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Review

A Comprehensive Review of the Potential of Stepwells as Sustainable Water Management Structures

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Abstract: Throughout history, many water conservation and management strategies have been employed, but only a few have proved successful. Stepwells were one such effective water management technologies used in India. Stepwells were constructed based on their geographical and topographical suitability, which revealed socio-cultural behaviors and beliefs. They form a unique, efficient system of hydraulic engineering that demonstrates the region's traditional understanding of the sustainable use and management of its land, water, and agricultural biodiversity. Ancient water harvesting techniques integrated stepwells into agricultural and irrigation networks using prefabricated structures, to allow open channel flow, networked with surface water bodies. They demonstrated the use of Persian wheels, non-mechanized farm machinery, other agricultural implements, etc., and their structure utilized a vast array of local building materials, including granite, marble, sandstone, bricks, lime, mud, wood, etc. The utilization of agricultural wastes, such as rice husk, in the production of lakhori bricks is strongly associated with circular economy principles. They not only communicated and guided communities regarding water management and cleaner production, but also revealed historic knowledge regarding how ancient societies achieved social-ecological resilience. In addition to that, in almost all types of stepwells, aesthetics and ornamentation played an important role and served as a rich source of history to disseminate knowledge of governance, political ideas, social practices and lifestyle. Just a few studies on these stepwells have been published and they have generally focused on their history or on the construction materials of a specific stepwell, rather than offering a wide perspective. This review article will explore the scientific, architectural, artistic, and functional dimensions of all major stepwells in India that have either disappeared or lost their relevance owing to expanding human population and environmental stress. Additionally, this will provide an opportunity to rethink modern water engineering systems and redesign water infrastructure with less negative environmental impacts to achieve the Sustainable Development Goals and ensure water for all.

Keywords: cultural heritage; ancient water conservation practices; sustainable consumption; underground water structures; integrated water management; India

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Citation: Selvaraj, T.; Devadas, P.; Perumal, J.L.; Zabaniotou, A.; Ganesapillai, M. A Comprehensive Review of the Potential of Stepwells as Sustainable Water Management Structures. *Water* **2022**, *14*, 2665. https://doi.org/10.3390/w14172665

Academic Editor: Adriana Bruggeman

Received: 9 May 2022
Accepted: 12 July 2022
Published: 29 August 2022

1. Introduction

Water, a finite and vulnerable resource, is the basis for all livelihoods, development, and the environment [1]. Water is a vital element in the evolution of large cities and the development of communities with roots in tradition, local knowledge, and culture. This is evident since most of the primordial civilization flourished around rivers and major waterways [2]. In today's world, water is a major constraint for both agricultural production and the income of rural poor populations [3,4]. Poverty reduction, food security, job creation, and GDP growth thrive primarily on water [5], which plays an important role in the world economy and sustainable development [6]. The sustainable management of this elixir of life will affect the attainment of SDG6 and other sustainable development goals, because water resources help to strike a sustainable balance between the social, economic, and ecological needs of the entire human race, the population of which is increasing world-wide.

Therefore, water management is one of the most important environmental practices for a healthy life and for global well-being [7]. Water management includes the conservation of water and the re-use of wastewater, which are two different, but intertwined, strategies. Although water conservation focuses on demand, the goal of wastewater reuse and recycling is to reduce this demand by closing the water loop and encouraging circularity in the flow of wastewater from the built to the natural environment [8].

It is important and essential to use water sustainably. Efficient systems for harnessing and collecting water have been in place since pre-historic times. Early civilizations were built on complex systems of water management and hydraulic engineering. Among the various technologies developed for water storage and re-use during the Bronze Age, very few were methodological. These few included qanats, aqueducts, canals, cisterns, deep wells, fountains, gutters, pipe ducts, water terraces, tunnels, sedimentation ponds, etc. [9]. With the aggravating water crisis across the world, new and exorbitant technologies have replaced traditional systems. During ancient Indian times, societies were affected by extreme droughts, forcing India to embark on a water-stressed future that led to construction of various stepwells. Before the existence of modern infrastructure marvels, these old buildings and well-tested water management practices were the strong support systems. This resilient water infrastructure is a hydro-supportive form of water management that aims to manage water systems so as to contribute to a more sustainable organization of human society and its activities.

Climate change is altering our environment and societies world-wide and in order to face it many adaption strategies in specific water management strategies are becoming especially important. By understanding how old civilizations were built on complex systems of water management and hydraulic engineering, systems in today's water-stressed regions of the world can be designed to be more sustainable and resilient by integrating traditional knowledge into modern times for current needs [10–12].

This study aims to provide a comprehensive overview of the various water conservation and management practices that are elements of Indian stepwells and to discuss their relevance to modern times. The objective for reviewing the ancient water harvesting strategies is to offer evidence of potential short- and long-term impacts that their re-implementation can have on the environment and local societies. It will provide engineers and planners with useful indigenous knowledge about the technical aspects of those systems, construction, site selection, shapes, and sizes. The technical features and their significance in architecture and aesthetics were also investigated as the essential feature of cultural heritage. The study will provide an opportunity to re-think modern water engineered systems and redesign water systems according to the new societal needs and sustainable development, with less detrimental effects on the environment and ensuring access to water and sanitation for all.

Stepwells have not only existed for centuries but have also met local needs without causing degradation to the environment [13]. Unlike many advanced technologies that exploit the ecosystem, stepwells emphasize conservation. These systems made use of misbegotten and yet simple technology that locals could easily maintain. These bigger structures are also significant because they have kept communities alive during prolonged times of drought or famine. Hence, archaeological knowledge on ancient sustainability and water management through stepwells can contribute to unique and long-lasting solutions for the future. The attempt at a recompilation and classification of stepwells in this review aims to be useful in the selection of not only the most discussed stepwells but also others. It also aims to be taken as the starting point for a deep study on their material, aesthetics, architecture, and other technical aspects, aiding in innovation for the current context of water conservation and water management decisions. The sustainability of stepwell structures is correlated to sound construction and maintenance. Several insights can be gained from the assessment of ancient hydraulic works, especially now as, largely due to climate change and over-exploitation of water resources, many hydrogeological crises have occurred [14].

2. Ancient Water Management Practices

Throughout history, many communities have developed their own culture tied to nature and the local landscapes. Ancient civilizations were dependent upon systems of water management [15]. The ability of ancient societies to harness the power of water facilitated the rise of agriculture and then the rise of urban centers. Without water management, ancient settlements and modern societies may never have emerged because the 'domestication' of water marked a crucial turning point in the world's cultural trajectory [16].

A significant influence on early society was the regulation and effective management of water [17]. The first application of water management culminated in the creation of the world's first civilization in Mesopotamia. The first agricultural civilizations were also dependent on the prediction of seasonal rains, requiring the development of accurate calendars and astronomical records. Under Babylonian rule, an extensive water system provided both private showers and toilets, while an advanced drainage system was used by administrative buildings under the palace complex to dispose of animal sacrifice waste [18].

Water wells were the initial systems that allowed drylands to be separated from natural perennial surface water sources [19]. The Persians, around 800 BCE, developed a technique for groundwater exploration called the Qanat in the form of man-made underground water channels [20]. Qanats are vast underground conduits or tunnels that access the upslope aquifer. In the Middle East, North Africa, Afghanistan, Spain, Morocco, India, Japan, and Egypt. Most qanats are dug where there is no water on the surface by a series of shafts (Figure 1) that are abundant even today [21–26]. They usually direct the groundwater to a reservoir that is often connected to the tunnel exit by a lined canal.

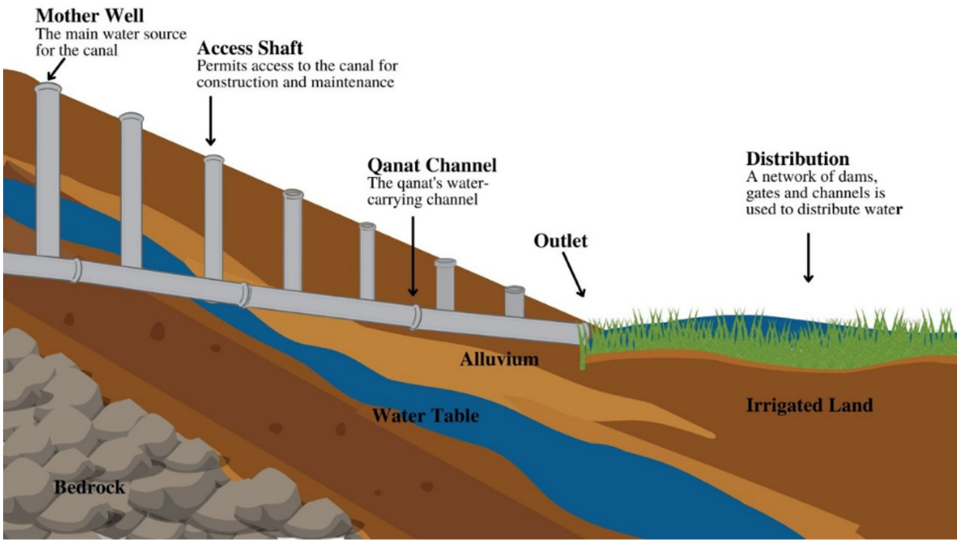

Figure 1. Design of a typical Qanat, the Persian underground irrigation canals.

The ancient Egyptians mastered sinking shafts (Figure 2a) and tapped the water after exploring these natural underground catchment areas. More than 2000 tons of fresh water were pumped daily from around 3000 of those galleries located between Alexandria and Sallum in Egypt [27].

