GRID ARCHITECTURE, PLANNING AND DESIGN JOURNAL
GRİD MİMARLIK, PLANLAMA VE TASARIM DERGİSİ

Vol. 8, No. 2, 2025, 486-518 / Cilt 8, Sayı 2, 2025, 486-518 / DOI: 10.37246/grid.1491361

Exploring the potentials of adaptive reuse of cisterns in historic cities: Case of Safranbolu

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Abstract

This study investigates a hypothetical scenario that addresses challenges such as the rapid depletion of water resources and increasing water demands driven by population growth, global warming, climate change, and indiscriminate water usage. Safranbolu, a city noted for its historically protected architecture, serves as a case study to illustrate these challenges. Rather than asserting a definitive solution, the research examines the potential of adaptive reuse of existing cisterns to enhance water efficiency in buildings. The literature review identified that the impacts of climate change and increasing population significantly contribute to higher water demand, which in turn affects both the availability and quality of water resources. It was concluded that implementing water-saving devices and expanding wastewater recycling can be effective strategies to improve water efficiency. Moreover, the adaptive reuse of cisterns and other historical water structures, which are abundant in cities like Safranbolu, may offer supplementary potential for advancing water efficiency goals, although feasibility and technical considerations remain beyond the scope of this study. In Safranbolu, a field study was conducted in two phases and included the examination and documentation of 11 significant cisterns. Additionally, detailed water consumption data; daily, monthly, and annually, from 12 mansion (guesthouses) and 13 houses within the city were collected through a structured questionnaire. The survey also provided insights into the spatial use of water and the application of water-saving technologies in these buildings. Preliminary findings suggest that the water consumed by these 25 buildings, combined with greywater reuse and limited rainwater collection, could potentially be partly managed, stored, and treated in local cisterns. However, this remains a theoretical approach that does not fully address economic feasibility, technical capacity, or maintenance processes. Despite these limitations, reusing cisterns may help preserve historical water structures while contributing to more sustainable water management in heritage urban settings.

Highlights

- Rising consumption in agriculture, industry, and residential sectors highlights the critical global issue of water scarcity.
- Water efficiency might be enhancing through the adaptive reuse of existing cisterns, particularly in historic cities like Safranbolu.
- Safranbolu's preserved architecture serves as a case study illustrating challenges and solutions in sustainable water management, including the preservation of historical water structures.

Keywords

Climate change; Sustainability; Cisterns; Safranbolu; Adaptive reuse

Article Information

Received:
28.05.2024

Received in Revised Form:
14.02.2025

Accepted:
14.05.2025

Available Online:
28.10.2025

Article Category

Research Article

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Kahyaoğlu, İ. & Harputlugil, T. (2025). Exploring the potentials of adaptive reuse of cisterns in historic cities: Case of Safranbolu. *GRID Architecture Planning and Design Journal*, 8(2), 486-518.

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Vol. 8, No. 2, 2025, 486-518 / Cilt 8, Sayı 2, 2025, 486-518 / DOI: 10.37246/grid.1491361

Tarihi şehirlerde sarnıçların yeniden kullanımı üzerine bir araştırma: Safranbolu örneği

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Anahtar Sözcükler

İklim değişikliği; Sürdürülebilirlik; Sarnıçlar; Safranbolu; Uyarlanabilir yeniden kullanım

Öz

Bu çalışma, su kaynaklarının hızla tükenmesi, nüfus artışı, küresel ısınma, iklim değişikliği ve bilinçsiz su kullanımı gibi etkenlerle artan su talebi sorunlarını ele alan varsayımsal bir senaryoyu incelemektedir. Tarihi dokusu koruma altına alınmış mimarisiyle tanınan Safranbolu kenti, bu sorunları örneklemek üzere bir vaka çalışması olarak seçilmiştir. Araştırma, mevcut sarnıçların uyarlanarak yeniden kullanımının binalarda su verimliliğini artırma potansiyelini değerlendirmektedir. Literatür taraması, iklim değişikliği ve nüfus artışının su talebini artırarak su kaynaklarının miktarını ve kalitesini olumsuz etkilediğini göstermiştir. Su tasarruflu uygulamalar ve atık suyun geri dönüşümünün artırılması, su verimliliğini geliştirmek için etkili stratejiler olarak belirlenmiştir. Ayrıca, Safranbolu gibi kentlerde bol miktarda bulunan sarnıçlar ve diğer tarihî su yapılarının yeniden kullanımı, su verimliliği hedeflerine ulaşmada ek bir potansiyel sunabilir. Ancak bu yaklaşımın uygulanabilirlik ve teknik boyutları çalışmanın kapsamı dışında bırakılmıştır. Safranbolu'da gerçekleştirilen saha çalışması iki aşamadan oluşmakta ve 11 önemli sarnıcın incelenmesi ve belgelenmesini de içermektedir. Buna ek olarak, kentteki 12 konak (pansiyon) ve 13 evden oluşan toplam 25 yapıdan günlük, aylık ve yıllık su tüketim verileri bir anket aracılığıyla toplanmıştır. Anket ayrıca bu binalarda suyun mekânsal kullanım türleri ile su tasarrufu sağlayan teknolojilerin uygulanmasına dair önemli bilgiler sunmuştur. Ön bulgular, bu 25 binada tüketilen suyun, gri suyun yeniden kullanımı ve sınırlı yağmur suyu hasadı ile, yerel sarnıçlarda kısmen yönetilebileceğini, depolanabileceğini ve arıtılabileceğini göstermektedir. Ancak bu yaklaşım, ekonomik, teknik ve bakım boyutlarını kapsamayan teorik bir çerçevedir. Tüm kısıtlara rağmen, sarnıçların yeniden kullanımı hem tarihî su yapılarının korunmasına hem de kültürel miras alanlarında daha sürdürülebilir bir su yönetimine katkı sağlayabilir.

Makale Bilgileri

Alındı:
28.05.2024

Revizyon Kabul Tarihi:
14.02.2025

Kabul Edildi:
14.05.2025

Erişilebilir:
28.10.2025

Makale Kategorisi

Araştırma Makalesi

Öne Çıkanlar

- Tarım, endüstri ve konut sektörlerinde artan tüketim, su kıtlığının önemli bir küresel sorun olduğunu ortaya koymaktadır.
- Su verimliliği, özellikle Safranbolu gibi tarihi şehirlerde mevcut sarnıçların adaptif yeniden kullanımıyla artırılabilir.
- Safranbolu'nun korunmuş mimarisi ve tarihi su yapıları sürdürülebilir su yönetimindeki zorlukları ve çözümleri gösteren bir vaka çalışması olarak ele alınmaktadır.

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Kahyaoğlu, İ. & Harputlugil, T. (2025). Tarihi şehirlerde sarnıçların yeniden kullanımı üzerine bir araştırma: Safranbolu örneği. *GRID Mimarlık Planlama ve Tasarım Dergisi*, 8(2), 486-518.

INTRODUCTION

Due to the developments in industry and economy, the urban population is increasing day by day. Accordingly, the need for infrastructure, transportation, housing, industry, and energy increases with the growth of cities. In rapidly growing cities, the demand for water which is vital for sustaining life, and the amount of water consumption also increase in parallel with population growth. With increasing consumption, limited water resources are becoming even more limited. Especially in large cities, intensive water consumption brings along problems such as wastewater and resource scarcity (Mazı and Tan, 2009; Okello et al., 2015). According to a United Nations report (2020), water usage has increased six-fold over the past century, with the trend continuing steadily. This underscores the critical importance of preserving and efficiently utilizing water resources.

Historical cities with protected cultural and architectural heritage, such as Safranbolu, are also vulnerable to the effects of global warming and climate change. In most of the buildings in historical cities with protected architectural heritage, the sanitary water supply system may be inadequate or outdated. Consequently, the water efficiency of these buildings cannot be easily adapted to modern conditions. However, while there is an assumption that reusing historical water structures might lead to improved water efficiency, this research focuses on examining a hypothetical scenario of adaptive reuse rather than providing a definitive solution. Safranbolu, a historical city listed in UNESCO's world heritage list, has water structures such as wells, fountains, rainwater depots, snow wells, and cisterns, which could offer significant options for storing and managing water. This study investigates the potential of reusing cisterns primarily for storage of greywater or other non-potable sources as a means of enhancing water use efficiency in these historical settings.

Nevertheless, it is important to note that certain dimensions—such as economic feasibility, maintenance processes, and technical capacity—are beyond the current scope and are therefore not fully addressed. Although numerous studies have examined the adaptive reuse of historical water structures and cisterns -such as Lepcha et al. (2024), Sharma and Ji (2024), the present research approaches the issue by exploring only the water storage capacity aspect, thus contributing a limited yet focused perspective on how cisterns might help mitigate increasing water demand.

As a tentative solution to the problems of rapid population growth, global warming, climate change, and rising water demand in historical cities, it is recommended to utilize abandoned water structures produced in the past in historical areas. It has been determined that especially cisterns can be reused after repair and maintenance works. However, this paper does not claim to offer a comprehensive model for full-scale implementation; rather, it seeks to illuminate the extent to which historical cisterns if repurposed might contribute to water efficiency.

