Stepwells as Sustainable Water Management Structures

Subjects: Water Resources

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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.

Keywords: cultural heritage ; ancient water conservation practices ; sustainable consumption

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][11][12].

Resaerchers 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 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][22][23][24][25][26]. They usually direct the groundwater to a reservoir that is often connected to the tunnel exit by a lined canal.

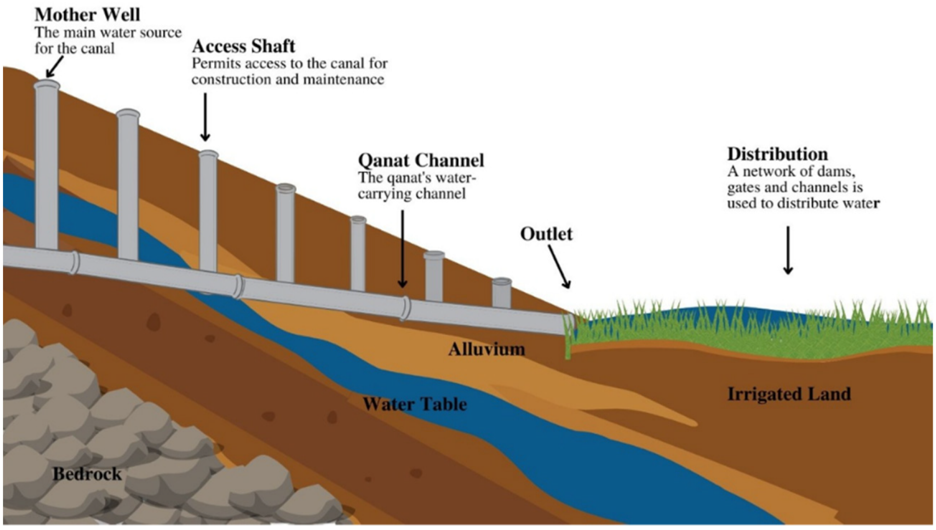

Figure 1. Design of a typical Qanat, the Persian underground irrigation canals.

The ancient Egyptians mastered sinking shafts (**Figure 2**a) 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].

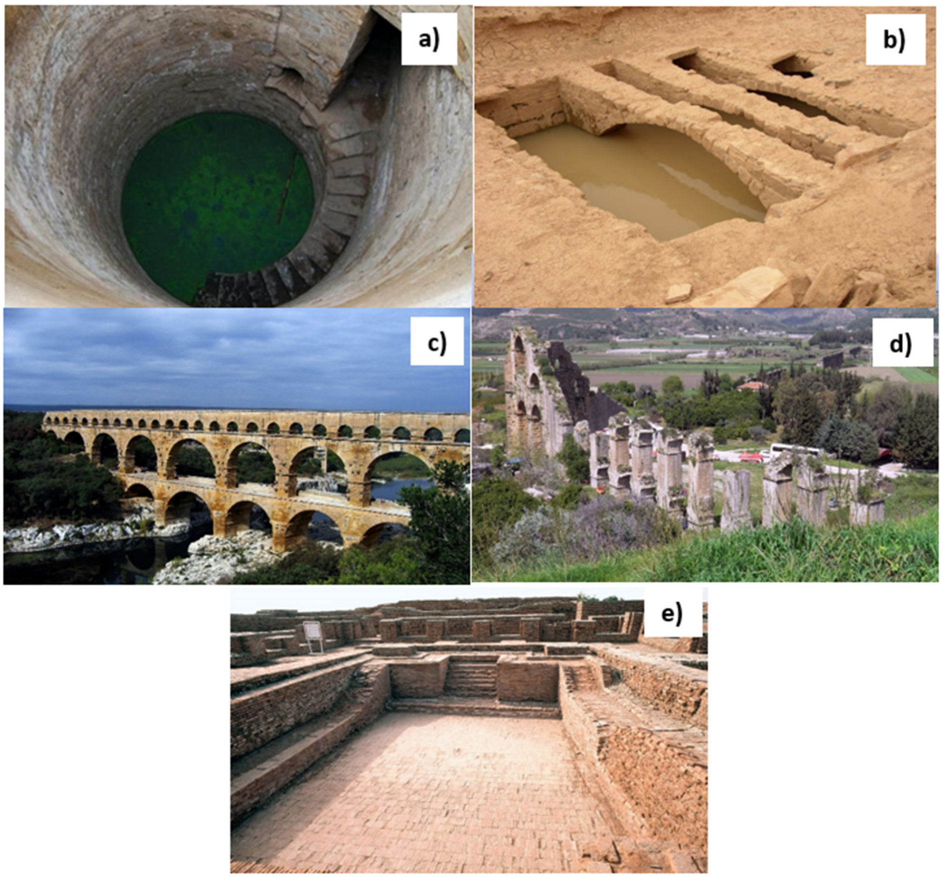

Figure 2. (**a**) Sinking shafts, Egypt (Claudio Caridi/Adobe stock); (**b**) cisterns, Jordan https://brewminate.com/controlling-the-municipal-water-supply-in-the-ancient-graeco-roman-world/, accessed on 20 July 2022; (**c**) aqueducts, Rome https://wallpapic.com/bridge-pont-du-gard-arch-vers/0xfGzO, 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 2**b, 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 2**c,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 2**e, 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.

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 [43]. Most of the stepwells are found in the states of Gujarat (**Figure 3**a,b), Rajasthan, and Delhi (**Figure 3**c) in the north-western part of India, and, in the south, Karnataka (**Figure 3**d). 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 [44].