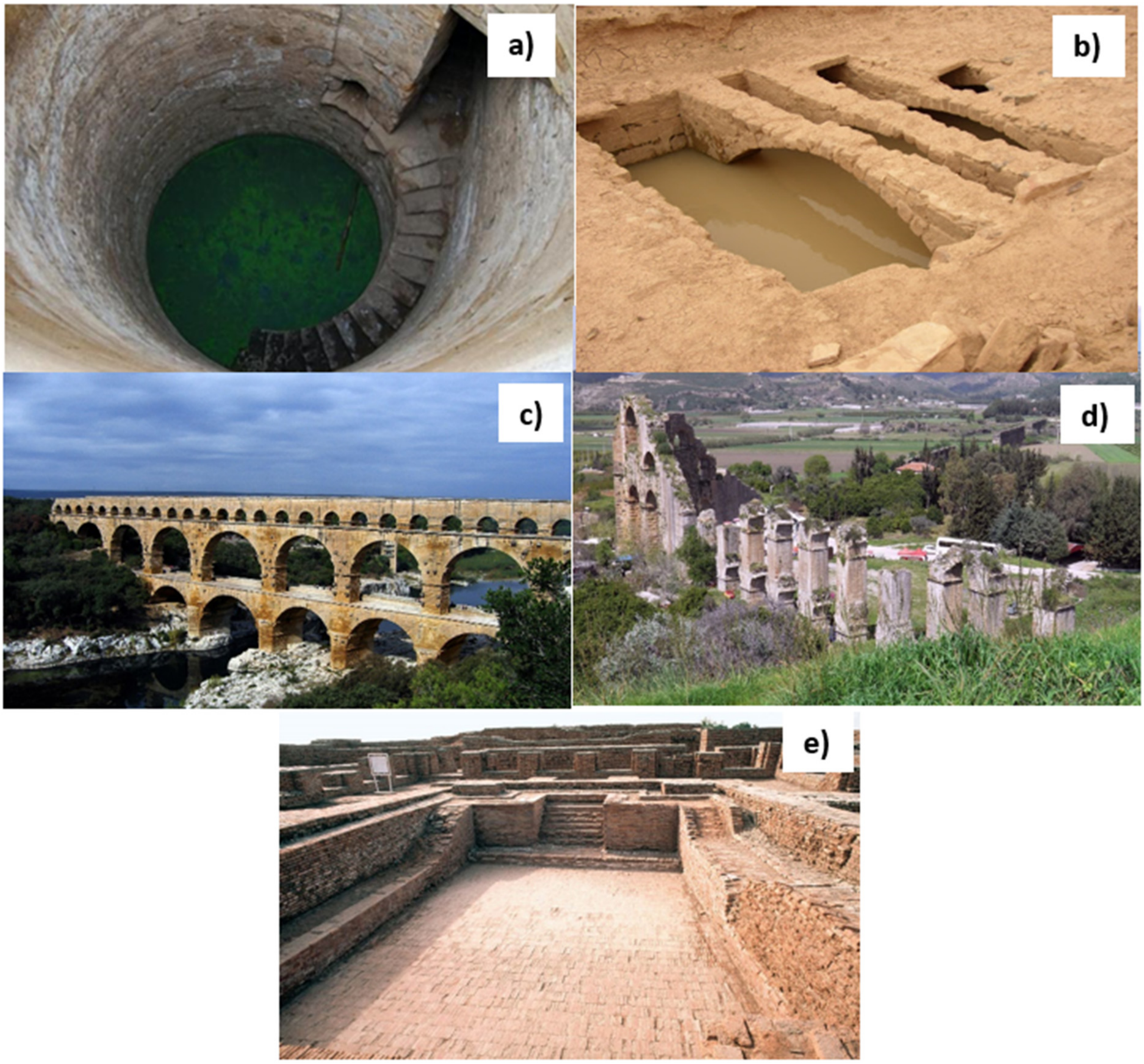

Figure 2. (**a**) Sinking shafts, Egypt (Claudio Caridi/Adobe stock); (**b**) cisterns, Jordan https://brewminate.com/controlling-the-municipal-water-supply-in-the-ancient-graeco-roman-world/, accessed on 20 July 2022; (**c**) aqueducts, Rome https://wallpapic.com/bridge-pont-du-gard-arch-vers/0xfGzO, accessed on 20 July 2022; (**d**) inverted siphons, Ancient Rome https://followinghadrian.com/2013/04/17/exploring-aspendos-images-from-a-wealthy-city-of-pamphylia/, accessed on 20 July 2022; and (**e**) great bath, Indus Valley Civilization https://delphipages.live/id/geografi-perjalanan/tempat-tempat-bersejarah/great-bath-mohenjo-daro, accessed on 20 July 2022.

In the ancient city of Petra, Jordan, which has scarce rainfall and spring water resources along with mountainous terrain, the Nabataeans, on the other side of the Red Sea, required a distinctive way of thinking to implement water technologies [28]. They built dams, partition walls, water terraces, and dug cisterns to stash water. They used numerous types of cisterns, depicted in Figure 2b, made from rocks and waterproofed by chalk. Besides, the rock-cut settlement basins, constructed along the gravity flow channel between the entrance to the treasury, were used to collect precipitates of lime and sediments from these waters [29]. The uniqueness of this system is that they used every slope and surface as a means of collecting and storing rainfall.

The variations between the ancient Greek civilization and the earlier civilizations of Mesopotamia and Egypt relate to water infrastructure [30]. Although Mesopotamia and Egypt depended on the extraction of water from large rivers, due to the lack of large rivers, developments in Greece were characterized by small natural water supplies [31]. In ancient Greece, the evolution of urban water management, beginning in Crete during the Early Minoan period (about 3500–2150 BCE), led to several remarkable developments. Implementing hygienic living standards, hydraulic technology for water transport, buildings for flood and sediment control, and sustainable urban water management practices have been important innovations, comparable with current practices [32]. To deal with the challenges of the construction of the canals, dams, and dikes that regulated the flow of water, mathematical concepts, especially geometry, were developed [33]. A variety of advanced technologies, including wells, cisterns, gutters, fountains, canals, sedimentation tanks, and aqueducts, were used by the Greeks to gather rainfall for water sources. Literature mentions the presence of aqueducts, probably pressurized from terracotta pipes, which crossed a bridge over a small stream, carrying water from a perennial spring on Gypsadhes hill. The aqueducts, cisterns, and wells were similar to those of the Minoans and Mycenaeans during the archaic (750–480 BCE) and classical (480–323 BCE) periods of Greek civilization. Minoan engineers had a practical knowledge of the basic hydraulic principles, as seen by these findings, which allowed them to distribute water from relatively large distances in the mountainous terrain and to ensure efficient use of local materials. The progress of urban water technology and management is illustrated in the extraordinary example of the water supply system of ancient Samos, revered both in ancient and modern times [34].

Romans are renowned for their engineering marvels. They developed extensive systems of aqueducts and inverted siphons (Figure 2c,d), to transport clean water from distant sources to their cities and provided the crowded urban population with relatively safe and potable water. The roman aqua canals allowed hundreds of kilometers of water transportation throughout the valleys. This water presence harbored and nurtured an engineering culture in the form of devices that used water, especially in aqueducts, latrines, fountains, watermills, baths, sewer systems, and so on [35].

In the Indian subcontinent, the history of the use and exploitation of water resources in the Indus valley civilization parallels the pattern of human use and living [36]. Around 5000 years ago, the Indus civilization, with 35,000 to 40,000 inhabitants, flourished in the basin of the Indus River. They used water effectively to drink, irrigate, and sanitize their neighborhoods to be more resilient to natural disasters and to raise living standards [37]. Harappans (Pakistan) developed effective water management, recycling, and storage program. The great bath at Moen-Jo-Daro, shown in Figure 2e, is also evidence of the water conservation and storage system in ancient India [38]. This sophisticated hydraulic engineering and other state-of-the-art innovations were implemented in the desert environment in an eloquent way [15]. Their hydraulic expertise was evident through the different types of cisterns, reservoirs, tanks, and wells they installed, including a rooftop collection system [39]. Besides their expertise of hydrology, they were pioneers in the selection of materials for the construction of wells that lasted for centuries, overcoming all natural disasters. Therefore, the water sciences in ancient India were well established [40]. The knowledge of hydrology was widespread starting with the days of the pre-Indus Valley Civilization, and are discussed in detail in Vedas, Puranas, and in many other popular ancient scripts [41]. From all of these practices, the simplest and most commonly followed method for water supply was water wells. The design of a new form of well, known as a stepwell, followed a similar approach. Stepwells are a distinctive type of underground reservoir and water storage system of the Indian subcontinent [42]. While normal wells had a deep hole, stepwells had a flight of stairs designed to reach the water table. A thorough review of major stepwells located across the country and constructed under different dynasties is listed in Table 1.

Table 1. List of Major stepwells in India constructed under different Dynasties.

Sl.	Stepwell	Region	Dynasty/Community	Completed Construction or Available Detail	References
1.	Rajan-ki-Baoli	New Delhi	Lodi dynasty	1506 CE	[43]
2.	Rani ki Vav	Gujarat	Chaulukya dynasty, Rani Udayamati	1063 CE	[44]
3.	Bara Imambara	Lucknow	Asaf-ud-Daula, Nawab of Awadh	1791	[45]
4.	Chandinath Mahadev	Rajasthan	Jagraraja	9th century	[46]
5.	Mukhed	Maharashtra	Chalukyas dynasty	12th century	[47]
6.	Hampi Stepwell/Pushkarini	Karnataka	Vijayanagar Empire	1340 to 1565	
7.	Jalore fort	Rajasthan	Paramaras	850–950 CE	[48]
8.	Adalaj	Gujarat	Queen Rudadevi	1498	[49]
9.	Navghan Kuvo	Gujarat	Chudasama king	2–5th century	[50]
10.	Bhamaria	Gujarat	Sultan Mahmud Begada	1459–1511	[51]
11.	Meratani ki Baori	Rajasthan	Queen Meratani ji	18th century	[52]
12.	Dada Harir Ni Vav	Gujarat	Sultan Bai Harir	1498–1506 CE	[53]
13.	Wankaner	Gujarat	Maharana Raj Sahib Amar Singhji	1930s	
14.	Kalesvari ni Nal	Gujarat	Rajput rulers of Lunawada state/Solanki period	14–15th century	[54]
15.	Caumukhi	Gujarat	Semi Rajput Kathi Rulers	1000 CE	[55]
16.	Dhank	Gujarat	Hindu rulers	550–626 CE	[54]
17.	Davad ni Vav	Gujarat	Queen Hansoldevi	11–12th century	
18.	Dumral Bhargov	Gujarat	Queen Minaldevi	11th century	
19.	Esali Vav	Rajasthan	No records found	10–12th century	[46]
20.	Khirni Vav	Rajasthan	No records found	No records found	[46]
21.	Ferozepur	Haryana	No records found	No records found	[56]
22.	Tunwarji ka Jhalra	Rajasthan	Queen Jaikanwer Tanwar	1834	[56]
23.	Mahila Bag Ka Jhalra	Rajasthan	Gulabrai, Pashwan of Manharaja Bijai Singh	17th century	
24.	L-shaped Nal Baori	Rajasthan	Maharaja Takhat Singh	1843–1873	
25.	Vanadhara	Rajasthan	Wealthy merchants	850–950	[46]
26.	Rajakiya Vapi	Gujarat	Maitraka King	642 CE	[57]
27.	Uvarsad	Gujarat	No records found	1669	[58]
28.	Khodiyar mata ni Vav	Gujarat	Islamic Period	1680 CE	
29.	Adi kadi Vav	Gujarat	Chudasama dynasty	15th century	[54]
30.	Mata Bhavani	Gujarat	Chaulukya dynasty	11th century	[53]
31.	Bundeli gardens	Madhya Pradesh	Chandela rulers	1298	[59]
32.	Baramotichi vihir	Maharastra	Virubai Bhosale	1641–1646	[60]
33.	Chand Baori	Rajasthan	Nikumbh Dynasty	1800 CE	[61]
34.	Jhilani	Gujarat	Hindu Rulers	600 CE	[62]
35.	Manjushri	Gujarat	Hindu Rulers	Early 7th century	
36.	Gebanshah	Gujarat	Fakir Gebanshah	16th century	[63]
37.	Helical	Gujarat	Islamic Rulers	16th century	