Aim and Motivation of the Research

In search of solutions to the problems mentioned, this study explores the potential of adaptive reusing of abandoned cisterns in a historical city like Safranbolu as part of a hypothetical scenario and examines their possible contribution to water efficiency. Within the scope of the study, numerical values were used to determine the suitability of the cisterns for reuse and to reveal the relationship between their water storage capacity and local water consumption. By analysing these data, a framework is developed to evaluate how cisterns might contribute to water efficiency and which strategies could be developed. While broader variables such as cost-effectiveness, technical feasibility, and long-term maintenance fall outside the immediate scope, this research is important in terms of raising awareness about revitalizing the forgotten architectural treasure of cisterns in historical cities, potentially recycling water, and making it available for urban use.

Scope of the Research

The research focuses on a specific area within Safranbolu, in the neighbourhoods of Barış and Atatürk, where cisterns are abundant. The water consumption data of residential buildings and mansion hotels in this area are determined through surveys and invoices (consumption-based documents). By comparing the obtained water consumption data with the capacities of cisterns, this study investigates to what extent the water usage in the region could potentially be met by reusing the cisterns, acknowledging that this remains a theoretical exercise without a detailed feasibility assessment.

Method of the Research

In the first phase of the methodology used in the study, a literature review was conducted on the effects of climate change and global warming within the scope of water efficiency, strategies to increase water efficiency, wastewater recycling, water storage elements, and adaptive reusing of cisterns. In addition, sources related to the historical city of Safranbolu and water structures in the region were also analysed.

In the second phase, fieldwork was carried out in the region where the cisterns are densely populated. In the first stage of fieldwork, the cisterns identified in Safranbolu were mapped and categorized according to their use, capacity, and location. Following this, a survey was conducted to determine the water consumption of the living spaces in the study area.

In the last phase, the results of the survey were analysed in various forms. Then, by comparing the determined cistern capacities with the water consumption data in the region, it was examined to what extent enhanced water efficiency might be achieved by adaptive reusing of the cisterns, bearing in mind that further research would be needed to account for technical, economic, and maintenance considerations.

LITERATURE REVIEW

The Industrial Revolution, which began in the late 19th century, accelerated the use of fossil fuels, thereby intensifying the impact of human activities on the environment (Cesur, 2014; Türkeş, 2022). Over the last century, rising greenhouse gas emissions, global warming, depletion of natural resources, and climate change have been closely linked to industrial growth and urban expansion (Cesur, 2014). Climate change is expected to exacerbate hydrological extremes, causing irregular water regimes, reduced freshwater availability, and shifts in precipitation patterns (IPCC, 2022). These changes heighten the risks of water scarcity for both agricultural and domestic needs, potentially leading to public health concerns, ecosystem degradation, and economic losses. In historical urban centers where aging infrastructure intersects with protected cultural and architectural heritage the adverse impacts of climate change can be even more pronounced. Rising temperatures and drought conditions, for instance, may intensify water scarcity, while extreme weather events and flash floods can endanger vulnerable heritage buildings (Cassar, 2009; Sabbioni et al., 2010). Factors such as rapid population growth, urbanization, and limited adaptive capacity further strain these cities' ability to cope with climate-induced water challenges (Türkeş, 2022). Consequently, safeguarding water resources and ensuring sustainable water management have become urgent priorities, underscoring the need for approaches that integrate conservation, reuse, and efficient resource utilization (Daly, 2007; Hostovsky, 2014; Aytuğ, 2014).

Amid these pressures, historical cities like Safranbolu face unique vulnerabilities tied to their distinctive architectural fabrics and heritage assets. While its UNESCO World Heritage status promotes cultural preservation, safeguarding the city's water infrastructure under evolving climatic conditions remains a critical task. Existing research indicates that water scarcity is likely to worsen if climate patterns continue to shift and temperatures rise. (IPCC, 2022; Türkeş, 2022). Although the present study does not incorporate a detailed scenario-based analysis, it seeks to contribute to adaptation dialogues by exploring how traditional water storage solutions—particularly cisterns—could be repurposed to mitigate growing water demands. By building on broader climate adaptation strategies (e.g., integrating rainwater harvesting, greywater systems, or modern filtration methods), the adaptive reuse of cisterns may offer a partial and localized response to the challenges posed by global warming. Future investigations might adopt model-based approaches, for instance, to quantify long-term cistern performance under different climate projections, further supporting the city's resilience initiatives and aligning with sustainable development goals (McPhearson, T. et al, 2016).

In terms of conserving water resources, sustainability involves the preservation, purification, management, and efficient use of water. A framework for regional-scale water resource management and the development of water-saving methods are necessary. The conservation of water resources can be achieved by minimizing water use and implementing strategies for reuse. The use of rainwater and greywater sources are also among the widespread methods for efficient and recycled water use (Mays, 2007; Thornton et al., 2006).

While the number of contemporary studies on the adaptive reuse of cisterns remains limited, a few noteworthy examples do exist. Lepcha et al. (2024) provide a comprehensive review of rainwater harvesting solutions, highlighting their potential to address water scarcity in modern contexts. Sharma and Ji (2024) argue that historical water management structures such as dams, reservoirs, canals, and cisterns, effectively mitigated droughts and floods in past societies, and they can still offer valuable insights for current climate adaptation efforts. Rosado-García et al. (2022) emphasize that architectural preservation in Europe often centers on monumental buildings, overlooking civil and industrial heritage, including historical hydraulic works. Their research on a 150-year-old underground reservoir in Madrid shows how such structures can be preserved and partially repurposed without compromising structural integrity, underscoring the importance of safeguarding them for future generations. In Türkiye, Emre N. Y. (2014) provides a significant case study on the Yerebatan Basilica Cistern, illustrating how a historical cistern can be integrated into contemporary urban life while retaining its cultural importance. Additionally, Vetter and Rieger (2019) examine the use of cisterns in agricultural contexts, further demonstrating the diverse applications and enduring relevance of these traditional water-harvesting systems.

Water is a basic need for human life, and various methods and structures are used to meet this need. Throughout history, water has contributed to the establishment and development of civilizations and many civilizations settling near rivers and lakes. After the establishment of settled life, water plays a significant role in the daily lives and settlement patterns of communities (Aykutlu and Pilehvarian, 2022). Water structures, which also reflect the architectural and technical skills of civilizations, facilitate the transportation and storage of freshwater resources to inhabited areas. The earliest water structures include irrigation canals, water transport systems, and cisterns for agricultural purposes (Güngör 2021). Important examples of such structures can be found in Anatolia, which has hosted many civilizations. As civilizations developed, the demand for water increased, and water structures gained importance. Various water structures were constructed during the Hittite, Urartian, Roman, Byzantine, Seljuk, and Ottoman periods. These structures include aqueducts, canals, cisterns, water mills, fountains, dams, and wells, which were used for water storage and distribution purposes (Aykutlu and Pilehvarian, 2022; Öziş et al., 2008).

Cisterns, water storage structures, have played a significant role in meeting the water needs and establishing living spaces from ancient times to the present. They can be constructed in two different forms: open and closed (Kerim and Süme, 2018). Open cisterns are generally collection pools used for water accumulation, while closed cisterns are typically built underground for the purpose of water storage (Emre, N.Y., 2014; Yıldırım, 2016). Cisterns were built for different purposes such as providing water from water sources, meeting water needs, levelling rough terrain and shelter for various purposes. Furthermore, cisterns have served different functions over time and have been utilized as agricultural or social areas (Yıldırım, 2016).

Within the continuity of time, societal changes affect human needs, leading to the transformation of the spaces in which people live over time. Buildings interact with social structures, change and evolve according to the changes occurring in society. However, various difficulties are encountered when buildings fail to adapt to the changing conditions of the present time. As a result of these challenges, buildings that do not meet the needs of today must be demolished or refunctioning for reuse (Douglas, 2006).

The reuse of historical buildings has become popular in recent years. Among the reasons for this are existing grants, timing, prevention of decay, efficiency improvement, change of use, legal restrictions, preservation, and environmental sustainability. Especially, environmental problems such as climate change and greenhouse gas emissions have gained importance, and in this context, the reuse of existing buildings with a new function is preferred more. The concept of adaptive reuse is defined as a transformation process that brings historical buildings back to life. The purpose of reuse is to refunctioning structures to meet the needs of the present while transferring them to future generations when the original function of the structures cannot be realized.

It is widely recognized that the first theoretical approach to the adaptive reuse of historic buildings— a concept with various definitions in scholarly literature—emerged in the 19th century. According to Plevoets and Cleempoel (2011), the optimal method for preserving historic buildings involves assigning them new functions. Adaptive reuse can be defined either as the process of extending a building's life and utility (Yıldırım and Turan 2012), or as the capacity to meet current needs and adapt to future changes while enhancing the building's value (Schmidt et al., 2009). As a crucial strategy for conserving cultural heritage, adaptive reuse not only supports the sustainable transformation of buildings but also has significant environmental, economic, and social impacts, thereby contributing to sustainability.

Adaptive reuse of heritage buildings also preserves architectural, social, cultural and historical values and protects not only the structure but also the effort, skill and dedication of the original builders (Love and Bullen, 2011). Economically, adaptive reusing an existing building is a cheaper and faster method compared to demolishing and constructing a new one. Additionally, reused buildings appreciate and contribute to the national economy (Douglas, 2006). Environmentally, adaptive reuse reduces the use of natural resources and decreases energy consumption. Historical buildings contribute to socio-cultural sustainability and reviving dormant industrial structures provides social benefits (Aydın and Okuyucu, 2009). Well-planned adaptive reuse of an architectural or historical building also brings prestige to its owner (Douglas, 2006). By preserving historic buildings, adaptive reuse ensures the continuation of the cultural identity of a society.

