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Original Article

Assessment of Groundwater Resources in the Hard Basement Rocks of Yemen, Al Bayda City Case Study

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Abstract:

The present study was carried out with the aim of assessing the availability of groundwater in a typical hard basement complex area in Yemen, the catchment area of Al-Bayda City catchment in the mountainous region of the country. The main objective of this study is to evaluate and quantify the groundwater resources available in this area. The available regional data on climate, topography, and geology as well as ASTER and Landsat imaginary data were collected, reviewed, and analyzed together with local hydrogeological studies and well inventories and then used to identify the general geohydrology of the catchment, characterize the local aquifer system, assess the groundwater situation and quantify the available groundwater in the study area. The results of this study show that the aquifer system accounts for only about 5 % of the entire catchment area and has a total thickness of 10 - 30 m. This aquifer has a small lateral extent and is interrupted by faults, dykes, and plutonic intrusions. Limited amounts of groundwater occur in isolated bodies along the main wadis at the base of the aquifer system. The groundwater level in these bodies has dropped by 19 m since 1983, on average by 0.5 m per year. Groundwater recharge for the current state is estimated at 1.95 million m^3/year, which is only 3% of the total annual precipitation. The total amount of groundwater withdrawn is estimated at 2.2 million m^3/year, which is 80% below the current (2023) total annual demand of around 11 million m^3. The study underlines the need to implement an urgent action plan to improve groundwater recharge through water extraction techniques. The research results can be used for the improvement and development of water resources in this area in particular and in the Yemen region in general.

Keywords: Assessment Groundwater Resources; Water Availability; Hard Basement Aquifers; Al Bayda City; Yemen

1. Introduction

Yemen, a country located in the southwest of the Arabian Peninsula with 555,000 Km^2 area and 30 million population, is an arid to semiarid climate with limited surface water and hence relies extensively on groundwater. Yemen has experienced an extreme water crisis, characterized by severe water shortages, very limited access of the population to safe drinking water, and rapid depletion of groundwater aquifers. The scarcity of water resources has become increasingly precious, resulting in serious environmental problems with socio-economic consequences. Yemen can be divided into two physical parts, the mountainous part in the west and the plateau in the east. The mountainous part of Yemen is composed mostly of volcanic rocks on the western slope and metamorphic or hard basement on the eastern slope [1]. In hard basement rocks, groundwater availability is limited to the weathered and fractured aquifers. The extent and potential of such aquifers are low, and their stored volume is small, which may lead to seasonal depletion or exhaustion of groundwater.

Al Bayda Governorate is an example of an area located on the hard basement complex rocks of Yemen. It is located in the central part of Yemen, lies within the arid zone, and is covered by the hard basement rocks for over 95 % of it is land area. Groundwater is available through dug wells but the yields of the wells are small and possibly only sufficient for drinking water supply. Being the capital of Al Bayda Governorate and representing an important city in the eastern highlands of Yemen, Al Bayda city has witnessed massive population growth and urban development. The water demand has increased with time but the availability of water decreased. Despite its significance in enhancing the availability of water resources in Al Bayda, there is no rare information about the hydrology of the region. In Al Bayda and the eastern mountains in general. Since the early 1970s, only three groundwater resource studies have been conducted in the region. The first was a comprehensive hydrogeological study, conducted by SGHORIAH in 1977/78 [2], but covered the lower part of Wadi Bayhan. The second was performed by ILACO [3], which covered some areas within Al Bayda Province including Al Bayda city. The third one was performed by GSHEC in 2008/9 [4] which aimed at evaluating the availability of groundwater in Wadi Bayhan to be used for supporting Al Bayda city water supply. The lack of information about water resources prevents proper planning and development. Therefore, there exists an urgent need for fast accurate data showing past and present water resource conditions (status) to help manage and utilize these valuable natural assets sustainably.

This research, therefore, has attempted to assess the change in the groundwater situation of the Al Bayda city catchment area. This study aims to review and update the hydrogeological information about the area with the main topic of groundwater quantity available in the area. The geological and hydrogeological situation of the area has been identified. The aquifer system underlying the study area has been characterized and then the obtained data have been used for evaluating the change that occurred in the groundwater system of the area. Hopefully, the results of this study will help the decision makers to provide solid and proper management for existing water resources and even find other alternative resources for water resources.

2. Description of the Study Area

2.1. Background to the Study Area

The basement rocks of Yemen are exposed basically in the west of the country, covering about 20 percent of its surface. The most prominent exposure of these rocks occurs in the eastern part of the mountainous region where it appears as a triangular belt covering about 40,000 sq. km area [5]. The basement region is bordered by the mountains zone to the west, the southern coastal plains to the south, the Empty Quarter, and the Ramlat Al Sbaatayn desert to the north and east (Figure 1). It is landscape is undulated (subdued) relief, with some local, bare hills, often there is no soil material at all rock outcrops. Plant cover is sparse in the hills and consists of shrubs and small trees in the valleys. The region observes arid climatic conditions characterized by warm, low rainfall, and high evaporation. The mean temperature range is 4° C to 29 ° C in January and 26° C to 41 ° C in July, and the relative humidity ranges from below 22 % to 80% [6]. The average rainfall in this region is generally below 200 mm and the average annual evaporation ranges from 1600-3000 mm [1]. Such a climate is crude to the sustainability of natural water bodies and also infiltration and percolation of the rainwater into the ground as much is lost into space.

Al Bayda, Governorate is located in the central part of Yemen and has an area of 11000 km² and a population of 0.8 million in 2023 [7]. It is situated at the top of the eastern mountain slope (~2000 m a.s.l). Five Wadi systems originated within the boundaries of Al Bayda and convey surface water to topographically lower zones, to the Ramlat al Sabaatain basin, and the Gulf of Aden basin. Groundwater resources in Al Bayda are very limited; it occurs only as a shallow local aquifer system that can be found in weathered, fractured, and faulted zones or the narrow alluvial fills of the wadi beds. Depth to groundwater is usually less than 15 m in these zones and lowest yields [3]. The people living in Al Bayda depend on the collector/dug wells that yield a small and possibly only sufficient drinking water supply. Al Bayda City, the capital of Al Bayda Governorate, has been selected as the target area in this study because of its importance and history of water shortage.

2.2. Location and population of the area

Al Bayda catchment, which is the study area, lies at the southern edge of the eastern mountainous region just to the north of the main water divide. The catchment has a drainage area of 330 km² and forms the upstream part of Wadi Bayhan and extends between latitudes 13° 55' and 14° 06' north and longitudes 45°25' and 45° 40' east (Figure 1). The area includes Al Bayda capital city and 10 groups of villages with a total population of 100000, i.e. a total population density of around 330/km² compared to 100 /Km² in the basement region. The population of the area has increased by 6 times during the last 40 years. The catchment area of Al Bayda has special social and economic importance not only because it includes the highest population density and agricultural activity in the region but also because it encompasses the well field that supplies water to 42,000 inhabitants of Al Bayda capital city [4]. The drinking water requirement of the city and rural areas is met through dug/collector wells that dry up during dry seasons. The water supply of Al Bayda City is derived from the fractured basement through hand-dug wells. More than 400 dug wells are found drilled in the watershed, but their production has declined [4]. The people in the city are striving very hard to collect water for drinking and household use. There is therefore a need for proper assessment of groundwater resources in the area to mitigate water scarcity. Assessment of groundwater resources availability in the region is a pre-requisite and an important step towards solving water sacristy in the area where groundwater is the only source of water supply.

3. Material and Methods

In this study, an attempt was made to gather maximum information about the hydrogeology of the area using different techniques viz., ASTER data, satellite images, hydrogeological reconnaissance, etc. The methodology adopted in this work included the collection, reviewing, processing, analysis, and comparison of available data concerning the groundwater resources of the area. The collected data included meteorological records, geologic and topographic maps, wells inventories and hydrogeological data, remote sensing, and field measurements. The meteorological records were available from Radaa station, 100 km west of Al Bayda city. The topographic map of Al Bayda (Yemen Survey Authority, 1981 at a scale of 1: 50,000) [8], and geological maps of Al Bayda region (Kruck, and Schäffer, 1991 [9] and Robertson Group Plc, 1992) [10]. The well inventories of ILACO (9/1983) [3] and that conducted by GSHEC (9/2008) [4], in addition to the drilling and pumping tests performed by SGHORIAH [2] and the field measurements conducted by the authors in 2013. The satellite image (Landsat 7ETM+ image acquired on January 14, 2005) and SRTM data were downloaded from the archive of the Global Land Cover Facility (GLCF) [11]. The fieldwork of 2013 included well point inventory, water sample collection, cross-section measurements, and well discharge measurements at various locations.

