The Aquifer Recharge Potential by Infiltration Tests in Arid Region, Ras Al Khaimah, United Arab Emirates

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Abstract. Water flow through soil layers (infiltration) encompasses the key element of the hydrologic cycle, where it characterizes the pathway of contribution to the groundwater aquifers. Infiltration tests are carried out in the field to measure the soil layers’ infiltration rate and their corresponding hydraulic conductivity. The investigation site, Wadi Al Bih dam, represents one of the significant locations for water harvesting and storing in the United Arab Emirates (UAE). The dam plays essential role in preventing and mitigating the flash flooding and assist the infiltration process to recharge the shallow groundwater aquifer. This study targets to measure the infiltration rate on both sides of the dam and emphasize the relationships between the precipitation and water percolation downwards as well as the dam ability to accumulate and store the surface water especially during the intensive water storm events. The results reveal a remarkable variability of the infiltration and the hydraulic conductivity values in both the upstream and downstream of the dam. The average infiltration rate varies from 23.9 to 27.71 cm/h and the average hydraulic conductivity ranges between 9.82 and 39.67 cm/s. This shows the noticeable changeability of the soil cover to absorb the surface water and push it down to recharge the shallow aquifer.

1. Introduction

The proper appraisal and handling of water resources in the United Arab Emirates (UAE) would certainly lead to groundwater preservation and improvement of both quality and quantity and mitigate the future depletion especially for shallow aquifers. The groundwater in the UAE is a principal natural resource and represented by different types of aquifers. The Quaternary shallow aquifer, which is composed of clastic bearing formations, mostly has a fresh water and lies along the borders between the UAE and the Sultanate of Oman. The aquifer recharge mainly occurs from the seasonal rainfall along the summit of Oman Mountains.

The study area lies in the northern emirate, Ras Al Khaimah, UAE at the downstream of Wadi Al Bih, which represent one of the main Quaternary clastic depositional system that can be considered as a significant rainfall water collective zone (Figure 1). During intensive rainfall, huge amounts of surface water bodies or bonds appear that either penetrates into the subsurface or creates temporarily local surface lakes and valley runoff through Wadi Al Bih area [1].
Therefore, the Ministry of Agriculture and Fisheries (MAF) has constructed number of dams across the main valleys of the UAE to harvest the rainwater, to sustain the water resources in the country, to protect the environmental system and to recharge the aquifers. The Wadi Al Bih dam is one of them and represents one of these major constructed ones in the study area. The effects of storm-related flush flooding and extent of the shallow aquifer recharge in the dam reservoir area where groundwater from the valley’s aquifer is used mainly for human consumption, farming and development purposes need to be carefully evaluated. Characters of the top clastic layers become vital for the water stability approximation and evidence about the infiltration capacity of the dam surface reservoir \[2\]. These data are not available and the current work intents to expose such information on the upper part of the aquifer system through field and laboratory investigations.

The objective of this study is to measure the infiltration rate and find out the hydraulic conductivity on both sides of the Wadi Al Bih dam and highlight to what extent the relationship between precipitation and water percolation underneath the ground surface. Accordingly, the findings reveal the possibility of the dam to collect rainfall water and rejuvenate the shallow groundwater aquifers in such areas.

2. Regional geology, climate and hydrogeology

Inflow and improvement of both surface and groundwater and the geomorphic features have a great role in the field of hydrogeological investigations. The characteristics and patterns of the storage layers, stratigraphic sequences and structural zones of hydrogeological systems are controlled by a local geology as well. Therefore, surface water runoff from rainfall events, infiltration rates, storage capacity, and groundwater level fluctuation in the system will be greatly affected by those factors.

Furthermore, the construction of major and minor dams along the area is important for harvesting rainwater, protecting environmental system and recharging aquifers through such areas that is characterized by the prevalence of geomorphologic features such as mountains, gravel plains, and drainage basins. The capability of the system to be recharged from rainfall would be determined to a high extent by the infiltration rate of the top most soil zone. The Wadi Al Bih comprises extensive network of tributaries covering a surface area of 483 km\(^2\). It refers to the biggest drainage basin in the
UAE and denotes one of the most significant aquifers in the northern part of the UAE. Also, thin soil and rare vegetation zones exist in the Wadi Al Bih area.

A rugged topography with steep slopes characterizes the Wadi Al Bih drainage basin and its catchment area underlain by limestone. The basin size is intermediate and with high degree of flush hazards [3]. The minimum and maximum elevations above mean sea level are 65 and 2,087 m respectively.

