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ASSESSMENT OF WATER RESOURCES IN DHAMAR GOVERNORATE, YEMEN REPUBLIC

Abdullah A. Abbas[1], Hassan I. Mohamed[2], Nashaat A. Ali[2], Gamal Abozeid[2]

[1]Ph.D. student, Civil Eng. Department, Assiut University, Egypt - From Thamar University, Yemen

[2] Civil Eng. Department, Assiut University, Egypt

E-mail: engaaabbas2011@gmail.com

E-mail: hassan1@aun.edu.eg

ABSTRACT

Being a country with limited freshwater resources, Yemen facing a water crisis due to rapid depletion of groundwater and the lack of surface water availability. Dhamar governorate, which is located about 100 km from the south of Sana'a (the capital), is one of the arid regions in the country. This research aims to explain the current situation of water resources and to get better planning for water resources management in the governorate. The rainfall is low and have spatial and temporal variation as well as the non-renewable groundwater abstraction is high. Previous studies in Dhamar plain showed that the total inflow and outflow were approximately 659.36 and 771.51 MCM/year respectively, which gives negative change in storage of about 112.15 MCM/year. Groundwater table declined in the last 40 years at a rate of 2.0 to 2.5 m/year, because of the high abstraction of groundwater from the entire area. It is predicted with the growth rate of 2% in water abstraction, which is normally expected in developing the economy, the shallow groundwater would be exhausted within the next 30 years. In Dhamar plain, it was found that the irrigation supply for irrigated areas of single, double and perennial crops were about 90, 95 and 95% from groundwater while the remaining percentage supplied from surface water. In general, the classification of cultivated area according to the sources of irrigation not only in Dhamar plain but in all the governorate in 2013 was about 27 and 73% from groundwater and surface water respectively, which was changed in 2015 to 39 and 61% respectively. This means that there is a probability stress on groundwater in the future in agriculture sector. Better water resources management and conservation with planning are very important to apply in the governorate to solve the problem of water shortage in the future and conserve the non-renewable water resources. From this study, different scenarios suggested to adopt with the scarce in water resources.

Keywords: *Dhamar, Groundwater, Surface water, Water Crisis.*

INTRODUCTION

Several studies indicated that Yemen facing a big problem in water crisis due to rapid depletion of groundwater and the lack of surface water availability. The country lives below the water poverty line and their poverty becomes absolute and extreme as projected in previous studies. The water gap worse in the continued waste of water resources. The Ministry of Water and Environment (MWE, 2011) referred that the annual available renewable water resources is about 2.5 billion m³ (BCM) of which 1.5 BCM is groundwater, 1.0 BCM is surface water, and the water demand is about 3.4 BCM, which shows that there is a gap between available and actually consumed about 0.9 BCM. This gap may be abstracted from non-

renewable groundwater, which was storage for a hundred of years. (Ward, Ueda, & McPhail, 2000) indicated that in most areas, groundwater is already being exploited below the recharge level, posing a danger to non-renewable groundwater. In terms of water use, agriculture sector consumption is the highest comparing with the other sectors. The household uses are estimated at 238 million cubic meters (MCM), industrial uses of about 68 MCM, and agricultural uses of about 3094 MCM represented by 7, 2 and 91% respectively (MWE, 2011). (CES, 2009; MWE, 2011) indicated that the rate of depletion of groundwater in Sana'a basin reached about 400% of the recharge rate, while in Taiz and Jahran (Dhamar government) basins reached to about 250% and 190% respectively. There are about 45,000 in 1994 private wells in the country and about 200 drilling platform (MWE, 2011). The government seeks to impose licensing and control of wells and rigs which increase dramatically each year.

The water level drops annually at a rate of 4-6 meters. Due to that, most of the dug wells in the critical areas has gone dry. In addition, suffer from decline in the quality of water and high salt concentration, making it unsuitable for drinking or even for irrigation (Ward *et al.*, 2000; MWE, 2011). The amount of water consumed by people and other purposes in the country is extremely low when comparing with the amount of water consumed in the world. For example, according to the number of population in 1994 - 2004, the per capita consumption does not exceed 130 -150 m^3/year whereas it is found to be about 1,050 - 1500 m^3/year average in the Middle East and North Africa, and reaches up to 7500 - 8300 m^3/year globally. (Ward *et al.*, 2000) also implied that the renewable water resources per capita in Yemen was found to be 246, 130, and 82 m^3/capita/year in 1980, 1997, 2015, respectively. In general 90% of the population in Yemen has under 90 m^3 annually (Ward et al., 2000). This indicates the obvious very low per capita in Yemen compared to other countries globally, which is not exceed 10% in general (Ward *et al*., 2000; Al Aizari, 2017).

Unfortunately, Dhamar governorate not excluded from the critical water problem. The governorate which is located about a hundred kilometers from the south of Sana'a (the capital), is one of the arid regions in the country. It is affected by what is, the country affected negatively or positively. Rainfall is the main source for surface water and groundwater in the governorate. There are no permanent rivers or big lakes. Groundwater currently considered the main source of agricultural crops, drinking and other purposes in the dry seasons. During the rainy season, Water withdrawal may be decrease for irrigation purposes but continue for other purposes. Agricultural terraces and some water structures such as small dams, small reservoirs and other structures usage to harvest rainfall. Most of the rainwater runoff goes outside the governorate through valleys (Wadis) in several directions. This is due to its topography and the lack of sufficient water harvesting and facilities. The available water resources are limited and are not enough to meet the high increase in the population and the expansion in cultivated areas. Most people in the governorate depend on agricultural activities as their primary source of livelihood. Previous study conducted in 2009 on Dhamar plain by Consulting Engineering Services – INDIA (CES) indicated that the total inflow and outflow were approximately 659.36 and 771.51 MCM/yr respectively, which gives negative change in Storage of about 112.1٥ MCM/yr. Groundwater table in the last 40 years declined at a rate of 2.0 to 2.5 m/yr. which is mainly attributed to alarming groundwater abstraction from the entire area. It is predicted that with the growth rate of 2% in water abstraction which is normally expected in developing the economy, the shallow groundwater would be exhausted within the next 30 years. In

Dhamar plain, it was found that the irrigation supply for irrigated areas of single, double and perennial crops were about 90, 95 and 95% from groundwater (CES, 2009).

This study aims to assess the current situation of water resources and to get better planning for water resources management in the governorate in order to reach sustainability in water resources and water conservation.

DATA AQUISITION

This study evaluates the past, current and future situation of water resources in Dhamar governorate using data collected from different resources. It also highlighted and presented past studies and their findings. This achieved through literature review for previous studies with analyzing, comparing and presenting the data collected. Digital Elevation Model (DEM) and Geographic Information System (GIS) in combinations with Arc Hydro are used in this study to derive an entirely standardized stream network. The extracted data from Digital Elevation Model (DEM) used to generate the drainage network. Flow direction, flow accumulation, and stream networks. The ASTER Global Digital Elevation Model V002 (ASTER GDEM) is obtained from the ASTER L1A. Digital Elevation Model V002 (ASTER GDEM) data product was retrieved from the online Data Pool, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center (DAAC, 2015). It was developed jointly by the U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI) with resolution of 30 m (DAAC, 2015).