The collected data were subjected to various processing steps. including, scanning, mosaicking, referencing, correction, verification, and analyzing until producing the final outputs (maps). The initial step was to prepare topographic and geologic maps that would serve as a base map on which the boundaries of the catchment area, drainage pattern, lithological units, and lineaments could be overlain; The next step was to locate and describe the aquifer system in terms of its occurrence and characteristics, the final step was to quantify the groundwater availability and usability in the area. The data processing steps were done by using ERDAS-Imagine 8.4, Arc Map 9.4, Surpher11, 3dem, etc.

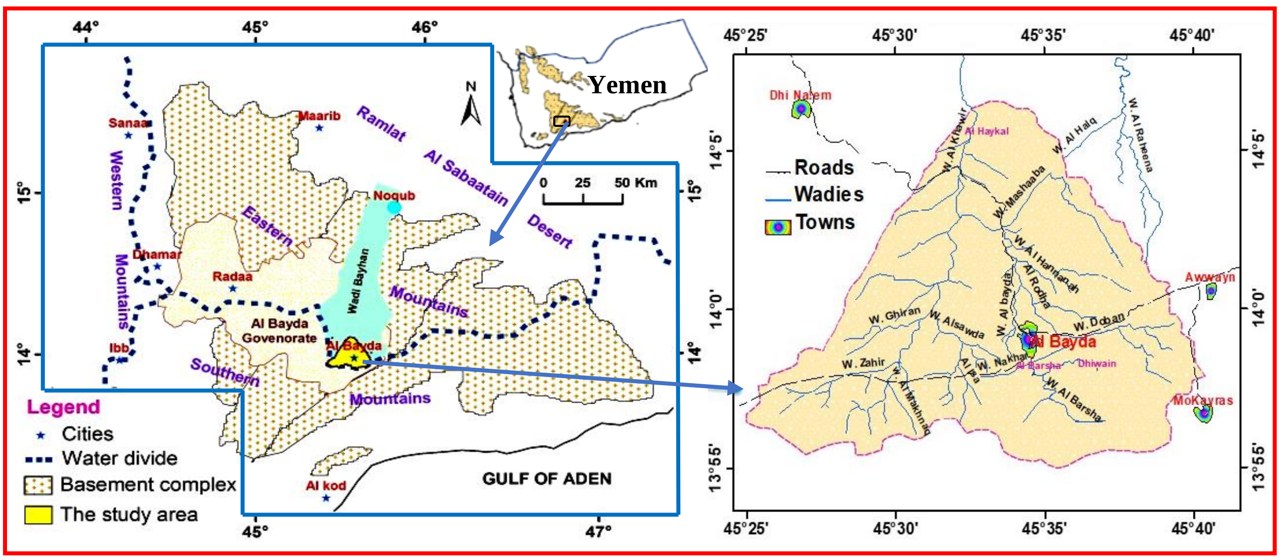

Figure 1: Location map of the hard basement region of Yemen (a), and the Al Bayda City catchment, study area (b).

The processed Landsat (ETM+) and ASTER data were used for addressing the topographical and geological variations, tracing the drainage lines, and mapping the alluvial cover of the study area. The well inventory data including locations, altitudes, depths lithology, etc., were used for the preparation of the hydrogeological cross sections which were used for characterizing the geometries of the aquifer system of the area. Areas of thick alluvial deposits were demarcated with the help of these imageries as well as ASTER data. For the first time, various maps, such as topographic, drainage, geologic, and hydrogeological maps have been prepared in this study, which were utilized for delineating the main surface hydrological features and then for preparation of hydrogeological cross sections for the aquifers in the area.

Assessment of groundwater resources in the study area has been done through the identification of its occurrence, depths, use, and quantification of its recharge and discharge areas. The water depth maps for the study area were plotted using ArcGIS and Surfer programs. A careful analysis of the water table contours provided an understanding of the groundwater flow pattern, which in turn, helped to delineate groundwater saturation zones. A comparative analysis has been made between the results of previous studies to evaluate the groundwater situation and its change during the last 30 years (1983-2013). Empirical equations were used to calculate the quantity of water available in the aquifer system of the area. As a result, estimates of ground-water use, demand, and deficit were calculated. Finally, the obtained information about the study area has been discussed in the following sections.

4. Results and Discussions

4.1. Topography and Climate

The study area is located at the edge of the eastern highlands, just to the north of the main water divide between the eastern and southern mountains slops (Figure 1). The digital elevation model (DEM), generated around Al Bayda catchment shows that the elevation of the catchment varies from 1900 to 2300 m above sea level (Figure 2a). The catchment area is a pen plain sloping slightly at north and surrounded in the south, west and east by mountainous ranges. The drainage system of the area is dendritic with a large number of short tributaries that have been dissected by hills and geologic structures. Small hills, short ridges, bare rock plateau. narrow wadis and shallow depressions are the main morphological features in the area (Figure 2b). The hills and ridges have gently sloping surfaces and rise to elevations of 50 to 200 m from the wadi floors. The wadis which are covered by alluvial deposits are mostly narrow (70-150 m width), and in some places, they become wider (200-500m) or disconnected by hills to form small basins. The ground surface dominated the area is shallow rocks and bar rocks outcrops (see pictures in Figure 2). Often there is no soil material at all in rock outcrops. The soils are found in the wadis. Only the deeper soils are suitable for cultivation. Whether they are cultivable or not depends on the availability of water.

The climate of the basement region is arid to semi-arid with low and erratic rainfall and high evaporation rates. According to AREA (2005), the region has moderate weather with an average temperature of 24 °C. The maximum and minimum temperatures are about 32 °C in July and 4 °C in January. The relative humidity ranges between a maximum of 70 % in winter and a minimum of 45% in summer [6]. Rainfall occurs in two seasons of the year but varies from year to year. The average annual rainfall is about 200 mm, but varies from year to year, fluctuating between 100 and 400 mm/year [12]. As there is no rain gauge station in the study area, the available daily rainfall records of the nearest rainfall station at Radaa for 15 years (1978-1992) were collected and averaged on an annual and monthly basis as presented in Figure 3. In Radaa, the average annual rainfall is 220 mm/year, fluctuating between 100 and 370 mm/year (Figure 3a). Most of the rainfall occurs in March and April as well as in July and August with maximum quantities of 53, 37, 22, and 38 mm, respectively (Figure 3b). Potential evaporation estimated by the Penman method was about 2400 mm in summer and 2000 mm in winter months with an annual average of 2280 mm [3]. As the potential evaporation is high during rainy seasons much of the surface rainwater (about 90%) evaporates to the atmosphere. Only 10% of the total rainfall forms the runoff part and may infiltrate into groundwater recharge [12].