Although there are advantages to adapting an existing building, there are also various constraints. These constraints include functional, technical, economic, environmental, and legal limitations. A reused old building may not be suitable for a new function and may not fully meet user demands. Reused building may have a shorter lifespan, and maintenance costs can be high (Douglas, 2006). Additionally, adaptive reuse of heritage buildings offers many sustainability benefits but also presents significant challenges, mainly related to technical difficulties. Materials used in these buildings are often no longer readily available and may need to be specially manufactured. Even if materials are sourced, finding qualified craftsmen locally or nationally can be a challenge. These issues can affect the economic feasibility of adaptive reuse projects and may make them impractical for developers as investments. (Love and Bullen, 2011).

When historical structures are used with an existing or new function, the main objective is to preserve the structure. Within this scope, reuse strategies should be implemented for buildings while maintaining a certain balance. The Principles of Intervention to Architectural Heritage, published by International Council on Monuments and Sites (ICOMOS), specify the principles of intervention for buildings. These principles emphasize preserving the authenticity of the building, not altering its characteristics, revealing the traces of the past, ensuring that the interventions are renewable or removable, establishing control structures and legal frameworks, and emphasizing the documentation process (ICOMOS, 2013).

Cisterns, historical water structures, were once vital for meeting the water needs of cities but are now largely unused. This research aims to identify potentials of adaptively reuse these cisterns for their original purposes following maintenance and repair. The literature reveals several studies focused on the conservation and enhancement of cisterns, including works by Enriquez et al. (2017), which examines cisterns in Santorini, and additional studies at Alanya Castle (Yetkin and Akman, 2021) and in Urla (Dere, 2022).

Safranbolu, the focus of this study, is a city in the Western Black Sea Region of Türkiye that has preserved its historical fabric, maintaining its material and formal characteristics from the past to the present. The city, developed within valleys divided by rivers, comprises three historically significant districts: Çarşı, Kıranköy, and Bağlar. Approximately 40% of the traditional residential buildings have been preserved, with most houses constructed from stone, wood, and earth/adobe materials (Bozkurt and Altınçekiç, 2013). Conservation efforts to protect Safranbolu's historical fabric and cultural heritage began in 1975 (Kuş, 2003; Özdemir, 2011). These efforts have led to the city's inclusion in the UNESCO World Heritage List, which has boosted tourism and provided financial resources for preserving its architectural heritage. Safranbolu is home to numerous historical artifacts, predominantly from civil architecture. Figure 1 illustrates the positioning of houses in the Safranbolu bazaar area.

Figure 1. The layout of traditional Safranbolu Houses (Photo: Author/s archieve)

Safranbolu is a settlement rich in water resources, which has led to a proliferation of various water structures in addition to traditional residential buildings. The availability of ample and diverse water sources has cultivated a unique water culture within the city. Traditional houses in Safranbolu feature several water-related sections, including pools in the sofa areas, bathhouses, fountains, toilets, and kitchens. The city also boasts other water structures such as courtyard fountains, open-air bathhouses, cisterns, and wells. Different water storage methods are evident across various regions of Safranbolu: wells and fountains are prevalent in the Bağlar neighborhood, cisterns in the Kıranköy district, and fountains dominate the Çarşı area. Additionally, some homes have independent pool rooms in their gardens (Bölükbaşı Ertürk et al., 2013). Figures 2(a,b), 5, and 6 illustrate some of the cisterns among the water structures in Safranbolu.

Figure 2(a,b): The cistern in the garden of Muhsin Bey Mansion (Photos: Author/s archieve)

Figure 3. The cistern in the Birdane Mansion (Photo: Author/s archieve)

Figure 4. The cistern in the garden of Nimet Hanım Mansion (Photo : Author/s archieve)

Figure 5. The well in the garden of the Birdane Mansion (Photo Author/s archieve)

Figure 6. The Rainwater tank in the garden of Erciyes Mansion (Photo: Author/s archieve)

The regions of Kıranköy and Yazıköy in Safranbolu were inhabited by Greeks, and they were used differently than the areas occupied by Turks. The Greek population consisted of individuals who spoke Turkish and were Christians. In 1882, Safranbolu had 6,827 Muslim households and 352 Greek households. In the years 1896-1897, there were 7 Greek neighbourhoods and a population of 2,684 Greeks identified. Greeks were predominantly engaged in arts and trade and had large mansions. After the population exchange in 1921, the houses and lands of Greeks were shared among Turkish immigrants. These changes had an impact on their lifestyles and housing structures (Ulukavak, 2017; Deniz and Ersöz, 2020). Cisterns, used as water storage structures in Safranbolu, are generally located in the basements or ground floors of houses in the Kıranköy neighbourhood, where Greeks were densely settled, while some are also found in gardens (Kılıç, 2018; Ulukavak, 2017).

Cisterns found in Greek houses are generally closed or filled with soil today. Cisterns, which appear as vaulted water reservoirs, have varying water levels depending on rainfall and seasons. Wells are water sources that utilize groundwater and are usually found in the Bağlar district (Ulukavak, 2017). Rainwater reservoirs, on the other hand, are located in the gardens of Greek houses in Kıranköy and are used for collecting rainwater. Fountains are generally located in the market area and were used by the public for domestic purposes and drinking water. It is estimated that there are 138 ornate and inscribed fountains in Safranbolu, but their significance has decreased over time and many have dried up due to neglect (Ulukavak, 2017). Pools are also part of Safranbolu's water culture and are found in the sitting areas or gardens of houses. Pools serve various functions such as fire safety, irrigation, and relaxation (Ulukavak, 2017).

This research distinguishes itself from previous studies by adopting a comprehensive adaptive reuse framework focused on maximizing the potential of historic water infrastructures, such as cisterns, within tightly regulated heritage city centers. Rather than solely emphasizing conservation, the study integrates contemporary technological solutions supported by quantitative calculations and feasibility analyses to demonstrate how architectural heritage can be leveraged to address modern challenges like water scarcity and resource efficiency. In doing so, it not only reinforces the cultural value of historical structures but also advocates for their functional revitalization, encouraging other cities on the UNESCO World Heritage List to explore similar strategies. By illustrating how traditional water systems can be adapted with current technologies, this research offers a replicable model for safeguarding and repurposing heritage buildings globally, ensuring their continued relevance and utility in the face of evolving urban and environmental demands.

MATERIAL AND METHOD

The method of research consists of four steps: literature review, field study, evaluation of outputs, and quantitative calculations for assessing potential water savings. In the first step, a literature review is conducted on climate change, sustainability, water storage elements, and cisterns. The second step involves planning and conducting a field study to test the hypothesis that cisterns can contribute to ensuring water efficiency in the context of combating climate change. In the initial phase of the field study, the study area is determined, and the current condition of cisterns is documented. In the second phase, the living areas in the region with a high concentration of cisterns were identified, and consumption data related to these living areas were collected through user statements, water bills, and administered surveys. The survey was conducted through in-person (face-to-face) interviews between May and December 2022, following the approval of the ethics committee. After data collection, the water consumption records were aggregated and

Vol. 8, No. 2, 2025, 486-518 / Cilt 8, Sayı 2, 2025, 486-518 / DOI: 10.37246/grid.1491361

statistically examined to determine minimum, maximum, and average consumption levels. These findings informed subsequent calculations that assess whether reactivating cisterns in the designated area can feasibly meet some or all of the identified water demand. Although tables and graphs are later used to present these results visually, the core analytical methods include comparative consumption analysis, capacity-demand matching, and volumetric calculations.

The theoretical framework of this research outlines the following structure: current cisterns undergo renovation to enable them to collect and store wastewater from designated buildings. This wastewater is then treated on-site using integrated wastewater treatment systems within the cisterns. The objective is to use the treated water for residential and urban applications. To support this framework, wastewater flow rates and qualities are first estimated based on survey data and historical consumption patterns**.** The selection of wastewater treatment technology to be integrated into the cisterns takes into account the quality and quantity of the wastewater stored. Factors such as cistern capacity, site conditions, and the quality of treated water are also considered to determine the most efficient treatment systems that utilize minimal space. Figure 7 provides a schematic section of the designed system for greywater reclamation; however, the underlying approach involves evaluating potential treatment methods (e.g., biological filters, membrane systems) against the projected flow volumes and pollutant loads calculated from field data.

Figure 7. Section Diagram of Proposed Theoretic Greywater Treatment System

In this research, the use of membrane bioreactor (MBR) treatment technology is proposed for domestic wastewater treatment. The use of membrane bioreactor (MBR) technology for municipal wastewater treatment and reuse is becoming increasingly popular worldwide. By combining traditional activated sludge treatment with low-pressure membrane filtration, MBR is appealing to water reuse planners due to its compact design, ability to produce high-quality effluent consistently, and low operator maintenance needs (Adham and DeCarolis, 2007). However, membrane bioreactor has some challenges, especially related to membrane fouling and concentration polarization. The operation and maintenance costs of membrane bioreactors can be high due to membrane fouling. Membrane fouling leads to permeability losses and consequently increases energy consumption (Song et al., 2008).