The climatic data are obtained from Agricultural Research and Extension Authority (AREA), National Water Resources Authority (NWRA) and Civil Aviation and Meteorology Authority (CAMA) (AREA, 2017; CAMA, 2017; NWRA, 2017). The other data for population, Agriculture, water resources, etc. are obtained from National Information Center (NIC), Central Statistical Organization (CSO), Ministry of Agriculture and Irrigation (MAI), Ministry of Water and Environment (MWE), Office of Agriculture and Irrigation (OAI -Dhamar city) (CSO, 2004; MAI, 2015; MWE, 2011; NIC, 2013; OAI, 2017). The groundwater data are obtained from National Water Resources Authority (NWRA) and Consulting Engineering Services (CES - INDIA) (NWRA, 2006; CES, 2009).

STUDY AREA

Dhamar Governorate is located in the middle of western part of Yemen Republic especially in the central highland between latitude of (14^o - 15^o) north and longitude of (43^o 30 - 44^o 50) east. It covers an area of approximately 7587 km^2 in elevation ranges from a few hundred meters (e.g. wusab As Safil district) to about 3200 m (e.g. Al-Lisi Mountain, Dhamar district) above sea level (Figure 1). (Al-Kohlani, 2009; Gibson & Wilkinson, 1995; NIC, 2013 Al Aizari *et al.*, 2017). The governorate divided between 12 administrative districts and additional divided into 312 sub-districts (Figure 1). These sub-districts contain 3,377 villages. According to the last Census in 2004, the total population for the governorate is about 1,330,108 which expected to be 3,311,033 in 2034 (60% of total increase in 30 years) (CSO, 2004; NIC, 2013).

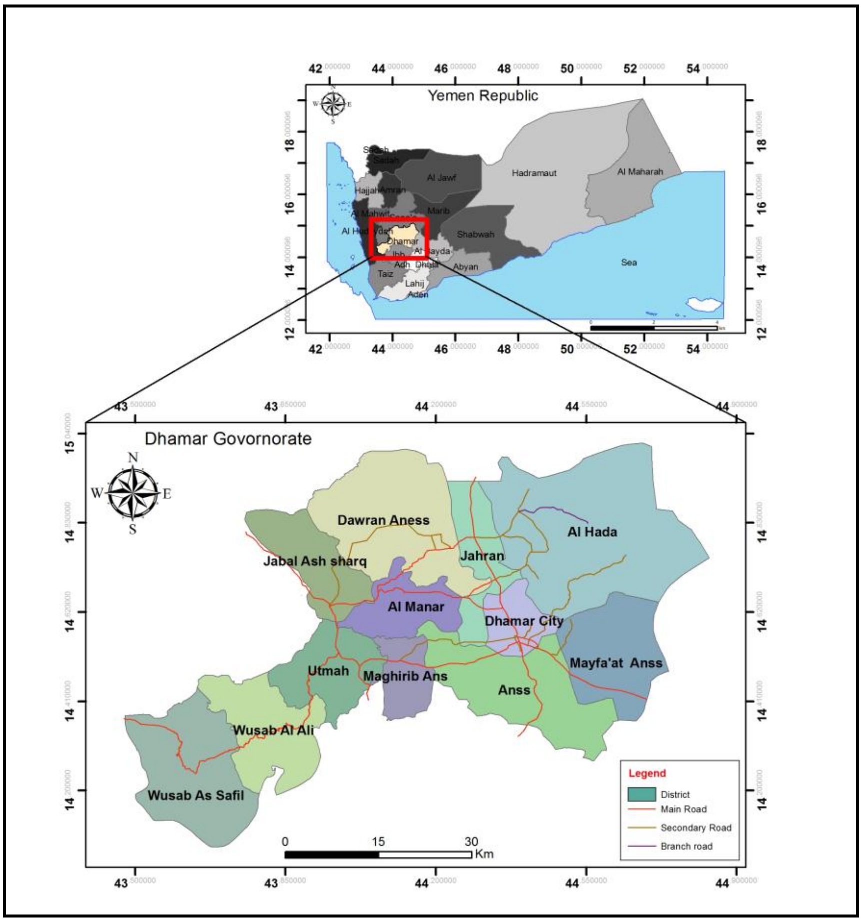

Figure 1: Dhamar governorate location map and its districts.

The data showed that Dhamar city (the capital of the governorate) has the highest number of population compared with the other region in the governorate such as Wusab Al Ali, Wusab As Safil, Utmah, Al Hada, Dawran Aness, Anss, Jahran, Jabal Ash sharq, , Mayfa'at Anss, Maghirib Ans and Al Manar. In view of its topographical structure, the governorate's eastern slopes is smoother than the western part (Noaman, 2005; Hadden, 2012). The governorate divided into high mountains overlapped with Wadis, highlands, and plains (e.g. area surrounded by hills and Wadis, which called Qa'). The most mountain peaks include Isbil, Al-Lisi, Dawran, Jabal As sharq, the two Wusab mountain, and the Utamah mountains. Wadis are distributed throughout the governorate but the most famous and longest wadi is Rima (also called Rema'a or Rima' in some earlier studies). Its lenght is about 160 km long started from the upper catchment area in Al Manar district toward the west to the Red Sea. It is one of the seventh important wadis in the country (Al-Eryani, 1979; Smith & Al-Mooji, 1985; NWRA, 2009). Furthermore, there are many Plains concentrated in the North, East and South of the governorate. The most important plains are located in six districts. These districts are Dhamar city, Jahran, Anss, Magrib Anss, Dawran Aness and Jabal Ash Sharq. For example, Dhamar plain located in the first four districts. It is the largest plain (834.56 km^2 area), which is consist of eight Qa's that is Qa' Jahran, Qa' Abisiyah, Qa' Aswad, Qa' Makhderah, Qa' Tinnan, Qa' Balasan, Qa' Maram, Qa' Sherah and intervening plain area between these Qa's. The other Qa's in the other two districts are Qa' Beqil followed by Qa' Marh and Qa'a blas (CES, 2009).

The governorate is located at an arid and semi-arid climate. According to the classification proposed by UNESCO in 1979, Dhamar is an arid governorate, which is based on the ratio between average annual precipitations (P) and annual reference evaporation (E) (Noaman, 2005). This ratio is within the range of 0.03 – 0.25. Due to its location in the mountain zones of western Yemen, the annual evapotranspiration reaches to about 1579 mm (Noaman, 2005).

The climate is moderate, although the eastern and central sections of the governorate are likely to be cold during the winter, while the wadis and western slopes are warmer. The average temperatures range from 10 to 19 °C in summer and from 8 to −5°C in winter (Atroosh & Al-Moayad, 2012) indicated that in the highlands, the climate is generally mild summers and cold winters. The average temperature in summer is between 20 and 28°C, while drops in winter between -1 and -18 ° C during the night and early morning (Atroosh & Al-Moayad, 2012). (Hadden, 2012) implied that the climate during summer remains hot during the day with average temperature of about 25 and 30 °C but frosts are very common at night during the winter months. In January 1986, temperatures are fallen as low as -12 °C (Hadden, 2012). On the other hand the data obtained from meteorological station located in Dhamar city (AREA) showed that the average maximum annual temperature is approximately 24°C during 1999- 2015(Al Aizari *et al.* (2017); AREA (2017). The average monthly wind speed, relative humidity, and sunshine are in the range of 1.8 – 2.5 m/s, 45 – 63 % , and 7.1 – 10.1 hr/day from 1999 to 2016 (AREA, 2017).

