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GROUNDWATER DAMS, GENERAL CHARACTERISTICS AND HISTORICAL DEVELOPMENT

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Abstract

A groundwater dam is any structure that serves to intercept or obstruct groundwater flow through an aquifer, both natural and artificial, and thereby provide storage of water underground. They are a suitable water supply structures for regions like Pakistan where arid and semi-arid climate conditions dominate. They can serve as an alternative solution for conditions where above-ground dams are not suitable or applicable because of complex geological situations, safety hazards, and/or silting up of reservoirs. They cannot be used for recreation, power generation, or as universal method of water supply. By using underground dams for storing water instead of surface dams, many of the aforesaid problems may be overcome. Besides their main purpose of providing groundwater storage, underground dams are a reliable means of preventing saltwater intrusion, which is a vital near shore problem. The disadvantages of groundwater dams include: inadequate reservoir capacities, more expensive operation costs (usually pumping), detailed hydrogeological site investigations, and in situ aquifer testing. Groundwater dams have been constructed in several regions around the world, and are not new engineering structures.
Historically, these kinds of structures were constructed in Roman times in Sardinia and around Carthage, in present-day Tunisia. This paper emphasizes the significance of this type of structures and reviews the general characteristics and historical development of groundwater dams.

Keywords: Ground Water Dam, Surface Dam, Reservoir, Salt Water Intrusion,

1. Introduction

A groundwater dam is a hydraulic structure that blocks and stores the flow of groundwater in aquifer layers, both natural and artificial. These “groundwater compartments” can be “farmed” during dry spells or drought years to sustain development for urban or agricultural usage. Groundwater dams usually consist of an impermeable barrier [1]. This type of barrier is favorable for arid and semiarid regions where water resources are scarce, to conserve rainfall and resulting runoff that is delivered naturally during seasonal monsoons by storing additional water underground for use during dry periods [2, 3]. Pakistan is an ideal place for the construction of ground water dams because there is surplus runoff in the northern areas, where there are heavy snow falls and intense monsoon rainfall, which can be stored for

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subsequent distribution to southern Pakistan, which have acute shortages of water supply during the year. Furthermore, groundwater dams permit the expansion of water resources in regions where the construction of surface dams is challenging, owing to unfavorable geological structure, high evaporation, and economic investment, and where groundwater cannot be used in its current state (for example, low water tables) [4, 5]. However, they cannot be considered for power generation or recreational use.

Although an underground dam with 20,000,000 m^3 capacity was constructed in Japan in 2001, underground dams are usually constructed on much smaller scale [6, 7]. They are not a universal method for water supply. Their storage capacities are typically between few hundred to several million cubic meters of groundwater, without causing disturbance to natural life [5]. In 1994, The United Nations Convention to Combat Desertification suggested groundwater dams as one technology that would normally be suitable for economic storage of water in arid and semiarid regions [4]. There are many areas in Sindh and Baluchistan provinces of Pakistan where droughts are a common phenomenon each year and people face acute shortages of water [8, 9]. This kind of situation demands the construction of subsurface and surface dams to conserve the heavy rainfall and runoff that accompanies the seasonal monsoons in the northern areas.

2. Historical Development of Groundwater Dams

Groundwater dams have been constructed, or proposed for construction, in several regions of the world, particularly in Libya and Tunisia of northwestern Africa, Sardinia, Namibia, Kenya, Burkina Faso, Ethiopia, Montenegro, Austria, Greece, Turkey, United States, Mexico, Brazil, Afghanistan, India, China, Korea, and Japan. Recent archaeological work has revealed that crude ground water dam-like structures were constructed on the island of Sardinia and Carthgae (Tunisia) during the Roman era, almost 2,000 years ago [10]. In Namibia, the first recorded attempt of building a sand storage dam was in 1907 [6].

In the United States, sand storage dams have been used as water sources since 1890 in arid areas, where evaporation rates preclude construction of above-ground reservoirs [5]. For example, a sand storage dam was constructed about one mile west of Kingman, Arizona, and another sand storage dam was erected in Pacoima Creek north of Los Angeles, California in 1890.

In Japan, the first underground dam, called the Kabashima Subsurface Dam, was constructed in 1973, with a storage capacity of approximately 20,000 m^3. In 1981, the Ethiopian Water Works Authority constructed two groundwater dams at Bombas and Gursum [2]. Four subsurface dams were constructed in Brazil in 1982 [5].

