions of Turkey were evaluated. These cities are Ankara, Bursa, Aydın, Trabzon, Erzurum, Mersin, and Diyarbakır, respectively. In studies that include both tests of machine learning models and applications for calculating the amount of rainwater, all stages for the Google Earth image taken from Ankara will be discussed in detail, and in subsequent case studies, the results and interpretations of the processes performed in the same way will be included. Four tables were created for each case study. In the first table, the outputs of the machine learning tasks are evaluated. In the second table, calculations are made for the current conditions which are assumed as 30% slope and “tile” material for pitched roofs and “concrete” material for flat roofs. In the third table, potential RWH amounts calculated according to minimum, average and maximum annual rainfall, different roof materials (based on maximum C values), and 30% and 40% slope are included. In the last table, different scenarios in which roof types, slope, and roof materials change are evaluated for the potential amount of rain that can be collected in line with the suggested calculations. Since the most common roofs within the scope of this study are considered flat, hipped, pyramid, and gable, only the projected area was used in the effective catchment area, and potential RWH calculations for the different roof types in the input images and the slope degrees for these roofs were not taken into account. In each case study, the presence of different numbers of buildings located in different ways was taken into account. Thus, it was aimed to compare both the amount of rainwater that can be collected and the performance of machine learning tasks. As the last case study, a building was selected which has known values for roof dimension, roof material and roof type. Thus, comparisons were made for different situations and maximum gains and losses were calculated.

4.2 Case Study-1: Ankara

In the first case study, to test the machine learning models, a Google Earth image taken from Ankara was used as an input image, as seen in Figure 4.3. The resolution of the image used is 0.3 meters per pixel.



Figure 4.3 Input Image Taken from Google Earth, Ankara (Developed by Author)

The input image was first tested with the first machine learning task, and the roof types and bounding boxes were determined, as seen in Figure 4.4.



Figure 4.4 Output Image of Machine Learning Task-1 (Developed by Author)

When the outputs of ML Task-1 are examined, it is seen that most of the roofs are detected and classified correctly. However, the classifications for some roof types

are not correct. When the image obtained by merging both tasks is examined, it is seen that 45 roofs were detected, and 11 roofs were not.

Various roof types are seen in the input image taken from Ankara. Hipped roofs have the largest share, with 66.7%, as seen in Figure 4.5.

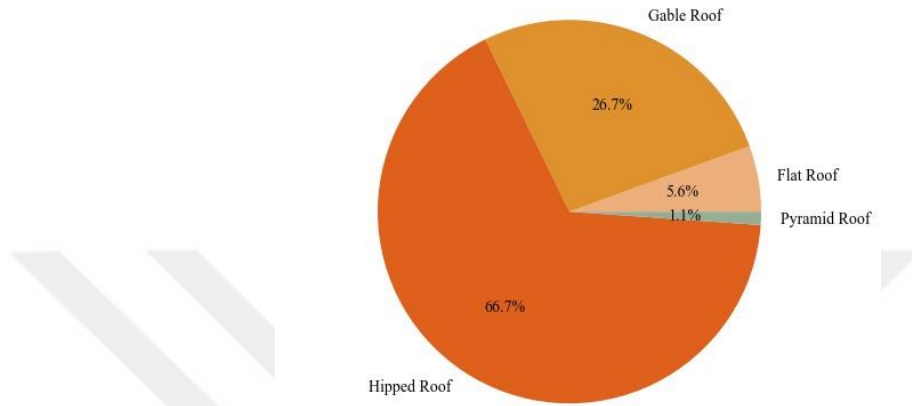


Figure 4.5 Roof Types in Ankara Case Study (Developed by Author)

Following ML Task-1, in which the roofs were detected and classified, the same input image was used to perform ML Task-2, in which the projected areas and edge lengths of the roofs were estimated. The output of ML Task-2 is shown in Figure 4.6.

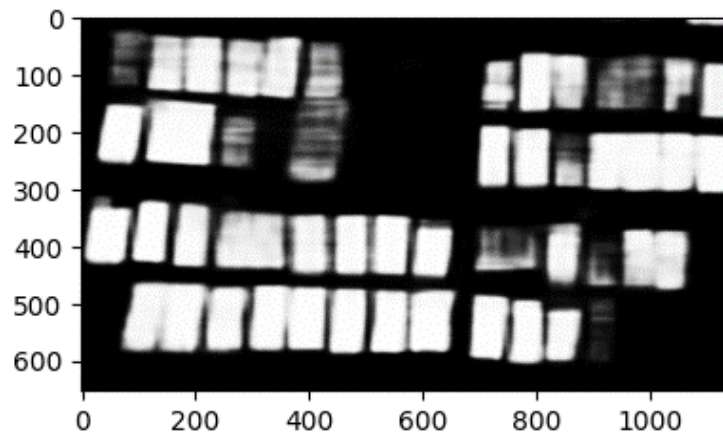


Figure 4.6 Binary Values of the Roof Areas (Developed by Author)

The output seen in Figure 4.6 are the binary value of the roof areas thresholded with a value of 0.5 (which takes values of 0 or 1, and the estimated value for each pixel whether it contains a roof area. ML Task-1 outputs and ML Task-2 outputs need to be matched to calculate the potential RWH amounts of the projected areas and detected roof areas of each roof in the next steps (see Figure 4.7).

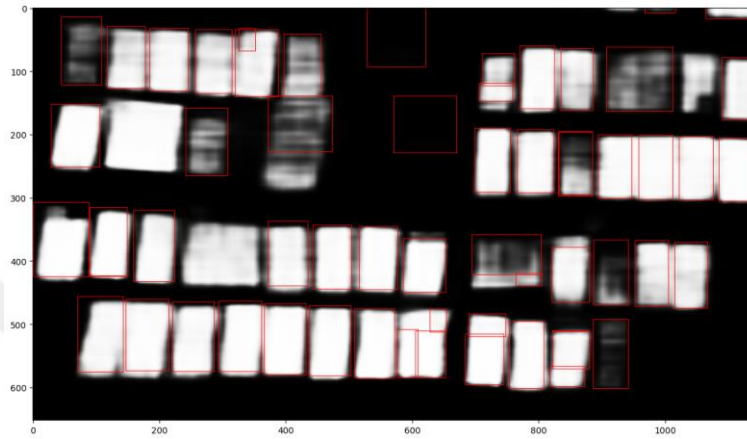


Figure 4.7 Matched Bounding Boxes (Developed by Author)

Thus, both the detection and classification of the roofs in an input image given for any area and the calculation of the projected areas were made. In order to evaluate the qualitative performance in both tasks, the extracted segmentation map and detected roofs were drawn on the input image, as seen in Figure 4.8. Thus, a convenience is provided for qualitative analysis.



Figure 4.8 Qualitative Analysis of Merged ML Tasks (Developed by Author)

In order to calculate the effective catchment areas recommended for each roof type in the methodology, side lengths must be known. Therefore, at this stage of the study, the distances between the corner points of the regions forming the projected roof areas were calculated by performing the ML Task-2.

Calculated side lengths were converted to meters by multiplying by the resolution value depending on the resolution of the photo. Then, the calculations suggested in the methodology section and the C values (runoff coefficient) of different roof materials were calculated separately for different roof types, and the potential amounts of rain that could be collected under different conditions were calculated and compared.

For the first case study, in which the Google Earth image taken from Ankara was used as input, the next step was to calculate the side lengths and effective catchment area of each roof. Since the resolution of the input image was 0.3, the values were converted to meters, and the recommended ECA (effective catchment area) calculations for each roof type were used. An average angle value was determined for the pitched roofs in the image taken from Ankara. This value was chosen as 30% for Ankara. According to the regulations of Ankara Metropolitan Municipality, since the maximum angle can be 40% in buildings with more than two floors, different roof angles up to a maximum of 40% were used in subsequent calculations. Calculations are shown in Table 4.6 according to the roof IDs seen in Figure 4.9.



Figure 4.9 Roof IDs in Ankara Case Study Input Image (Developed by Author)

Table 4.6 Calculations for Ankara Case Study (Developed by Author)

Roof ID	Roof Type	Side Length (a)	Side Length (b)	Current Effective Catchment Area (for 30% slope)
0	Hipped	16,80	28,80	646,79
1	Hipped	20,10	31,20	860,38
2	Hipped	18,00	29,10	710,86
3	Hipped	15,90	29,10	608,65
4	Gable	19,80	24,90	635,34
5	Gable	24,00	28,50	881,45
6	Hipped	19,50	31,50	833,79
7	Hipped	15,00	22,20	462,90
8	Hipped	15,00	27,30	539,40
9	Hipped	15,90	29,40	613,42
10	Hipped	18,00	28,20	694,66
11	Hipped	19,50	31,80	839,64
12	Hipped	17,70	31,20	733,12
13	Gable	17,40	25,20	565,06
14	Hipped	15,30	29,70	589,56
15	Gable	17,70	23,70	540,59
16	Gable	18,30	32,10	757,01
17	Hipped	14,40	28,80	534,44
18	Gable	22,50	28,80	835,06
19	Hipped	15,90	29,70	618,19
20	Gable	20,10	30,60	792,61
21	Hipped	15,60	28,80	589,78
22	Gable	28,20	10,50	381,58
23	Hipped	16,80	29,10	651,83
24	Hipped	19,50	30,30	810,39
25	Gable	18,60	27,30	654,36
26	Flat	9,60	22,50	216,00
27	Hipped	11,40	7,50	117,98
28	Gable	16,80	25,50	552,07
29	Hipped	20,10	32,70	890,53
30	Flat	7,50	10,20	76,50
31	Gable	17,40	30,30	679,42
32	Gable	25,50	23,10	759,09
33	Hipped	17,70	27,30	664,09
34	Hipped	13,80	13,20	282,76

Table 4.6 (Continued)

35	Gable	13,80	21,90	389,46
36	Hipped	18,30	21,90	594,12
37	Flat	10,50	5,70	59,85
38	Gable	17,10	28,50	628,04
39	Gable	15,00	8,10	156,57
40	Hipped	14,40	27,60	517,16
41	Hipped	17,10	27,60	640,78
42	Gable	17,10	17,40	383,43
43	Gable	15,30	27,90	550,10
44	Gable	15,90	31,50	645,43
45	Hipped	20,10	32,10	878,47
46	Flat	7,50	8,40	63,00
47	Gable	14,40	12,90	239,38
48	Gable	13,80	13,20	234,75
49	Hipped	1,80	0,00	0,00
50	Gable	16,20	9,30	194,15
51	Hipped	17,40	30,00	696,80
52	Gable	16,80	9,60	207,84
53	Hipped	21,60	4,50	125,26
54	Gable	21,90	4,50	127,00
55	Flat	17,10	17,40	297,54

Since the current roof slopes are unknown for this case study, the effective catchment area was also calculated for the same roof types and different slope values, as shown in Figure 4.10

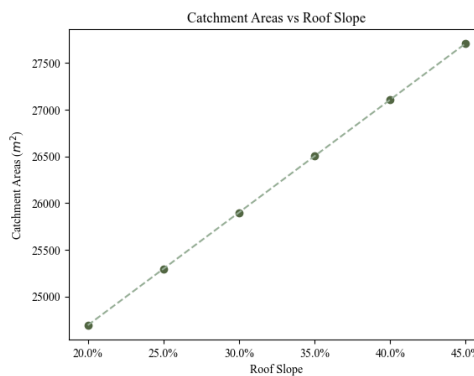


Figure 4.10 Effective Catchment Area Values for Different Roof Slopes in Ankara Case Study (Developed by Author)

After calculating the current effective catchment area, both cases were included in the calculations since the C (runoff coefficient) values varied from a minimum of 0.75 to a maximum of 0.90 to calculate the potential amount of rainwater for the roof material in the current state, which was determined as "tile". Ankara's annual average rainfall was calculated at 372.16 mm, based on a total of 10 years between the years 2010 and 2020. The minimum annual rainfall amount is 265.80 mm, and maximum value is 451.10 mm. Potential rainwater harvesting values are calculated in m³.

In Table 4.7, the potential RWH amount is given in m³ according to the calculations made for 30%, which is accepted as the average slope value, and 40%, which is accepted as the maximum roof slope. For roof materials, which are considered as concrete for flat roofs and tile for pitched roofs, in order to compare the cases where the roof types remained the same but only the roof materials were changed, galvanized sheet for pitched roofs and metal materials for flat roofs with maximum C values were selected.

Table 4.7 Potential RWH Values for Current Roof Types According to the Different Annual Rainfall Values and Roofing Materials for Ankara Case Study-1 (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
Roof Slope	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	6205.06	8688.02	10530.86	6547.35	9169.96	11113.99
40 %	6492.04	9092.5	11020.11	6852.19	9596.90	11631.44
GAIN	286.98	404.48	489.25	304.84	426.94	517.45

As seen in Table 4.7, the amount of rain that can be collected varies depending on the slope, material and rainfall amount. According to the calculations made, the maximum gain that can be obtained for average annual rainfall;

- When the roof slope is kept at the same value and the material is changed, was calculated as 5.54%.
- When the material is kept the same and the roof slope is changed, was calculated as 4.65%.
- When both the roof material and the roof slope changed, was calculated as 10.46%.

These calculations are valid for cases where the roof type remains the same. In Table 4.8, the calculations, gains, and losses for the scenarios where all roof types are replaced are given.

Table 4.8 Potential RWH Values for Different Scenarios for Ankara Case Study-1 (Developed by Author)

POTENTIAL RWH VALUES FOR DIFFERENT SCENARIOS (m ³) with max C Values				
Roof Slope	All Roofs are Flat	All Roofs are Gable	All Roofs are Pyramid	All Roofs are Hipped
%30	8290.4	9057.2	8845	9401.6
%40	8290.4	9451	9168.1	9910.2

According to the calculations, in the scenario which all roofs are hipped with 40% slope, maximum collectable rainwater gain is 508,6 m³.

In the next stage, the C values of different materials and the potential RWH amount were calculated separately for flat and pitched roofs.