SURFACE WATER

Rainfall

The analysis of collected data shows that the rainfall patterns changed temporally and spatially throughout the governorate. (NWRA, 2009) implied that the main rainfall periods (March-May) and (July-September) are produced due to the effects of the Red Sea convergence zone effect (RSCZ) and inter tropical convergences zone (I.T.C.Z) respectively. It is found that mean annual rainfall amount varies from <100 mm in the western coastal areas to about 500 mm in the eastern mountain areas (NWRA, 2009). The first observations and measurements of rainfall began in 1970 for different objectives by various consultants who carried out water resources studies in Zabid district for Rima and Zabid wadis from the period 1970 to 1984 (NWRA, 2009). Rainfall stations have established in the catchment area of these wadis by NWRA. This catchment is located in the eastern mountain areas of wadi Rima. In addition, different rainfall stations have established on Successive years in the governorate. About 30 meteorological and rainfall stations have distributed in different locations as shown in the map in figure (2). These stations are managed by different Authorities such as, NWRA, AREA, CAMA, Tehama Development Authority (TDA) and Groundwater & Soil Conservation Project (GSCP - Dhamar branch) (AREA, 2017; CAMA, 2017; NWRA, 2017).

Unfortunately, most of these stations have established in order to achieve some projects and then discontinued after that. As well as, there are missing data in these stations for many years during 1970s, 1980s and 1990s and discontinued after the year 2000 (CES, 2009). It is clear From figure (2) that the number of stations has increased from about 7 to 17 rainfall and meteorological stations in 1976 to 1983, and then decreased to 11 and 3 in 1991 and 2008 respectively (Figure 2:a-d). The currently working stations are 1, 2 and 3 stations according to the available and recorded data. Stations 1 and 3 are

meteorological stations, while the other one is rainfall station. The first two (1 & 2) stations are maintained by AREA, while the station number 3 is maintained by CAMA.

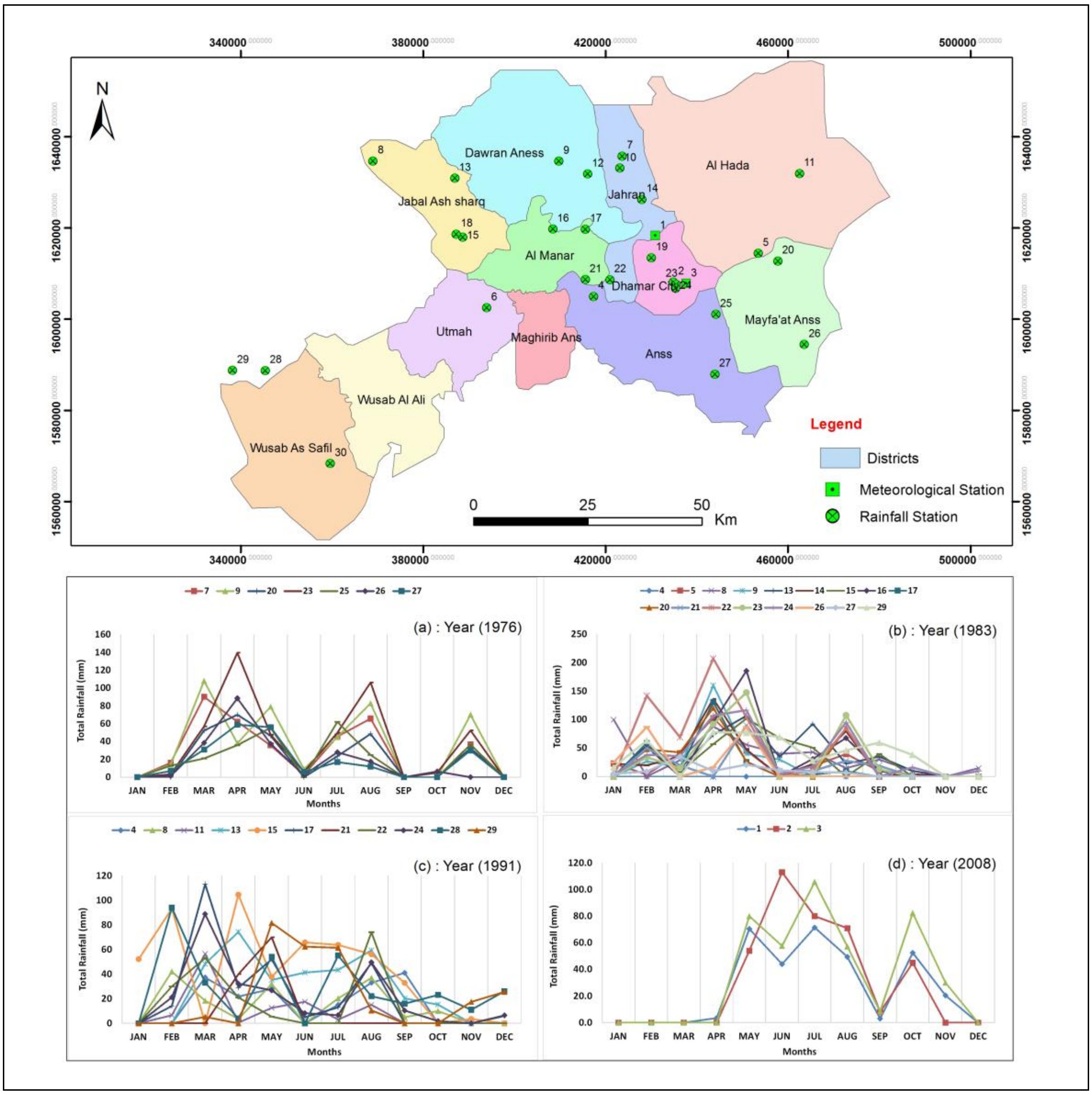

Figure 2: Meteorological and Rainfall stations distribution map in the governorate and rainfall variability charts for some station records in selected years 1976, 1983, 1991 and 2008, [Labels numbers in Figs (a-d) refer to Stations numbers].

Some data selected in this study for different stations to display the temporal and spatial change of rainfall. These selected data are for the years: 1976, 1983, 1991 and 2008 as shown in figure2 a, b, c and d respectively. In 1976, all rainfall stations have the same behavior of rainfall recorded, but the amount of monthly rainfall is different as shown in figure 2a. The amount of rainfall occurs within six months (e.g. Mar-May, July, Aug and Nov), while it was dry in the remaining months. The rainfall station 23 (located in Dhamar city) recorded more rainfall in April (140 mm) and Aug (106 mm) than other stations (Figure 2a). Furthermore, the annual rainfall amount was the highest in this station, about 467 mm followed by 446, 355, 274, 249, 220 and 218 mm in stations number 9, 7, 20, 25, 26 and 27, respectively (Figure 2a). This means that there was a temporal and spatial change of rainfall in 1976 in the rainfall stations located in different locations.

In 1983, 1991 and 2008, the rainfall stations have different behavior of rainfall recorded as presented in figure2: b-d. This confirmed that there was a temporal and spatial change of rainfall in these years.

