water

Review

Water Dams: From Ancient to Present Times and into the Future †

Andreas N. Angelakis [1,2], Alper Baba [3], Mohammad Valipour [4], Jörg Dietrich [5], Elahe Fallah-Mehdipour [5], Jens Krasilnikoff [6], Esra Bilgic [7], Cees Passchier [8], Vasileios A. Tzanakakis [9,*], Rohitashw Kumar [10], Zhang Min [1], Nicholas Dercas [11] and Abdelkader T. Ahmed [12]

1 School of History and Culture, Hubei University, Wuhan 430061, China; info@a-angelakis.gr (A.N.A.); zhengxy0011@qq.com or 82214580@qq.com (Z.M.)
2 National Foundation for Agricultural Research, Institute of Irak lion, 71307 Iraklion, Greece
3 Izmir Institute of Technology, Department of International Water Resources, 35430 Izmir, Türkiye; alperbaba@iyte.edu.tr
4 Department of Engineering and Engineering Technology, Metropolitan State University of Denver, Denver, CO 80217, USA; mvalipou@msudenver.edu
5 Institute of Hydrology and Water Resources Management, Leibniz Universität Hannover, Appelstraße 9A, 30167 Hannover, Germany; dietrich@iww.uni-hannover.de (J.D.); fallah@iww.uni-hannover.de (E.F.-M.)
6 Department of History and Classical Studies, School of Culture and Society, Aarhus University, 8000 Aarhus, Denmark; hisjk@cas.au.dk
7 Institute of Technology, Department of Civil Engineering, 35430 Izmir, Türkiye; esrabilgic@iyte.edu.tr
8 Institute for Geosciences, University of Mainz, 55122 Mainz, Germany; cpasschi@uni-mainz.de
9 Department of Agriculture, School of Agricultural Science, Hellenic Mediterranean University, Iraklion, 71410 Crete, Greece
10 College of Agricultural Engineering and Technology, SKUAST-Kashmir, Srinagar 190025, India; rohituhf@rediffmail.com
11 Natural Resources Management and Agricultural Engineering Department, Agricultural University of Athens, 11855 Athens, Greece; ndercas1@aua.gr
12 Civil Engineering Department, Faculty of Engineering, Islamic University of Madinah, Madinah 42351, Saudi Arabia; dratahmed@iu.edu.sa
* Correspondence: vtzanakakis@hmu.gr; Tel.: +30-6977441455

† In memoriam: This paper as a small tribute is dedicated to the memory of Prof. Dr. Jens Krasilnikoff. His commitment to his work, even during the very last days of his life, reflects his professionalism and passion for the field. Let us ensure that his legacy lives on through our continuing efforts and dedication to our work. We very much appreciate his contribution to the study of the evolution of various hydro-technologies from Archaic, Classical, Hellenistic, and Roman periods to the present and into the future.

Citation: Angelakis, A.N.; Baba, A.; Valipour, M.; Dietrich, J.; Fallah-Mehdipour, E.; Krasilnikoff, J.; Bilgic, E.; Passchier, C.; Tzanakakis, V.A.; Kumar, R.; et al. Water Dams: From Ancient to Present Times and into the Future. *Water* **2024**, *16*, 1889. https://doi.org/10.3390/w16131889

Academic Editor: Barry T. Hart

Received: 17 May 2024
Revised: 20 June 2024
Accepted: 21 June 2024
Published: 1 July 2024

Abstract: Since ancient times, dams have been built to store water, control rivers, and irrigate agricultural land to meet human needs. By the end of the 19th century, hydroelectric power stations arose and extended the purposes of dams. Today, dams can be seen as part of the renewable energy supply infrastructure. The word dam comes from French and is defined in dictionaries using words like strange, dike, and obstacle. In other words, a dam is a structure that stores water and directs it to the desired location, with a dam being built in front of river valleys. Dams built on rivers serve various purposes such as the supply of drinking water, agricultural irrigation, flood control, the supply of industrial water, power generation, recreation, the movement control of solids, and fisheries. Dams can also be built in a catchment area to capture and store the rainwater in arid and semi-arid areas. Dams can be built from concrete or natural materials such as earth and rock. There are various types of dams: embankment dams (earth-fill dams, rock-fill dams, and rock-fill dams with concrete faces) and rigid dams (gravity dams, rolled compacted concrete dams, arch dams, and buttress dams). A gravity dam is a straight wall of stone masonry or earthen material that can withstand the full force of the water pressure. In other words, the pressure of the water transfers the vertical compressive forces and horizontal shear forces to the foundations beneath the dam. The strength of a gravity dam ultimately depends on its weight and the strength of its foundations. Most dams built in ancient times were constructed as gravity dams. An arch dam, on the other hand, has a convex curved surface that faces the water. The forces generated by the water pressure are transferred to the sides of the structure by horizontal lines. The horizontal, normal, and shear forces resist the weight at the edges. When viewed in a horizontal section, an arch dam has a curved shape. This type of dam can also resist water pressure due to its particular shape that allows the transfer of the forces generated by the stored water to the rock foundations. This article takes a detailed look at hydraulic engineering in dams over the millennia. Lessons should be learned from the successful and unsuccessful applications and operations of dams. Water resource managers, policymakers, and stakeholders can use these lessons to achieve sustainable development goals in times of climate change and water crisis.

Keywords: water dams; water reservoirs; hydroelectricity; prehistoric and historical times; dam hydraulic system; arch dam; gravity dam

1. Prolegomena

By studying ancient civilizations, we study ourselves and learn from the past about the present and the future.

Andreas N. Angelakis

Traditional water dams have been built since prehistoric times, primarily for the extraction, storage, and utilization of water in arid and semi-arid regions. Since early civilizations, people have relied on the collection and storage of surface and rainwater in regions with uneven water distribution and dry summers [1]. As a rule, most ancient civilizations were founded in areas that had an adequate water supply, at least in winter. This is particularly true for the arid and semi-arid climatic conditions in the regions around the Mediterranean, such as southeastern Greece, where the availability of water resources is extremely low, especially in summer [2,3].

The development of large dams has a very long history [1] and they were built and operated in many countries over centuries. For example, such dams have been operated in Mehrgarh and Mesopotamia since the Neolithic period, ca. 7000–3200 BC [4]. Subsequently, during the Bronze Age (ca. 3200–1100 BC), dams were constructed in southeastern Greece and the Indus Valley to increase water availability, to make civilizations more resilient to destructive natural elements, and to improve living standards [2,5].

The construction of dams and reservoirs is associated with significant natural and anthropogenic impacts. In general, the aim of dams and reservoirs is regional socio-economic development through irrigation, flood control, power generation, water supply, recreational purposes, deforestation reduction, drought shortening, fishing operations, mining purposes, and navigation. It is also a landscape enhancement that includes the development of new infrastructure and the creation of new employment opportunities, as well as many secondary benefits [6].

Modern dams can be categorized as concrete or masonry dams and embankments for the control of streams and river flows that run through valleys. The former block streams that run through narrow gorges. A concrete or masonry dam is curved upstream so as to transmit the major part of the water load to the abutments. An arch dam is curved vertically as well as horizontally as a double-curvature arch dam. Furthermore, dams can be categorized by purpose: (a) storage dams, the most common type of dam (in fact, all dams are built to store water, unless otherwise stated); and (b) diversion dams, which are intended to divert water from rivers. The latter are usually constructed to avoid hindering the natural course of a river and to create enough pressure to divert the water through channels to farms for irrigation. Diversion dams are common in areas with large plantations and mostly rely on gravity to channel the water. The most common uses of dams are: (a) the conservation of water in reservoirs to provide freshwater to residential, irrigated, industrial, and mining areas; (b) the process of generating energy from renewable sources, like hydropower; (c) regulation of the flow of water in rivers and streams to protect communities from flooding events; (d) protection and upgrading of the environment; (e) improving navigation; and (f) facilitation of water conservation to meet future requirements. Today and in the future, most of the constructed new dams will have multiple uses.

Critical challenges in the concept of dams from a technical/technological point of view are aging, sedimentation, and climate-driven issues (e.g., flooding), which are associated with the structural integrity of dams and their safety and economic/environmental sustainability, requiring extensive and costly monitoring, maintenance, and management actions. Moreover, in addition to the addressing of potential socio-economic and environmental impacts from the construction and operation of dams, technological issues arise from current and future increasing water demands, caused by a growing population with the associated anthropogenic activities (e.g., hydropower and irrigation demands) and problems from the climate crisis [7]. Both growing demands and the climate can cause a increase of the water deficit between the availability of stored water and water requirements across sectors, threatening the sustainability of dams. To address such an issue, valid approaches that quantify future water demands at a local and a regional scale by each sector are needed to highlight potential gaps between the existing capacity of infrastructure and future demands to support current and future adaptation measures [7]. Overall, we need a thorough evaluation of current and future dam projects that can incorporate advances in digital technologies, the sciences of materials, and construction techniques. We need to incorporate sustainable and climate change-compatible management operations and management practices, serving proper decision-making goals (e.g., proper site selection), operational multitasking for multi-purpose dams (e.g., integration with renewable energy systems), and (risk) management goals, such as an increase in water storage, flood control, and the protection of ecosystems and humans.

A comprehensive review of the history of dams is needed to improve our knowledge of their design and construction, requirements, and impacts. Emerging trends in dam development should also be considered to improve future water management under conditions of more frequent and more intensive droughts due to climate change, as well as changing water demand patterns due to the further development of human societies. As Confucius (551–479 BC) said, "Study the history if you would define the future". Thus, the academic advance of this overview is to present past examples, to study ancient dams and to learn the lessons that can prepare us in the present and future to increase water availability, particularly in increasingly urbanized areas. This work highlights ancient technological practices to cope with limited regional water resources by the use of dams, which were developed in several regions and over several millennia. Ancient technologies could be combined with today's knowledge to address challenges of the future.

This study presents a chronological history of dams, with relevant examples from different geographical regions being selected for each period. For this reason, a thorough review of the relevant references describing the historical data for dams in the ancient places was conducted. Moreover, simple articles, comments, consultations, photos, and the relevant data available in cyberspace were considered in this review. The information was evaluated and used within a structural framework to highlight the provided knowledge and facilitate the potential reader. Specifically, the article is organized in seven sections. Section 1, Prolegomena, is an introduction to the topic and the elements of this review. It is followed by Section 2, which explains the diverse history of dams from prehistoric times to the Medieval Era (up to ca. 1400 AD). Section 3 deals with dams in the Early and Middle modern periods (ca. 1400–1850 AD). Section 4 deals with dams in contemporary times (1850 AD–present). Section 5 focuses on new trends and possible future challenges for dams. Section 6 deals with the rehabilitation of water dams. Finally, Section 7, Epilogue, comprises conclusive remarks and highlights.

2. From Prehistoric Times to the Medieval Era (ca. 7000 BC–1400 AD)

2.1. Prehistoric Times

2.1.1. Middle East Prehistoric Civilizations (ca. 7000–1100 BC)

In the area that is today called the Middle East, the oldest known dams for water reservoirs in the world are found. The Jawa Dam in the Black Desert of modern Jordan is a masonry and earthen embankment, which was built around the middle of the fourth millennium BC in the historic Levant region. Its purpose was to hold back the water of a small river and to increase irrigation production on the semi-arid farmland area downstream [7]. The oldest large dam is the Sadd el-Kafara Dam in the Garawl Valley (30 km south of Cairo) in Egypt, which was built in the first half of the third millennium BC with the assumed purpose of flood protection. Its ruins still exist and it was built as an earth-fill dam [8] with a height of 12 m, a crest length of 108 m, and a width of 36 m between two stepped masonry walls with a base width of 24 m each. The Sadd el-Kafara Dam collapsed shortly after its completion, when it was inundated by a flood and washed away due to the lack of a spillway to stop erosion. The oldest dam still in use is a rock-fill dam on the Orontes in Syria, about 6 m high, which was built around 1300 BC for local irrigation purposes.

In Iran, the oldest known dams were built 2200 years ago (Bahman Dam, (Figure 1) The dams of Shapour and Mizan were built during the reign of King Shapur I about 1700 years ago, and the Tilkan and Sheshtarz dams were built 1000 years ago.

Other examples of ancient Iranian dams are the Akhlemad Dam (Figure 2), with a crest length of 230 m, a height of 12 m, and a capacity of 3 million m^3, and the Fariman Dam (Figure 3), which is 400 years old. Both are buttress dams and are still in operation [9]. Also, the Amir Dam north of Shiraz, which is 1000 years old, is still in operation [9,10] (Figure 4).

Figure 1. Bahman Dam, Iran. Constructed approximately 2200 years ago (adapted from [11]).

Figure 2. Akhlemad Dam (adapted from [9]).

Figure 3. A view of Fariman Dam. An ancient dam possibly dating back to the reigns of the Sassanid kings of Persia (224–710 AD), it was rebuilt during the Timurid and the Qajar eras in its current form (adapted from [9]).

Figure 4. The Amir Dam, 1000 years old and still in operation, is an example of the exceptional water designing works accomplished by the architects of the Persian Empire [12].

2.1.2. Minoan Civilization (ca. 3200–1100 BC)

The Minoan civilization was a Bronze Age Aegean civilization in southeastern Greece (i.e., the island of Crete and other Aegean islands) that flourished from ca. 3000 BC to ca. 1450 BC. Its earliest beginnings have been dated to ca. 3200 BC and it declined from ca. 1450 BC until it ended around 1100 BC, during the early Greek Dark Ages [13].

Agriculture was one of the cornerstones of the Cretan economy in the Bronze Age, and it is not surprising that the ancient inhabitants of the island went to great lengths to control the water runoff and make it available for human use. Despite the use of traditional archaeological survey methods, the full extent of the water management systems is not fully understood, because the island's rugged topography has prevented intensive and thorough investigation of many sites. However, excavations at several locations in eastern Minoan Crete (e.g., Choiromandres, Pseira Island, Gournia, and others) have uncovered the remains of sophisticated water retention systems, which include the construction of retaining walls to protect against erosion. Furthermore, massive dams with associated reservoirs and small retention dams on ravines have been discovered that were over a hundred meters long and were intended to control water runoff and make it available mainly for water supply and irrigation uses [14]. Most of those dams were very old (the late Minoan period) and small scale.

A small valley known as Choiromandres in the eastern–southern end of the island of Crete contains an integrated farming system over an area of 7.5 ha, which ensured water for irrigation and protected the soil, not only of this valley, but also of downstream areas from erosion. Choiromandres could offer insights into other archaeological sites in Crete and other regions and contribute to a better understanding of Minoan technologies related to the management of water resources. A robust wall of megalithic masonry from the Neo-Palatine period (ca. 1750–1430 BC) remains with a length of 27 m and a height that is currently 3.10 m [2]. The particularly strong construction of this wall and its location suggest that it was a dam designed to hold fast flowing water and to protect the soil from erosion. The wall was constructed much thicker at its base to ensure its stability. The eastern channel was formed on the surface of the rock, which may have served as a funnel to drain excess rainwater. The dam must have been built during the dry summer months when the gorge was dry [15]. The upper part of the wall was probably reconstructed in the Late Classical and/or Hellenistic period. A plan and view of the main dam and the retention dam of the Choiromandres irrigation project are shown in Figure 5.

(**a**)

(**b**)

Figure 5. Choiromandres Dam and irrigation system: (**a**) view of the major dam; and (**b**) irrigation practices in the small valley (with the permission of A. Angelakis).

2.1.3. Hittite Era (ca. 1600–1180 BC)

Anatolia, where civilizations met, intersected, and developed, is home to the world's leading hydraulic engineering structures in terms of the diversity of ancient water technology. The remains of civilization-related artifacts dating back 10,000 years have been found in Anatolia. However, information on hydraulic structures or springs has only been found from the Hittite period in the second millennium BC.

Considering the conflict in Anatolia between an increased water consumption in the summer months with a low water inflow and a lower consumption in the winter and spring months with a high water inflow, there is a clear need for comprehensive water planning, which can only be achieved through the construction of hydraulic structures. Therefore, several notable dams have been built in this region serving various purposes such as water storage, irrigation, and flood control [16]. Water planning played a crucial role in the Hittite civilization. The success of this planning was achieved through the construction of massive reservoirs in the form of dams or large basin structures in front of productive water reservoirs or cities [17,18].

In Anatolia, the dams constructed during the Hittite Empire period appear in the Upper Kızılırmak section of the Central Anatolian Region, which is called the Hittite Empire's core region. It is believed that the dams built during the Hittite Empire period played a significant role in meeting the increased water demand during the summer months, benefiting livestock and agricultural activities [16,18,19]. These dams not only made production more secure but also increased productivity. The most important Hittite dam structures in this region are the Hattusa (Boğazköy) Dam, Alacahöyük Gölpınar Hittite Dam, Çakır Köy Hittite Dam, Karakuyu Hittite Dam, and Köylütolu Hittite Dam [20–23]. The oldest dam remnant in Anatolia is the Karakuyu Dam, which the Hittites built in the middle of the second millennium BC to irrigate Uzunyayla, located between Kayseri and Sivas [17,18,24]. It is stated that the Karakuyu Dam, with a height of 8 m and a total crest length of 400 m, had a soil-fill structure with a stone-clad downstream face [18].

In the Hittite Empire period, the use of clay fillings in the construction of dam walls and the reinforcement of the inclined downstream face with stone support were common features in all dams [16,19,25]. In Hittite dams without stone cladding, the lower section was constructed with large stones and reinforced with clay soil to prevent permeability [16,19,25]. Among the dams built during the Hittite period, the Köylütolu Hittite Dam is the longest structure in the Anatolia region with a length of 700 m [16,18]. Another important dam that was built during the Hittite period is the Gölpınar Hittite Dam, located in Çorum Alacahöyük. It is still operational today after undergoing repairs. The dam wall, with a length of 130 m and a width of 15 m, has a storage pool or reservoir in the middle [16,26]. The bottom of the pool, which is 8 m wide, is covered with clay [19,26]. The Çakır Köy Hittite Dam was constructed with parallel walls filled with clay core, indicating a different technique from the other Hittite dams. Except for the Gölpınar Hittite Dam, spillways were not identified in other dam structures built during the Hittite Empire period [16].

2.1.4. Babylonian, Assyrian, and Other Civilizations

The Assyrians, Babylonians, and other civilizations built dams between 700 and 250 BC for water supply and irrigation. A dam built at the same period was the earthen Ma'rib Dam in the southern Arabian Peninsula, which was more than 15 m high and nearly 600 m long. Flanked by spillways, this dam delivered water to a system of irrigation canals for more than 1000 years. The remains of the Ma'rib Dam are still evident in present-day Ma'rib, Yemen [27]. Other dams were built in this period in Sri Lanka, India, and China.

The Dujiangyan Irrigation Project, located in Chengdu, Sichuan Province, China, was built in 256 BC and has a history of nearly 2300 years. There are many ancient large-scale water conservancy projects in the world, but the Dujiangyan Irrigation Project is still full of vitality and is regarded as a miracle in the history of world water conservancy. The person who presided over the construction of the Dujiangyan Irrigation Project was Li Bing, the governor of Shu County in the State of Qin. The diversion structure of the Dujiangyan Irrigation Project is shown in Figure 6.

Figure 6. Aerial view of part of the Dujiangyan Project [28].

The entire project consists of three main projects: the Fish Mouth Water-Dividing Dam, the Flying Sand Weir, and the Bottle-Neck Channel. It has a magnificent scale, a suitable location, a reasonable layout, and three functions: flood control, irrigation, and navigation.