By 1990, at least four subsurface dams had been constructed in India for irrigation, using stone masonry, plastic bricks, and other materials. Five subsurface dams with storage capacities of between 1 and 5 million m3 have been constructed using grout curtains in South Korea; and five more subsurface dams have been constructed in Japan [2,5]. During the 1990s, about 500 small subsurface dams were built in the Agreste and Sertao areas of the interior of Pernambuco State in northeastern Brazil (Ishida et al. 2011). Some of these were up to 3 m deep and developed without technical advice or follow-up. The others were larger subsurface structures, up to 10 m deep (where alluvial cover was deeper) constructed by following some technical criteria. The idea was to support and improve small-scale agriculture systems (irrigated cultivation) in the respective areas. In 1995, Kenya initiated a program of constructing nearly 500 underground dams to store surplus water for livestock, small irrigation plots, and local domestic usage [11]. By 1995, 52 underground dams had been constructed in the karst regions of southern China. The total storage capacity of these dams reached 40 million m^3, which was enough to irrigate 8,900 km^2 of fields.. In Burkina Faso, a subsurface dam was constructed by the Japanese Ministry of the Environment in 1998, in a fossil valley [5].

In 2001, the largest reservoir capacity (~20,000,000 m^3) groundwater dam was constructed in Japan [7]. In 2005, Malibogazi groundwater dam was constructed in Turkey with total active storage capacity of approximately 55,000 m^3.. It has dam wall depth (height) of 20.6 m, with a crest length of 50 m [4]. Most of these schemes focused on narrow bedrock channels filled with pervious alluvium, most often in volcanic terrain.
In addition to those projects mentioned above, subsurface dams have been proposed in several other countries; such as Austria, Greece, Mexico, Thailand, and Afghanistan [2].

3. Classification of Groundwater Dams

According to Hanson & Nilsson [2], groundwater dams can be classified into two principal types; 1) underground or subsurface dams, and 2) sand storage dams. An underground dam structure is usually constructed in the subsurface (in situ) to halt the flow of a natural channel aquifer (Figure 1). Sand storage dams are intended to accumulate and retain moisture in sediments caused by the dam itself (Figure 2).