The monthly rainfall is fluctuated from rainfall station to other and from year to year (figure2: b-d). For instance in 1983, the monthly maximum rainfall was exceeded the 200 mm in April at rainfall station 22 (located at As-Sanam). However, it reached 113 mm in Mar at rainfall station 17 (located at Masna'ah), and in 2008 it reaches the same amount but in Jun at rainfall station 17 (located at Dhamar city). In general, the total annual rainfall ranges between 216 – 618 mm. The monthly rainfall distribution shows that most of the rainfall amounts occurs within five months. These months are March, April and May and the other higher amount occurs in July and August

STREAM FLOW

Rainfall is the main source for surface water in the governorate (Noaman, 2005). Stream flow or network runoff in the governorate is generated by the rainfall in streams (wadis) and other waterways (Noaman, 2005). Water flowing in wadis comes from surface runoff, which accumulated from nearby hill slopes or watersheds. Water from these wadis constitute the most important source of groundwater recharge in the governorate (Negenman, 1997). Two maps created by ArcMap 10.2 in combination with ArcHydro using DEM as shown in figure 3 presented stream flow directions and flow accumulation. The main and sub streams are formed from highland and mountains in the central districts, and moved through the slopes into the wadis. Four directions of water accumulated into four main wadis. These are Wadi Rima, Wadi Siham, Wadi Athana (to Marib Dam), and Radaa. Wadi Rima is the longest wadi, which has about 160 m from the upper catchment area to the Red sea. (Smith & Al-Mooji, 1985) indicated that wadi's Rima total area is about 4702 km^2 (catchment area: 2760 km^2) and the rainfall is in the range of about 500-700 mm. Furthermore (Al-Eryani, 1979) implied that the channel long is about 75 km, while width and depth are in the ranges of 1-10 m, and 0.3 – 4 m respectively. It was found that the base flow in wadi Rima was ranged between 0.25 and 1.0 m^3 /sec and the runoff volume was 97.9 and 99.9 MCM during 1975 and 1976 respectively (Al-Eryani, 1979). There is no data available for stream flow amount for the other wadis.

Most of the rainfall produced by high storms are carried out as runoff through wadi Rima and other wadis, whereas other rainfall are harvested by agricultural terraces and traditional harvesting water structures such as small dams, reservoirs, ponds etc. Mountainous areas and villages are the most affected areas suffering from water scarcity. Small dams, reservoirs and ponds have been battling the water crisis for a few months, but those are not enough because of the large increase in population and water consumption.

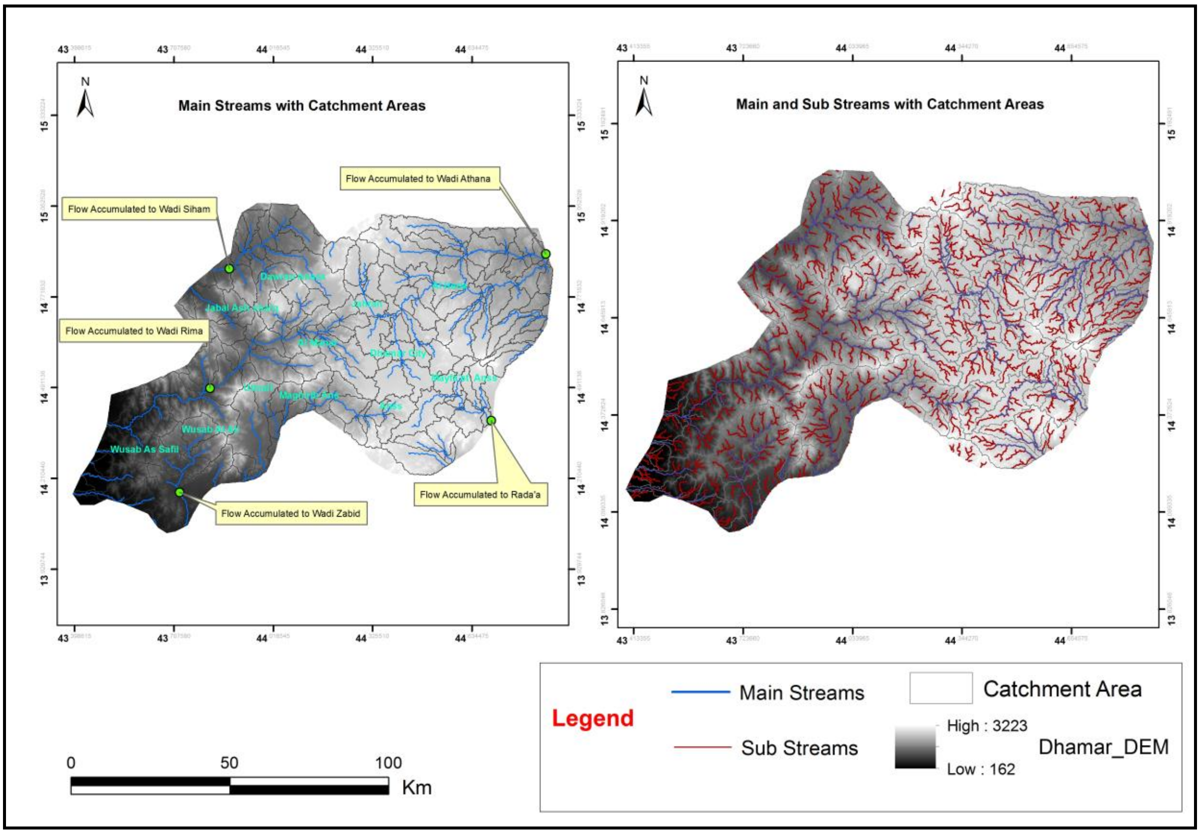

Figure 3: Main and sub streams flow directions in the governorate.

The government tried to reduce this suffering through constructing a number of small dams, water harvesting ponds, and reservoirs sources for domestic use, irrigation and recharging groundwater aquifers. (Vermillion & Al-Shaybani, 2004) stated that "a variety of programs, funding sources and procedures are used by external organizations to develop small dams in Yemen, including the Agriculture and Fisheries Production Promotion Fund (AFPPF), Ministry of Agriculture and Irrigation (MAI), Social Development Fund (SFD), the European Union, USAID and other providers of bi-lateral assistance". In Dhamar governorate, some varieties of structures developed by the Office of Agriculture and Irrigation (OAI), the Social Fund for Development (SFD) and others, but these structures are insufficient to cover the water needs. There is no clear and enough data about the number of water structure built in the governorate. Some data obtained from the OAI about some structure in the last period. (OAI, 2017) implied that the number of small dams and reservoirs have been constructed until 2010 were 123 projects with a storage capacity of approximately 9 MCM as shown in the Map (Figure 4), which is created using ArcMap 10.2. These water structures distributed in some villages in all the districts, but those are not enough to meet the water demand especially in the rural areas where there is no any groundwater resources.

