Artificial Recharge (AR) of Groundwater Aquifers in Saudi Arabia

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Abstract

Saudi Arabia in general is one of hottest and most arid countries in the world, with average maximum summer temperature reaching 46^{o}C and an average rainfall of 120 mm per year. Huge amounts of collected seasonal rainfall water are lost by evaporation. Saudi Arabia has three primary types of water resources. These are non-renewable groundwater, renewable ground and surface waters, and desalinated sea water.

Huge amounts of fresh water supply in Saudi Arabia come from non-renewable groundwater aquifers. Natural recharge cannot replace the amounts of exploited fresh water; therefore, there is a necessity for artificial recharge (AR) of groundwater aquifers with surface fresh water. Artificial recharge is used to directly recharge surface collected fresh water (rainfall) into depleted groundwater aquifers through specially drilled wells to save it from evaporation and pollution for save in current or future needs.

In this paper, the main conditions necessary for groundwater aquifers to be suitable candidate for artificial recharge (water injection) are presented with direct emphasis on groundwater aquifers in Saudi Arabia. The typical design of injection station is outlined. Furthermore, the engineering calculations necessary for design, predictions and management of artificial recharge projects are presented.

Keywords: *Groundwater, Artificial recharge, Rainfall, Evaporation, Fresh water, Injection well, Permeability, Dams.*

1. Introduction

Saudi Arabia (2.25 million square kilometers) in general is one of hottest and most arid countries in the world, with an average maximum summer temperatures of 46^{o}C and an average rainfall of 120 mm/year. Water resources in Saudi Arabia are conventional which includes groundwater and surface water, and non-conventional such as desalinated seawater and treated waste water. About 88 percent of the water consumption in Saudi Arabia is met by groundwater. The western coastal plain (Tihama) receives 60 percent of the country's total rainfall. Rainfall in this region provides an average fresh water supply of approximately 1.85 billion cubic meters of water [1, 2]. 251 dams (26 are under construction [3]) with approximate capacity of 778 million cubic meters were constructed in the kingdom to control water flood and to collect water for drinking and agricultural purposes [4]. For example, King Fahd dam in wadi Bishah (103 m height, 80 m average width and 507 m length) is the second biggest in the Middle East with 325 million m^3 (see **Fig. 1**) [5]. Unfortunately, most of the collected water is lost by either evaporation (an average evaporation rate of 1805 mm/day [4]) of leak into shallow unconfined formations.

Desalinated water production is approximately two and a half million cubic meters per day (57% from the Arabian Gulf and 43 from the Red Sea), constituting approximately 45 percent of annual water consumption in the main cities in Saudi Arabia [1]. **Table 1** lists the major aquifers in Saudi Arabia [1, 6]. All wells drilled in these formations for groundwater production are vertical [6].

There are ten principal and five secondary aquifers, based on their real extent, groundwater volume, water quality and development potential as shown in **Table 1**[7]. These aquifers are formed millions of years ago and most of these aquifers are not receiving natural recharge at the present leading to either depletion and/or water quality deterioration with time [8-11].

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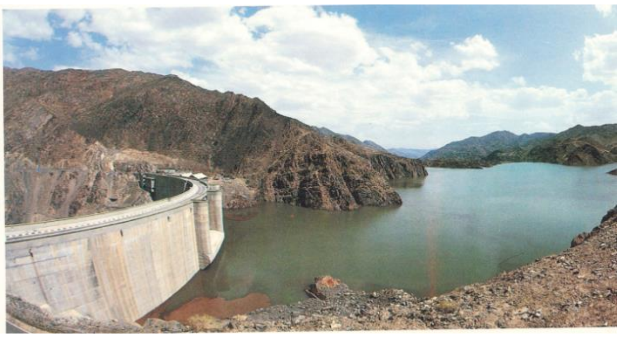

Fig. 1. King Fahd dam in wadi Bishah in Saudi Arabia [5].

Table 1. Major groundwater aquifers in Saudi Arabia [2].

Aquifer's name (Rock type)	Water depth, m	Thickness, m	Productivity, 10^3 m^3/day	Location
Saq (Sandstone)	150–1500	650	8640	Central-North
Wajid (Sandstone)	150–900	600	3456–6912	Southern
Tabuk (Sandstone and Shale)	60–2500	1072	1296–1728	Central-North
Minjur (Sandstone)	1200 –2000	315	518 –10368	Central-South
Dhruma (Sandstone and Limestone)	100	375	518 –10368	Central
Biyadh (Sandstone)	30–200	425	2160–4320	Northern
Wasia (Sandstone and Shale)	100–800	150	7344–9504	Central-East
Umm-Er-Radhuma (Limestone)	100–400	330	4320–8640	Eastern
Dammam (Limestone)	160–200	80	605–1900	Eastern
Neogene (Sandstone and Limestone)	50–100	100	4320–8640	Eastern

Wajid groundwater aquifer is the nearest to King Fahd dam in wadi Bishah and therefore the most suitable candidate for artificial recharge. Wajid groundwater aquifer area encompasses a variety of geomorphologic units that are characteristic for the southwestern part of the Kingdom of Saudi Arabia. From east to west the main units are: the Rub' Al-Khali desert, the Tuwayq Escarpment, the Wajid Plateau, the Hijaz Plateau and the Najd Peneplain on the Arabian Shield, and the Asir Highlands (455,000 square kilometers)[7]. The Wajid Sandstones are made up of two permeable formations, the Upper and Lower Wajid Sandstones, which are separated by a less permeable shale formation. They are hydraulically connected over a long distance to constitute a regional aquifer system.

