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Review

An Overview of Historical Development, Current Situation, and Future Prospects of Managed Aquifer Recharge in Türkiye

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Abstract: Climate change, rapid population growth, and unsustainable water use in industry and agriculture have all significantly harmed the quantity and quality of groundwater resources. Managed aquifer recharge (MAR) offers a solution to these challenges, encompassing a variety of methods and strategies for protecting and improving groundwater systems. This article provides a complete overview of MAR in Türkiye, concentrating on its historical development, current situation, and future prospects. MAR has been increasingly used to combat water scarcity since the 1960s, particularly in arid and semi-arid regions in Türkiye with significant groundwater depletion. The majority of completed managed aquifer recharge (MAR) projects in Türkiye employ in-channel modifications, accounting for 77%. This is followed by well recharge techniques and surface spreading methods, with values of 16% and 4%, respectively. Future projects are expected to focus on the southeastern and central regions, with in-channel modifications increasing to 90%. In comparison, methods such as well recharge (6%), surface spreading (3%), and other methods are limited. Despite the growing application of MAR, Turkey requires strong regulatory frameworks to ensure the safe and successful implementation of these methods, including groundwater quality, source water regulations, and geological concerns regionally. MAR can promote sustainable water management by minimizing the effects of population growth and climate change on groundwater resources.

Keywords: artificial recharge; managed aquifer recharge; water management; Türkiye

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1. Introduction

The rising water demand, coupled with inadequate management of water resources, has led numerous countries to confront the critical threat of declining surface and groundwater quality, as well as the depletion of these vital resources. Because of the rising scarcity of this vital resource, there is an increasing awareness of the significance of managing the quantity and quality of water in surface and underground reservoirs during high availability periods. Controlling the dangers associated with new entities, such as synthetic chemicals and heavy metals, is a significant topic for sustaining water quality [1]. MAR can be an effective and alternative approach to managing water resources, increasing the availability of groundwater to meet demand and ensuring its quality for existing and new entities [2]. It refers to the process of transferring and storing water from the earth's surface to underground aquifers for future use by surface spreading methods, well, shaft and borehole recharge, induced bank filtration, in-channel modifications and runoff harvesting methods. MAR techniques are used to enhance the productivity and storage capacity of aquifers, and the aquifer recharge can be increased by unintentional human activities such as leakage from irrigation systems and pipes, unmanaged human activities such as stormwater drainage and septic tanks, or managed human activities such as rainwater, surface water, or water recovery from other aquifers [3–6].

Extensive studies carried out in recent years have contributed to a better understanding of the natural mechanisms active in the MAR process and the development of the applicability of various MAR technologies. They also provide significant information on how MAR applications can be managed more effectively in different geological and hydrogeological environments. The International Groundwater Resources Assessment Centre (IGRAC) has collected nearly 1200 MAR studies from six continents to create a global inventory of MAR sites available via a web-based GIS platform [7]. The database shows that MAR studies are more widespread in Asia, Europe, and North America than in other continents. However, the variation might be related to regional preferences for MAR approaches driven by topographical, geological, hydrological, and socioeconomic variables or insufficient data input into the system. It was observed that 229 studies were conducted for "natural storage enhancement", 202 for "water quality management", and 188 for "physical sediment management" across six continents. North America shows the highest number of studies (308), while Europe and Asia closely follow with 282 and 281 studies, respectively. According to global MAR inventory data, well, shaft, and borehole charging is the most popular MAR technology, with 350 uses. This is followed by spreading methods (328), in-channel modifications (225), and induced bank filtration (168). The global MAR system categorizes MAR practices by continent but only contains registered research. As a result, it may not accurately reflect the total number or distribution of MAR applications, as certain current methods in different areas may not be included in the system. In the 50 years from 1965 to 2015, several studies have reported that MAR has also been implemented in India, the USA, China, Thailand, Qatar, Israel, Oman, Australia, Italy, the Caribbean and South Africa [8–13]. The majority of active MAR sites in Europe are located in Germany (n = 64), followed by the Netherlands (n = 41), France (n = 21), Finland (n = 14), Sweden (n = 11), Switzerland (n = 10), and Spain (n = 10). In other countries, fewer than 10 active MAR sites were identified [8].

This paper aims to investigate the potential of MAR techniques and methods that have been completed so far and will be implemented in the future for the sustainable management of water resources in Türkiye. For this purpose, the first part of the article gives an overview of managed aquifer recharge with its basic information and classification. Then, the historical development of MAR in the world was outlined and its current status was defined. The final section outlined Türkiye's water potential and examined the historical development of MAR in Türkiye. It evaluated MAR projects implemented and planned to be implemented in Türkiye in recent years managed by DSI under the Ministry of Agriculture and Forestry's action plan. This is an initial comprehensive study that examines the historical development, current situation, and perspectives of MAR applications in Türkiye. Based on data provided by the State Hydraulic Works (DSI), Türkiye's water potential and existing MAR projects have been thoroughly examined, filling an essential gap in the literature. The historical development of MAR in Türkiye has been explored, and this process has been clarified through a combination of both historical and present data. The report is a significant resource for researchers and practitioners interested in groundwater management in Türkiye's various basins. Furthermore, the paper includes specific recommendations for improving and making MAR implementations in Türkiye more effective, involving the creation of monitoring systems, legislative improvements, and technology advancements.

2. MAR Definition and Classification

The term 'Managed Aquifer Recharge (MAR)' refers to systems where surface water is infiltrated underground and transported to aquifers to recharge groundwater resources [14]. Previously known as "artificial recharge", the term was modified to avoid the impression that the water was unnatural [3,15,16].

MAR can be used to store water from a variety of sources, including surface water, reclaimed water, municipal water, desalinated saltwater, storm water, and even groundwater from alternate aquifers [5]. Controlled groundwater recharge and water storage in aquifers, which have the potential to provide solutions to the water crisis, are carried out for the purpose of later recovery or environmental benefit [6]. The most common reasons for MAR use include meeting increasing water demand [4,6,17], eliminating temporary imbalances between supply and demand [18,19], increasing water resources, and improving groundwater quality [8]. The prevention of saltwater intrusion into coastal aquifers, the reduction in evaporation of stored water [5], and the maintenance of environmental flows and groundwater-dependent ecosystems such as algae blooms and atmospheric fallout of pollutants during subsurface storage are also benefits of MAR. Furthermore, it can mitigate the effects of floods and flood damage [5,6]. Additionally, it can increase agricultural yields due to reliable irrigation [3], provide management of wastewater and impede land subsidence or sinkholes [19,20].

The disadvantages of MAR systems are based on the requirement of unsuitable natural aquifer systems and characteristics. There will always be some uncertainty in performance predictions before system design and testing [21]. Surface water–groundwater interactions can cause adverse changes in water quality. Also, clogging can affect system performance and increase maintenance and operating costs [21].

The two primary categories of managed aquifer recharge approaches are techniques targeted mainly at water retention and focused primarily on water infiltration (Table 1). Water infiltration techniques aim to naturally or intentionally increase the infiltration of groundwater from the surface to the subsurface. These methods are split into three subsections: induced bank filtration, surface spreading recharge methods, and well, shaft, and borehole recharge. Water spreading methods aim to increase the wet area on the surface and recharge to enhance the infiltration of surface water through the groundwater [22]. Spreading methods are the easiest, conventional, and most common MAR techniques [8,21,23,24]. This technique is applied when the unconfined aquifer to be recharged is at or closer to the surface recharge that is provided by infiltration through the permeable layer at the surface to maintain the infiltration rate [3]. Surface spreading recharge techniques are subdivided into soil aquifer treatment (SAT), flooding, ditches, furrows, drains, and excess irrigation techniques. SAT refers to the method by which treated wastewater infiltrates and percolates through the soil and aquifer transition [8]. Induced bank filtration is a technique that lowers water pressure on lake or river banks, allowing water to infiltrate in the aquifer [25]. In contrast to natural bank filtration, induced bank filtration involves wells removing surface water on purpose [8]. With well, shaft, and borehole recharge techniques, water is infiltrated from the surface into the aquifer at deeper levels. The most commonly used technique is deep well infiltration, where water is directly introduced into the aquifer [3]. Deep well injection techniques are the preferred aquifer filling techniques in places where there are low permeability layers between the surface and the target aquifer that cannot be practically disturbed by means of wells or bypassed by excavation or trenching in any other way [18]. The ASR method is suitable for confined and unconfined aquifers. Areas with optimum conditions are where groundwater is in close proximity to the surface. The ASTR technique represents an enhanced version of the ASR method, whereby water is injected and recovered from different wells [25]. Rinck-Pfeiffer et al. [26]. defined ASTR as the utilization of distinct injection and recovery wells for chemical and microbial contaminant attenuation [21].

Table 1. MAR method classification (modified after [3,7,22,27]).

Aim	Main MAR Type	Specific MAR Type
Techniques referring primarily to water infiltration	Spreading methods	Infiltration ponds and basins Soil Aquifer Treatment (SAT) Flooding Ditch, Furrow and Drainage Excess irrigation
	Induced bank infiltration	
	Well, shaft and borehole recharge	Deep well injection (ASR/ASTR) Dug well/shaft/pit injection
Techniques referring primarily to interception of the water	In-channel modifications	Recharge dams Subsurface dams Sand dams Channel spreading
	Runoff and rainwater harvesting	Barriers and bunds Trenches

Water interception techniques aim to recharge source water from both natural and artificial sources, whether on the surface or subsurface. They are generally divided into two categories: recharge methods including in-channel modifications and those dependent on runoff or rainwater harvesting. Each of these basic strategies is further subdivided into specialized sub-techniques, which are intended to deal with different environmental and hydrological conditions. In-channel modification techniques change or regulate the direction of rivers, streams, or canals to store water and increase vertical recharge. It is primarily carried out using infiltration ponds, sand storage dams, underground dams, and recharge dams [25]. They are common in arid and semi-arid regions with intermittent and/or ephemeral streams. Sand dams are impermeable structures placed throughout ephemeral river basins with the purpose of storing sand and gravel in order to create an artificial aquifer [18,28–31]. Runoff and rainfall harvesting techniques are typically part of integrated, multi-purpose measures that complement each other, contributing to soil and water protection and enhanced agricultural productivity [22]. This method has been demonstrated to improve runoff storage in terraced areas, increasing infiltration rates and assisting groundwater recharge [22,32]. Barriers and bunds are watershed management strategies that store soil moisture. This technology is often utilized on gently sloping agricultural fields with yearly rainfall of less than 800 mm [22].