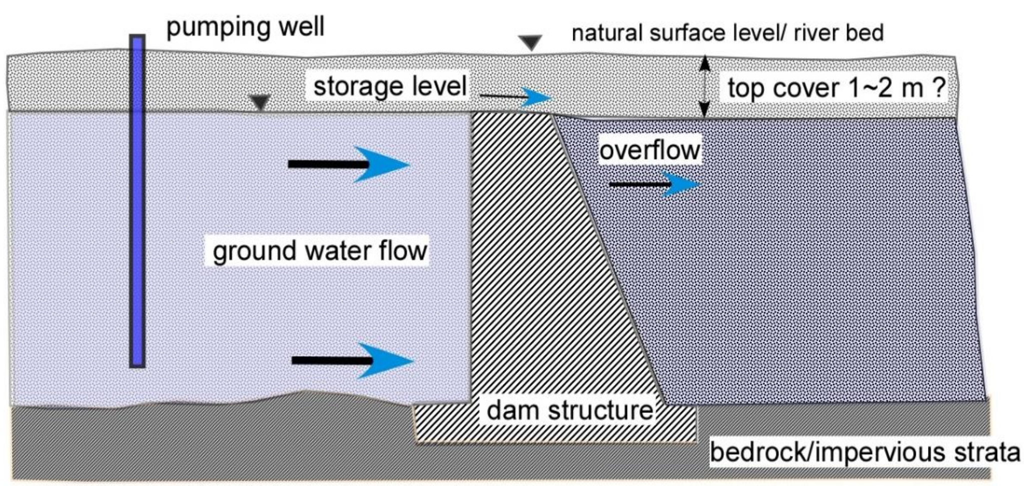

Figure 1. Typical scanrio for a subsurface dam

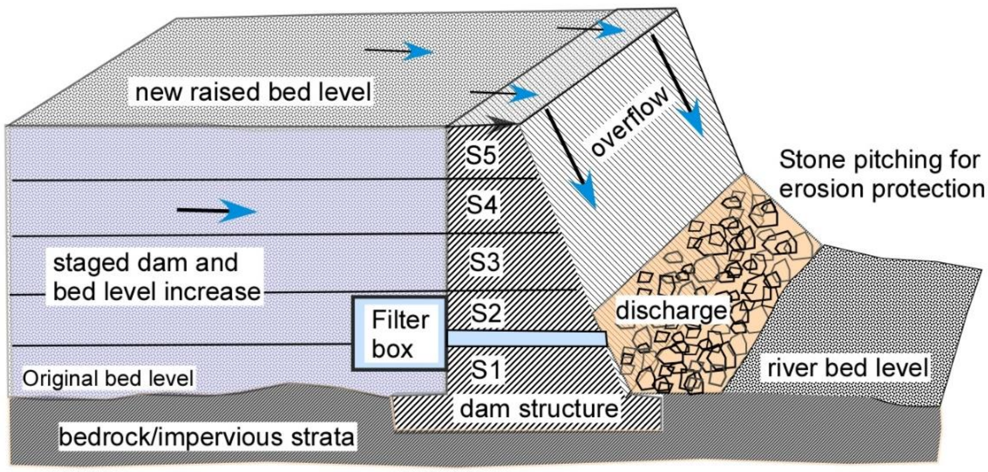

Figure 2. Scamatic repsresentation of a staged sand storage dam

In addition, underground dams can serve an important role in prevention of salt-water intrusion, because of the lower hydraulic conductivity of dam wall [6]. Underground dams used for this purpose are called salt water intrusion prevention dams, as shown in Figure. 3. They are the most reliable method to prevent saltwater intrusion which is a vital offshore problem [5,12].

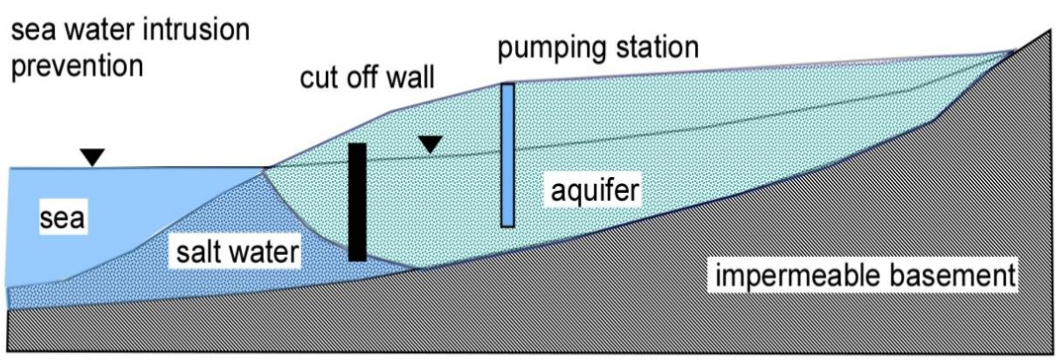

Figure 3. Typical cross section illustrating how a cutoff wall can serve as a saltwater intrusion prevention dam (modified after [5].

3.1.Underground Dams

An underground dam is a hydraulic structure that inhibits the natural flow of subsurface water to store it underground in the respective aquifer behind the barrier [13]. For this type of structure a trench is excavated across a valley to depth of bedrock or an impervious stratum at the desired location. After this, an impermeable wall structure (preferably of masonary or concrete material) is constructed in the excavated trench to halt the underground flow of ground water [13]. A subsurface storage reservoir generated by this manner could store ground water during wet seasons, which could be withdrawn later (during the dry season) to provide a semi-continuous supply of water.

The impermeable barriers or wall-like structures could also be constructed from the suitable and conviniently available materials like clays, stone masonry, reinforced concrete, brick, plastic, sheets of steel, corrugated iron, or PVC sheets. According to Onder & Yilmaz [3], the impermeable wall may also be obtained by using injection screen. There is another construction method, soil mixing method which was pioneered by the Japanese [5]. Although an underground dam with 110 m height has been constructed in Brazil [3], the average height of the underground dams is usually in the range of 2 to 6 m. However, in some cases (See Figure 4), the injection screen method has been employed to create seepage barriers up to 10 m or more [2,3,10].

