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A Tool of Sustainable Control of Groundwater Resources: Underground Dams

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Abstract: Climate change, global warming, and drought have been on the world's agenda since the first years of the 21st century. Türkiye, which has a semiarid climate, has also experienced periodic droughts. One of the most economical and effective measures for the sustainability of water use is underground dams. An underground dam is constructed as a barrier that blocks groundwater flow to retain and store water in a porous and permeable underground environment. Although underground dams have moderate disadvantages, they are one of the most effective groundwater management methods for efficient and sustainable use of water. As in many countries, the construction of underground dams is on the agenda in Türkiye, and there are many underground dams under construction. Moreover, the "Underground Dams Action Plan" (YBEP) is a project announced by the Minister of Agriculture on July 22, 2019, with the slogan "100 underground dams in honor of the 100th anniversary of the Republic of Türkiye." This article aims to emphasize underground dams as a useful tool for sustainable water management. Moreover, there is no literature and database containing statistical data on the number and location of underground dams in developed and developing countries in the world. In this article, it is aimed to make a brief review of underground dams in the world and to contribute to the literature by presenting data on the number and location of current underground dams in Türkiye.

Keywords: water management, sustainable groundwater control, underground dams

1. Introduction and Literature Review

The increase in the world population causes an increase in the demand for water in general and especially an increase in the demand for clean drinking water [1, 2]. In this case, water resources must be used efficiently, and water management must be planned and sustainable. Water management is the whole of policy development, planning, quality protection, investment, monitoring, permitting, inspection, sanction, and coordination activities that will ensure the optimum beneficial use of water resources and control their negative effects, taking into account the demands of all living things in all sectors [3]. Sustainable water use means ensuring the efficient use of water in an environmentally compatible manner without wasting water. In this context, it is necessary to reduce water consumption rates, determine methods for efficient reuse of water, and develop and implement water-saving models for a sustainable water management system [4, 5]. The current accessible water resource in the world constitutes only 1.2% of the total water resource [6, 7].

According to the "Water Efficiency Strategy within the Framework of Adaptation to the Changing Climate" published by the Ministry of Agriculture and Forestry of the Republic of Türkiye in 2023, available water resources decrease due to many factors, including drought, climate change, population growth, and unmanaged excessive water use. Due to the temperature increase and global climate change, changes in the world and the quantity and quality of water resources have a great impact on the water cycle (hydrological cycle) [8]. Especially due to climate change, average precipitation and changes in temperatures, more severe and longer droughts, and changes in evaporation and transpiration due to changes in vegetation, these are seen as issues of great importance for the sustainability of potential surface and groundwater resources [9, 10]. For this reason, many countries encounter increasing pressure on water resources due to the increasing demand for domestic, agricultural, and industrial water resources and construction costs. For this reason, various methods have been developed for the sustainability management of available water and water consumption around the world. The most well-known and effective way of using these methods is through underground dams [11–13]. Figure 1 shows a typical underground dam construction.

Underground dams are alternative constructions to control underground water and are mostly built in valley alluviums to store groundwater resources in aquifer environments with a high void ratio, raise groundwater levels, minimize evaporation losses, and use them in cases where there are limited or no surface water resources [14–16].

An underground dam essentially consists of a dam trunk built on a relatively impermeable substrate of soil and fractured rocks. In this way, the natural flow of groundwater in the aquifer that stores and transmits groundwater is prevented; the groundwater level rises, and water can be withdrawn and used throughout the year [11].

Underground dams are classified according to their purpose of use, method of construction, reservoir type, and materials of construction [17]. When classification by purpose of underground dam types are divided into two types: (1) the dam-up type, which is used just to store water, and (2) the saltwater intrusion prevention type, which is used to prevent saltwater (Figure 2). The

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Figure 1
An image of underground dams

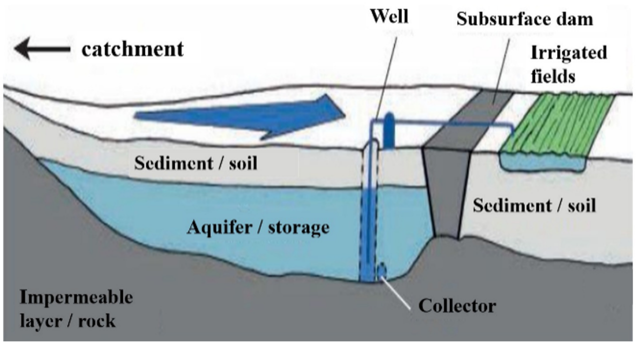
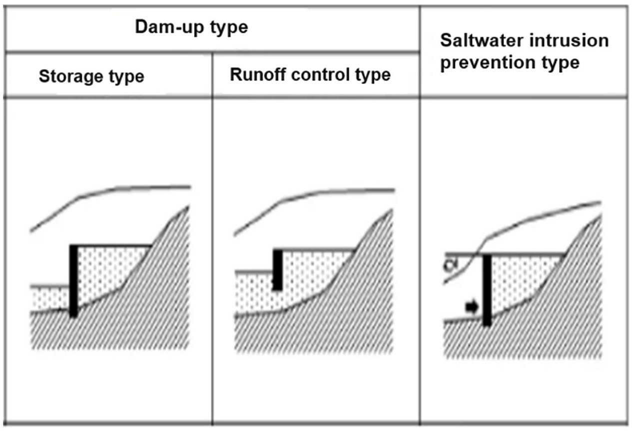