The Fish Mouth Water-Dividing Dam divides the Minjiang River water flow into two streams, one of which leads to the Chengdu Plain and could not only divert floodwater to reduce disaster but also irrigate fields and turn harm into benefit. To enable the water of the Minjiang River to flow eastward, Li Bing first made a 20 m wide opening in Yulei Mountain, calling it "the Bottle-Neck Channel". The separated end of Yulei Mountain, shaped like a large stone pile, was called "Li Dui". In addition, the method of constructing a diversion weir in the heart of the river was applied, dividing the river water into two branches and forcing one of them to enter the Bottle-Neck Channel [29].

In the process of building the Fish Mouth Water-Dividing Dam, Li Bing did not simply drop stones into the middle of the river to build the dam. Instead, he ordered workers to weave large bamboo cages 10 m long and 0.6 m wide, which were filled with pebbles, and sank one by one to the bottom of the river. Finally, he overcame the rapid flow of the river and built the diversion dike. The front end of the embankment looks like a fish's head, and is therefore called "the Fish Mouth". It heads towards the upper reaches of the Minjiang river, dividing the surging river water into two streams: east and west. The western river is the mainstream of the Minjiang river; the eastern river is the main canal of the irrigation canal system. The canal flows through Baopingkou and is divided into many large and small channels, forming a crisscrossing fan-shaped water network to irrigate thousands of miles of farmland in the Chengdu Plain.

To further contribute to flood diversion and disaster reduction, Li Bing built a 200 m long spillway between the Fish Mouth Water-Dividing Dam and the pile to flow into the outer river, ensuring the prevention of disasters in the inner river. There is a bend in front of the spillway, which causes a circulation of river water. When the river water exceeds the top of the weir, the debris carried by the flood flows into the outer river, so as not to clog the inner river and Baopingkou waterway, hence the name "the Flying Sand Weir".

When the water level in the inner river is too high, the flood overflows the Flying Sand Weir through a flat-water channel and flows into the outer river, ensuring that the amount of water entering the Bottle-Neck Channel is not too large and protecting the inner irrigation area from floods. At the same time, the water flowing over the Flying Sand Weir and into the outer river generates a vortex. Due to centrifugal action, mud, sand, and even boulders are thrown over the Flying Sand Weir, which can effectively reduce sediment deposition. The scientific design and effective management of the Dujiangyan Irrigation Project ensure that the whole project can still play an important role more than 2200 years after its construction.

In 2000, the 24th UNESCO World Heritage Committee included the Qingcheng Mountain Dujiangyan Irrigation Project in the World Heritage List; thus, the project officially became China's 17th World Cultural Heritage Site.

2.2. Historical Times (ca. 1100 BC–330 AD)

2.2.1. Urartian Era (ca. Ninth to Sixth Centuries BC)

The Van basin, the center of the kingdom of Urartu, is rich in water resources. The Urartian kingdom built dams, reservoirs, and irrigation canals to ensure the efficient use of these sources [16]. Archeological investigations carried out between 1987 and 2010 in Eastern Anatolia and on the territory of the Nakhchivan Autonomous Republic identified a total of 133 hydraulic structures, including dams, reservoirs, and irrigation canals [21]. The dams and reservoirs constructed during the Kingdom of Urartu were built by filling the space between the upstream and downstream walls with a blockade of earth and stone [20,30]. The walls of these structures were usually built from limestone and andesite blocks, which were abundant in this region [16].

The Faruk Dam was built on Çorak Creek (Değirmen Creek), 10 km east of Van. It was built around the middle of the first century AD, but the wooden, latticed part may have been added in the 1800s [16,20,31]. Faruk Dam was built in the Urartu era and rebuilt in the Roman period [16] and is classified as a gravity dam. It was built to store fast-flowing water and ensure a more controlled outflow. The lower part of the upstream wall is rectangular, and the upper part consists of square blocks. The upstream–downstream walls are 40 m long, 12 m high, and 4 m wide [23,32]. It is assumed that the upper part of the weir, with a height of 2–3 m, was added in later periods [20]. In addition, it has been determined that the Faruk Dam was filled with "opus caementicium" after the investigations at the weir [16,20]. Opus caementicium increased the strength and impermeability between the two walls. Opus caementicium is a type of cast concrete used by the Romans from the second century BC onwards and consists of lime, lava rock dust, crushed stone, and brick shards. It is used by being poured into a mold or filling the space between walls [16,33].

The spillway sections of the Faruk Dam are located in the lower middle part of the dam wall and allow water to flow out. There is an arch-shaped weir on the upstream wall of the dam and rectangular weirs on the downstream wall [32]. Using this technique, the Urartu kingdom built numerous dams and reservoirs of different sizes. Among the dams built in the Urartian era, the Kelle Dam, with a length of 208 m, is the longest Urartian dam built in the Eastern Anatolia region [16,34]. Urartian engineers sometimes built structures with two or three walls when building dams and reservoirs. Two different walling techniques, which are considered examples of advanced hydraulic engineering, can be observed in dams such as Rusa (Keşiş Göl), Köşebaşı, Kız Kapan, Tasmalı, and Bendmurat. The technique of building with three walls can be seen in structures such as Meydan Boğazı and Kırca Göl [16,20,31,34]. It is assumed that these additional walls increased the durability of the dam against the pressure exerted by the water. The dams and reservoirs of Urartu were generally built in a straight direction, but some other dams, spillways, and reservoir walls show deviations in their construction. The dam walls of structures such as Şekersu, Köyüstü, Düzlük, Kilise Gölü, and Reşan were built in a semi-circular shape [21,34]. In addition, the dams at Gövelek, Rusa (Keşiş Göl), Bendmurat, and Şekersu have a double spillway. The double spillway system is considered an advanced technical achievement of the Urartu period [21]. There are also openings in the spillway sections of the Urartu dams and reservoirs, such as the Çavuştepe reservoir and the Hırsız Dam, which serve to regulate the flow of the water [16,20].

2.2.2. Archaic, Classical, and Hellenistic Periods (ca. 750 BC–31 BC)

Mainland Greece as well as the islands of the Aegean Sea to the east and the Ionian Sea to the west experience erratic weather conditions with major differences in precipitation from year to year and between neighboring regions and landscapes. Dry southeastern and wetter northeastern climate patterns prevailed during antiquity. These climatic conditions are observed today, with prolonged summer droughts in recent decades. Moreover, the nature of many Greek landscapes, dominated by rugged mountains and hilly country, increases the risk of seasonal flash floods and thus continuously (and very much so in the wet winter period) poses threats to human development, including food security and hygiene. Thus, in this context, lack of access to clean water for household purposes and agricultural production represents the most critical type of threat [35].

From this perspective, one would have expected the Greece of the past to have developed dams on a massive scale to prevent such threats. However, the overall picture is more limited; this probably has to do with past strategies that focused on settlement locations where flash floods would have fewer, if any, devastating effects. The Alyzia Dam of northwestern Greece on the Akarnanian coastline is an example of the above.

The Alyzia stone dam was probably built during the fifth century BC near the city of Alyzia, which is located in Western Greece, on the coastline of the Akarnania area. It was equipped with a stone-carved lateral spillway (Figure 7).

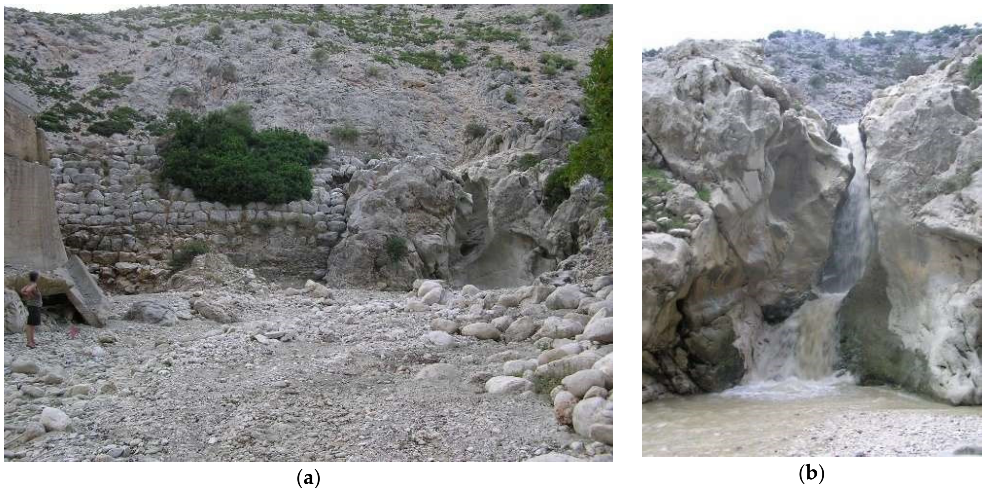

Figure 7. The dam of Alyzia: (**a**) the dam and the spillway with its irregular shape formed by erosion through the centuries; and (**b**) the spillway under operation [36].

The body of the dam is characterized by a different bottom and upper zone. The bottom zone was built with irregularly placed squared blocks, and the upper zone with softer stones, uniformly shaped with small gaps which did not require filling with smaller stones [36]. According to Murray [37]: "This is the clearest, largest, and most technologically advanced ancient specimen yet known in the whole country".

Various scenarios have been considered about the reasons that led to its construction. Most of these approaches conclude that the dam was built to collect drinking water or irrigation water, or for washing. A recent study [38] proposes a different scenario. Floods in the valley of ancient Alyzia were exceptionally intense, leading to serious problems in the urban and suburban areas of the city. To mitigate the floods and withhold the coarse sediments that inundated the valley, the inhabitants of Alyzia constructed the dam at the most suitable site of the watercourse. Even today, this is one of the most effective solutions for flood and sedimentation control. In general, this dam is an impressive work of infrastructure, not only for its scale or the overall quality of its design and construction but also for its continuous and successful operation for 2500 years.

The Greek world, with only a few examples, demonstrates that the Greeks knew about the principles of water storage as a precondition for irrigation. This involved the principle of storing winter rain in cisterns or other forms of reservoirs, and, in some cases, dams were constructed and applied. We know of examples of this in Metaponto and Herakleia in Magna Grecia, modern Southern Italy; Gortyn in Crete; Delos and Lake Copais in central Greece (Boeotia); and potentially also in Attica. The practice of combining drainage with irrigation was also a distinct feature of the drainage project at the city-state of Eretria in modern-day Evia [2,39].

The Nabateans built small dams in present-day Jordan to contain water from flash floods and divert it away from the Siq, the gorge that leads to Petra [40,41]. In 1963, 20 tourists died in a flash flood in the Siq, but, after the Nabatean dams had been reconstructed, the risk of flash flooding in the Siq was much reduced.

2.2.3. Roman Period (ca. 31 BC–476 AD)

The construction of dams by the Romans has received little scholarly attention compared to their other civil engineering activities [40], although their contributions in this field have been equated with their expertise in the construction of the well-known Roman aqueducts, bridges, and roads [40,42–48]. Roman dam building began in earnest in the early imperial period [49]. It was largely concentrated on the semi-arid fringes of the empire in Northern Africa, the Near East, and Spain [40,42–44,47]. Only a few examples are known from Italy, France, and the Balkans, although Roman dams may have been destroyed or gone undetected there (Ibid.).

The relative abundance of dams in Spain is partly due to intensive fieldwork there, while in Northern Africa and the Middle East, dams stand out and have often not been restored after abandonment. For Italy, only the Subiaco Dams are attested, which were constructed by Emperor Nero (54–68 AD) for recreational purposes [40,50]. However, these dams are notable for their exceptional height of 40–50 m, which remained unsurpassed worldwide until the Late Middle Ages [40,49].

Roman engineering excelled in the practical application of dam concepts tried on a smaller scale in previous times [46] and the use of older ideas to larger scale projects. Most Roman structures were gravity dams that were simple low embankments [40,47,48]. These dams usually had a triangular cross-section, some with a masonry wall on the water side that was either bare (Figure 8a) or supported by buttresses. The dams were usually straight but could be arched or of irregular shape, affected by the position of suitable foundations in the underground. Massive earthen embankments supported dam walls on the downstream side. The largest Roman dam is the Lake Homs Dam in Syria. This dam on the Orontes River was a concrete gravity dam, 2 km long and 7 m high, built under Diocletian and containing 90 million m^3 of water. Other typical examples are the dams of Almonacid de la Cuba, Muel, Alcantarilla, Proserpina, and Cornalvo in Spain [44–47].

(**a**)

(**b**)

Figure 8. Roman dams: (**a**) ruined dam of Alcantarilla, Toledo, seen from the reservoir side (the reservoir wall collapsed into the basin at some stage, possibly due to the absence of buttresses; photograph: Cees Passchier); and (**b**) the Cornalvo Dam in Spain, which was erected in the first to second centuries AD.

The Alcantarilla Dam (Figure 8a) was a simple straight masonry wall with a supporting earth embankment, which collapsed into the reservoir, probably due to the lack of support on the inside wall during a period of low water. Proserpina and Cornalvo are two dams that supported the aqueduct for the city of Emerita Augusta (Merida), the capital of the province of Lusitania. The Proserpina Dam is similar to the Alcantarilla Dam but has buttresses on the reservoir side, probably to avoid collapse in case of low water. The Cornalvo Dam is a Roman gravity dam with a crest length of 194 m and a height of 20.80 m dating from the first or second century AD (Figure 8b). The earth dam, made of Roman concrete and stone facing the water side, is still in use.

The Proserpina and Cornalvo dams were originally thought to have been built at the origin of two Roman aqueducts to the city of Emerita [40,43,44,46,47]. However, following the recent discovery of an extensive network of abandoned aqueducts upstream of these dams, it seems likely that the dams are a late-Roman addition to the aqueduct structure, built after the upstream parts of the long city aqueducts of Emerita went out of function [51].

Most Roman dams were built for agricultural purposes to retain water for dry periods (ibid.). In some cases, notably in Northern Africa, dams were planned to hold back the topsoil washed from the hills, so that the area of the reservoir, after being filled, could be used as agricultural land [40]. Contrary to modern practice, the Roman developers of water supply systems preferred to use spring water or other groundwater sources over dam reservoirs to provide cities with water. However, some dams supplied water for this purpose, notably for the cities of Toledo, Merida, Andelos, Consuegra, and Zaragoza in Spain [52]; Glanum and Vienne [53] in France; Wroxeter in England [54]; Rome (the Anio Novus aqueduct [46]); and Sebastopolis in Türkiye [55]. Many examples are also known from small towns in Northern Africa, such as Uchi Minus, Agbia, Numluli, Thibaris, Thabbora [56], Zabi [57], and Zama [58]. Small weirs in rivers supported the aqueducts of some cities, such as Segovia [59], Syracuse [60], and Cahors [61]. Another application of dams was to block rivers to divert floodwater away from harbors, as in the case of Leptis Magna [40,46] and Seleuceia [45]. In the delta of the Rhine in the Netherlands, a dam was built to modify the discharge of water into individual river branches (the Carvium Dam [62]).

2.2.4. Han China Dynasties (ca. 206 BC–220 AD)

The Han Dynasty was very powerful in ancient Chinese history. After the establishment of the dynasty, rulers built large-scale water conservancy projects near the capital Chang'an, including the Dragon Head Canal, Liufu Canal, Baiqu Canal, and Chengguo Canal.

The Longshou Canal and Ancient Luohe River Irrigation District of Shaanxi Province are located on the terraces of the Weihe River and Luohe River. This area is plagued by frequent drought. Therefore, diverting water from the Luohe River for irrigation was an essential means to tackle the water shortage challenge faced by local agricultural production (Figure 9). The Longshou Canal was the first underground water channel in Chinese history, built during the reign of Emperor Wu of the Han Dynasty. The channel needed to pass through Shangyan Mountain. The soil here is loose and the canal banks are prone to collapse, so ordinary construction methods could not be used. The Han working people invented the well canal method and built the 3.5 km long Tielian Mountain tunnel, which allowed the Dragon Head Canal to pass through Shangyan Mountain underground. The evenly arranged vertical shaft divided the long distance underground channel into multiple sub-projects, which were then excavated in opposite directions, reducing errors and improving work efficiency. Adopting a vertical shaft can achieve three benefits with one stone: it is not only a labor passage but also a way to dispose of soil and debris and to take into account ventilation and lighting. The well canal method was introduced to the Western Regions during the Han Dynasty through the Silk Road, and some researchers believe that the "Karez" in Xinjiang today evolved from "the Jingqu method" of the Han Dynasty.

Figure 9. The flat cave at the west exit of Longshou Canal [63]).

In the first century BC, Zhao Xinchen served as the governor of Nanyang and presided over the construction of the Six Gates Weir. The total length of the Six Gates Weir was nearly 200 miles, with 29 ponds and weirs built along the main canal, forming an irrigation system of a "long vines and melons" style, benefiting an area of over 5000 ha [64]. He also focused on management and maintenance and formulated water use rules to support the water supply for humans and agricultural production and to prevent water conflicts.

2.2.5. Roman and Byzantine Period (ca. 330–1453 AD) in Anatolia

Throughout history, many civilizations that needed water resources built hydraulic structures to meet their water needs or to protect themselves from the destructive effects of water. Some of these structures date back to the Byzantine Empire, also known as the Eastern Roman Empire. Among the dams from the Eastern Roman period, are those of Çavdarhisar (for flood control and irrigation in Aizanoi, Kütahya), Örükaya (for irrigation in Çorum), and Böget (for drinking water in Niğde). For the period of Justinian (527–565), the Dara Dam can also be counted [17]. The dams of the Roman era in Anatolia were generally built with a few meters of earth-fill between two 1 m thick masonry walls [65]. In all the dams in Anatolia, "opus caementicium" was filled between two parallel walls, except for the Ankara Dam, where "opus incertum" was used by incorporating large stones into the "opus caementicium". A single construction technique was used in the dams [33]. When looking at the spillway shapes of the dams, two types of spillways can be distinguished: arched and rectangular spillways. Arched spillways are found both in Anatolia and in dams from the Roman period outside Anatolia, while rectangular spillways have only been observed in Anatolia [16]. The Örükaya Dam and Çevlik Dam were constructed by opening beds in the rocks on both sides of the valley and placing blocks in these beds [16,66]. Thanks to this technique, the structures have remained sturdy for many years. Additionally, in front of the downstream walls of these two dam structures, steps were likely built to support the structure. Örükaya Dam was built between two main rock blocks in a narrow valley [32]. It is classified as a gravity dam and may have been built in the second century AD. The water level tends to rise in winter, due to irregular precipitation, and become uncontrollable, while in summer the amount of water decreases due to the high temperature and evaporation. Therefore, it has been stated that the dam was built for irrigation purposes and flood control. The Örükaya Dam had a water collection basin with a capacity of approximately 865,000 m^3 [16,66]. It is thought to have consisted of a wall with elaborately worked upstream–downstream walls and an arched drainage channel on the downstream surface, built close to the Örükaya Valley. The dam wall was determined to be 16 m high, 40 m long, and 5 m wide [16]. The building between the two cladding walls filled with an "opus caementicium" core is considered a "typical Roman" construction style. As such, it constitutes an example of concrete-infilled dams from the Roman period. The blocks used in the construction of the Örükaya Dam consisted of rectangular blocks of cut limestone with bossage varying between 1 and 2 m in length and between 0.6 m and 0.7 m in width [16,65]. Thanks to the clay used between the blocks, impermeability was increased. In addition, these clay joints were thought to be strengthened by pouring lead on them [16]. In the lower middle section of the Örükaya Dam wall, a spillway section is observed to have been constructed on the outlet wall in an arched manner. The arch was made with a double row. The spillway is 2.50 m high and 2.10 m wide, with a void in the middle of its vault. On the inner wall of the arch, 0.8 m below the void, there is a rectangular drainage opening with a size suitable for a metal closure plate to enter in front of it [66]. It is believed that by utilizing a lever system placed in the void of the outlet wall, the metal plate in front of the rectangular opening could be moved up and down, allowing a controlled discharge of water. Additionally, towards the east of the source section, there is a canal believed to have been constructed at a later stage, which facilitates the drainage of excess water from the dam. The dam's reservoir area was filled with sediment carried by the river to the upper part of the upstream wall, causing the dam to lose its function.