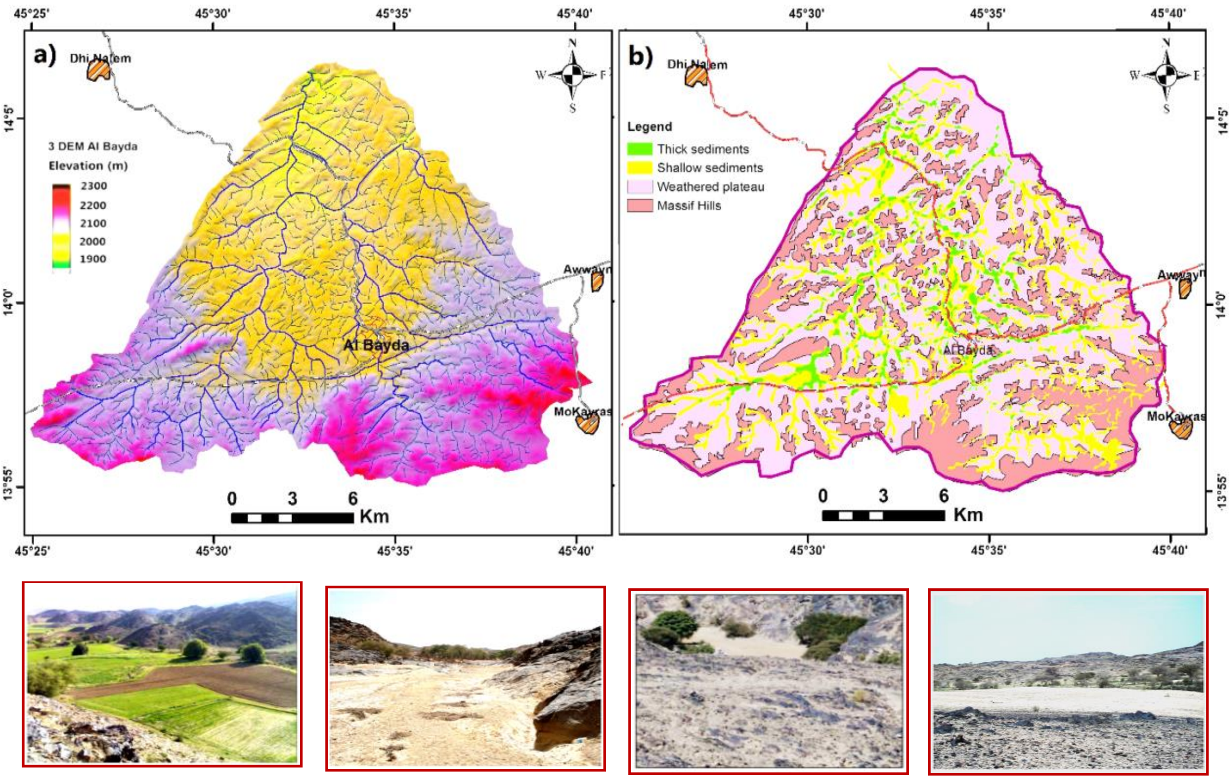

Figure 2: Topography (DEM) and drainage map generated from SRTM of the study area (a); Morphological features of Albayda City catchment area (b), and field photos showing examples of morphological features in the area.

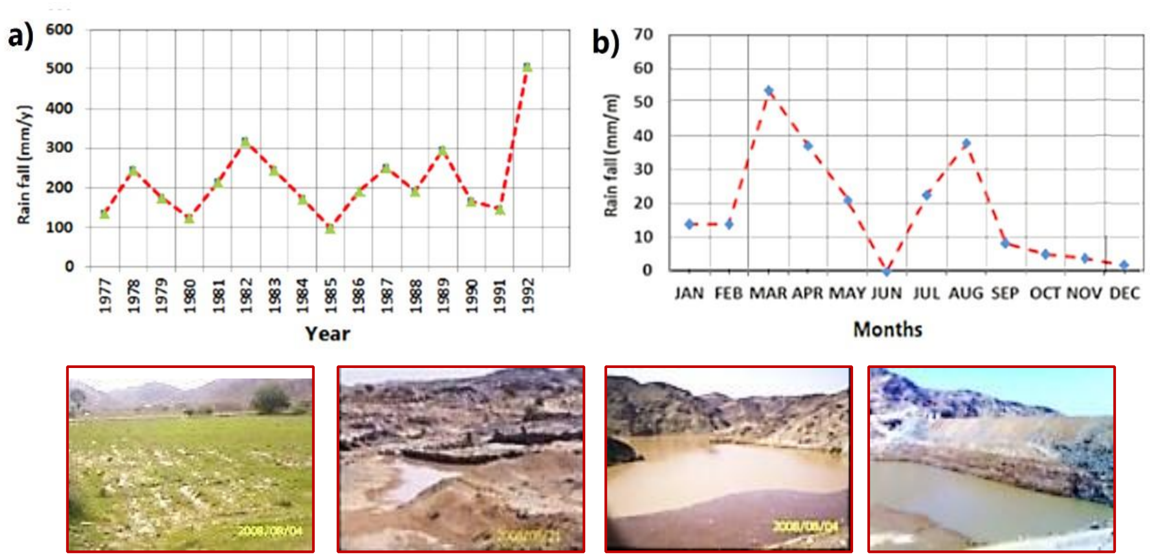

Figure 3: Mean annual values of rainfall at Radaa station from 1977 to 1992 (a) and mean monthly values Al Khabar rainfall station (b); Field photos showing examples of surface water features found in Albayda catchment.

4.2. Geology and Structure

The geology of Al Bayda is dominated by the Precambrian Basement Complex composed mainly low grade metamorphic rocks over 2700 million years of age [13]. A geological overview map of the study area is generated by tracing and lithologic units from the satellite image (Figure 4a) and geologic maps of Robertson 1992 and El Selwi, 2005. As can be seen in Figure 4b, the surface geology of the study area is made up only of two lithologic groups: The old core basement includes Archaean high-grade migmatized gneisses; the Layered basement is predominantly of the Neoproterozoic age and includes: schist, ophiolitic mélange and arc metavolcanics, and Intrusive rocks comprise of granodiorite, gabbro and granite, occur as zoned plutons traversing the older units [14-16]. Intrusive dikes and sometimes dike swarms, often associated with faulting, cut the Precambrian rocks in many places [5]. Overlaying the basement rocks, but in the wadi channels and shallow depressions, are the recent alluvial deposits that consist of silts, clays, and fine sands with some intercalation of gravels. The thickness of alluvial deposits ranges between 2 m and 5 m in the southern part of the area and increases to 15 m in the central parts of wadis and at the conjunctions of the main faults [3]. Based on the geological and morphological maps (Figs. 2b and 4b), the thematic layer of each formation has been calculated. The results indicated that the alluvial deposits cover about 60 km^2 (15%) and the remaining area (270 km^2 or 85%) is covered by hard basement rocks.

The region in general has been affected by at least three tectonic phases that were caused by folding, faulting, and fracturing. Folding is indicated by the presence of ridges that bound the catchment from the west and east and the presence of lowlands in the central part of the area. Faulting is represented by a large number of faults of different directions, ages, and origins, varying from high-angle thrusts to almost vertical strike-slip faults [5]. In this study, the faults of the area were traced from the geologic map of Eselwi (2005) and completed using satellite image interpretation. The predominant trends of fault systems are NE, NW, N-S, and E-W. The NE faults are the oldest and have been traversed by the NW and by the NW faults consequently. Two faults are of highly effective influence on the surface hydrogeological features of the area. These are the NE-SW fault that traverses the area from the southwest into the northeast and the E-W fault that delineates the southern part of the catchment to south of Al Bayda city. The two faults are cross-cut by the other local faults creating a large number of sub-basins. Comparison of the drainage pattern of the area and lineament directions shows that the drainage pattern is controlled by the main structural elements. The present wadi system usually follows the faults. The alluvium in most of the wadi beds and the weathered rock zone underlying the wadis form the groundwater reservoir storing the infiltrating rainwater and runoff waters from the surrounding hills. However, many faults and fractures in the area have been intruded by dykes that may interrupt the groundwater flow.

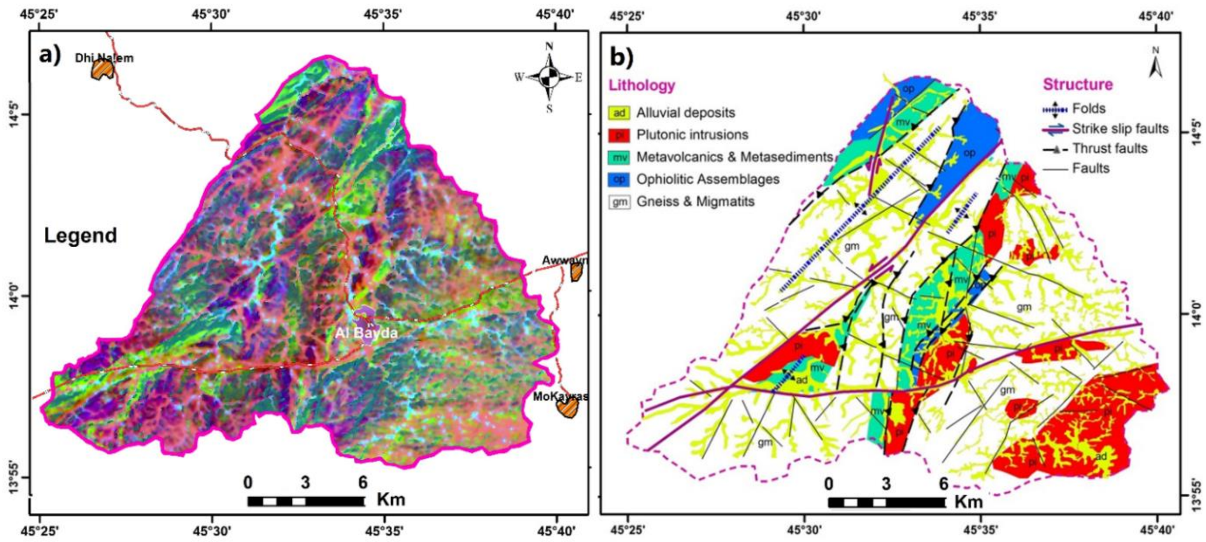

Figure 4: Satellite image (a) and interpreted geology map (b) of Al Bayda catchment area.