Figure 2
Classification by purpose of underground dam



classification by construction method consists of the grouting method, impermeable body driving method, and diaphragm wall method types. On the other hand, the classification by reservoir types includes fully subsurface storage types, partially surface storage types, and surface dam hybrid types. Finally, the classification by construction material types is made by using construction materials such as concrete, stone masonry, injected bentonite slurry, etc. [17].

1.1. Effective parameters in underground dams

1.1.1. Estimation of obtainable water and analysis of seasonal changes

The calculation of groundwater recharge and the amount of water that can be obtained from an underground dam is a difficult task. It is not enough to define the porous medium in which the dam would be constructed physically and hydraulically; it is necessary to investigate the change of recharge with time depending on meteorological conditions. This requires multifaceted field and laboratory studies. Groundwater systems generally respond to drought later than surface water bodies [18]. However, especially in arid or semiarid regions, significant changes in groundwater levels and consequently in flow rates during dry and wet periods are an important problem, and this should be taken into account in the planning phase, and the seasonal behavior of the system should be monitored for a sufficient period of time. For this purpose, data should be collected for at least 2–3 years, and the conditions represented by the obtained data within the climate cycle should be well analyzed. For example, the water flow and groundwater level obtained from underground dams constructed in Türkiye in the 2000s could only be measured in short-term or one-off measurements. If regular records could have been taken, detailed analyses could have been made. Nevertheless, there is some experience. For example, while the flow rate was 30 l/s when the Malıboğazı underground dam was constructed at the end of 2004, it decreased to 13 l/s at the end of the irrigation season in the summer of 2005. Between 2006 and 2010, the flow rate measured several times was between 15 and 30 l/s. Since the region received good rainfall in 2010–2012 compared to the previous 5–6 years, the flow rate at the dam increased to 60 l/s in July 2012. Another example of seasonal variation is the Elmadağ Kargalı dam. The surface reservoir of the dam, which has both underground and aboveground storage, was completely emptied in June 2016 due to the use for drinking purposes, but water continued to be obtained from the aquifer below for a while. The dam reservoir was filled again with the precipitation in the following year.

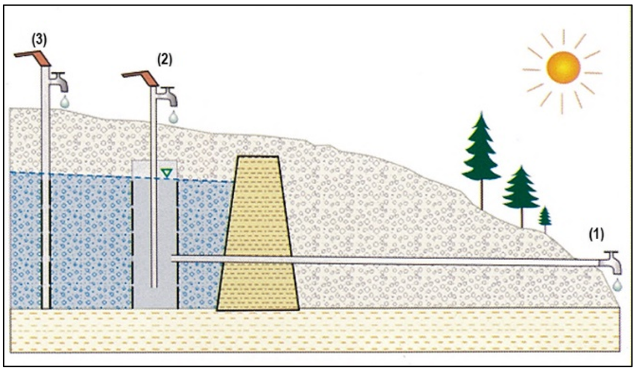
1.1.2. Selection of the most appropriate dam type and water intake method

Site selection and deciding on the most appropriate and cheapest water intake method (gravity or pumped option) is another important task for water supply. In this context, the location of the water intake facility and the number and location of wells, if any, should be planned. Moreover, the construction cost is also important. This mainly depends on exploration and drilling, aquifer tests, construction material, transport, excavation volume, and water intake structure (in case of gravity flow) or operation wells, pumps, and energy supply. Each component mentioned above requires expertise and good planning. The choice of dam body type is determined by the purpose, function, and material conditions. Whatever the dam type (earth or rock fill, concrete, conventional mortar, plastic concrete, etc.), the most important issue in an underground dam for water supply is how the water is obtained and how the plant is operated. In pumped projects, the work consists of the construction and pumping of the casing to seal the groundwater with the production wells in the reservoir behind the dam (Figure 3). If water is to be obtained by gravity, where the water will be taken from (bottom, center, or overflow over the body), how the water intake structure will be constructed, how the water will be transmitted, and how and where it will be brought to the surface are determined at the project stage. The topography and location of the aquifer are decisive for gravity and pumped underground dams. For example, in groundwater dams constructed in alluvial aquifers in high slope valleys, there is no need to take water from the bottom since no significant additional volume can be gained behind the dam. In such a case, water can be taken from the center of the dam body by a pipe or by overflowing over the crest. However, in low slope valleys and thick aquifers, pumping from wells and gravity method can be considered. If the gravity method is chosen, it should be preferred to take the water as deep as possible so that the aquifer volume above the water intake elevation is high (Figure 3). In such a case, the deeper the water intake structure is built, the more water can be taken by gravity. However, the deeper the intake level, the higher the excavation volume and cost for the pipeline.