Another dam constructed in the second century AD is the Aizanoi Dam, located on the Bedir Stream in the Kütahya Province [67]. Hard limestone blocks, which are common in the area where the dam is located, extend to the bottom of the valley in some places and cause the river valley to narrow. Aizanoi Dam belongs to the "gravity dam" type. Built with meticulously crafted blocks, the dam is 7 m high, 6 m wide, and 80 m long [68]. Researchers indicate that the Aizanoi Dam was constructed in two stages, and these stages can be separated by the reuse of marble pieces, most of which were located in the seating steps [67,68]. The dam was built for flood protection purposes. From this information, it can be understood that the Aizanoi Dam, which was damaged due to floods, has been rebuilt [16]. Other studies show that in the initial construction phase of the Aizanoi Dam, the blocks were joined without mortar, while, in the second and third phases, they were reinforced with mortar fillings. The Aizanoi Dam, similar to the Örükaya Dam, was constructed by filling the space between the source and outlet walls, which is 4–5 m wide, with "opus caementicium" to enhance the stability of the walls and ensure water impermeability [16,23]. Looking at the blocks used in the construction of the upstream–downstream walls, they consist of smoothly cut rectangular limestone blocks with a length of 1–2 m and a width of between 0.6 m and 0.7 m [23]. The dam walls were built in a "pseudo-isodomic" style [16]. The upstream–downstream walls were constructed by giving a convex inclination according to the direction of the water flow. With this construction style, the aim was to distribute the high water pressure that occurs in the middle section to the sides. This type of construction is also seen in today's dams. In the Aizanoi Dam, an arched sluice section opens to the lower left part of the upstream–downstream walls, which allows the water collected in the dam to be discharged. The arched sluice sample found in the Aizanoi Dam is similar to the sluice found in the Örükaya Dam. The sluice section has a width of 6 m, and it is estimated that the water would reach a height of 2.5–3.0 m before the dam floor was filled with alluvium [16]. Today, the arched ceiling of the sluice is 1.5 m above the alluvial layer and the water level. Thanks to this weir, the river, whose violence is broken by the dam set wall in times of flood, can be controlled more efficiently.

Another gravity-type dam is the Böğet Dam, also built in the second century AD and located in the province of Aksaray [69]. The volume of water produced by the Böğet Dam is 9 hm3. The dam was built in a valley, with a width of about 250 m, that consists of limestone rocks with volcanic tuffs [16]. With a length of 300 m, the Böğet Dam was the longest dam structure built in Anatolia during the Roman period [16]. Parallel to the dam walls, earth dams with a height of 1–1.5 m and a width of 10 m were built in both directions [16,23,70]. These dams were intended to prevent water from seeping under the walls. The dam was built to obtain drinking and irrigation water [23,69]. It has been mentioned that the valley in which the dam was built is very wide and no high walls were needed to raise the water to the desired level [16], so the lower height of the dam wall made it possible to build the dam at a lower cost.

Similar to the Örükaya and Aizanoi dams, the Böğet Dam was constructed by filling a 2.5 m wide "opus caementicium" between the main and counterfort walls to ensure water impermeability and to strengthen the structure [16,23]. Additionally, unlike other Anatolian dams, to prevent leakage from under the walls, earth embankments with a width of 10 m and a height of 1 to 1.5 m were created on both the main and counterfort sides, rising towards the dam walls [16,23,69,70]. The main wall of the Böget Dam is linear, while the counterfort wall was constructed in a convex curve [16,71]. No spillway section in the dam wall allows the water to be discharged from the dam [16]. In this aspect, the Böget Dam partially differs from the Örükaya and Aizanoi dams.

During an archaeological survey of the Sanchi area in central India, a group of ancient dams (from the second to the first centuries BC) was located. A comparison of the volume of the dams with the estimated inflows indicates that their construction was based on hydrological knowledge [72]. The dams in the Sanchi area are prominent and easily identifiable archaeological features of the landscape. However, except for two dams that have been restored, they are all in a ruinous state and show signs of breakage at points where natural drainage channels cross the dams. The dams have not been excavated, but they consist of an earth core, generally made of black cotton earth and reinforced with a facing of dressed sandstone masonry, especially on the upstream side. In some places, the facing slabs are laid horizontally; in others, the slabs are interlocked, with most of the blocks laid parallel to the wall and the head slabs just perpendicular to the embankment (Figure 10). The height of the dams ranges from 1 to 6 m, with the shallow sections downstream apparently designed to prevent the dams from overtopping [73,74]; some dams are up to 60 m wide. At least two of the higher dams (7 and 12) have spillways cut into the rock adjacent to the man-made dam [72,74].

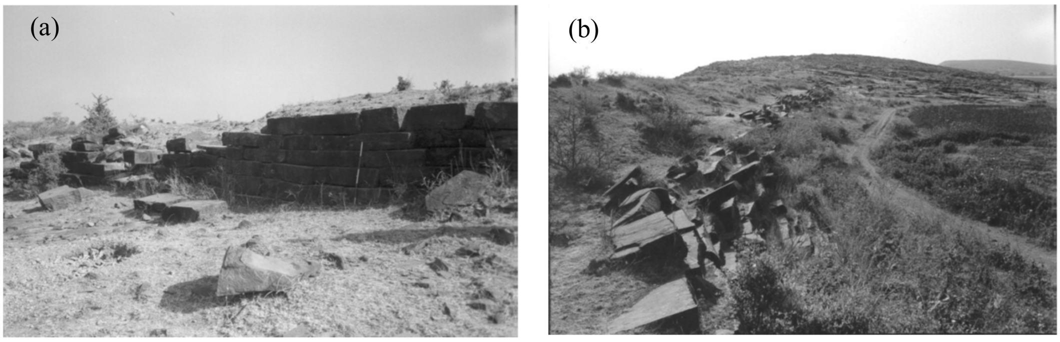

Figure 10. Devrajpur Dam: (**a**) horizontally laid dam facing; and (**b**) interlocked stone facing (adapted from [73]).

2.2.6. Medieval Times (ca. 476–1400 AD)

Beach and Dunning [75] studied an ancient Maya reservoir and dam at Tamarindito, El Peten, Guatemala. The dam and reservoir probably date from the Late Classic period (ca. 550–800 AD). Today, the reservoir or depression is an inconspicuous feature that has been obscured by more than a thousand years of natural geomorphologic and soil processes that have accumulated sediments and partially destroyed the dam that once impounded the water. The dam was about 60 m long and spanned a depression that is now 3 m deep and was intended to hold a reservoir of about 0.25 ha and up to 2000 m^3 of water.

3. Water Dams in Early and Mid-Modern Times (ca. 1400–1850 AD)

It is well known that the development of civilizations during antiquity depended on the existence of fertile soil. The inhabitants of cities founded near rivers had to build various hydraulic structures not only to benefit from the advantages of these rivers but also to protect themselves from floods. Dams were also built to prevent drying out during dry periods. The dams, which formed the starting point of the waterways, stored the water coming from the streams. Many hydraulic structures in Anatolia were built for this purpose.

The early and middle modern time (ca. 1400–1850 AD) in Anatolia coincides with the Ottoman period. The hydraulic structures during the Ottoman period were built on the Halkalı waterways, the Kırkçeşme waterways, the Taksim waterways, and the Üsküdar waterways [76]. Among these waterways, important dams were built on the Kırkçeşme and Taksim waterways. The purpose of these dams is to supply drinking water, and they are concentrated in Istanbul and its surroundings. These dams can be divided into small dams or embankments. In the Belgrad Forest of Istanbul, where the most important examples are located, there are seven dams in total, with four in the Kırkçeşme Water Facilities and three in the Taksim Water Facilities [77]. The dams that supply Istanbul with water are the Topuz Dam, Büyük Dam, Ayvat (Ayvalı) Dam, and Kirazlı Dam at the Kırkçeşme waterways. The Topuzlu Dam, Valide Dam, and Yeni Dam are located on the Taksim Waterway. None of these dams are higher than 15 m from the ground and their reservoir volume does not exceed 1×10 m^3 [65]. They are also categorized as masonry and gravity dams.

The Topuz Dam is located on the Belgrad Stream in the Belgrad Forest. It was built in 1620 [65,78]. The dam is a masonry structure with a straight axis and gravity dam. The capacity of the reservoir is 70,000 m^3. There is a simple sluiceway on the right bank [65]. The freeboard is 0.20 m and the height from the foundations is 10 m [78]. Another dam on the Belgrad River is the Büyük Dam. The Büyük Dam is a masonry gravity dam built on a straight axis and was built in 1748 [65]. The dam was built after the Topuz Dam and had a larger storage capacity. The crest length of the Büyük Dam is 84.50 m and its height from the foundations is 15 m. There is also a spillway channel on both sides of the dam, and the freeboard is 0.22 m.

Another dam built in the Belgrad Forest region during the Ottoman era is the Topuzlu Dam (the Sultan I. Mahmud Dam) on the Eskibağlar Stream [65]. The dam was built in 1786. The catchment area is 0.92 km^2, and the capacity of the reservoir is 160,000 m^3 [78]. The floodwater in this region is expected to flow from a maximum height of 0.18 m. Another dam from the Ottoman period is the Ayvat Dam, which was built in 1765. The masonry gravity dam is located on the Kağıthane Stream in Istanbul. It has a catchment area of 2 km^2 and a reservoir volume of 156,000 m^3 [65,78]). Its height is about 15 m. The crest length along the polygonal axis is 65.80 m. There is a spillway on each side of the dam. The spillways on the right and left banks divert the floodwater safely to the downstream section. The Valide Dam is one of the oldest hydraulic structures in Istanbul. It was built in 1796 for the water supply [70]. It is a masonry structure of the gravity dam type, whose crest and upstream surface are clad in marble. There are two large buttresses on the downstream side. The spillway has a wide crown and is located on the right-hand side of the dam.

Arch dams were also built during the Ottoman period. The most important example is the Yeni Dam [65,79]. This dam is a circular masonry gravity dam with a height of about 17 m from the foundations. The storage capacity of the dam is 217,500 m^3, and its catchment area is 0.83 km^2 [65]. Its storage capacity was increased by a downstream parapet. The ratio between the length of the dam crest and the height of the Yeni Dam was six, which was the largest ratio ever applied. The dam has a single spillway, which is located on the left side and has the shape of an opening measuring 1×0.48 m^2. There is also a freeboard of 0.28 m [65].

Other significant dams include the Şamlar Dam near Küçükçekmece and the Elmalı I Dam near Anadolu Hisarı. In Istanbul, a total of 226 water structures were built in the 18th–19th centuries, which include seven dams, four aqueducts, one hundred and seventy-eight fountains, twenty-eight public water fountains, two fountains with spouts, four ornamental fountains, and three water scales [79]. The Kirazlı Dam, Yeni Dam, and Şamlar Dam were built to provide water to the European side of İstanbul. Only the Elmalı Dam in Beykoz is located on the Anatolian side. They have reached the present day in their original forms [79]. Finally, most of the dams constructed during the Ottoman period were of the embankment type, although there were also masonry dams that were built as straight-crested gravity or arch dams. These dams can be classified as small dams based on their reservoir capacities, drainage areas, and dimensions. Many of these dams are still functional today. With their ages and operational periods ranging from 140 to 400 years, most of these small dams have forest catchment areas, which have significantly reduced erosion, prevented the dams from filling up with transported sediments, and ensured that the reservoirs remain free from siltation.

Between the 16th and 19th centuries, a mining industry was developed in the upper Harz region in central Germany, with a focus on ore and silver. The mines had a large energy demand, for which a sophisticated water management system was developed to drive "water column machines" by converting gravitational water flow into mechanical energy [80] and for dewatering. These machines were a huge step of innovation after the invention of water wheels. The water column machines reached a major advancement in the middle of the 18th century in the mining industry, before electrical engines became available. Within the context of the so-called Upper Harz Water Regale, numerous ponds, reservoirs, and diversion channels were constructed to store and distribute water to the mines. Due to the uniqueness of this complex historic mining water management system, it was declared as part of the "Mines of Rammelsberg, Historic Town of Goslar and Upper Harz Water Management System" UNESCO World Heritage Site [81].

One of the reservoirs of this system, here presented as an example, is the Oderteich reservoir (Figure 11). It was put in operation in 1722 to supply water to mining in St. Andreasberg via the Rehberger Graben ditch. The Oderteich reservoir was one of the earliest large reservoirs in Europe and for 169 years the largest reservoir in Germany with a dam height of 20 m and a storage volume of 1.7 million m^3. The degree of expansion was relatively low (0.14), which allowed fast filling but also resulted in a frequent spill flow. The dam was constructed with an inner dense core of granite sand surrounded by massive cyclopean masonry. The outlet was in the middle of the dam on the ground of a 14 m deep shaft (marked by the house in Figure 11). Unlike the predominant wooden construction in the region, it was made from local granite. The flood spillway, seen on the left, was protected by granite pylons against ice drift. Today, the reservoir is operated as part of the historical Upper Harz system. While the upper part is a nature conservation area, the lower part is used as a natural mountain swimming pool with a beach.

Figure 11. Oderteich Dam (with the permission of J. Dietrich).

4. Water Dams in Contemporary Times (1850 AD–Present)

Globally, the register of the International Commission on Large Dams shows that 70% of large dams and their associated reservoirs (out of almost 28,000 currently in operation) are designed for a single purpose. The four biggest dams worldwide are:

(a) The Three Gorges Dam in China with an energy-generating capacity of 22,500 MW and a surface area of 1.080 km^2.
(b) The Guri Dam in Venezuela with an energy-generating capacity of 10.200 MW and a surface area of 4.250 km^2.
(c) The Tucurui Dam in Brazil with an energy-generating capacity of 8.370 MW and a surface area of 3.014 km^2.
(d) The Itaipu Dam in Brazil and Paraguay with an energy-generating capacity of 14.000 MW and a surface area of 1.350 km^2.

About half of the world's single-purpose dams have been built for irrigation purposes, followed by hydropower, water supply, and flood control. A single-purpose dam for hydropower is more financially attractive to private investors. However, dams designed for a single purpose are often used for multiple purposes over time. If this development is not managed, the benefits and synergies of multi-purpose infrastructure from the outset cannot be fully exploited [82].

Pumped storage hydropower (PSH) projects are a type of hydroelectric energy storage that has grown in the last few years. It is a configuration of two water reservoirs at different elevations that can generate power as water moves down from one to the other (the discharge), passing through a turbine [83].

4.1. Greece

As mentioned above, dams have been built in various regions of the world since prehistoric times. Dams were built in Crete, Greece, approximately 4500 years ago, mainly for water supply. The main characteristics of these projects were the high cost of construction, their one-dimensional use, and the relatively limited operating time.

Today, it is generally accepted, especially in the developed world, that dams should not be built for just one purpose (irrigation and/or water supply). Instead, multi-purpose dams are being promoted and built, combining water supply, irrigation, flood protection, power generation, and other uses. For example, such projects have been built in Germany and France that utilize 100% and 97%, respectively, of their economically usable hydroelectric potential. However, in Greece, two-thirds of economically usable hydroelectric potential has not yet been utilized. Greece is the last among EU countries regarding the use of hydroelectric power, with, unfortunately, only 20% of consumed electricity being hydroelectric.

The most impressive negative example is the Mesochora project, in Thessaly. The idea for an Acheloos to Thessaly diversion project was first envisioned in the 1930s, but lack of funding precluded construction. Interest in the project was revived in 1984 and what was supposed to be a small dam at Mesochora apart from the diversion project was increased in size to support river diversion. Over the next few years, a series of legal battles led to the construction stalling, most recently in 2005. The project comprises a power plant in Ano Acheloos with an installed capacity of 170 MW and an energy potential of 340 GWh/yr [84]. The dam was originally intended to be 60 m high, having been designed by PPC as a hydroelectric project alone. Subsequently, however, for the river diversion project, its height was increased to 155 m, allowing the storage of very large amounts of water for irrigation of the Thessaly Plain in the summer months. The projected works will also cause flooding in Mesochora, Armatoliko, and three smaller residential areas. Following the issuing of compulsory purchase orders, compensation payments will be decided by the courts.

Many environmental organizations are expressing concern that the dam will cause real damage to the ecosystem. Despite seven Council of State rulings canceling the project over the last 35 years, it has been largely completed since 2001 [85]. Although an investment of EUR 500 million has been made since the beginning of this century, the dam has not been put into operation, thus causing a loss of EUR 25 million/year to the national economy [84]. This completely absurd situation is a representative example of the causes that led Greece to the current economic crisis. It reveals the problems of exploiting the national natural resources, sloppiness, and the lack of control of cost/reciprocal benefit.

On the contrary, a well-known example of a multi-use and high-performance dam in Greece is the project known as Plastira Lake (with useful volume of water of 400 million m^3), which has been operating since 1962. It is a concrete arched dam in Karditsa, Greece, that impounds the Tauropos River, creating an artificial lake called Plastira Lake. Since 1962, it is used for water supply, irrigation, power generation (with a power unit of 129.90 MWatts), touristic and environmental utilization, and flood protection. Other characteristics of the lake and its basin are shown in Table 1.

Table 1. Characteristics of the Plastira lake and its basin [86].

Characteristics	Value
Basin area	161.3 km^2
Highest basin altitude	2140 m
Maximum designed lake level	794 m
Spill level	792 m
Minimum release level	776 m
Lake area at spill level	25 km^2
Lake area at minimum release level	15 km^2
Mean annual inflow	153 hm^3
Mean annual inflow depth	1029 mm

The Kremasta Dam was built in 1966 and created the largest artificial lake in Greece. In this dam, four power plants with hydro turbines with a total capacity of 437.20 MW are installed. A large hydroelectric plant is installed on the banks of the river and has a detour tunnel (as long as the water is not needed or threatens to flood the area) with a diameter of 12.5 m and a length of 808 m. The Kremasta Dam is 165 m high and forms an artificial lake that can hold 3.8 km^3 of water [87] as solved many of the country's electrification problems.

Lake Alpheios is an artificial lake in Ilia, in the western Peloponnese near ancient Olympia, which was created in 1962 on the Alpheios River after the construction of the Flokas Dam, near the village of Flokas [88]. The dam is 315 m long and is crossed by the Alpheios Bridge, which is 390 m long. It is made of concrete, is jumpable, and works as an automatic spillway. It was originally built as a water reservoir for the irrigation of the area, but, since 2010, it has been operating as a PPC hydroelectric plant with two hydro turbines. The dam is a natural barrier for transported sediments that accumulate over time, and thus, every 5 to 10 years, the lake is cleaned. Furthermore, to restore the link between the fish fauna upstream and downstream of the dam, the construction of a fish passage with a small slope and continuous water supply is planned, parallel to the hydroelectric plant. The dam is a natural barrier to sediment that accumulates over time, and the lake must be cleaned. It is precisely this accumulation that has resulted in the loss of at least 150 m of land from the beach over the years, because the sea destroyed the land and the river could not effectively make up for the ground lost. Thus, in addition to land, many houses along the wider beach nearby were lost.