Hundreds of these stepwells and tanks are found in southern India, built-in Tamil Nadu before the northern parts of India. Rock built stepwells made their emergence in Tamil Nadu before the 8th century CE. Most likely, the earliest stepwells date back to around 550 CE, but the most prominent were constructed in the medieval period. However, at the later stage, stepwells became an integral part of the northwestern part of ancient India, especially in the regions of Rajasthan, Gujarat, Madhya Pradesh, and Lucknow, where water for domestic and drinking purposes was scarce [14]. It has been reported that around 3000 stepwells have been constructed in the North Indian states of Rajasthan and Gujarat to ensure water is available during times of drought [64]. Most of the stepwells are found in the states of Gujarat (Figure 3a,b), Rajasthan, and Delhi (Figure 3c) in the north-western part of India, and, in the south, Karnataka (Figure 3d). During the earliest human settlements in ancient India, the great bath, the predecessor of stepwells and similar structures, was unearthed. After this period, through to the Gupta Empire, no definite proof for stepwell structures had been discovered. The earliest known stepwell structure is dated to this period [43].

With political turmoil and external invasion, India faced many changes and chaos during the Delhi Sultanate, but this period was considered the "golden period of stepwell building" because thousands of stepwells were constructed in patronage by the rulers, merchants, and the wealthiest members of the society. Figure 4 shows the distribution of stepwells across the country and a detailed classification of stepwells is presented in Figure 5.

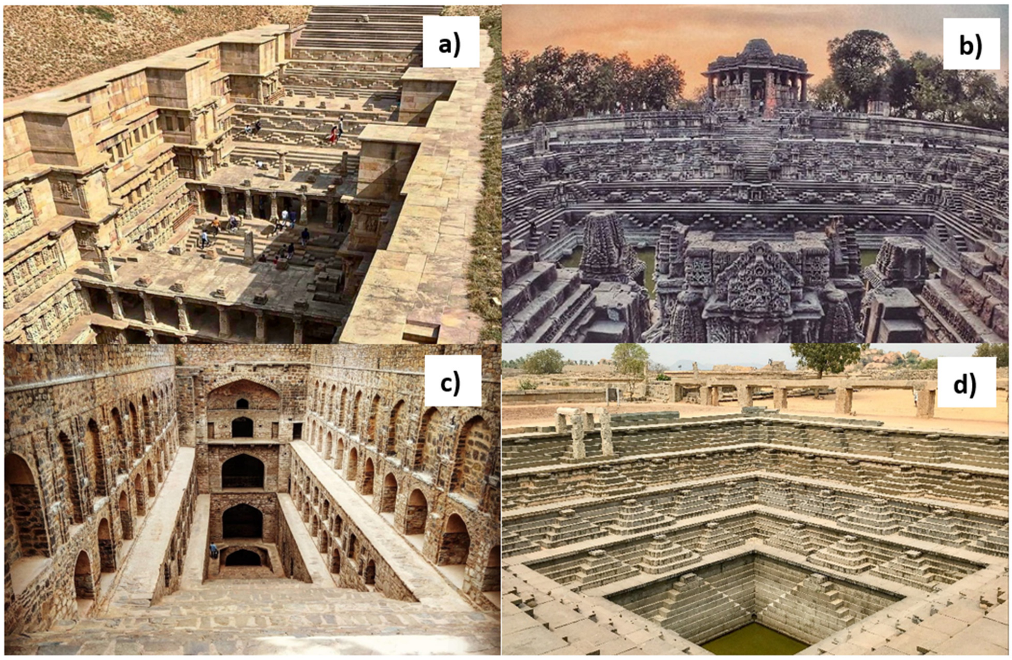

Figure 3. (**a**) Rani ki vav, Gujarat https://www.gujarattourism.com/north-zone/patan/rani-ki-vav.html, accessed on 20 July 2022; (**b**) Modhera stepwell, Sun temple, Gujarat; https://kevinstandagephotography.wordpress.com/2015/03/29/modhera-sun-temple/, accessed on 20 July 2022; (**c**) Agrasen ki baoli, New Delhi https://so.city/delhi/article/agrasen-ki-baoli, accessed on 20 July 2022; and (**d**) Hampi, Karnataka https://www.karnataka.com/hampi/pushkaranis/, accessed on 20 July 2022.

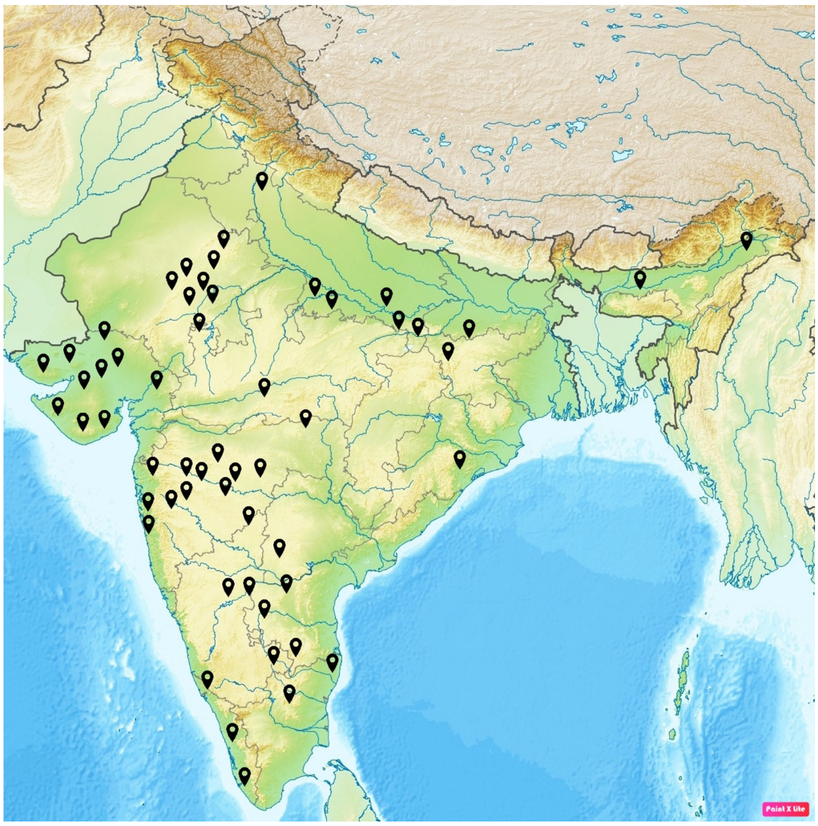

Figure 4. Distribution of stepwells across the Indian Subcontinent. White sign represents Madhya Pradesh and parts of Maharashtra. Blue sign represents Gujarat, Karnataka and Andhra Pradesh. Light Grey sign represents Jharkhand and Bihar.

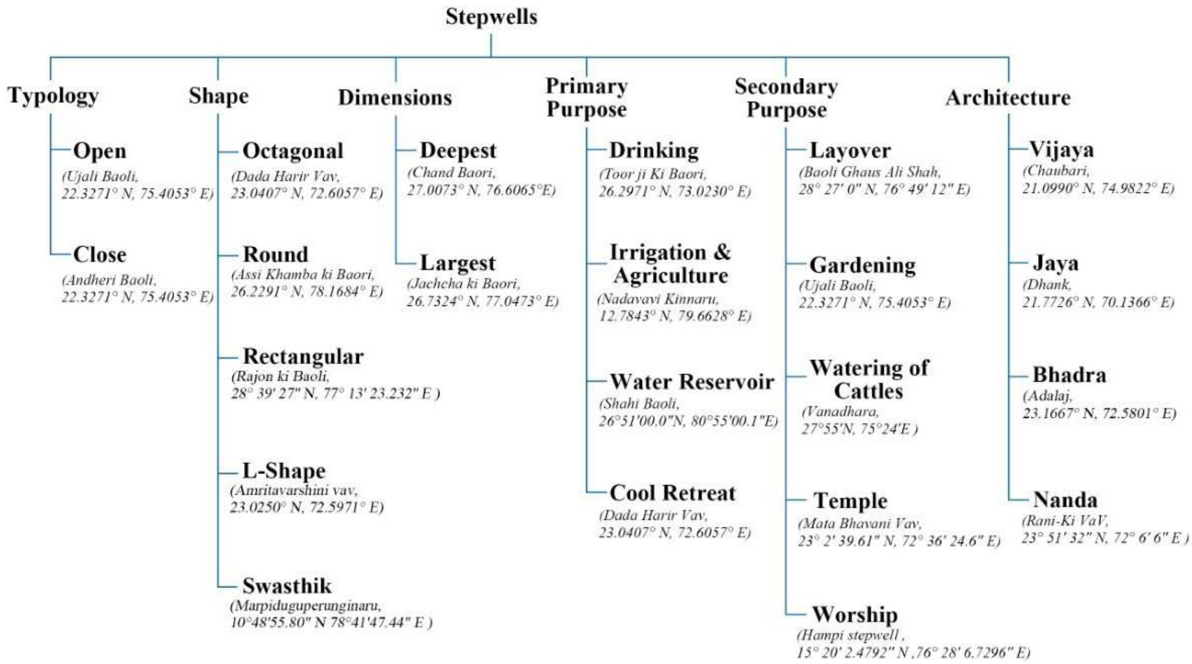

Figure 5. Broad classification of stepwells.