1.2. Site selection for underground dams

Before selecting and planning the basic parameters of an underground dam construction, such as groundwater recharge and the site where the dam will be constructed, and evaluating it under

Figure 3
Methods of obtaining water from underground dams (1) by attraction; (2) by pumping from caisson wells; (3) by pumping from boreholes



technical, economic, and social conditions along with the water need, basic parameters such as precipitation, surface flow, and groundwater recharge should be investigated within the scope of basin hydrology and hydrogeology [19, 20]. The site selection of an underground construction depends on the following conditions:

- The effective porosity and hydraulic conductivity of the soil layers that will be reservoirs must be suitable for the collection and storage of groundwater.
- There must be a base soil layer with lower permeability under the reservoir to provide the necessary storage.
- There must be an impermeable environment beneath the alluvium or rock aquifer at a depth that can be excavated or where effective injection can be made.
- The depth of the soil layer that will be the foundation must be at the depth where the dam axis is to be built.
- There must be sufficient groundwater recharge to supply the planned water volume.
- Groundwater usage needs should be sufficient.
- The quality of the water must be appropriate.
- Water quality must be within the appropriate range in terms of water usability.
- Its impact on the downstream side should be low [17, 21, 22].

In addition to these basic conditions, it is extremely important that the recharge conditions in the aquifer storage area and behind the storage area are of the desired quality, even if there is a sufficient volume of porous media behind the body to be built [23]. For this reason, it is advantageous for the aquifer and the soil cover above it, if any, to be coarse-grained, to have a wide spread of the aquifer, and to have higher percolation. In addition to the dimensions of the aquifer, the storage characteristics (determined by pumping tests and laboratory experiments), the permeability and depth of the base formation, the groundwater level and its variation, how the water to be stored can be obtained (by gravity or pumping from wells), the gravity and pipe diameter and, if possible, the elevation of the water intake structure, the availability of impermeable materials for the construction of the casing are effective parameters.

2. Underground Dams in the World and in Türkiye

Storing both underground and surface water underground for later use is not a new practice. The fact that underground dams were built in Sardinia Island and Tunisia during the Roman period shows that these structures have been built in North Africa since ancient times [24]. In the last 50 years, underground dams of various sizes have begun to be built in many parts of the world, especially in South and East Africa and India [17, 25, 26]. The capacities of old underground dams are smaller than the recently constructed underground dams and were used to meet domestic needs in small rural settlements. Underground dams have been built with larger capacities since the 1990s and thus have been used to meet the drinking water needs of larger settlements and to irrigate larger agricultural areas.

Recently, many underground dams have begun to be built in the world. In the 1990s, approximately 500 small-scale groundwater storage structures were built in rural areas against drought in Brazil and some sediment storage dams in Kenya [24, 25, 27, 28]. Several underground dams have been built in Iran and in India in 2000–2001, and six underground dams have been built in Korea in the last century [29, 30]. After the 1990s, some large underground dams were built in China and Japan [22, 31, 32]. It is seen that studies have been carried out on underground dams to provide water for various purposes and scales and to prevent saltwater intrusion [18, 26, 33–41].

The average annual precipitation in Türkiye is approximately 574 mm, which corresponds to an average of 450 billion m^3 of water per year. Within the framework of today's technical and economic conditions, the surface water potential that can be consumed for various purposes is an average of 94 billion m^3 per year. The consumable surface and 18 billion m^{3}groundwater potential of our country is an average of 112 billion m^3 per year, of which 57 billion m^3 is used. Of this, 44 billion m^3 is used for agricultural irrigation, and 13 billion m^3 is used as drinking water and domestic and industrial water [2]. The annual amount of usable water per person in our country was 1652 m^3 in 2000, 1544 m^3 in 2009, and 1346 m^3 in 2020. Considering these data, Türkiye will be among the countries whose water needs cannot be supplied.