4.3. Hydrogeological Sitting

The hydrogeological setting of the Al Bayda area was affected by many factors including geological, structural, and climatic conditions that have been discussed above. Based on the topographic, drainage, and geologic maps (Figs. 2 and 4) as well as the rainfall data, the hydrogeology of the study area can be described here through the identification of surface and subsurface hydrological features, including rainfall-runoff, aquifer characteristics, and groundwater situation, as in the following section.

4.3.1. Surface Water System

Rainfall and runoff are the only ways to input water into the hydrologic system of Al Bayda catchment. The principal features of rainfall in the area are seasonal, poor distribution, and variable from year to year. Daily rainfall amount is usually the result of only one rainstorm of low intensity (> 10 mm), which does not generate any form of surface water feature. Since the catchment is a rough surface area and mostly covered with bare rocks, flash floods do not occur, and the surface runoff occurs only after heavy rainstorms. During and after heavy rainstorms (> 10 mm), water runs off over the ground, first collecting in shallow depressions, and then overflowing into the tributaries and somewhere into the main wadis where it may generate other surface water features such as springs streams, bonds, and marshes, which in turn either evaporated or infiltrated to the aquifer.

As previously mentioned, the 330 km^2 area of the catchment consists of the 270 km^2 area that is bar rocks from which runoff occurs, and the 60 km^2 area of the wadis into which runoff flows. The mean annual rainfall is considered to be 200 mm and the runoff coefficient in the study area is estimated to be 8.4 % of total annual rainfall [17]. Therefore, the total annual rainfall over the entire catchment area is (0.200 m x 330 x 10^6 m^2) 66 Mm^3. The total runoff is (0.200 m x 330 x 10^6 m^2 x 0.084) 5.5 Mm^3. Most of this amount is evaporated or used for irrigation. There are three small dams (Al Barsha, Al Haykal, and Dhiwain) and some manmade structures (see pictures Figure 3). The total surface water stored behind such dams is estimated to be 0.9 Mm^3. This amount represents about 16% of the total surface water resources that have been already utilized. Therefore, there is at least 80 % of surface water available for further development inside the area. This water can be exploited by the construction of small boulder surface or subsurface dams.

4.3.2. Aquifer System

In arid and semi-arid areas of the hard basement, where rocks are generally impervious, groundwater occurs mainly in the weathered overburden (regolith) and structural traps (fractures, fissures, and intrusive bodies) in the hard rocks [18]. Recent research studies showed that aquifers located in hard rock formations (granite, gneiss, schist) were considered a highly heterogeneous media that is made of two main superimposed hydrogeological layers, each layer characterized by quite homogeneous specific hydrodynamic properties [19-21]. The occurrence and depth of groundwater in the basement aquifer system are controlled by the pervasiveness of secondary structural entities. The depth of the water table in hard areas varies from place to place and from season to season [22,23]. In general, the groundwater potential and yielding capacity of the basement aquifers differ much from place to place due to variability in their thickness, hydraulic properties, and recharge mechanisms [21].

In this study, an attempt is made to characterize the aquifer system of the area. It was based on the data presented in this study and the well inventories and drilling and testing that were carried out in the region. The good inventory data for 168 wells (location, elevation, depth, lithology, water level, yield, salinity, etc.) obtained from ILACO [3] were used to construct several hydrogeological cross-sections. Examples of these cross-sections are shown in Figure. 5. The hydraulic properties of the aquifer system of the area were taken from SOGREAH (1978) [2] and other studies that were conducted in hard basement regions in other countries [e.g. 22, 23, 24].

The representative SW-NE and SE-NW cross sections AA, and BB (Figure 5) reveal that the aquifer system in Al Bayda formed of (1) topsoil and sandy/alluvium; (2) weathered zone or regolith, and (3) fractured bedrock. The alluvium zone varies in thickness from 3 to 10 m and could reach 15 m in some locations. The weathered zone behaves similarly to the alluvium in terms of thickness vis a viz the wad orientation and varies also from 2 m to 15 m. Isolated fractured zones extend for a few tens of meters into the fresh basement. The compound aquifer thickness from the topographic surface to the fresh basement varies from less than 10 m to 30 m. The aquifer systems show a wide variation in geometry from place to place, which is the result of variations in basement topography. As can be seen in Figure 5, the aquifer system in the study area occurs as isolated bodies as it is disconnected by faults, dykes, and plutonic intrusions. The water table is locally very irregular following the bedrock topography. It occurs at shallow depths upstream of Wadis and becomes deeper towards the central parts of the numerous water bodies.

Based on similarity in hydrogeological properties, the basement aquifers in the study area can be subdivided into two potential aquifer types, viz. the weathered (regolith) and the fractured (deep) aquifer systems. The first is thin (< 10 m thick), consisting of one or two zones (alluvium and weathered), and found across all the wadis and most of the tributaries. The second is comparatively thicker (10-30 m), consisting of three layers (alluvium, weathered and fractured), and usually found as isolated bodies distributed along the main wadi channels, closer to the hills, and at the intersections of the major faults. The general characteristics of the two types are summarized in Table 1. The shallow aquifer system covers 33 km^2 or 10% of the total surface area, while the deep aquifers constitute only about 16.5 km^2 or 5 % of the catchment area. The surface distributions of the shallow and deep aquifers were illustrated in the constructed hydrogeological map (Figure 6).

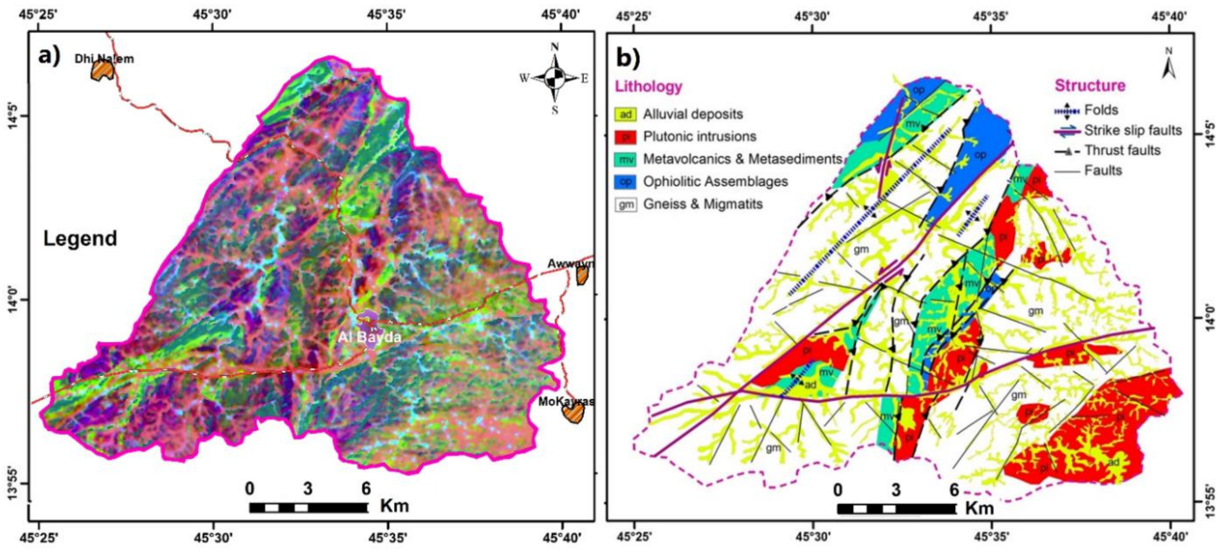

Figure 4: Satellite image (a) and interpreted geology map (b) of Al Bayda catchment area