In the Moghul period until the 17th Century, there was a decline in such structures. When the British extended their presence in India, they stopped the new construction and use of these stepwells because they found them to be unhygienic for various domestic purposes as they draw water from public places. This wonderful architecture in India reveals various connections to human communities, the design of the building, and the natural environment, sometimes even aspects of pollution and waste management.

3. Ancient Knowledge and Wisdom in Water Conservation and Management Practices in India

The traditional wisdom regarding water has been gained from the creation of wealth and the promotion of an integrated ecosystem management [65]. Since rainfall has always been an important source of water, the use of water resources has been heavily dependent on the distribution of rainfall throughout the Indian subcontinent. Based on their requirements, the ancient Indians developed the concepts of the hydraulic cycle, precipitation rate, rainfall forecasting, groundwater source, distribution of water resources, in addition to prospecting and exploitation of the water resources [40], and demonstrated a deeper understanding of these concepts. Their main intention was to harvest and store water for sustainable future use [66].

The Indian subcontinent experiences almost six different seasons and encompasses five climatic zones. Understanding these climatic zones and seasonal variation was a prerequisite for the development of ancient methodologies of harvesting water [67]. The unreliability and the poor distribution of rainfall in these regions during the monsoon had a significant effect on the supply of water and crop yields [68].These varied climatic conditions and rainfall demonstrated different water management techniques for agricultural purposes. The customary process of this practice of water management consisted of deciding the allocation, scheduling, and increasing the efficiency of water use to various crops during an irrigation season to get maximum economic returns. However, when the quality and the quantity of the accessible water had sore constraints, this decision making was difficult. The management of these water resources to yield higher productivity even under scarce conditions was of prime consideration [69]. Thus, it became necessary to design frameworks with efforts to find an opportunity to prevent exploitation and to design a sustainable system for water management.

In the north-eastern region of the country, where the climate is cold and rainy, the *Appatani* water management system was a common practice integrated with land farming and fishing practices [70–72]. Water storage tanks were built with paddy rusk liners along the slopes of hills to avoid flooding and the accumulation of silt along with the runoff. In the southern part of the country, with a warm and humid climate, the *Surangams* (wells) were drilled along the slopes of mountain regions. These surangams were very similar to the *Qanats* of the Middle East and Mediterranean countries [73,74]. A vivid network of small tanks for the handling of surplus/deficit water was interconnected with rivers, ponds, and other water bodies, under the system named Eri (Bhattacharya, 2015). This system had additional advantages such as rainwater harvesting, artificial groundwater regeneration, soil erosion reduction during floods, etc [75,76]. Archaeological proof has shown that the rock-built stepwells during the 8th century CE in Tamil Nadu preceded the famous stepwells in North India.

Stepwells were advanced innovative constructions inherited from wells and the most common and simple method of water supply. Shreds of evidence of long, shallow sets of stairs on the shores of major rivers dating back to the first century CE throw light on early water conservation activities [77]. Stepwells comprise a central, vertical shaft with water extending to a pool with a wide mouth around which steps are built [51].They may be round, rectangular, or square and they are built with the ease or magnificence of the means at the command of the builder. The same number of underground tunnels and rooms are still in operation. The level of subterranean water depended on the depth of the steps and the inspired complex stair designs. These stepwells were the precursors of ancient and medieval clubs in India, where tourists from out-of-town could hang out, and even get water for their everyday needs.

4. Engineering Design and Technology behind Stepwells

The stepwells were architectural marvels with diverse styles, highly accomplished in form and design with pleasing aesthetics. Stepwells are perhaps the only underground heritage sites in the world, recognized in India for their building tradition and outstanding architecture [62] (Livingston and Beach, 2002). The technology of these stepwells relies on green building materials and sustainable construction technology, with concept cognizance as the driving force [78]. With outstanding reliability and longevity, these multi-functional stepwells stood the test of time, covering a wide variety of shapes, sizes, typologies, and purposes (Figure 5).

Stepwells were generally constructed in arid or semi-arid regions, where the depth of water was between six to seven stories deep, a depth at which the excavated soil or rock was fully saturated with water. The condition of the soil, depth of water, and soil erosion were the major criteria for the construction of these structures. These stepwells were resilient to earthquakes up to a magnitude of 7.6 on the Richter scale [63]. Although stepwells are on par with present-day hydraulic structures, there is only limited knowledge of the technical aspects of these stepwells in terms of structural design, choice of building materials, the inner lining of the well-shaft, etc.

4.1. Building Materials and Practices of Stepwells—Correlation with the Current Cleaner Production and Circular Economy Frameworks

In the past, various materials and practices used in the stepwell construction have been found to correlate with current cleaner production and circular economy concepts. Based on a location's geographical and geological features, a wide variety of stones, bricks, lime, mud, wood, etc. have been used as building materials.

The Great Bath is a predecessor to all the stepwells that existed during the prehistoric times of the Harappa and Indus Valley civilization, and it functioned as a public water tank of primeval origin. The Great Bath, located in the archeological site of Moan-Jo-Daro, measures roughly 12 m north-south and 7 m long with a maximum depth of 2.4 m [79]. Fine-fitted brick masonry with gypsum plaster was used in the construction of inner walls to hold water tightly inside. A thick layer of bitumen (natural tar) was applied on the sidewalls and on the rear side of the tank floor to avoid water percolation and losses. Furthermore, the structure did not have any drain facility. The principal community bath was a structure of considerable size, conforming to ancient ideas of a swimming pool (rainwater based), and it stood the test of time [80]. The structural features of the Great Bath suggest an excellent construction capability, given the building materials available at that time and place. For example, waterproofing was executed by a membrane or an asphalt coating between the inner and outer walls of the pool or tank [81]. Cities developed near the facility had a strong earthen bank, and manmade islands were built at an elevated level to keep water out of their cities during possible floods and to protect themselves from natural calamities [82].

The development of an efficient water harvesting and storage system at Dholavira, one of the five largest Harappan sites in the Indus Valley, speaks eloquently about its advanced hydraulic engineering and state-of-the-art technology [83]. The site followed a distinct and sophisticated water conservation practice. The massive stone made canals and reservoir systems were either filled with rainwater or with water from nearby rivulets. A seasonal stream running in the site's north-south direction was found dammed at several points to collect water in the wake of the Kutch's desert climate and dry conditions, where several years passed without rainfall [84].

The rectangular-shaped Rajon ki Baoli (28°39′27″ N, 77°13′23.23″ E) in New Delhi is one of the largest stepwells constructed using lime plasters in its vicinity. This well obtained its delicate architectural erection because of its incised plaster works [85]. While regular lime mortars are prepared from sand and limestone mixtures in a fermented organic extract, the lime mortars used in the Rajon ki Baoli were made exclusively from brick surkhi, powder bricks, and jute fibers [86]. Lime and brick powder were used as the binder, river sand as fine aggregate, while brick surkhi as coarse aggregate allowed the lime mortars to gain strength equal to cement concrete with increased pozzolanic reaction and additional Calcium silicate hydrate formation. These brick powders acted as a strength enhancer and were highly durable against environmental forces [87]. The mixture interacted with lime resulting in pozzolanic reactions leading to higher amounts of calcium silicate hydrate gels produced in mortars. This lime brick mortar was comparatively stronger, and the inclusion of jute fibers avoided the development of tensile cracks, thus improving the building's lifespan. Sandstones were used as a primary construction material for their valued qualities. The construction material used in the most ornate and well-structured Rani Ki Vaav (23°51′32″ N, 72°6′6″ E) was sandstone. The sandstone used in the construction was creamy in color and sedimentary, with the rock strata differing from fine grain to coarse grain in the structure. Pillars, niches, and slabs were made of coarse-grain stone to withstand heavy loads and to prevent the possible collapse of the structure, while fine grains were used for finishes and ornamental decorations. Also, stone wooden dowels were used as a joint for adhesion [44].

Since ancient times agricultural residues have been recycled into the construction of bricks, indicating that circular economy aspects were applied at that time in India. The Lakhori brick, a unique and rare variety made from rice husk ash, were used in the construction of the Bara Imambara stepwell (26°51′38″ N, 80°54′57″ E). Rice husk ash that is rich in silica and aluminum oxide evinces the finest pozzolanic properties when burned, thus making those bricks stronger and more durable than others. These construction materials are one of the best examples of today's circular economy and cleaner production strategies because they showed little or no use of toxic substances, produced zero waste and negligible emissions, all of which which further assisted in innovative advances on sustainable resource usage and the reuse of resources [88].

Bhinmal town in Rajasthan was once a thriving business hub with worldwide ties. The Chandinath Mahadev stepwell (25°0′5″ N, 72°15′57″ E) located in this city was five-stories tall, with an edifice made of marble slabs with decorative panels a or niches. The construction of the pillar was made of masonry, and the panels at the top were decorated with petals of flower leaves. The archway was designed in Mehrab style, with no ledges connecting the pavilions. An exceptional fact is that this stepwell was constructed with exquisite marbles by wealthy merchants to make it more elegant and embellished. Except for the locally accessible granite blocks, the stepwell was built with expensive marble blocks [46].

Another world wonder would be the construction of hydraulic structures in the Vijayanagara empire. The dynasty was popularly known for its harmonization of natural topography and engineering techniques to channel water from hilly terrain to urban areas. Unlike other stepwells in western India that are recognized for their aesthetics and ornamental embellishments, the stepwells of this region are recognized for their peculiar construction [89]. In the 1980s, a stepwell (Figure 3d) was found around the Vira harihara palace in Hampi during an archaeological excavation that resembled Mukhed's stepwell (18°42′19.98″ N, 77°22′6″ E). On exploration, it was found that this stepwell consisted of five stages receding in conjunction within. The square-shaped stepwell was planned and constructed in a prefabricated manner due to the war in the Vijayanagara empire. This kind of construction method had been the trend since the 19th century, so it is a marvel that this approach came into being in the early 13th century. Since the prefabricated building technique requires comparatively less time than the normal process, it has been found that the stepwell dressing of stones had been removed from the site and that the other sections of the stepwells had also been built simultaneously. During dressing, the stones were sequentially numbered in a peculiar way to determine their position in the stepwell. The influence of Chalukya architecture was seen on Hampi's stepwell (15.334022° N, 76.468536° E) in landing strategies, jointing, recesses, access to water, and the water deities [47]. These stepwells were an exception, where water was supplied by gravity from the upper end from an inland source through the stone masonry canal network instead of water flow.