In Türkiye, usable water is generally supplied from storage facilities such as dams and ponds, as well as from aquifers that provide natural storage. However, Türkiye, along with the rest of the world, has made future plans due to the negative scenarios and difficulties in accessing water and sustainability in water use that are expected to be experienced in the world. The first large-scale underground dam was designed in İzmir Çeşme in 1998 to prevent seawater intrusion and store the groundwater in the coastal aquifer in Çeşme. However, since the construction of this project was completed, this underground dam has never been used successfully [22]. The second underground dam built in Türkiye is the Yahşihan Dam, which was built in 2003 in the Yahşihan district of Kırıkkale to provide drinking water to Yahşihan. Other underground dams built in Türkiye between 2003 and 2012 are Malıboğazı, Ağır Olunlu, Sancar, Bahşılı, İskilip, Baskil, and Elmadağ underground dams [22]. Some underground dams in Türkiye are shown in Figure 4.

Within the scope of the "Groundwater Artificial Recharge and Underground Dams Action Plan" prepared by the Turkish Ministry of Agriculture and Forestry, 41 projects have been carried out in the cities of Izmir, Manisa, Çankırı, Konya, Bursa, Eskişehir, Antalya, Kütahya, Balıkesir, Nevşehir, Kayseri, Niğde, Malatya, and Kayseri, where the project was implemented successfully. The ministry plans to complete nearly 200 underground dams by 2023, and 150 of them have been constructed.

Figure 5 shows the distribution of some underground dams built in Türkiye with the number of completed dam construction in use.

Figure 4
Some underground dams in Türkiye (a) Hatay Ceylanlı Underground Dam Construction Phase; (b) Aydın Kuyucak Beşeylül Artificial Feeding Project; (c) Seyitler Village Godrahov Stream Underground Dam; (d) Artificial recharge by diversion of water into Timraş sinkhole from the transmission canal

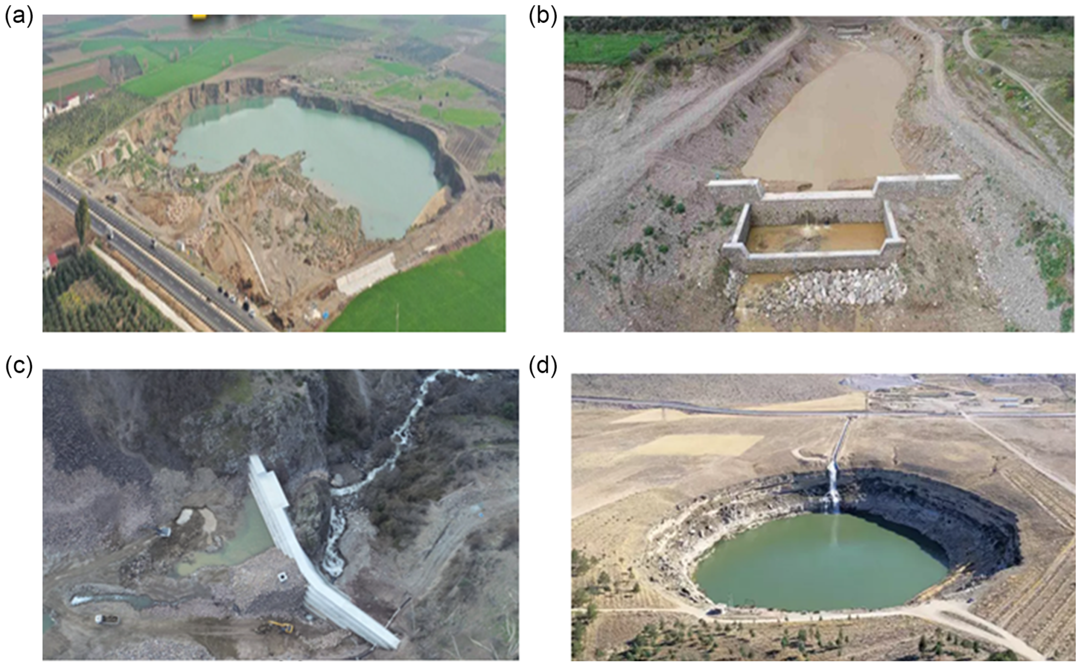
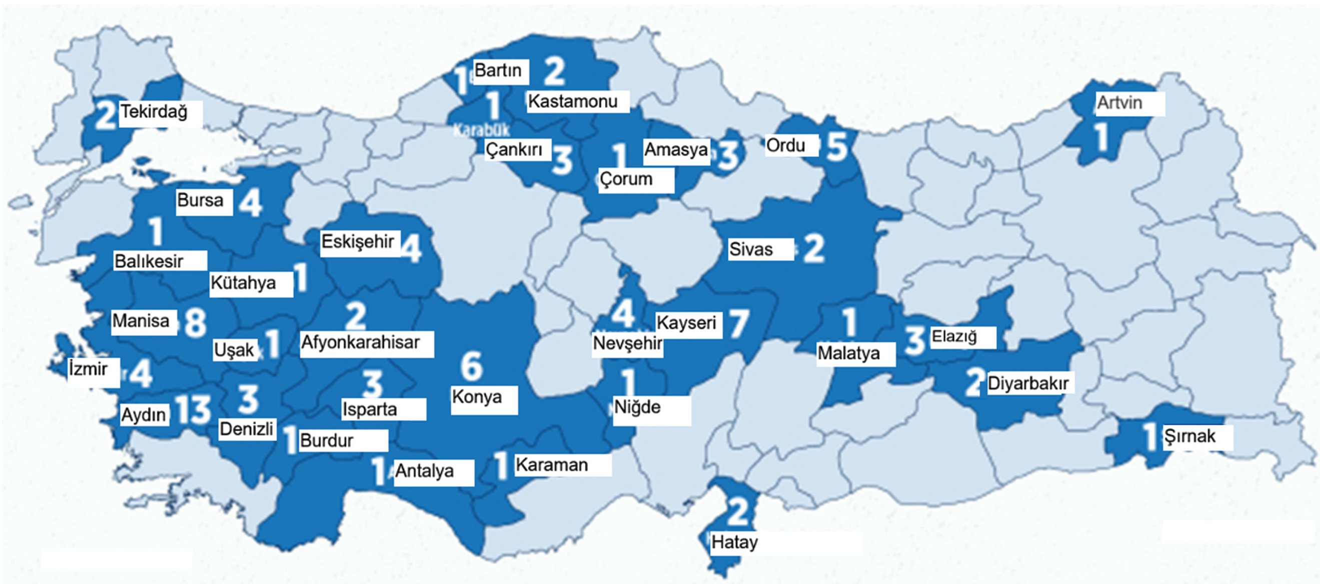