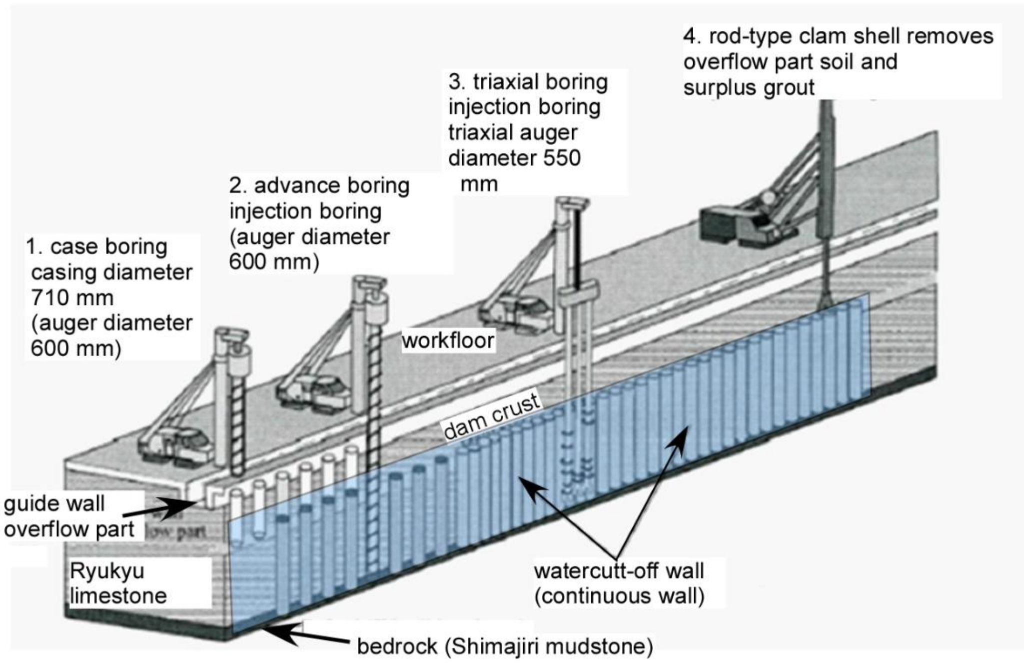

Figure 4. Conceptual diagram of the mix-in-place (or soil mixing) construction method (modified after [5]).

3.2.Sand Storage Dams

A sand storage dam is a particular type of sub-surface structure built across ephemeral stream on an impermeable layer [14]. This type of groundwater dam is generally a weir constructed in stages, as shown in Figure 3. Thess structures allowa n increase the water storage capacity in stages by accumulating sand and gravely material upstream of the dam structure, which is raised gradually in steps before the start of each rainy season, until it extends to an appropriate height. The normal height of this type of dam typically varies from 3-5 m, depending upon the the maximum channel bank height during flash flooding events [15, 16]. A sand storage dam is generally constructed from stone masonry, reinforced concrete, gabions with clay cover, stone-fill concrete, and flat stonework [3].

4. General Characteristics of Groundwater Dams

Groundwater dams are relatively simple to construct and function similar to conventional surface dam, but with some limitations [4]. The most common attributes of these structures are: zero evaporation losses, very little siltation, environmental friendly, remain stable during small earthquakes, and less construction expense. Sometimes as an exception there is an accumulative increase in precipitation of dissolved solids, which gradually diminish unit permeability and specific yield of the aquifers under specific subsurface conditions. The limitations of groundwater dams are: less reservoir capacities, the expenses associated with pumping and maintenance of well pumps, casings, and pipeline, detailed hydrogeological investigations (including pumping and sustained yield tests), aquifer quality tests, and groundwater modeling prior to construction.

The feasibility of constructing groundwater dams with adequate recharge conditions and reduced seepage losses are governed to a large extent by topographical conditions, geological environments, and geographic settings [2]. It is generally preferable to site groundwater dams in well defined or narrow valleys. In addition, the groundwater basin in which water is to be stored must be underlain by bedrock or formations of relatively low permeability to preclude vertical and lateral seepage losses. Furthermore, the impervious layer, bedrock, or low permeability materials must be at such a depth that it is technically possible to carry out the construction at reasonable cost. The optimum sites are often situated near the transition zones between mountains and plains.The storage capacity of both groundwater dams and sand storage dams is often a function of the specific yield of the formation (sediment). Dams should preferably be constructed in geological environments where the weathering products contain a substantial amount of sand and gravel. Climate also exerts significant influence on sediment characteristics in that it governs the relationship between mechanical and chemical weathering. A lower rate of chemical weathering in arid climates may result in more coarse-grained sediments.