Classic examples of rainwater harvesting are the baories of Jalore fort (25°20′14.28″ N, 72°36′51.84″ E), forming an underground structure that is rectangular in shape, 15 ft long and 90 ft wide. Water is supplied either from the underwater veins or from the rainwater collected from the narrow channel running along the entire length of Janani Dyodi (female quarters). The rainwater from the roof of Janani Dyodi flows down a roof channel to the ground, where a wider channel runs through it toward the stepwell that feeds rainwater into it [46]. Since the well of the baoli is very deep, a long and inclined ramp measuring 78.75 m ahead of the stepwell was built to facilitate the movement of oxen for charas, and to draw water from the well. While stones were used as a building material for construction, lime was used as binding material for these stepwells. Furthermore, the entire baoli was surrounded by a garden [52].

4.2. Aesthetic Features and Sculptures—Relevance to Cultural and Religious Identity

The cultural and religious identity of a nation is portrayed in various forms of art. With the emergence of various architectural styles in India, aesthetics and ornamentation played an important role in nearly all forms of construction. From ancient times, the design of water storage in Indian temple architecture is significant, Stepwells were beautifully ornamented for their time and offered space for the local artistic talents to express themselves. They crafted decorated side walls, galleries, and rooms, ranging from simple to intricate carvings [63,90]. They were as majestic as any grand temples in the particular region's structure or ornamentation. Every aspect of human life was symbolized [91].

Stepwells are one of the finest ancient pieces of evidence of how humans lived in a particular region. These historical monuments served as a testimony to both aesthetics and its functionality, perhaps no other forms of wells have been recorded in history [61]. The stepwells that were originally built between the 11th and 13th centuries were of excellent aesthetic standard. The reason for this is that the Solanki Kingdom, which was rich in maritime trade with the Arabs and Persians, and the patrons of this wealth spent it on architecture [91]. Stepwells are a unique form of underground water architecture. It is hard to imagine that these wells slipped off from the pages of art and architecture of Indian History [54].

The traditional craftsmen of the Somparas created their beautiful architecture according to Shilpa Shastras (the science of arts and crafts). The Vishwakarma Vaastu shastra, a traditional architectural study, discusses stepwell shapes such as circular, square, rectangular, octagonal, quadrangular, or oblong [92]. Through the sculptures, the artisans tried to express the fundamental truth which governed their daily actions [93]. There was an influence of Indo-Islamic architecture in a few stepwells. One of the reasons for this can be attributed to the employment of local Hindu artisans for construction during the Muslim rule.

Stepwells were either single or multi-storied with simple to complex geometric patterns (Figure 6a). The ceilings were either dome, flat, or, rarely, pyramid [54]. As in many temple architectures, delicately painted friezes and figures have been found carved in high and low reliefs [91] that are also found filled in the well's entire surface wall. One of the main features of the stepwells is their overwhelming figurative embellishments. They abound in carved depictions of Lord Shiva and Vishnu in various forms. The sculptures on the pillars include floral designs and intricately carved inscriptions that represent different moods of life all in one place. In the stepwells, there are also many secular pictures depicting village life, families, children, birds, singers, and musicians [53,54]. The dancing maiden poses represent mudras, and there are also several scenes of battle and war. The descriptions in the stepwell wall carvings are very profound and clear [94].

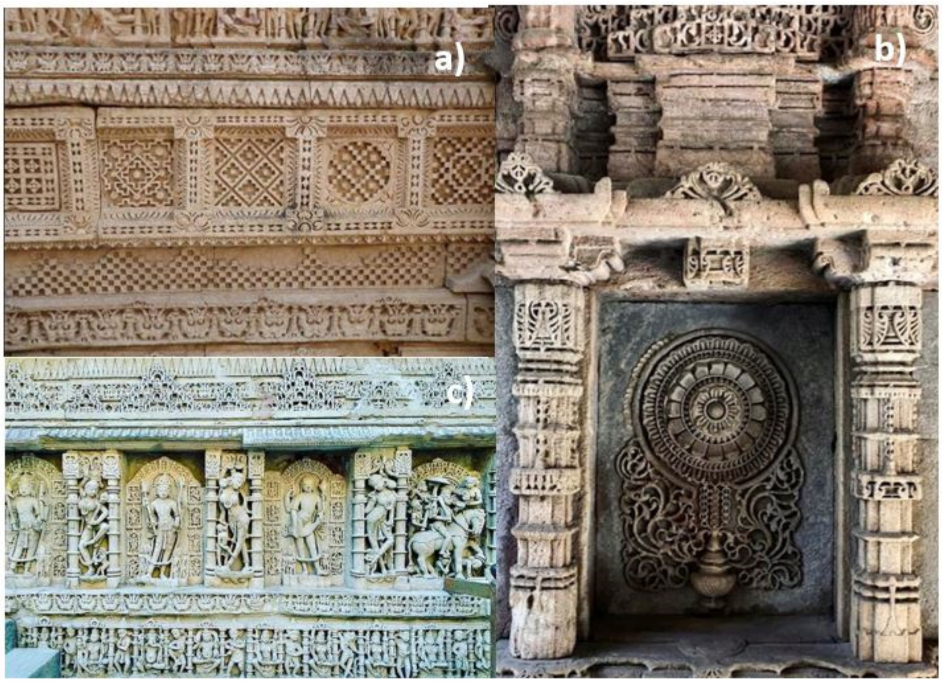

Figure 6. Major aesthetics features: (**a**) Ingenious geometric patterns https://www.shutterstock.com/image-photo/rani-ki-vav-stepwell-on-banks-1365740735, accessed on 20 July 2022; (**b**) floral motifs and filigrees http://modestryliving.com/2018/02/07/adalaj-stepwell-ahemdabad-travel/, accessed on 20 July 2022 and (**c**) voluptuous female figurines and male deities of Shaivism-Vaishnavism https://www.thrillophilia.com/tours/rani-ki-vav-patan, accessed on 20 July 2022.

In Gujarat and Rajasthan, the stepwells were identified with mixed sculpt designs and features of Hindu symbolism and domes and arches from Islamic influences, reflecting religious tolerance [95]. Comparatively, those found in Gujarat were most intricate and ornamental in design [48]. Although the Adalaj stepwell (23.1667° N, 72.5801° E) has some of the finest stone carvings of any Indian well, many scholars consider the Navghan stepwell in Junagadh (21.523894° N, 70.471578° E) to be the successor of all stepwells [49], where the sidewall has the simplest designs with equally divided square columns [63]. The walls of the Rajon-ki-Baoli stepwells of Delhi has its lowest visible level lined with small but deeply recessed arches. Whereas the Bhamaria stepwell (22°48′39.78″ N, 72°44′55.82″ E) has tassel-like ornamentations on its balcony windows and geometric designs [51].

Another notable difference is that the stepwells designed during the Muslim patronage displayed a large number of floral motifs, filigrees (Figure 6b), vase leaf branches and geometric designs, and fewer human and animal depictions. Similarly, the northern and southern walls of Meratani ki Baori, Jhunjhunu (28°7′43.95″ N, 75°23′58.22″ E) are decorated with merlons [52]. The motifs of the Bai Harir stepwell (23.0407° N, 72.6057° E) and Adalaj stepwell were very similar to each other.

The sidewalls of the Rani ki vav stepwell, which was restored after nine centuries of oblivion, had niche corridors and its well wall was adorned with exquisite sculptures [44]. It has rich and elaborate art with seven stories and 400 surviving sculptures [95] also depicting a variety of living beings, voluptuous female figurines, male deities of Shaivism-Vaishnavism (Figure 6c) iconography and interaction between human and nature, etc. Some of the pure carvings are the male and female gods such as Mahishasur Mardini, Lord Vishnu's Dashavatar, Lord Shiva, from whose matted hair river Ganges flows out into Wankaner stepwell (22°37′24.67″ N,70°58′10.6″ E). Buddha in padmasana pose as the ninth incarnation of Lord Vishnu is found in the stepwell of Kalesvari ni Nal (23°19′18.45″ N, 73°34′54.74″ E), apart from this depiction, the mythology of Buddhism or Jainism are not found in any stepwell.

Nearly 200 of the 400 remaining sculptures in Queen's stepwell are of sensuous women [95]. There are detailed carvings of a snake attempting to enter the bowl coiling around a Serpent queen's leg with her stance indicating that she is trying to stop the snake from going further (Figure 7). Even the pedestals are carved in a sitting position with three owls, peacock and more often there are appearances of Garuda or Eagle [94]. The lintels of Caumukhi Stepwells (22.2665° N, 71.2102° E) are decorated with rows of Geese. Dhank stepwell (21.7726° N, 70.1366° E) walls had chiseled niches with intricate pediments. Cultural decorations of the romantic love scenes (maithuna) can be found in Davad ni vav (23.7273° N, 72.8523° E) [54]. Representations of provocatively positioned women are found in niches, panels, or compartments and are so glamorous and realistic that it is possible to see women wearing long skirts wrapped around their hip decorated with jewels and intricate hair knots. The Goddess poses as per Natyashastra, with a shield, bow arrow, and dagger, and also carves musical instruments such as Drum, Vina, cymbals (kanjira), and some unspecified horns or musical instruments [64]. While the Dumral Bhargov Stepwell had Arabic inscriptions, Dada Hari Ni Vav (23.0407° N, 72.6057° E) had inscriptions in Sanskrit.

4.3. Stepwells in Irrigation System—Relevance to the Current Integrated Irrigation Approaches

Freshwater was withdrawn for agriculture including irrigation and it had direct relevance to both sustainable water management and sustainable agriculture [96]. Besides utilitarian purposes, a majority of stepwells constructed in arid and semi-arid areas provided irrigation and agricultural water for intermittent and small-scale irrigation [97]. Such stepwells drew on deep aquifers and supplied water during dry seasons [98].