Figure 5
Distribution of underground dams built in Türkiye



The irrigation water was provided to an area of 36 thousand decares, and 21 million[3] hectometers of drinking water was provided with the underground dams in Türkiye. Moreover, approximately 50 million cubic meters of water will be stored with the start of use of 150 underground dams completed by the end of 2023. By allocating all of the water stored in these dams to drinking water, drinking water will be provided to 750 thousand people, and if allocated for irrigation, 80 thousand decares of land would be irrigated.

3. Discussion

Two basic issues arise in the management of water resources: one is to protect water resources, and the other is to manage the use of water resources in a sustainable manner. For this reason, it is necessary for public institutions, local governments, and universities that undertake both decision-making and research tasks regarding the management of water resources to organize the studies within a standard and to continue the implementation by creating a water management policy. While 75% of the total water resources in Türkiye are used for irrigation, 33% of the total water resources in the Europe (EU) are used for agricultural irrigation. This rate increases to 75% in Southern Europe. On the other hand, in Central and Western Europe, most of the water (57%) is used for energy production, especially for cooling purposes, and as drinking water in cities. In the EU, as in Türkiye, the amount of water used for irrigation varies according to climate, soil structure, product type, water quality, and irrigation techniques, but many environmental and economic problems arise due to the nonuse of irrigation technologies [42, 43]. The priority of using the potential water is listed as follows: (1) Drinking and usage needs. (2) Water needs for the continuation of animals and natural life. (3) Agricultural irrigation water needs. (4) Energy and industrial water needs. (5) Water needs for trade, tourism, fishing, etc. [2].

Today, underground dams, which are an alternative in terms of sustainability in water use, are generally built in granular aquifers with shallow thicknesses, and although they can sometimes be built in rock environments with developed fracture-crack systems and aquifer properties, they are a limited alternative due to limitations in site selection. Moreover, underground dams are not only built for water sustainability, but they are also built against the salinization of groundwater in living areas by the sea. With 50% of the world's population living near the seashore and 60 km away from the sea, seawater causes the salinization of the available water in coastal areas. It causes soil salinization and a significant decrease in agricultural production [26, 32].

The underground dams have advantages but also some disadvantages compared with traditional dams [2, 33, 44]. Since the aquifer in which water will be stored cannot be homogeneous at every point, it is difficult to determine hydrogeological parameters precisely. Despite this, some parameters of the aquifer, such as storage coefficient and permeability, are generalized in projects as if they would represent the entire aquifer. The amount of water to be stored in underground dams may be considerably lower than the projected or calculated amount of water. Another important disadvantage is that storing and retaining groundwater causes the ground pore pressure to increase, which in turn causes an increase in the stress balance in infrastructures and also causes liquefaction in the ground in a possible earthquake [45].