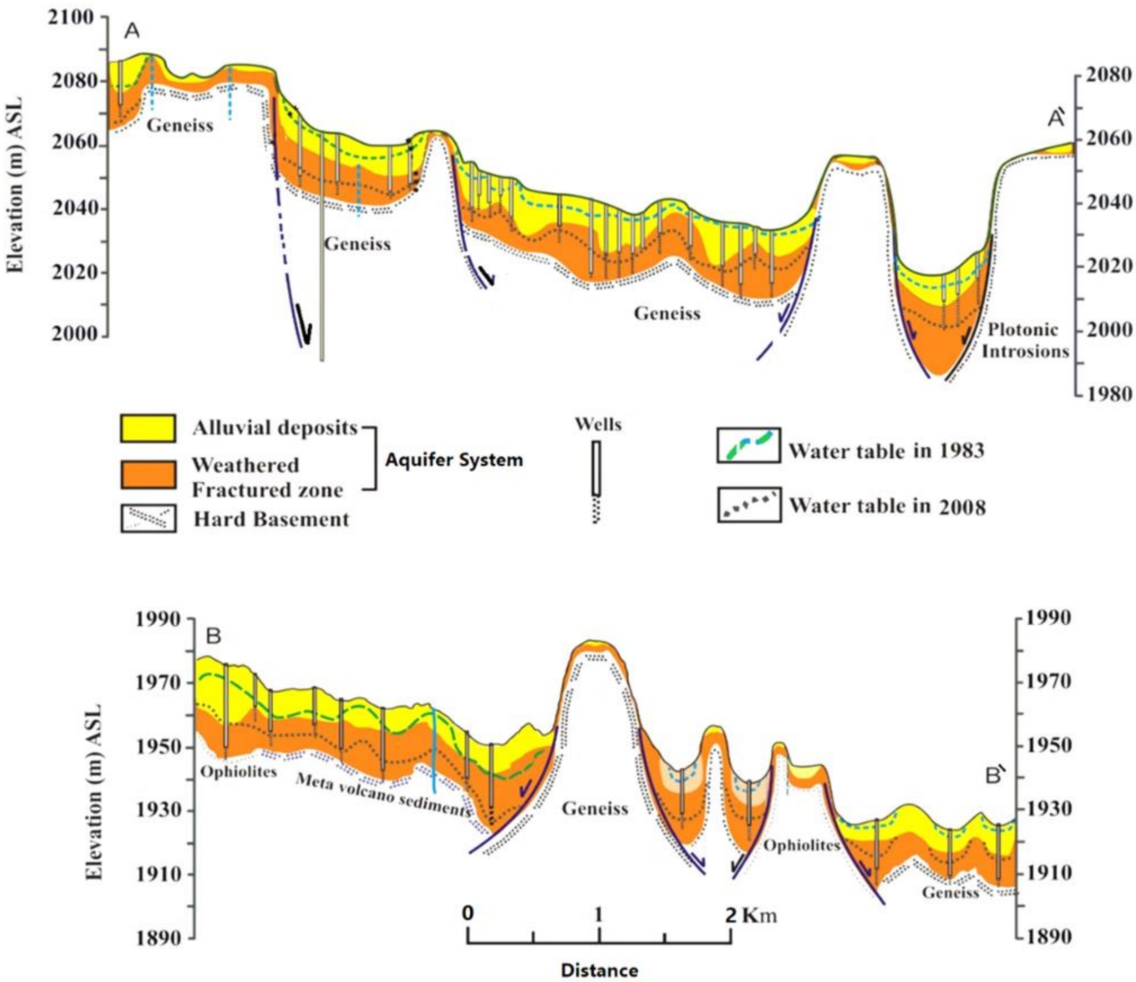

Figure 5: Hydrogeological cross-section AA' (W. Zahir) and BB' (W. Hananna), showing the aquifer zones and variability groundwater levels with bedrock topography. Locations of the cross-section profiles are shown in Figure 6.

Pumping tests carried out by SOGREAH (1977) in the lower part of Wadi Bayhan show that the weathered zones aquifers have hydraulic conductivities of < 0.8 m/d, transmissivity values of < 40 m^2/d, specific yield of < $1x10^{-3}$, and well yield of < 86 m^3/d. The fractured aquifers have hydraulic conductivities of < 8 m/d, transmissivity values of < 80 m^2/d, specific storage of < $1x10^{-3}$, and yield of < 86 m^3/d [2]. Despite its wide distribution, the shallow aquifer should not be considered an aquifer. It has a small thickness, and the water is usually found below the boundary of its zone. The deep aquifer can be considered the main storage compartment in the area but its yield is low depending on its saturation thickness.

Table 1: Characteristics of the aquifer system in the hard basement rocks of Al Bayda.

Aquifers Type	Shallow Aquifer (Alluvium & Weathered)	Deep Aquifer (Fractured)
Area km^2	33	16.5
Thickness (m)	4 -10	11- 30
Depth of water table (m)	4-10	11-25
Saturated thickness (m)	0-5 seasonal	0 -10
Depth of wells (m)	< 10 m	10-30
Well yields (L/s)	<1	2 - 2.5, 0.5 – 1.7
Hydraulic Conductivity (m/d)	0.003 - 36	0.02 – 0.39
Transmissivity (m^2/s)	0.01 - 0.87	0.2 – 87
Storage Coefficient (%)	1 - 0.01	< 0.01

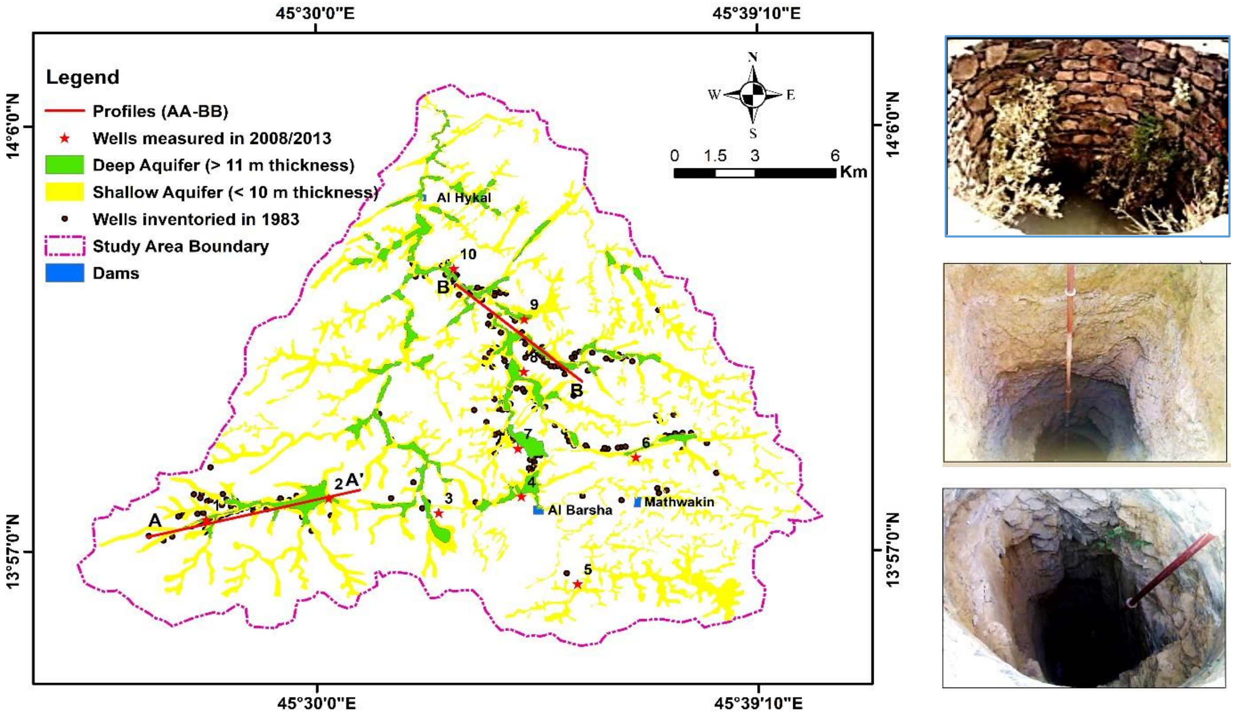

Figure 6: Map shows surface distribution of aquifer systems, locations of wells and measuring points for the hydrological years 1983, 2008 and 2013, and field photographs showing types of wells in the study area.

