# Climatic and Hydrogeologic Characteristics of Wadi Al-Lith in Saudi Arabia

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ABSTRACT. The groundwater represents the main water source all over the Kingdom of Saudi Arabia, where, intensive quantitative and qualitative studies are urgently needed. Wadi Al-Lith basin is chosen as one of Tihama basins, that run in the Western Arabian Shield. In this study an evaluation of the groundwater aquifer of the basin was made, including the hydrogeological and the climatological characteristics that are required to estimate the hydrological characteristics of wadi Al-Lith. The different conditions of wadi discharges and recharge were determined. The calculated groundwater gradients were 0.0042, 0.008, and 0.009 m/m in the three main wadi tributaries. The average hydraulic conductivity and specific yield reached 120 m/d and 0.25, respectively. The recharge ratio due to rainfall was calculated utilizing the observed soil moisture distribution after infiltration. The calculated recharge ratios downward the top four soil layers were 40%, 30%, 4%, and 0.0 % at depths 0.0 m, 1 m, 2 m, and 3 m, underground surface, respectively. These ratios could be used for modeling of groundwater status of the basin.

#### 1. Background

Based on the nature of environment and sacristy of water resources, the Kingdom of Saudi Arabia is classified as an arid country. It has a low precipitation, high evaporation and limited water resources in terms of quantity and quality. In addition, groundwater abstraction is much greater than replacement by recharge. Excessive draw down, and small well yield takes place in addition to contamination by irrigation and salt water. However, the most challenging task for the water resources planner is to achieve the optimum ground water management. The Tihama region in the South Western part of Saudi Arabia is of special interest because it has more frequent rainfall and runoff than other regions in the kingdom. This part contains a number of wadis where their aquifers are classified as unconfined shallow aquifers. The water bearing formations mainly consist of alluvium deposits that are silt, sand and gravel in addition to weathered and fractured bedrock. Due to similarities in the physiographic and ground water characteristics of Tihama wadis, the ground water study for one of its wadis could represent the groundwater status for other wadis in the region. However, Wadi Al-Lith was selected as a representative case of the region of Tihama wadis. This wadi was selected due to its potential development including the quality and quantity of ground water, as well as urban and agricultural activities.

Wadi Al-Lith is located about 200 km south of Jeddah City, with 3080 km<sup>2</sup> catchment area. It lies between longitudes 40°15' and 40°30' and latitudes 20°00' and 21°31', as shown in Fig. 1. The study area is a part of the western province of Saudi Arabia. Many organizations and investigators had studied the water status in this part. Surman and Abdulrazak (1988), presented a study about flood prediction in Wadi Al-Lith. Dames and Moore (1987) performed an intensive study about five wadis in the western provinces of the Kingdom, including Wadi Al-Lith. Abu-Al-Heija (1985), described the geotechnical properties of Al-Lith Sabkha. In 1984, the Ministry of Agriculture and Water in Saudi Arabia (MAW) presented a water atlas for the Kingdom of Saudi Arabia. Othman (1983), presented a study on water resources in Saudi Arabia including Tihama Wadis. The hydrological study of the Arabian shield and its coastal areas on the Red Sea were summarized by Hoztl and Zolt (1982). Al-Syari and Zolt (1978) described the quartenary deposits in Saudi Arabia. Skipwith (1973), studied the geology and geomorphology of the Red Sea coastal plain. Segoreah (1970) tested the wells in Wadi Al-Lith basin for groundwater assessment.

#### 2. Climatic Condition

The Kingdom of Saudi Arabia locates between latitudes 16° and 32° North in the dry tropical desert range. In winter, it is under the high-pressure zone, which is effected by the dry Trade Winds, while in summer, it comes under low climatic pressure. All these factors in addition to the dry Continental Winds, make it dry through out the year with high temperature in summer. The general climatic feature of the basin is hot and dry, where the Kingdom is classified as arid region according to UNESCO classification. The climatic data was collected from Sogreah (1970), Dames and Moore (1984 through 1986) and from the Ministry of Agriculture and Water (MAW) reports as well.



FIG. 1. Location map of Wadi Al-Lith in Saudi Arabia.

#### i) Air Temperature

The mean monthly temperature varies from 26°C to 36°C (MAW, 1987). The available data shows that the highest and the lowest temperature during the period 1984 through 1992 were 49°C in July and 15°C in January, where the mean annual temperature is 32°C. It has been observed that the maximum temperature occurs in July and the minimum temperature occurs in January.