Underground dams and environmental interaction are also a separate issue. Although groundwater resources are renewable, it is very difficult to naturally refill reservoirs emptied due to excessive withdrawals. However, in cases where natural recharge is insufficient, artificial methods allow faster renewal of groundwater resources [46, 47]. Since the underground dam, which is one of the artificial recharge and development methods, significantly changes the groundwater level in the aquifer, it also causes a change in quality. As the water level rises in the reservoir, more water is obtained by consuming less energy. However, the problem of salinization arises when the water level rises to the surface or moistens the soil zone. Contamination of groundwater stored in underground dams is more difficult than surface water. In addition, the soil cover and the underlying vadose zone function as a natural purification for the water filtering into the underground dam. Despite this, the issue of pollution and quality change is an issue that must be taken into consideration and carefully monitored for underground dams. One of the important problems in quality is nitrate (NO_3) pollution. Nitrate pollution is an issue that should be taken into consideration and monitored with other quality parameters, especially in projects with agricultural activities at the source. A typical example of increased nitrate concentration in stored groundwater after dam construction is the Sunagawa underground dam on Miyako Island, Japan. The dam construction was completed in 1998, and the reservoir was completely filled two years later. Since 2001, water has been pumped to agricultural lands from 100 wells in the dam with powerful pumps. While the nitrate concentration in the groundwater in the region was 5 mg/l in 1975 before the dam was built, there was an increase due to fertilizers on sugar cane cultivated lands, and it rose to around 10 mg/l in 1988. This amount is the upper limit for drinking water according to Japanese standards [2].

4. Conclusions

The most important issue of the 21st century is that there will be "wars for water" as water resources diminish due to rapidly increasing climate change. In addition to drought, rainfall turning into heavy downpours and urbanization reduce the amount of water stored in surface dams. In addition, pollution of the natural environment makes access to clean water more difficult.

It is possible that underground dams can be an alternative to surface dams in some cases. This is because increasing average temperatures accelerate water loss from reservoirs in surface dams. In semiarid regions where nutritional and geological conditions are not suitable for traditional dam construction, alternative solutions against drought have been developed where underground dams would be more appropriate and economical to meet the water demand. In this context, it is clearly seen that the importance of underground dams increases the potential to utilize more water in the natural hydraulic cycle.

As in many countries, the importance of underground dams is on the agenda in Türkiye, and there are many underground dams under construction. Although underground dams are expensive to survey, they are cheaper to operate than surface dams when methods such as gravity water supply are used. Since underground dams also prevent seawater from mixing with fresh water in coastal areas, both the groundwater of the delta plains on the coast of the country and the aquifers on the high coasts will be protected from salty seawater.

Although underground dams have moderate disadvantages, they are one of the most effective groundwater management methods for efficient and sustainable use of water. This paper aims to draw attention to the importance of underground dams and their construction as there are not many studies in the literature. In addition, this paper aims to contribute to the literature by providing data on the number and location of underground dams in Türkiye and to overcome the lack of data and archives on underground dams in the world.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Pinar Sari Çavdar: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

References

[1] Raskin, P. D., Mansen, E., & Margolis, R. M. (1996). Water and sustainability global patterns and long-range problems. *Natural Resources Forum*, *20*(1), 1–15. https://doi.org/10.1111/j.1477-8947.1996.tb00629.x

[2] Kolay, E., & Öztürk, B. (2021). Underground dams in water supply: A case study. *Electronic Letters on Science & Engineering*, *17*(2), 76–88.

[3] Fakhimi, E. L. H. A. M., Salehi, F., & Emami, S. N. (2024). Changes in vegetation indices and species diversity in plowed and abandoned agricultural lands and the natural cover of the rangelands around the Yan Cheshme underground dam, Chaharmahal and Bakhtiari province. *Iranian Journal of Range and Desert Research*, *30*(4), 505–520.

[4] Serageldin, İ. (1995). Su kaynakları yönetimi: Sürdürülebilir bir gelecek için yeni bir politika. *Uluslararası Su Kaynakları Geliştirme Dergisi*, *11*(3), 221–232. https://doi.org/10.1080/07900629550042191

[5] Kırtorun, E., & Karaer, F. (2018). Water management and sustainability of water. *Sürdürülebilir Mühendislik Uygulamaları ve Teknolojik Gelişmeler Dergisi*, *1*(2), 151–159.

[6] Yılmaz, A. (2015). Küresel ısınmanın dünya su rezervleri üzerindeki etkileri. *Journal of Urban Academy*, *8*(2), 63–70.

[7] Dewandel, B., Lanini S., & Frissant N. (2024). Steady-state semianalytical solutions for assessing the two-dimensional hydraulic head distribution induced by an underground dam in a sloping aquifer with artificial aquifer recharge and pumping. *Hydrogeology Journal*, *32*(3), 801–816.