Jain Prakrit's investigation in '*Kuvalaymala*' found the construction of stairwells during the 8th Century to be worthy and noted that they helped to ensure fast irrigation water supply [99]. The use of waterwheels, leather buckets, channels, chamber attachment, presence of an additional well, etc. served as clear evidence that certain stepwells were used for irrigation purposes [47]. Archeological findings revealed the presence of a large number of stepwells spread across central and northern India, used for irrigation in particular. A summary of evidence found from major stepwell sites used for irrigation in central and northwest India are as given in Table 2.

Figure 7. Serpent queen with a peacock gazing steadily at the snake at the pedestal (https://www.dreamstime.com/photos-images/patan-step-well.html, accessed on 20 July 2022).

Table 2. Summary of evidence identified from major stepwell sites used for irrigation in central and northwest India.

Stepwell and Its Location	Proofs Identified in the Location	References
Ferozepur Stepwell, (30°55′24.36″ N, 74°36′36.77″ E)	Lifting tools—Pans, Animal-drawn leather bags, and Persian wheels	[56]
Tunwarji ka Jhalra, (73°01′22.5″ N, 26°17′49.2″ E)	Well built on the slope of the hill, water redirected towards a pond	[52]
Mahila Bag Ka Jhalra, (26.2965° N, 73.025° E)	Huge Persian wheel with 8 wheels (used for drawing water), Operated by Oxen	
L-shaped Nal Baori, (23.0250° N, 72.5971° E)	Cistern (Octagonal), Persian wheel	
Meratani ki Baori, (28°7′43.95″ N. 75°23′58.22″ E)	Inclined ramp for the movement of Oxen	
Vanadhara stepwell, (27°55′ N 75°24′ E)	The site, Cultivated land	[46]
Rani ki Vav, (23°51′32″ N, 72°6′6″ E)	Presence of non-mechanized farm machinery, Surrounded by agricultural land.	[100,101]
Rajakiya Vapi, (20°22′19.2″ N, 72°55′1.2″ E)	The site, Located between agricultural lands	[57]
Uvarsad stepwell, (23°12′07.9″ N, 72°35′40.5″ E)	Waterwheels, Channels for the flow of water (around the well)	[58]
Khodiyar mata ni Vav, (21°23′1″ N, 71°59′25″ E)	Presence of tiny troughs for livestock	[58]

Table 2. *Cont.*

Stepwell and Its Location	Proofs Identified in the Location	References
Bundeli gardens stepwell, (22°00′57.4″ N, 81°42′09.5″ E)	Connections, collection chambers, and channels	[59]
Baramotichi vihir stepwell, (17.7728° N, 74.0075° E)	Animal powered lifting wheels, perennial water supply, water storage facilities	[60]

Note: Some reliable information about water bodies such as Vapi, Tataka, Sarah, and Pushkarini is found in Odisha, India. Though there are many inscriptional epigraphic pieces of evidence no definite research has been performed or properly examined on the water [102].

There were excellent water conservation techniques for drinking, irrigation, and other utilitarian purposes at Hampi, a world heritage site in Karnataka [103]. This small town on the banks of the Tungabhadra River loses its altitude as it flows through the rugged terrain, and the engineering methods over the period have enabled people to build a huge number of storage structures such as stepwells and other conveyance as depicted in Figure 8a,b [47,104]. As we head south, there is much less evidence of the existence of stepwells or their use in irrigation or agriculture except for a few arid districts of Tamilnadu [105]. Even these wells cannot be called stepwells because they had just a few steps and were not as elaborate as those in the northern part of India [106].

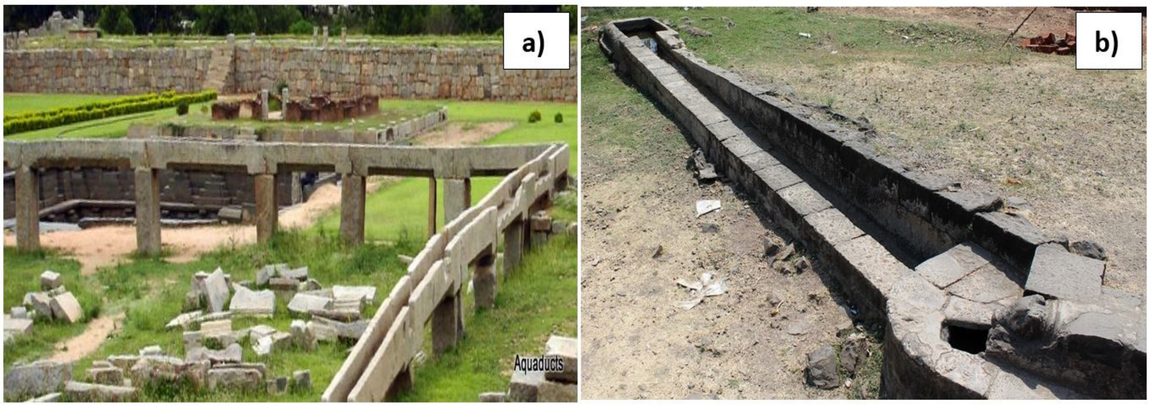

Figure 8. (**a**) Network of irrigation works and canals https://hampi.in/aqueducts-and-canals, accessed on 20 July 2022; (**b**) surface drains connecting agriculture fields from stepwells of Hampi, Karnataka a UNESCO world heritage site https://www.flickr.com/photos/indiawaterportal/33046414414/in/album-72157682207239506/, accessed on 20 July 2022.

Even though they are one of the greatest examples of ecologically sensitive architecture, the occurrence of monsoons and rainfall show that there is not much need for this water architecture. Also, during the colonial and post-colonial era more recent, complex groundwater irrigation water continued to function and new water technologies for irrigation developed that were implemented to eradicate conventional systems such as stepwells [107].

The Meratani Ki Baori stepwell in the Shekhawati region had a unique pumping mechanism to draw water out of the well. This massive rectangular stairway was constructed in 1783 CE in three apartments. The well shaft in the western direction of the stepwell had two minarets erected that represented the intricate elements of the well. The water from the well was collected by a water lifting device called a Charas, that was fixed on a slanted stone in the wall around the minarets. Water was collected from the well by Oxen moving on a long ramp taking into consideration the depth of the well. Water from these charas was transferred to two smaller tanks on both sides of the water channel, followed by two other tanks that were converted into a larger one.

The Esali vav (25.3370° N, 72.6160° E) near Jalore fort had a Persian wheel to draw water, whereas another lifting equipment known as a Chansua was used at Khirvi Vav

(25.3370° N, 72.6160° E). As Persian wheels were not accessible in this region, the localities directly drew water from traditional Dolachi or pitchers [46].

4.4. Architectural Styles in Stepwells—Relevance with Societal Values

The relevance of architecture and its history has been felt throughout history through its representation of society, its values, successes, and eventual downfall of its civilizations over time. At its roots, architecture is more than just the built environment, it is a part of our culture, and it epitomizes the values, beliefs, traditions, and aspirations of a specific community [108]. The semblance of architecture in stepwells is the most exclusive structure since early Indian history [63]. Contemporary research has led to the revelation of simple stepwells from the ruins of the Indus Valley civilization [109]. More than 700 stepwells in the Mohenjo-Daro and Harappa civilizations were found during excavations and were considered to have no architectural significance [63]. With time, stepwells emerged with immense architectural features in them. For an extended period, they were an elemental component of Western Indian culture as sites for performing everyday chores such as drinking, washing, and bathing as well as for special occasions like festivals and rituals [61]. Since the royals, nobles, wealthy, and aristocrats constructed most of the stepwells, they delineated ravishing Indo-Islamic architecture [110]. From a design perspective, scale, shape, form, and functionality were the main criteria seen in the stepwells. Most of the stepwells in India, from small to gigantic structures, have unique features with incredible architecture and well-defined functional characteristics. The features and construction aspects of the stepwells solely depended on the ruler's commission and based on geographical and topographical suitability of location [61]. The styles of stepwells did not reflect on one single architectural design across the country. Though they were constructed as a source and storage of water, they were also architectural output and showcase cultural aspects that prevailed from one period of history to another [64]. The forms of architecture followed in the construction of stepwells in India since prehistory include rock-cut, temple (Nagara, Vesara, Chola and Pallava), ornamental, Indo-Islamic, Mughal, Saurashtra, and Rajputana architecture [111].

4.4.1. Rock-Cut Architecture

The first rock-cut stepwells in India are dated between the 2nd and 4th centuries CE. [61] Navghan Kuvo, Junagadh in Gujarat, and Chand Baori, Abhnaeri (27.0073° N, 76.6065° E) are existing examples of magnificent stepwells featuring rock-cut architectural style.

As shown in Figure 9a Navghan Kuvo (21.5238° N 70.4692° E), located in the upper part of the Uparkot Fort, was built at the beginning of 1026 CE. The well—being partially hewn out of a delicate shale of sandstone—illustrates a beautiful example of the emergence of rock-cut architecture in the common era [50]. It is constituted of a flight of spiral steps leading down to a 52 m water source in the square-shaped shaft. There are openings in the sidewall to let in light and air for circulation. The large forecourt (Figure 9b) surrounding the well is slightly younger than the well in terms of age. These winding stairs are straight first, and then transverse, turning right around the shaft. The array of square holes in the stone wall of the shaft and the opening in the side divider allow light and air to circulate [63,112] and the well is named after Ra'Navghon as the forecourt existed in this reign (1025–44 CE). It reflects on the Nanda style of architecture (source: ASI).

Built between the 9th and 10th century, Chand Baori, Abhnaeri (27.0073° N, 76.6065° E) is one of India's most profound, highest stepwells with 13 terraced stairs reaching a depth of 30 m. Three hundred and five hundred narrow steps, arranged in perfect symmetry, form a mystical labyrinth and the consequent play of light and shadow, which gives it a fascinating look. This stepwell, said to be an upside-down pyramid (Figure 10a,b), was made of porous volcanic rocks and stones, which allowed water to seep through the rocks and reach the bottom of the pool or well. Although there is a prominent multistoried pavilion on one side of the four-sided structure, the remaining three sides were covered with visually striking geometrical steps. Later on, the bottom of the well was added to the upper palace building, which can be seen from the Mughal arches and the tribulated arches that the Chauhan rulers used. King Chand of the Nikumbh dynasty built this stepwell just opposite to the temple of Harshat Mata, to eventually devote it to the goddess between 800 and 900 CE [61].