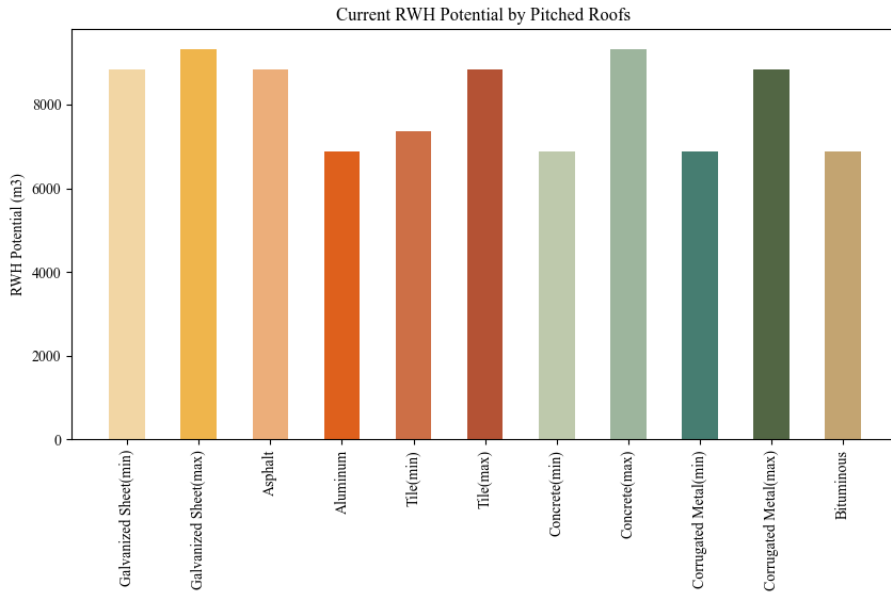


Figure 4.11 Current RWH Potential with Different Roof Materials for Ankara Case Study for Pitched Roofs (Developed by Author)

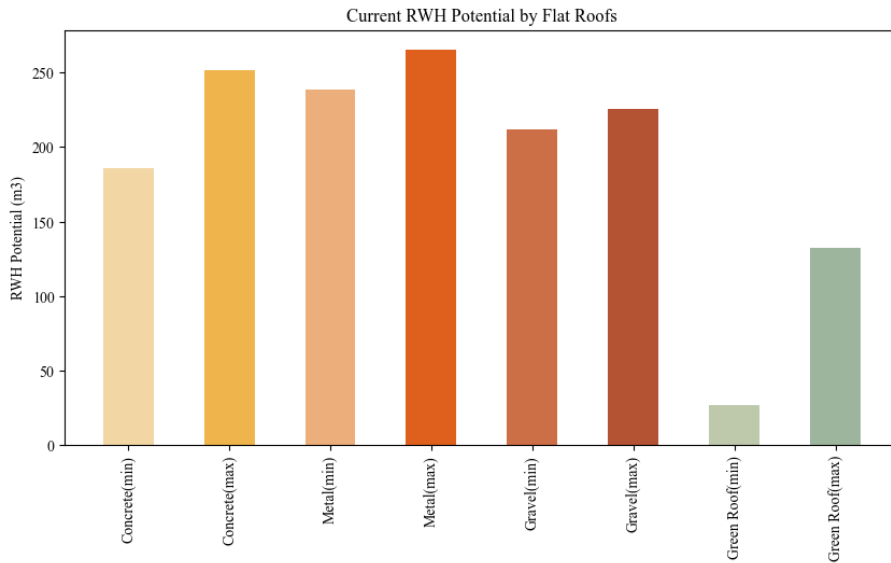


Figure 4.12 Current RWH Potential with Different Roof Materials for Ankara Case Study for Flat Roofs (Developed by Author)

After the calculations for current roof type situations with different roof materials which were given in Figure 4.12, and Figure 4.13, calculations were made for different material types and roof types. Potential RWH values for different scenarios

where all roofs are flat, hipped, pyramid, and gable are shown in details in Figure 4.14 and Table 4.9.

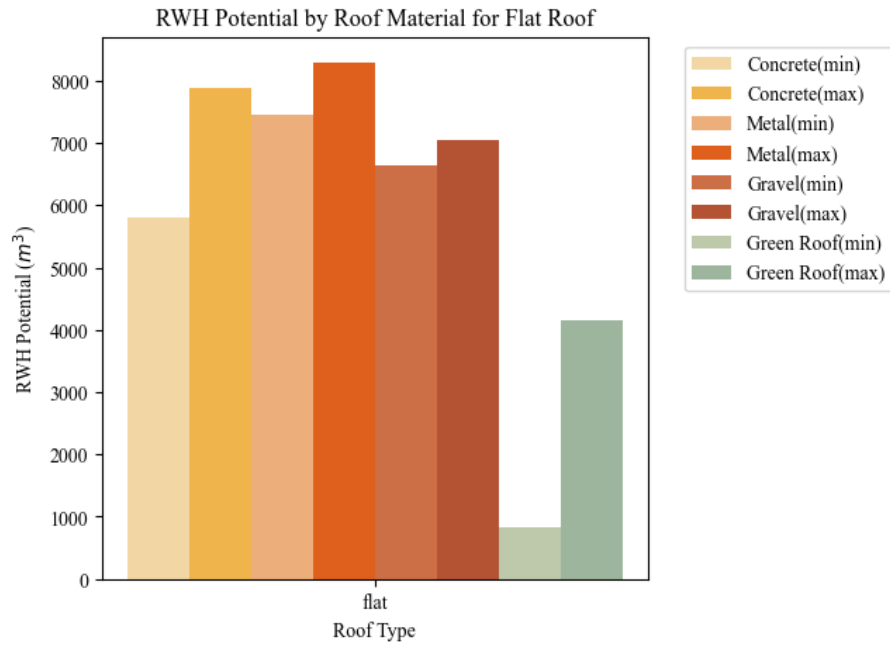


Figure 4.13 RWH Potential for Flat Roof According to the Different Materials for Ankara Case Study (Developed by Author)

Table 4.9 RWH Potential for Different Pitched Roofs According to the Different Materials for Ankara Case Study (Developed by Author)

Roof Types	Potential RWH (m ³)																								
Gable	<table border="1"> <caption>Gable Roof RWH Potential (m³)</caption> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Galvanized Sheet(min)</td><td>8500</td></tr> <tr><td>Galvanized Sheet(max)</td><td>9000</td></tr> <tr><td>Asphalt</td><td>8500</td></tr> <tr><td>Aluminum</td><td>7000</td></tr> <tr><td>Tile(min)</td><td>7500</td></tr> <tr><td>Tile(max)</td><td>8500</td></tr> <tr><td>Concrete(min)</td><td>7000</td></tr> <tr><td>Concrete(max)</td><td>9000</td></tr> <tr><td>Corrugated Metal(min)</td><td>7000</td></tr> <tr><td>Corrugated Metal(max)</td><td>8500</td></tr> <tr><td>Bituminous</td><td>7000</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Galvanized Sheet(min)	8500	Galvanized Sheet(max)	9000	Asphalt	8500	Aluminum	7000	Tile(min)	7500	Tile(max)	8500	Concrete(min)	7000	Concrete(max)	9000	Corrugated Metal(min)	7000	Corrugated Metal(max)	8500	Bituminous	7000
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Bituminous	7000																								
Pyramid	<table border="1"> <caption>Pyramid Roof RWH Potential (m³)</caption> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Galvanized Sheet(min)</td><td>8500</td></tr> <tr><td>Galvanized Sheet(max)</td><td>9000</td></tr> <tr><td>Asphalt</td><td>8500</td></tr> <tr><td>Aluminum</td><td>6500</td></tr> <tr><td>Tile(min)</td><td>7000</td></tr> <tr><td>Tile(max)</td><td>8500</td></tr> <tr><td>Concrete(min)</td><td>6500</td></tr> <tr><td>Concrete(max)</td><td>9000</td></tr> <tr><td>Corrugated Metal(min)</td><td>6500</td></tr> <tr><td>Corrugated Metal(max)</td><td>8500</td></tr> <tr><td>Bituminous</td><td>6500</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Galvanized Sheet(min)	8500	Galvanized Sheet(max)	9000	Asphalt	8500	Aluminum	6500	Tile(min)	7000	Tile(max)	8500	Concrete(min)	6500	Concrete(max)	9000	Corrugated Metal(min)	6500	Corrugated Metal(max)	8500	Bituminous	6500
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Hipped	<table border="1"> <caption>Hipped Roof RWH Potential (m³)</caption> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Galvanized Sheet(min)</td><td>9500</td></tr> <tr><td>Galvanized Sheet(max)</td><td>10000</td></tr> <tr><td>Asphalt</td><td>9500</td></tr> <tr><td>Aluminum</td><td>7500</td></tr> <tr><td>Tile(min)</td><td>8000</td></tr> <tr><td>Tile(max)</td><td>9500</td></tr> <tr><td>Concrete(min)</td><td>7500</td></tr> <tr><td>Concrete(max)</td><td>10000</td></tr> <tr><td>Corrugated Metal(min)</td><td>7500</td></tr> <tr><td>Corrugated Metal(max)</td><td>9500</td></tr> <tr><td>Bituminous</td><td>7500</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Galvanized Sheet(min)	9500	Galvanized Sheet(max)	10000	Asphalt	9500	Aluminum	7500	Tile(min)	8000	Tile(max)	9500	Concrete(min)	7500	Concrete(max)	10000	Corrugated Metal(min)	7500	Corrugated Metal(max)	9500	Bituminous	7500
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Potential RWH values are given in Table 4.9 for the same material for different pitched roofs. In this case, the gain between the highest and lowest values for maximum values of each roof type was calculated as 834.88 m³ in total for this case study for pitched roofs. It means annually, 834880 L of water for this area.

4.3 Case Study-2: Bursa

When the output of the Google Earth image with a resolution of 0.24 taken from Bursa was examined, it was seen that the detection and classification of hipped roofs were largely correct, but the types of roofs classified as flat roofs were different. Additionally, flat areas without a roof (such as a pitch) are also classified as flat roofs. However, when looking at the ML Task-2 output for calculating roof areas, it can be seen that almost all of the roofs are detected, as seen in Table 4.10.

In the input image, where there are many roof types, the largest share seems to belong to the hipped roof, as seen in Figure 4.15.

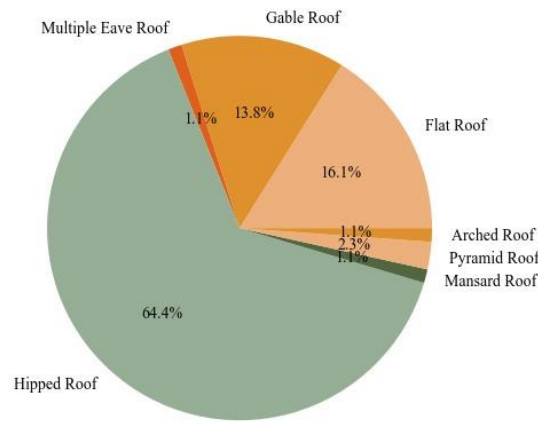


Figure 4.14 Roof Types in Bursa Case Study (Developed by Author)

Current ECA and potential RWH values are given in Table 4.10, while Table 4.11 includes the different values for ECA and potential RWH values for various scenarios. Thus, potential RWH values that vary depending on roof slope, material runoff coefficient values, and roof type have been reached. Potential RWH values are given in Table 4.12 for the same material for different pitched roofs for the Bursa case study.

Table 4.10 Outputs of ML Tasks for Case Study-2 (Developed by Author)

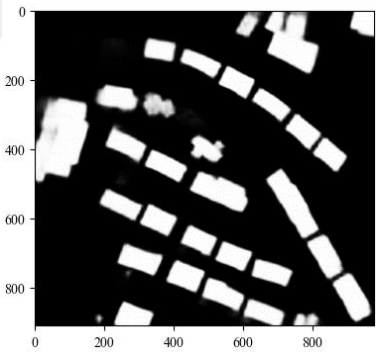
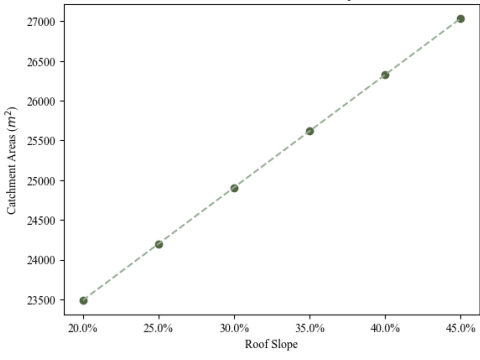
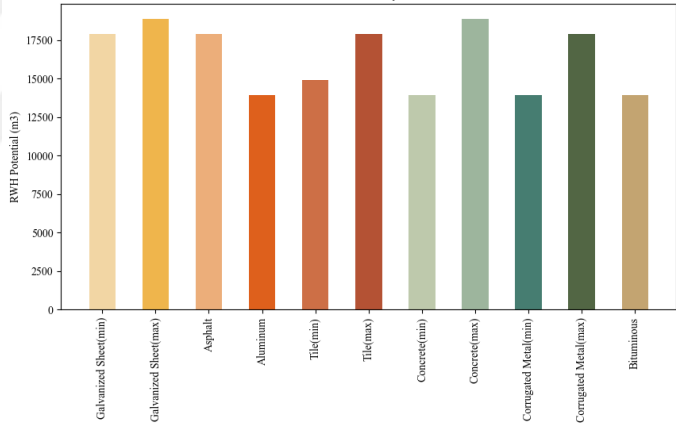
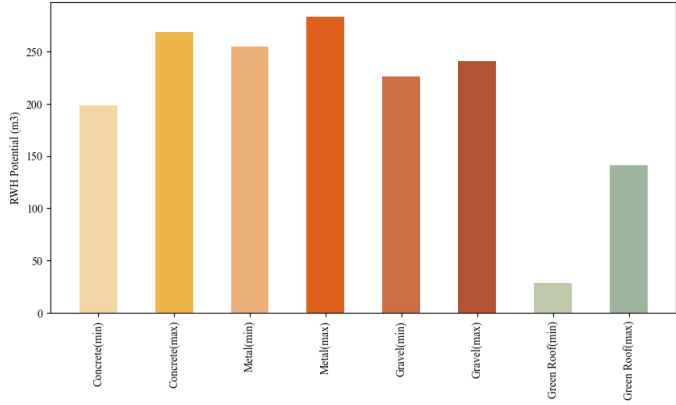
Location	Bursa
Input Image	
ML Task-1 Output	
ML Task-2 Output	
Visualization of Output of Merged ML Tasks	