In 1922, with the huge influx of refugees from Asia Minor, Athens (the capital of Greece) had a sharp increase in population with a devastating effect on its water consumption. In 1925, a contract was signed between the Greek Government, the Bank of Athens, and the American firm ULEN for the financing and construction of new water supply works. The first major project was the construction of the Marathon Dam (1926–1929). Over 900 people were involved in the construction of a dam, with a total height of 54 m and a length of 285 m, that is considered unique because it is entirely paneled externally with Pentelikon white marble [89]. The Boyati Tunnel (13.4 km long, 2.6 m wide, and 2.1 m high) was constructed to transport water from the Marathon Dam to a new water treatment plant in Athens.

Thereafter, in 1956, the water from the Yliki Lake was added to the system, and, in 1981, the operation of the Mornos Dam and aqueduct officially began. The Mornos Dam is one of the highest earth dams in Europe with a height of 126 m. The Mornos aqueduct, with a total length of 188 km, transports water from the Mornos reservoir to Athens and is the second longest aqueduct in Europe. It is made up of 15 tunnels (71 km) of 3.2 m diameter, 12 siphons (7 km), and 15 canals (110 km). It was also the first time that Tunnel Boring Machines (TBMs) were used in Greece. Finally, the last major project, which provided Athens with additional water in 2001, is the Evinos River Dam, also including a diversion tunnel for the river water [89,90]. Work on the Evinos project began in 1992 and was completed in 2001. The major structures of the project are a 120 m high earth-fill dam with a reservoir volume of 12 million m3, a total barrage capacity of 120 million m^3, and 29.4 km of length from Evinos to Mornos [90]. The tunnel, constructed with the TBM method is one of the longest hydraulic tunnels in the world. The adverse geological conditions, the high cover, and the short construction schedule were a great challenge for the successful construction of this tunnel [91]. The tunnel was completed in just two years, which is considered to be a significant achievement. This major water supply project is shown in Figure 12.

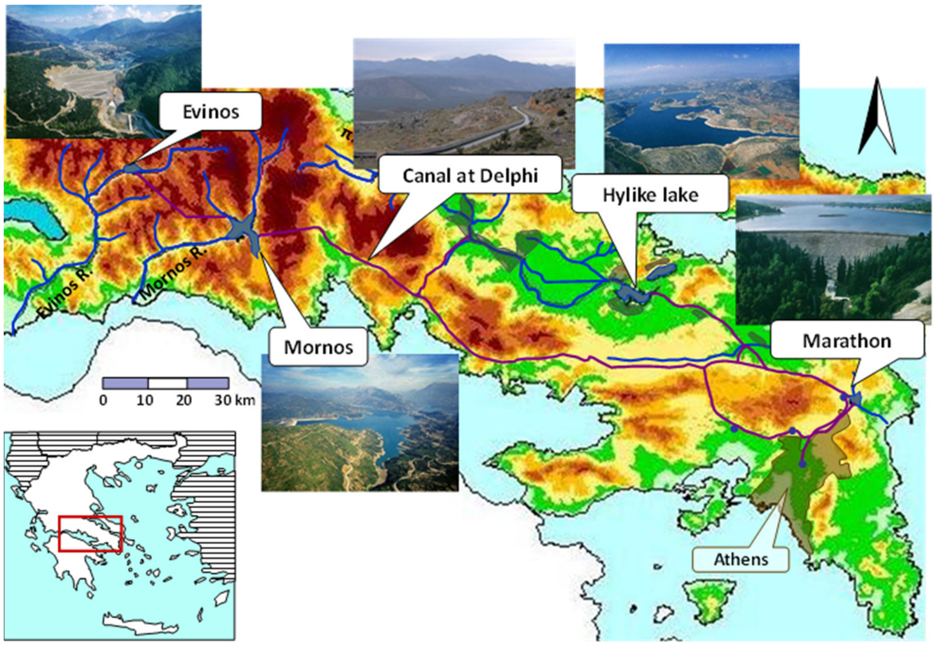

Figure 12. Dams are the major water supply projects in Athens, Greece.

4.2. China

The most important multi-purpose dam in the world is the “Three Gorges Dam” in China, one of the largest infrastructure projects in modern China (Figure 13). Construction of this massive structure began in 1994, and most of the work was completed by 2006. However, interest in the project dates back several decades. The American engineer J. L. Savage, who had played an important role in the building of the Hoover Dam, was working on preliminary designs for a large dam on the Yangtze River (Chang Jiang) in the mid-1940s before the Communist Party took control of mainland China in 1949. Planning for the existing structure began in the 1980s and the construction began following approval by the National People’s Congress in 1992. The Three Gorges Dam was built as a linear concrete gravity structure. A trestle and crane method, similar to that used in the 1930s for the Grand Coulee Dam on the Columbia River in the northwestern United States, was used to transport and pour the concrete [92].

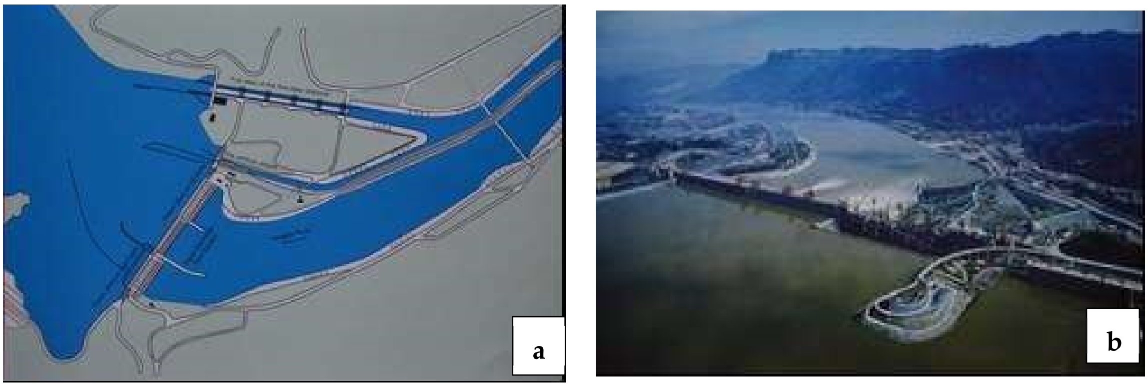

Figure 13. General view: (**a**) map; and (**b**) view of the main part of the dam.

The Three Gorges Dam is 2335 m long with a maximum height of 185 m. Its construction involved 28 million m^3 of concrete and 463,000 tons of steel. When it was fully commissioned in 2012, the dam's hydropower plant had the largest power generation capacity in the world at 22,500 megawatts. The reservoir dammed by the dam extends more than 600 km up the Yangtze. The length of the dam crest is 2039.50 m. The useful volume is 39,300 million m^3, of which 21,100 million m^3 is intended for flood protection for around 15 million inhabitants [92].

The Three Gorges Dam is a multi-purpose project. It is primarily a hydroelectric dam on the Yangtze River in the Sandouping District of Yichang City (Yiling Province, Hebei Province, China). In terms of its installed capacity, it is the largest power plant in the world. The dam is also intended to promote tourism in the area, increase the carrying capacity of the Yangtze River, and prevent flooding. Large wind turbines were also designed to limit greenhouse gas emissions. The dam has improved navigation for transportation and tourism purposes [93]. A transportation hub was established in the city of Chongqing, from which up to 10,000 tons are currently transported to Yichan. The ship lift can transport 3000 tons (with a total lifting capacity of 11,800 tons) of total cargo in one direction in 40 min.

The Three Gorges hydropower plant on the Yangtze River in China generated 112 TWh in 2020, a new world record. The clean energy generated by the Three Gorges Hydropower Plant in 2020 is estimated to be equivalent to saving about 34.39 million tons of standard coal and avoiding carbon dioxide emissions of 94.02 million tons [94].

The volume of concrete used was 5500 million m^3. On the negative side, archaeological and cultural sites disappeared, about 1.90 million people were displaced (13 cities, 140 small towns, and 1350 villages), and significant ecological changes occurred, including an increased risk of landslides [93].

The cost of the Three Gorges Dam reached RMB 180 billion (EUR 17.3 billion). By the end of 2008, expenditure amounted to around RMB 148 million, of which around EUR 9 million was spent on construction, EUR 8 million on the resettlement of residents, and EUR 2 million on other financing (expropriations, studies, etc.). It is estimated that the construction costs will be recouped once the power plant has generated around 1000 billion kWh of electricity, which corresponds to around EUR 35.7 billion [93]. Full cost recovery is expected after ten years of full operation.

4.3. Türkiye

With the increase in population and the development of industry over time in the world, the need to benefit more from rivers or water resources has arisen. Therefore, it is of great importance to protect the existing water resources under the changing climate conditions. Dams are one of the most important structures that serve this purpose. Before the establishment of the Republic of Türkiye, dams were built as small dams. The construction of large dams started after establishement of the Republic.

Nowadays, Türkiye consists of 25 river basins [95], and the rivers have a potential for hydroelectric power generation due to their steep slopes. In 1991, the number of dams constructed in Türkiye amounted to 150, and by 2016 that figure had increased to 694 (Figure 14) [96]. Today, the number of dams in Türkiye is 861 [95]). With a total hydropower potential of 440 billion kWh per year, Türkiye can also generate an amount of energy equivalent to 1% of the world's and 10% of Europe's energy [17].

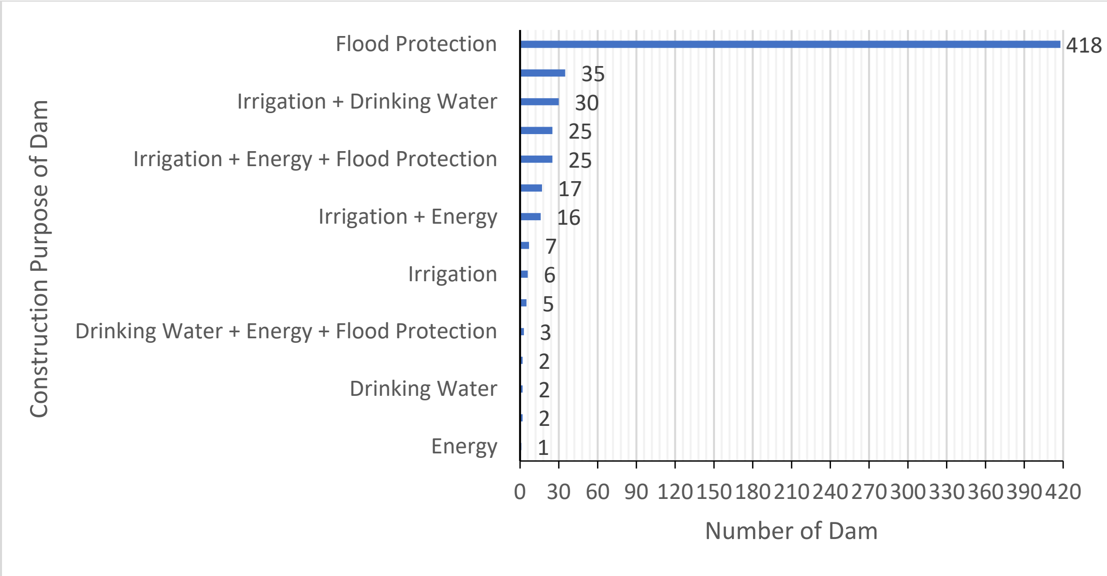

Figure 14. Number of dams in 2016 [97].

Türkiye made a significant contribution to hydraulic engineering by undertaking important projects on a global scale. Türkiye's surface water potential is 185 billion m^3/yr, a third of which comes from karst springs. The groundwater capacity is around 8 billion $m^3/year$ [17]. However, this potential is not evenly distributed across the country. Only half of the surface water potential is currently being used. Therefore, hundreds of small hydropower plants and dams are in the planning, design, construction, and operation phases.

The first studies on a more efficient and effective utilization of water resources in the Republic of Türkiye began in the era of Mustafa Kemal Atatürk, and the first dam built was the Çubuk Dam, which was built in 1930 to supply Ankara with drinking water [98,99]. The annual precipitation in this region, which falls as rain and snow, averages around 250 mm [93]. The catchment area of the Çubuk Dam is not very precipitous and has an area of 700 km^2. The dam is of the embankment type with a concrete core. It has a height of 250 m from the foundations and a capacity of 5.6 hm^3 [99]. The Çubuk Valley is covered with dense alluvial soil and has a rocky geological structure consisting mainly of andesite rocks, which are generally not very hard. Originally, the Çubuk Dam was planned to be built with stone and masonry construction methods [69]. However, since there was no rocky ground with a sufficient hardness and resistance in the Çubuk Valley and it was not possible to obtain solid stones from nearby quarries for construction, as well as the high cost of transporting stones from distant quarries, it was decided to build the Çubuk Dam with concrete [100,101]. Cement was injected to seal the cracks in the rocks. In addition, holes were drilled into the rock with hammer drills at a depth of 0.60 to 8 m and air pipes were inserted [101]. The rocky bottom was then covered with concrete consisting of an aggregate of water-soaked pebbles.

Türkiye's largest dams are the Atatürk Dam, the Keban Dam, the Ilısu Dam, the Karakaya Dam, the Hirfanlı Dam, and the Altınkaya Dam. Among the dams in Türkiye, the Atatürk Dam has a lake that covers an area of 817 km^2, the Keban Dam 675 km^2, the Ilısu Dam 313 km^2, the Karakaya Dam 268 km^2, the Hirfanlı Dam 263 km^2, and the Altınkaya Dam 118 km^2 [95]. The Atatürk Dam was built between 1983 and 1992 for energy and irrigation purposes [102]. In terms of dam volume, the Atatürk Dam is in the first dozen in Türkiye with a volume of 84.5 million m^3, placing it among the top 10 in the world. The geology of the dam has different geological and tectonic formations along the riverbed. The region is crisscrossed by different fracture systems, including significant faults that cut diagonally across the river. The Atatürk Dam was built on limestone: bituminous, mainly intermediate limestone and dolomitic limestone [103]. The completion of the dam created the Atatürk reservoir, the third largest lake in Türkiye. The dam has eight turbines with an installed capacity of 2400 MW (8 × 300 MW). The height of the Atatürk Dam is 169 m and it is a rock-fill dam with a volume of 84.5 million m^3 [102,103]. The outer surface consists of rock, clay, and earth. Due to the pressure of the reservoir, its height was reduced by 10 m during the original construction. The dam ranks fifth among the dams built worldwide. The minimum water level is 513 m, the ideal water level is 526 m, and the maximum is 542 m [102,104]. The dam requires a minimum depth of 133 m to generate electricity. It has a length of 1644 m and a width of 15 m [104].

The Atatürk Dam is considered the sixth largest dam in the world in terms of fill volume [103,104]. It is also the largest dam in Türkiye. The Atatürk Dam was built on the Euphrates River. It has a catchment area of 817 km^2 [105]. The Euphrates has the largest catchment area in Türkiye. In this region, as the winter precipitation falls in the form of snow, the flow rate is 200 m^3/s. Due to rainfall and snowmelt, the flow rate rises rapidly in spring and reaches 2000 m^3/s [106]. The water level, which begins to fall in July, reaches its lowest level in September–October. The flow of the Euphrates is irregular. The fill rate of the Atatürk Dam is shown in Figure 15.

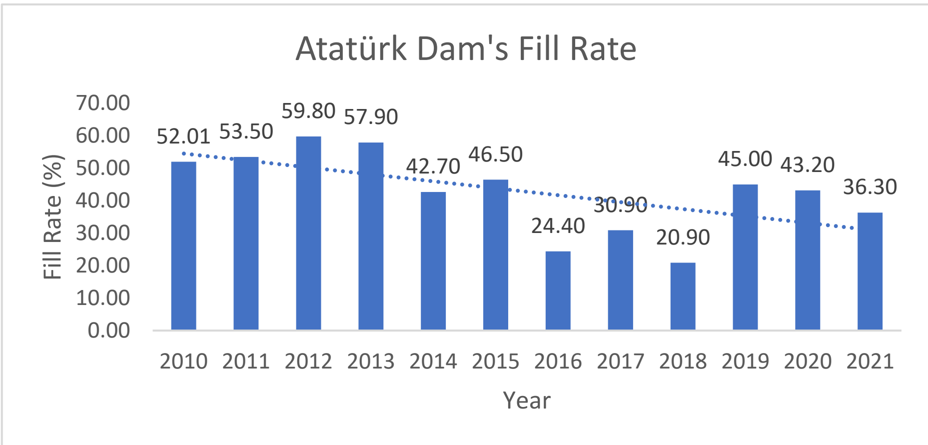

Figure 15. Atatürk Dam fill rate year by year [107].

The Atatürk Dam has six spillways, each of which is controlled by 16 × 17 m^2 radial gates [108]. The maximum discharge is 16,800 m^3/s [108]. Three diversion tunnels with a total length of 4090 m are located on the left bank of the river, each with a discharge capacity of 2100 m^3/s [108]. Each group has eight turbine generators with a capacity of 300 megawatts each [104,109]. Despite being a rock-fill dam, the Atatürk Dam used a total of 2,875,000 m^3 of concrete in various units [103]. These structures include spillways, water intake structures, pressure tunnels, hydropower plants, diversion tunnels, and injection galleries. Its contribution to the country's economy amounts to around 5.5 billion $, and it can supply 20% of the hydroelectric energy generated in Türkiye [102].

The Keban Dam is the third largest dam in Türkiye after the Atatürk and Karakaya dams and was built as a rock-fill and concrete gravity dam. It was built between 1965 and 1975 at the narrow and deep mouth of the Euphrates River to generate electricity [110]. The dam has a foundation height of 210 m, a crest length of 1125 m, a filling volume of 15.5 million m^3, and a concrete volume of 1.24 million m^3 [106,111]. The reservoir has a volume of 30.6 billion m^3 and covers an area of 675 km^2 [112]. The Keban reservoir, the fourth largest lake in Türkiye, was created after the completion of the dam. The maximum water level is 845 m, the minimum operating level is 813 m, the normal lake volume is 31 billion m^3, and the dead lake volume is 14 billion m^3 [113,114]. The Keban Dam was built in a gorge with karstic morphology at the point where Permian and Carboniferous schists and marble come together. The faults and fractures created by tectonic movements have accelerated karstification, connecting the marbles and creating a highly effective porosity environment suitable for water flow in all directions [101,104]. In the valleys of the Euphrates and Keban rivers, there are water leakages, cave openings, and various forms of karst cavities on the surface of the massive marble. To prevent water leakage from the Keban Dam reservoir, injection reinforcement and drainage drilling were carried out. Despite these efforts, when the dam started impounding on November 4, 1973, the pressure of the water volume on the ground reactivated the paleokarstic pathways, resulting in water leaks in the form of vortices and whirlpools on the lake's surface [104]. The escaping water from the lake appeared as a river in the Keban Stream and as large springs in the downstream area of the dam. This water leakage problem was also faced in 1974, 1975, and 1976 [104]. The dam has eight units with a total installed capacity of 1330 MW, producing 6 billion kWh of electricity annually [106,110]. The Keban Dam and Hydroelectric Power Plant were among Türkiye's first major energy investments. When established, it supplied 20% of the electricity produced in Türkiye; however, as of 2020, it meets only 1.8% of the total electricity consumed due to the increased overall electricity production [115]. The amount of water in the Keban Dam reservoir has decreased in recent years (Figure 16).