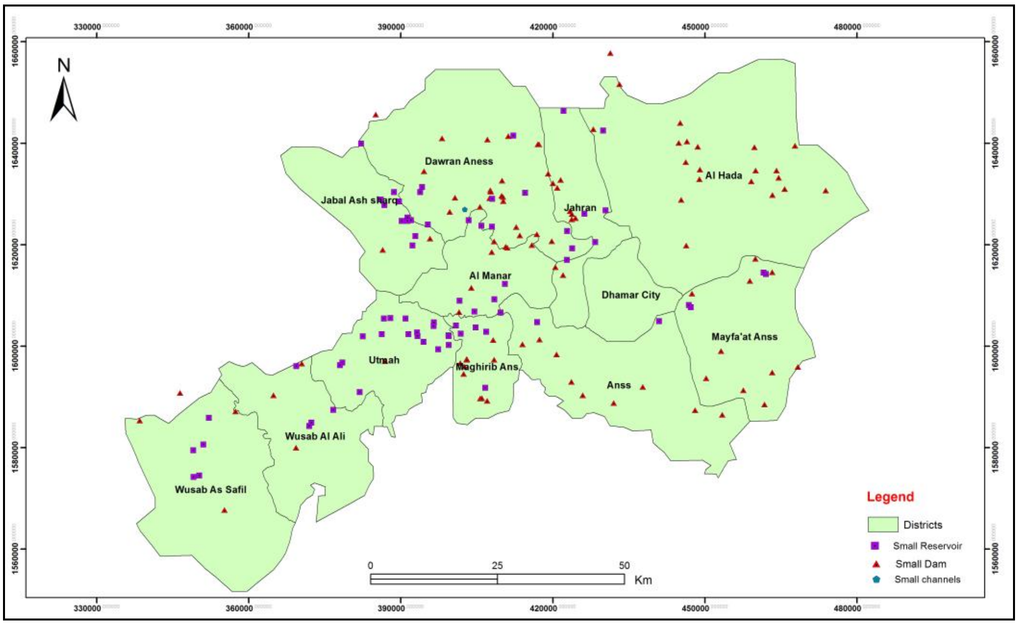

Figure 4: **Some small dams and reservoirs constructed and under constructed by OAI until 2010.**

GROUND WATER

There is no available data and or previous published studies about the groundwater system (aquifers types, groundwater depth, discharge/ recharge etc.) in all Dhamar governorate except some studies have conducted in Dhamar plain, wadi Al-Har and wadi Akarem. There are may be some unpublished studies or reports that are difficult to obtain, because of the current difficult circumstances currently prevailing in Yemen. Anyway, the high resources of groundwater availability are concentrated in plains (Qa's) and wadis, while in the highlands rural area people depend on spring (Ghayl) as the main source. The major use of groundwater is for irrigation besides drinking and for household use. (Varisco, 1983) indicated that the seasonal flood (sayl) is exploited mainly in the coastal area and foothills, whereas spring flow (ghayl) is important in the highland. (Bruns & Taher, 2009) has been conducted study in wadi Al-Har and wadi Akarem. The study implied that most of the springs fade away and the area faced water shortages, due to the earthquake in 1982. Before that time, the cultivated area (e.g. vegetables and other crops) was irrigated from springs (Bruns & Taher, 2009). Then people decided to drill wells to overcome the water shortages and to irrigate the vegetables, however this costs a lot of money (Bruns & Taher, 2009). This occurred in most districts that are affected by the earthquake.

The analysis of data collected from MAI and NWRA showed that there is an increase in the number of wells in the governorate during last decades especially in plains. The number of wells has been exceeded 10 thousand wells in all districts. It is found that approximately 7202 wells in the districts at the end of 2007. About 4493 wells are classified according to their status, out of which, 3630 wells are fully operational (81%), while 15 % (dry and Note in Use), and 4 % (Intermittent and Under Construction). This indicates that groundwater is under risk of depletion. The remaining 2709 wells are not classified a status. The maximum number of wells are concentrated in Dhamar plain in the eight Qa's, followed by Mayfa'at Anss, Anss, Dawran Aness, etc. as shown in figure 5.The number of wells in the other districts are not so much (e.g. Al Manar, Jabal As sharq, Maghirib Ans, Utmah, Wusab Al Ali, and Wusab As Safil) (figure 5). The classification in terms of type and ownership shows that the number of deep well

(artesian) for partnership is much higher than the other types (e.g. surface well with and without pump) for individual ownership. It represents about 57% than other types as shown in figure 6. The depths of wells range from 3 m to more than 1000 m in some regions. Since the maximum number of wells is concentrated in Dhamar plain, (CES, 2009) presented that there is about 5179 wells, which is distribute in the eight Qa's (figure 5). Out of them, 2722 wells are operational, which is 53%. The deep bore wells (82.78% of the total wells) take the major share among the various types of wells. It is also found that the maximum number, i.e. 2381 wells (46%) are located in Qa' Jahran, while the minimum number, i.e. 116 wells (2.24%) are located in Qa' Maram. (CES, 2009) indicated that the expected depth of the aquifers ranges from 79–907 m in Dhamar plain. The annual groundwater abstraction estimated at about 181.38 MCM in Dhamar plain, whereas there is no available data about the annual amount of water abstracted from the other wells distributed in the governorate. Groundwater table declined in the last 40 years at a rate of 2.0 to 2.5 m/year, because of the high abstraction of groundwater from the entire area (CES, 2009). CES (2009) implied that with the growth rate of 2% in water abstraction, which is normally expected in developing the economy, the shallow groundwater would be exhausted within the next 30 years.

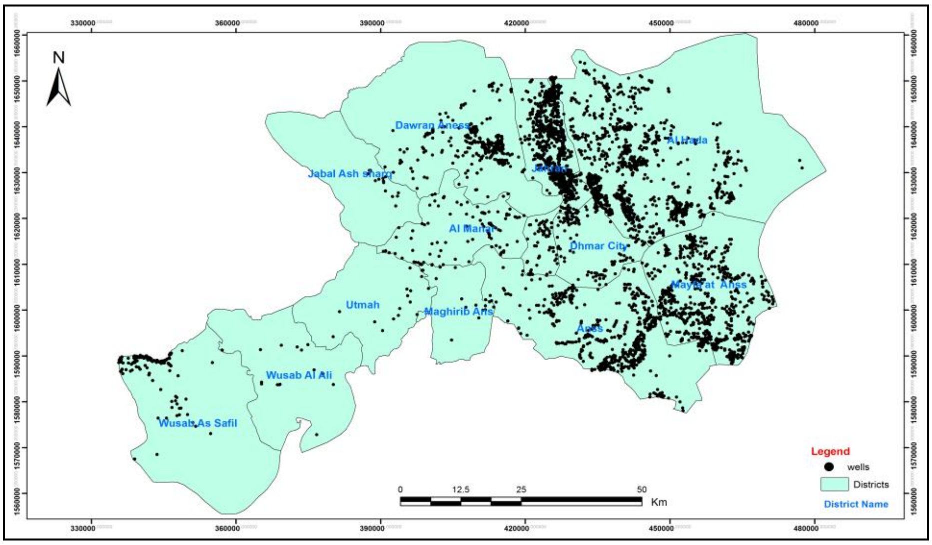

Figure 5: wells distribution through the districts.

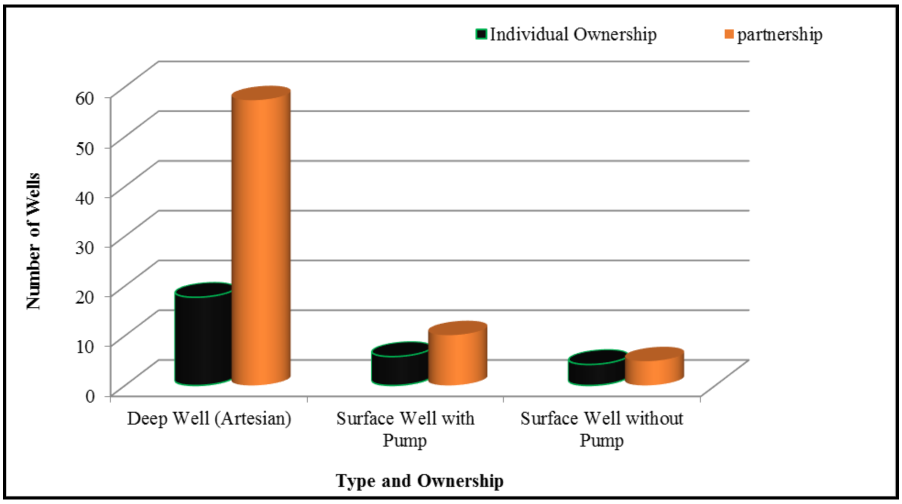

Figure 6: The percentage of wells in Dhamar districts classified by type and ownership in 2002.