The size of the systems used for greywater treatment is determined separately for each treatment system based on the requirements. Calculations take into account the characteristics of the installation site, water demand, and greywater quantity. In the designed greywater recycling system in this study, various equipment is needed in the building structure and tanks. Within the building, in addition to the system carrying the tap water, there should be a separate pipeline carrying the black wastewater connected to the sewer network and a pipeline carrying the greywater from showers, sinks, washing machines, and dishwashers. Additionally, if rainwater and surface runoff are also to be treated and reclaimed, another pipeline should be present for collecting rainwater and surface runoff. Greywater is transported to the greywater collection tank in the tanks through the mentioned pipeline. The stored greywater is then sent to the membrane bioreactor tank via a pump. Here, the water undergoes biological treatment followed by various filtration processes, is treated, transferred to the clean water tank, and becomes suitable for use. Ventilation should also be provided to prevent potential odours, and the ventilation pool can be one-third the size of the standard dimension. Furthermore, there is no need for a final settling tank during biological treatment. In this research, the selected membrane bioreactor system consists of the following elements in order: screen (filter), greywater tank, treatment tank with membrane filters, and clean water tank. Pipes should be designed to prevent the attachment of substances such as hair that may be present in greywater and cause problems in practice. Filters, pumps, and other equipment should be easily accessible for repair and maintenance.

Outputs of the Field Study

In addition to the literature research, information about the cisterns discovered to be densely located in Kıranköy was obtained by meeting to the municipal authorities of the city and the tradesmen of the neighbourhood. In the light of the data obtained, it was determined that there are cisterns in Atatürk, Barış and Bağlarbaşı neighbourhoods. The identified cisterns are marked on the maps in Figures 8(a, b) and 9(a,b).

Vol. 8, No. 2, 2025, 486-518 / Cilt 8, Sayı 2, 2025, 486-518 / DOI: 10.37246/grid.1491361

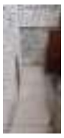
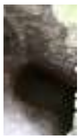
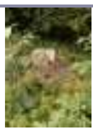
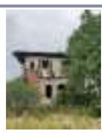
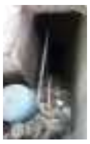
Figure 8(a,b): Map of Safranbolu (left) and Atatürk and Barış Neighborhoods (right)

Figure 9 (a,b): Map of Safranbolu (9a) and Safranbolu Bağlarbaşı Neighborhood (9b)

Since the identified cisterns are mostly located in the Atatürk and Barış neighbourhoods, this study focuses on these two neighbourhoods and focuses on the area surrounded by Utku and Baysal streets opposite the ulu mosque.

A total of 11 cisterns were found in Safranbolu and they are scattered in different neighbourhoods. The cisterns were examined and it was determined that 5 of them were covered and the others were still in use. The capacities of the cisterns vary between 4 m^3 and 15 m^3. In addition, rainwater tanks were also identified in mansions such as Birdane Konak and Erciyes Konak. The identified cisterns and water structures are given in Table 1.

Table 1. List of Identified Cisterns

	Name of Cistern	Capacity of Cistern	Picture of Cisterns	State of Cisterns		Rain Water Tank	Snow Well
				Not in use	In use		
Barış Neighborh	1.Garden of the Çelik Palace	≈ 4 m³	 	√		-	-
Atatürk Neighborhoo	2.Muhsin Bey Mansion	≈ 15 m³	 	√		-	-
Barış Neighborhood	3.Sarnıçlı BirdaneMansion	≈ 15 m³	 	√			-
Barış Neighborhood	4.Nimet Hanım Mansion	≈ 6 m³	 	√		-	-
Barış Neighborhood	5.Erciyes Mansion	≈ 9 m³	 	√			-
Barış Neighborhood	6.Demir Kapı Mansion	≈ 5 m³	 	√		-	-
Barış Neighborhood	7.Mosque	≈ 6 m³	 	√		-	-
Barış Neighborhood	8.Garden of Sobacı Üzeyir's Mansion	≈ 7 m³	 	√		-	-
Atatürk Neighborhoo	9.Yılanlı Mansion	≈ 9 m³	 		√	-	-
Bağlarbaşı Neighborhood	10.Değirmen Cafe	≈ 7 m³	 	√		-	-
Bağlarbaşı Neighborhood	11.Paçacıoğlu Mansion	≈ 9 m³		√		-	-

In this section, the details of the survey conducted through in person (face-to-face) interviews are narrated. The surveys were conducted among residents of two types of buildings in the study area: residential houses and mansions. These groups were selected because they represent the primary water consumers in the region. Participants were selected using purposive sampling, focusing on households and mansions located in areas with a high density of cisterns. A total of 25 surveys were conducted, including 12 mansions and 13 residential houses. The surveys were conducted through in-person (face-to-face) interviews between May and December 2022, following approval from the ethics committee. The survey included questions about water consumption habits, such as where, how frequently, and for how long water was used. Participants were also asked to provide their water bills to validate their responses. The survey aimed to gather data on daily, monthly, and yearly water consumption patterns, as well as seasonal variations. Two different types of buildings, namely residential houses and mansions, exist in the region; therefore, two types of surveys were prepared. The surveys inquired about the users' consumption of water in their living spaces, including where, how frequently, and for how long they consumed water. Participants were requested to provide their water consumption bills, and these documents were compared with the survey responses. The survey results were analysed using various tables and graphs. Through the analysis, the water requirements of residential houses and mansions in the region were determined and compared with the capacities of the cisterns. A total of 12 mansions and 13 residential houses in the study area were surveyed. The scope of the survey, prepared in Figure 10, and the areas where the survey was conducted are presented in detail in Figure 11.

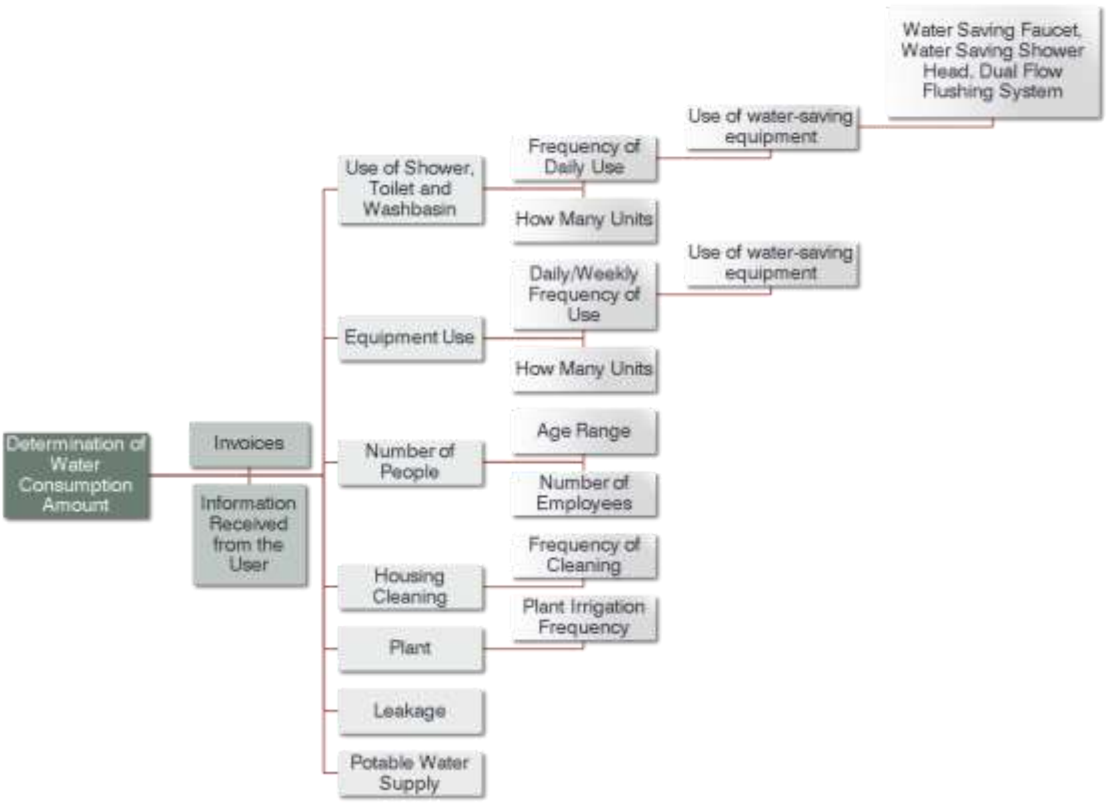


Figure 10: Scope of the Survey

Figure 11: Surveyed Mansions and Residences

In this research, the daily, monthly, and yearly water consumption of mansions were determined using billing documents and user statements. The consumption data corresponds to the year 2022, and seasonal water consumption was also analysed. Considering that water bills are received every two months, the seasonal water consumption between March-August and September-February was examined. Graphical representations of the consumption values are provided in Figures 12, 13, 14, 15 and 16.