Permian to Mesozoic shallow-water, carbonates, which are exposed in a couple of west-verging thrust sheets, are the main components of the regional geology of the study area (Figure 2). Due to the obduction of the Semail ophiolite during the Late Cretaceous, these rocks are part of the Arabian shelf deposits and were thrust [4]. During the mid-Tertiary and eventually in the formation of the Musandam Mountains and the peninsula, a later tectonic phase, related to the folding of the Zagros Mountains, resulted in thrust culmination [5]. These Permian and Mesozoic sediments were deposited Paleo-geographically, on a shelf located between the Arabian shield in the SW and the Tethys Ocean in the NE. The complete sedimentary succession is more than 3,000 m in thickness and denotes less tectonic overprint than age equivalent sequences in the Oman Mountains [5]. The Upper Permian and Triassic strata are about 1,700 m in thickness. The Hagab and Yabana anticlines, in the Wadi Al Bih area as well as on the eastern shore of the peninsula in Omani Musandam represents two main outcropping structures in Permian deposits [6]. Triassic and younger Mesozoic rocks have been encountered in several offshore wells and are found throughout the area [7].

The UAE is in the eastern part of the Arabian Peninsula with arid climate. In summer, infrequently rainfall and temperature may reach up to 48 °C. In winter, approximately 14 °C is the lowest temperature recorded. The average temperature variations across the country in overtime [8-10]. Over 80% of the annual rainfall takes place during the winter. The average monthly rainfall pattern fluctuates widely through the year and the average annual rainfall was about 120 mm/year during the period of 1970-2001. Rainfall decreases from mountain areas to desert and coastal areas over the whole year [8, 9, 11,12].

Generally, the study area gets little rainfall, but some seasonal unexpected water storms occur and cause extensive flooding in the province. The available data from 1977 to 2014 point out irregularity of rainfall and temperature. Rainfall averaging 120 mm/year mainly happened in winter from November to March [11]. Temperature varied over the period and acquired its high value in summer [11-13]. The maximum and minimum rainfall values recorded in 1982 and 1985 were 381 and 14 mm/year, respectively. The maximum and minimum temperatures were 28.8 °C and 14 °C in 2010 and in 1992 at Ras Al Khaimah Airport. The annual mean temperature was 27.7 °C (Figure 3).

The UAE aquifers are classified as northern limestone, ophiolite, gravel, sand dune and coastal Sabkha aquifers (Figure 4). The major fresh groundwater reserve in the UAE is available in the gravel alluvial deposits (blue colour in Figure 4). Around 74% of the total area of the UAE is covered by the sand dune aquifer that receives most of its recharge from the western side of the mountain. The Arabian Gulf and Gulf of Oman are the main discharge area [14].

Based on the lithological composition, the study area aquifer is classified into the upper gravel and the lower limestone units consequently. The upper unit composed from loose, coarse, and high permeable alluvial gravels originated from carbonate and the lower part consist of fissured limestone, which underlain the gravel deposits. Therefore, the gravel deposits of the valley might have a good ability to carry water with small storage volume. Most of the natural recharge to the aquifer systems is expected from the heads of alluvial fans by infiltration form valley’s flows originated in the mountain zone [15]. The recharge to the Wadi Al Bih aquifer happens from a catchment area of average elevation
of 1,050 m above mean sea level (AMSL) [13]. Groundwater flows in the study area is from the upper segment in the northeast to the lower segment in the southwest.

![Geological map of the study area](image)

**Figure 2.** Geological map of the study area [5].

Recharge amount in most arid regions would be in the order of 2% to 10% from the total volume of annual precipitation. However, this could be considerably increased through the suitable implementation of water harvesting plans including the construction of retention and detention dams across the main valleys [16]. The vertical hydraulic conductivity of the alluvial gravel decreases from 10 m/day at the unconfined and non-cemented upper aquifer to 0.1 m/day in the middle semi confined and semi-cemented aquifer [17]. The lateral (horizontal) hydraulic conductivity of the upper unconfined aquifer ranges from 32 to 67 m/day, which can serve as channels for sideward transport of surface water [18].
Figure 3. Rainfall and mean temperature of the Ras Al Khaimah emirates from 1977 to 2014 [6-7].

Figure 4. Main aquifers in the UAE [14].

3. Materials and methods
In the study area, five sites were selected to perform double ring infiltration test and seven for borehole investigations (Figure 1). However, site seven, has no double ring infiltration test but it was selected to carry a single ring test. The representative test sites were designated based on the sediment composition and textural variability, recharge orientation and accessibility (Figure 5 a-d). Five tests were carried out in the upstream and seven tests were conducted in the downstream (Figure 1). According to the ASTM standards [19], increment infiltration rate was measured using double ring device of 30 cm diameter (inner ring) and 60 cm (outer ring) while the borehole infiltration test was done manually by recoding the elapsed time and the total depth of water lowering in the borehole. In double ring tests, water level in the outer and inner rings was automatically maintained at a constant head using two floating siphons. Maintaining a constant head in the outer ring was not as critical as maintaining constant head in the inner ring to measure the infiltration rates. This is because the purpose of the outer ring head (the annular space between the two rings) is to reduce or prevent the leakage of water outward under the inner ring.
area however, the flow rate (cm$^3$) was taken in consideration for calculating the increment infiltration along the test duration time. In situ, cumulative infiltration rates and corresponding time were recorded for each double ring tests, which generally continued for about 4-6 hours or when the infiltration rate becomes constant that reveal the saturation of the underneath soil by the injected water. Sediment information for each site was obtained from field hand specimen description as well as laboratory sieve analysis of eleven soil samples were collected from all the tested locations. Finally, field data of each test was graphically represented to visualize the soil behaviour with respect to the infiltration rate.