[8] Bai X., Jia Y., & Liu H. (2023). Analysis of the current situation and problems of drinking water quality testing in the new period. *Journal of Global Humanities and Social Sciences*, *4*(2), 83–87. https://doi.org/10.47852/bonviewGHSS23208630208

[9] Can, A. B., & Yılmaz, D. (2023). Kızılırmak Havzası Barajlarının Kuraklığa Etkisi. *MAUN Mühendislik-Mimarlık Fakültesi Dergisi*, *4*(1), 1–10.

[10] Alley, W. M., Reilly, T. E., & Franke, O. L. (1999). *Sustainability of ground-water resources*. U.S. Geological Survey.

[11] Nishigaki, M., Kankam-Yeboah, K., & Komatsu, M. (2004). Underground dam technology in some parts of world. *Journal of Groundwater Hydrology*, *46*(2), 113–130. https://doi.org/10.5917/jagh1987.46.113

[12] Şahin, Y., Baba, A., & Tayfur, G. (2018). Küçük menderes havzası su kaynaklarının sürdürülebilirliği. *DÜMF Mühendislik Dergisi*, *9*(2), 955–962.

[13] Boz, B. (2022). *Bursa ilinde yeraltı barajlarının inşası için potansiyel yerlerin belirlenmesinde CBS yaklaşımı [Yüksek lisans tezi]*. Bursa Teknik Üniversitesi.

[14] Yılmaz, M., & Önder, H. (2005). Underground dams: A tool of sustainable development and management of groundwater resources. *European Water Dergisi*, *11*(12), 35–45.

[15] Kaya, S. (2020). *Doğru akım özdirenç yöntemi ile yeraltı barajlarında yer seçimi uygulaması.* [Yüksek lisans tezi]. Ankara Üniversitesi, 49.

[16] Ngoch, N. M. (2024). Solution of subsurface dam for water supply. *GreenEnergy E3S Conferences*, *508*, 08012. https://doi.org/10.1051/e3sconf/202450808012

[17] Hansson, G., & Nilsson, A. (1986). Groundwater dams for rural water supplies in developing countries. *Ground Water*, *24*(4), 497–506.

[18] Ouerdachi, L., Boutaghane, H., Hafsi, R., Boulmaiz Tayeb, T., & Bouzahar, F. (2012). Modeling of underground dams application to planning in the semi-arid areas (Biskra, Algeria). *Energy Procedia*, *18*, 426–437.

[19] Apaydın, A. (2022). Kuraklığa karşı yeraltı barajları: 'Yeraltı Barajları Eylem Planı' ekseninde bir değerlendirme. 2. *International Cappadocia Scientific Research Congress*, 971–977. https://doi.org/0000-0002-6437-7208

[20] Talebi, A., Mandegar, A. R., Parvizi, S., Poordara, H., & Barkhordari, J. (2023). Underground dam site selection using hydrological modelling and analytic network process. *Groundwater for Sustainable Development*, *23*, 100976.

[21] Osuga, K. (1997). *Miyakojima adaları'ndaki yeraltı suyu kaynaklarının geliştirilmesi*. United Nations University.

[22] Apaydın, A. (2014). Yer seçiminden işletmeye yeraltı barajları. DSİ Genel Müdürlüğü Destek Hiz. *Daire Başkanlığı Basım ve Foto-Film İşletme Müdürlüğü, (Basılı kitap)*, 76–211. ISBN:978-605-64763-0-3

[23] Ekhtiari, M., Zandieh, M., & Tirkolaee, E. B. (2023). Optimizing the dam site selection problem considering sustainability indicators and uncertainty: An integrated decision-making approach. *Journal of Cleaner Production*, *428*, 139240.

[24] Ertsen, M., & Hut R. (2009). Two waterfalls do not hear each other. Sand-storage dams, sciences and sustainable development in Kenya. *Physics and Chemistry of the Earth*, *34*, 14–22.

[25] Foster, S., Azevedo, G., & Baltar, A. (2002). Subsurface dams to augment groundwater storage in basement terrain for human subsistence-Brazilian experience. *World Bank*, *GWMATE Case Profile Collection*, *5*, 5.

[26] Zarkesh, M. M. K., Ata, D., & Jamshidi, A. (2012). Performance of underground dams as a solution for sustainable management of drought. *Journal of Biourbanism*, *1*, 35–45.

[27] Foster, F., & Tuinhof A. (2004). Brazil, Kenya: Subsurface dams to augment groundwater storage in basement terrain for human subsistence. *World Bank Sustainable Groundwater Management Lessons from Practice*, 1–8.

[28] Hut, R., Ertsen, M., Joeman, N., Vergeer, N., Winsemius, H., & Giessen, N. (2007). Effects of sand storage dams on groundwater levels with examples from Kenya. *Physics and Chemistry of the Earth*, *33*(1), 56–66.