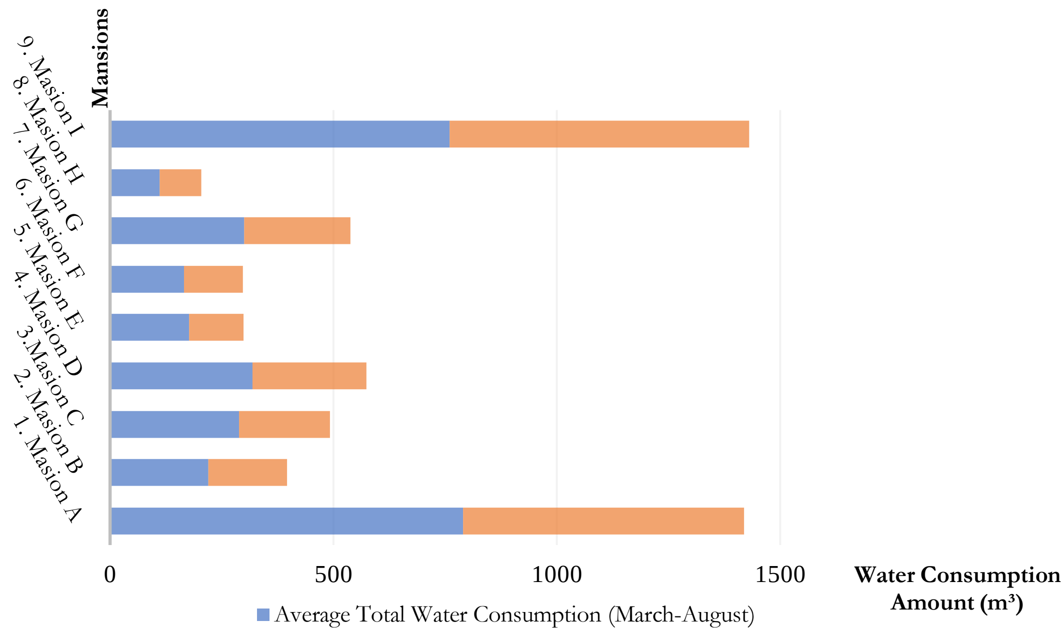


Figure 12: Annual and Seasonal Water Consumption of Mansions

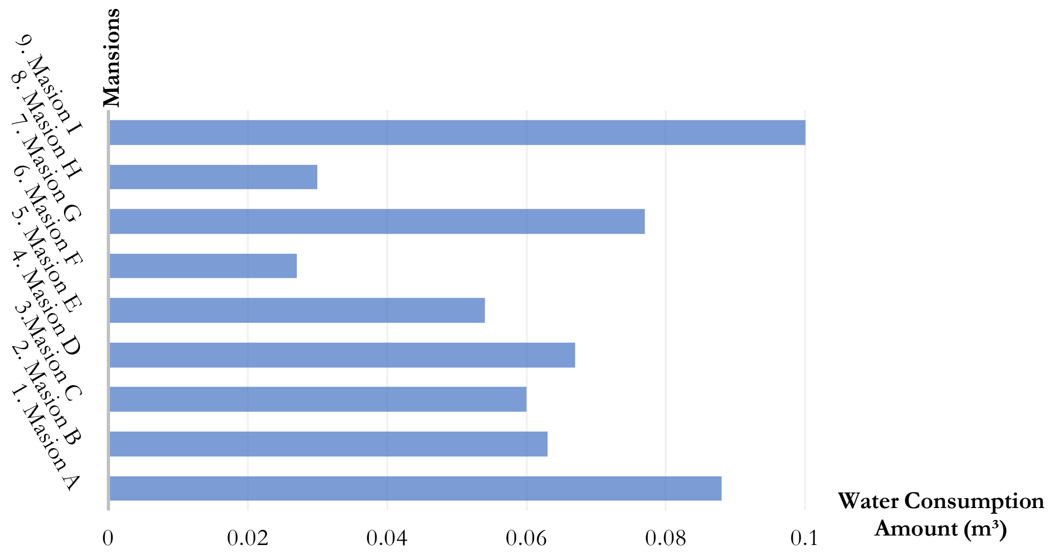


Figure 13: Per Person Water Consumption of Mansions

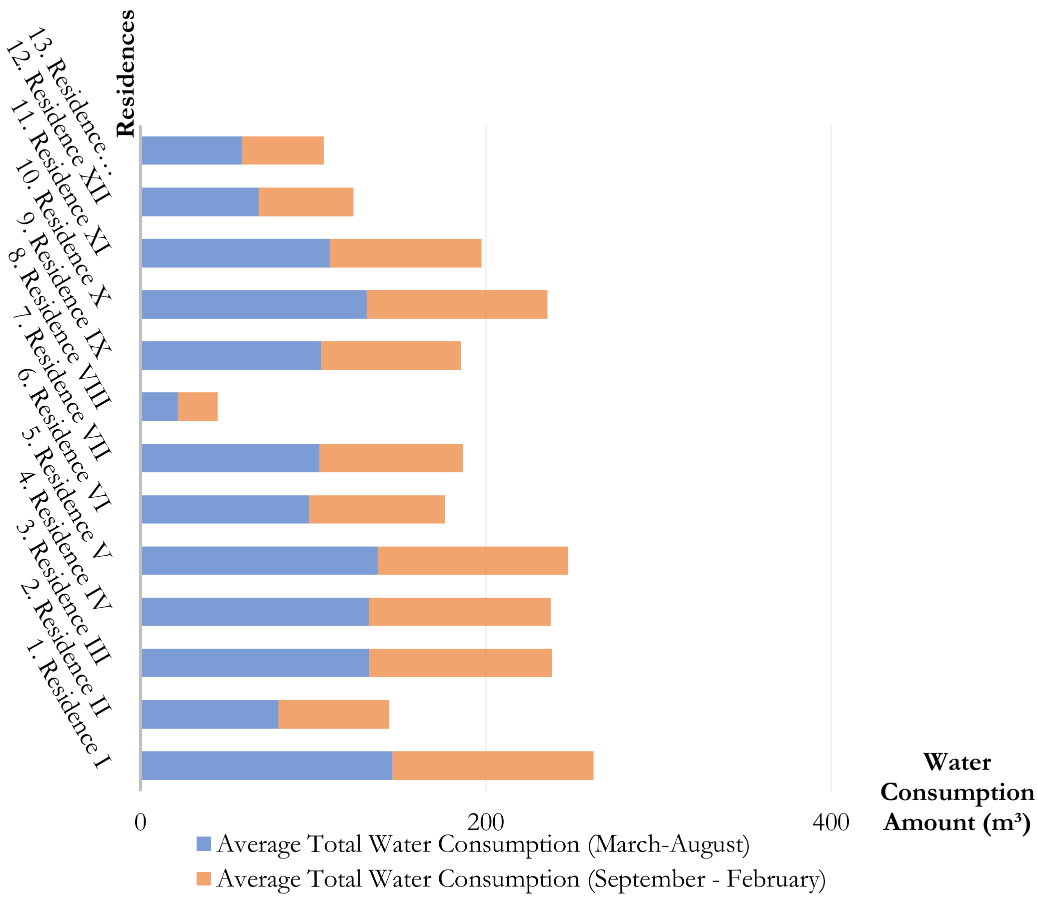


Figure 14: Annual and Seasonal Water Consumption of Residentials

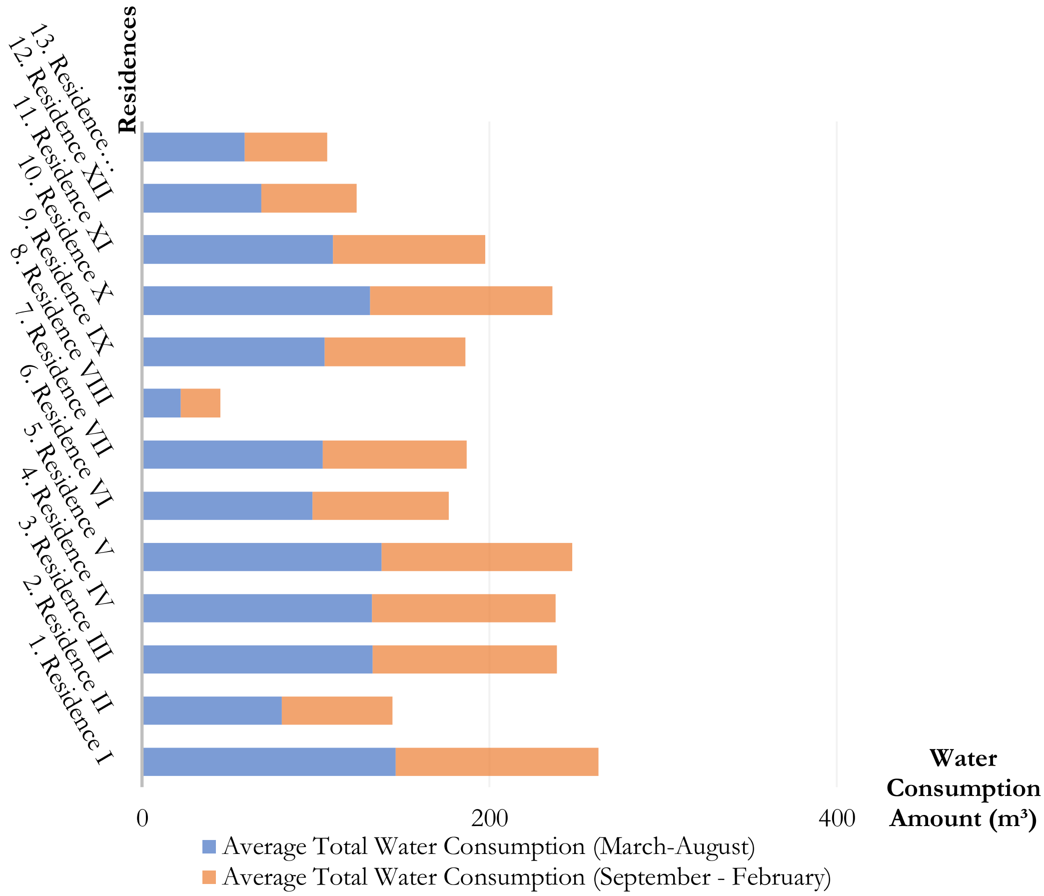


Figure 15: Water Consumption of Residentials Per Person

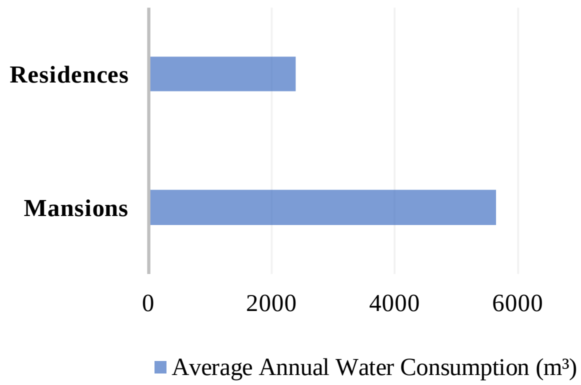


Figure 16: Total Annual Water Consumption of Mansions and Residences

The total water consumption of the investigated mansions and residences throughout the year was calculated as 8034.70 m³. The daily water consumption of the operated mansions ranged from a maximum of 3.91 m³ to a minimum of 0.55 m³. On the other hand, the daily water consumption data for the residences were determined to range from a maximum of 0.71 m³ to a minimum of 0.12 m³. The average daily consumption value for the mansions was calculated as 2.23 m³, while for the residences, it was 0.42 m³. The graphical representation of the obtained water consumption values is presented in Figure 17.

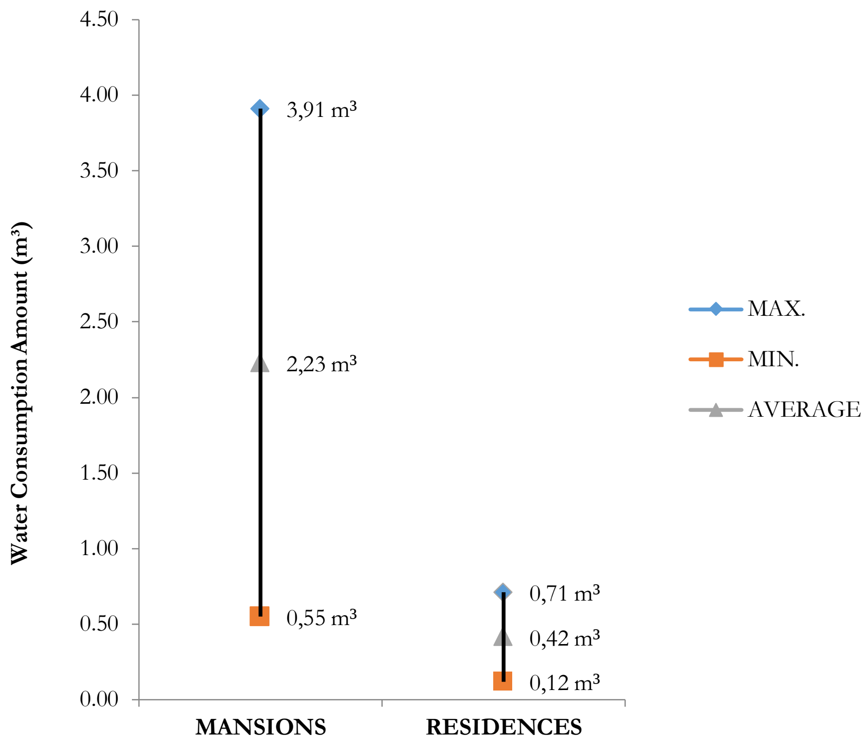


Figure 17: Maximum and Minimum Amount of Water Consumed

In the research area, it was determined that each of the 12 mansions had a daily water consumption of 2.23 m³, while each of the 13 residences had a daily water consumption of 0.42 m³. Consequently, the daily average water consumption was determined as 32.22 m³. The water consumption amounts were determined through the use of user water bills and survey questions during the field