![Figure 5](image)

**Figure 5.** Upstream: a) double ring test and b) borehole test, Downstream: c) soil sampling after double ring test and d) borehole test.

4. Results and discussions

The infiltration rate results including both double ring and borehole tests in the upstream and downstream of the dam vary from 3.9 to 72 cm/h and from 2.55 to 67.3 cm/h (Figure 6). The overall average values for the upstream and downstream are 23.9 cm/h and 27.71 cm/h, respectively. This point out that the infiltration rate of the dam area, upstream and downstream, are strongly matching to each other even though the infiltration data highly fluctuate. The nature and textural changeability of the top most layer of soil zone in the dam site could be the main reason of this variation. The minimum infiltration rate was recorded at the downstream (Dr-4) as 2.55 cm/h and the maximum infiltration rate was distinguished at the upstream (Bh-1) as 72 cm/h. Mostly, the infiltration rate at the upstream during the first two hours indicates fast decreasing trend, then either vary (Dr-1 and 2) or stabilize (Dr-3) during the test period (see Figure 7a). As it is expected, the infiltration rate at the downstream, test site Dr-5, displays increasing trend, but at test site Dr-4, the trend is not clear and has mixed behavior, decreasing-
increasing and also highly scatter during the first two hours of testing (see Figure 7a). This could be directly related to test site that was controlled by the nature of soil cover that are mainly composed of either gravel or greater than gravel and some fine grains. The pore spaces between coarse grains may filled by fine grain matrix sediments (silt and clay) or calcium carbonate cement which give rise to drop in the infiltration rate values. On the other hand, during the test duration time the fine sediments may be either washed away or dissolved under the water rock interaction then lead to increase of the infiltration rate.

Figure 6. Infiltration rate and hydraulic conductivity distribution for double ring and borehole tests.

Figure 7. Observed infiltration rate versus time for a) double ring b) borehole tests.
Furthermore, all borehole infiltration tests either at upstream (Bh-1 and 3) or downstream (Bh-4, 5, 6 and 7b) site indicate clear increasing trend in time (Figure 7b). The average values of hydraulic conductivity at upstream (9.83 cm/s) is about 4 times less than the average values of hydraulic conductivity at downstream (39.67 cm/s). This could be understandable insight of the topsoil conditions and the controlling factors on both sides of the dam area.

The graphical illustrations of some selected sieve analysis results for double ring tests display recognizable variability in the grain size which were represented by well graded sand with gravel (Figure 8a-b). On the other hand, sieve analysis of some boreholes shows poorly graded gravel with sand. These variations in the texture of the deposits are apparently belongs to the complex nature of the lithological constituents as well as the geomorphological conditions of the study area.

**Figure 8.** Example of sieve analysis plots for double ring tests.
5. Conclusions and recommendations
As clearly perceived in the study area (Figure 5) and shown by the test results (Figure 7), soil features at the top most zone (about 0–100 cm) have a vigorous role in surface water infiltration or perching. Especially, the coarse-grained nature of the sediments and the mud cover (approximately 0–50 cm thick) in the dam reservoir (upstream) are pushing up the water seepage in some zones and perching the water for sometimes in the other areas (Figure 7). In most cases, the infiltration rate and hydraulic conductivity in the downstream site is greater than the upstream site despite having the larger reservoir area. However, the infiltration rate and hydraulic conductivity in both sites are expected to be similar to each other. Although, the average infiltration rate in both sites are almost the comparable to each other (upstream 23.9 and downstream 27.71 cm/h), the average hydraulic conductivity in the downstream is about four times greater than the average hydraulic conductivity in the upstream (upstream 9.83 and downstream 39.67 cm/s). This could be due to effect of the mud cover of top most seditious, which composed of mix of clay and silt. Accordingly, this clayey soil can be dissolved and dissolve in the rainfall water and moves downward to decrease the hydraulic conductivity and infiltration capacity. In addition, some areas close to the dam construction has relatively thick mud cover which prevent completely the water movement downward into the shallow aquifer. Also, the composition and textural variability of the sediments and its dryness conditions, enforce the soil to absorb more water and increase the underneath flow.

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