3. Historical Development of MAR in the World

The history of MAR applications can be traced back to prehistoric times. It is estimated that the first application of MAR in the world was in China (475~221 BC). This involved the construction of canals to facilitate the infiltration of surface water into the soil to improve groundwater quality [25]. Artesian wells with depths ranging from 10 m to 200 m are known to have been constructed during the Qin and Han dynasties (221 BC to 220 AD) [33]. In Peru, aquifers were recharged through water supply and flow control techniques between the 5th and 10th centuries CE [34]. In Spain, infiltration channels called careos, which are often dug in soil or rock, are used to artificially recharge aquifers in the Sierra Nevada range [35]. Geochronological techniques (OCL) have shown that the workability of these channels dates back to the 11th century [36].

In the nineteenth century, the advent of industrialization and the increase in the global population placed new demands on water suppliers. From 1850 to 1950, MAR and its applications proved to be an effective solution to the problems [25]. The first reported application of MAR in Europe was in Glasgow in 1810. The Glasgow Water Works Company removed filtered water by constructing a perforated collector pipe parallel to the River Clyde [8,37]. In the 1860s, the concept of naturally filtered groundwater was first proposed in the United Kingdom [38] and was subsequently adopted by several other European countries, including the Netherlands, Belgium, Sweden, France, Austria, and Germany [8]. The initial implementation of riverbank filtration for the enhancement of hygienic surface water quality and the mitigation of rising water demand was undertaken in Germany, where infiltration basins were constructed. Similar to the developments in Germany, riverbank filtration (RBF) and infiltration basins were subsequently adopted in the Netherlands, Sweden, and Switzerland. Afterwards, Eastern European cities, including Hungary, Romania, and Finland, have also employed MAR [8].

The use of infiltration basins for storm runoff in the state of California, USA, commenced around 1900 and was subsequently adopted on a widespread basis in the 1930s [39]. These practices were demonstrably effective in enhancing the quality of degraded surface water and increasing water availability to meet the demands of industrial users [25]. From 1950 to 1990, the application of MAR was more widely used to meet the needs of the post-World War II era. During this period, the concepts of groundwater storage and recovery (ASR) were born [25]. Research and development of well-injection methods began in the 1960s. The initial installations were predominantly situated in the Netherlands, where preliminary trials were conducted on a pilot scale. In the early 1970s, ASR wells were constructed in Spain and remain operational to the present day [8]. In 1968, the first long-term aquifer storage and recovery (ASR) well field in the United States was developed in Wildwood, New Jersey. Its primary purpose was to prevent saltwater intrusion into the aquifer and to help meet increased water demand during peak seasons [19]. In Australia, the initial implementation of MAR project operations was undertaken in the Burdekin Delta and Queensland during the mid-1960s [40]. In Shanghai, China, the practice of artificial recharge through wells was employed in the 1960s as a means of addressing land subsidence concerns [41]. It was later expanded to Beijing, Tianjin, Shijiazhuang, and Xi'an [42]. Since 2000, geothermal reinjection has become an increasingly prominent aspect of geothermal management in Beijing and Tianjin [43].

4. The Water Potential and Aquifer Types in Türkiye

Türkiye's total annual precipitation is 450 billion m^3, and the yearly average precipitation is 574 mm. Türkiye's average annual surface water potential (natural flow) is 178.7 billion m^3, its safe groundwater reserve is 28.6 billion m^3, and its groundwater allocation is approximately 18.6 billion m^3 as of the end of 2022. It has been calculated that the surface water potential is 91.9 billion m^3, the groundwater potential is 18.6 billion m^3, and the average annual technically and economically available water potential is 110.5 billion m^3 [44]. According to TUIK data, Türkiye's population is 85,279,553 as of 31 December 2022. Considering Türkiye's technically and economically available water potential, the amount of water per capita is calculated as 1297 m^3/year. When evaluated according to the Falkenmark index (Table 2), Türkiye is among the countries experiencing water stress.

Table 2. Falkenmark index limits [45].

Index (m^3/Capita/Year)	Category
>1700	No stress
1000–1700	Stress
500–1000	Scarcity
<500	Absolute scarcity

In total, 25 main river basins in Türkiye have varying precipitation and runoff values based on climate and geography (Table 3, Figure 1). While Türkiye has a continental climate in the central region and a milder Mediterranean climate at the coast [46]. Climate, geography, and geological factors are the most important elements influencing runoff. The key elements influencing runoff include basin geometry, drainage networks, slope, soil type, vegetation, geology, and land use [47,48]. Basins may have varied climates and so receive varying quantities of precipitation based on their geographic location. A smaller basin, such as the Antalya basin, may be able to catch more water than a larger basin due to its location in a Mediterranean environment with heavy precipitation. Watershed characteristics play an important role in flow. The greater the slope and the elevation values, the greater the flow of water. The Western Black Sea basin can be used as an example of this phenomenon. The Western Black Sea basin has a high runoff due to its climate and location. While broad, gentle plains reduce surface runoff, irrigation in large basins where intensive agricultural activity occurs can limit runoff, reducing surface and groundwater resources. The infiltration rate is especially essential in arid, semiarid climates, where vegetation, soil type, and catchment basin slope influence surface water infiltration into the subsurface. The Konya Closed Basin can act as an illustration of this circumstance.

Table 3. Annual surface water potential of 25 main river basins between 2013 and 2022 (adopted from [49]).

Basin/Basin No.	Catchment Area (km^2)	Average Annual Runoff (mm/y)	Average Annual Rainfall (mm/y)	Average Annual Runoff Area (mm/y/km^2)	Average Annual Rainfall Area (mm/y/km^2)	Runoff/ Rainfall Ratio
Antalya (9)	20,081.8	617.1	768.6	0.031	0.038	0.8
Eastern Black Sea (22)	23,215	687.9	1000.1	0.030	0.043	0.7
Eastern Mediterranean (17)	21,550.8	403.3	582.0	0.019	0.027	0.7
Seyhan (18)	21,600.8	317.5	576.2	0.015	0.027	0.6
Western Mediterranean (8)	21,008.7	347.2	739.9	0.017	0.035	0.5
Çoruh (23)	20,135.4	338.0	705.5	0.017	0.035	0.5
Ceyhan (20)	21,609.8	345.4	649.1	0.016	0.030	0.5
Marmara (2)	23,388.4	330.1	693.9	0.014	0.030	0.5
Western Black Sea (13)	29,092.9	354.2	761.1	0.012	0.026	0.5
Euphrates-Tigris (21)	178,775.4	307.3	565.3	0.002	0.003	0.5
Asi (19)	7864.3	202.0	829.5	0.026	0.105	0.3
North Aegean (4)	9926.1	191.4	606.9	0.019	0.061	0.3
Van Lake (5)	18,347.4	134.3	518.7	0.007	0.028	0.3
Susurluk (3)	23,745.6	206.6	649.8	0.009	0.027	0.3
Aras (24)	27,774.8	161.1	483.5	0.006	0.017	0.3
Yeşilırmak (14)	38,557.3	170.3	538.7	0.004	0.014	0.3
Küçük Menderes (6)	6965.5	109.9	611.1	0.016	0.088	0.2
Meriç Ergene (1)	14,499.8	109.8	591.7	0.008	0.041	0.2

Table 3. *Cont.*

Basin/Basin No.	Catchment Area (km^2)	Average Annual Runoff (mm/y)	Average Annual Rainfall (mm/y)	Average Annual Runoff Area (mm/y/km^2)	Average Annual Rainfall Area (mm/y/km^2)	Runoff/ Rainfall Ratio
Gediz (5)	17,375.3	100.7	578.5	0.006	0.033	0.2
Büyük Menderes (7)	25,699.4	116.6	598.7	0.005	0.023	0.2
Sakarya (12)	61,771.1	99.5	463.8	0.002	0.008	0.2
Kızılırmak (15)	80,984	81.7	451.3	0.001	0.006	0.2
Burdur Lake (10)	6320.4	50.1	476.0	0.008	0.075	0.1
Akarçay (11)	7875.5	50.8	476.3	0.006	0.060	0.1
Konya Closed (16)	51,127.6	60.0	390.1	0.001	0.008	0.1

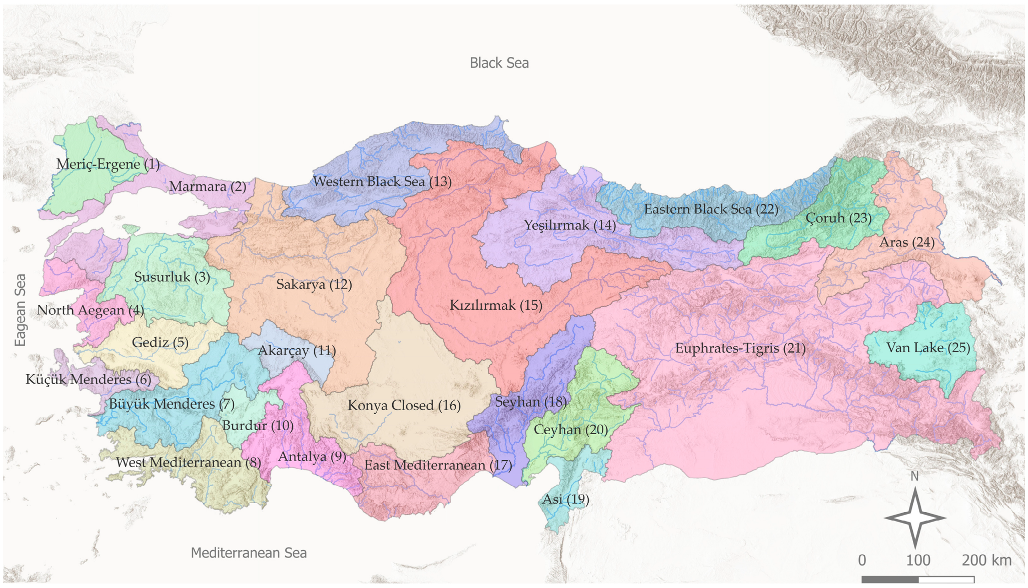


Figure 1. Map of major river basins in Türkiye.