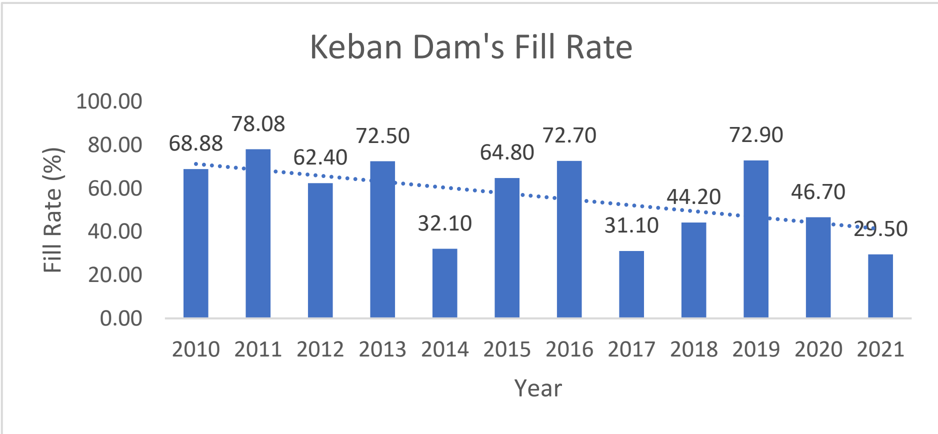

Figure 16. Keban Dam fill rate year by year [107].

The Keban Dam stands as an important example of the relationship between earthquakes and karstic water pathways. Located in a second-degree earthquake zone, the dam area has experienced moderate earthquakes from its construction to the present day. Thus, studying the relationship between rainfall, karst morphology, water leaks, and seismic activity has contributed valuable experiences to the literature [104].

The Ilısu Dam and Hydroelectric Power Plant Project (the Ilısu Project) is the largest dam on the Tigris River (Batman Governorate, 2023). The construction purpose of this dam is to produce energy, to control floods, and for irrigation [116]. Ranking as the fourth largest dam in Türkiye and the second largest dam in terms of fill volume, the Ilısu Dam is a concrete-faced rock-fill dam, making it the largest of its kind in the world in terms of fill volume and dam length with a foundation height of 135 m and a crest length of 1820 m [116–118]. The maximum water level of the dam is 525 m, and its total body volume is 23.9 million m^3 [117]. The reservoir covers an area of 313 km^2 and has a storage volume of 10.6 billion m^3 [117,118]. With a 10.6 billion m^3 storage capacity, the Ilısu Dam ranks as the third largest in Türkiye after the Atatürk and Keban dams [117]. The installed capacity of the Ilısu Dam is 1200 MW, and it is estimated to generate a total energy of 4.12 billion kWh [116]. With this capacity, the electricity generated by the Ilısu Dam will constitute 10%

of the total hydroelectric energy produced in Türkiye. In addition to electricity generation, the water stored in the Ilısu Dam will be used for irrigation.

Another important dam for Türkiye is the Yusufeli Dam, which is the highest dam in Türkiye and the fifth highest dam in the world, consisting of a double-curved concrete arch [119]. The dam has a foundation height of 275 m and a crest length of 490 m [120]. The Yusufeli Dam has a storage capacity of 2.2 billion m^3, and the spillway structure on the dam body is designed as a common type with three openings. The water flowing from the triple spillway with a discharge capacity of 2940 m^3/s is collected in the energy dissipation reservoir (EDP). The main purpose of the dam is power generation with a planned installed capacity of 558 MW [114]. In recent years, a movement has started in underground dam construction in Türkiye [121].

4.4. Egypt

Ancient dams in Egypt, as mentioned above, were built as earth-fill dams. Modern dams and barrages were built in Egypt first in masonry and then recently in concrete as described below.

More than 100 years ago (in 1903), the Assiut Barrage Dam was built to provide water for the Ibrahimiya Canal, the largest irrigation canal in Egypt. This comes about through the diversion of river water into the canal during the low water season. The barrage is a gravity dam consisting of around 95,000 m^3 of concrete, 64,600 m^3 of masonry, 1,824,000 m^3 of earthwork, 95,000 m^3 of pitching, and more than 4000 tons of pipes made from cast iron [122].

The Delta Barrage was used for controlling irrigation and navigation processes in the two branches of the Nile River downstream of the Nile division, north of the Egyptian capital, Cairo (Figure 17). The barrage is a gravity-type dam. Its construction started in 1833 and continued for 30 years. Its purpose was to improve irrigation and navigation along the main Rosetta and Damietta branches of the Nile downstream of the point where they divide north of Cairo, Egypt. However, during this long period of construction, a problem, perhaps caused by the foundations, affected its quality. Thus, its main irrigation purpose had to be largely restricted for safety reasons [123].

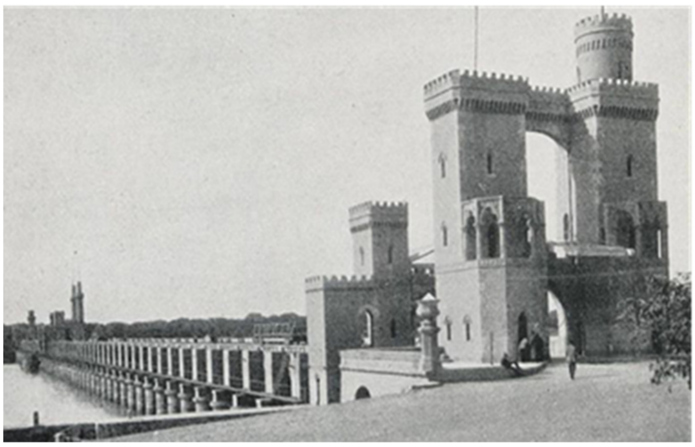

Figure 17. Delta Barrage in Cairo.

One example of rehabilitation is the Aswan Dam in Egypt, where the hydropower stations are being renovated after a long period of use. Over the decades, the machines in these power plants have been stressed by frequent starts and stops due to peak and medium loads. Important components are now obsolete, resulting in a loss of environmentally friendly power generation. As a result, the Aswan hydropower plants have been gradually refurbished in recent years [124]. The earliest recorded attempt to build a dam near Aswan dates to the 11th century and is attributed to the Arab polymath and engineer Ibn al-Haytham (known in the West as Alhazen)

Aswan Low Dam (1898–1902): The history of modern water management in Egypt begins with the construction of the old Aswan Dam in 1902 and the barrages on the Nile in the 19th and early 20th centuries. The old Aswan Dam partially stored the water of the Nile to enable the cultivation of several crops per year in the Nile delta, while the barrages raised the water level of the Nile so that the water could be diverted into large irrigation canals running parallel to the river. The Aswan Low Dam is a masonry gravity dam on the Nile in Aswan, Egypt. The dam was built at the first waterfall of the Nile and is located 690 km south–southeast of Cairo (Figure 18). It was originally built between 1899 and 1902. It was the largest masonry dam in the world. The dam was designed to store the annual floodwater and supplement the dry season runoff to support irrigation development and population growth in the upper part of Egypt. The dam, which was originally limited in height for conservation reasons, functioned as planned but did not provide sufficient storage capacity for the planned development. The dam was raised twice, in 1907–1912 and 1929–1933, to become 5 and 10 m higher, respectively. These increases were still insufficient to meet irrigation needs, and the dam was nearly overtopped despite efforts to maximize the basin height [125].

Figure 18. Aswan Low Dam [119].

Aswan High Dam (1954–1960): The storage capacity of the lake is 162 km^3 [126]. The Aswan High Dam has had a significant impact on the economy and culture in Egypt. The most important impact is that it has transformed the highly fluctuating annual flow of the Nile into a predictable source with a constant supply. A view of the High Aswan Dam can be seen in Figure 19.

Figure 19. Aswan High Dam.

The Aswan High Dam is of enormous benefit to the Egyptian economy. For the first time in history, the annual flooding of the Nile can be controlled by human hands. The dam impounds floodwaters and releases them when needed to maximize the benefits to irrigated land, to irrigate hundreds of thousands of new farmlands, to improve navigation above and below Aswan, and to generate enormous amounts of electrical power (the dam's 12 turbines can generate 10 billion kWh/year). The reservoir, which has a depth of 90 m and an average width of 22 km, supports the fishing industry.

4.5. Other Examples

The Diamer Bhasha Dam is a multi-purpose mega-dam project to be developed in Pakistan. It will be located with a huge reservoir on the Indus River in the district of Diamer in the Gilgit-Baltistan province of Pakistan, about 315 km upstream of the Tarbela Dam, 165 km downstream of the Northern Area capital Gilgit, and 40 km downstream of the city of Chilas. This dam is the largest dam project ever undertaken in Pakistan. With a height of 272 m, it is also set to become one of the highest dams in the world. The method used for the construction of the Diamer Bhasha Dam is the Gabarband and Khushkaba system. The dam is the tallest roller-compacted concrete dam in the world. The proposed dam would have a reservoir of about 9.25 billion m^3, with a live storage of more than 7.89 billion m^3. The average annual discharge of the Indus River at this location is 62 billion m^3. The dam will thus impound 15% of the annual flow. The dam project will cover an area of 110 km^2 and extend 100 km upstream of the dam to the Raikot Bridge on the Karakoram Highway (Figure 20). The main outcomes of the dam are the availability of annual surface storage to supplement irrigation supply during periods of low runoff, energy resources, reduced dependence on thermal energy and hence foreign exchange savings, and job creation, especially for local people, during its construction and operation [127,128].

Figure 20. Diamer Bhasha Dam [128].

5. Emerging Trends and Challenges of Water Dams

5.1. Emergence of Mathematical Models in the Design and Operation of Dams

Dam construction is one of the most remarkable fields that needs knowledge in the field of design, operation, maintenance, and rehabilitation. The first published attempts to apply engineering methods were concerned with estimating the required storage volume of a dam. Rippl [129] determined the capacity of the reservoir for a proposed dam site using a simple mathematical method called the mass curve. It is based on the maximum positive cumulative difference between a sequence of pre-desired dam releases (demands) and inflows [130]. Although the mass curve is a simple concept, it is still used as the method applied in water engineering handbooks (e.g., [130]) and the literature (e.g., [131]). Gradually, optimization methods, which had been introduced in the mathematical field, were applied to dam design to determine the best option within a defined set of possibilities. Hall and Buras [132] introduced Dynamic Programming (DP) to the field of water resources. Hall and Howell [133] first used DP to determine the optimal size of a reservoir considering carryover storage for consumptive use. Parallel to dam design methods, engineers have been formulating more precise operational policies to store and release water at the best time and in the most efficient amount. The Standard Operational Policy (SOP) is the first simple method that was used as the main policy for many dams. In this policy, the SOP guides the operator/s to release available water as much as demand/s and if extra water would be stored in the dam. However, the SOP is a very simple strategy, because it releases water based on current available water and there is no overview of the time horizon and future. It can, therefore, lead to significant system failures in water supply and increase vulnerability. To overcome the SOP disadvantage, Loucks [134] proposed a linear decision rule (LDR) in which the release was a function of the volume of stored water and the inflow. To determine the best LDR, the chance constraints method was applied, which confirmed the potential of optimization to find efficient and precise solutions compared to those methods just based on the simulation. Later, Nayak and Arora [135] applied a modification of the original LDR in the Minnesota River basin. More recently, hedging strategies have been developed and used in response to climate change, droughts, and water scarcity, which place greater constraints on water supply from water resources in general and on inflows to dams in particular. Hedging in reservoir operations means storing water in the dam from immediately beneficial deliveries to reduce future impacts. The hedging policy is still applied in the case of water shortages in reservoirs. During the 20th century, general policies and standards of water supply have been improved, which have directly affected the development of the design and operation of dams. In the USA, the Water Resources Council's Principles and Standards (1973) established two equally important objectives for federal water resources projects: (1) national economic development, and (2) environmental quality [136]. Therefore, studies have considered other aspects of dam design and operation in addition to meeting the dam's purpose. Nowadays, comprehensive methods are available for determining dam volumes, based not only on the desired reservoir release but that also consider a trade-off between multiple criteria and environmental factors.

5.2. Balancing Benefits with Potential Negative Impacts

Optimal strategies for the development of water resources are an important prerequisite for socio-economic development. Because of the increasing demand for energy, especially in many developing countries, dams and reservoirs are still necessary structures. The construction of dams changes the environment, which may have a negative impact. In most cases, the impacts are positive: flood control, irrigation, water supply, power generation, infrastructure improvement, deforestation reduction, recreation, fisheries, and many secondary benefits. Some negative impacts cannot be avoided: population displacement; the flooding of arable land and historical and cultural monuments; impact on the survival of endemic species and migratory fish; the degradation of aquifers; and the possibility of triggering seismicity, collapses, and similar events [11].

An important question is how to maintain a balance between the need for development and the preservation of the environment. Optimal environmental protection requires a multidisciplinary approach involving the close cooperation of a broad spectrum of geologists, civil engineers, biologists, chemists, hydrologists, hydrogeologists, archeologists, sociologists, and many others. The aim is to identify the decisive parameters that define the causes and consequences of human activities (in the dam construction) and the effects on the environment (such as cause–effect relationships); for example, a recent study deals with the cooling/warming potential impact of dams, developing a data-based predictive and diagnostic tool [137]. The criteria for determining environmental protection and regulatory procedures are important elements in this process [11]. It has become necessary before and during the design preparation of such hydro-structural projects to carefully study their impact on the surrounding environment, including all flora and fauna. It also includes the impact of projects on neighboring countries. This study should be done through what is called environmental impact assessment and risk assessment. In addition to known environmental aspects, there is a socio-economic one, which impacts people's properties, traditions, and businesses. The effect of dams and their reservoirs on these issues is indisputable, including land flooding to form the reservoir, people relocation, and interruptions to the aquatic life and water flow [138]. Many problems were faced in the past due to ignoring such studies. For instance, in Egypt, due to the construction of the High Dam, the sediments of the Nile were held back and the land missed the fertilizing silt. In addition, many Nubian villages were dispersed under Nasser, a lake generated by the dam for water storage, and they were relocated to the north of the Aswan governate. For the Three Gorges Dam, its construction and operation led to the relocation of more than one million people and many cities and villages under the Yangtze water. Another dam in China, called the Xiluodu Dam, displaced around 180,000 people from their land [138]. Even recently, in some ongoing dam construction projects such as the Renaissance Dam in Ethiopia, studies showed many problems related to the dam construction, such as environmental aspects and the impact on the downstream countries [139,140].

An example of dam construction with catastrophic effects for the environment and local economy is the Gotvand Dam in the north of the Khuzestan province in southwest Iran, built on the Karun River, the largest river of Iran with an average annual discharge of 12 billion cubic meters. Studies for this dam began in the 1960s, and the dam was finished in 2012. With a height of 185 m, this dam is the highest earth-fill dam in the Middle East. It currently has an installed capacity of 1000 MW with another 1000 MW in the works for a second phase. According to previous investigations, its water salinity in the absence of remedial action could be hazardous and even critical, since an oversaturated layer could form in the bottom of the reservoir. The building of the dam at this site was, therefore, controversial, because of the abundant presence of rock salt in the formations below the future reservoir. The salinity in the dam reservoir has now dissolved over 66 million tons of salt, and salinity has risen locally to over 200 g/L, threatening the agriculture and environment downstream of the dam [141].

Dam designers should learn from dam accidents. The cases of Malpasset Dam (France) and Vajont Dam (Italy) are typical examples, among many others. The Malpasset Dam (near Fréjus, France) was a double-curvature dam. The sudden failure of the dam (2 December 1959), which was due to deficiencies in geological investigation prior to its construction, caused the death of 421 people. The Vajont Dam (Italy) is a very tall double-curved arch dam. On the night of 9 October 1963, a massive rockslide occurred, waves of water reached over the dam, and very deep and fast-moving flood waters caused a high number of fatalities (more than 2000 people died and many more were injured). Vajont highlights the need for a thorough geotechnical investigation during dam design, especially reservoir slope stability analyses. This tragic event shows the complexity of dam design, operation, and maintenance, which goes beyond the safety of the dam itself.

The construction of large dams and reservoirs in highly developed karst is particularly sensitive and complex, as most of the water may escape through the underground karst channels. The impact of dams on the karst environment can be unpredictable, rapid, and unique. Similar situations are rarely, if ever, repeated. "Expecting the unexpected" should always be kept in mind as a basic philosophy for the construction of dams in karst. The main goals of the proper planning of water resource systems in karst areas are to minimize negative and to maximize positive environmental impacts by keeping water on the surface as much as possible [11]. Dried-up reservoirs or reservoirs with unacceptably high leakage are common in many karst areas of the world: the Hales Bar Dam (USA), Montejaque (Spain), Vrtac (Montenegro), Lar (Iran), May (Türkiye), Perdika (Greece), Wolf Creek (USA), Apa (Türkiye), and many others. A distinctive example is the Montejaque Dam in Spain.

The Nova Kakhovka Dam was built on the Dnipro River, Kherson Oblast, in southern Ukraine. The Secretary-General of the United Nations, Antonio Guterres, condemned the destruction of the Nova Kakhovka Dam, calling it a "monumental humanitarian, economic and environmental disaster" and "another example of the terrible human cost of war". The intact dam is shown in Figure 21. It was built in 1956 on the Dnipro River as part of the

Nova Kakhovka hydropower plant. It was 30 m high and 3.2 km long and had a capacity of 18 billion m^3. It supplied large parts of southeastern Ukraine and the Crimean Peninsula, which was annexed to Russia in 2014, with water [142]. The reservoir of the dam also supplied water for the necessary cooling of the six reactors of the Zaporizhzhia Nuclear Power Plant (ZNPP), the largest plant of its kind in Europe. Many fuel and emergency diesel generators had to be used repeatedly when the external power supply failed [143]. It is unclear what exactly destroyed the dam, but, from images broadcast from the scene, it appears that an explosion blew up a large section of the structure.

Figure 21. The Nova Kakhovka hydroelectric power dam.

5.3. Shaping Future Multi-Purpose Dams

Dams affect the environment and climate and simultaneously undergo their impact in a continuous interaction that defines the dams' function, efficiency, and sustainability, as well as the potential socio-economic impacts [144–146]. In the future, projected increases in the frequency of extreme weather events (e.g., droughts, extreme temperatures, and floods) can threaten the operation and safety of dams, stressing the need for an in-depth understanding of the mechanisms/processes behind the potential impacts, as well as proposals for the necessary adjustments needed in the design, construction, and management of dams. The negative potential impact of the climate on certain properties of dams has been highlighted, such as on the concrete (e.g., its compressive strength, elastic modulus, and shrinkage deformation), as well as changes in the overall water-supply capacity, mainly arising from changes in the frequency and characteristics of the temperature and precipitation patterns. There are also other issues for the planning, operation, and management of different types of dams, such as changes in dam capacity as a result of aging, damage, and/or sediment accumulation [147], which should also be incorporated in the risk assessment and management of dams [148]. Thus, reassessments of the potential risks are required to preserve future dam operation. From the opposite perspective, direct or indirect impacts are expected from the operation of dams on the local microclimate and the surrounding area, mainly due to changes in the thermal properties, radiation balance, and heat balance of the area [144], as well as due to changes in the biochemical processes in the soil–water–plant–atmosphere matrix. From these points of view, regional or national legislation and policy should be explored and adjusted accordingly, as mentioned above, to address arising issues and threats to humans and ecosystems, by focusing on proper infrastructure management, water supply management, water monitoring, and the prevention and/or mitigation of future floods, as well as on the impacts on the surrounding ecosystems, their services, and the environmental and climate footprints.

Recently, water infrastructure is increasingly used for more than one purpose; hence, the term multi-purpose water infrastructure (MPWI) has emerged. In the future, multi-purpose dams may be implemented, combining storing and supplying water for irrigation, industry, or human consumption; flood control; power generation and power storage; navigation; water regulation; environmental releases; and recreational purposes. Multi-purpose water infrastructure includes all constructed water systems, including dams, dikes, reservoirs, and associated irrigation canals and water supply networks, which can be used for more than one purpose for economic, social, and environmental activities. There are more than 8000 large MPWI systems worldwide, as well as a significant number of systems that are operated as multi-purpose facilities, although they were designed for single-purpose use [82].