study. The survey inquired about the frequency and duration of water consumption in various locations by the users. Based on the survey conducted in all mansions and residences, water consumption data were identified for each location of use, and the average of these data was calculated. The spatial analysis of the obtained water consumption data is presented in Figure 18.

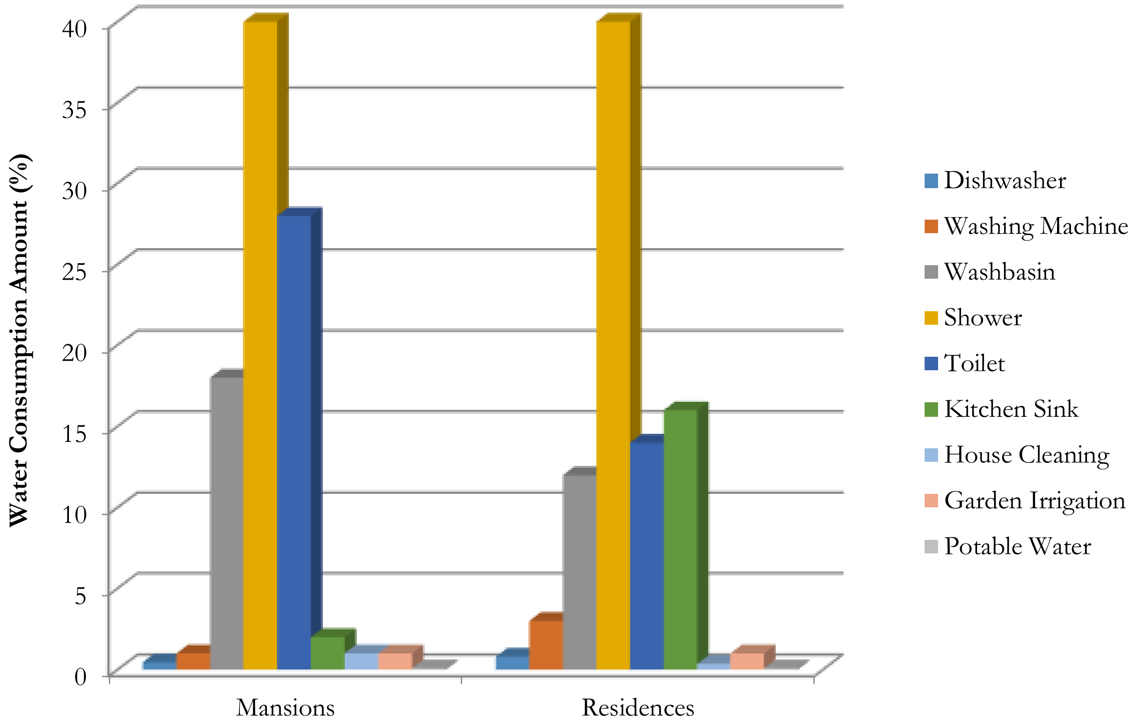


Figure 18: Spatial Analysis of Water Consumed in Mansions and Residences

In addition, in the survey, users were asked questions about whether the equipment in their living spaces were water-efficient or not. They were expected to answer yes or no to these questions. As a result of the answers given, the use of water-saving versions of the equipment used in the living spaces is analysed in terms of percentage value and given Figure 19 and 20.

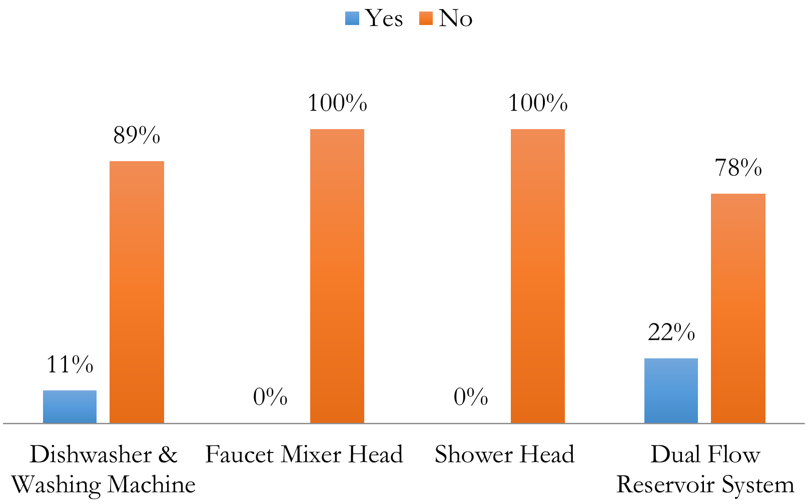


Figure 19: Percentage Expression of the Use of Water Saving Equipment by Mansions

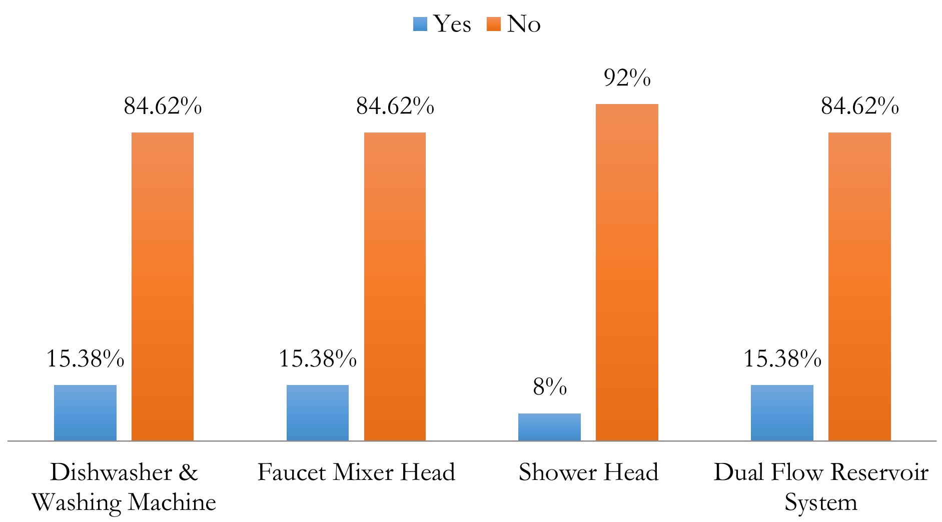


Figure 20: Percentage Expression of the Use of Water Saving Equipment by Residences

According to the analysis conducted based on the responses to the survey questions, the use of water-saving dishwashers is more prevalent in residences compared to cottages. On the other hand, the preference for water-saving faucets and showerheads is lower in cottages but more common in residences. The usage of dual-flush toilet systems is 22% in cottages and 15.38% in residences. The analysis results indicate that water-saving equipment usage is low in both cottages and residences.