WATER DEMAND

1- Municipal and Industrial Water

Today, securing people's demand for Municipal (drinking and domestic) water is a big challenge facing people and government together, especially in rural areas (villages). The main cities depend on groundwater for drinking and domestic use, while villages depend on groundwater by drilling wells that may be dug in wadis, or depend on springs, which is usually scarce and insufficient in the dry season (winter season). The people lives in some rural areas also depend on the traditional water structures such as small dams, small reservoirs, and ponds by harvesting rainfall. These small water structures can help to reduce the water demand, but those still are not enough. Meanwhile, some people use donkeys and cars to collect water (free of charge) from local agricultural wells or from springs that located far away from their locations (van Buitenlandse Zaken, 2007).

Currently, because of the current situation in Yemen, the problem of shortage water is not limited to villages, but also to the major cities such as the capital city of the governorate (Dhamar city). To estimate the water demand for Dhamar Governorate. It is assumed that people consume the minimum estimated in previous studies per capita in Yemen, which is estimated from 82 to 130 m^3/capita/year (Ward *et al*., 2000). Based on that, two scenarios (S1-G, S2-G) and (S1-D, S2-D) are assumed to determine the amount of water demand for the governorate and Dhamar city respectively. The first scenario (S1-G) is at 82 m^3/capita/ year, whereas the second scenario (S2-G) is at 130 m^3/capita/year. The estimated water demand is for 2004, 2017, 2020, 2030, 2040 and 2050, based on the population in 2004 with the population growth rate of 3.04 for the governorate.

The results show that at the S1-G scenario, the yearly amount of water demand is about 109.1, 161.9, 177.2, 240.3, 325.5 and 441.1 MCM/year for 2004, 2017, 2020, 2030, 2040 and 2050 respectively. However, it increased in the S2-G scenario and reached to approximately 172.9, 256.6, 281.1, 380.9, 516.1 and 699.3 MCM/year for the same previous years respectively (figure 7). In general, the estimation of water demand for Dhamar governorate is in the range of 109.1 - 699.3 MCM/year from 2004 to 2050 in the two scenarios S1-G and S2-G. Furthermore, following the same procedure under the same scenarios for Dhamar city (the capital). The two scenarios that are called (S1-D) for 82 m^3/capita/year and (S2-D) for 130 m^3/capita/ year. The results for Dhamar city show that the water demand projected to be in the range of 14.4 - 92.1 MCM/year from 2004 to 2050 for the two scenarios as shown in figure 7.

The analysis of data obtained from LWSA indicated that the water supply is operated for the city from different number of wells located in the east and west of the city. LWSA (2016) presented that there are about 20 operational wells, which are used to supply water to the city, while 7 wells are out of service (dried). The weekly operational work of wells is in the range of 20 – 96 hr. The water production from these wells is in the range of 20.42 – 115 m^3/hr (LWSA, 2016) . The actual monthly average water supply from all operational wells ranges between 0.326 and 0.465 MCM/month in the emergency and normal situations of available electricity (LWSA, 2016). This means that the actual yearly average water supply ranges between 3.9 and 5.6 MCM/year. When comparing between this amount of water supplied and the estimated of water demand in 2017 (e.g. ranges 21.3 – 33.8 MCM/year), there is a significant deficit between the water supply and demand. The government has decided to increase the amount of water produced by drilling more wells, repairing the distribution water network to reduce water losses. As well

as, constructing two additional water reservoirs to distribute water with an approximate capacity of 12,000 m^3, as solutions to cover the current shortage of water. Unfortunately, these solutions are not meet the high demand of water. Overall, the better solutions for shortage of water in the governorate is how to bring water from different sources, balance water supply with water demand, and conserve water. Increasing the amount of water through constructing more dams, reservoirs, hydraulic structures and harvesting water structures. The water demand for Industrial is not significant. There are some industries located in Dhamar city. (CES, 2009) indicated that the water demand for indiries in 2010 is about 6.86 MCM/yr.

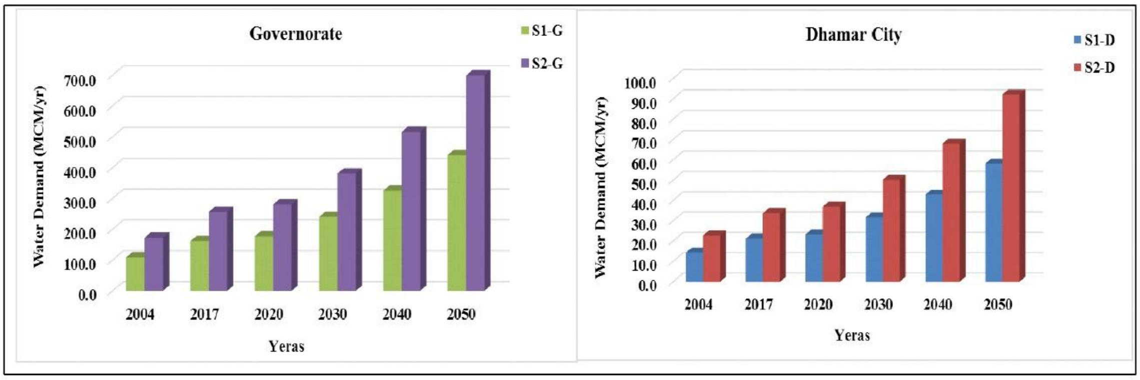

Figure 7: Water demand prediction for Dhamar governorate and Dhamr city.

[S1-G: 82 m^3/capita/ year, S2-G: 130 m^3/capita/year for the governorate].
[S1-D: 82 m^3/capita/ year, S2-D: 130 m^3/capita/year for Dhamar city (the capital)].

2- Agriculture Water Demand

Agriculture Water Demand (AWD) prediction for the agriculture sector in Dhamar governorate is very important for water resources management and water conservation in the future. The governorate classified as the third important area in agriculture sector in the country (9.3%) after Sana'a and Amran governorates as shown in figure (8).