Table 4.11 Current Effective Catchment Area and Potential RWH Values for Bursa Case Study (Developed by Author)

Current Effective Catchment Areas for Different Roof Angles	 <table border="1"> <caption>Catchment Areas vs Roof Slope</caption> <thead> <tr> <th>Roof Slope (%)</th> <th>Catchment Area (m²)</th> </tr> </thead> <tbody> <tr><td>20.0</td><td>23500</td></tr> <tr><td>25.0</td><td>24250</td></tr> <tr><td>30.0</td><td>24900</td></tr> <tr><td>35.0</td><td>25550</td></tr> <tr><td>40.0</td><td>26200</td></tr> <tr><td>45.0</td><td>26850</td></tr> </tbody> </table>	Roof Slope (%)	Catchment Area (m²)	20.0	23500	25.0	24250	30.0	24900	35.0	25550	40.0	26200	45.0	26850										
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Current RWH Potential	Flat Roof RWH Potential (concrete-minimum): 198.06 m³ Flat Roof RWH Potential (concrete-maximum): 268.78 m³ Pitched Roof RWH Potential (tile-minimum): 14110.50 m³ Pitched Roof RWH Potential (tile-maximum): 16932.62 m³																								
Current RWH Potential by Pitched Roofs	 <table border="1"> <caption>Current RWH Potential by Pitched Roofs</caption> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Galvanized Sheet(min)</td><td>17500</td></tr> <tr><td>Galvanized Sheet(max)</td><td>18500</td></tr> <tr><td>Asphalt</td><td>17500</td></tr> <tr><td>Aluminum</td><td>14000</td></tr> <tr><td>Tile(min)</td><td>15000</td></tr> <tr><td>Tile(max)</td><td>17500</td></tr> <tr><td>Concrete(min)</td><td>14000</td></tr> <tr><td>Concrete(max)</td><td>18500</td></tr> <tr><td>Corrugated Metal(min)</td><td>14000</td></tr> <tr><td>Corrugated Metal(max)</td><td>17500</td></tr> <tr><td>Bituminous</td><td>14000</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Galvanized Sheet(min)	17500	Galvanized Sheet(max)	18500	Asphalt	17500	Aluminum	14000	Tile(min)	15000	Tile(max)	17500	Concrete(min)	14000	Concrete(max)	18500	Corrugated Metal(min)	14000	Corrugated Metal(max)	17500	Bituminous	14000
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Current RWH Potential by Flat Roofs	 <table border="1"> <caption>Current RWH Potential by Flat Roofs</caption> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Concrete(min)</td><td>200</td></tr> <tr><td>Concrete(max)</td><td>260</td></tr> <tr><td>Metal(min)</td><td>250</td></tr> <tr><td>Metal(max)</td><td>280</td></tr> <tr><td>Gravel(min)</td><td>230</td></tr> <tr><td>Gravel(max)</td><td>240</td></tr> <tr><td>Green Roof(min)</td><td>30</td></tr> <tr><td>Green Roof(max)</td><td>140</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Concrete(min)	200	Concrete(max)	260	Metal(min)	250	Metal(max)	280	Gravel(min)	230	Gravel(max)	240	Green Roof(min)	30	Green Roof(max)	140						
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In Table 4.12, potential RWH calculations were given for minimum, average, and maximum annual rainfall, different roof slopes and different materials.

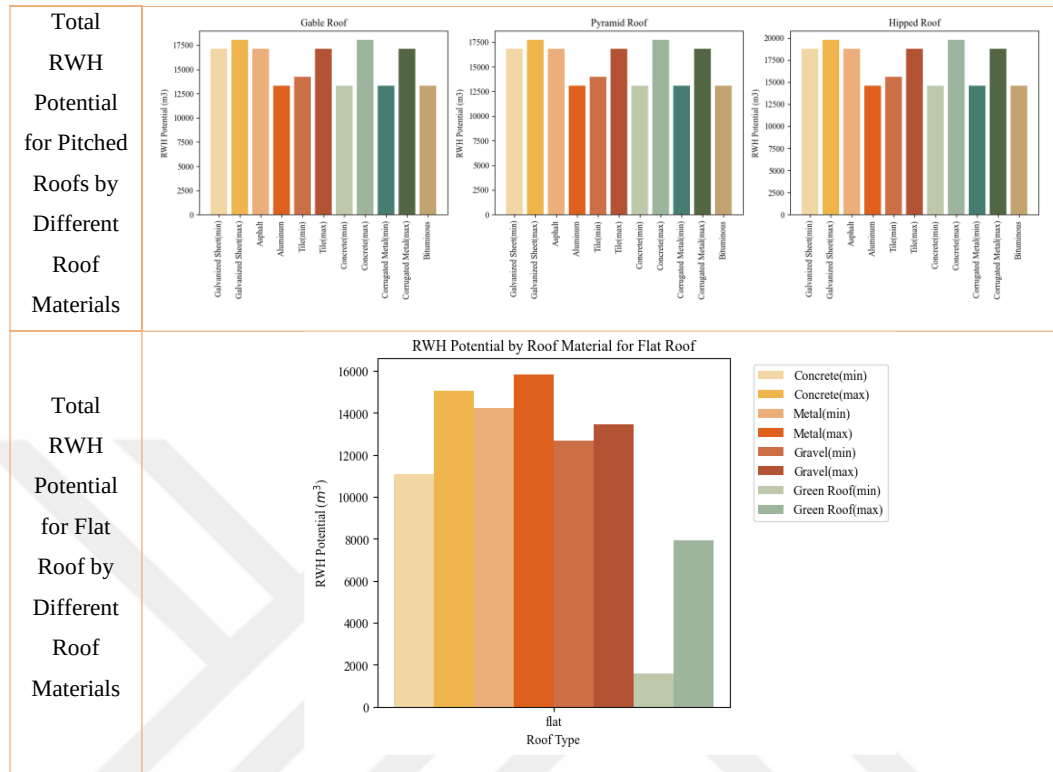
Table 4.12 Potential RWH Values for Current Roof Types for Bursa Case Study (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
Roof Slope	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	12952.66	17201.41	24770	13671.66	18156.26	26145.01
40 %	13690.11	18180.76	26180.30	14450.08	19190.02	27633.63
GAIN	737.45	979.35	1410.30	778.42	1033.76	1488.62

- When the roof slope is kept at the same value and the material is changed, the maximum gain is calculated as 5.55%.
- When the material is kept the same and the roof slope is changed, the maximum gain is calculated as 5.69%.
- When both the roof material and the roof slope changed, the maximum gain is calculated as 11.56%.

In the next stage, calculations were made for different scenarios in which roof types were changed, as seen in Table 4.13.

Table 4.13 Total Effective Catchment Area and Potential RWH Values for Different Scenarios for Bursa Case Study (Developed by Author)



According to the calculations,

- Maximum RWH Potential for Gable Roof: 18049 m³, and minimum RWH Potential for Gable Roof: 13299.2 m³.
- Maximum RWH Potential for Pyramid Roof: 17726.9 m³ and minimum RWH Potential for Pyramid Roof: 13061.9 m³.
- Maximum RWH Potential for Hipped Roof: 19770.4 m³ and minimum RWH Potential for Hipped Roof: 14567.7 m³.

4.4 Case Study-3: Aydın

In the third case study, the Google Earth image taken from Aydın was evaluated. The resolution of the input image is 0.25. When looking at the outputs of ML tasks, it can be seen that the roofs are largely detected correctly. Although accurate predictions are often made in the classification of roof types, flat roof classification has been made for some pitched roofs. The dome roof type in the input image could not be determined as seen in Table 4.14. In the input image, which includes different roof types, the majority of the roofs are flat roofs, as seen in Figure 4.16.

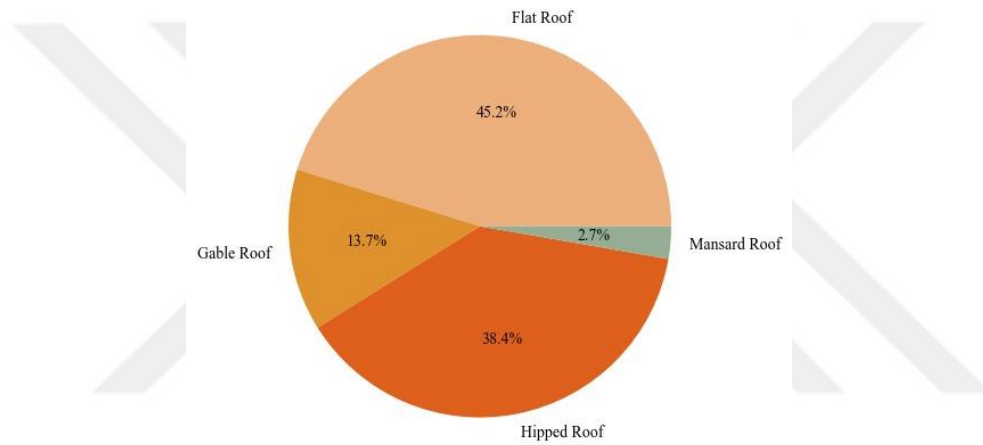


Figure 4.15 Roof Types in Aydın Case Study (Developed by Author)

The maximum effective catchment area value that can be achieved by simply increasing the slope values without changing the types of current roofs is approximately 10400 m² as seen in Table 4.15. With current roof types, different calculations were made for different slope values and roofing materials in Table 4.16. In Table 4.17, potential RWH values are given for different pitched roofs.

Table 4.14 Outputs of ML Tasks for Case Study-3 (Developed by Author)

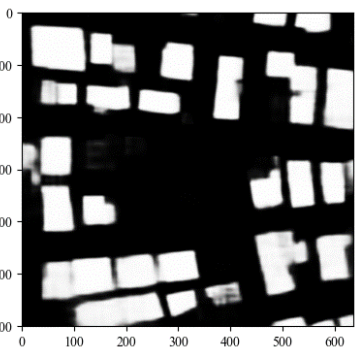
Location	Aydın
Input Image	
ML Task-1 Output	
ML Task-2 Output	
Visualization of Output of Merged ML Tasks	

Table 4.15 Current Effective Catchment Area and Potential RWH Values for Aydın Case Study (Developed by Author)

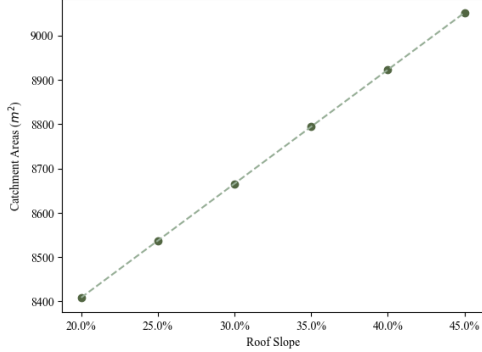
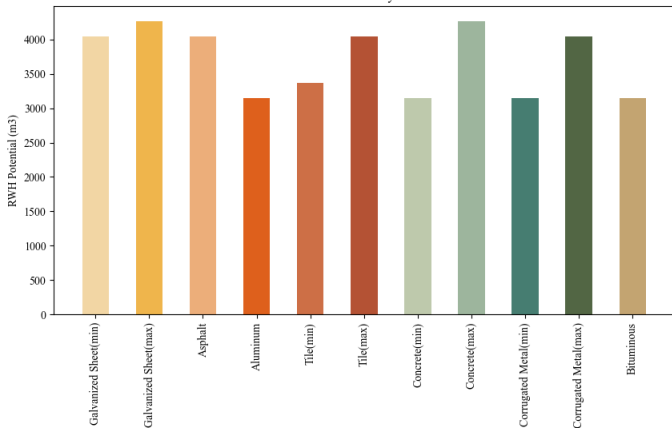
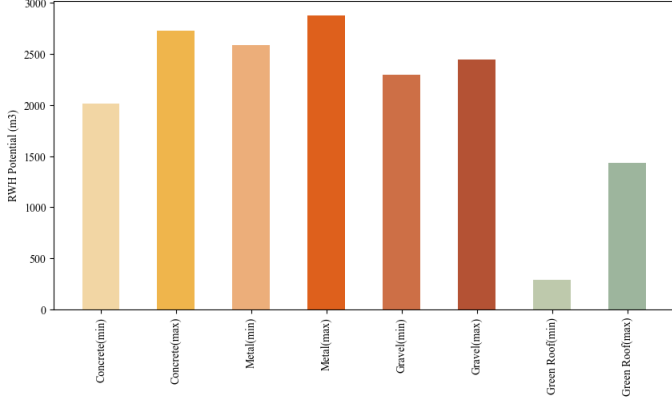
Current Effective Catchment Areas for Different Roof Angles	
Current RWH Potential	Flat Roof RWH Potential (concrete-minimum): 2013.58 m³ Flat Roof RWH Potential (concrete-maximum): 2732.71 m³ Sloped Roof RWH Potential (tile-minimum): 3210.64 m³ Sloped Roof RWH Potential (tile-maximum): 3852.77 m³
Current RWH Potential by Pitched Roofs	
Current RWH Potential by Flat Roofs	