A good example of a dam with multiple use is the Three Gorges Dam, which was referred to above. The main objective of the dam is to supply water for the largest hydroelectric plant in the world and to help control the devastating floods that plague the lowlands downstream from the dam. With its installed capacity (22,500 MW), the Three Gorges Dam generates 95 $\pm$ 20 TWh of electricity per year on average, depending on the amount of precipitation in the river basin. Furthermore, by providing flood storage space, the dam reduces the potential for flooding downstream, which historically plagued the Yangtze Plain. In addition, erosion is low because the flow is slower above the dam, so much of this sediment settles there instead of flowing downstream; as a result, there is less sediment downstream [149]. The environment in the area is, therefore, improved and protected. The environmental flows program of the Three Gorges Dam can serve as a precedent for the re-operation of other dams in China—the country with the most dams in the world. Furthermore, Chinese companies and investors have achieved substantial market shares in the construction of hydropower dams around the world. A high-profile example of dam management for environmental objectives could influence how dams are planned, designed, and operated in other countries [150] The installation of ship locks is intended to increase river shipping from 10 million to 100 million tons annually; as a result, transportation costs will be cut between 30 and 37%. Shipping will become safer since the gorges are notoriously dangerous to navigate. There are two series of ship locks installed near the dam. Each of them is made up of five stages, with a transit time of around four hours [151]. Finally, water supply, irrigation, and touristic and navigational uses highly increased.

In Greece, a project was planned, studied, and built in Almyros Iraklion in Crete. It was assumed that by raising the existing dam to 20–25 m, a complete separation of saline water and freshwater could be achieved in the total supply of the Almyros spring, which is between 0.3 and 9.0 million m^3/d. Even if the separation was not fully achieved, the utilization of the waterfall created for power generation could likely amortize the construction costs of the project [152]. The project will also be used for irrigation and water supply to the northern villages of central Crete. In another recent research study, the possibility of installing floating photovoltaics in the existing water reservoirs in the island of Crete was investigated. It was estimated that floating panels could cover from 2.57 to 7.72% of the island's annual electricity consumption, based on 2018 data [153].

For countries of the European Union (EU) and in many parts of the world, the available technically feasible potential for the development of hydroelectric power is much greater than the actual production, as shown in Figure 22 In many EU countries, 100% of their hydroelectric potential is used. However, Greece remains almost the last country when the different countries are compared. The percentage of the potential hydroelectric capacity in the country is estimated to be 65% and, of this, only one-third is used. Many countries in Africa, South America, China, India, and Russia, are still not using yet their full potential hydroelectric capacities, as shown in Figure 22.

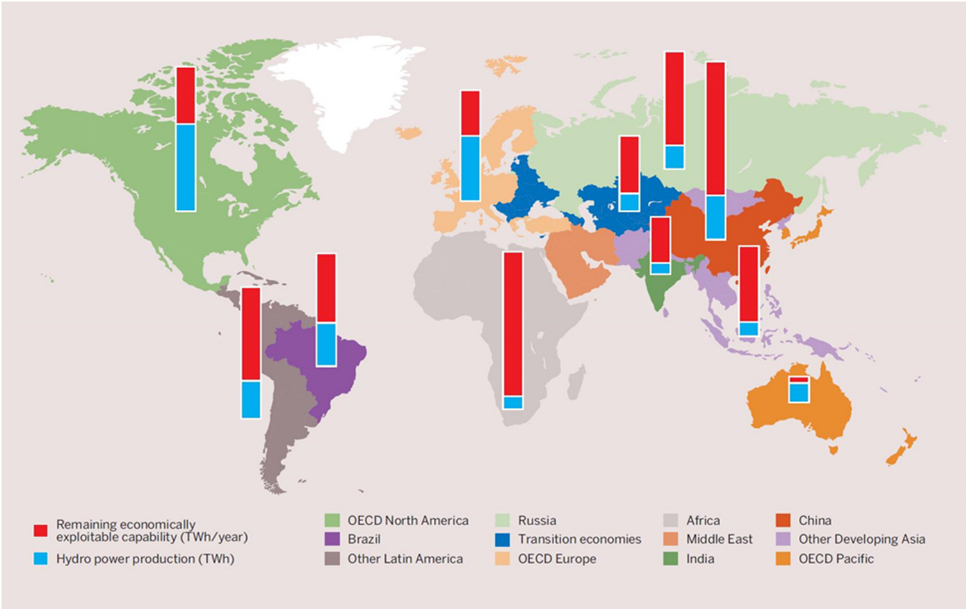

Figure 22. Produced and expected hydroelectric power in the world [138].

Current and future dams face challenges in the domain of how these infrastructures can be fairly judged and evaluated in the context of potential benefits and impacts for the dependent local communities. A recent study has discussed a profound conflict between the proponents and opponents of such projects, highlighting, on the one hand, a substantial overlap in articulated values and knowledge, such as valuing human life, material livelihood, and well-being, and, on the other hand, an extreme power imbalance in many cases between growth-focused governments and profit-focused corporations and people that claim to be adversely affected (focusing mostly on environmental issues) [154]. The study concludes that, in such cases, it is common that democratic processes and justice are overlooked during the decision-making processes for the benefit of the former entities, causing significant ethical issues and obstructing transformative change [154]. Apart from the local perspective, dams may be part of a broader water resources management framework involving different areas, regions, or even countries, being in many cases a source of conflict between users and governments [155,156].

Achievements in various technologies, such as artificial intelligence, machine learning, geographic information systems, remote sensing, and drone technology, could be valid tools during the decision-making, planning, construction, evaluation, and management of future dams. However, there are issues and challenges that need to be addressed. Some of them are analyzed in a recent study focusing on dam engineering projects [157]. In this study, the advancements and merging trends in technology, such as the virtual cloud, augmented reality, smart robotics, and 3D/4D printing, are highlighted in the context of future research and development [157]. Another example comes from Korea, including the development of a digital twin dam and watershed management platform, based on real-time data and simulation models, as presented above. The platform incorporates GIS-based geospatial data, artificial intelligence technology, a geotechnical safety evaluation module, and advanced monitoring by drones for dams and rivers to support decision-making and the optimum and smart dam/water management [158].

Taken together, the decision-making processes, planning, construction, operation, and management of future dams presuppose a deeper understanding by the scientific community, policymakers, and stakeholders of the complex dam–climate–environment–economy–society nexus, including political initiatives and the use of advances in technology. This can provide sophisticated dam and water management and the settlement of potential conflicts between interested parties, as well as necessary adjustments not only at a technical level but also at legislative and socio-economic levels in the context of the safe and sustainable operation and use of future dams.

6. Rehabilitation of Dams

A dam is a large structure that requires maintenance, repair, and rehabilitation. If these subjects are neglected, there is a probability of failure of the system, which may affect the public. Rehabilitation means repairing, replacing, reconstructing, or removing a dam to fulfill dam safety standards [159]. The aim of rehabilitation is usually to strengthen the foundations by grouting, to improve the drainage, or to install an impervious apron upstream of the dam. The flow of water through erodible or fractured rock can lead to increasing leakage from the reservoir. The rehabilitation of dams, depending on their height, age, and condition, can be a costly activity, sometimes requiring national support. A study published by the US Association of State Dam Safety Officials (ASDSO) in 2023 estimated the cost of dam rehabilitation for the period 2003–2023. According to the study, approximately USD 34.1 billion was needed in 2023 for non-federal high-hazard potential dams, where loss of life is likely if dams fail or are misoperated [160].

Dam rehabilitation can be carried out on the dam structure or on facilities that have been installed to meet the dam's operational purposes. The Oroville Dam in the USA is an example of dam rehabilitation, where concrete erosion had occurred and some spillway rehabilitation had been carried out. This dam is the tallest in the United States and plays an important role in water storage [161].

As mentioned above, Iran is one of the first countries in dam construction and operation. According to the website of the Iranian National Committee of Large Dams (IRCOLD), the number of large operating dams is 523, and the total water storage of all the dams is 51.7 billion m^3 [10]. Some of these dams, due to age, need rehabilitation to ensure a continued efficient performance. The Dez Dam is one of the first large dams built in the Zagros Mountains in southwest Iran. It was completed in 1962, and the filling of the reservoir began in December 1962. The operational purposes of this dam are hydroelectric power generation, downstream demand supplementation, and flood control. The Dez underground powerhouse contains eight 65 MW units with a total installed capacity of 520 MW, which has generated an average of 2400 GWh/yr of power over a 45-year operating period. Thus, the high value of the hydroelectric power generated shows the important role played by the Dez Dam in the electricity sector. The minimum and normal operating volumes are 726.5 and 2698.5 million m^3, respectively. The power plant's design discharge is 357 m^3/s; however, unfortunately, the high sedimentation rate has recently caused many difficulties for the operation of the dam. The first major impact is that the irrigation gates of the dam, which are currently 35 m below the sediment deposit, are out of use and the hydroelectric outflow, which is at a higher level, is also used for irrigation purposes. In addition, the hydropower intake is only approximately 5 m above the sediments, and, if dredging is delayed, hydropower generation/operation will be difficult [162–165]. There are some scenarios to rehabilitate the Dez Dam due to its role in increasing electricity production, such as improving the demand and supply or extending the reservoir life. A rehabilitation package that is being studied consists of three main components, as follows: (a) construction and installation of a new power plant with a total capacity of 720 MW; (b) dam heightening by 8 m; and (c) a new bottom outlet construction [162].

The Chimoni Dam in Kerala, India, is a masonry dam along with an earth dam, having a length of 1211 m. It is a multi-purpose dam for hydropower, drinking water, and irrigation. The Chimoni Dam was built between 1975 and 1996, and the first full level of water was in 2005. The dam capacity is 179.39 Mm^3. Many problems recently started to become apparent, such as severe seepage, which was observed in the passageway and downstream of the masonry section. The drainage holes in the dam were also blocked due to mud transported with the water. Some recommendations were proposed to fix these problems. The masonry dams were examined by geo-physical investigation to determine their status. It was suggested to plaster the whole masonry body from bottom to top to reduce seepage. Sand and crushed rocks as filling materials were added to cement to provide a toe drain downstream of the masonry dam. In addition, it was recommended that the broken spillway gates be made operative by repairing the lifting/movement of the gate and eroded spillway glacis with high-strength concrete [166].

The Kariba Dam lies in the Zambezi River basin between Zambia and Zimbabwe. It has the largest artificial reservoir worldwide, with a capacity of 181 billion m^3. The dam consists of a double concrete arch dam which was constructed between 1956 and 1959. It is a hydropower dam giving power to the whole southern region of Africa. Recently, the dam needed major rehabilitation to continue its operation safely and efficiently. In 2015, the rehabilitation plan was to be applied over the next ten years without interrupting the power production. It was planned to complete the plunge pool and spillway by 2019 and 2023, respectively [167].

Current advances in technology and data collection may help in evaluating the status of a dam, providing valid assessments not only regarding their structural and operational performance but also of potential impacts on the surrounding environment and humans. These can support future decisions regarding the removal or modification of the dam. A recent study has developed a set of social and ecological metrics that can be used to create a GIS database for numerous dams in New England [168]. Another example includes the determination of the future creep and seismic behaviors of dams by using 3D finite-difference analyses, validated by long-term levelling measurements [169]. Furthermore, there are detection technologies for underwater concrete cracks [170]. In China, dams were evaluated by the creation of a first silted land vectorized dataset, combining high-resolution and easily accessible Google Earth images with object-based classification methods [147].

7. Epilogue

The development of dams shows that there are many lessons from the past that can be of use for future generations. There are still many old dams in operation today. The purpose of holding back river water for future supply, as implemented by the first known water reservoir dam in Jawa, and of protecting humans from floods, as implemented by the first known larger dam in Sadd el-Kafara, are both still relevant for many of today's water reservoir dams more than five millennia later. It is only in modern times that other major purposes of water reservoir dams have been added, such as hydropower generation.

Today, it is generally accepted, especially in the developed world, that dams are not built for just one use (irrigation and/or water supply). Instead, multi-purpose dams are being promoted and built, combining water supply, irrigation, flood protection, power generation, and other uses. The ''Three Gorges Dam" in China is a good example. Another smaller but good example is the Tavropos Dam (Lake Plastira, Central Greece) that allowed tourist development of the lake area, as well as power generation, irrigation, and drinking water supply. Similar examples have been built in Germany and France, which utilize 100% and 97%, respectively, of their economically usable hydroelectric potential. In general, the available technically feasible potential for the development of hydroelectric power in Greece and in other parts of the world is much larger than the actual production. In Greece, two-thirds of the economically usable hydroelectric potential has not yet been utilized. In the present, there are reactions from ecological organizations to the construction of new dams in order to protect the environment. While hydropower is estimated to be able to provide 65% of the country's needs, today less than 30% is used, compared to other countries that use almost 100% of their hydroelectric potential [171] e.g., in Norway. In the list of EU countries, regarding the use of hydroelectric power, Greece appears last. Unfortunately, only 20% of consumed electricity is hydroelectric.

Dam designers should consider previous experience to ensure that dams' failures/accidents that may threaten human life, impair the sustainability of ecosystems, and destroy the environment are not repeated. A common example of failure is the construction of reservoirs in karsts, which can fail despite potential investigation and sealing measures. Moreover, the overbuilding of dams could lead to serious problems. One example is the 500 dams in Iran, which have seriously affected watersheds and water bodies. These mostly useless structures have led to deforestation, impaired the productivity of ecosystems, and significantly destroyed the physical and biological environment. The building of dams in Iran can be considered a prominent national activity that has contributed to desertification and thwarted development efforts. Finally, and perhaps most importantly in terms of the direct cost to human lives, dams have disrupted indigenous communities both upstream and downstream, completely disregarding their knowledge and traditions, as well as the rich cultural traditions and heritage of many civilizations in Iran [172].

Overall, it becomes necessary before and during the design preparation of dam construction projects to carefully study their impacts on the surrounding environment, including flora, fauna, and all environmental and socio-economic aspects that impact people's properties, traditions, and businesses. There are many methods of evaluating the adequate environmental flow rate that is essential for the fauna and flora of a watershed. It is also essential to understand the relationships between the biota and the environment, since less water means less space for riverine organisms [173]. Experiences from the past and present showed that maintenance, repair, and rehabilitation must be applied to dams. If these items are neglected, efficiency is reduced, and there is the probability of a failure of the system that may affect public safety. Current technological achievements are an important tool against current and future challenges of being able to efficiently support the planning, operation, and decision-making/management of dams, supporting in parallel a fair judgement and evaluation of these infrastructures in the context of the potential benefits and impacts on local communities.

Author Contributions: A.N.A. had the original idea and wrote the original draft. A.B. and E.B. contributed to the following sections: Hittite Era, Urartian Era, Byzantine Period, Water Dams in Early and Mid-Modern Times, Water Dams in Contemporary Times, and Emerging Trends and Challenges of Water Dams. M.V. contributed to the following sections: Prolegomena, Iranian and Other Prehistoric Civilizations, Byzantine Period, Medieval Times, Emerging Trends and Challenges of Water Dams, and Epilogue. E.F.-M. and J.D. contributed to the sections on Dams in the Early and Mid-Modern Times, Emergence of Mathematical Models in the Design and Operation of Dams, and the Rehabilitation of Dams. J.K. reviewed and contributed to the section on Archaic, Classical, and Hellenistic Periods. C.P. contributed to the sections on the Roman Period and the Nabatean part of the Archaic, Classical, and Hellenistic Periods section. V.A.T. contributed to the sections on Emerging Trends and Challenges of Water Dams and Rehabilitation of Dams and reviewed, edited, and submitted the manuscript. R.K. contributed to the Asian sections and reviewed them. Z.M. contributed to the Chinese sections and reviewed them. N.D. contributed to the Greek sections and reviewed them. A.T.A. wrote about dams in ancient and modern Egypt and also contributed to other sections. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We wish to acknowledge Cynthia Lynn Hann for her considerable contribution to the English grammar of this paper and improvements to its fluidity during the development of this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Şenturk, F. *Hydraulics of Dams and Reservoirs*; Water Resources Publication: Highland Ranch, CO, USA, 1994; p. 788, ISBN 0-918334-80-2.
2. Angelakis, A. Hydro-technologies in the Minoan Era. *Water Sci. Technol. Water Supply* **2017**, *17*, 1106–1120. [CrossRef]
3. Antoniou, G.; Kathijotes, N.; Spyridakis, D.; Angelakis, A. Historical development of technologies for water resources management and rainwater harvesting in the Hellenic civilizations. *Int. J. Water Resour. Dev.* **2014**, *30*, 680–693. [CrossRef]
4. Jarrige, C. The figurines of the first farmers at Mehrgarh and their offshoots. *Pragdhara* **2008**, *18*, 155–166.
5. Quddus, S.A. *Sindh: The Land of Indus Civilisation*; Royal Book. Co.: Karachi, Pakistan, 2010.
6. Milanović, P. Dam engineering and its environmental aspects. In *Encyclopedia of Sustainability Science and Technology*; Springer: New York, NY, USA, 2012; pp. 2788–2804.