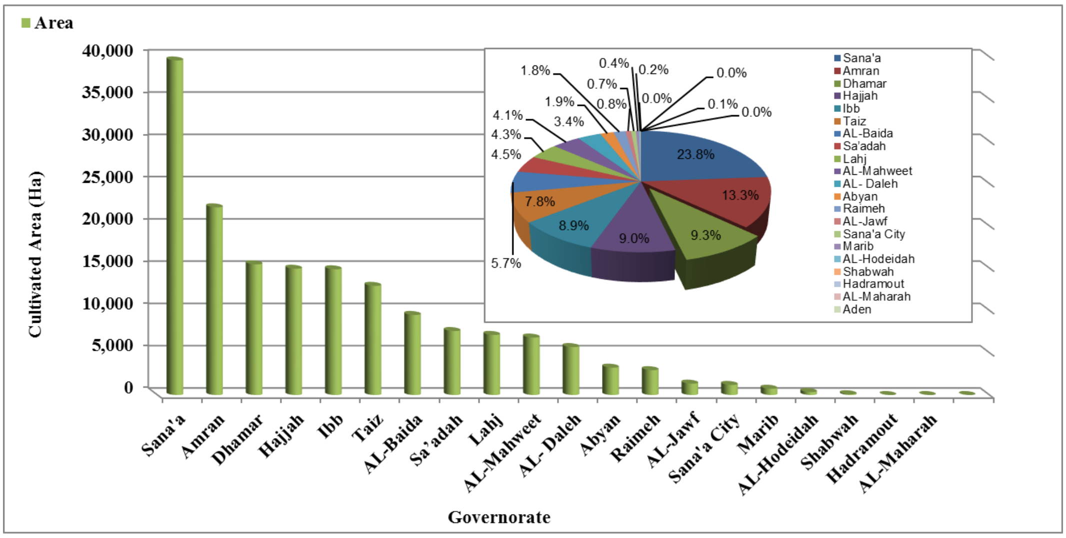

Figure 8: The cultivated area in Hectare and in percentage for governorates in Yemen

The crop water requirement (CWR) for different types of crops is the main key to estimate the AWD. Two studies have conducted to estimate the CWR for different types of crops and Qat plantations

in the study area at different growing seasons. First, for crops, (Yaya & Al Weshali, 2006) found that the CWR for Cereal crops, Legumes (pulses), Vegetables (including tomato and potato) and Fruits ranges from 293 - 642, 384 - 425, 382 - 935 and 713 - 775 mm respectively. The CWR for coffee is not mentioned for the governorate, but it has been studied at Sana'a basin and found to be 5000 m^3/ha of actual irrigation water use (Hellegers, Perry, Al-Aulaqi, Al-Eryani, & Al-Hebshi, 2008). Secondly, the average actual crop evapotranspiration for Qat plantation was predicted in the study area by (Atroosh & Al-Moayad, 2012) under irrigated and rainfed systems which was found to be in the ranges 602.8 -786.7 mm/yr and 412.8 - 506.2 mm/yr respectively. On the other hand, (Ward & Gatter, 2000) indicated that the yearly CWR for Qat was to be around 12,000 m^3/ha in the Sana'a area. It is also found to be in the range of 400 - 600 mm using the Penman method (Ward & Gatter, 2000). As well as, (Hellegers *et al*., 2008) implies that the actual irrigation water use for Qat was in the range of 8900-12500 m^3/ha in Sana'a basin in 2005. Since the prediction of CWR for Qat is not clear and not confirmed, the water demand will be predicted in different scenarios.

Based on the previous estimations of CWR for crops and Qat, sensitivity analysis for the Agriculture Water Demand (AWD) is anticipated in this study with considering the smallest, biggest of CWR values and the behavior change in the cultivated areas between the main crops and Qat (figure 9 (a-b)). The AWD will be projected for the previous years from 2009 - 2015 as an indicator for the probable amount of the water demand in the future. The data obtained from MAI showed that the agricultural areas for cultivated crops and Qat plantations are varied from year to year (figure 9 (a-b)). The cultivated area for Qat plantations is increased during the last period, while the main crops are decreased as shown in figures 9 (a-b). The high increase in the agricultural area of Qat was instead of the agricultural areas of the main agricultural crops from 2009 to 2015, as noted in the figure 9 (a-b). It is found that the cultivated areas for cereal, vegetable and coffee crops were decreased, while there was an increase in the cultivated area of Qat plantations as observed in figures 9 (a-b). This variation will adversely reflect to the amount of AWD prediction.

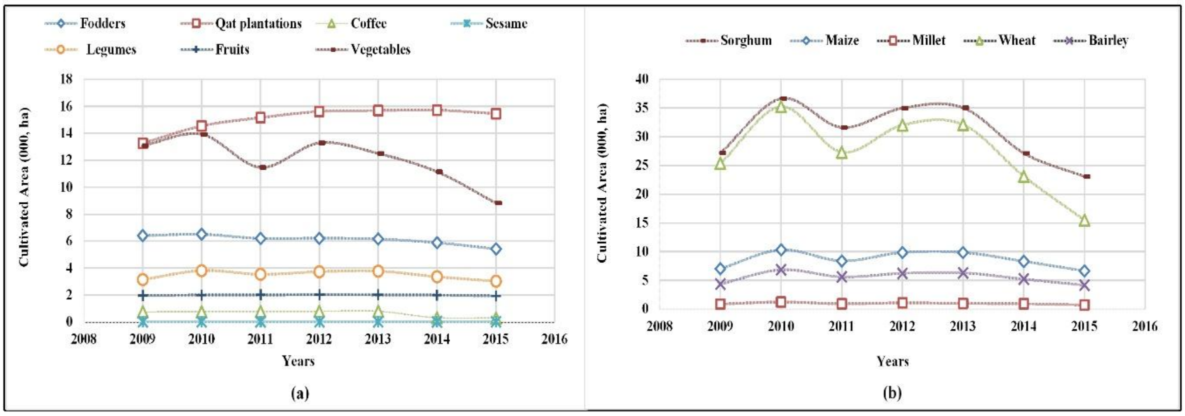

Figure 9: **Changing in cultivated area from 2009-2015 for crops and Qat plantations in Dhamar Governorate**

The AWD predicted in this study is according to the finding of CWR. Firstly, in terms of crops, the expected total AWD is in the range of about 191 – 580, 12 -16, 34 – 130, 14 -16, 79 – 94 and 2 – 4 for cereals, legumes, vegetables, fruits, fodder and coffee. Secondly, in terms of Qat, the expected total AWD has two different scenarios according to values of CWR presented in previous studies. The first scenario

(S1) used to predict the AWD is in the ranges of 6028 – 7867 m^3/ha of CWR, while the second scenario (S2) ranges from 8900 to 12500 m^3/ha of CWR. For the S1, the estimated AWD ranges from about 80 to 124 MCM/yr, whereas for the S2 the AWD, it increased in this scenario to amount of 118 and 197 MCM/yr. Finally, the expected total AWD for crops and Qat in the governorate are in the range of about 500 – 768, 613 – 954, 539 – 825, 590 – 914, 587 – 907, 499 – 760 and 424 – 634 MCM/yr in 2009, 2010, 2011, 2012, 2013, 2014 and 2015. Thus, the maximum projected of total AWD is about 954 MCM/yr, while the minimum is about 424 MCM/yr during 2009 – 2015 with the S1 scenario. Moreover, with the S2 scenario the maximum projected of total AWD increased to approximately 1.02 BCM/yr, while the minimum is about 468 MCM/yr during 2009 – 2015. Consequently, the estimated of AWD at these ranges for agriculture sector may probably applied as amount of water demand at any year in the future under the same conditions. This water demand obtains from any water resources in the governorate. (MAI, 2015) implied that there are many sources of irrigation in the governorate. Water supply developed from different sources as shown in figure (10). The figure presented the cropped area by source of irrigation, which is change from 2013 to 2015. However, there is a slight decrease in the cultivated area that irrigated by rain, spate irrigation, streams from10, 3 and 0.2%, there is opposite an increase of about 11.9% and 1.3% in area irrigated by wells and tanks on car (figure 10).