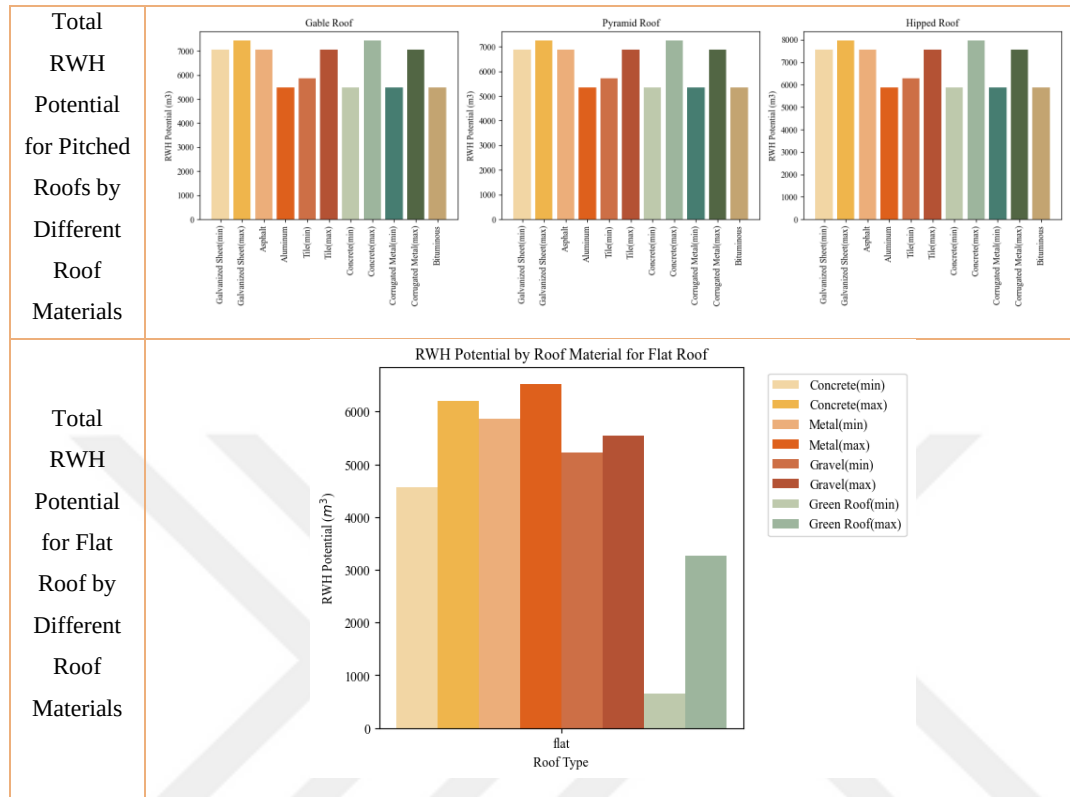
Table 4.16 Potential RWH Values for Current Roof Types for Aydın Case Study (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
Roof Slope	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	5426.43	6585.48	7560.13	5721.32	6943.35	7970.96
40 %	5583.86	6776.53	7779.46	5887.50	7145.02	8202.48
GAIN	157.43	191.05	219.33	166.18	201.67	231.52

- When the roof slope is kept at the same value and the material is changed, the maximum gain is calculated as 5.43%.
- When the material is kept the same and the roof slope is changed, the maximum gain is calculated as 2.9%.
- When both the roof material and the roof slope changed, the maximum gain is calculated as 8.49%.

After calculations which made for current roof types, the results of different scenarios were given in Table 4.17.

Table 4.17 Total Effective Catchment Area and Potential RWH Values for Different Scenarios for Aydın Case Study (Developed by Author)



According to the calculations which made for different roof types,

- Maximum RWH Potential for Gable Roof: 7433.4 m³, and minimum RWH Potential for Gable Roof: 5477.3 m³.
- Maximum RWH Potential for Pyramid Roof: 7249.5 m³ and minimum RWH Potential for Pyramid Roof: 5341.8 m³.
- Maximum RWH Potential for Hipped Roof: 7965.7 m³ and minimum RWH Potential for Hipped Roof: 5869.4 m³

4.5 Case Study-4: Trabzon

In this case study, where the majority of the roofs are hipped roofs with a rate of 60%, the image taken from Trabzon with a 0.41 resolution value was used as input, as seen in Figure 4.16. When the outputs of ML tasks are examined, it is seen that the majority of the roofs are classified correctly. The outputs of the second machine learning task show that all of the roofs were detected. However, since buildings are photographed from different perspectives in Google Earth images, it can be inferred that the probability of estimating the exact projected areas of the roofs is low (see Table 4.18).

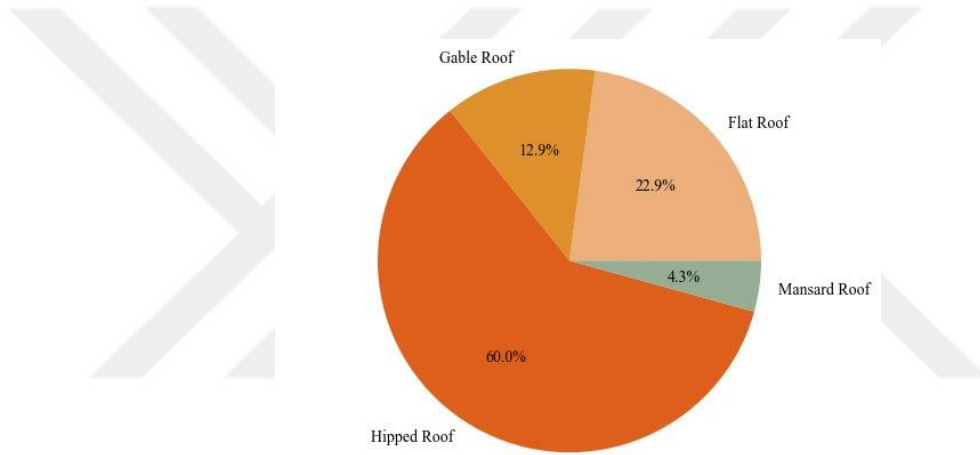


Figure 4.16 Roof Types in Trabzon Case Study (Developed by Author)

In Table 4.19 and Table 4.20, the current situation and different scenarios for the roofs included in the input images are evaluated. Thus, potential RWH values that vary depending on roof slope, material runoff coefficient values, and roof type have been reached. As a result, potential RWH values are given in Table 4.21.

Table 4.18 Outputs of ML Tasks for Case Study-4 (Developed by Author)

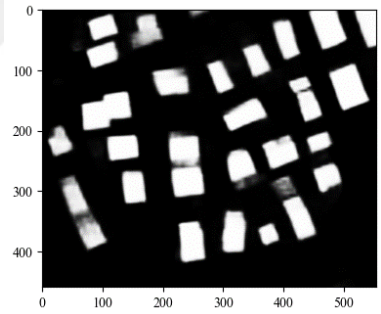
Location	Trabzon
Input Image	
ML Task-1 Output	
ML Task-2 Output	
Visualization of Output of Merged ML Tasks	

Table 4.19 Current Effective Catchment Area and Potential RWH Values for Trabzon Case Study (Developed by Author)

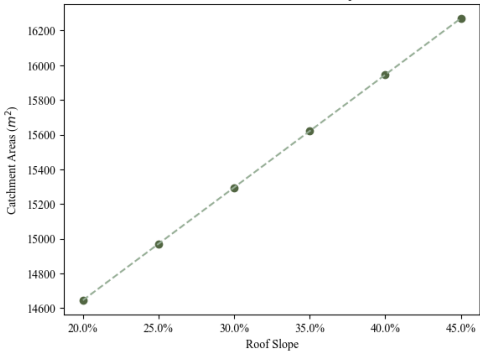
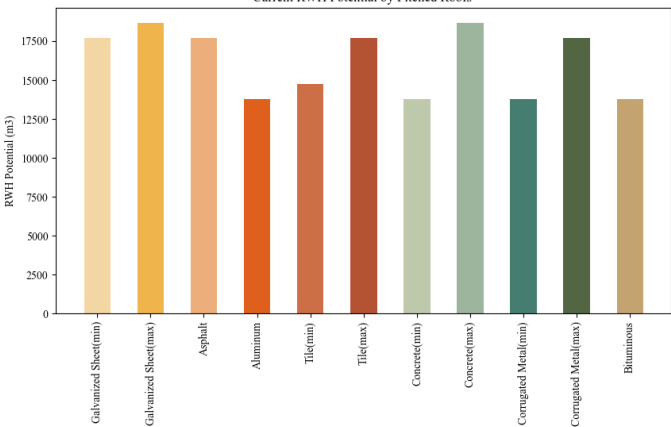
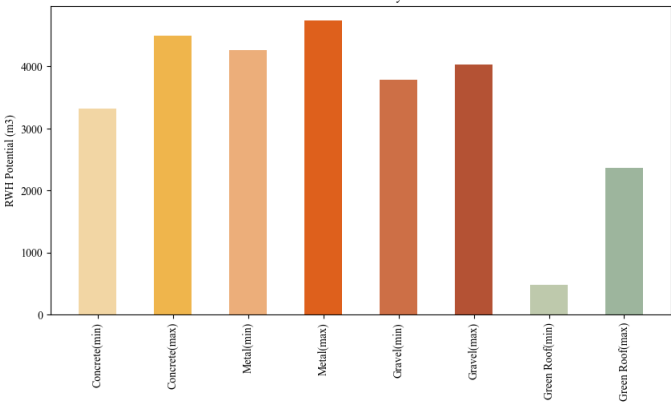
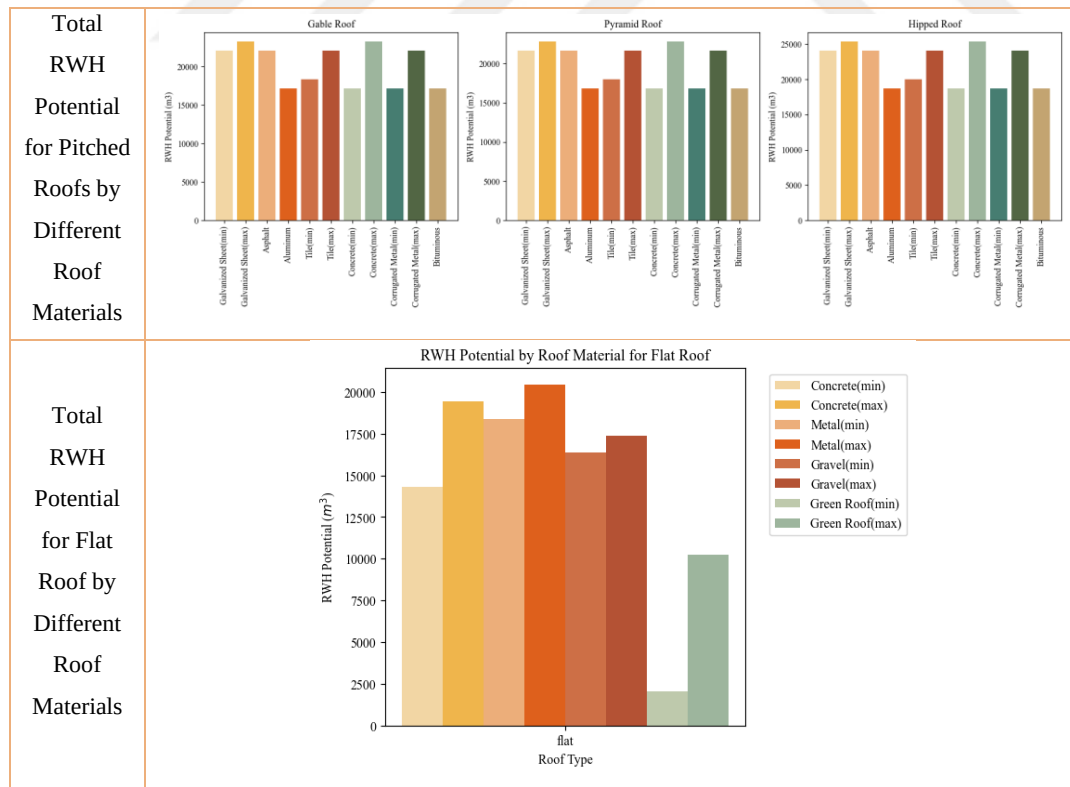
Current Effective Catchment Areas for Different Roof Angles	 <table border="1"> <caption>Catchment Areas vs Roof Slope</caption> <thead> <tr> <th>Roof Slope (%)</th> <th>Catchment Area (m²)</th> </tr> </thead> <tbody> <tr><td>20.0</td><td>14600</td></tr> <tr><td>25.0</td><td>15000</td></tr> <tr><td>30.0</td><td>15300</td></tr> <tr><td>35.0</td><td>15600</td></tr> <tr><td>40.0</td><td>15900</td></tr> <tr><td>45.0</td><td>16200</td></tr> </tbody> </table>	Roof Slope (%)	Catchment Area (m²)	20.0	14600	25.0	15000	30.0	15300	35.0	15600	40.0	15900	45.0	16200										
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Current RWH Potential	Flat Roof RWH Potential (concrete-minimum): 3316.29 m³ Flat Roof RWH Potential (concrete-maximum): 4500.68 m³ Sloped Roof RWH Potential (tile-minimum): 14008.50 m³ Sloped Roof RWH Potential (tile-maximum): 16810.20 m³																								
Current RWH Potential by Pitched Roofs	 <table border="1"> <caption>Current RWH Potential by Pitched Roofs</caption> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Galvanized Sheet(min)</td><td>17500</td></tr> <tr><td>Galvanized Sheet(max)</td><td>18000</td></tr> <tr><td>Asphalt</td><td>17500</td></tr> <tr><td>Aluminum</td><td>14000</td></tr> <tr><td>Tile(min)</td><td>15000</td></tr> <tr><td>Tile(max)</td><td>17500</td></tr> <tr><td>Concrete(min)</td><td>14000</td></tr> <tr><td>Concrete(max)</td><td>18000</td></tr> <tr><td>Corrugated Metal(min)</td><td>14000</td></tr> <tr><td>Corrugated Metal(max)</td><td>17500</td></tr> <tr><td>Bituminous</td><td>14000</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Galvanized Sheet(min)	17500	Galvanized Sheet(max)	18000	Asphalt	17500	Aluminum	14000	Tile(min)	15000	Tile(max)	17500	Concrete(min)	14000	Concrete(max)	18000	Corrugated Metal(min)	14000	Corrugated Metal(max)	17500	Bituminous	14000
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Green Roof(max)	2400																								

Table 4.20 Potential RWH Values for Current Roof Types for Trabzon Case Study (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
Roof Slope	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	10804.62	21310.88	27832	11398.20	22481.66	29361.04
40 %	11258.38	22205.88	29000.88	11877.18	23426.38	30594.86
GAIN	453.76	895	1168.88	478.98	944.72	1233.82

- When the roof slope is kept at the same value and the material is changed, the maximum gain is calculated as 5.49%.
- When the material is kept the same and the roof slope is changed, the maximum gain is calculated as 4.19%.
- When both the roof material and the roof slope changed, the maximum gain is calculated as 9.92%.