4.4. Groundwater Situation

The groundwater situation in the study area is discussed by defining its occurrence, depth, use, and quality; the past and the recent water situation were also compared. The groundwater resources situation in the Al Bayda catchment has been presented on the hydrogeological cross sections and map (Figs 5 and 6). It can be noted that the main factors controlling the occurrence and depth of groundwater are, the quantity of rainfall, the thickness of the aquifer (the thicker the aquifer the lower the water level), and also the quantity of abstraction or use of groundwater. In shallow aquifer systems, groundwater does not exist throughout the year and dries out soon after the rains end. In the deep aquifer, groundwater usually occurs at the base of the weathered zone but varies in depth from place to place following basement topography. A considerable rise in the water table (3-6 m) is observed in the area during the rainy seasons.

4.4.1. Groundwater Use

Groundwater is used exclusively to satisfy the water needs of the different uses. In the past, groundwater was used mostly for irrigation. At present, most of the groundwater is used for domestic purposes with limited amounts being used for small-scale irrigation during the rainy season. For obtaining groundwater, dug wells and collector wells are commonly used. There were about 300 wells in 1983 which increased to 400 wells in 2008, of which 8 wells for the city. The distribution of the wells is shown in Figure 6. The wells in the area have depths of 10-30 m, diameters of 2-3 m, and water levels of 5-25 m below land surface. Most wells are not lined, and some wells are lined with stones or concrete. Water lifting devices include manual rope-bucket and diesel-powered pumps. Typical examples are shown in Figure 6. Quality analyses of groundwater samples from the wells of Al Bayda catchment reported by ILACO and GSHEC indicate that salinity may not be a problem for this aquifer as low electrical conductivities (ranging from < 300 mg/L to 1500 mg/L) were found in the groundwater.

4.4.2. Change in Groundwater Situation

The change in the groundwater situation that occurred during the periods between 1983 and 2008 is presented in water depth contour maps (Figs. 7a and b). These maps were prepared by using the depths of groundwater for 168 wells inventoried by ILACO in the summer of 1983 and for 30 wells measured by GSHIC in September 2008. Figure 7a shows that water depths were generally 0 to 3 m below the surface in most parts of the catchment; near-surface water levels of 3 to 10 m were found in the northern parts of the catchment. Three prominent depletion cones (10, 12 m, 14 m b.g.s) were observed in waterlogged areas near Al Bayda, city (W. Al Barsha, W. Zaher, and Al Isa) in the city well fields. Figure 7b shows that the depth of groundwater has increased all over the area. It is generally 10 to 25 m below the surface in most parts of the catchment. Several depletion cones were generated in the area including the three depletion cones that formed in 1984 at the city well fields. As shown by arrows representing groundwater flow directions, the groundwater is limited to the cone of depressions, flowing from all sides towards extensive pumping areas.

A comparative analysis has been made also for ten wells measured in the three periods (1983, 2008, and 2013. The results are summarized in Table 2 and presented in Figures (8a and b). As can be seen in Figure 8a, the depth to water level was very shallow in 1983 and ranged between 0 and 10 m with an average depth of 4.5 m. In 2013, the depth of water in the ten wells increased to a range between 10 and 25. The deepest groundwater levels were observed in wells 3, 6, and 8 which are located in the intensive pumping areas (Al Bayda city well fields). However, the salinity variation in the ten selected wells shown in Figure 8b indicated that there was no significant variation over the years. The water salinity in 1983 was near the average of 2013. The lowest salinity values were observed in wells no.4. 5, and 6 which are located in the intensive pumping areas. Salinity is low in the southern part of the study area and increases gradually with groundwater flow toward the north. Generally, the groundwater lying at deeper depths is of good quality as compared to shallow groundwater.

Based on the statement discussed above, the changes in groundwater conditions over the 30 years, between 1983 and 2013 can be summarized as follows: **1)** In 1983, the water levels were encountered in the alluvial zone at depths varying from 0 to 10 m; the thickness of the saturated zone was more than 20 m. The yield of wells was ranging between 0.2 and 4.7 l/s with an average of 0.5 l/s or 47 m^3 per day. **2)** In 2013, the depth of the water increased to range between 12 and 25 m, and the saturated thickness decreased to 6 m. In total, there was a net fall in water level over the 30 years by about 19 meters, with a rate of 0.5 m per year. The yield of wells has decreased to range between 0 and 2.4 l/s with an average of 0.2 l/s or 18 m^3 per day. Generally, there is no significant change in water salinity over the years. Quality analyses of groundwater samples from the wells of Al Bayda catchment reported by ILACO and GSHEC indicate that salinity may not be a problem for this aquifer as low electrical conductivities (ranging from < 300 mg/L to 1500 mg/L) were found in the groundwater. The quality of groundwater in the area is generally good for multi-purpose use.

4.5. Groundwater Availability

Groundwater availability in aquafer is determined and influenced largely by the recharge and discharge rates. The principal controls on groundwater recharge are the topography, soil properties, vegetation, and meteorological variables such as precipitation, temperature, wind, etc [24,25]. Discharge from the aquifer is influenced by the rate of recharge and its controlling factors. In the case of the study area, groundwater recharge occurs either directly by infiltration from rainfall or indirectly by infiltration from runoff, whereas discharge occurs only by well abstraction. To quantify the water available in the aquifer system underlain the study area, the water balance analysis method has been used, which was based on the two main comports (i.e. Recharge through the infiltration from direct rainfall and Discharge through the abstraction from wells). The recharge, discharge, and potential in storage were estimated using a combination of available previous data, rainfall-run-off data, and computation of the water balance for the Wadi Bayhan by (SOGREAH (1978), and by ILACO (1984), and GSHEC (2009). The available water production records of Al Bayda Local Water Authority were taken into consideration. It is worth mentioning that both recharge and discharge occur from wadi fill deposits. Table 3 contains all data and information that were used for water balance components to arrive at an estimate of the groundwater recharge and discharge from the aquifer systems of Al Bayda catchment area.

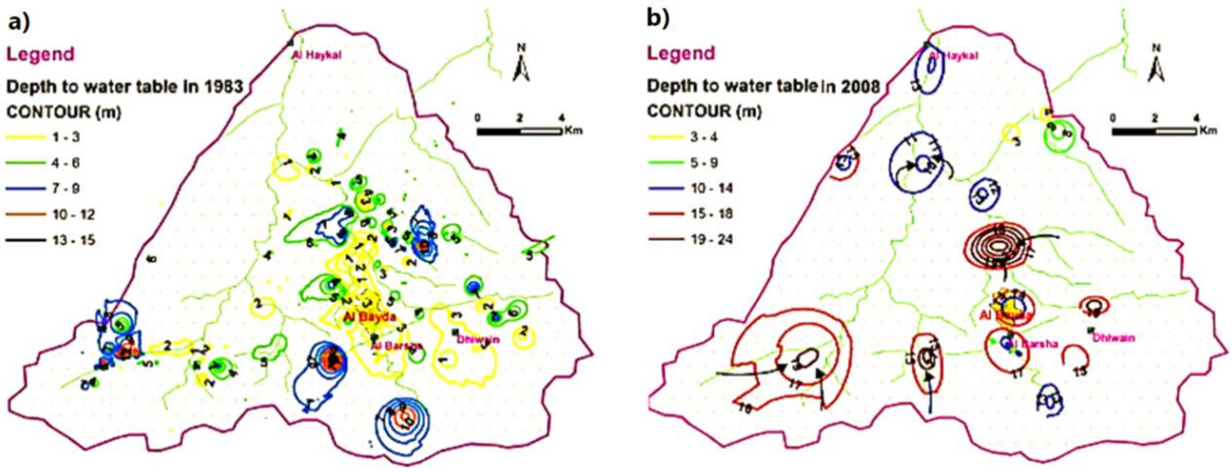

Figure 7: Groundwater depth contour maps showing patterns and flow directions in Al Bayda area for 1983 (a) and 2008 (b).

Table 2: Groundwater measurements in ten selected wells for the years 1983 and 2013.