The relationship between average annual rainfall and runoff in various river basins has been evaluated to gain insight into hydrological patterns and water resource productivity. The average runoff and rainfall correlation per catchment area, supported by a comprehensive table of hydrological measurements, provides insight into the regional variations in water availability and water supply (Figure 2). The 1:1 line shows that precipitation in these basins is primarily converted to runoff, with little loss due to evapotranspiration, infiltration, or restricted permeability. These basins are likely to have little vegetation cover, fully saturated soil moisture conditions, and primarily impermeable surfaces. Notably, the Euphrates-Tigris basin has a nearly perfect precipitation-runoff connection, with the vast majority of rainfall directly contributing to runoff. In contrast, the Susurluk basin has an excessive discharge considering minimal rainfall. Conversely, although receiving considerable rainfall, the Eastern and Western Black Sea basins have smaller runoff. This fluctuation is most likely due to high infiltration rates, allowing groundwater recharge, and enhanced evapotranspiration caused by dense vegetation. Additional factors that could influence these patterns include agricultural irrigation, industrial activity, urban water demand, and the existence of storage systems such as dams. Basins such as Yeşilırmak, Seyhan, and Ceyhan have a more balanced rainfall–runoff connection, approaching a 1:1 ratio. However, in low-precipitation basins like Meriç-Ergene, Gediz, Küçük Menderes, and Antalya, runoff is much lower than precipitation. This imbalance can be attributable to high evaporation rates at high temperatures, significant infiltration into aquifers, and excessive water withdrawals for agriculture and urban use. Furthermore, geological and hydrogeological properties, along with topographical features, could limit rapid surface runoff generation. These factors explain the observed variations in precipitation–runoff dynamics between the basins. It has been observed that the relationship between precipitation and runoff results in surface runoff amounts close to the amount of precipitation in some basins (Table 3 and Figure 2). This situation becomes especially evident in basins with impermeable surface structure and high precipitation rates, such as Antalya and the Eastern Black Sea Region. The high runoff coefficient in these basins indicates that a large portion of the precipitation is converted into surface runoff without infiltrating into the soil. Because of the impermeable soil structure (clayey soils) in Antalya and the Eastern Black Sea basin, the majority of precipitation does not permeate the soil and instead runs off the top. Furthermore, penetration in these areas is limited due to the low vegetation density. In high-precipitation basins like the Eastern Black Sea, the soil is already wet, increasing surface runoff. In addition, the evaporation rate is low in these areas, contributing to surface runoff. Precipitation and surface runoff rates are strongly associated in basins with impermeable soil structures [48]. This finding has significance for both basin management and water resource protection.

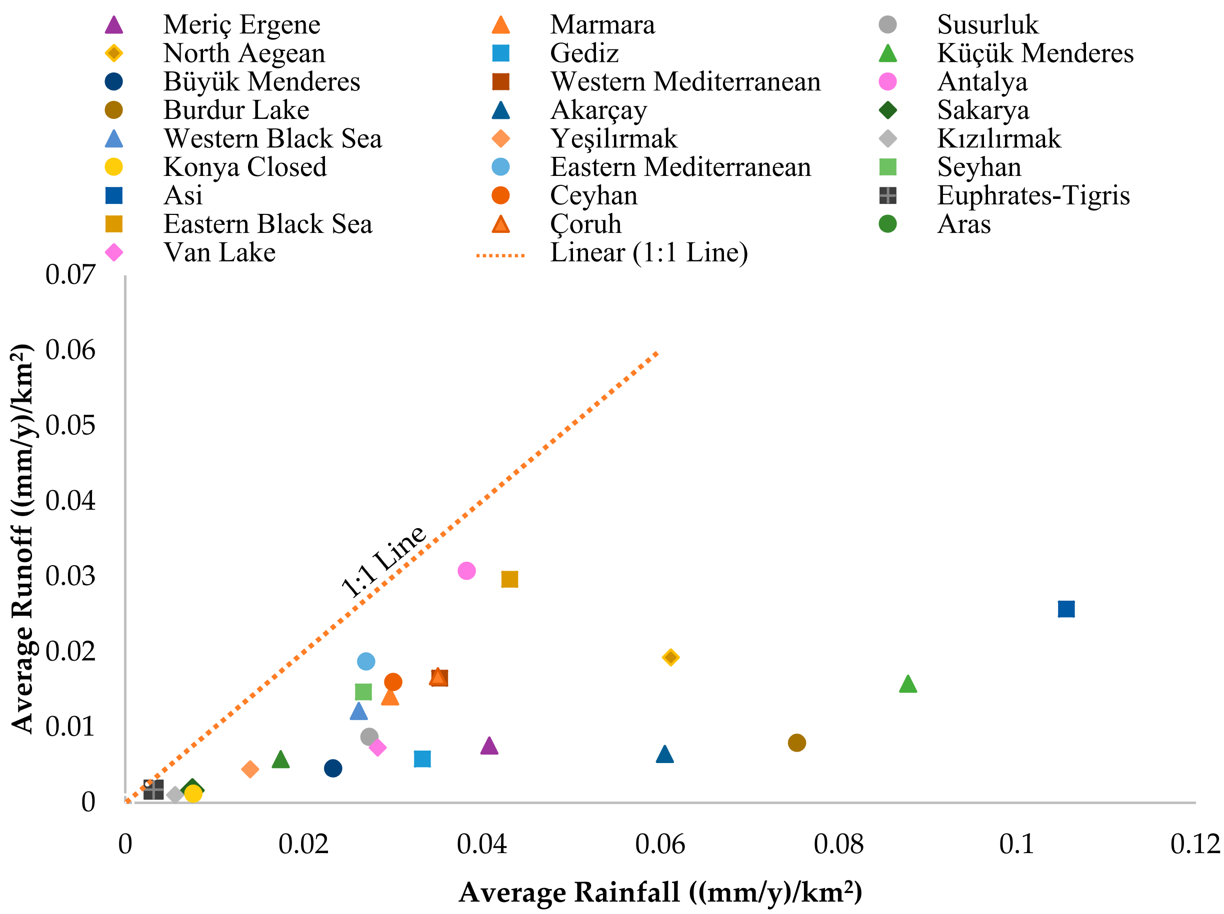


Figure 2. Average rainfall–runoff ((mm/y)/km^2) of river basins (2013–2022).

Türkiye's groundwater resources are based upon various geological characteristics and aquifer types. These include alluvial, karst, volcanic, and fractured rock aquifers. Each of them has distinctive hydrogeological properties and is crucial to groundwater management. Alluvial aquifers are found throughout Türkiye's major river basins, particularly in the regions of Küçük Menderes, Büyük Menderes, Gediz, and Sakarya. These aquifers are often shallow and highly permeable, allowing surface water to rapidly infiltrate underground. The storativity of alluvial aquifers ranges from 0.001 to 0.2, whereas their transmissivity values range from 100 to 1500 m^2/day. This fluctuation is most noticeable in gravel layers related to major rivers. The specific capacity typically ranges between 0.1 and 5 L/s/m [50]. Alluvial aquifers range in depth from 10 to 50 m, which makes them ideal for surface spreading methods. However, coastal aquifers are under pressure from saltwater intrusion and agricultural chemical contamination. In particular regions, MAR projects supported by underground dams are required to avoid seawater intrusion. Karst structures are some of Türkiye's best-known groundwater systems, particularly in the Mediterranean, Taurus Mountains, Eastern Anatolia, and Central Anatolia regions [51]. These aquifers can hold significant volumes of water due to their large cavities and fracture networks. They provide immense advantages, particularly in areas where rainfall is unpredictable. Storm water injection and rainwater harvesting can both recharge karst aquifers in the Mediterranean region. However, the rapid movement of water challenges regulated MAR uses. Furthermore, karst aquifers are extremely vulnerable to contaminants and have limited natural filtration capability. As a result, extensive water quality evaluations should be conducted in MAR projects, and appropriate measures should be adopted. Although volcanic rocks cover the majority of Türkiye, only a few of these serve as productive aquifers. Volcanic aquifers in Central Anatolia are often associated with low-permeability rocks such as andesite and basalt. These aquifers maintain local water resources, but their low permeability limits the potential benefit of MAR techniques. In these areas, surface water storage and delayed infiltration techniques may be used. These aquifers are found in rural locations with low water resources; therefore, rainwater harvesting and infiltration methods may be appropriate in these areas. Fractured rocks may carry water due to surface fissures, although this capacity decreases with depth.