# ii) Relative Humidity

The relative humidity is very high due to the area is closed to the Red Sea. The mean monthly humidity ranges from 41% to 64%, while the average annual humidity reaches 54%. The highest relative humidity is in April when it reaches 90%, and the lowest value is in July, when it reaches 21% (Dames and Moore, 1987).

#### iii) Solar Radiation

The highest value of monthly average solar radiation occurs in April at rate of 526 ly/d and the lowest one is in December at rate of 331.8 ly/d (Dames and Moor,1987). The annual daily average solar radiation is 448.4 ly/d. The annual average sunshine hours are about 8.7 hours per day. The maximum number of sunshine hours was observed in April, while the minimum one was observed in December.

## iv) Evaporation

Due to the hot climate and the aridity, the evaporation rate was relatively high. The maximum monthly evaporation value was 556 mm/month in July, while the minimum value was 202 mm/month in December. The total annual pan evaporation reaches 4195 mm (Dames and Moore, 1987)

# v) Rainfall

Rainfall in the study area is generally high when compared with the other regions in the Kingdom. The rainfall data was collected from Dames and Moore reports (1984 through 1987) and the Ministry of Agriculture and Water publications (MAW 1981 through 1987). The storm usually starts in mid-afternoon producing 1 to 2 hours of rainfall duration. The study area is characterized by short duration and high spatial variability of storms rainfall. The annual average of the rainfall in the basin is 206 mm/year. From Dames, and Moore (1985 through 1987), the maximum monthly rate was 13 cm/month in March and 12 cm/month in August.

# 3. Geology

Al-Lith basin runs throughout the Western part of the Arabian Shield in East-West direction. The Arabian shield, which follows Precambrian period, is located parallel to the Red Sea in the western part of Arabian Peninsula. It is mainly composed of igneous and metamorphic rocks. The ages of rocks are in between 450 and 1000 million years (Shanti, 1993). Structurally, the study range area consists of two main types of rocks. The first one is the layered rock that includes all volcanic, pyroclastic and sedimentary rocks, (Fig. 2). The second one is the intrusive plutonic rock, which consists of dykes, laccolith, batholith and some other kinds of igneous intrusive bodies (Shanti, 1993). The Arabian Shield rocks are affected by different categories of organic movements. These movements are accompanied by different sizes and shapes of intrusive igneous rocks, metamorphism and crystallization of available sedimentary rocks to metamorphic rocks and violent deformation movements. The result of previous tectonics creates miscellaneous types of structural geological features such as folds, faults, dykes, joints ... etc., which incorporates keeping movement of ground water.

The upstream part of the wadi is restricted between rugged mountainous terrain, which gets dissected by several tributaries flowing towards the main wadi. The middle and the down streams of the wadi have low relief area covered by several types of quaternary deposits including alluvium, sand plains, gravel and silt and eolion sand dune. Meanwhile, the upstream has more complicated relief area covered with relatively thin alluvium layer of sand and gravel. Precambrian layered and intrusive rocks which comprise gabrow, tonalite , grandorite basalt andesite, rhyolite, and amphibolite schist and green schist surround the upper part of the wadi. These rocks are characterized by weathered surface cover with angular blocky fragments. Unconsolidated quaternary deposits comprise the main alluvium deposits in the main wadi channel and principal tributaries. These deposits increase in thickness from upstream to downstream.

Generally, the wadi alluvium can be classified into two main categories. The first one is a primary alluvium wadi, consisting of fine coarse sand. Thin silt layer forms the first category which predominant at the surface in the main wadi. The second one is a secondary alluvium, which is represented by flat deposits overlying on the bedrock. The secondary alluvium characterizes the common out-crop bedrock. The alluvium thickness of all study area varies from a site to another depending on the geological and the hydrological factors. Based on the wells inventory, the soil analysis and the physiographical maps, the geological subsequence starts ends with crystalline bedrock followed by weathered bedrock and finally with alluvium deposits at the ground surface.



FIG. 2. Geographical map of the study area (Dames, and Moore, 1984-1987).