Table 4.21 Total Effective Catchment Area and Potential RWH Values for Different Scenarios for Trabzon Case Study (Developed by Author)



According to the calculations, as seen in Table 4.21,

- Maximum RWH Potential for Gable Roof: 23292.7 m³, and minimum RWH Potential for Gable Roof: 17163 m³.
- Maximum RWH Potential for Pyramid Roof: 22830 m³ and minimum RWH Potential for Pyramid Roof: 16822.1 m³.
- Maximum RWH Potential for Hipped Roof: 25377.4 m³ and minimum RWH Potential for Hipped Roof: 18699.1 m³



4.6 Case Study-5: Erzurum

The resolution of the Google Earth image taken from Erzurum is 0.35. When the outputs of the ML tasks were examined in this case study, it was seen that there were undetected roofs. However, most of the classified roofs are classified correctly. On the other hand, when the output of ML Task-2, which was planned to calculate the areas of roofs, was compared with other case studies, the results were not found successful. It can be seen that most of the roofs cannot be segmented as seen in Table 4.22. Since the performance of ML Task-2 was evaluated as low for this case study, the calculations made are likely to contain large errors for both effective catchment area and potential RWH values. However, in line with the outputs of ML Task-1, which was developed for the detection and classification of roofs, the ratio of roof types can be evaluated accurately, as seen in Figure 4.17.

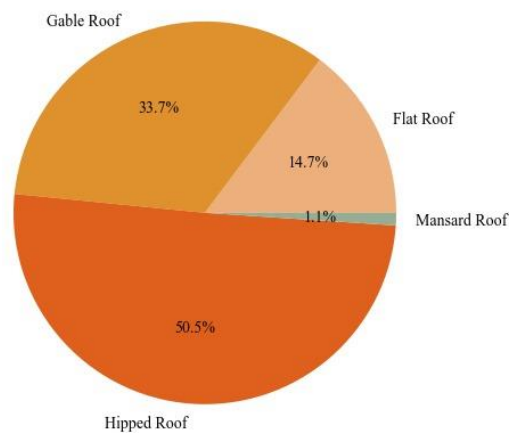


Figure 4.17 Roof Types in Erzurum Case Study (Developed by Author)

In Table 4.23 and Table 4.24, the current situation and different scenarios for the roofs included in the input images are evaluated. Thus, potential RWH values that vary depending on roof slope, material runoff coefficient values, and roof type have been reached. After evaluating the results of different calculations, potential RWH values are given for different pitched roofs in Table 4.25.

Table 4.22 Outputs of ML Tasks for Case Study-5 (Developed by Author)

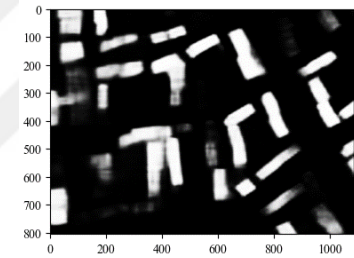
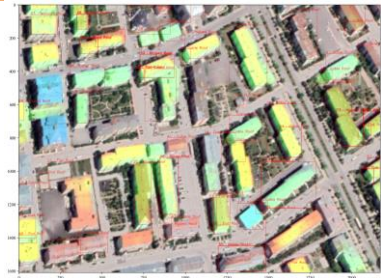
Location	Erzurum
Input Image	
ML Task-1 Output	
ML Task-2 Output	
Visualization of Output of Merged ML Tasks	

Table 4.23 Current Effective Catchment Area and Potential RWH Values for Erzurum Case Study (Developed by Author)

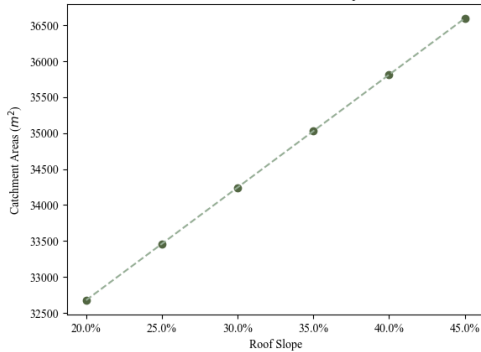
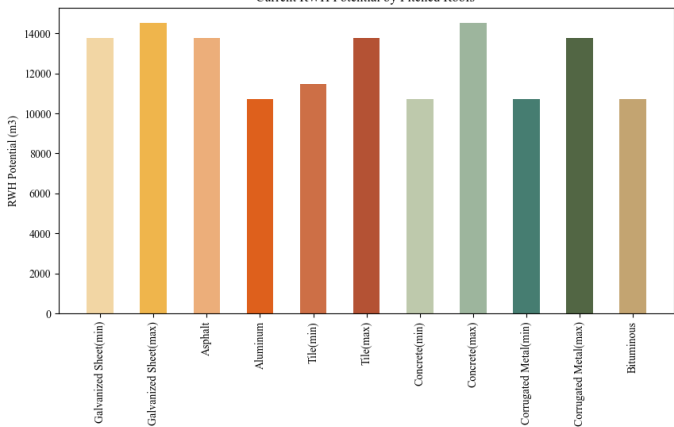
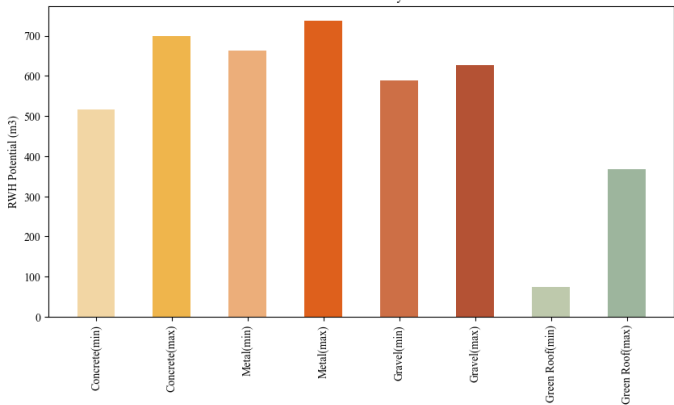
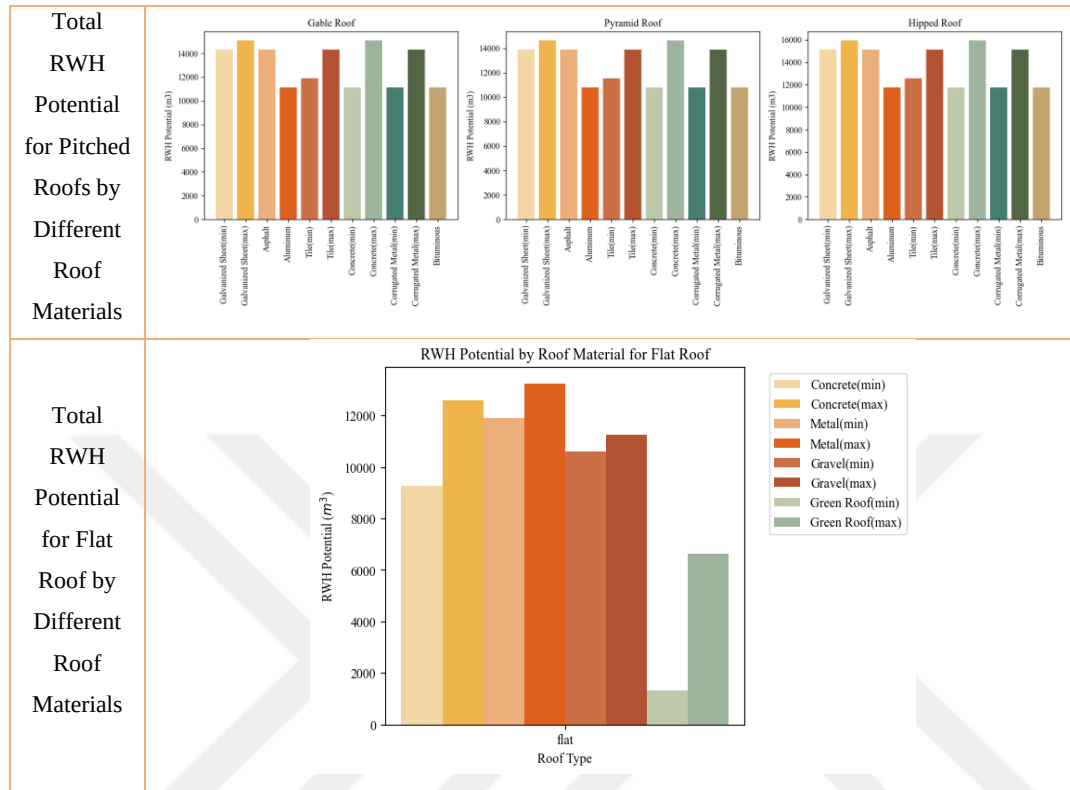
Current Effective Catchment Areas for Different Roof Angles	 Catchment Areas vs Roof Slope <table border="1"> <thead> <tr> <th>Roof Slope (%)</th> <th>Catchment Area (m²)</th> </tr> </thead> <tbody> <tr><td>20.0%</td><td>32500</td></tr> <tr><td>25.0%</td><td>33500</td></tr> <tr><td>30.0%</td><td>34250</td></tr> <tr><td>35.0%</td><td>35000</td></tr> <tr><td>40.0%</td><td>35750</td></tr> <tr><td>45.0%</td><td>36500</td></tr> </tbody> </table>	Roof Slope (%)	Catchment Area (m²)	20.0%	32500	25.0%	33500	30.0%	34250	35.0%	35000	40.0%	35750	45.0%	36500										
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Current RWH Potential	Flat Roof RWH Potential (concrete-minimum): 515.78 m³ Flat Roof RWH Potential (concrete-maximum): 699.99 m³ Sloped Roof RWH Potential (tile-minimum): 10948.53 m³ Sloped Roof RWH Potential (tile-maximum): 13138.24 m³																								
Current RWH Potential by Pitched Roofs	 Current RWH Potential by Pitched Roofs <table border="1"> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Galvanized Sheet(min)</td><td>13800</td></tr> <tr><td>Galvanized Sheet(max)</td><td>14500</td></tr> <tr><td>Asphalt</td><td>13800</td></tr> <tr><td>Aluminium</td><td>10800</td></tr> <tr><td>Tile(min)</td><td>11500</td></tr> <tr><td>Tile(max)</td><td>13800</td></tr> <tr><td>Concrete(min)</td><td>10800</td></tr> <tr><td>Concrete(max)</td><td>14500</td></tr> <tr><td>Corrugated Metal(min)</td><td>10800</td></tr> <tr><td>Corrugated Metal(max)</td><td>13800</td></tr> <tr><td>Bituminous</td><td>10800</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Galvanized Sheet(min)	13800	Galvanized Sheet(max)	14500	Asphalt	13800	Aluminium	10800	Tile(min)	11500	Tile(max)	13800	Concrete(min)	10800	Concrete(max)	14500	Corrugated Metal(min)	10800	Corrugated Metal(max)	13800	Bituminous	10800
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Table 4.24 Potential RWH Values for Current Roof Types for Erzurum Case Study (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
Roof Slope	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	5867.15	13837.62	16702	6192.23	14604.33	17627.42
40 %	6134.79	14468.83	17463.88	6474.74	15270.61	18431.62
GAIN	267.64	631.21	761.88	282.51	666.28	804.20

- When the roof slope is kept at the same value and the material is changed, the maximum gain is calculated as 5.54%.
- When the material is kept the same and the roof slope is changed, the maximum gain is calculated as 4.56%.
- When both the roof material and the roof slope changed, the maximum gain is calculated as 10.35%.

Table 4.25 Total Effective Catchment Area and Potential RWH Values for Different Scenarios for Erzurum Case Study (Developed by Author)



According to the calculations, as seen in Table 4.25,

- Maximum RWH Potential for Gable Roof: 15082 m³, and minimum RWH Potential for Gable Roof: 11113 m³.
- Maximum RWH Potential for Pyramid Roof: 14628 m³ and minimum RWH Potential for Pyramid Roof: 10779 m³.
- Maximum RWH Potential for Hipped Roof: 15933 m³ and minimum RWH Potential for Hipped Roof: 11740 m³.

4.7 Case Study-6: Mersin

In this case study, unlike the others, an input image with very few roofs was selected. Thus, a comparison can be made for cases where the number of roofs changes. The resolution of the input image is 0.11. It is seen that the relatively larger roofs in the input image are classified correctly, but some areas that are not roofs are also detected as roofs, as seen in Table 4.26. In this case, the possibility of errors in both the ratios of the roof types and the calculations made depending on the roof types is considered to be quite high. For example, although the percentage ratios of roof types are calculated as in Figure 4.18 when the input image is examined, it is clearly seen that these ratios are wrong.