No.	Location		Well depth (m)		Water Depth (m)		Yield (m3l/d)		Salinity EC (µS/cm)	
	Lat. N	Long. E	1983	2013	1983	2013	1983	2008	1983	2013
1	551702	1543737	18	20	2.6	19	2.4	<2	810	940
2	553512	1544700	8	16	8.3	15	5	<2	2000	1000
3	558370	1543823	16	27	6.5	24	7	<2	680	800
4	561471	1544530	8	16	2.2	12	2.3	4	700	1000
5	564848	1542229	14	17	11.2	16	5	<2	460	400
6	566191	1546365	18	22	3.7	19	12.8	<1	1400	900
7	562413	1546103	25	16	3	13	5	<2	1400	600
8	561064	1550059	14	27	1.2	25	6	<1	2000	1500
9	561420	1551383	12	17	0.7	15	5	2	1500	1200
10	558396	1556774	18	15	3.4	13	7	<2	2200	2000
	Average		**15**	**19**	**4.4**	**19**	**5.7**	**1.2**	**1315**	**1034**

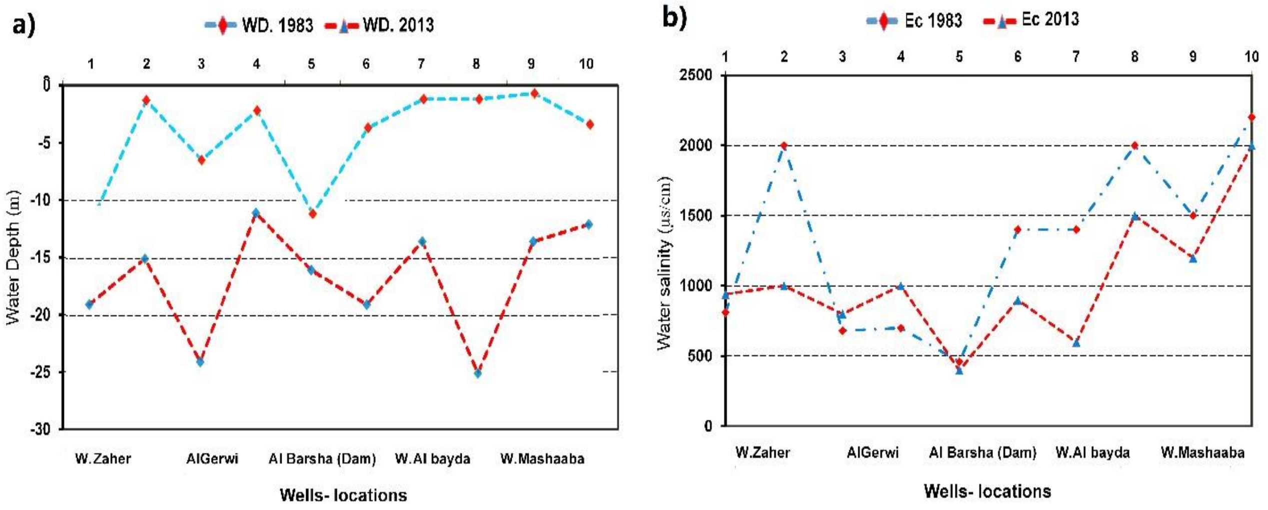

Figure 8: Long-term variation in water depth (a) and salinity EC (b) in ten selected wells for 1983 and 2013.

4.5.1. Recharge Estimation

Estimation of spatial and temporal variation of groundwater recharge is a prerequisite for resourceful management of aquifers, particularly where these estimates form the basis for assigning groundwater withdrawal rates [23,25]. Recharge has been estimated in (semi-) arid regions using a variety of techniques, including physical, chemical, isotopic, and modeling techniques. These techniques have been described in previous studies and reviews [26 and 27]. Studies on hard basement areas reported that the natural recharge rates in such areas are ranging between 3% and 15% [26,28]. In the present study, the quantity of recharge is estimated by using the infiltration factor method through the equation: $R = 0.001 \times P \times A \times Ci$; where R is the total amount of infiltration; P is the mean annual rainfall (200 mm); A is the infiltrated area (60 km^2), and Ci is the infiltration coefficient of alluvial deposits. TSHWC (1992), estimated that the infiltration coefficient from direct rainfall is 5% and that from direct runoff in the wadis is 30%. [29]. It is worth to mansion that flashflood does not occur in the study area. Runoff occurs only 2 to 4 times a year but most of intercepted water in the wadis is immediately evaporated or used by farmers. The infiltration from direct rainfall over the study is estimated to be (0.200 m × 60 × 10^6 m^2 × 0.05) 0.6 Mm^3 per year, and the infiltration from direct runoff is (4.5 × 0.3) 1.35 Mm^3 (Table 3). Hence, the total recharge is 0.6 + 1.35 = 1.95 Mm^3 which represents only 3% of the total annual rainfall. This value is on the limit of the range given previously by SOGOREAH (9 - 11 Mm^3/year) for the upper Wadi Bayhan (1500 km^2.). Also, it is well within the range obtained by TS - HWC (1992) on a national basis (0.5 - 3.0 Mm^3/year/l00 Km^2). A comparison of this amount (i.e., 1.95 Mm^3) with that estimated by ILACO and GSHEC, indicated that there was a continuous decrease in groundwater recharge over time. This is due to the continuous depletion of groundwater levels. Continuous decrease of saturation thickness reduces the rate of infiltration into the aquifer. Therefore, it is necessary to increase the rate of infiltration to the aquifers through the construction of surface and subsurface dams.

4.5.2. Discharge Estimation

Discharge from the aquifer system of the area occurs mainly by abstraction through the wells, natural evaporation and groundwater outflow are neglected. Given the lack of data on the amount of water pumped from Al Bayda wells, the abstraction volumes obtained from previous studies in addition to the abstraction records of Al Bayda city wells (NWSA) were extrapolated to estimate the current condition. The extrapolation takes into account the number of years that have passed, the trends observed in the past, and the present conditions in the area.in 1983, 300 wells were producing about 5.2 Mm^3 [3], with an average yield of 47 m^3/day. However, in 2008, there were about 400 wells in the area but the total abstraction volume is estimated to be 2.6 Mm^3, and the average yield of wells was 18 m^3/d [4]. This means that the total abstraction volume has decreased by about 50 % during 25 years between 1983 and 2008, and the average yield of the wells has decreased by 60 %, and hence the rate of decrease of wells yield is 20% per 10 years. Accordingly, the total abstraction volume for 2014 can be estimated by multiplying the number of wells (400) and the average daily pumping rate (14.6 m^3/day). Hence, total discharge is (400 × 14.6 × 365) 2.2 Mm^3. Comparison of this amount with the calculated amount of recharge (1.95 - 2.2 Mm^3), gives an imbalance in groundwater storage by 0.25 Mm^3 (Table 3).

4.6. Evolution of Water Supply in Al Bayda City

Data regarding water sources of Albayda area were collected and analyzed to evaluate the supply of groundwater within the catchment area. Over time different kinds of water sources have been developed in the area. Before 1970, the water supply of Al Bayda was limited to traditional wells and springs that were present in the vicinity of the city until the 1970s. After that, a large number of wells were drilled in the area and used for irrigation. The result has been a decline in aquifer water tables, causing the springs and traditional wells to dry up. By the 1980s, significant urban and rural groundwater supply systems have been developed within the area. During the 1990s, more wells were drilled in Al Barsha and Al-Isa well fields. By 2004, the Local Water and Sanitation Authority (NWSA) Al Bayda built a small dam in Wadi Al Barsha to the south of the city. The existing water supplies for Al-Bayda city come from 8 wells distributed in three well fields (Wadi Al Barshah south of the city and Al Isa and W. Zahir to the east of the city. The water production capacity of Al Barsha wells was about 400,000 m^3 in 2004 but decreased in 2008 to 200,000 m^3/year. Water is transported to various distribution networks and small tanks via two pumping lines. Currently, only around 40% of the city's population is connected to the public water network. The people connected to the water network, have access to 10-20 l/c/d. The remainder population relies on private water sources, purchasing their water from water tankers.