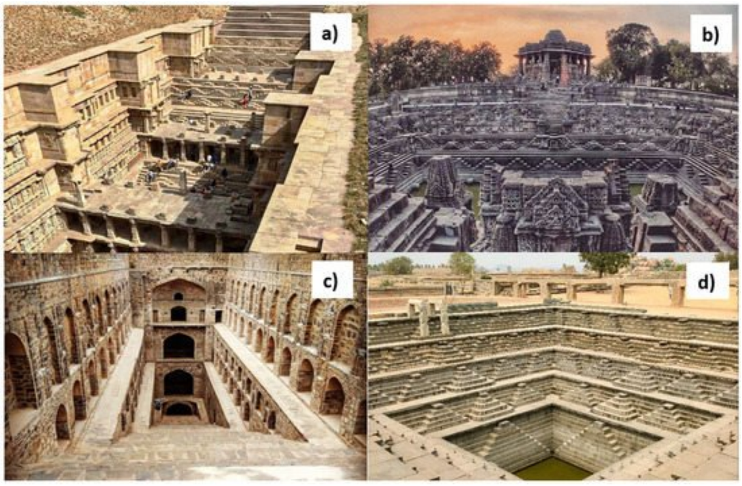

Figure 3. (**a**) Rani ki vav, Gujarat https://www.gujarattourism.com/north-zone/patan/rani-ki-vav.html, accessed on 20 July 2022; (**b**) Modhera stepwell, Sun temple, Gujarat; https://kevinstandagephotography.wordpress.com/2015/03/29/modhera-sun-temple/, accessed on 20 July 2022; (**c**) Agrasen ki 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.

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**.

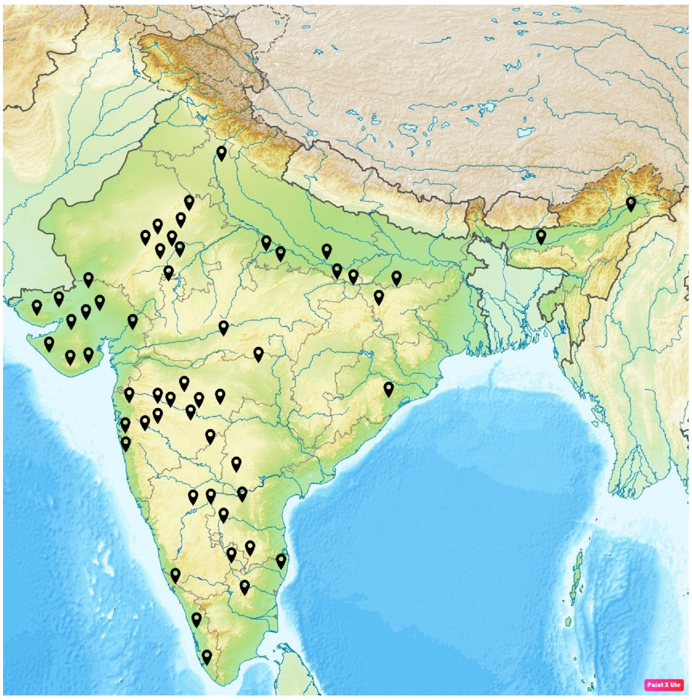

Figure 4. Distribution of stepwells across the Indian Subcontinent. White sign represents Madhya Pradesh and parts of Maharashtra. Blue sign represents Gujarat, Karnataka and Andhra Pradesh. Light Grey sign represents Jharkhand and Bihar.

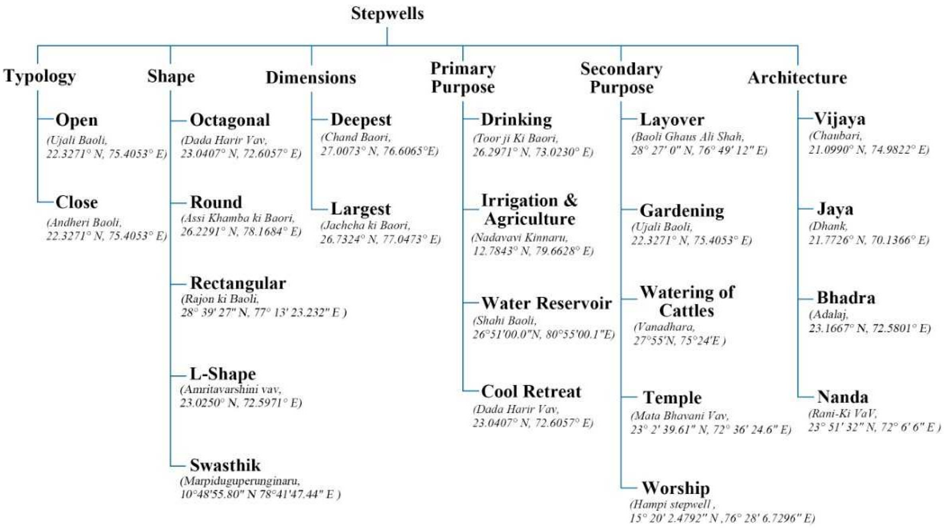

Figure 5. Broad classification of stepwells.

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 [45]. 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 [46].

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 [47]. 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 [48].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 [49]. 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 [50][51][52]. 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 [53][54]. 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 [55][56]. 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 [57]. Stepwells comprise a central, vertical shaft with water extending to a pool with a wide mouth around which steps are built [58].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 [59] (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 [60]. 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 [61]. 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.

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