The soil type and geological characteristics of different regions of Türkiye have a direct impact on the performance of aquifer recharge (MAR) programs [52]. Clayey soils in Central and Southeastern Anatolia may have an impact on the performance of MAR initiatives in these areas by reducing water infiltration. Clayey soils make it difficult for water to travel underground; consequently, improvements in drainage infrastructure are required for efficient water storage. In such areas, the effectiveness of surface spreading methods may decline, lowering the performance of MAR systems. On the other hand, in Türkiye's alluvial regions, particularly the Marmara, Aegean, and Mediterranean regions, sandy and gravelly soils are more widespread, and water penetration is rapid and effective. MAR projects have the potential to be more effective in these areas. However, the thickness of unsaturated layers in these areas is often restricted to a few meters, which accelerates water movement to the underground but requires greater filtration capacity. This condition needs an accurate estimate of filtering capacity, particularly in areas where the risk of water contamination with contaminants increases. Low filtration capacity in karst and coastal areas raises the possibility of pollutants reaching aquifers [53]. In Istanbul's Bakırköy and Çırpıcı regions, aquifers with inadequate filtration capacity play a crucial role in assessing the impact of wastewater filtration and saltwater barriers [54]. The effectiveness of MAR methods employed in these places is dependent on an accurate assessment of filtration capacity and the creation of strategies adapted to regional geological conditions. As a result, managing groundwater resources in different locations of Türkiye requires distinct strategies based on soil type, geological structures, and water filtration ability.

The term "water allocation" refers to the decision-making process related to access and use of water resources, which is managed by various stakeholders and affected by multiple issues [55]. Allocation of groundwater resources involves different responsibilities and risks in terms of both distribution and resource management. Establishing clear allocation rules and a systematic prioritization process is crucial to effectively address water scarcity [56]. Sector-based water allocation is a fundamental aspect of sustainable water management [50].

An examination of sectoral water allocation in Türkiye shows that 74% of the total water volume is used for agricultural irrigation, 22% for drinking water, 3% for industrial applications, and 1% for other needs. Consumption patterns for drinking, domestic, and industrial water have remained relatively stable from 1995 to 2022, which may reflect improved water management (Figure 3). However, groundwater reserves face significant pressure from extraction, with nearly three-quarters of allocated resources being directed to agriculture. Increasing agricultural water demand caused by population growth suggests that this pressure will continue to intensify [57]. Groundwater use has almost doubled between 1995 and 2022, from approximately 8.5 km^3 in 1995 to over 18 km^3 in 2022. Groundwater abstraction for irrigation has shown a steady increase; irrigation accounted for 4.6 km^3 (55%) of groundwater use in 1995, rising to 12 km^3 (67%) by 2022. Climate change is intensifying drought conditions, reducing precipitation, and thus increasing irrigation demand. This trend not only increases agricultural water consumption but also threatens the sustainability of water-dependent agriculture. Water demand has increased, especially for crops that require more water, such as corn, rice and cotton. Conventional irrigation methods, including water-intensive practices such as sprinklers, further contribute to the overuse of groundwater. In addition, farmers' lack of awareness about water management and the limited use of technological innovations may increase the risk of depletion of water resources in the long term. Precautions that can be taken against this situation include more efficient use of groundwater resources, adoption of sustainable irrigation techniques, and managed aquifer recharge. Such practices both ensure the sustainability of water resources and help maintain groundwater levels.

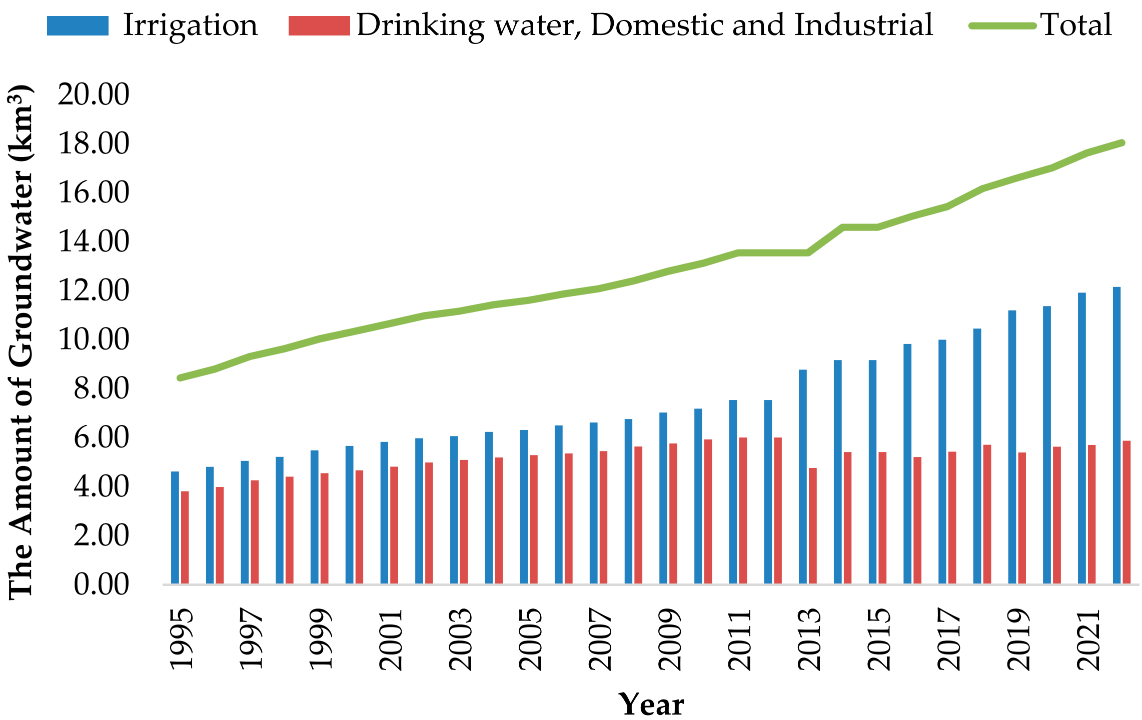


Figure 3. Changes in the sectoral allocation of the amount of groundwater, 1995–2022 [49].

5. Managed Aquifer Recharge in Türkiye

The requirements that must be met for Türkiye to adopt the concept of MAR, which has been periodically discussed for various purposes since the 1960s, appear to exist today. The most significant of these is the growing awareness of the need to protect the natural and artificial environments, the increasing water demand that is occurring and will continue to increase, particularly in light of climate change, and the nearly free availability of excess water potential required for aquifer recharge in the form of treated wastewater.

The evaluation of MAR in Türkiye has been divided into two sections: historical development, current situation, and potential future developments.

5.1. Historical Development of MAR in Türkiye

Managed aquifer recharge approaches are widely used globally, including in Türkiye, as successful solutions for increasing groundwater levels while ensuring the sustainability of present groundwater supplies. Artificial recharge/MAR techniques have been studied in Türkiye since the early 1960s on a local or small scale, with research showing that water resources can be sustained in the long term.

While MAR techniques have been discussed since the 1960s, detailed studies and comprehensive applications were limited during this period. Between 1960 and 2000, MAR studies were limited to small-scale experimental studies or local project reports, and they were not reflected in academic literature. Most previous artificial recharge projects are project-level research that focus on early theoretical concepts rather than comprehensive implementations.

Surface spreading is an effective method for recharging aquifers through surface infiltration. In İzmir-Bornova, groundwater has been artificially recharged since 1970 by recharging surface water in winter to the aquifer consisting of sand and gravel [58]. In the Küçük Menderes Basin, studies by Peksezer [59] and Sayit and Yazicigil [60] evaluated the potential of using infiltration basins to capture and recharge stream flows during wet seasons. Peksezer [59]'s research incorporated two-dimensional groundwater modelling using SEEP/W software, which is geotechnical and hydrogeological modeling software developed by GeoStudio, to analyze both saturated and unsaturated data under various water level scenarios. Despite the promise of these methods, the study concluded that artificial recharge alone might not suffice to address long-term water storage needs in the basin. Further research in the Eğri Dere Sub-basin of the Küçük Menderes Basin by Sahin and Tayfur [61] studied artificial recharge methods including surface spreading and underground dams. In this study, the effects of these methods on groundwater levels were simulated using the HYDRUS-3D model, which is a modeling tool used to simulate soil water movement, heat transfer, and the transport of contaminants. The findings suggest that surface spreading is a more cost-effective and practical approach than underground dams in this context. Well and borehole-based recharge methods are designed to target deeper aquifer zones, offering an effective approach to enhancing groundwater resources. For instance, in the Dörtyol-Erzin plain, irrigation cooperative wells were modified to function as artificial recharge wells, aiming to increase groundwater availability. Similarly, in the Niğde-Altınhisar region, experiments demonstrated that borehole-based recharge methods were suitable for increasing groundwater levels [58] Sakiyan and Yazicigil [62] conducted a study on the Küçük Menderes River Basin in Western Türkiye to evaluate sustainable aquifer management practices. Using geological and hydrological data, they simulated groundwater flow and identified the risks posed by over-abstraction, such as long-term aquifer damage and ecosystem disruption. The study highlighted that artificial recharge methods could mitigate overexploitation and serve as an alternative source for agricultural irrigation. In Istanbul, Öztaş et al. [63] proposed using treated wastewater to recharge aquifers as a cost-effective and sustainable strategy. They suggested this approach could address decreasing groundwater levels and combat seawater intrusion, particularly in the Bakırköy-Çırpıcı groundwater basin, Tuzla-Darıca coastal aquifers, and Gebze-Dil Creek alluvial aquifer. The study recommended utilizing infrastructure such as abandoned deep wells, large-diameter caisson wells, and infiltration ponds to inject treated wastewater into these aquifers. This method would not only recharge groundwater but also reduce seawater intrusion and recover the efficiency of previously unproductive wells. Mouhoumed et al. [64] introduced a GIS-based multi-criteria decision analysis (MCDA) approach to identify optimal locations for artificial recharge and groundwater protection zones in Kayseri. By analyzing hydrogeological, topographic, meteorological, and land use data, they assessed groundwater pollution hazards and pinpointed suitable sites for recharge. The study concluded that GIS-based MCDA techniques could effectively guide water resource management strategies and create sustainable solutions. The resulting maps of potential recharge zones were validated as reliable tools for planning and implementation in Kayseri.