[29] Hartung, F., & Kuros, G. R. (1987). Historische Talsperren im Iran. Historical dams in Iran. *Historische Talsperren*, *1*, 221–274.

[30] Raju, N. J, Reddy, T. V. K., & Munirathban, P. (2006). Subsurface dams to harvest rainwater—a case study of the Swarnamukhi river basin. *Southern India Hydrogeology Journal*, *14*, 526–531.

[31] Nagata, S., Enami, N., Nagata, J., & Katho, T. (1993). Design and construction of cutoff walls for subsurface dams on Amami and Ryukyu islands in the most southwestern part of Japan. *IAH Selected Papers on Environmental Hydrogeology*, *4*, 229–245.

[32] Ishida, S., Kotoku, M., Abe, E., Fazal, M. A., Tsuchihara, T., & Imaizumi M. (2003). Construction of subsurface dams and their impact on the environment. *RMZ - Materials and Geoenvironment*, *50*, 149–152.

[33] Ishida, S., Tsuchihara, T., Yoshimoto, S., & Imaizumi, M. (2011). Sustainable use of groundwater with underground dams. *Japan Agricultural Research Quarterly [JARQ]*, *45*(1), 51–61.

[34] Raju, N. J., Reddy, T. V. K., Muniratnam, P., Gossel, V., & Wysick, P. (2013). Managed aquifer recharge (MAR) by the construction of subsurface dams in the semi-arid regions: A case study of the Kalangi river basin, Andhra Pradesh. *Journal of the Geological Society of India*, *82*(6), 657–665.

[35] Jamali, I. A., Olofsson, B., & Mörtberg, U. (2013). Locating suitable sites for the construction of subsurface dams using GIS. *Environmental Earth Sciences*, *70*(6), 1–15.

[36] Kaleris, V. K., & Ziogas, A. I. (2013). The effect of cutoff walls on saltwater intrusion and groundwater extraction in coastal aquifers. *Journal of Hydrology*, *476*, 370–383.
[37] Botero-Acosta, A., & Donado, L. D. (2015). Laboratory scale simulation of hydraulic barriers to seawater intrusion in confined coastal aquifers considering the effects of stratification. *Procedia Environmental Sciences*, *25*, 36–43.
[38] Cantalice, J. R. B., Piscoya, V. C., Singh, V. P., da Silva, Y. J., de FC Barros, M., Guerra, S. M., & Moacyr Filho, C. (2016). Hydrology and water quality of a underground dam in a semiarid watershed. *African Journal of Agricultural Research*, *11*(28), 2508–2518.
[39] Abdoulhalik, A., & Ahmed, A. A. (2017). The effectiveness of cutoff walls to control saltwater intrusion in multi-layered coastal aquifers: Experimental and numerical study. *Journal of Environmental Management*, *199*, 62–73.
[40] Luiz, D. S. G. J., Vieira, F. P., & Mannathal, H. V. (2018). Use of electrical resistivity tomography in selection of sites for underground dams in a semiarid region in southeastern Brazil. *Groundwater for Sustainable Development*, *7*, 232–238. S2352801X17301868.
[41] Chang, Q., Zheng, T., Zheng, X., Zhang, B., Sun, Q., & Walther, M. (2019). Effect of subsurface dams on saltwater intrusion and fresh groundwater discharge. *Journal of Hydrology*, *576*, 508–519.
[42] Thao, V. B., Thanh, N. C., & Vuong, N. H. (2020). Horizontal groundwater collecting solution for improving the water collecting ability of check dams in the Northeastern region, Vietnam. *Agriculture and Rural Development*, *1*(06), 59–66.
[43] Şen, Z. (2023). Longitudinally and laterally trench-supported subsurface dam innovative design procedures. *Water Supply*, *23*(2), 821. https://doi.org/10.2166/ws.2023.023
[44] Gomes, J. L, Vieira, F. P., & Hamza, V. M. (2018). Use of electrical resistivity tomography in selection of sites for underground dams in a semiarid region in southeastern Brazil. *Groundwater for Sustainable Development*, *7*, 232–238.
[45] Sun, Y., Xu, S. G., Kang, P. P., Fu, Y. Z., & Wang, T. X. (2019). Impacts of artificial underground reservoir on groundwater environment in the reservoir and downstream area. *International Journal of Environmental Research and Public Health*, *16*(11), 1921.
[46] Peksezer Sayit, A., & Yazicigil, H. (2012). Assessment of artificial aquifer recharge potential in the Kucuk Menderes River Basin, Türkiye. *Hydrogeology Journal*, *20*, 755–766.
[47] Ebrahimi, J., Moradi, H. R., & Chezgi, J. (2021). Prioritizing suitable locations for underground dam construction in south-east of Bushehr Province. *Environmental Earth Sciences*, *80*, 680.

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