In the research, the aim is to collect, store, and treat the domestic wastewater generated in living spaces within the cisterns located in the region and recover it for reuse. Domestic wastewater is divided into two categories: greywater and blackwater. Greywater refers to wastewater generated from sources other than toilets, such as sinks, showers, washing machines, and dishwashers. Blackwater, on the other hand, is the dirty wastewater generated from toilet usage. Greywater constitutes a significant portion of domestic wastewater, has a low pollutant content, and high organic matter content. After treatment, greywater can be reused for purposes such as garden irrigation and toilet tank filling. The amount of wastewater generated based on water consumption in mansions and residences, as well as the amount of water recovered through the treatment system in cisterns, has been calculated and represented as percentages in the Sankey diagrams in Figures 21 and 22.

The inputs and outputs indicated in the Sankey diagrams were derived from the actual water meter readings of the mansions and residences in the study area, as well as information collected from users based on their daily living usage patterns. The 100% annual water consumption quantities in the diagrams are the calculated annual consumption values.

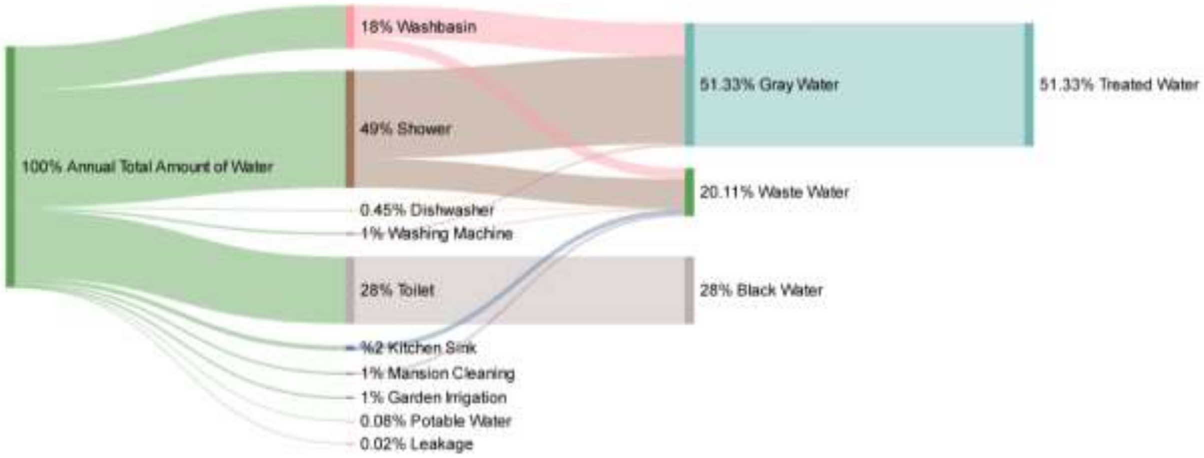


Figure 21: Sankey Diagram Showing Water Consumption of Mansions and the Amount of Water that can be Treated

The 100% annual water consumption quantity in Figure 22 corresponds to 5644.91 m³. This consumption is composed of approximately 49% shower water, 18% sink water, 0.45% dishwasher water, and 1% washing machine water. Greywater, which constitutes approximately 75% of the water consumed in these areas, can be treated and recovered by the treatment systems in the cisterns. The remaining 25% of the water consumed in the mentioned areas is discharged as blackwater. In other words, 75% of the combined water from showers (49%), sinks (18%), washing machines (1%), and dishwashers (0.45%) is recovered. Thus, (49+18+1+0.45) x 0.75 = 51.33% corresponds to the recovered greywater. In total, 2897.94 m³ of water is recovered with a 25% loss. The wastewater consisting of toilet and kitchen waste, as well as the water used for house cleaning that contains cleaning agents, is discharged as wastewater, amounting to 2715.88 m³.

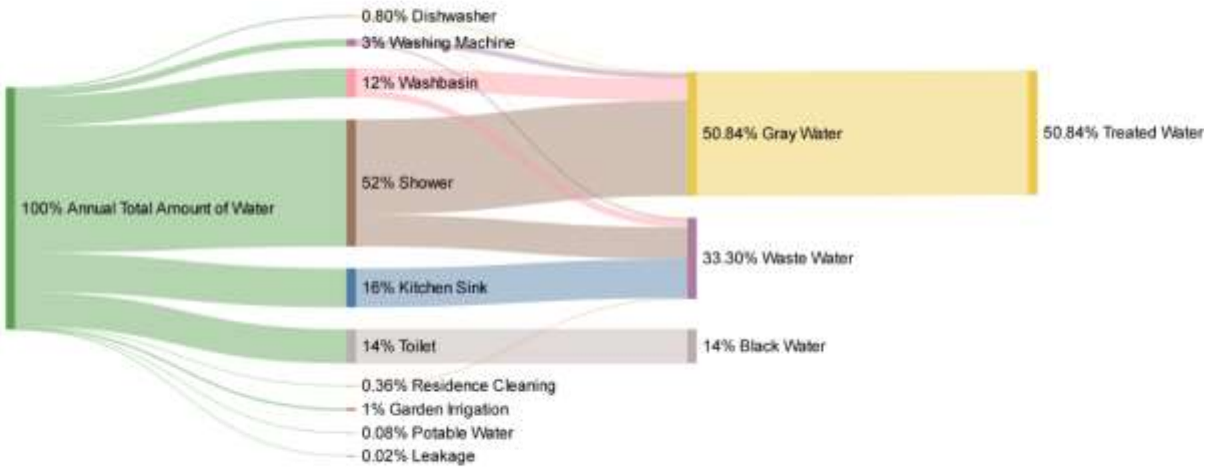


Figure 22: Sankey Diagram Showing Water Consumption of Residences and the Amount of Water that can be Treated

The 100% annual water consumption quantity in Figure 23 corresponds to 2389.79 m³. This consumption is composed of approximately 52% shower water, 12% sink water, 0.80% dishwasher water, and 3% washing machine water. Greywater, which constitutes approximately 75% of the water consumed in these areas, can be treated and recovered by the treatment systems in the cisterns. The remaining 25% of the water consumed in the mentioned areas is discharged as blackwater. In other words, 75% of the combined water from showers (52%), sinks (12%), washing machines (3%), and dishwashers (0.80%) is recovered. Thus, (52+12+3+0.80) x 0.75 = 50.84% corresponds to the recovered greywater. In total, 1215.17 m³ of water is recovered with a 25% loss. The wastewater consisting of toilet and kitchen waste, as well as the water used for house cleaning that contains cleaning agents, is discharged as wastewater, amounting to 1130.58 m³.

In this study, it is mentioned that rainwater is also considered as an alternative water source in addition to greywater resulting from domestic water consumption. Rainwater is collected from the roof through gutters, stored, and filtered for reuse both inside and outside the building. Due to the large capacity of cisterns in the structures, the plan is to store and treat the wastewater generated from rainwater harvesting, as well as surface runoff, in the cisterns, in addition to the wastewater from the living areas of the buildings. Rainwater and surface runoff water undergo a collection and treatment system consisting of collection surfaces, gutters, filters, pumps, storage areas (cisterns), and distribution systems. In the system, silica sand is used to filter rainwater and surface runoff water. However, the sand filtration system increases the cost of the wastewater recovery system. Additionally, the total amount of rainwater has been calculated considering the annual precipitation in the Karabük province and the roof areas of the structures for rainwater harvesting. Similarly, the quantity of surface runoff water has been determined based on data from the General Directorate of Meteorology (GDM) and area calculations. As a result, the possible amounts of rainwater and surface runoff water that can be collected have been determined in the study.

In the study area, the area of impervious surface excluding Utku and Baysal Streets and residential areas is 8143.7718 m². The amount of water that falls on this area in one year is 8143.7718 m² x 0.487mm = 3966.016 m³. According to the detailed analysis by Rezaei, A. R. et al. (2019) regarding surface runoff assumptions, approximately 55% of this water (2181.3092 m³) continues as surface runoff. To calculate the amount of water from rainwater harvesting; Roof Area of the Building x 487.5 x 0.75 = liters/year.