#### 4. Geomorphology

The physiographic study of wadi Al-Lith shows that it is a typical one of the wadi systems flowing from western part of the escarpment ridge of the Arabian shield. It starts from the eastern mountainous slopes of the escarpment down to the Tihama coastal plain close to the Red Sea. The main wadi runs towards the sea from elevation 205 meters above the sea level, to the sea Red Sea in a distance of about 50 kilometers. The wadi starts with steep slope in the east and gentling slope at the west near the Red Sea. The high mountainous relief of the Arabian shield in the eastern region of the basin plays an important role in the precipitation events of the hydrological cycle. The high mountainous series with their orographic effect prompts the atmospheric convection that plays as heat raps to causing a low-level atmospheric convergence, which finally produces different intensities of rainfall. The relief of the wadi surface usually changes due to some physiological processes such as erosion, deposition, and transportation that may create or erase sand dune bodies.

# 5. Hydrogeological Status

The aquifer in the study area occupies  $276 \text{ km}^2$ , with 50 km and varies from 0.3 to 1.5 km in width. The aquifer consists of heterogeneous sedimentary deposits composed of gravel, sand, silt and clay with clear variations in their thickness. The thickness of the alluvium formation varies between 5 m and 40 m, from the upstream to the downstream, respectively. The upstream deposits consist of coarse gravel, where the downstream consists of clayey silt. The aquifer receives its water from the surface flow, and hot spring. In the upstream, the groundwater table intersects the surface land, where the surface and ground water are forming one unit of water. The hydrogeological map of the study area is illustrated in Fig. 3. The direction of basin drainage lies on the western side of the Tihama coastal plain to the Red Sea (Fig. 1). About 30% of the wadi's area comprises of outcrop bed rocks and shallow soils in the upstream or the upper ridges of the wadi.

The aquifer can be classified as an unconfined one where the water table responds significantly to the amount of precipitation. The wadi was divided into two main tributaries. These tributaries are Tusbih and Bathan, which may contribute water recharging into the aquifer. The seepage water, from, recharges the water to the wadi causing a rising of water table. Due to the recharge from the high escarpment, The wadi has an intermittent and a continuous base flow, approximately along 28 km wadi's length. Nearby Al-Safra Hot Springs, the hot water which emerge from the fractured bedrock, meets the previous base flow forming a different base flow in quality and quantity. The rainfall intensity and storm duration has a great effect on the base flow as discharge and distribution



FIG. 3. Hydrogeological map of Wadi Al-Lith (Dames, and Moore, 1984-1987).

rates. The resulting base flow moves along the main channel towards the downstream, where it disappears as a sink at a certain location. This location was determined with some physiographical factors such as infiltration rate, intensity and duration of rainfall and evaporation rate. The surface runoff that occurs in the wadi is generally ephemeral due to random low duration events of rainfall. The flow that occurs after rainfall events was characterized by the hydrographic comprising of steep rising limbs and rapid recessions to zero base flow. As a result of infiltration and evaporation, the runoff hydrograph decreases in magnitude. As measured by Dames and Moore(1985 through1987), the maximum runoff discharge was 30 m<sup>3</sup>/sec after 5 hours from rainfall start. This results was observed at date of 10/19/1985.

#### i) Well Inventory

Many wells and hot springs, which are allocated in the basin, had been investigated. The inventory includes well type, pumping rates, statistic and dynamic water heads, three dimensional lithology, and analysis of water quality (pH value and total dissolve of salts, TDS). Dames and Moore,(1985 through 1987) collected the well inventory, where the total dissolved salts(TDS) for the wells varied from 100 to 2500 ppm. The water pH was in the range of 6.9 through 8.

# ii) Hot Springs

Near Al-Safra village, about 50 km South East of Al-Lith City there are thermal springs that emerges from the fractured crystalline rocks. Their temperature ranges from 79°C to 90°C. The average discharge of these springs are from 5 to 10 lit/sec, where drainage its water into the principal wadi alluvium. Some physical and chemical analysis for these springs had been made by Dames and Moore(1985 through 1987). They found that the Total Dissolved Solids (TDS) was in the range of 2590 and 2660 ppm. The values of pH were between 6.3 and 6.8. The average discharge varied between 45 to 65 lit/min.

According to Segoreah (1970), the spring water is recent. Due to limitation of the data availability, it is difficult to describe the heating process and water flowing system of hot spring. Finally, it rises and emerges as Hot Springs, which may indicate that there is a deep system of ground water flow.