Induced bank filtration, a process where surface water infiltrates through riverbanks to recharge aquifers, has been successfully implemented in Bursa. In this region, surface water was directed into Kaplıkaya Cave [58]. Öztaş [54] highlighted that rapid and unplanned urbanization since the 1950s has led to the overexploitation and contamination of water resources. To mitigate these issues, strategic land use planning, technical evaluations of existing wells, restrictions on new well drilling, and targeted identification of pollution sources are suggested. Furthermore, recharging aquifers with treated wastewater presents an effective and economical solution to restore groundwater levels while addressing contamination.

In-channel modifications, such as underground dams, have been employed to manage water resources in regions with variable precipitation. Underground dams have become a vital tool for managing water resources in Türkiye, particularly in regions where surface water availability is unreliable or insufficient. Yilmaz [65] conducted a study using the MODFLOW program to examine the effects of underground dams in Muğla Çamlı village and emphasized that these dams prevent groundwater discharge into the sea, contributing to sustainable development. Apaydın et al. [66] discussed the advantages of underground dams over surface dams, emphasizing the importance of suitable geological and hydrogeological conditions. They cited several examples of underground dams in Türkiye, including the Yahşihan Underground Dam in Kırklareli and the Ankara Kalecik Underground Dam. The Çeşme Underground Dam in İzmir, Türkiye's first coastal aquifer dam, was built to prevent seawater intrusion and provide clean drinking water. While Yahşihan and Malıboğazı underground dams provide water supply and irrigation, Çorum-İskilip and Ankara Elmadağ underground dams meet local drinking water and agricultural demands. Apaydın et al. [67] recommended underground dams as an effective solution to address the drought challenges faced by Central Anatolia. Their study emphasized the importance of hydrogeological conditions, aquifer hydraulic parameters, and topography when selecting suitable locations for the construction of underground dams. Apaydın [68] noted that the dams' locations were chosen based on the hydrogeological conditions of the regions, and the structures were successful in providing water even during periods of drought. The construction of an underground dam in Sinop, northern Türkiye, was studied by Kolay and Öztürk [69]. The study highlighted the dam's importance in water management and the wider purposes of underground dams while providing comprehensive technical insights into the dam's design and construction. Sahin and Tayfur [61] found that surface spreading was more cost-effective and applicable than underground dams using the HYDRUS-3D model in the Küçük Menderes Basin. While underground dams did raise groundwater levels, they were insufficient to justify their construction in some cases. Studies suggest that the successful implementation of these dams requires a careful understanding of regional hydrogeological conditions and other environmental factors. In Türkiye's "Underground Dams Action Plan", Çavdar [70] emphasized the importance of underground dams and their role in sustainable water management. This paper emphasized how these structures contribute to maintaining drinking and agricultural water supplies, reducing water scarcity, and improving groundwater sustainability.

Runoff/rainwater harvesting is a highly effective method for enhancing aquifers, particularly in arid and semi-arid regions. The studies showed that expanding the Mamasın Dam's body in the Niğde-Aksaray was a more suitable solution than pursuing artificial recharge methods, leading to the abandonment of the latter [58]. Tanik et al. [71] explored the reuse of treated wastewater and rainwater as part of sustainable water management strategies in Türkiye. Groundwater–seawater interaction is one of the most significant issues in coastal aquifers due to the over-extraction of groundwater. Irtem [72] emphasized the risks of groundwater salinization due to excessive water depletion and recommended addressing this issue through field research, numerical analyses, and public and local government involvement in evaluating management solutions.

Turkey has a long history of effectively managing its water resources by adopting creative approaches to water management. Techniques such as surface spreading, well-shaft borehole recharge, underground dams, and rainwater harvesting have proven effective across various regions. These studies, supported by hydrogeological analyses, numerical modelling, and local solutions, have achieved remarkable success under diverse geographical and climatic conditions. The results of these projects offer valuable knowledge that provides solid foundations for upcoming large-scale and creative water resource management applications.

5.2. Current Situation and Future Potential of MAR in Türkiye

Türkiye's focus has predominantly been on aquifer recharge through underground dams. As of 2019, 28 projects utilizing this technique have been completed in Türkiye. On 22 July 2019, the Minister of Agriculture and Forestry officially introduced the "Underground Dams Action Plan" (YEP) initiative to the public, announcing "100 underground dams in honour of the 100th anniversary of the Republic" and "local and underground storage" [73]. At least 100 groundwater dams and groundwater artificial recharge facilities were to be constructed throughout Türkiye between 2019 and 2023 according to this action plan, which was finished by the General Directorate of State Hydraulic Works (DSI) [74].

In total, 257 artificial recharge projects were planned to be carried out in Türkiye between 2019 and 2023 [74]. 114 of these projects have been successfully completed and are currently active and 37 of the 143 projects are currently under construction. There are 106 more projects planned to be completed in the future. This study examines projects in two categories: completed and future MAR projects. Future projects refer to projects planned to be carried out between 2019 and 2023 but still in the construction and design phase. In order to address Türkiye's growing water demand and the effects of climate change, there has been an increase in research on MAR projects. These projects, which are being implemented in many provinces, are focused on providing drinking water, meeting irrigation requirements, protecting groundwater supplies, and maintaining ecological balance. Dams and wells are being built to recharge an alluvial aquifer, together with irrigation networks and agricultural infrastructure in Aydın. In Balıkesir, drilling and transmission line construction are being carried out to increase groundwater levels and prevent salinization. Concurrently, construction on artificial recharge projects in Artvin, Erzincan, Manisa, Izmir, Nevşehir, and Erzurum has started. Planned projects in Adıyaman aim to preserve water resources by increasing groundwater reserves. Enhancements to existing facilities in Yalova's Altınova region aim to increase groundwater supply for irrigation. In Sivas, artificial recharge methods will be implemented to meet the animals' drinking water requirements. In Niğde, groundwater recharge is achieved using infiltration ponds in specific locations. The provinces of Artvin, Bolu, Çorum, Erzincan, Kahramanmaraş, Kayseri, Konya, Nevşehir, and Yozgat are now performing feasibility studies to enhance groundwater levels. These projects have tremendous potential for sustainable water resource management in Türkiye, as well as strategic significance for agriculture, drinking water, and the environment. The project funding has come from public sources managed by the Ministry of Agriculture and Forestry. The completed projects can supply irrigation to 3596 hectares of land, provide 21.2 hm^3 of drinking water per year, and store 33,977,319 m^3 of water. When all projects are completed, a total of 10,122 hectares of land will be irrigated, 21.9 hm^3 of drinking water will be provided each year, and 70,632,703 m^3 of water will be stored [49].

The managed aquifer recharge projects in Türkiye for 2019–2023 engage an integrated and methodologically distinct approach to groundwater resource development, taking into account geological, hydrological, hydrogeological, climatic, and water resource requirements. This strategy additionally defines the types of MAR used in Türkiye. The distinctions between basins and the techniques used by decision-makers in water management show promise in meeting water demand. The majority of completed projects used in-channel modifications (77%), with well, shaft, and borehole recharge (16%) and surface spreading (4%). Other methods, including recharging from quarries, dolines, and sinkholes, contributed to 3% (Figure 4a). However, future MAR projects, particularly in water-stressed regions such as southeastern and Central Anatolia, have experienced considerable strategic developments, including modifications in method selection. In future projects, the percentage of in-channel modifications rises from 77% to 90%, explaining their capacity as well as accuracy as preferred solutions. On the other hand, the application of well, shaft, and borehole recharge declines from 16% to 6%, while surface spreading drops from 4% to 3%. Occasionally implemented techniques, such as those including quarries and karst structures, have a minor role, accounting for only 1% of future projects (Figure 4b).