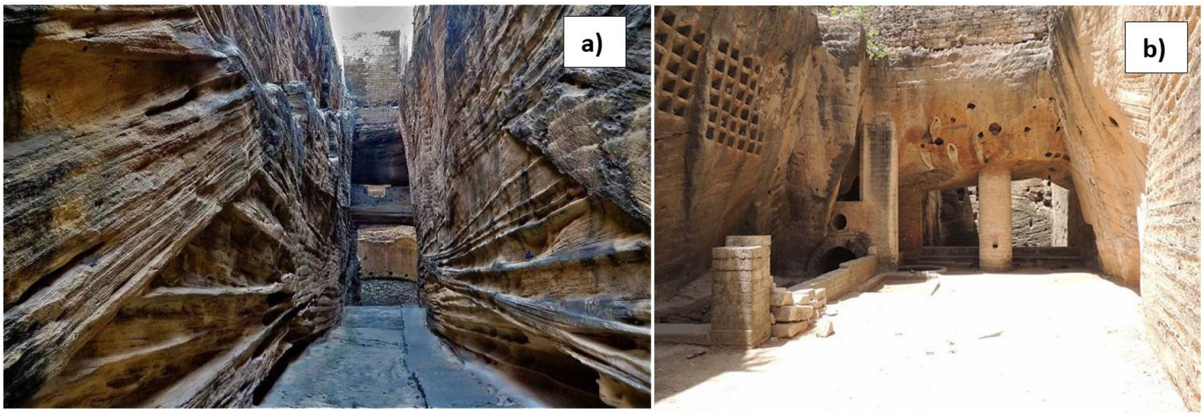

Figure 9. Navghan Kuvo stepwell in the Uparkot Fort complex. (**a**) Front view of slanting shaft driven into sandstone https://www.smithsonianmag.com/travel/review-vanishing-stepwells-india-180962637/, accessed on 20 July 2022 and (**b**) forecourt surrounding the well https://www.travel-history.com/2021/05/navghan-kuvo-about-navghan-kuvo-history.html, accessed on 20 July 2022.

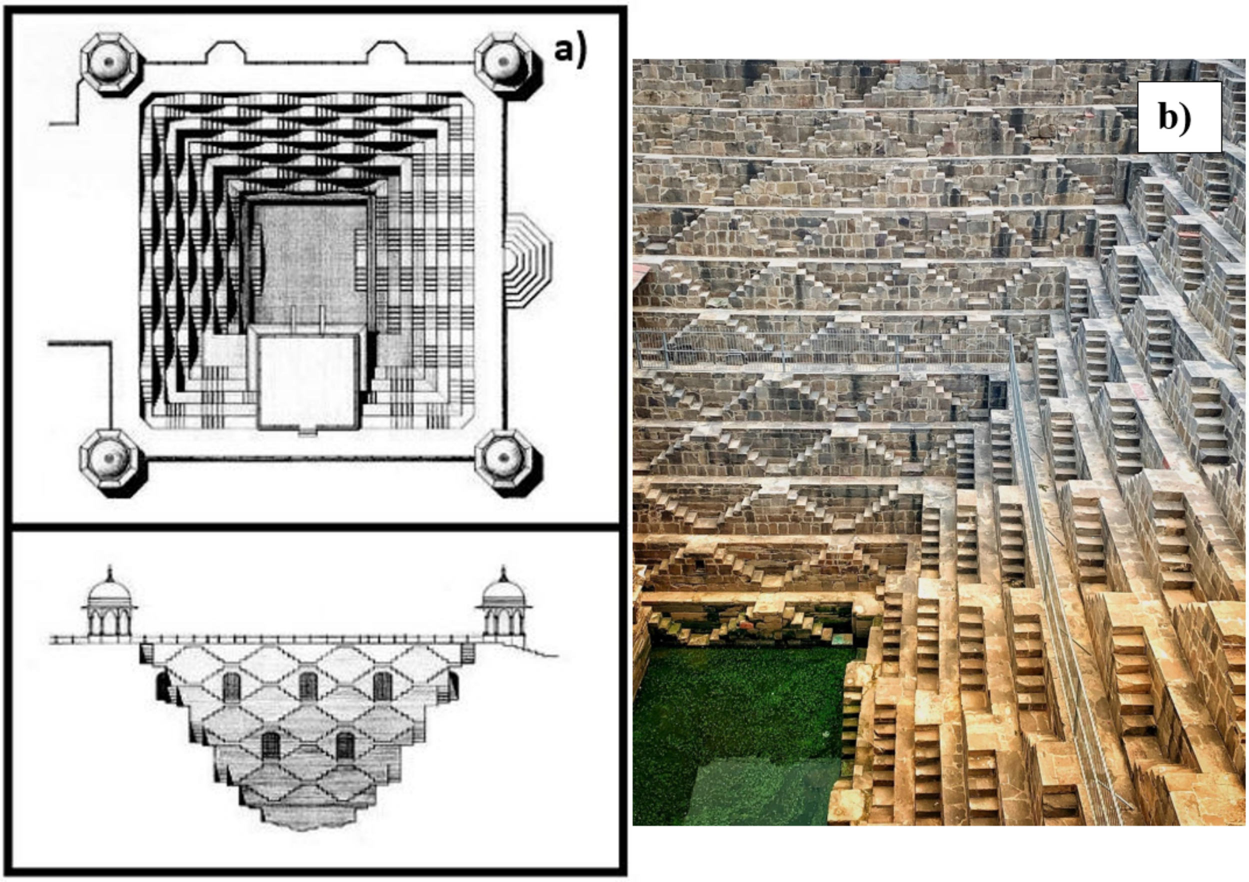

Figure 10. Chand Baori: (**a**) Plan and elevation view https://in.pinterest.com/pin/119626933831362019/, accessed on 20 July 2022 and (**b**) bird's eye view of the structure. (https://10.16943/ijhs/2020/v55i2/154675, accessed on 20 July 2022).

4.4.2. Temple Architecture

Although these stepwells were hailed from Rajasthan, Gujarat, some parts of Western India and Madhya Pradesh, it is in Gujarat alone that they obtained an incomparable beauty of subterranean temple architecture. Gujarat is famous for its vast subterraneous stepwells which served as a resting place all around the well for travelers and a common meeting place for women. Temple architecture mainly comprises Nagara (northern style) and Dravida (southern style) architecture. Within the Nagara style of architecture, there existed four forms of architectural styles, namely Saaurastra style, Maha-Maru style, Maha-Gurjara style, and Maru-Gurjara style. The Saurashtra style mainly prevailed in the southern peninsula of Saurashtra from the 6th to 10th centuries under the guardianship of Maitraka and Saindava rulers. The Jhilani stepwell (23° N, 72° E) dated to 600 CE and the Manjushri stepwell (21.7726° N, 70.1366° E) dated to the early 7th century based on this style of architecture. The temples or the stepwells belonging to the Saurashtra style showcased some of its unique features such as the averagely sized structures. In terms of sculptural ornamentation, they are less decorative compared with the later forms.

The Maha-Maru and Maha-Gurjara architecture coexisted between the 8th and 10th centuries. The Maha-Maru style, predominantly found in the Marwar region had a high and molded terrace, multi-turreted spire, aesthetics with sophisticatedly worked ghata-Pallava motifs on pillars and sculptures. Whereas, the Maha-Gurjara style prevailed in the southern region of Marwar. The structures had a molded basement and a pyramidal roof-mounted on the diminishing tiers representing this style of architecture. In comparison, Maha-Gurjara style had slightly less ornamentation than the Maha-Maru style [64]. The two latter styles hybridized to form the fourth style, Maru-Gurjara incorporating the unique features of both styles. This style prevailed through the 10th and 14th centuries manifesting a binding uniformity in architecture and decorative designs over the region of Southern Rajasthan to Prabhas Patan, extending to the southernmost tip of the peninsula of Saurashtra. During the 11th century, the Maru-Gurjara style evolved to distinguish itself from the latter styles. The individual characteristics of this style are the carved basements with several moldings and an absence of terrace [53].

Temple Nagara style architecture is exhibited in the stepwells of Gujarat mainly in the Rani-Ki-Vav stepwell or "the Queen's stepwell" in Patan, which is arguably one of the foremost marvels of India. Rani Udayamati commissioned Rani ki Vav in the memory of her late husband King Bhimsen I (1022–1063 CE) during the period of the Solanki dynasty [113]. Initially, the stepwell was seven storied with colonnades and retaining walls that connected the steps to a circular tank well after many natural calamities. This 11th-century built stepwell, with its highly perceived structure in terms of architecture and ornamentation, imitate the Maru-Gurjara style [61]. Although the Vaav was constructed to store water during droughts, there was also a secret motive behind the construction. The last step of the well leads to an opening gate of a tunnel which is 30 km long and was used solely for the escape of kings in case of danger or war [63]. Rani Ki Vav was built as an inverted temple structure and depicts the relevance of temple architecture in history. Not only Gujarat but also many stepwells of the Southwestern region had a predominance of a type of temple architecture called the Vesara Architecture. Vesara style lasted from the Early Chalukyas to the late Chalukyas period.

One of the most excellent examples portraying Vesara style is the stepwell of the Vijayanagara Kingdom, Hampi, Karnataka. In an excavation conducted by the Archeological Survey of India in 1980, it was reported that the stepwell found near the King's Palace in Hampi was very close to the stepwell of Mukhed in Maharashtra. The stepwell, square in shape had been built in five stages with shriveling dimensions inside. In connection with the method of construction, the landings, jointing, recesses, and access to water and sculptures of deities, the dominance of Vesara-Chalukya architecture can be seen in the stepwells of Hampi [47].

4.4.3. Ornamental Architecture

Bawdi is an outstanding accomplishment of ornamental architecture. Although stepwells were excavated to reach the underground water level, they correlate culture, religion, ceremonies of a particular reign by embellishing the distinguishing characteristics of a structure through antiquity. Rani ki Vav of Gujarat, containing the standard multistoried pavilions, is an outstanding illustration of the ornamented architecture of the 11th century CE [112].