#### iii) Water Table Fluctuations

The ground water in the study area, generally, moves from the East (upstream) to the West (downstream). There are some sources of flow from the sub-wadies and minor tributaries. The maximum hydraulic gradient in the main direction of wadi Al-Lith was about 0.0042 m/m as measured in 7/22/93. Meanwhile, it was 0.008 and 0.009 m/m, in the secondary tributaries of Tusbih and Buthan basins, respectively. Eleven observation wells were selected for observing the water table fluctuations during the study period.

The water table was quite deep in the downstream, and shallow in the upstream. The measured water levels were used for constructing the water table map for the study area during Summer of 1993.

The calculated average Darcy's velocity of groundwater was in the range of 0.32 and 0.5 m/day. These values can be more or less depending on the hydraulic gradient, the permeability, and the pumping rate. As reported by Dames and Moore (1985 through 1987), the aquifer parameters in the basin were estimated, where the average hydraulic conductivity was 120 m/d and the specific yield was 0.25.

# iv) Aquifer Recharge by Infiltration

The process of infiltration under surface pounding water, during and after rainfall events, is of major importance to ground water recharge and water balance processes in the basin. The portion of rainfall of known intensity and duration, that can recharge to the ground water, must be estimated prior to the groundwater simulation. Therefore the previous studies in the region including moisture movement in soil and infiltration capacity were carried out to obtain that proportion.

The study area has an unconfined aquifer type in which the natural recharge to the groundwater through unsaturated zone may occur when rainfall drives water from the surface to the water table. The hydrological process of infiltration is assumed to take place as one-dimensional flow in the vertical direction. This vertical flow rate depends on location, topography, soil properties, soil moisture condition, rainfall, and water table depth. Dames and Moore (1984 through 1987) made field experiments in sandy soil locations at the wadi basin to estimate the infiltration characteristics. The pounding infiltration method was followed to observe the infiltration and soil moisture distribution in soil profile. Seven subsequent profile measurements including initial soil moisture condition were made using the Neutron Probe device with total time measurements of 865 minutes. Different experiments were conducted to illustrate different water application and duration times of infiltration. These duration times were 21.0 min, 37.0 min, 64.0 min, 79.0 min, 300.0 min and 840.0 min. The result of duration of 300.0 minutes was selected and applied in this study, where the average duration time of the affecting runoff-storm in the study area was 240 min. The results of field experiments showed that the infiltration process could reach depth

300 cm of soil in heterogeneous profile under duration time corresponding to the average storm duration time.

#### 6. Calculation Steps of Aquifer Recharge by Infiltration

The soil profile is divided into three layers in terms of soil moisture distribution over the depth (Fig. 4). These three soil layers are at depths 0-1 m, 1-2 m, and 2-3 meters below the soil surface. By considering the recharge during rainfall on over-land (no-runoff), then the infiltration can be considered as the only water flux into soil layers. The infiltration water can be generalized by using the concept of  $\phi$ -index, which represents the ratio of total infiltrated water depth (D) to the total rainfall water depth (P), as follows,

$$\phi = \frac{D}{P} \tag{1}$$

where, D is the total infiltration water depth (cm) and is equivalent to the total water stored depth in the different soil layers (cm). The portion of water that recharges to the water table can be expressed (Eqn. 1) as a fraction from the total rainfall depth (P). By considering  $F_j$  as the recharge ratio that moves downward in soil layer (j), (Fig. 4), it can be estimated by applying the water balance concept, as follows,

$$F_j = \phi \cdot (1 - \sum_{i=1}^{J} R_i)$$
 (2)

Where,  $R_i$  is the retained water fraction in soil layer *i* during the infiltration process. This water fraction can be estimated by knowing the soil-moisture distribution curves before and after infiltration events. However, the ratio  $R_i$  can be calculated as follows,

$$R_i = \frac{A_i}{D} \tag{3}$$

Where,  $A_i$  is the retained water depth (cm) in soil layer i during infiltration and it can be calculated as a function of soil water content  $\theta_i$  at layer *i* as follows,

$$A_i = \theta_i \cdot d_i \tag{4}$$

where  $\theta_i$  is the volumetric soil-moisture content in layer *i*,  $d_i$  is thickness (cm) of soil layer *i* (cm). Meanwhile, the total infiltrated water depth (*D*) could be considered as the total stored water in the different soil profile layers, as follows,

$$D = \sum_{i=1}^{n} \theta_1 \cdot d_1 \tag{5}$$



FIG. 4. Schematic diagram showing the definition of the recharge parameters.

where, *n* is the number of soil layers. Four cases of water recharging by infiltration to the aquifer were investigated. The first case is valid when the groundwater table is within a layer thickness 1 m from the ground surface, where the recharge ratio is 40%, which is the same as  $\phi$ -index of soil (the total surface ratio). The second case would occur, when the ground water table is located at depth between a and 2 m below the land surface, where the recharge ratio reaches 30%. The third case meets the condition when the ground water table is located at depth between 2 and 3 meter, where the recharge ratio becomes 4%. The fourth case would be valid if the groundwater was located at depth greater than 3 meter below the soil surface. Then the recharge ratio would be equal to 0.0%.