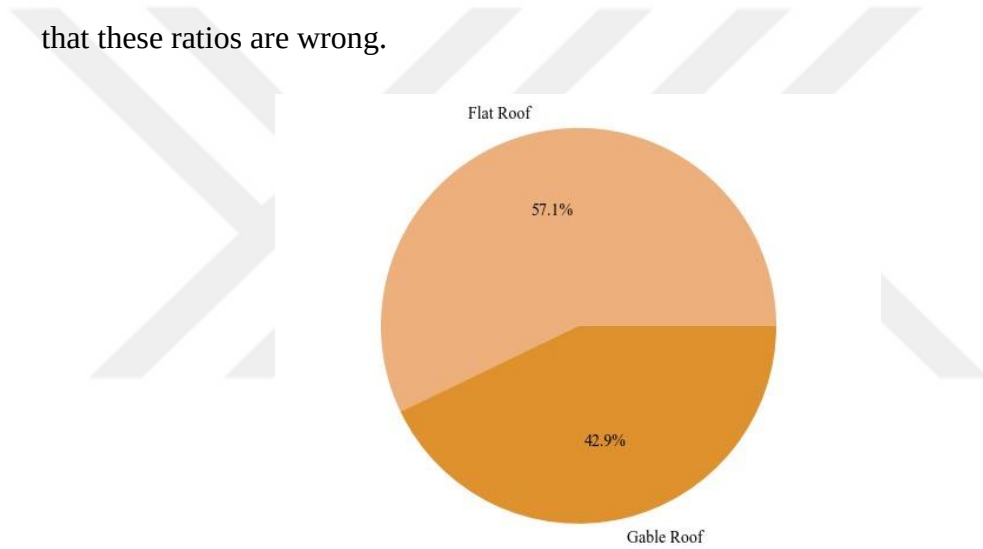


Figure 4.18 Roof Types in Mersin Case Study (Developed by Author)

In Table 4.27 and Table 4.28, the current situation and different scenarios for the roofs included in the input images are evaluated. Thus, potential RWH values that vary depending on roof slope, material runoff coefficient values, and roof type have been reached. Minimum and maximum potential RWH values for different pitched roofs are given in Table 4.29.

Table 4.26 Outputs of ML Tasks for Case Study-6 (Developed by Author)

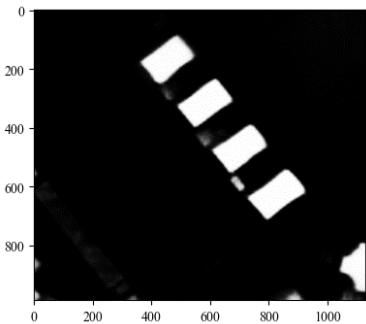
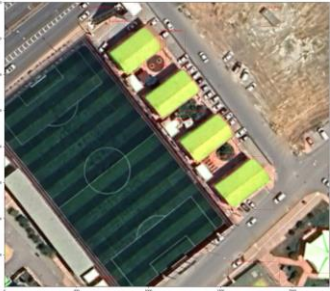
Location	Mersin
Input Image	
ML Task-1 Output	
ML Task-2 Output	
Visualization of Output of Merged ML Tasks	

Table 4.27 Current Effective Catchment Area and Potential RWH Values for Mersin Case Study (Developed by Author)

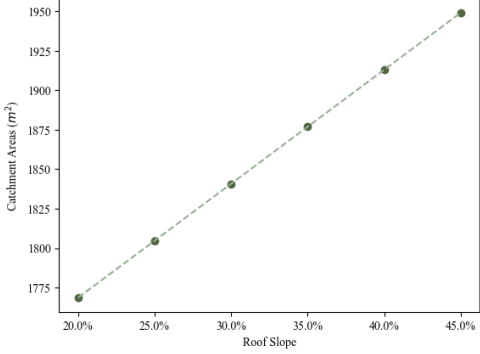
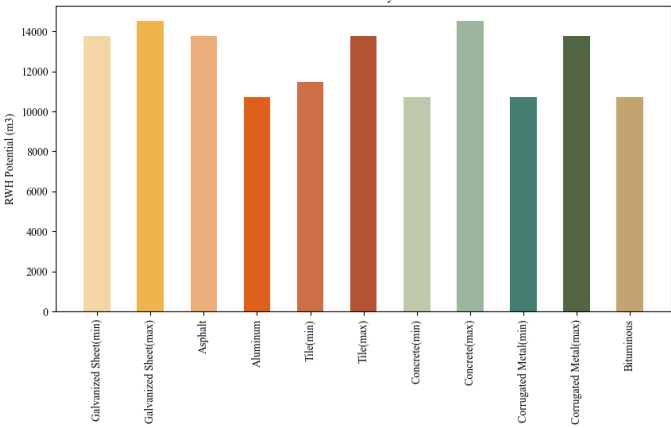
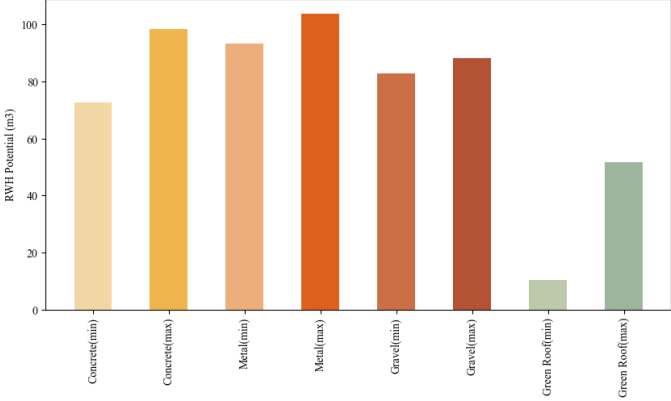
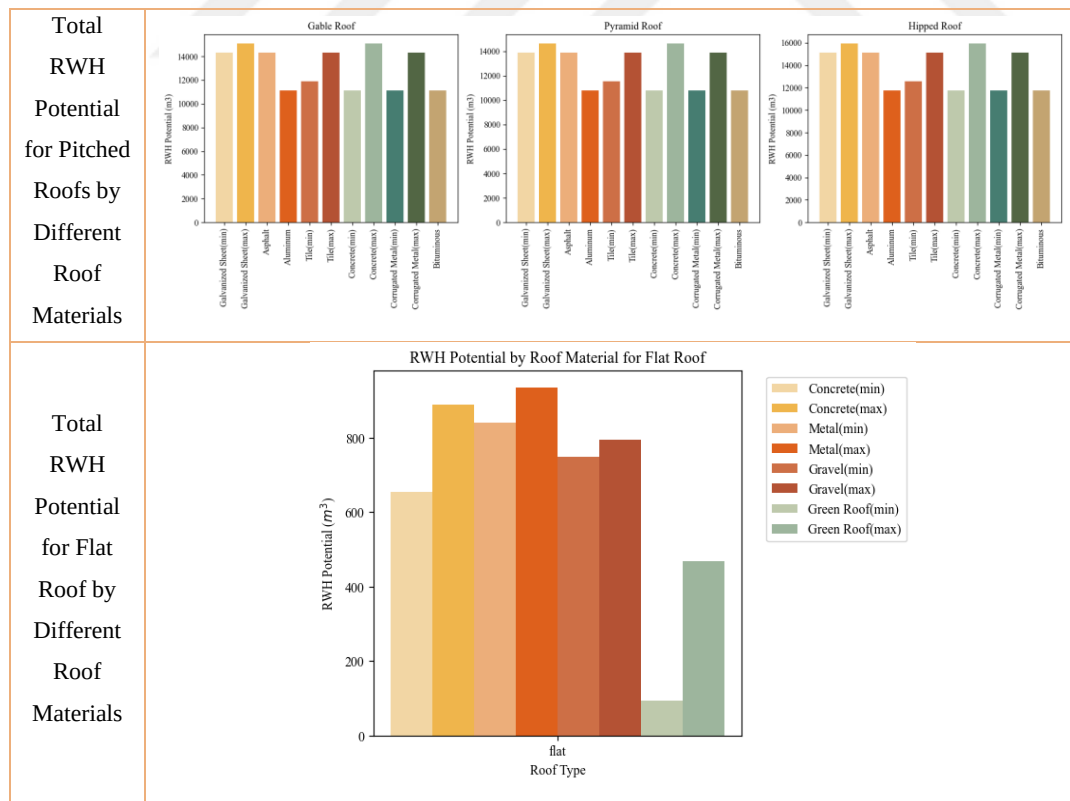
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45.0%	1950																								
Current RWH Potential	Flat Roof RWH Potential (concrete-minimum): 72.58 m³ Flat Roof RWH Potential (concrete-maximum): 98.50 m³ Sloped Roof RWH Potential (tile-minimum): 716.17 m³ Sloped Roof RWH Potential (tile-maximum): 859.40 m³																								
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Table 4.28 Potential RWH Values for Current Roof Types for Mersin Case Study (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
Roof Slope	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	581.44	957.90	1367.88	613.57	1010.83	1443.46
40 %	604.12	995.26	1421.23	637.51	1050.27	1499.78
GAIN	22.67	37.36	53.35	23.94	39.44	56.32

- When the roof slope is kept at the same value and the material is changed, the maximum gain is calculated as 5.52%.
- When the material is kept the same and the roof slope is changed, the maximum gain is calculated as 3.9%.
- When both the roof material and the roof slope changed, the maximum gain is calculated as 9.64%.

Table 4.29 Total Effective Catchment Area and Potential RWH Values for Different Scenarios for Mersin Case Study (Developed by Author)



According to the calculations for different scenarios as seen in Table 4.29,

- Maximum RWH Potential for Gable Roof: 15082.35 m³ and minimum RWH Potential for Gable Roof: 11113.31 m³.
- Maximum RWH Potential for Pyramid Roof: 14628.08 m³ and minimum RWH Potential for Pyramid Roof: 10778.58 m³.
- Maximum RWH Potential for Hipped Roof: 15932.87 m³ and minimum RWH Potential for Hipped Roof: 11740 m³.



4.8 Case Study-7: Diyarbakır

For this case study, the Google Earth image taken from Diyarbakır with a 0.25 resolution value was used as input. When the outputs were examined, as seen in Table 4.30, it was determined that most of the roofs were classified correctly, but approximately 20% of the segmentations could not be made. Almost half of the roofs in the input image are hipped roof types, as seen in Figure 4.19.

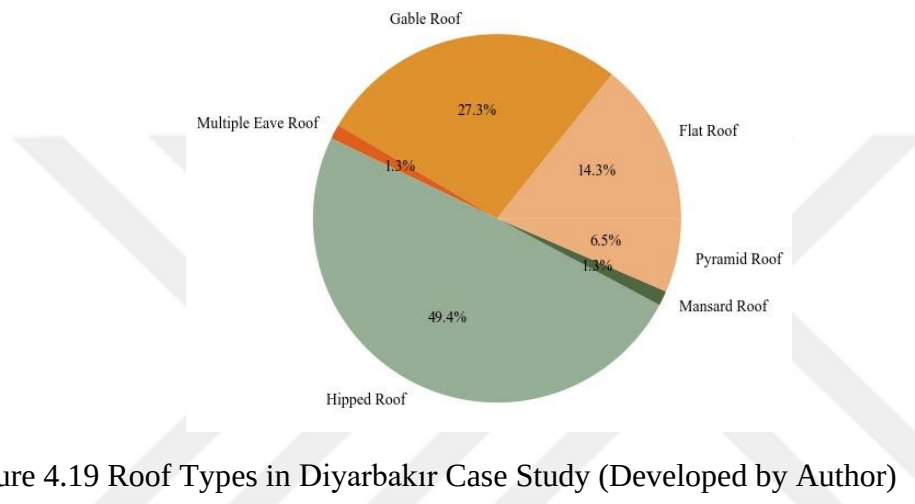


Figure 4.19 Roof Types in Diyarbakır Case Study (Developed by Author)

In the current situation, by increasing the slope of the roofs, the effective catchment area becomes approximately 35000 m², while in the case where all roof types are hipped, the effective catchment area can be increased to approximately 40000 m² as seen in Table 5.16. In this case, it seems that the amount of potential RWH can be increased up to 15%.

In Table 4.31 and Table 4.32, the current situation and different scenarios for the roofs included in the input images are evaluated. Thus, potential RWH values that vary depending on roof slope, material runoff coefficient values, and roof type have been reached. Finally, in Table 4.33, potential RWH values are given for different pitched roofs.