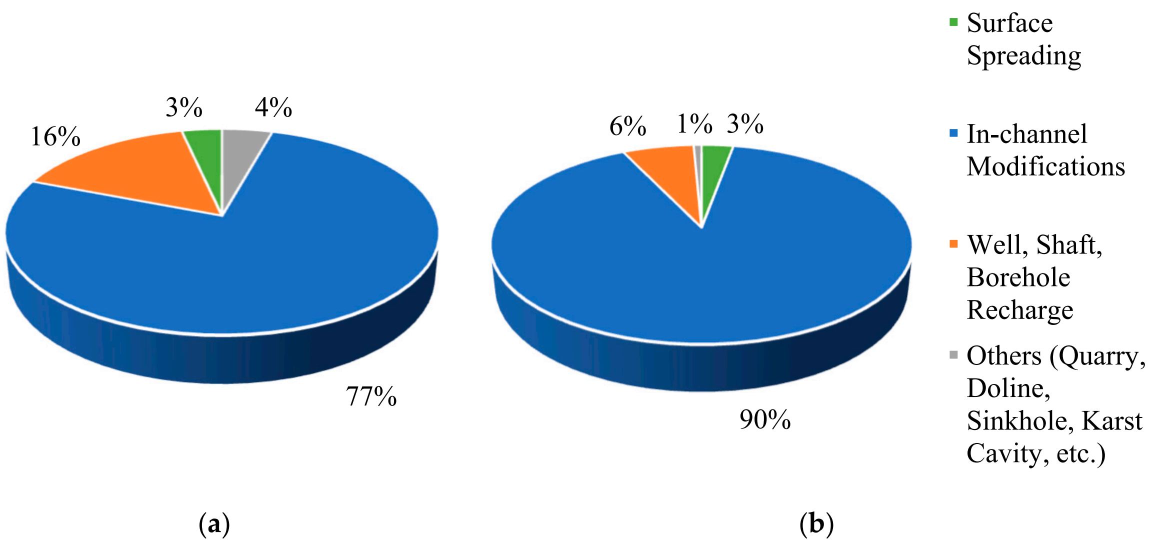


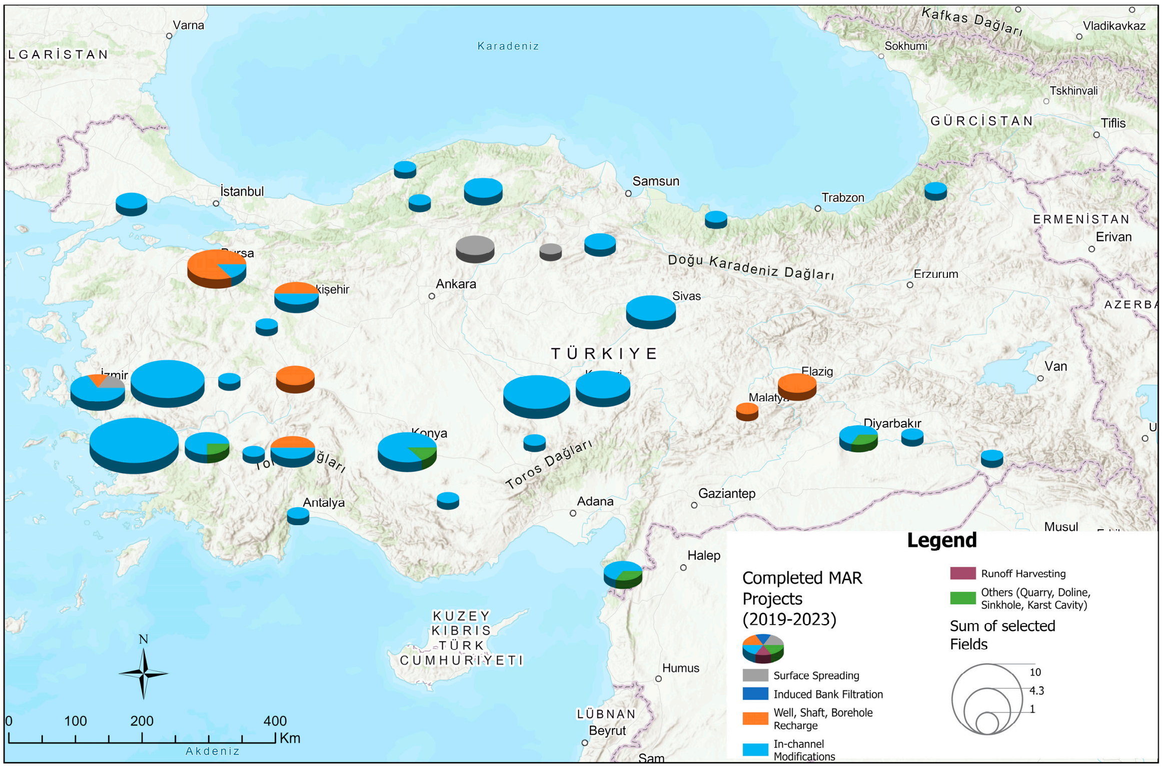
Figure 4. (**a**) Completed MAR projects and (**b**) future (under construction, planned and tender phase) MAR projects (2019–2023) (adopted from [49]).

In-channel modifications are followed by the well recharge method, which can be performed individually or in combination with the different methods in both completed and future projects. Surface spreading recharge and recharge through sinkholes, dolines, and karst cavities are both promising and effective methods implemented locally. These methods have been utilized in unconfined aquifers along with soils that have high surface permeability. Examples of such regions include the Western Mediterranean and Kızılırmak basins. The type of water source used significantly influences MAR projects. In Türkiye, 95% of the water used in these projects is from rivers and lakes, with groundwater accounting for the remaining 5%. Significant changes are expected as alternate water sources, particularly treated wastewater or stormwater, become integrated into soil aquifer treatment (SAT) initiatives. It also is expected to drive additional creativity and change in both current and future MAR projects.

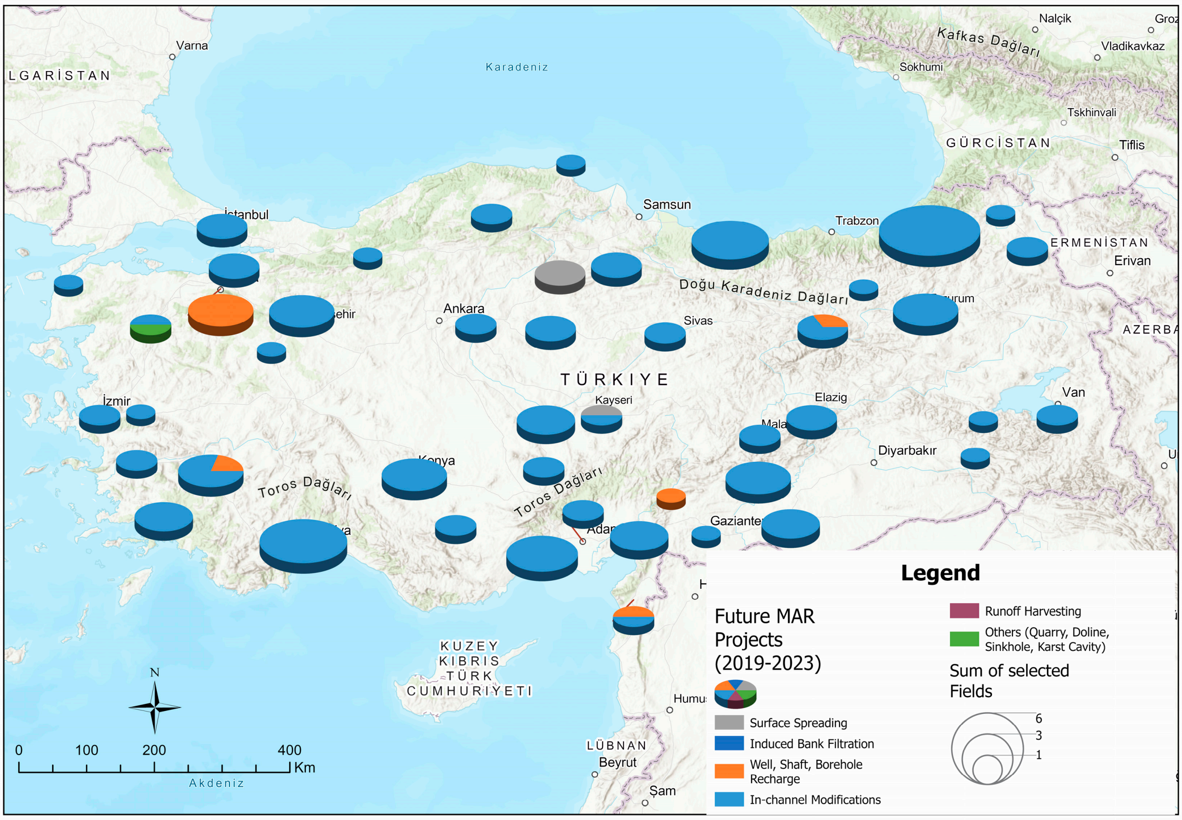
Surface spreading methods and recharging through karst structures are significant MAR methods in particular basins such as the Kızılırmak Basin (Kayseri: three completed, three planned) and the Antalya Basin (Denizli: four completed, five planned) [74]. Surface spreading is effective in basins regarding unconfined aquifers and permeable soils, allowing for slow infiltration and groundwater recharge.

In basins like the Western Mediterranean Basin (Denizli and Antalya), recharging is used in karstic limestones through natural sinkholes and quarries. In comparison with alternative methods, the percentage of in-channel modifications considered in future MAR projects has increased. The implementation of in-channel modifications has effects on managing flood and inundation risks, as well as setting up water management strategies to limit excessive precipitation in the Eastern Black Sea Basin. In comparison, deep well recharge projects result in a 10% decrease. Because in-channel modification methods require relatively fewer resources than drilling techniques, the decrease in decline has been integrated into water management strategies. The variations in estimated enhancements, together with the other alternatives to conventional methods for optimal water usage, highlight Türkiye's stability in water potential. The successes of the sinkhole recharge technique and karstic limestone recharge method, particularly in the Konya closed basin, offers insight into possible future initiatives in the region.

The status of the projects in each province is determined by colour codes, and the size of the slices in the pie charts indicates the numerical distribution of the projects (Figure 5a,b). The Western and Southwestern regions of Turkey have the most MAR projects, followed by Central Anatolia, while Eastern and Southeastern Anatolia, along with the Black Sea region, have comparatively fewer initiatives.. The main reasons for this situation include the morphological differences between regions, climate change and the dependence of the agricultural and industrial sectors on groundwater resources. Especially since the Konya Plain is a critical region in terms of agriculture, the sustainable use of underground water is supported by these projects. Because of its geographical location, the Konya closed basin has a high demand for groundwater, which is intensively used for agriculture. The gradual increase in agricultural productivity due to technological development has caused excessive water abstractions from karst aquifers in the region. Such regions have been focused on controlling groundwater usage and ensuring its sustainability. When the map is examined, it is seen that the number of projects in the Black Sea Region is relatively low. This situation is due to the region's climate with abundant rainfall, and the requirement for groundwater projects is lower compared to other regions. Unlike the projects carried out in other regions, it has been observed that projects have been created to prevent some flood events encountered in suitable climate conditions and to be able to use excess water at the same time.



(**a**)



(**b**)

Figure 5. Spatial distribution of (**a**) Completed MAR projects and (**b**) future (under construction, planned and tender phase) MAR projects (2019–2023) (adopted from [74]).