7. Schmitt, R.J.P.; Rosa, L. Dams for hydropower and irrigation: Trends, challenges, and alternatives. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114439. [CrossRef]
8. Fahlbusch, H. Early dams. *Proc. Inst. Civ. Eng.-Eng. Hist. Herit.* **2009**, *162*, 13–18. [CrossRef]
9. Sanizadeh, S.K. Novel hydraulic structures and water management in Iran: A historical perspective. *Options Mediterr.* **2008**, *83*, 26–43.
10. IRCOLD; Iranian National Committee on Large Dams. *A General View on Iranian Dams, Past-Present-Future*; Ministry of Energy: Teheran, Iran, 1993.
11. Milanović, P.T. Dam Engineering and Its Environmental Aspects. In *Environmental Geology*; Encyclopedia of Sustainability Science and Technology Series; LaMoreaux, J., Ed.; Springer: New York, NY, USA, 2019.
12. TNA. Tasnim News Agency. Amir Dam: One of the Most Glorious Ancient Dams. Retrieved 8 November 2023. 2017. Available online: https://www.tasnimnews.com/en/news/2017/07/17/1460596/amir-dam-one-of-the-most-glorious-ancient-dams (accessed on 19 June 2024).
13. Vasilakis, A. *Minoan Civilization*; Iraklion: Crete, Greece, 2000. (In Greek)
14. Betancourt, P.P. *The Dams and Water: Management Systems of Minoan Psei-Ra*; INSTAP Accademy Press: Philadelphi, PA, USA, 2012.
15. Baba, A.; Tsatsanifos, C.; El Gohary, F.; Palerm, J.; Khan, S.; Mahmoudian, S.A.; Ahmed, A.T.; Tayfur, G.; Dialynas, Y.G.; Angelakis, A.N. Developments in water dams and water harvesting systems throughout history in different civilizations. *Int. J. Hydrol.* **2018**, *2*, 150–166. [CrossRef]
16. Torun, Ö. Roman Period Dams in Anatolia. Master's Thesis, Ankara University, Social Sciences Institute, Archaeology Department, Classical Archaeology Science Branch, Ankara, Turkey, 2020. Available online: http://hdl.handle.net/20.500.12575/72970 (accessed on 24 June 2024).
17. Baykan, N.O.; Baykan, N. Water Engineering in Anatolia Over Millennia. In *4th Symposium on Hydraulic Structures*; IMO: Antalya, Turkey, 2015; pp. 145–156. Available online: https://www.imo.org.tr/eklenti/6575,176463817pdf.Pdf?0&_Tag1=0a33b7f856d3c009cb423f319175a5bcf0823bf2 (accessed on 25 July 2023). (In Turkish)
18. Üke, A. Water Weirs and Pool Structures in the Hittite Period in the Light of Philological-Archaeological Data. *Hitit Univ. Soc. Sci. Inst. J. Anarsan Symp.* **2018**, *11*, 1529–1551. (In Turkish) [CrossRef]
19. İpek, Ö.; İbiş, R. Çakır Village Hittite Dam: Preliminary Report on the 2012 Excavation and Survey Work. In Proceedings of the 3rd Çorum Excavation and Research Symposium, Çorum, Turkey, 3 September 2012; pp. 37–59. Available online: https://corum.ktb.gov.tr/Eklenti/112498,3-kazisempozyumpdf.pdf?0 (accessed on 25 July 2023). (In Turkish).
20. Belli, O. *A Comprehensive View of Urartian Dams Discovered in the Eastern Anatolia Region*; Turkish Historical Society: Belleten, LX, USA; Ankara, Turkey, 1996; pp. 631–756. (In Turkish)
21. Belli, O. Investigation of Urartian Dams, Reservoirs, and Irrigation Channels in the Eastern Anatolia Region in 2010. In Proceedings of the 29th Research Results Meeting, Malatya, Turkey, 23–28 May 2011; Volume 3, pp. 293–316. Available online: http://www.kulturvarliklari.gov.tr/Eklenti/4650,29arastirma3.pdf?0 (accessed on 25 July 2023). (In Turkish).
22. Özsoy, S. Evaluation of Water Structures Built During the Hittite Period from the Perspective of the Historical Development of Science. *Mavi. Atlas.* **2017**, *5*, 489–501. (In Turkish) [CrossRef]
23. Öziş, Ü. *Historical Dams in Turkey*; Ankara, Turkey, 1999.
24. Öziş, Ü. Water works through four millenia in Turkey. *Environ. Process.* **2015**, *2*, 559–573. [CrossRef]
25. Apaydın, A.; Çınaroğlu, A.; Inal, I.; Dilektaşlı, C.; Çelik, D. Return to 3260 Years Ago at Çorum-Alaca Mound: Improvement of the Ancient Hittite Dam and Revival of Hittite Life. *State Hydraul. Work. Tech. Bull.* **2020**, 18–35. (In Turkish)
26. Çelik, D. Architectural Findings in the Light of the Most Recent Excavations in Alaca Höyük. Master's Thesis, Ankara, Turkey, 2008; pp. 1–201. (In Turkish).
27. Encyclopedia, B. Marid, Yemen. Dam History. 2023. Available online: https://www.britannica.com/place/Marib (accessed on 25 July 2023).
28. Ma, Z. Impression and enlightenment of Dujiangyan Irrigation Project. *China Water Resour.* **2020**, *71*, 4–11.
29. Li, S. Dujiangyan Irrigation Project:a great splendid program. *Disaster Prev. Expo.* **2021**, *21*, 48–49.
30. Belli, O. Investigation of Urartian Dams, Reservoirs, and Irrigation Channels in the Eastern Anatolia Region in 2000. In Proceedings of the 19th Research Results Meeting, Ankara, Turkey, 2001; Volume 2, pp. 239–256. Available online: http://www.envanter.gov.tr/belge/makale/detay/68037 (accessed on 25 July 2023). (In Turkish).
31. Öğün, B. *Irrigation Facilities of Urartu and the Shamram (Semiramis) Canal in Van*; Ankara, Turkey, 1970.
32. Bildirici, M. *Historical Water Structures: Konya, Karaman, Niğde, Aksaray, Yalvaç, Side, Mut, Silifke*; Ministry of Environment and Forestry, State Hy-draulic Works Directorate General: Ankara, Turkey, 2009. Available online: https://cdniys.tarimorman.gov.tr/api/File/GetFile/425/KonuIcerik/767/1115/DosyaGaleri/tarihi-su-yapilari.pdf (accessed on 25 July 2023). (In Turkish)
33. Kadıoğlu, M.; Görkay, K.; Mitchell, S. *Ankyra in the Roman Period*; Istanbul, Turkey, 2011; ISBN 978-975-08-2025-0.
34. Belli, O. Investigation of Urartian Dams and Irrigation Systems in the Eastern Anatolia Region in 1997. In Proceedings of the 16th Research Results Meeting, Ankara, Turkey, 1998; Volume 2, pp. 267–291. Available online: http://www.envanter.gov.tr/belge/makale/detay/67830 (accessed on 25 July 2023). (In Turkish).
35. Angelakis, A.N.; Capodaglio, A.G.; Passchier, C.W.; Valipour, M.; Krasilnikoff, J.; Tzanakakis, V.A.; Sürmelihindi, G.; Baba, A.; Kumar, R.; Haut, B. Sustainability of Water, Sanitation, and Hygiene: From Prehistoric Times to the Present Times and the Future. *Water* **2023**, *15*, 1614. [CrossRef]

36. Koutsoyiannis, D.; Zarkadoulas, N.; Angelakis, A.N.; Tchobanoglous, G. Urban water management in Ancient Greece: Legacies and lessons. *J. Water Resour. Plan. Manag.* **2008**, *134*, 45–54. [CrossRef]
37. Murray, W.M. The ancient dam of the Mytikas Valley. *Am. J. Archaeol.* **1984**, *88*, 195–203. [CrossRef]
38. Zarkadoulas, N. The Dam of Ancient Alyzia (Το φράγμα της αρχαίας Αλυζίας). Master's Thesis, Department of Water Recourses. Hydraulic and Maritime Engineering-National Technical University of Athens, Athens, Greece, 2005; 94p. (In Greek).
39. Krasilnikoff, J.A. Irrigation as Innovation in Ancient Greek Agriculture. *World Archaeol.* **2010**, *42*, 108–121. Available online: http://www.jstor.org/stable/25679730 (accessed on 24 June 2024). [CrossRef]
40. Hodge, A.T. Reservoirs and Dams. In *Handbook of Ancient Water Technology*; Wikander, Ö., Ed.; Technology and Change in History; Brill: Leiden, The Netherlands, 2000; Volume 2, pp. 331–339.
41. Lindner, M. Nabaräische Talsperren. In *Historische Talsperren*; Garbrecht, G., Ed.; Verlag Konrad Wittwer: Stuttgart, Germany, 1987; Volume 1, pp. 147–174.
42. Schnitter, N. Römische Talsperren. *Antike Welt.* **1978**, *8*, 25–32.
43. Schnitter, N. Die Entwicklungsgeschichte der Pfeilerstaumauer. In *Historische Talsperren*; Garbrecht, G., Ed.; Verlag Konrad Wittwer: Stuttgart, Germany, 1987; Volume 1, pp. 57–74.
44. Schnitter, N. Die Entwicklungsgeschichte der Bogenstaumauer. In *Historische Talsperren*; Garbrecht, G., Ed.; Verlag Konrad Wittwer: Stuttgart, Germany, 1987; Volume 1, pp. 75–96.
45. Garbrecht, G.E. *Historische Talsperren*; Verlag Konrad Wittwer: Stuttgart, Germany, 1991; Volume 2.
46. Smith, N. *A History of Dams*; Peter Davies: London, UK, 1971; pp. 25–49, ISBN 0-432-15090-0.
47. Viollet, P.-L. *Water Engineering in Ancient Civilizations. 5000 Years of History*; CRC Press: Boca Raton, FL, USA, 2007.
48. Vogel, A. Die historische Entwicklung der Gewichtsmauer. In *Historische Talsperren*; Garbrecht, G., Ed.; Verlag Konrad Wittwer: Stuttgart, Germany, 1987; Volume 1, pp. 47–56.
49. Hodge, A.T. *Roman Aqueducts & Water Supply*; Duckworth: London, UK, 1992; ISBN 0-7156-2194-7.
50. Smith, N. The Roman Dams of Subiaco. *Technol. Cult.* **1970**, *11*, 58–68. [CrossRef]
51. Martínez, S.F.; Rodríguez, D.G. Descubrimiento y análisis de dos nuevas conducciones en el entorno de Mérida: Avances y resultados. In *Ingeniería Hidráulica Romana: VI Congreso Internacional de las Obras Públicas Romanas*; Moreno Gallo, I., Ed.; Instituto de Estudios Riojanos: La Rioja, Spain, 2023; pp. 169–187.
52. Arenillas, M. Presas romanas en España. *Ing. Territ.* **2003**, *62*, 72–78.
53. Marcellin, C. Les aqueducs de Vienne. *Cart. Archéologique Gaule* **2014**, *38*, 157–170.
54. Burgers, A. *The Water Supplies and Related Structures of Roman Britain*; BAR Publishing: Oxford, UK, 2001.
55. Yaşar, M.; Baykan, N.O.; Tanriöver, Y.E. Sebastapolis (Kızılca/Tavas/Denizli) Pınar Compilation Structure and Embankment. In Proceedings of the Historical Water Structures Conference, Izmir, Turkey, 26–27 June 2008; pp. 129–132. (In Turkish).
56. Casagrande, M. Gli impianti di adduzione idrica romani in Byzacena e in Zeugitana. In *Studi di Storia e di Archeologia*; Nuove Grafiche Puddu: Ortacesus, Italy, 2008; Volume 4.
57. Slimani, S. Types d'ouvrages hydrauliques antiques dans le Hodna occi-dental Etat des lieux. *Nouvelles de l'Archéologie Algérienne* **2020**, *2*, 92–99.
58. Ferjaoui, A.; Pailler, J.-M.; Darles, C.; Bordes, J.-L. L'approvisionnement en eau de Zama (Tunisie), le barrage d'Aïn Jebour. In *Regards Croisés d'Orient et d'Occident*; Baratte, F., Robin, C.J., Rocca, E., Eds.; Les Barrages dans l'Antiquité tardive; 2013. Available online: https://africa.hypotheses.org/2946 (accessed on 25 July 2023).
59. Sanchez Lopez, E. Los acueductos urbanos en Hispania. In *Arquitectura Hidráulica y Forma Urbana*; Camara Muñoz, A., Revuelta Pol, B., Eds.; Asociación Cultural y de Estudios Jamilenudos (ASCUESJA): Jaén, Spain, 2019; pp. 11–28.
60. Bouffier, S.; Curie, J.; Dumas, V.; Lenhardt, P.; Marchello, A.; Ollivier, V.; Paillet, J.-L.; Trefiletti, M.; Turci, M. *Aux Origines du Galermi. Un Aqueduc à Travers L'histoire*; Maison Meditérannéenne des Sciences de l'Homme, Aix-Marseille Université: Aix-en-Provence, France, 2018.
61. Rigal, D. L'aqueduc antique de Cahors et ses captages. In *L'eau: Usages, Risques et Représentations dans le Sud-Ouest de la Gaule et le Nord de la Pé-Ninsule Ibérique*; Bost, J.-P., Ed.; Aquitania Université de Bordeaux M de Montaigne: Pessac, France, 2012; Aquitania supplement 21; pp. 443–456.
62. Breeze, D.J.; Jilek, S.; Graafstal, E.; Willems, W.J.H.; Bödecker, S. Frontiers of the Roman Empire. 2018. Available online: https://whc.unesco.org/en/list/430/ (accessed on 25 July 2023).
63. Yongmei, H. General Survey and Research on the Longshou Canal of Guanzhong Water Conservancy Project. *Relics Museolgy* **2009**, *26*, 80–83.
64. Li, P. Irrigation in the Upper Reaches of the Han River in History. *Agric. Archaeol.* **1990**.
65. Görcelioğlu, E. Historical Weirs in Belgrad Forest. *J. Fac. For. Istanb. Univ.* **1985**, 42–59. (In Turkish) [CrossRef]
66. İpek, Ö.; Sökmen, E. Örükaya Archaeological Excavation and Research Project: 2017 Work Report. In Proceedings of the 40th Excavation Results Meeting, Çanakkale, Turkey, 7–11 May 2018; Volume 3, pp. 225–238. Available online: https://kvmgm.ktb.gov.tr/Eklenti/63785,40kazi3pdf.pdf?0 (accessed on 25 July 2023). (In Turkish).
67. Rheidt, K. *Aizanoi, Çavdarhisar Guide*; Ankara, Turkey, 1998; pp. 3–28.
68. Özer, E.; Özcan, S. Archaeological and Restoration Work at Aizanoi Ancient City Penkalas Creek. *Art-Sanat J.* **2022**, 295–318. (In Turkish) [CrossRef]

69. Bildirici, M. Historical Irrigation, Water Storage, and Flood Protection Facilities. Ministry of Environment and Forestry, State Hydraulic Works Directorate General, Ankara. 2009. Available online: https://cdniys.tarimorman.gov.tr/api/File/GetFile/425/KonuIcerik/767/1115/DosyaGaleri/tarihi-sulama-su-depolama-ta%C5%9Fkin-koruma-tesisleri.pdf (accessed on 25 July 2023). (In Turkish)
70. Ozis, U. Historical water schemes in Turkey. *Int. J. Water Resour. Dev.* **1996**, *12*, 347–384. [CrossRef]
71. Çeçen, K. DSI Conference on the Development of Water and Soil Resources/Session on Historical Water Structures in Anatolia, 12–14 April 1994, Ankara/Proceedings Book 1994; Volume 1, pp. 11–22.
72. Shaw, J.; Sutcliffe, J. Ancient dams, settlement archaeology and Buddhist propagation in central India: The hydrological background. *Hydrol. Sci. J.* **2003**, *48*, 277–291. [CrossRef]
73. Parker, H. *Ancient Ceylon. Repr. 1981*; Asian Educational Services: New Delhi, India, 1909; ISBN 81-206-0208-0.
74. Shaw, J.; Sutcliffe, J. Ancient irrigation works in the Sanchi area: An archaeological and hydrological investigation. *S. Asian Stud.* **2001**, *17*, 55–75. [CrossRef]
75. Beach, T.; Dunning, N. An ancient Maya reservoir and dam at Tamarindito, el Peten, Guatemala. *Lat. Am. Antiq.* **1997**, *8*, 20–29. [CrossRef]
76. Angelakis, A.N.; Capodaglio, A.G.; Valipour, M.; Krasilnikoff, J.; Ahmed, A.T.; Mandi, L.; Tzanakakis, V.A.; Baba, A.; Kumar, R.; Zheng, X. Evolution of Floods: From Ancient Times to the Present Times (ca 7600 BC to the Present) and the Future. *Land* **2023**, *12*, 1211. [CrossRef]
77. Öziş, Ü. Ancient Water Works in Anatolia. *Int. J. Water Resour. Dev.* **1987**, *3*, 55–62. [CrossRef]
78. Arif, A.Ş.; Keçeci, N. Investigation of Water Dams Built in Istanbul during the Ottoman State Period. *Online J. Art Des.* **2021**, *9*.
79. Güngör, S.S. Ottoman Hydraulic Architecture and Ottoman Water Structures in the 19th Century. *Turk. Hydraul. J.* **2021**, *5*, 32–48. Available online: https://dergipark.org.tr/tr/pub/turhidder/issue/61342/912922 (accessed on 25 July 2023).
80. Döring, M. Energieerzeugung Unter Tage–Die Reichenbach-Jordan'schen Wassersäulenmaschinen. In *UNESCO-Weltkulturerbe Oberharzer Wasserwirtschaft*; Schriften der DWhG 19; Ohlig, C., Ed.; Siegburg, Germany, 2012; pp. 39–59, ISBN 978-3-8482-0803-6.
81. Roseneck, R. Die Oberharzer Wasserwirtschaft als UNESCO-Weltkulturerbe. In *UNESCO-Weltkulturerbe Oberharzer Wasserwirtschaft*; Schriften der DWhG. 19; Ohlig, C., Ed.; Siegburg, Germany, 2012; pp. 1–21, ISBN 978-3-8482-0803-6.
82. OECD. *Multi-Purpose Water Infrastructure Policy: Perspectives Recom-Mendations to Maximize Economic Benefits*; OECD: Paris, France, 2017. Available online: https://www.oecd.org/env/outreach/MPWI_Perspectives_Final_WEB.pdf (accessed on 25 July 2023).
83. Rehman, S.; Al-Hadhrami, L.M.; Alam, M.M. Pumped hydro energy storage system: A technological review. *Renew. Sustain. Energy Rev.* **2015**, *44*, 586–598. [CrossRef]
84. Koutsoyiannis, D. Past and modern water problems: Progress or regression? In *IWA Regional Symposium on Water*; International Water Association: London, UK, 2014.
85. Fragkos, E. The Mesochora Dam. European Parliament, Brussels, Belgium, Retrieved 24 October 2022. 2022. Available online: https://www.europarl.europa.eu/doceo/document/E-9-2022-003391_EN.html (accessed on 25 July 2023).
86. Christofides, A.; Efstratiadis, A.; Koutsoyiannis, D.; Sargentis, G.-F.; Hadjibiros, K. Resolving conflicting objectives in the management of the Plastiras Lake: Can we quantify beauty? *Hydrol. Earth Syst. Sci.* **2005**, *9*, 507–515. [CrossRef]
87. Anonymous. Kremasta (lake). Wikipedia. 2023. Available online: https://en.wikipedia.org/wiki/Kremasta_(lake) (accessed on 25 July 2023).
88. Manariotis, I.D.; Yannopoulos, P.C. Adverse effects on Alfeios River Basin and an integrated management framework based on sustainability. *Environ. Manag.* **2004**, *34*, 261–269. [CrossRef]
89. Tsatsanifos, C.; Mihalis, I. Tunnelling in Greece: Past, Present, and Future. In Proceedings of the 2nd Eastern European Tunnelling Conference, Athens, Greece, 28 September–1 October 2014.
90. Wessels, J.I.; Vardakos, S.; Weingartner, H.; Eslamian, S.; Angelakis, A.N. Underground aqueducts: Past, present, and future trends. In *Underground Aqueducts Handbook*; CRC Press: Boca Raton, FL, USA, 2016; pp. 491–509.
91. Grandori, R.; Jaeger, M.; Antonini, F.; Vigl, L. Evinos-Mornos Tunnel-Greece. Construction of a 30 km long hydraulic tunnel in less than three years under the most adverse geological conditions. In Proceedings of the RECT, San Francisco, Society for Mining, Metallurgy, and Exploration 1995; pp. 747–767.
92. Jackson, D.C.; Brown, J.G. Dam Engineering. Encyclopedia Britannia. 2003. Available online: https://www.britannica.com/topic/Three-Gorges-Dam/History-and-controversy-of-the-Three-Gorges-Dam (accessed on 25 July 2023).
93. Angelakis, A.N. About Dams: Past, Present and Future. PATRIS of Irakli-on, Greece 15 October 2015. 2015. Available online: https://archive.patris.gr/articles/289182 (accessed on 24 June 2024). (In Greek).
94. Xinhua, Y. Three Gorges Hydropower Station Hits World Record of Electricity Generation. 2021. Available online: http://www.xinhuanet.com/english/2021-01/05/c_139642485.htm (accessed on 25 July 2023).
95. DSİ. Soil and Water Resources. General Directorate of State Hydraulic Works (DSİ). 2023. Available online: https://www.dsi.gov.tr/sayfa/detay/754# (accessed on 25 July 2023). (In Turkish)
96. Yiğitbaşıoğlu, H. Dams in Turkey. *J. Turk. Geogr. Res. Appl. Cent.* **1996**, *5*, 171–181. Available online: http://tucaum.ankara.edu.tr/wp-content/uploads/sites/280/2015/08/tucaum5_7.pdf (accessed on 25 July 2023). (In Turkish).
97. Erdoğan, G. Dams in Turkey. Data source: Netdata. 2023. Available online: https://www.netdata.com/member/project/91e87094#selectoptions (accessed on 25 July 2023).