The objectives of this study are to shed lights on the possibility of artificially recharging groundwater aquifers with collected rain water in several parts of the Kingdom of Saudi Arabia, and to present technical and theoretical aspects of artificial recharge technique.

2. Artificial Recharge (AR) Theory

Collected rain water must be physically treated to remove solid contaminates and bio-chemically treated as well to remove organic pollutants before injection into groundwater aquifers. Furthermore, the injected water must be free of clay particles to minimize permeability damage. For vertical injection wells, water injection rate is highly dependent on aquifer average permeability ($\bar{k}$, Darcy), radius of the well drainage area (r_e, m), wellbore radius (r_w, m), injected water viscosity (μ_w, cp), water formation volume factor (β_w, dimensionless), aquifer thickness (h, m) and pressure drop (ΔP, kPa). By the combination of the above parameters, injection rate through vertical wells (Q_{inj}, m^3/day/well) can be calculated using the following expression (Darcy equation) [12]:

$$Q_{inj} = \frac{3.368\,\bar{k}\,h\,\Delta P}{\mu_w\,\beta_w \ln(r_e/r_w)} \qquad \ldots(1)$$

Realistic predictions based on equation 1, require precise evaluation of the equation's parameters for the aquifer under consideration. Calculations made in this work were based on hypothetical data shown in **Table 2**.

Table 2. Technical data used in calculation in this study.

Average permeability ($\bar{k}$) = variable (0.5, 1.0 and 1.5 Darcy).
Single vertical well drainage radius (r_e) = 423 m.
Wellbore radius (r_w) = 0.1143 m.
Aquifer thickness (h) = 366 m.
Water formation volume factor (β_w) = 1.0.
Fresh water viscosity (μ_w) = 1 cp.
Pressure drop (ΔP) = Variable (50, 100, 150 and 200 kPa).

3. Candidate Aquifers for Artificial Recharge

As mentioned previously, sedimentary formations (sandstone and limestone) are covering the central, northern and western of the Kingdom of Saudi Arabia. These formations are dipping towards the east. Outcrops of these formations can be seen in the central and northern regions. All groundwater aquifers are located in these sedimentary formations as shown in **Table 1**. Massive impermeable rocks called the Arabian Shield as shown in **Fig. 2** cover the western and southern regions of the Kingdom and receive the maximum rainfall.

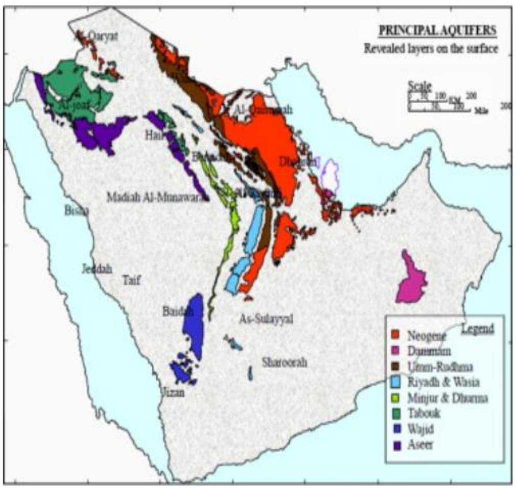

Fig. 2. Principle aquifers for groundwater in Saudi Arabia [6].

In some parts, thick layers of soil cover the Arabian Shield rocks. Therefore, injection wells must be drilled to the nearest aquifer of those mentioned in **Table 1**. Based on capacity and location, Wajid and Minjur aquifers are the most suitable candidates for artificial recharge by rainfall water collected in the southern region of Saudi Arabia.

4. Typical Design of Artificial Recharge Wells

Artificial recharge of groundwater aquifers is the process of injecting collected rain water after physical and bio-chemical treatment into targeted aquifer through specially designed and drilled injection wells. Treatment stations and injection wells should be drilled away from the dam location to be safe from floods. Treated water is then pumped to injection wells and for local users in the area. Injection and production wells must strictly satisfy the following requirement as shown in **Fig. 3**:

i) Rotary drilling tool with suitable drilling fluids must be used to minimize contamination between different aquifers during drilling process.

ii) Isolating all formations overlaying the targeted aquifer. This is done using cement slurry and steel casing.

iii) Injected water is directed exactly into the required depth through the perforations in the cemented casing III.

iv) Installing a wellhead with specially designed valves to minimize contact with adjacent surface environment.