The projects carried out by DSI focus on cities such as Aydın, Manisa, İzmir, Konya, and Ankara, which are especially important in terms of agriculture and industry. The majority of these projects have been carried out to combat drought and contribute to agricultural irrigation. The absence of any projects in some provinces can be explained by reasons such as either the fact that natural water resources are sufficient in these regions or that priority is not given to other regions or provinces in terms of water management, planning, and strategy, or the current infrastructure and economic conditions delay the implementation of such projects. However, these provinces need to be re-evaluated in future strategic planning. The projects will play a critical and strategic role in Türkiye's groundwater management, which is under water stress, especially when evaluated in terms of the sustainability of groundwater, and will make a major contribution to meeting the country's water demand in agriculture, industry, and domestic use.

By replenishing groundwater supplies, MAR promotes the sustainable use of water in industry, domestic supply, agriculture, and environmental preservation. The distribution of both completed and future MAR projects among these sectors provides an understanding of Türkiye's water management priorities today and in the future.

The agricultural sector leads MAR projects (46%), with upcoming projects considerably above those that have already been completed (Figure 6). This trend emphasises the increasing requirement for irrigation to guarantee food security, particularly in nations like Türkiye, where the demand for agricultural water is rising dramatically. The environmental sector also contributes significantly (40%), with completed and planned initiatives roughly equal, emphasising the requirement of protecting the ecosystem and ecological balance in satisfying groundwater demands.

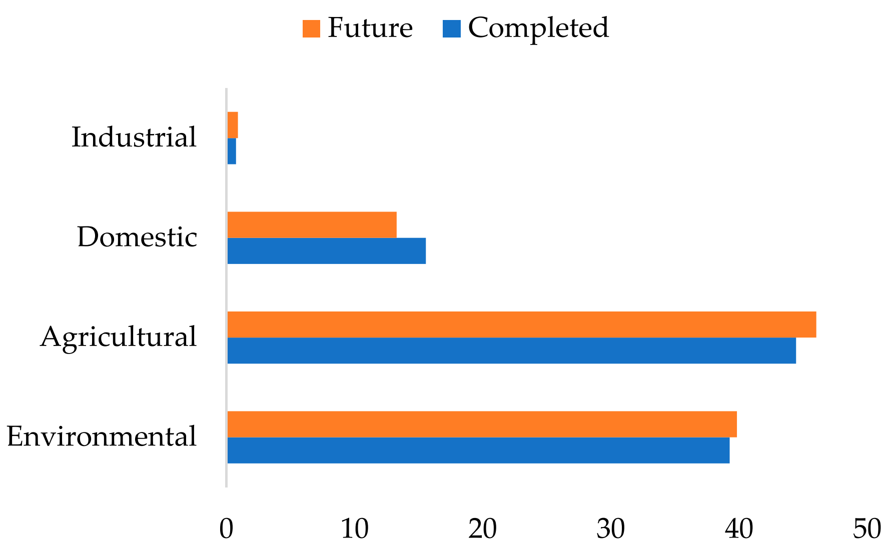


Figure 6. Completed and future artificial recharge projects concerning end-use purposes [74].

In comparison, there are fewer MAR initiatives in the domestic (13.5%) and industrial sectors. However, the inclusion of future industrial projects demonstrates an increasing awareness of their importance. Effective MAR planning must be altered at the strategic and regional levels to account for changing water demands across all sectors, promising equal resource allocation and long-term sustainability.

Through the development, creation, and implementation of new water resources, the gathering of treated wastewater into depleted aquifers and rainwater harvesting methods will become one of the most practical options that may be implemented in industrial and economic sectors in the near future. The integration of these two techniques with MAR projects and their use in groundwater recharge can both protect groundwater and enable more efficient use of water resources. Currently, hundreds of thousands of cubic meters of treated water from existing or newly constructed wastewater treatment plants can be used to recharge aquifers rather than being released directly into the sea. For transporting treated wastewater from treatment plants to aquifers, deep-drilling wells and large-diameter caisson wells can be used. Infiltration ponds can also be created as needed [75]. By supplying treated wastewater into the aquifers, the groundwater level will rise, the seawater intrusion zone will be regressed, some dry wells will be restored to service, and more effective production with lower operating costs will be possible in wells that produce.

In urban areas, rainwater harvesting from rooftops is a highly successful strategy for enhancing groundwater recharge or storage [76]. Türkiye has made significant progress in terms of rainwater harvesting. The Ministry of Environment and Urbanization published in 2017 legislation that requires the installation of a “rainwater harvesting system” in every new construction larger than 2000 square meters, with the goal of harvesting rainwater from building roofs and storing it in subsurface. In order to increase the applicability of MAR projects, it is necessary to determine suitable areas and to map underground water resources in detail. In this regard, a comprehensive hydrogeological inventory study should be conducted throughout Türkiye, as well as regional evaluations that take into account the effects of climate change on rainfall regimes. Encouraging rooftop rainwater harvesting systems can both eliminate natural recharge deficiencies and provide solutions to drainage problems frequently experienced in cities by directing collected rainwater to underground aquifers.

Reusing treated wastewater, on the other hand, can enhance water management measures by incorporating it into MAR projects. Treated wastewater can be utilized for agricultural irrigation, industrial processes, and groundwater recharge, decreasing the pressure on freshwater resources. In this context, increasing the capacity of wastewater treatment plants and conducting modernization studies should be among the primary concerns. Expanding the use of treated water in urban areas, such as garden irrigation, parks, and golf courses, can have a substantial impact on urban water management strategies. In industrial facilities, treated water can be used for cooling, cleaning, and other operational activities, lowering production costs while also protecting water supplies.

6. Limitations and Opportunities in MAR

There are a number of challenges and boundaries in implementing MAR studies in Türkiye, as well as around the world. These barriers are generally based on technical, environmental, and socio-economic factors and limit the efficiency of MAR systems. MAR applications include a wide range of contaminants, which can be transported to groundwater through infiltration. The abundance of nutrients like nitrogen and phosphorus in surface waters from agricultural areas can cause groundwater pollution and eutrophication [77]. Furthermore, fluctuations in the redox equilibrium during infiltration can cause the oxidation of iron and manganese oxides, resulting in the release of hazardous agents like arsenic into groundwater, which can have a severe impact on water quality. Solids and organic material deposited in infiltration zones may limit the capacity of water to flow into aquifers, decreasing storage efficiency because of clogging. Furthermore, surface waters may contain pathogenic microorganisms such as *Escherichia coli* and Enterococci, which can represent a major risk to human health. Trace organic pollutants (per- and polyfluoroalkyl substances (PFASs), pesticides, and pharmaceutical residues) are typically not fully removed in the MAR systems [78]. Alam et al. [79] emphasized that the MAR method is effective in increasing groundwater sustainability, and the main factors in the selection of MAR types are water availability, soil properties, and pollutant removal efficiency. Said et al. [80] used the DRASTIC model to construct a pollution risk map in the Kahe aquifer and concluded that high water tables and alluvial formations enhance pollution risk, recommending monitoring and waste management. Okoli et al. [81] used the DRASTIC model to assess pollution risks in Owerri, focusing on the risk of low-slope lands.

Many coastal cities and agricultural areas that rely on coastal aquifers for freshwater supplies are at risk of saltwater intrusion [79,82]. This infiltration produces groundwater insufficient for both urban and agricultural use, reducing agricultural land production. MAR can be an effective option in such areas, reducing seawater intrusion and providing a sustainable water source for agricultural and urban demands [79,83–85]. Abdel Monem et al. [86] demonstrated that isotopes such as oxygen-18 and carbon-14 are beneficial with salinity control and transboundary aquifer management in coastal aquifers when used effectively.

Another significant environmental impact is land subsidence and geotechnical challenges that might develop as a result of uncontrolled injection of water or abstraction. Excessive water extraction may destroy soil structure, causing surface land subsidence or deformation [87]. If water abstraction causes clay layer compaction or peaty soil oxidation, the subsidence can be irreversible [88]. This condition can have serious consequences, including concerns about water quality [89], disruption of services and infrastructure [90], increased flood risk [91], and loss of reservoir storage [88,92]. These consequences can be prevented by carrying out soil tests following field research and gradually pumping water. Faunt et al. [93] claimed that groundwater abstraction causes land subsidence in California, emphasizing the significance of long-term management measures. Seidl et al. [88] found that the (MAR) technique relies on hydrogeological conditions, effective water management, and good governance structures to reduce land subsidence. He underlined the requirement for proper monitoring and economic analysis tools.

To reduce environmental risks, water quality should be thoroughly analyzed during the design and construction stages of MAR projects, pathogens and trace organic pollutants should be pretreated, and waters with high organic matter content should be treated with granular activated carbon to avoid biological clogging [25]. Furthermore, in order to prevent clogging, sediments accumulating in infiltration regions should be cleaned mechanically or chemically, and pollutants ought to be removed chemically or biologically through the use of reactive barriers. Flooding in agricultural areas in MAR applications can be avoided by properly planning drainage systems and managing water levels. Continuous monitoring and maintenance are important to the long-term success and viability of MAR applications [79]. In recent years, extensive modeling methodologies have been critical for effective MAR project planning, design, and management because of the complexities of hydrogeological and geochemical processes. The contributions of modeling tools to MAR projects offer many benefits, such as reducing risks, optimizing recharge and recovery processes, estimating long-term effects and performance assessment in different hydrogeological conditions, estimating changes in groundwater quality and quantity, and analyzing contaminant transport [94–96]. Advanced technologies such as airborne electromagnetic (AEM) methods have allowed for better mapping of groundwater resources and identification of potential recharge areas [97]. MODFLOW, one of the most used groundwater flow modeling tools, is frequently applied to predict changes in groundwater levels, estimate flow paths, and evaluate recovery efficiency. Furthermore, geochemical models such as PHREEQC are useful for determining the impacts of water on pH, mineral solubility, and ion balance. The unsaturated flow models HYDRUS and MARTHE were used to determine the infiltration paths and durations of water directed from the surface to the subsurface [96]. Zhou et al. [98] used the SEAWAT model to investigate groundwater levels under tidal influence in China, whereas Sadeghi-Tabas et al. [99] used MODFLOW with optimization techniques to produce the best solution for the pumping regime in an Iranian basin. Deng et al. [100] investigated the impact of groundwater abstraction on land subsidence using MODFLOW.