98. Karabatan, Y. The Importance of Water and Soil Resources and Applied Strategy-Water Structures, Dams. Türkiye Mühendislik Haberleri Dergisi, Issue: 442-443/51-200672-3, 2006; pp. 90–115. Available online: https://eski.imo.org.tr/resimler/dosya_ekler/be9fde963dd860b_ek.pdf?dergi=154 (accessed on 25 July 2023). (In Turkish).
99. Özgen, Y.; Büyüktolu, R. The First Dam of the Republic: Çubuk Dam (1929–1936). *J. Atatürk Yolu* **2016**, *15*. (In Turkish) [CrossRef]
100. Öztekin Eke, D. The Status of the Cultural Heritage Under Dam Lakes and Protection of This Cultural Heritage. Master's Thesis, İstanbul University, Institute of Social Sciences, Department of Conservation and Restoration of Movable Cultural Heritage, Istanbul, Turkey, 2014. Available online: https://acikbilim.yok.gov.tr/handle/20.500.12812/174955 (accessed on 25 July 2023).
101. Polatoğlu, M.G. The First Dam Built within the Scope of the Water Case in The Early Republican Period: Çubuk Dam. *J. Atatürk Yolu* **2019**, 343–380. Available online: https://dergipark.org.tr/tr/pub/ankuayd/issue/51828/675142 (accessed on 25 July 2023). (In Turkish).
102. Ertunç, A. The Geological Problems of the Large Dams Constructed on the Euphrates River (Turkey). *Eng. Geol.* **1999**, *51*, 167–182. [CrossRef]
103. Şehitoğlu, N. Geomorphological and Hydrogeological Observations in the Vi-cinity of the Atatürk Dam. *J. Türk Coğrafya* **1994**, 495–513. Available online: https://dergipark.org.tr/tr/pub/tcd/issue/21258/228186 (accessed on 25 July 2023). (In Turkish).
104. ŞGDWSA. Atatürk Dam. Şanlıurfa General Directorate of Water and Sewerage Administration (ŞGDWSA). 2023. Available online: https://www.suski.gov.tr/icerik/39/75/ataturk-baraji#:~:text=Nehir%20seviyesinden%20y%C3%BCksek-lik%20bak%C4%B1m%C4%B1ndan%20minimum,Eni%20ise%2015%20m%20dir.&text=2400%20MW%20g%C3%BCc%C3%BCyle%20y%C4%B1ll%C4%B1k%208%20900%20GW%20elektrik%20enerjisi%20%C3%BCretim%20kapasitesine%20sahiptir (accessed on 25 July 2023). (In Turkish)
105. Çakırtaş, Ş. A Transformation Story: Tigris-Euphrates. Indyturk.com. Re-trieved 18 May 2021. 2021. Available online: https://www.indyturk.com/node/360836/t%C3%BCrki%C3%A7eden-sesler/bir-ba%C5%9Fkala%C5%9Fma-hikayesi-dicle-f%C4%B1rat-4 (accessed on 25 July 2023). (In Turkish).
106. Yıldırım, A. Karakaya Dam and Its Effects on the Natural Environment. Dicle University. *J. Ziya Gökalp Educ. Fac.* **2006**, 32–39. Available online: https://dergipark.org.tr/tr/pub/zgefd/issue/47964/606855 (accessed on 25 July 2023). (In Turkish).
107. Platform, E.T. Active Capacity. Data Source: DSI. 2023. Available online: https://seffaflik.epias.com.tr/transparency/barajlar/aktif-doluluk.xhtml (accessed on 25 July 2023).
108. Turfan, M. Atatürk Dam and Hydroelectric Power Plant. *J. Türkiye Mühendislik Haberleri* **1981**, *297*, 3–15. Available online: https://www.imo.org.tr/eklenti/3297,3408pdf.pdf?0 (accessed on 25 July 2023). (In Turkish).
109. Ultraenerji. Atatürk Dam and Hydroelectric Power Plant. Retrieved 31 January 2014. 2014. Available online: https://www.ultraenerji.com/hidroelektrik/hidroelektrik-santraller/ataturk-baraji-ve-hidroelektrik-santrali.html (accessed on 25 July 2023). (In Turkish).
110. Özdemir, M.A.; Özgen, N. Water Leaks from Keban Dam and Its Natural Potential. *Afyon Kocatepe Univ. J. Soc. Sci.* **2004**, *6*, 65–85. (In Turkish)
111. Güner, B. Culture Fisheries in Lake Keban. *Fırat Univ. J. Soc. Sci.* **2016**, *25*. (In Turkish) [CrossRef]
112. Akbay, N.; Anul, N.; Yerli, S.; Soyupak, S.; Yurteri, C. Seasonal distribution of large phytoplankton in the Keban Dam Reservoir. *J. Plankton Res.* **1999**, *21*, 771–787. [CrossRef]
113. Alpaslan, K.; Sesli, A.; Tepe, R.; Özbey, N.; Birici, N.; Şeker, T.; Koçer, M.A.T. Vertical and seasonal changes of water quality in Keban Dam Reservoir. *J. Fish. Sci.* **2012**, *6*, 252–262. [CrossRef]
114. Gülşen, K. The influence of dams on surrounding climate: The case of Keban Dam. *Gaziantep Univ. J. Soc. Sci.* **2016**, *15*, 193–204. [CrossRef]
115. EÜAŞ. Keban HEPP. The Electricity Generation Corporation (EÜAŞ). 2023. Available online: https://www.euas.gov.tr/en-us/power-plants/keban-hepp (accessed on 25 July 2023).
116. Aydin, M.C.; Ulu, A.E.; Karaduman, Ç. CFD analysis of Ilısu Dam sluice outlet. *Turk. J. Sci. Technol.* **2018**, *13*, 119–124.
117. EÜAŞ. Ilısu HES. The Electricity Generation Corporation (EÜAŞ). 2023. Available online: https://www.euas.gov.tr/santraller/ilisu-hes (accessed on 25 July 2023). (In Turkish)
118. DSİ. The Longest Dam in The World, Ilısu, was Opened with a 2 Thousand Meters Ribbon. General Directorate of State Hydraulic Works (DSİ). 2021. Available online: https://dsi.gov.tr/Haber/Detay/4170 (accessed on 25 July 2023). (In Turkish)
119. Ertunç, A.; Çetin, H. Dam Projects Affected by Landslides on the Çoruh River, Turkey. *Bull. Eng. Geol. Environ.* **2007**, *66*, 335–343. [CrossRef]
120. DSİ. Yusufeli Dam and Hepp Project. General Directorate of State Hydrau-lic Works (DSİ). 2022. Available online: https://bolge26.dsi.gov.tr/haber/detay/2352 (accessed on 25 July 2023). (In Turkish)
121. Apaydın, A. Applicability of Underground Dams in Turkey and Evaluation of the Underground Dams Action Plan. *Konya J. Eng. Sci.* **2022**, *10*, 130–146. (In Turkish) [CrossRef]
122. Schamp, H. Sadd el-Ali, der Hochdamm von Assuan (Sadd el-Ali, the High Dam of Aswan). *Geowiss. Unserer Zeit* **1983**, *1*, 51–85. (In Germany)
123. Willcocks, W.; Craig, J.I. *Egyptian Irrigation*; E. & F. N. Spon: London, UK, 1913.
124. Cairo, G.E. Rehabilitation of Hydropower Plants in Aswan–Securing an Important Renewable Energy Resource. 2022. Available online: http://kairo.diplo.de/eg-de/aktuelles/-/2523132 (accessed on 25 July 2023).

125. Çeçen, K. *Sinan's Water Supply System in İstanbul*; Istanbul Water and Sewerage Administration, General Directorate: İstanbul, Turkey, 1992; p. 218.
126. Elba, E.; Urban, B.; Ettmer, B.; Farghaly, D. Mitigating the impact of climate change by reducing evaporation losses: Sediment removal from the High Aswan Dam reservoir. *Am. J. Clim. Chang.* **2017**, *6*, 230. [CrossRef]
127. Chen, J.; Shi, H.; Sivakumar, B.; Peart, M.R. Population, water, food, energy and dams. *Renew. Sustain. Energy Rev.* **2016**, *56*, 18–28. [CrossRef]
128. Dorcey, A.H. *Large Dams: Learning from the Past Looking at the Future: Workshop Proceedings, Gland, Switzerland, 11–12 April 1997*; World Bank Publications: Gland, Switzerland, 1997.
129. Rippl, W. The capacity of storage-reservoirs for water-slpply.(including plate). In *Minutes of the Proceedings of the Institution of Civil Engineers*; Thomas Telford-ICE Virtual Library, 1883; pp. 270–278.
130. Loucks, D.P.; Van Beek, E. *Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications*; Springer: Berlin/Heidelberg, Germany, 2017.
131. Alrayess, H.; Ülke, A.; Gharbia, S. Comparison of Different Techniques about Reservoir Capacity Calculation at Sami Soydam Sandalcık Dam. *Celal Bayar Univ. J. Sci.* **2018**, *14*, 23–29. [CrossRef]
132. Hall, W.A.; Buras, N. The dynamic programming approach to water-resources development. *J. Geophys. Res.* **1961**, *66*, 517–520. [CrossRef]
133. Hall, W.A.; Howell, D.T. The optimization of single-purpose reservoir design with the application of dynamic programming to synthetic hydrology samples. *J. Hydrol.* **1963**, *1*, 355–363. [CrossRef]
134. Loucks, D.P. Some comments on linear decision rules and chance constraints. *Water Resour. Res.* **1970**, *6*, 668–671. [CrossRef]
135. Nayak, S.C.; Arora, S.R. Optimal capacities for a multireservoir system using the linear decision rule. *Water Resour. Res.* **1971**, *7*, 485–498. [CrossRef]
136. Yeh, W.W.G. Reservoir management and operations models: A state-of-the-art review. *Water Resour. Res.* **1985**, *21*, 1797–1818. [CrossRef]
137. Ahmad, S.K.; Hossain, F.; Holtgrieve, G.W.; Pavelsky, T.; Galelli, S. Predicting the likely thermal impact of current and future dams around the world. *Earth's Future* **2021**, *9*, e2020EF001916. [CrossRef]
138. Boyé, H.; Vivo, M.d. The Environmental and Social Acceptability of Dams. 2016. Available online: http://journals.openedition.org/factsreports/4055 (accessed on 25 June 2024).
139. Ahmed, A.T.; Elsanabary, M.H. Hydrological and environmental impacts of grand Ethiopian renaissance dam on the Nile river. In Proceedings of the Eighteenth International Water Technology Conference, IWTC18, Sharm El Sheikh, Egypt, 12–14 March 2015; pp. 12–14.
140. Mulat, A.G.; Moges, S.A. Assessment of the impact of the Grand Ethiopian Renaissance Dam on the performance of the High Aswan Dam. *J. Water Resour. Prot.* **2014**, *2014*, 45460. [CrossRef]
141. Jalali, L.; Zarei, M.; Gutiérrez, F. Salinization of reservoirs in regions with exposed evaporites. The unique case of Upper Gotvand Dam, Iran. *Water Res.* **2019**, *157*, 587–599. [CrossRef]
142. Xenaki, K. Who Gains from Sabotage? TA NEA,"The news" Journal, 7/6/2023; Athens, Greece, 2023. (In Greek).
143. Jazeera, A. All to Know About Ukraine's Nova Kakhovka Dam Explosion. Al Jazeera News. 2023. Available online: https://www.aljazeera.com/news/2023/6/6/the-nova-kakhovka-dam-what-you-need-to-know (accessed on 6 June 2023).
144. Zhang, J.; Shang, Y. Nexus of dams, reservoirs, climate, and the environment: A systematic perspective. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 12707–12716.
145. Hassan, S.; Masood, M.U.; Haider, S.; Anjum, M.N.; Hussain, F.; Ding, Y.; Shangguan, D.; Rashid, M.; Nadeem, M.U. Investigating the effects of climate and land use changes on rawal dam reservoir operations and hydrological behavior. *Water* **2023**, *15*, 2246. [CrossRef]
146. Shi, W.; Qin, B. Sediment and nutrient trapping by river dams: A critical review based on 15-year big data. *Curr. Pollut. Rep.* **2023**, *9*, 165–173. [CrossRef]
147. Zeng, Y.; Jing, T.; Xu, B.; Yang, X.; Jian, J.; Zong, R.; Wang, B.; Dai, W.; Deng, L.; Fang, N. Vectorized dataset of silted land formed by check dams on the Chinese Loess Plateau. *Sci. Data* **2024**, *11*, 348. [CrossRef] [PubMed]
148. Wang, T.; Li, Z.; Ge, W.; Zhang, Y.; Jiao, Y.; Zhang, H.; Sun, H.; van Gelder, P. Risk assessment methods of cascade reservoir dams: A review and reflection. *Nat. Hazards* **2023**, *115*, 1601–1622. [CrossRef]
149. Qing, D.; Thibodeau, J.G.; Williams, M.R.; Dai, Q.; Yi, M.; Topping, A.R. *The River Dragon Has Come!: Three Gorges Dam and the Fate of China's Yangtze River and Its People*; Routledge: London, UK, 2016.
150. Cheng, L.; Opperman, J.J.; Tickner, D.; Speed, R.; Guo, Q.; Chen, D. Managing the Three Gorges Dam to Implement Environmental Flows in the Yangtze River. *Front. Environ. Sci.* **2018**, *6*, 64. [CrossRef]
151. Dam, T.G. Missouri Chapter American Fisheries Society. 20 April 2002. Available online: https://web.archive.org/web/20081118193954/, https://www.moafs.org/newsletter/April%202002/3gorgestats.htm (accessed on 25 June 2024).
152. Tzanakakis, V.A.; Angelakis, A.N.; Paranychianakis, N.V.; Dialynas, Y.G.; Tchobanoglous, G. Challenges and Opportunities for Sustainable Management of Water Resources in the Island of Crete, Greece. *Water* **2020**, *12*, 1538. [CrossRef]
153. Vourdoubas, J. Estimation of solar electricity generation from floating photovoltaics installed in water dams in the island of Crete, Greece. *Eur. J. Environ. Earth Sci.* **2023**, *4*, 27–33. [CrossRef]

154. Lele, S.; Del Bene, D.; Avcı, D.; Roa-Avendaño, T.; Roy, B.; Sahu, G.; Harris, M.; Moore, D. Values and knowledges in decision-making on environmentally disruptive infrastructure projects: Insights from large dams and mines. *Curr. Opin. Environ. Sustain.* **2023**, *64*, 101346. [CrossRef]
155. Haftendorn, H. Water and international conflict. *Third World Q.* **2000**, *21*, 51–68. [CrossRef]
156. Angelakis, A.N.; Valipour, M.; Ahmed, A.T.; Tzanakakis, V.; Paranychianakis, N.V.; Krasilnikoff, J.; Drusiani, R.; Mays, L.; El Gohary, F.; Koutsoyiannis, D.; et al. Water Conflicts: From Ancient to Modern Times and in the Future. *Sustainability* **2021**, *13*, 4237. [CrossRef]
157. Hariri-Ardebili, M.A.; Mahdavi, G.; Nuss, L.K.; Lall, U. The role of artificial intelligence and digital technologies in dam engineering: Narrative review and outlook. *Eng. Appl. Artif. Intell.* **2023**, *126*, 106813. [CrossRef]
158. Park, D.; You, H. A Digital Twin Dam and Watershed Management Platform. *Water* **2023**, *15*, 2106. [CrossRef]
159. Central Water Commission of Ministry of Water Resources, River Development & Ganga Rejuvenation Government of India. *Manual for Rehabilitation of Large Dams*; 2018; Chapter 1; pp. 1–4.
160. Association of State Dam Safety Officials (ASDSO). *The Cost of Rehabilitation Dams in U.S.*; ASDSO: Lexington, KY, USA, 2023.
161. France, J.; Alvi, I.; Dickson, P.; Falvey, H.; Rigbey, S.; Trojanowski, J. *Independent Forensic Team Report for Oroville Dam Spillway Incident*; Final Report; 2018.
162. Amini, R. Dez Dam Rehabilitation Project Role in Flood Damage Reduction. *E3S Web Conf.* **2022**, *346*, 02007. [CrossRef]
163. Boroujeni, H.S. Sediment Management in Hydropower Dam (Case Study–Dez Dam Project). In *Hydropower Practice and Application*; Boroujeni, H.S., Ed.; IntechOpen Limited: London, UK, 2011; pp. 115–142, ISBN 978-953-51-0164-2.
164. Delpasand, M.; Fallah-Mehdipour, E.; Azizipour, M.; Jalali, M.; Safavi, H.R.; Saghafian, B.; Loáiciga, H.A.; Babel, M.S.; Savic, D.; Bozorg-Haddad, O. Forensic engineering analysis applied to flood control. *J. Hydrol.* **2021**, *594*, 125961. [CrossRef]
165. Sepehri, M.; Soudkhah, M.; Paknejad, A. Sedimentation and Assigning of Dredger for Dez Dam Hydropower Intake. *Proc. Ninth Int. Sympo-Sium River Sediment.* **2004**, *17133*, 1023–1028. Available online: https://www.iahr.org/library/infor?pid=17133 (accessed on 24 June 2024).
166. CWC (Central Water Commission). Manual for Rehabilitation of Large Dams, Central Water Commission Central Dam Safety Organization Doc. No. CDSO_MAN_DS_02_v1.0. 2017. Available online: https://damsafety.cwc.gov.in/ecm-includes/PDFs/Manual_for_Rehabilitation_of_Large_Dams.pdf (accessed on 24 June 2024).
167. WB. The World Bank. The Kariba Dam Rehabilitation Project: Fact Sheet. 2014. Available online: https://documents1.worldbank.org/curated/en/312711468191648859/pdf/PAD9070P146515010Box385378B00OUO090.pdft (accessed on 24 June 2024).
168. Parent, J.R.; Gold, A.J.; Vogler, E.; Lowder, K.A. Guiding decisions on the future of dams: A GIS database characterizing ecological and social considerations of Dam decisions. *J. Environ. Manag.* **2024**, *351*, 119683. [CrossRef]
169. Cavuslu, M.; Inyurt, S. Determination of future creep and seismic behaviors of dams using 3D analyses validated by long-term levelling measurements. *J. Civ. Struct. Health Monit.* **2024**, *14*, 1505–1532. [CrossRef]
170. Chen, D.; Huang, B.; Kang, F. A Review of Detection Technologies for Underwater Cracks on Concrete Dam Surfaces. *Appl. Sci.* **2023**, *13*, 3564. [CrossRef]
171. Angelakis, A.N. Το Ενεργειακό πρόβλημα της Ελλάδος. PATRIS, Iraklion, Crete, Greece, 16 November 2022. 2022. Available online: https://www.patris.gr/2022/11/16/to-energeiako-provlima-tis-elladas/ (accessed on 24 June 2024).
172. Zafarnejad, F. The contribution of dams to Iran's desertification. *Int. J. Environ. Stud.* **2009**, *66*, 327–341. [CrossRef]
173. Papadaki, C.; Soulis, K.; Ntoanidis, L.; Zogaris, S.; Dercas, N.; Dimitriou, E. Comparative assessment of environmental flow estimation methods in a Mediterranean mountain river. *Environ. Manag.* **2017**, *60*, 280–292. [CrossRef] [PubMed]