4.4.4. Indo-Islamic Architecture

A fusion of Hindu and Islamic architecture became very famous at the beginning of the Mughal era. A perfect illustration of Indo-Islamic architecture was [114]. The plan and elevation are presented in Figure 11a,b, with a four-way flight in Figure 11c. The stepwell was built by Queen Rudabai, wife of Veer Singh the chief of the Vaghela dynasty, in 1499 CE in Adalaj, a small village near Ahmedabad to serve as a halting-place for the travelers as well as the local people. This five-storey stepwell was emblazed with Islamic, Hindu, and Jain motifs with divine attributes [112]. Other exciting aspects of this stepwell is that it is octagonal (Figure 11b), is a serene retreat that is 5° cooler inside, has three-entrance staircase leading women to a place in which to pick up water, to love the Gods and goddesses and share notes with friends (Adalaj Vaav—An Architectural Marvel). In addition to the religious aspect, it is Ami Khumbor (a water pot of life) that creates a single mark of sandstone and little Navagraha frieze (nine planets) with the Kalpa vriksha (a tree of life). There is a three-dimensional lattice, a rhythm of light and shade, that is very charming to the eye [114]. Speculation suggests that even the tiny, dynamic sculptures adorning the Vav's walls mimic those in the buildings.

Another exemplar is the famous Dada Harir Vaav of Ahmedabad. This octagonal-shaped stepwell is a less complicated Nanda style architecture featured in the east-west direction. It is situated in the Asarwa area of Ahmedabad city in Gujarat. It was built in 1485 CE by the Muslim king Sultan Bai Harir and thus acquired its name. There is an open octagonal pavilion on the eastern side and steps leading down with many landings on the western side of the well. In addition to this there is also a rectangular tank for storing water. The well is oriented at five levels, each provided with magnificently sculptured pillars and motifs. Stone ledges, open sky, and passageways at all levels to connect the shaft to octagonal space are provided for resting, air circulation, and ease of travelling respectively. The well shaft is circular with the walls of the shafts covered in geometric designs [115]. The stepwell also functioned as a shrine as it was situated in the compound of a mosque. Although the stepwell seems to have intricate Islamic architecture, the ornamentation and carvings were superimposed on and were adopted by the typical Hindu form. Dada Harir stepwell, now completely dry, had water that reached a depth of three stories and which lasted through to the end of the preceding century. Traces show that the ground level operated as water-channeling systems, cisterns, and troughs for watering animals and a bathing place for men and women [53].

4.4.5. Mughal Architecture

The Gebanshah stepwell is supposed to have been built by a fakir named Gebansha in the 16th century CE (22°28′49″ N, 73°31′52″ E). These well steps alternate with covered landings (Kutas) that come under the division of Nanda type. The well is fully open up to the sky, which shows the best aesthetic view of the beams and columns that cross each other in angles. Looking at it is like staring at the very bare bones of the well. With a shaft diameter of six meters, the well is 20 m deep and about 50 m long at ground level [63] Situated near the area of Gebanshah Stepwell is the Helical stepwell (22°29′03.84″ N, 73°30′56.16″ E). This well consists of a 1.2-meter-wide spiral stairway along the brick parapet wall of the well to the well shaft as well as into the well.

The spiral stairway is attached to the wall while descending to the water "like the coil of a snake" as advertised in Viswakarma Vastu Shastra. Unlike Gebanshah stepwell, the steps of this well are narrower towards the center and wider at the wall [116]. The stepwell is disbursed in the north-south direction, the well situated in the north, and the entrance in the south. Made entirely of brick and stone plates on the steps, the general architectural ground plan of this stepwell is elementary. Thus, implying a very early stage of stepwell architecture.

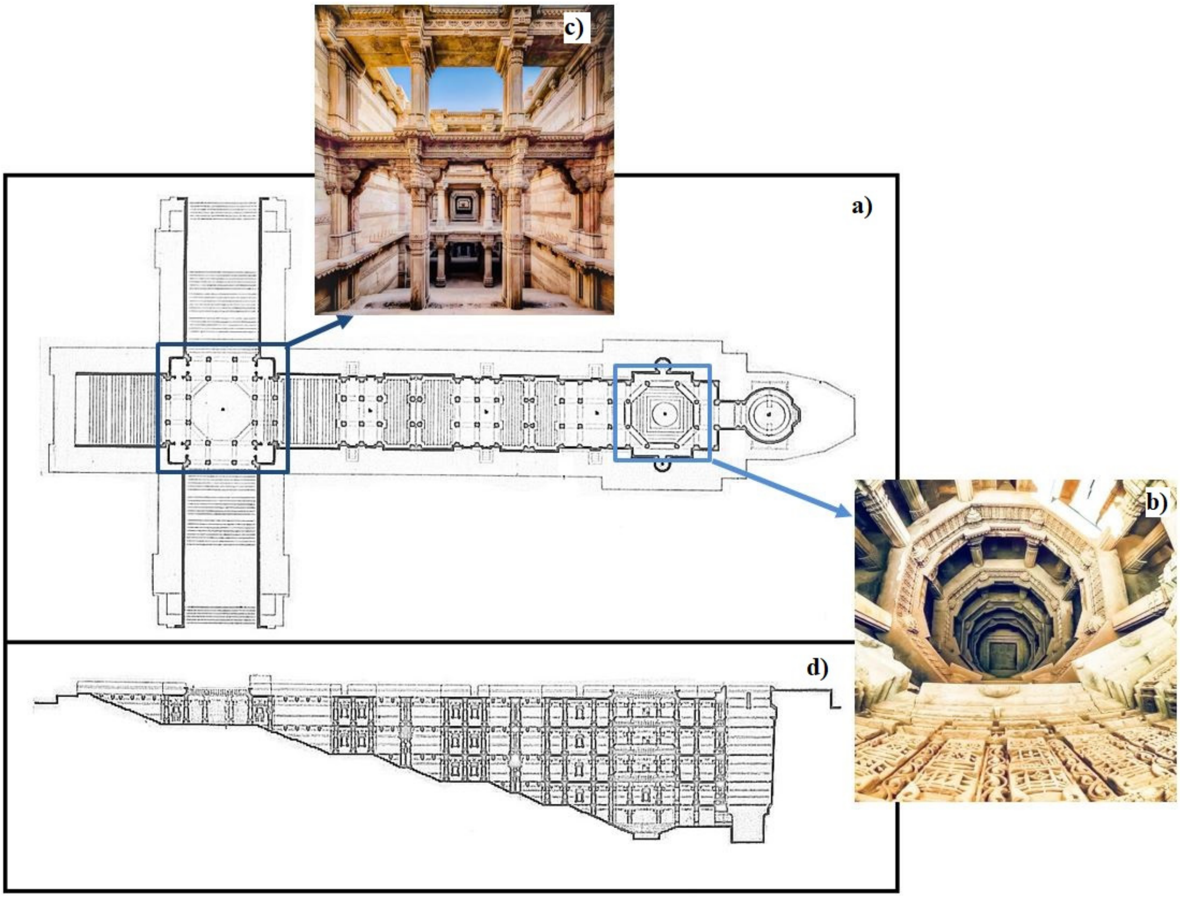

Figure 11. Adalaj Vav. (**a**) Plan https://hkblabla.wordpress.com/2011/09/12/step-well-getrapt-waterreservoir/amp/, accessed on 20 July 2022; (**b**) cross-section at entrance https://www.facebook.com/115080539883854/phtos/a.173309787394262/252012039524036/?type=3, accessed on 20 July 2022; (**c**) cross-section at junction of well https://touristinformationcenter.net/the-adalaj-stepwell/, accessed on 20 July 2022 and (**d**) underground elevation https://hkblabla.wordpress.com/2011/09/12/step-well-getrapt-waterreservoir/amp/, accessed on 20 July 2022.

4.4.6. Saurashtra and Rajputana Architecture

Gujarat stepwells were influenced by a whole slew of architectural styles from other states. Rajputana architecture dates back to a 319 BCE ancient stepwell located at the foot of the Girnar hills near Junagadh called the Adi-Kadi Vav (21°31′25.26″ N, 70°28′10.27″ E). A number of kings over the centuries rebuilt the Adi-Kadi stepwell, rediscovered in 976 CE. This stepwell was well distinguished from others by some of its unique features. Adi–Kadi Vav was built in 15 CE becoming one of the oldest stepwells in India. An amusing fact of this stepwell is that it has a zig-zag staircase approaching directly to the circular well shaft which appears to be apsidal at the bottom. This feature implies that the stepwell itself has been constructed into a single stone. Another striking feature is that the steps were carved straight into the hard rock and thus do not contain any decorative motifs, sculptures, or even any beams or pillars. In the Pre-Chalukyan period, two stepwells imitated Saurastrain Architecture in Gujarat.

5. Conclusions

Various methods of sustainable water supply and management have been in use since ancient times. Understanding ancient practices and strategies offer a framework for considering the present and the future. Ancient water management techniques were able to ensure year-round irrigation and drinking water supply in arid and semi-arid regions. In this review, interesting insights for stepwells and a unique, massive, multifunctional underground water storage system were discussed. While traditional approaches to water management had been focused on ensuring sufficient water supply and sanitation, they do not necessarily reflect sustainable approaches to today's climate change challenges with global population growth and higher patterns of urbanization. The primary objective of these structures was to entrap rainwater and replenish groundwater level over time. Generally, collected water was recorded to be used by those in the local community to facilitate their sustenance. Most stepwells were observed to be underground structures, designed to form a cool microclimate inside. They were also equipped with a wide catchment area to facilitate ample storage capacities. Stepwells were largely constructed of clean and renewable materials with enhanced durability and longevity. The stepwells also housed a repertoire of aesthetic geometric patterns and historical features. Hence, stepwells can be the potential nexus node between different water management techniques. Such ancient setups have sizeable potential to be adopted as the foundation for the development of sustainable water engineering solutions. The conservation of existing stepwells through modern sustainable technology along with newly developed infrastructure could address the problems of basic drinking water requirements in India. This approach will not only contribute to the preservation of cultural heritage but also help achieve key sustainable development goals (SDG) and a circular economy. It is important to apply ancient water management techniques to modern societies to integrate traditional knowledge and to explore whether physical and socio-cultural circumstances are comparable for building sustainability and climate-related aridification resilience.

Author Contributions: Conceptualization, M.G. and T.S.; methodology, P.D.; validation, J.L.P., A.Z. and P.D.; writing—original draft preparation, M.G., T.S. and A.Z.; writing—review and editing, T.S., M.G. and P.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from Vellore Institute of Technology, VIT, Vellore for Article Processing Charges (APC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

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