Table 4.30 Outputs of ML Tasks for Case Study- 7 (Developed by Author)

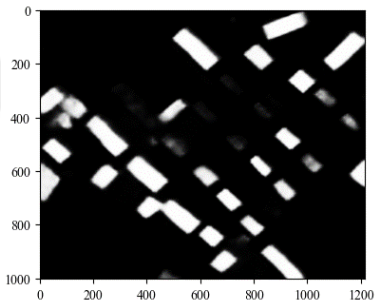
Location	Diyarbakır
Input Image	
ML Task-1 Output	
ML Task-2 Output	
Visualization of Output of Merged ML Tasks	

Table 4.31 Current Effective Catchment Area and Potential RWH Values for Diyarbakır Case Study (Developed by Author)

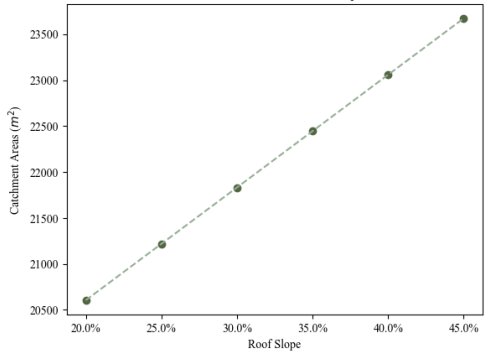
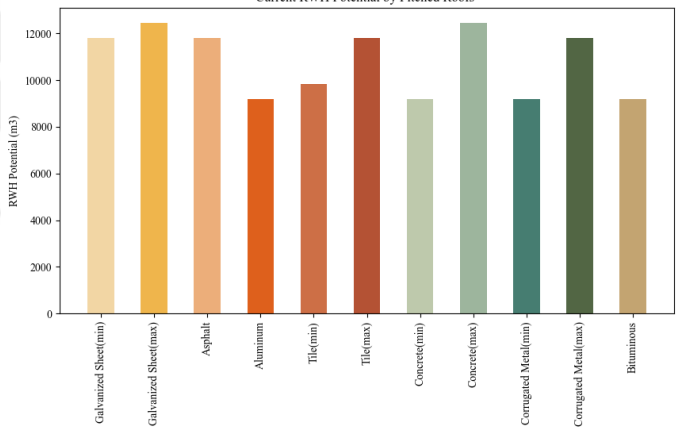
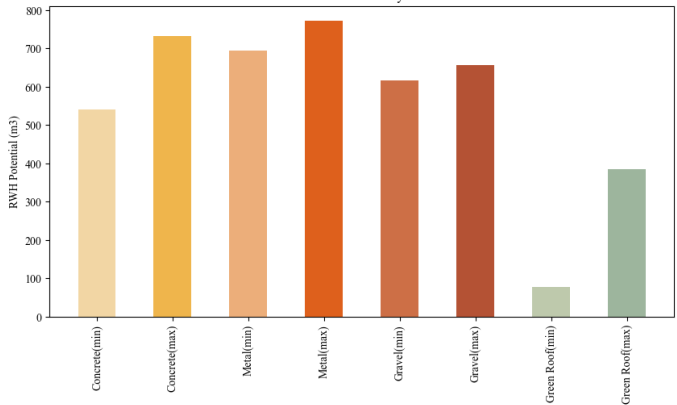
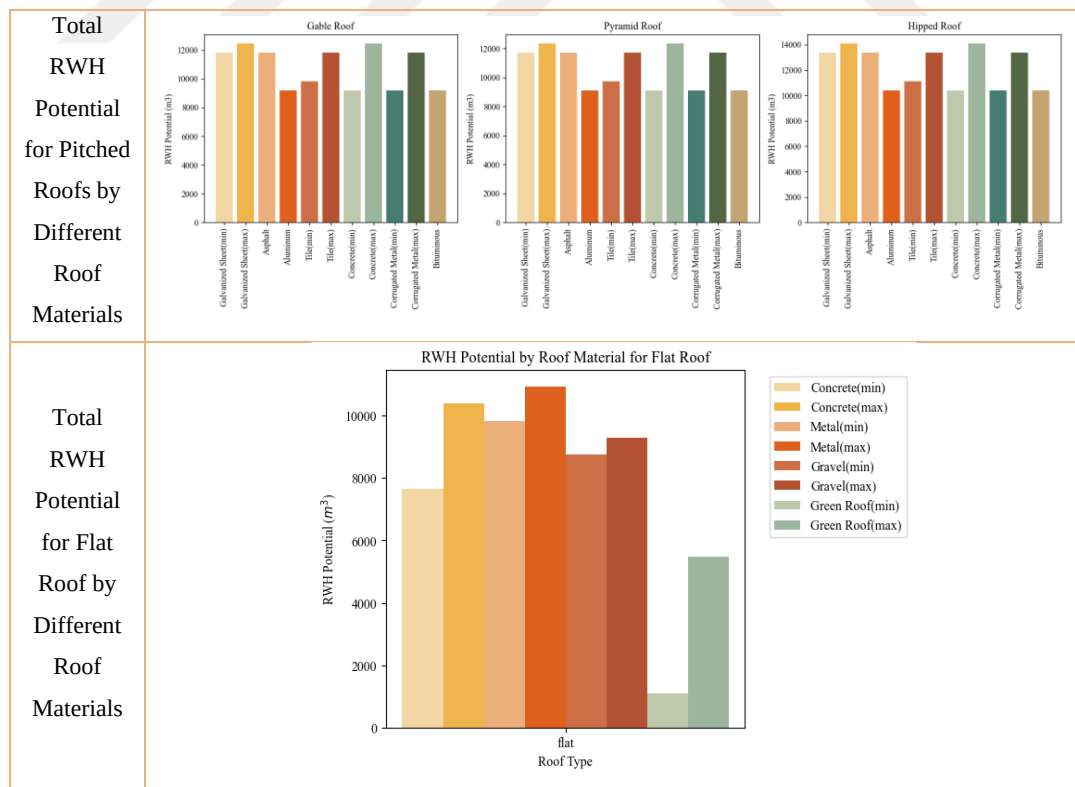
Current Effective Catchment Areas for Different Roof Angles	 Catchment Areas vs Roof Slope <table border="1"> <thead> <tr> <th>Roof Slope (%)</th> <th>Catchment Area (m²)</th> </tr> </thead> <tbody> <tr><td>20.0</td><td>20500</td></tr> <tr><td>25.0</td><td>21250</td></tr> <tr><td>30.0</td><td>21900</td></tr> <tr><td>35.0</td><td>22450</td></tr> <tr><td>40.0</td><td>23000</td></tr> <tr><td>45.0</td><td>23500</td></tr> </tbody> </table>	Roof Slope (%)	Catchment Area (m²)	20.0	20500	25.0	21250	30.0	21900	35.0	22450	40.0	23000	45.0	23500										
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Current RWH Potential by Pitched Roofs	 Current RWH Potential by Pitched Roofs <table border="1"> <thead> <tr> <th>Material</th> <th>RWH Potential (m³)</th> </tr> </thead> <tbody> <tr><td>Galvanized Sheet(min)</td><td>11800</td></tr> <tr><td>Galvanized Sheet(max)</td><td>12500</td></tr> <tr><td>Asphalt</td><td>11800</td></tr> <tr><td>Aluminum</td><td>9200</td></tr> <tr><td>Tile(min)</td><td>9800</td></tr> <tr><td>Tile(max)</td><td>11800</td></tr> <tr><td>Concrete(min)</td><td>9200</td></tr> <tr><td>Concrete(max)</td><td>12500</td></tr> <tr><td>Corrugated Metal(min)</td><td>9200</td></tr> <tr><td>Corrugated Metal(max)</td><td>11800</td></tr> <tr><td>Bituminous</td><td>9200</td></tr> </tbody> </table>	Material	RWH Potential (m³)	Galvanized Sheet(min)	11800	Galvanized Sheet(max)	12500	Asphalt	11800	Aluminum	9200	Tile(min)	9800	Tile(max)	11800	Concrete(min)	9200	Concrete(max)	12500	Corrugated Metal(min)	9200	Corrugated Metal(max)	11800	Bituminous	9200
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Table 4.32 Potential RWH Values for Current Roof Types for Diyarbakır Case Study (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
Roof Slope	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	7288.84	11871.08	14328.39	7692.46	12528.44	15121.83
40 %	7697.20	12536.16	15131.15	8123.51	13230.47	15969.18
GAIN	408.36	665.08	802.76	431.05	702.03	847.35

- When the roof slope is kept at the same value and the material is changed, the maximum gain is calculated as 5.53%.
- When the material is kept the same and the roof slope is changed, the maximum gain is calculated as 5.6%.
- When both the roof material and the roof slope changed, the maximum gain is calculated as 11.45%.

Table 4.33 Total Effective Catchment Area and Potential RWH Values for Different Scenarios for Diyarbakır Case Study (Developed by Author)



- Maximum RWH Potential for Gable Roof: 12460.53 m³ and minimum RWH Potential for Gable Roof: 9181.44 m³.
- Maximum RWH Potential for Pyramid Roof: 12349.96m³ and minimum RWH Potential for Pyramid Roof: 9099.97 m³.
- Maximum RWH Potential for Hipped Roof: 14095.08 m³ and minimum RWH Potential for Hipped Roof: 10385.85 m³.



4.9 Case Study-8: Single Building with Known Current Condition

The last case study examined within the scope of this study includes calculations made for a single building located in Çankaya, Ankara, with a roof height of 2 meters, a roof slope of approximately 30%, and tile roofing material. Values were calculated from Google Earth. The building whose roof type is gable roof appears as roof number 5 in Figure 4.20.

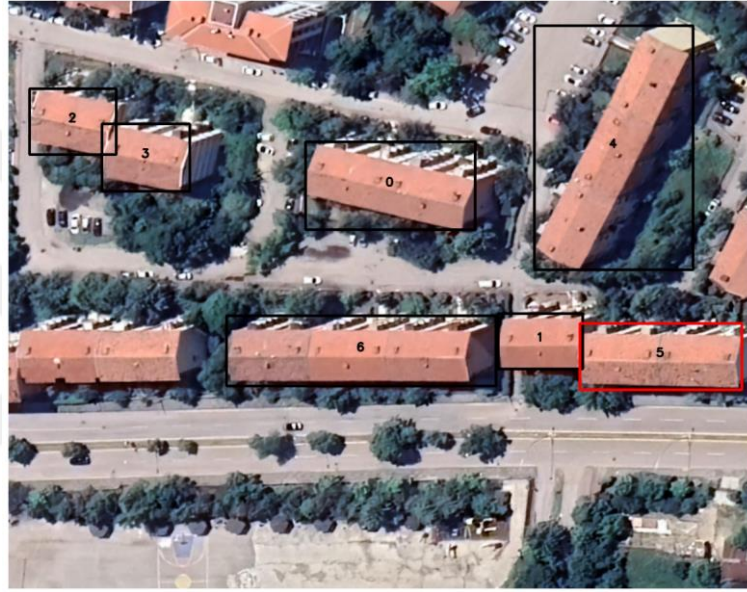
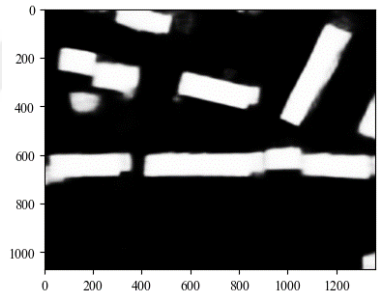


Figure 4.20 Roof IDs and Selected Roof for Case Study-8 (Developed by Author)

As seen in Table 4.34, like all other roofs in the input image, the roof (5) examined for this case study was correctly detected and classified. In addition, in line with the controls made, the roof area and the edge lengths of the roof calculated with ML Task-2 were also estimated correctly.

Table 4.34 Outputs of ML Tasks for Case study-8 (Developed by Author)

Location	Ankara, Çankaya
Input Image	
ML Task-1 Output	
ML Task-2 Output	
Visualization of Output of Merged ML Tasks	

The current effective catchment area of the selected roof is calculated as 639.95 m². The effective catchment area for different slope values is shown in Figure 4.21.

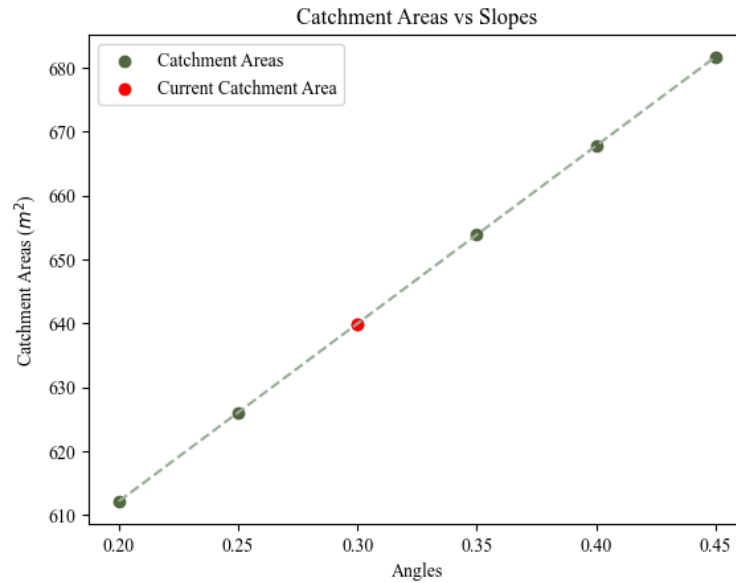


Figure 4.21 Effective Catchment Areas for Different Slope Values for Case Study-8 (Developed by Author)

The current potential RWH amount for the selected roof is calculated as 214.35 m³. If the current slope and roof type of the roof remain the same, the potential RWH values calculated for different roof materials are shown in Figure 4.22.

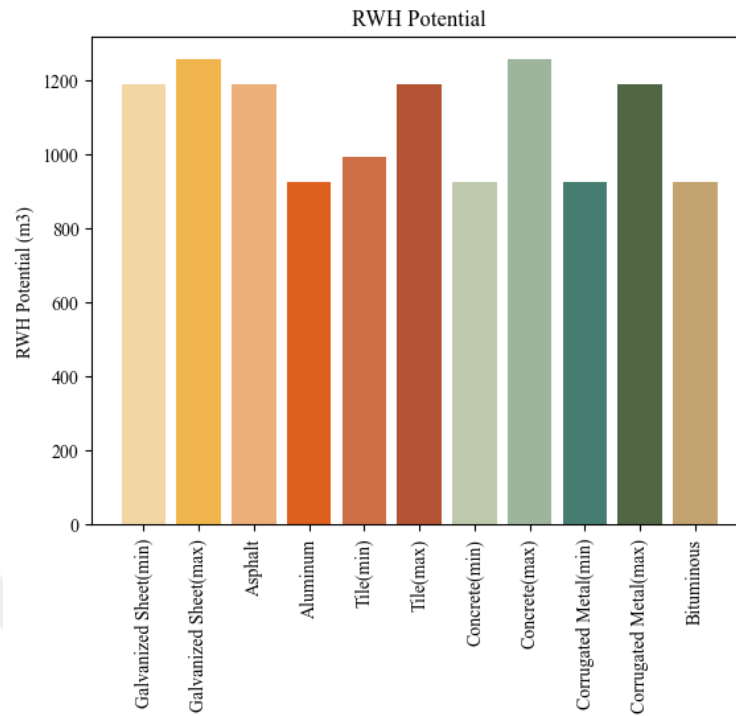


Figure 4.22 RWH Potential for Different Materials for Case Study-8 (Developed by Author)

If the roof type and materials are changed, the relationship with potential RWH changes, as shown in Figure 4.23.