4.1.Underground dams

Underground dams are mostly commonly constructed in riverbed aquifers consisting of sand or gravel. Other types of aquifers that may be utilized for groundwater reservoirs include weathering zones, alluvial or colluvial layers, or any type of overburden that is reasonabally pervious. Infiltration conditions must be such that the reservoir is properly recharged during rainy periods.

General characteristics of underground dams can be summarized as follows [2, 15]:

- underground dams are subsurface structures, hence, they don't affect the utility of the ground surface above the storage reservoir area.
- underground dams store surplus water during heavy rainfall seasons that could be accessed later, during dry seasons.
- The physical properties, like temperature of the groundwater, remain more or less constant throughout the year, which helps to provide a continuous supply of cooling water.
- The construction procedures employed in building underground dams are conceptually straight forward. No strict quality control is required as compared to an embankment dam (surface). There is no any anticipated disaster that could be caused in the case if an underground dam fails.
- Underground dams can be constructed in stages, which allows the quality and functionality of the structure to be verified before the completion of the structure.

- These types of structures (several meters deep) can augment water storage capacity by as much as 100 million cubic meters, in depending on the volume of storage media (usually uncemented channel alluvium).
- Underground dams not only play an effective role in the proper utilization of groundwater resources, but help control undesired fluctuations of groundwater level. For example, it can avoid the variation of the groundwater level in areas normally subjected to changes in water table, common near lakes or rivers. This is quite helpful in preventing saltwater intrusion along coastlines, which can pollute fresh water aquifers (Figure 3).
- The crest of a groundwater dam is usually placed at some depth (usually one meter below the ground surface) in order to preclude loss of soil bearing capacity and creation of undesired wetlands upstream of the dam structure (see Figure. 1). The stored water can be extracted by drilling wells in the groundwater reservoir or by a gravity pipelines placed under the favorable topographical settings.

4.2. Sand storage dams

Sand storage dams are a type of weir constructed across a channel in multiple stages. The staged construction of the weir should be progressed in such a way that it facilitates the fine grained material (silts and clays) to be sluiced out of the sand and gravel layers by the anticipated turbulent overflow. In this situation, the reservoir storage capacity depends upon the coarseness of the material. The deposited sand and gravel upstream of the dam, can store water up to 35% of their total volume, depending upon the size and shape of voids [2, 14].

Suitable sites for sand storage dams are usually governed by topography, land use, and river channel characteristics. Steep slopes and vegetation cover in the catchment area govern the extent of erosion. Ephemeral-fluvial sand deposits are ideal for storage of run-off in a sandy reservoir in arid regions along the ephemeral streams [2]

Sand storage dams must have a strong body to resist all the applied forces and should be constructed in a proper way to provide adequate slope stability of the structure. In addition, the main body and the toe dam should be designed to withstand the erosive action of water which often carries suspended silt and sand [3]. The stored water is usually extracted by providing a drainage structure at the lower end of reservoir in the upstream of the dam, and joining this drainage to a well for pumping out to the surface, or to a pipe through the dam wall as gravity flow (Figure 2). Sand storage dams are most favorable for gravity water extraction.

5. Conclusions

Groundwater dams are suitable water supply structures to store groundwater in arid and semi-arid climate dominated regions. They have been employed for about 2,000 years, beginning with the Roman Empire. They can be an alternative solution for conditions where traditional surface dams are not suitable or applicable due to unsuitable geological conditions (such as old landslides, sinkholes, caverns, etc.), evaporation losses, pollution problems, land losses, and silting problems. Although there are hundreds of groundwater dams serving irrigation, domestic consumption, and livestock in some parts of the world. With considerate attention, groundwater dams can serve as alternative water supply and storage infrastructure. Groundwater dams are most suitable for arid areas, where open storage is subject to considerable water storage loss through direct evaporation and evapotranspiration, like Sindh and Baluchistan provinces of Pakistan. Groundwater dams could also allow greater storage of runoff that occurs during the seasonal monsoon and utilize it effectively during periods of drought.

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