As a result, from the annual domestic water consumption of the buildings, which is 8034.70 m³, the amount of water collected as annual greywater is 4113.11 m³, the amount of water obtained from rainwater harvesting is 1217.257 m³, and the amount of surface runoff water collected from the impervious surface excluding Utku and Baysal Streets and buildings in one year is 2181.3092 m³. In one year, a total of 7511.6762 m³ of greywater is collected when domestic water consumption, rainwater harvesting, and surface runoff waters are included. The total amount of wastewater generated, and the amount of water recovered through treatment systems in cisterns are calculated and presented through a Sankey diagram in Figure 23.

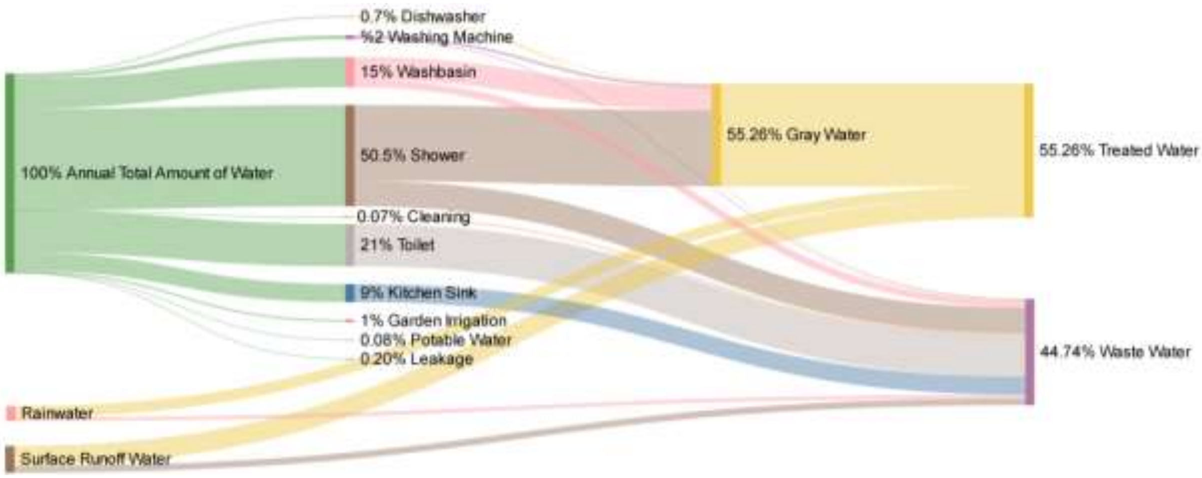


Figure 23: Sankey Diagram showing the amount of water that can be treated through domestic water consumption, rainwater harvesting and surface runoff

DISCUSSION

According to the calculated average values, each of the 12 mansions consumes approximately 2.23 m^3 water per day, while each of the 13 residences consumes approximately 0.42 m^3 water per day. Therefore, according to this calculation, 7.93 m3 (51.33% of the water consumed in the mansions) and 3.32 m3 grey water (50.84% of the water consumed in the residences) can be stored in cisterns. In addition, when 3.33 m^3 of rainwater and 5.9 m^3 of surface runoff water are added on a daily average, it is estimated that approximately 20.48 m^3 of grey water will be stored in the cisterns daily. The cisterns have a total water storage potential of 33.6 m^3 after the treatment system is integrated. Therefore, it was seen that the cisterns can store all the wastewater consumed in the designated living spaces.

Since it is foreseen that there are other cisterns in the region that have not yet been identified, it is thought that it is possible to store, treat and recover more water. With the cisterns to be discovered, more living spaces can be evaluated, and the amount of wastewater stored and recovered in the cisterns can be increased. In addition, it has been observed that more water can be recovered when water from rain harvesting, and surface runoff water are included in the recovery cycle. However, in the near future, due to climate change and global warming, the amount of rainwater and runoff water is expected to decrease in parallel with precipitation rates. For this reason, it is concluded that when the wastewater recovery strategy is evaluated regionally over the housing group instead of individual houses, more water can be recovered and offered for urban use. A mixed group of buildings consisting of mansions and residences thought to have more potential for water to be treated in cisterns. Therefore, each cistern is recommended to work with 3 or 4 buildings depending on the cistern capacity and the amount of water consumed in the buildings.

Reclaimed water is envisioned to be used for many purposes in the region. One of these purposes is to pump the recycled water back into living spaces and reuse it in toilet reservoirs, apartment or car cleaning, thus reducing water consumption and ensuring water efficiency.

Another objective is to use the recycled water in fire tanks. Fire is a major concern for traditional timber-framed buildings and more fires are expected to occur due to climate change. In a city like Safranbolu with old narrow city streets, it is difficult for fire trucks to access. For this reason, fire tanks can store more water by using recycled water.

Another use is to store runoff water to prevent flooding and drought, which are side effects of climate change. In addition, it will be possible to irrigate green areas in the city with the recycled water and water consumption will be saved.

Although it is not directly related to our current research scope, and is offered only in response to the reviewer's request, future work could incorporate detailed cost-benefit analyses and feasibility studies examining installation costs, maintenance requirements, and long-term operational expenses for adaptive cistern reuse. These expanded investigations might also explore diverse funding models, heritage management policies, and the technical parameters necessary to integrate modern treatment systems within historical settings. By evaluating financial sustainability and compliance with relevant regulations, such an approach could further demonstrate how adaptive reuse strategies may be optimized to balance both cultural preservation and economic viability.

CONCLUSION

This research addresses the escalating challenges of water scarcity and rising demand in historically preserved cities, using Safranbolu as a focal example. Rapid population growth, global warming, climate change, and careless water consumption have intensified the depletion of water resources, prompting the need for effective mitigation strategies. Against this backdrop, the study explored methods to enhance water efficiency by revitalizing historical cisterns.

A literature review highlighted how climate change, coupled with population growth, adversely affects both the quantity and quality of freshwater resources. The discussion then focused on increasing water efficiency using water-saving equipment in buildings and the recycling of wastewater, with particular attention to the capacity, proximity, and adaptability of cisterns in historic contexts. Although existing case studies are limited, the findings suggest that revitalizing cisterns could play a substantial role in addressing modern water demands while preserving cultural heritage.

Safranbolu was identified as an ideal case due to its rich array of water structures—wells, fountains, rainwater reservoirs, snow pits, and cisterns. A two-stage field study in the Kıranköy region included mapping these cisterns and collecting water consumption data through interviews, questionnaires, and utility records. Analysis indicated that renovated cisterns could store and treat greywater, rainwater, and runoff, thereby providing a significant volume of reclaimed water. This result validates the hypothesis that adaptive cistern reuse can substantially boost water efficiency in a historically protected city, despite the pressures of climate change and expanding urban needs.

Certain constraints, however, were apparent. Terrain difficulties, inaccessible covered cisterns, and unverified survey data complicated the assessment, while evolving climate patterns may alter water consumption habits over time. Nonetheless, the study demonstrates how systematically reviving these traditional water systems can alleviate immediate water demands and support broader sustainability goals in heritage settings.

Although the present research offers valuable insights, several areas warrant further exploration. First, a more detailed financial feasibility study—covering installation, operation, and maintenance costs—could inform practical decision-making and policy support for cistern rehabilitation. Second, incorporating scenario-based climate models would enable more precise forecasting of long-term water availability and consumption patterns in historic urban environments. Third, an expanded geographic scope, examining additional cisterns and cities with diverse climatic or socioeconomic conditions, could validate and refine the findings for broader application. Finally, closer coordination with heritage management authorities and community stakeholders may illuminate legal and cultural considerations pivotal for effectively blending historical preservation with modern water resource planning. Looking ahead, it is evident that water consumption will likely continue to rise, necessitating complementary solutions to traditional supply systems. By integrating refurbished cisterns into modern infrastructure, historic cities can preserve their architectural identity while making proactive strides in water management. Further research could extend these findings by exploring additional cistern sites, expanding strategies for treating wastewater locally, and refining cost and feasibility considerations to strengthen the long-term viability of adaptive reuse initiatives.

Acknowledgements | Teşekkür Beyanı

This paper is based on İrem Kahyaoğlu's thesis supervised by Timuçin Harputlugil, in Çankaya University titled "A research about adaptive reuse of cisterns in historic cities: Case of Safranbolu".

Conflict of Interest Statement | Çıkar Çatışması Beyanı

There is no conflict of interest for conducting the research and/or for the preparation of the article.

Financial Statement | Finansman Beyanı

No financial support has been received for conducting the research and/or for the preparation of the article.

Ethical Statement | Etik Beyanı

All procedures followed were in accordance with the ethical standards. All necessary ethical clearances were obtained prior to initiating fieldwork in Safranbolu, ensuring compliance with local and international research standards. Ethical clearence was provided from the ethical committee of Çankaya University with E-80281877-050.99-105711 numbered letter on the date of 03.06.2022.

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Author Contribution Statement | Yazar Katkı Beyanı

AUTHOR 1: (a) Idea, Concept, (b) Study Design, Methodology, (c) Literature Review, (e) Material, Resource Supply, (f) Data Collection, Processing, (g) Analyses, Interpretation, (h) Writing Text

AUTHOR 2: (a) Idea, Concept, (b) Study Design, Methodology, (d) Supervision, (g) Analyses, Interpretation, (h) Writing Text, (i) Critical Review

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