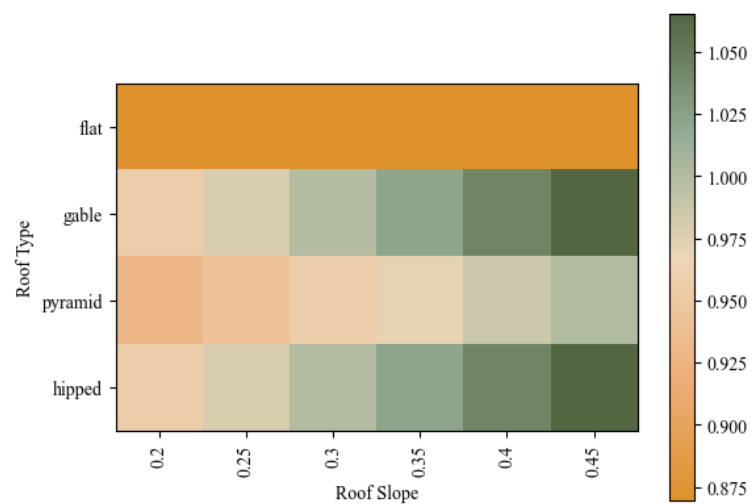


Figure 4.23 Potential RWH by Different Roof Types and Roof Slopes for Case Study-8 (Developed by Author)

As seen in Figure 4.23, if the chosen roof is flat, the maximum loss of potential RWH will be 13.1%. This amount corresponds to 27.86 m³ of water and 27860 L of water annually for the selected roof alone. Additionally, if the chosen roof is a gable roof, there will be a potential RWH gain of 6.5% if the roof slope is changed. When the roof type is pyramidal, the maximum gain increases by 0.5%, while when it is hipped, there is a potential RWH gain of 6.5%, which is the same value as the maximum gain that can be achieved in the current state of the roof. This value corresponds to 13.93 m³, or 13930 L of water, annually.

As seen in case studies, the performances of ML tasks vary depending on the input images chosen independently of each other. This situation affects the calculations made. The results and their interpretations obtained for different materials and roof slopes will be discussed in detail in the next chapter. However, the common result for all case studies is that the effective catchment area increases with the hipped roof and high-angle values. The effects of different materials on the amount of potential RWH are seen in the calculations of case studies. However, the effects of these materials on calculations when compared to each other will be discussed in more detail.

Table 4.35 Potential RWH Values for Current Roof Types for Case Study-8 (Developed by Author)

POTENTIAL RWH VALUES FOR CURRENT ROOF TYPES (m ³)						
	Current Materials (Tile and Concrete)			Different Materials (Galvanized Sheet and Metal)		
Roof Slope	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall	Minimum Annual Rainfall	Average Annual Rainfall	Maximum Annual Rainfall
30 %	7201.21	10085.72	12224.90	7601.27	10646.04	12904.07
40 %	7514.30	10524.23	12756.42	7931.76	11108.91	13465.11
GAIN	313.09	438.51	531.52	330.49	462.87	561.04

- When the roof slope is kept at the same value and the material is changed, the maximum gain is calculated as 5.55%.
- When the material is kept the same and the roof slope is changed, the maximum gain is calculated as 4.34%.
- When both the roof material and the roof slope changed, the maximum gain is calculated as 10.14%.



CHAPTER 5

CONCLUSION

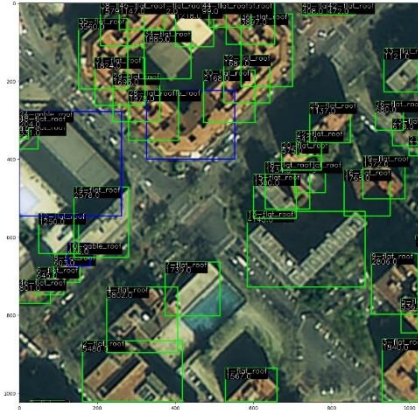
5.1 Results and Discussion

In this part of the study, the results of the tests and case studies carried out in line with the calculations made by considering the roof types, roof materials, and roof slopes at the building scale in order to increase the amount of rain that can be collected in the built environment are included.

First of all, when the performances of the machine learning tasks are evaluated, it is clear that both ML tasks are of great importance in performing the calculations suggested within the scope of the study. If at least one of these tasks runs with low performance, it negatively affects all calculations to be made. One of the factors that may negatively affect the performance of ML tasks when considered in order is that in ML Task-1, in which the DFC23 dataset is used in training, Google Earth images are used as input, unlike the images in the dataset because different resolution values, colors and perspective angles affect the performance of the ML task.

Although the successful performance of machine learning models can be considered high in detecting roofs and correctly classifying roof types, both the accuracy rate of the labels in the dataset and the fact that the satellite images and photographs taken from Google Earth affected the results. For instance, one of the input images taken from the dataset within the scope of this study is a satellite image of Barcelona. In Table 6.1, the image from Barcelona in the dataset and the image taken from Google Earth with the same coordinates are compared.

Table 5.1 Comparison of Different Image Outputs of Same Location (Developed by Author)

	Image Taken From The Dataset	Image Taken From The Google Earth
Input		
Output		

As seen in Table 6.1, although it is included in the dataset, Google Earth images taken from the same coordinates show a lower performance in terms of detection and correct classification of roofs when used as input. In this case, images taken from completely different locations are expected to have different performances in ML tasks where they are used as input.

Secondly, when considering the proposed calculations, different roof materials, and slopes, it was seen that although the effective collection area varies according to different roof types, as a result of the calculations made, the roof with the maximum ECA value for the same slope value is the hipped roof. As the slope angle increases, the amount of rain that can be collected increases. When the roofing materials

selected within the scope of this study are examined, it is seen that the amount of rain collected from metal surfaces on flat roofs and on pitched roofs, when the maximum runoff coefficient values depending on the slope of the surface on which the material is applied are taken into consideration, the amount of rain collected from surfaces with galvanized sheet and concrete materials is relatively higher. In addition, the role of green roofs in collecting rainwater was taken into account, but since the amount of rain to be collected from the roof surface was calculated within the scope of this study, the runoff coefficient value in green roof applications, which varies depending on the type of vegetation used, is lower compared to the values of other materials. The relationship between potential RWH values for different roof types and materials is shown in Figure 5.1 and Figure 5.2.

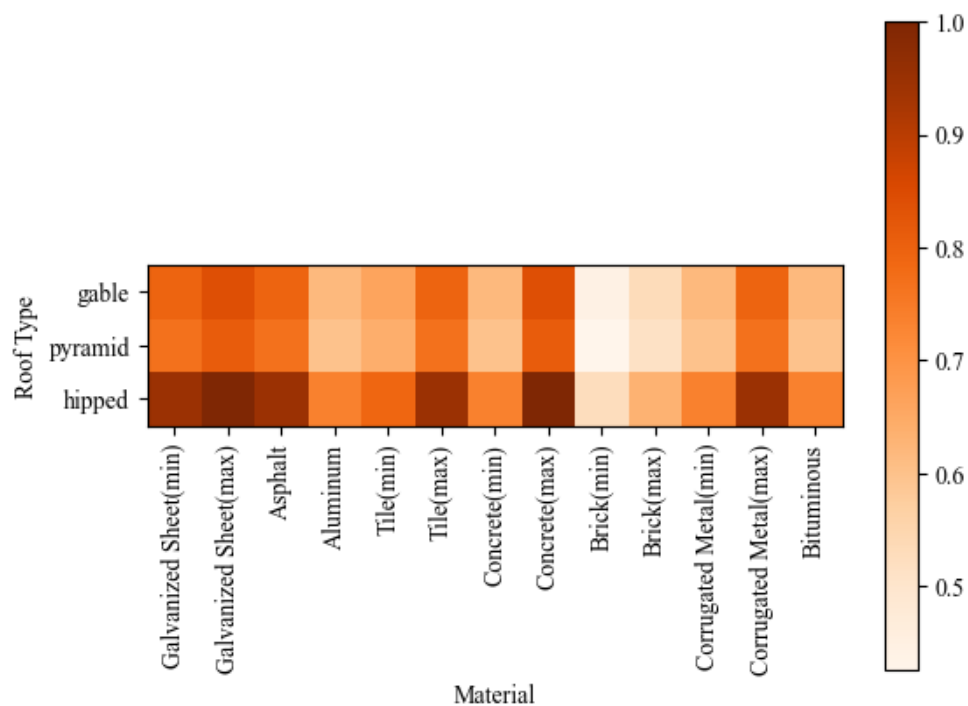


Figure 5.1 Relationship Between Roof Materials and Potential RWH amount for Pitched Roofs (Developed by Author)

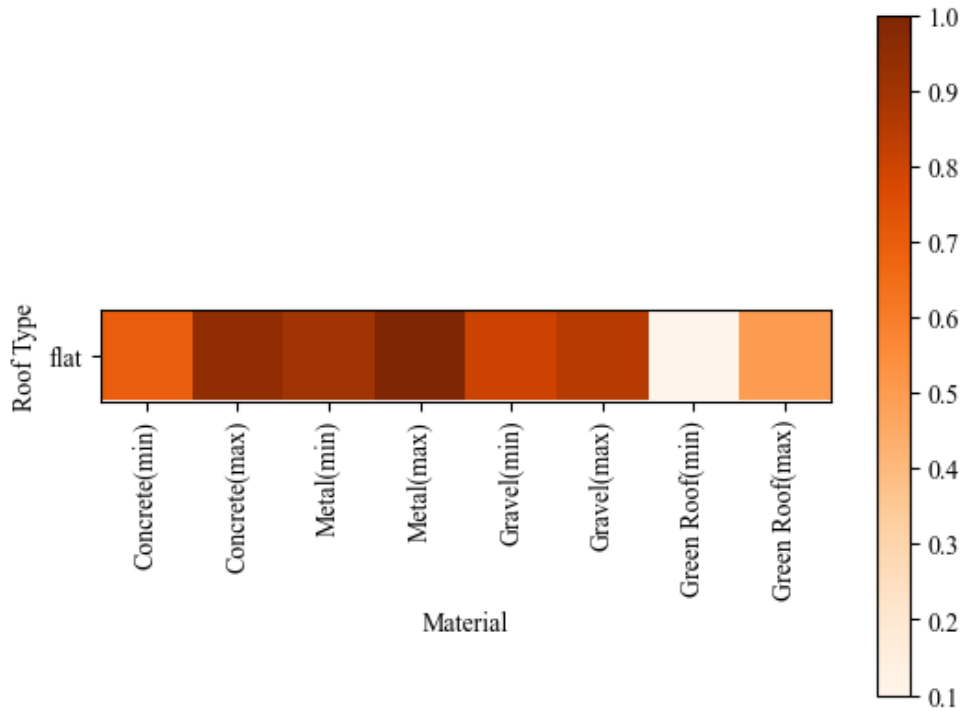


Figure 5.2 Relationship Between Roof Materials and Potential RWH amount for Flat Roofs (Developed by Author)

It is thought that these calculations can be increased for different materials and roof types, and the amount of rainwater that can be collected can be increased by using different roof designs and materials in modern architecture with the advancements of technology.

In addition, each of the examples selected as a case study was tested with Google Earth images taken from different geographical regions of Turkey. In the selection of these images, it was consciously chosen to include different numbers of roofs, the distances between the roofs to be as diverse as possible, and the buildings to be positioned differently. Thus, it is aimed to test ML models in different ways in each case study. ML tasks performed differently in each case study. Although the current situation cannot be evaluated in case studies where roof types cannot be classified the projected roof area is estimated correctly, potential RWH values of projected roof areas can be calculated for different situations when planning in the built environment.

Within the scope of this study, in line with research aiming to increase the rainwater that can be collected in the built environment, the stages of defining and classifying roofs on an urban scale and calculating the projected areas and side lengths were carried out. Later, a method was developed in which different roof materials, roof types, and roof slopes were suggested to increase the amount of rainwater that could be collected. Many different factors play a role in the selection of roofing materials. Climatic conditions, architectural texture, economic factors, and roof slopes are just a few of them. However, in this study, calculations were made for some specified roof materials, slope values accepted in Turkey, and commonly used roof types.

Additionally, it is also possible to use plans that can be obtained through municipalities in determining and classifying roof types. However, thanks to the machine learning models trained and used within the scope of this study, it is possible to quickly detect and classify roof types in any region, in cases where it is not possible to reach them through municipalities.

Lastly, another issue is that building heights, which have a large potential for collecting rainwater, were not evaluated within the scope of this study. The potential amount of rain to be collected using only aerial photographs and information about the projected areas of the buildings was calculated only for the roof surfaces. However, by including the height of buildings, the rain load that can be collected can be increased significantly, so that the decisions to be made in planning and design can be reviewed to increase the rainwater that can be collected.

5.2 Further Work and Limitations

It is thought that with the advances obtained within the scope of this study and the accurate prediction of roof types, a step has been taken for optimizations in different disciplines working both in the field of rainwater collection and the built environment. If improvements are to be made in roof design and rainwater harvesting and control in future studies, the correct classification of roof types will be an important step. This is because, as previously mentioned and illustrated by examples,

the behavior and collection mechanisms of rainwater on different roof types differ greatly. In future studies, research can be carried out on the controlled direction of rainwater collected from the roof surface, materials, and roof types can be expanded, and in addition to this study carried out at any built environment, the amount of rainwater to be collected can be increased by making improvements at the detail scale.

It is also possible to achieve significant gains by identifying and effectively using other elements of the built environment, such as roads and pavements, for the potential amount of rain that can be collected by identifying and classifying roofs. It is thought that developing research on rainwater harvesting at urban scale, in addition to the building scale in the built environment, will make a great contribution in future studies.

In addition, it is possible to use the method developed within the scope of this study in different studies that have the problem of determining the effective surface area. Thus, it is possible to make progress not only in rainwater harvesting, which is the subject of this research, but also in many different issues such as the effective placement of solar panels.

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