#### 7. Conclusions

The basin aquifer has alluvium deposits (silt, gravel, and weathered bedrock) as water bearing formations. Al-Lith basin is extending in the Western Arabian shield, which structurally consists of two types of rocks. The wadi alluvium can be classified into a primary alluvium (fine coarse sand with frequently includes silt at surface), and a secondary alluvium (flat deposits overlying the bedrock). The climate feature is classified as hot and dry, where the average temperature varies between 26°C and 36°C, the relative humidity varies between 41% and 64%. The annual evaporation rate is 4195 mm/year, where the annual average rainfall is 206 mm/year with average runoff storm duration of 1 to 2 hours. Around 30% of the area are out-cropped and shallow soils. The measured hydraulic gradient of groundwater in the main wadi stream is 0.0042m/m, while are 0.008 m/m and 0.009 m/m at the two secondary tributaries. The average Darcy's velocity is in the range 0.32 and 0.5 m/day. The average hydraulic conductivity reaches 120 m/year and the specific yield is 0.25. The penetration water depth into soil under the average rainy storm at the basin was 3.0 meter as observed during the change of soil-moisture content under infiltration experiment, when the average runoff-storm duration reached 240 hrs. The recharge by infiltration was estimated as water fraction from the rainfall excess water depth, where these fractions were 40%, 30%, 4% and 0.0% downward of the ground depths, 1 m, 2 m, 3 m, respectively.

#### Acknowledgement

The investigators would like to express their appreciation to the King Abdulaziz University in Saudi Arabia for their financial support for this study (Grant No. AR15-S17). Acknowledgement is extended to the staff of Hydrology Department, Ministry of Agriculture and Water.

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حبيب محمد خياط \* و محمد الشربيني محمد كيوان \*\* \* قسم تنمية موارد المياه ، وزارة الزراعة والمياه ، جـــدة – المملكة العربية السعودية \*\* قسم علوم وإدارة موارد المياه ، كلية الأرصاد والبيئة وزراعة المناطق الجافة جامعة الملك عبد العزيز ، جـــدة – المملكة العربية السعودية

> المستخلص . تمثل المياه الجوفية المورد الرئيسي للمياه على مستوى المملكة العربية السعودية حيث إن هناك ضرورة كبيرة للعديد من الدراسات المكثفة المطلوبة لتقييم هذا المورد ووصفه . ولقد تم اختيار حوض وادى الليث كأحد أحواض منطقة مرتفعات تهامة الواقعة ضمن سلسلة المرتفعات الغربية في المملكة . و قد تناولت هذه الدراسة الخصائص الهيدروجيولوجية والمناخية لمنطقة الدراسة في حوض وادى الليث . وفي نفس الوقت تم تقدير مختلف مصادر التغذية ومعدلات السحب المائي من الخزان الجوفي . وكانت قيم الميول الهيدروليكية لسطح المياه الجوفية وكان متوسط معامل التوصيل الهيدروليكي ومعامل التخزين النوعي ١٢٠ متراً/ اليوم ، ٢٥ , • على التوالي . ولقد كان أقصى عمق يصل إليه ماء المطر هو ٣ أمتار (داخل التربة) وذلك أثناء المطر . حيث كان متوسط مدة الجريان السطحي لمياه الأمطار هو ٢٤٠ ساعة . ووصلت نسبة مياه الأمطار المخترقة لطبقات التربة ٤٠٪ ، ٣٠٪ ، ٤٪ ، صفر ٪ وذلك أسفل سطح التربة مباشرة وعلى أعماق • ١ ، متر • ٢ ، متر ، • ٣ ، متر من سطح التربة على التوالي . وهذه النسب يمكن أن تستخدم في نمذجة الوضع المائي الجوفي للحوض .