The development of population and the growth of municipal demands versus renewable water resources and shortage in the Al Bayda area between 1984 and 2024 are shown in Figure 9 and listed in Table 4. The total population of the area has increased from 24600 in 1984 to 80,000 in 2014 and will be 110,000 by 2024. The total water demand of the study area is estimated to be 4.8 Mm^3 in 1984, 7.8 Mm^3 in 2004, and is estimated to be 11 Mm^3 by 2024 (Table 4). On the other hand, the renewable water resource has decreased from about 5.2 Mm^3 in 1983, to about 2.6 Mm^3 in 2008, and is estimated as 1.95 Mm^3 in 2014 and expected to be 1.4 Mm^3 by 2024. Thus, the water deficit in Al Bayda has increased from minus 4.25 Mm^3 in 1984 to be minus 7.3 Mm^3 in 2014 and expected to be 9.3 by 2024. Concerning Al Bayda city, the total annual demand for the city is estimated to be 2.2 Mm^3 in 2014 and is expected to be 3 Mm^3 in 2024. The annual per capita share of water in Al Bayda has decreased from 216 Mm^3 in 1983 to 24 m^3 in 2014 and is expected to be less than 12.7 m^3 by 2024. The current water shortage is estimated to be 400 % of renewable water resources. The availability of water in Al Bayda is much lower than that of Yemen's average (70 m^3/c/y) and lower than that in other cities like Taiz and Sanaa which are considered the most water scariest cities in Yemen.

Table 3: Proposed estimation of groundwater recharge, discharge, and the resulting water balance in the groundwater system of Al Bayda area.

General information	Wadis	Bar rocks & hills	Catchment
Area (km²)	60	270	330
Slope %	< 5	3 -15	< 5
Average annual rainfall (mm/y)	200	200	200
PET (mm/y)	190	-	2000
Runoff Coefficient (% of runoff)	<1	7.4 - 8.6	8
Infiltration Coefficient (% of rainfall)	5	-	-
Infiltration Coefficient (% of runoff)	30	-	-
Total number of wells	300 in 1983, 400 in 2013		
Total abstraction volume (Mm^3/y):	5.2 in 1983, 2.2 in 2013		
Total rainfall P (Mm^3/y)	0.200 mm x 60 x10^6 =12	0.200 mm x 270 x10^6 = 5466	
Total Runoff FR (Mm^3/y)	12 x 0.01 = 0.12	54 x 0.08 = 4.42	= 5. 5
Net recharge from Direct rainfall	12 x 0.05 = 0.6		
Indirect runoff (FR)	4.4 x 0.3 = 1.35		
Total recharge (Mm^3/y)	1.95		
Net discharge by: Abstraction from 400 wells	2.2		
Groundwater Evaporation	0		
Total discharge (Mm^3/y)	2.2		
Groundwater Balance (Mm^3/y)	1.95 – 2.2 = - 0.25		

Table 4: Evolution of groundwater demand, consumption, and expected future demand and deficit until 2024 in Al Bayda area, Yemen.

Years	Population City	Population Villages	Total	Total Demands Mm^3	Available GW. Mm^3	Deficit Mm^3	City Demands Mm^3	City Water Supply	Actual per capita share m^3/y
1975	7122	7000	14000		6.00			0.012	428
1984	10000	14600	24600	4.80	5.20	+ 0.40	0.90	0.04	216
2004	26600	25400	52000	7.80	3.60	- 4.20	0.97	0.024	69
2014	44000	36000	80000	9.00	1.95	- 7.30	1.6	0.016	24
2024	60000	50000	1100000	11.00	1.40	- 9.60	2.2	0.08	12.7

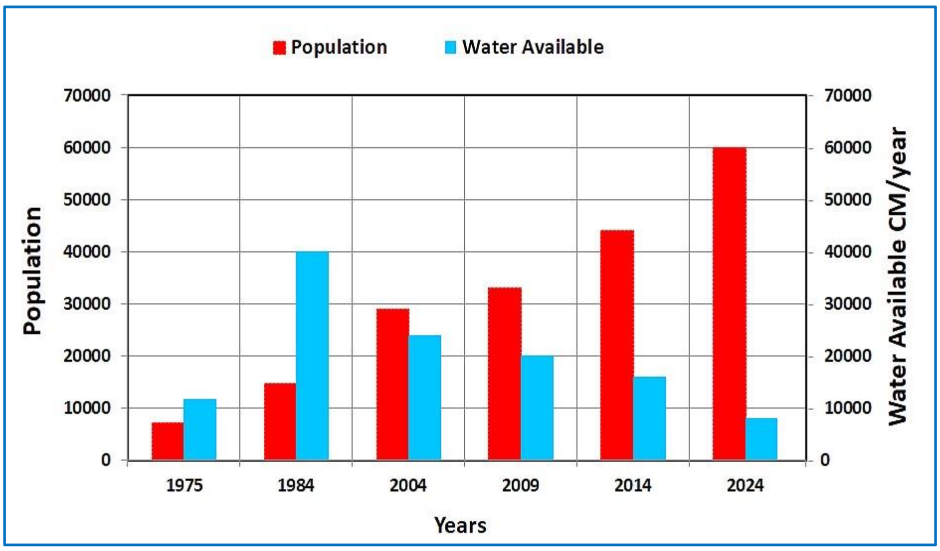

Figure 9: Al Bayda City water supply about its population growth between 1975 and 2014 and expected future demand until 2024.

From the previous discerption, we can conclude that the main causes of water scarcity in the region are low surface run-off and poor infiltration combined with the fundamental problem of limited aquifer storage. Therefore, there is a need to conserve rainwater and increase infiltration to recharge aquifers. An integrated approach to conserve rainwater and recharge aquifers is possible through harvesting of roof water, percolation tanks, ponds, subsurface barriers, minor check dams, injection wells, etc. In this regard, it is suggested that further studies to quantity the of rainwater that could be conserved. Detailed hydrogeological studies should be directed to evaluating the role of runoff water as the source of indirect recharge.

5. Conclusions and Recommendations

Al Bayda City is one of Yemen's urban areas that have witnessed a water supply shortage, mainly due to the continuous decrease in the quantity of groundwater resources. The catchment area of Al Bayda city has been chosen as a case for this study because it represents the source of water for Al Bayda city, in which the well fields that supply the city exist. This research has made a literature review on Al Bayda city groundwater resources. Then the availability of groundwater resources in Al Bayda catchment area has been assessed by an interpolation of the information from DEM, ETM+, and geological maps, well logs as well as field observations and hydrogeological knowledge of the area under study. A general description of the catchment topography, morphology, and geology has been made. These with the aid of well data, allowed the correlation of permeable zones and to identify the nature, extent, and spatial distribution of the aquifer system. The study also made a general review of the groundwater situation within the aquifer system as well as their potential for future water supply.

This research review revealed that the climate is an arid and undulating plateau; narrow Wadis and short tributaries; and small hills and short ridges in the area represent morphology. The area is covered by Precambrian basement rocks for over 85% of the complex. Recent alluvial deposits are covered in the wadis and shallow depressions. Aquifers tend to be developed in local depressions along the valley floors. They consist of topsoil and alluvial deposits and the underlain fracture or fissure zones. Groundwater occurs mainly at the upper weathered/laminated portion of rocks and other pore spaces found in the form of cracks, joints, and fractures. The depth of the groundwater table has declined from the late 1980s by 19 m, with a rate of 0.5 m per year. The lowering of the water table in the aquifers led to the reduction of the well yields. Many wells, which had been productive, became dry. Estimated groundwater recharge indicates only 1.95 Mm^3 while, the total volume of groundwater abstraction is estimated to be 2.2 Mm^3. The share per person of water in the city is estimated to be 23 Mm^3 per year, which represents the lowest in Yemen. The current water shortage is estimated to be 400 % of renewable water resources.

The water shortage in the study area could be mitigated by increasing or decreasing the loss of rainwater in rainy seasons and increasing infiltration to the aquifers. Traditional rainwater harvesting techniques such as storage tanks, and cistern bonds should be encouraged and developed to conserve rainwater. The recharge in Al Bayda catchment must be increased by enhanced by constructing small dams, either surface or subsurface dams. Detailed hydrogeological studies should be directed to evaluating the role of runoff water as the source of indirect recharge. Hopefully, the information provided in this study could be used by the local planners and policymakers to manage the water crises and support sustainable water resources management in Al Bayda City and other cities that are located in the hard basement region of Yemen.

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