Casing used in artificial recharge injection wells must be corrosion resistance with sufficient collapse, burst and tensile strength. Casing size must be carefully selected to allow drifting of tools required in any future workover and logging jobs.

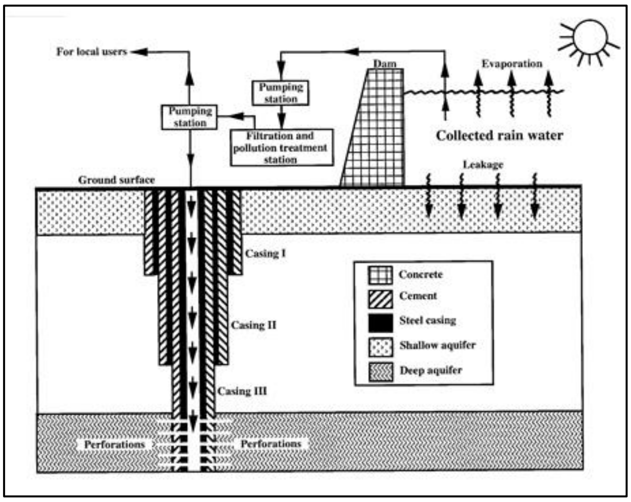

Fig. 3. Schematic diagram of a suggested groundwater artificial recharge station.

5. Results and Discussion

As mentioned above, if rain water is injected into deep groundwater aquifers, huge amounts of water will be saved from evaporation and contamination. The injected rain water is then becomes available for drinking and farming throughout the aquifer. As shown in equation 1, water injection rate in a particular groundwater aquifer is directly proportional to pressure drop and aquifer's average permeability and thickness (**Figures 4** and **5)**. Injection pressure must be high enough to force injected water into the aquifer and it must be lower than the fracturing pressure of the aquifer rock as well. If the injected water contains suspended solids and clays, then, the near wellbore aquifer permeability will be damaged leading to decline in the injection rate. Injected water will fill large pores first. Small pores filling with water requires higher pumping pressure. Pumping pressure must not exceed aquifer's rock fracturing pressure to avoid initiating new fractures or enhancing the existing fractures to open. Uncontrolled fractures may lead to communication between different aquifers leading to water mix-up.

6. Conclusion

Based on the analysis conducted in this study, the following conclusions are obtained:

- Using artificial recharge process, appreciable amounts collected rainfall water can be saved from evaporation and contamination.
- Collected rainfall water must be physically and bio-chemically treated before injected into deep aquifers.
- Injected water must be free of solids to minimize aquifer permeability damage.
- Injection wells must be carefully designed and drilled in the proper place with respect to the recharged aquifer.
- Wajid and Minjur aquifers are the nearest and the most suitable candidates for artificial recharge by rainfall water collected in the southern region of Saudi Arabia.

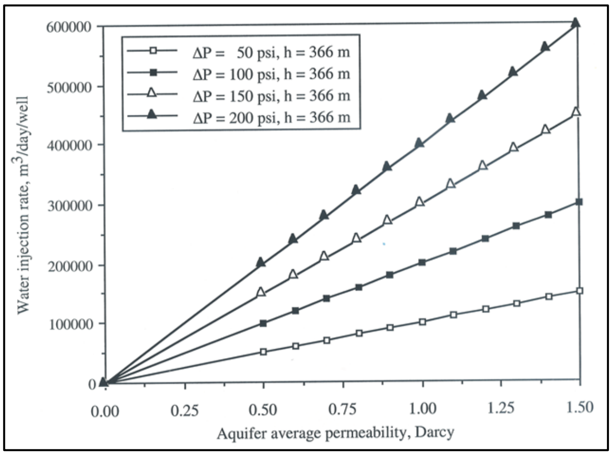

Fig. 4. Relationship between aquifer average permeability, pressure drop and water injection rate.

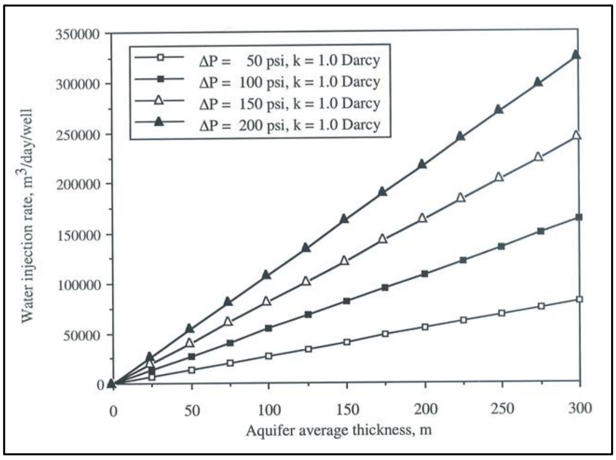

Fig. 4. Relationship between aquifer average thickness, pressure drop and water injection rate.

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