In general, the literature has limited research on the historical development of MAR applications in Türkiye. After the 1960s, records of MAR applications were rare, and MAR application attempts were described as small-scale application projects. This situation made it impractical to analyze technical specifics and application results between 1960 and 2000, limiting the ability to build a reliable information base for future projects. Because of the lacking documentation of MAR initiatives completed during this time period, historical development conclusions are incomplete. Since the 2000s, MAR initiatives in Türkiye have grown in prominence as a means of managing groundwater resources sustainably. Surface spreading and underground dams were frequently selected in these projects, but other techniques such as recharge wells and induced bank filtration were not extensively investigated due to technological, financial, and legal limitations at the time. The widespread usage of underground dams for drinking water and agricultural irrigation by State Hydraulic Works in Anatolia has played a crucial role in water resource sustainability. However, the lack of understanding of the geological and hydrogeological environments, water quality issues, and technological difficulties faced in these initiatives has highlighted the need for more comprehensive research. These challenges have become increasingly significant in project management, particularly in terms of cost and time. In this context, investigating the potential of alternative approaches and technology investments to improve water quality, as well as modeling the aquifer, will lead to more effective results in terms of economic and environmental sustainability for MAR projects. The achievement of MAR projects is dependent on the proper assessment and planning of geological, hydrological, hydrogeological, and water quality and quantity characteristics. The efficacy of MAR projects is limited by incomplete or inaccurate estimations of aquifer-forming environment characteristics (porosity, void ratio, hydraulic conductivity storage coefficient, aquifer thickness). The efficiency of geohydraulic parameters in certain environments has a direct impact on groundwater recharge and infiltration rate. Soil type, ground moisture, vegetation, and land use characteristics should all be carefully addressed in aquifers with heterogeneous units that affect the quantity of recharge in the region. In exceptional circumstances, they can prevent the recharge process by restricting infiltration capacity and causing clogging problems. For example, the negative results of the pumping test in the underground dam project planned for the Mut district of Mersin have shown that the region's geological features are unsuitable for recharge projects, causing unfavorable study results [74]. Owing to its geographical location, Türkiye experiences a variety of climate conditions. Changes in groundwater levels can negatively impact MAR projects in arid and semi-arid climate basins like the Konya closed basin, as well as temperate basins with more precipitation [68]. Infiltration will be limited due to significant surface runoff during rainy seasons, particularly when impulsive precipitation occurs.

MAR applications in Türkiye can become more efficient and effective by integrating technological improvements. In particular, combining hydrological modeling software with artificial intelligence and machine learning-based algorithms can strengthen and optimize MAR project design procedures. These technologies allow for a more in-depth analysis of current hydrogeological conditions as well as predictions of aquifer responses under various climatic scenarios. Elçi et al. [101] used MODFLOW software to predict recharge rates and water table levels in a polluted area in İzmir. They combined a limited, transient water budget-based rainfall–runoff model with a groundwater flow model. Furthermore, Ayvaz and Elçi [102] created a simulation-optimization model using MODFLOW-2000 and

HS-Solver algorithms to reduce groundwater abstraction costs in İzmir's Tahtalı basin. The model optimized pump flow rates and well locations for various well numbers. These tools improve the success rate of MAR projects while also providing more reliable groundwater management solutions. Adopting a national MAR plan can assist groundwater management in integrating and coordinating more effectively. This technique can encourage cooperation among local governments, universities, public institutions, and the commercial sector, resulting in more successful project implementation. Furthermore, additional regulations and monitoring procedures are required to avoid exploitation of water resources, limit pollution, and assure the long-term success of MAR projects. Lastly, advancing public awareness and encouraging local engagement are essential for the success of MAR projects. Educational programs can be developed to raise local awareness of these projects and encourage community involvement in water management operations. Such approaches ensure that projects are not only technically sustainable but also socially and economically viable.

7. Historical Development of Water Policy and Legal Framework

The water resource management in Türkiye has shifted and evolved, shaped by a combination of legal regulations and institutional developments. Despite being one of the most abundant resources, water may not always be available at the right time, in the right place, or in sufficient quantities to meet demand. Water companies, including those in agriculture, municipalities, and industry, are therefore in intense competition with each other. This competition sometimes leads to disagreements. It has become necessary to resolve these disagreements and ensure that water is used fairly by people and institutions. Village Law No. 442 (1924) and Water Law No. 831 (1926) are regarded as fundamental documents for water resource management. Nevertheless, the rapid increase in water demand in the agricultural and industrial sectors made these early laws insufficient [50,103].

The General Directorate of State Hydraulic Works (DSI), which was established in 1953, is an investment institution affiliated with the central government budget and responsible for the planning, management, development, and operation of water resources in Türkiye [50,104]. DSI aims to use the country's water and soil resources in the most efficient way and carries out its activities based on the Law No. 6200 on the "Organization and Duties of the General Directorate of DSI", the Law No. 167 on "Groundwater", and the Law No. 1053 on "Drinking, Utility, and Industrial Water for Settlements with Municipal Organizations". Groundwater studies have been carried out by the Geotechnical Services and Groundwater Department, which started with the Groundwater Agency established in 1952 and joined DSI in 1956 [104].

The Groundwater Law No. 167, enacted in 1960, ensured that Türkiye's groundwater resources were considered public property and that the management of these resources was carried out by the state. Under this law, groundwater was not considered property, but rights of use were granted, and these rights could not be transferred or sold. This law authorized DSI as the central public institution responsible for the exploration, use, and protection of groundwater resources [50,103,105].

Environmental Law No. 2872, Türkiye's fundamental environmental law, was implicitly enacted in 1983 with the "Law on Copying Permission in the Environmental Law" No. 5491. The three basic principles of this law are protection of the environment, improvement of the environment, and prevention of environmental pollution. The Water Pollution Control Regulation, published in 1988, aims to protect Türkiye's water resources and ensure the optimal utilization of these resources following the principles of sustainable development [50,106].

The EU Water Framework Directive has played an important role in water management reforms carried out to protect and ensure the sustainable use of groundwater resources in Türkiye. Within the scope of integration studies carried out in the EU harmonization process, two main water institutions, the General Directorate of Water Management and the Turkish Water Institute, were established in 2012. While the General Directorate of Water Management is responsible for the implementation of the EU Water Framework Directive and related directives, the Turkish Water Institute carries out studies to develop effective water policies at national and international levels [50].

As a result, the legal regulations regarding groundwater in Türkiye generally consist of Law No. 6564. 167 Groundwater, and various regulations. The aim of these regulations is to ensure the protection, use, and management of groundwater resources. However, the current regulations in Türkiye are not as comprehensive and sufficient in terms of administrative elements as the legal regulations regarding groundwater resources and aquifer management in other regions such as Asia, Europe, America and Australia. To ensure a sustainable utilization of water resources, groundwater legislation must be revised to consider regional differences as well as geological and hydrogeological factors affecting groundwater management. In addition, more effective solutions that can be modified according to various aquifer environments should be developed.

8. Conclusions

This study addressed both the historical development and future potential of managed aquifer recharge (MAR) applications in Türkiye and evaluated different techniques and their regional impacts. The challenges Türkiye faces in water resource management have been driven by global factors such as climate change, rapid population growth, increasing agricultural demands, and unsustainable water use. In this regard, MAR techniques offer a promising solution for the sustainable management of groundwater resources.

These techniques were first considered in Türkiye in the 1960s, but large-scale applications have become more popular recently. Projects carried out by the State Hydraulic Works (DSI) have achieved significant success in line with both local and national water management strategies. In particular, the objectives outlined in the "Underground Dams Action Plan" align with Türkiye's excellent future prospects in MAR projects. By improving water quality, these projects help to preserve ecosystems while meeting the demands of industrial, drinking, and irrigation water in terms of sustainable water management. Projects planned to be completed in the future have strategic value, especially in terms of combating drought and more efficient use of water.

Türkiye has both barriers and opportunities in implementing MAR approaches due to its geographical, geological, and hydrogeological variety. These approaches are particularly effective in the Marmara, Aegean, and Mediterranean regions, where alluvial aquifers exist, due to their rapid water infiltration and storage capacity. Nevertheless, increased agricultural activity in these places, as well as issues like saltwater intrusion in coastal aquifers, require more careful planning and monitoring. In the Mediterranean and Central Anatolia regions with karst formations, low filtration capacity makes it difficult to preserve water quality, requiring extensive quality control procedures in MAR applications.

The sustainability of MAR projects is directly related not only to technical achievements but also to regulatory frameworks, public awareness, and planning appropriately according to regional characteristics. In this regard, ongoing monitoring and implementation of new approaches, the use of advanced technologies such as deep learning and artificial intelligence, the deepening of geological and hydrological analyses, raising local awareness, and the strengthening of existing regulatory frameworks in water resources management are all required. Regulatory procedures should be adaptable to changing geological and hydrogeological circumstances based on regions to ensure safe and efficient operation of MAR systems. Future research could involve comparative evaluations of various MAR techniques and comprehensive comparisons of global cases supported by models, thus contributing to addressing existing knowledge gaps in this field.

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