Therefore, there is an increase in the water consumption rate from wells by 11.9%, due to the increase in the Qat plantations (figure 9a) as indicated by the water demand, which was estimated above. In general, the classification of cultivated area according to the sources of irrigation not only in Dhamar plain but in all the governorate in 2013 was about 27 and 73% from groundwater and surface water respectively, which was changed in 2015 to 39 and 61% respectively. This poses an additional risk to groundwater depleted in the governorate. In Dhamar plain, it was found that the irrigation supply for irrigated areas of single, double and perennial crops were about 90, 95 and 95% from groundwater while the remaining percentage supplied from surface water. Unfortunately, in most areas, cultivation of some crops has replaced by Qat plantations. Bruns & Taher (2009) indicated that Qat plantations are the main income source for people in Wadi Al-Har, Anss district. People have been replaced the cultivated area of vegetables to cultivate Qat, which earns a lot of money. That happened also in the other regions of the governorate such as Hamam Ali, Al-Manar districts (e.g. replaced Orang trees by Qat) and so on. People know that Qat consumes a lot of water, but they have no choice since it is the main source of income (Bruns & Taher, 2009). In consequence, current estimates in this study show that Qat production consumes about 19 - 27% of total water use in agriculture. This percentage is approximately close to the estimation conducted by FAO, which is about 22.5 percent of total water use and 24.7 percent of total water use in agriculture (FAO, 2008).

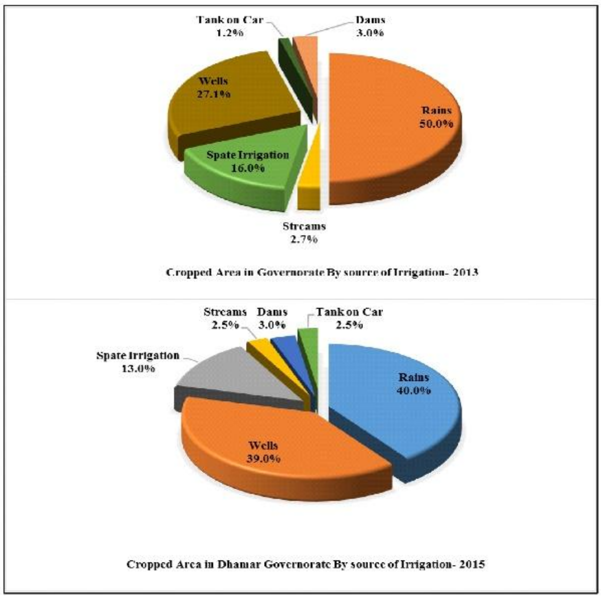

Figure 10: **Crops area in Dhamar governorate by source of Irrigation in 2013 and 2015.**

WASTEWATER REUSE

There is only one wastewater treatment plant located in the capital city of Dhamar governorate (Dhamar city). It is called Wastewater Treatment Plant (WWTP) or called Almawaheb Wastewater Treatment Plant, referring to its location outside towards 2 km North-East of the city at 2400 m elevation above the sea level (Al Aizari et al., 2017; Rageh, Al-Garadi, & Al-Mashreki, 2017). It was established in 1991 and designed to receive an average wastewater flow of about 12.000 and 8,000 m^3/day during summer and winter respectively (van Buitenlandse Zaken, 2007; Al Aizari *et al.*, 2017). Three-stage stabilization pond system provided for treatment the wastewater. Due to the increase of population, the WWTP is not sufficient for the current wastewater flows. The effluent from this plant is reuse to irrigate the large area of agriculture located in wadi Almawaheb, located in Dhamar plain downstream of the WWTP. The common crops grown in the area are mainly cereals (e.g. sorghum), while some vegetables are grown (e.g. potatoes) (Rageh *et al.*, 2017). The establishment of a continuous and free source of effluent would allow farmers to increase cropping and reduce dependence on groundwater for irrigation and saving pumping costs.

Unfortunately, it is indicated that there is significant amounts of water lost by evaporation from the large surface areas of the ponds and extended retention times in the WWTP (Rageh *et al*., 2017). These reduced the amounts of effluent produced to less than the inflows to the WWTP with stabilization ponds. It is found that there would be sufficient effluent to irrigate 30 ha, at the current design capacity by assuming an annual irrigation of 20,000 m^3/ha for two crops per year. As well as, the maximum demand for irrigation is in June when there would be sufficient effluent to irrigate only 50 ha (Rageh *et al.*, 2017).

The reuse of domestic wastewater for irrigation is useful for several reasons such as water conservation especially groundwater, ease of removal, and avoidance of surface water pollution (Al Aizari *et al.*, 2017). The most important factors that need to consider, containing salinity and impacts on soil structure, chemical contaminants and the presence of pathogens. These can all be controlled through

treatment and effective farm management practices (Rageh *et al.*, 2017). The current WWPT need to be increase in the capacity to meet the increase in the population.

CONCLUSION

This paper presented and discussed the water resources in Dhamar governorate. An assessment is done to the past, current and future situations of water resources. GIS and DEM in combinations with Arc Hydro used in this study to derive an entirely standardized stream network. Water demand discussed and projected for drinking, domestic, industrial, irrigation and wastewater reuse. More studies need to investigate the amount of groundwater and surface water in order to get better planning for water resources management and water conservation. Reaching the sustainability in water resource should be the main target for the governorate in the future.

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تقييم مصادر المياه في محافظة ذمار، الجمهورية اليمنية

[١]عبدالله عبده عباس، [٢]حسن ابراهيم محمد، [٢] نشأت عبداللاه علي، [٢] جمال ابو زيد

[١] طالب دكتوراه، قسم الهندسة المدنية، كلية الهندسة، جامعة اسيوط – من جامعة ذمار، اليمن

[٢] قسم الهندسة المدنية، كلية الهندسة، جامعة اسيوط

الملخص :

نظراً لكون اليمن بلداً ذات مصادر مياه عذبة محدودة، فإنه يواجه أزمة مائية بسبب إستنفاذ المياه الجوفية بسرعة وعدم توفر المياه السطحية. تعتبر محافظة ذمار الواقعة على بعد حوالي ١٠٠ كم من جنوب العاصمة صنعاء إحدى المناطق القاحلة في البلاد. يهدف هذا البحث إلى شرح الوضع الحالي للمصادر المائية والحصول على تخطيط أفضل لإدارة المصادر المائية في المحافظة. هطول الأمطار منخفض وله تباين مكاني وزماني فضلاً عن إستخراج المياه الجوفية غير المتجددة. أظهرت الدراسات السابقة في سهل ذمار أن إجمالي التدفق الداخلي والخارجي بلغ حوالي ٦٥٩,٣٦ و ٧٧١,٥١ مليون متر مكعب / سنة على التوالي، مما يعطي تغيراً سلبياً في تخزين حوالي ١١٢,١٥ مليون متر مكعب في السنة. إنخفض منسوب المياه الجوفية في السنوات الأربعين الماضية بمعدل يتراوح بين ٢,٠ و ٢,٥ متر في السنة، ويعزى ذلك أساساً إلى استخراج المياه الجوفية المثير للقلق من المنطقة بأكملها. من المتوقع أنه مع معدل نمو ٢٪ في استخراج المياه وهو ما يتوقع عادةً في تطوير الاقتصاد، سيتم إستنفاذ المياه الجوفية الضحلة في غضون السنوات ال ٣٠ المقبلة. تبين في سهل ذمار أن إمدادات الري للمناطق المروية من المحاصيل المفردة والمزدوجة والمعمرة كانت حوالي ٩٠ و ٩٥ و ٩٥٪ من المياه الجوفية في حين تم توفير النسبة المتبقية من المياه السطحية. وبصفة عامة، كان تصنيف المساحات المزروعة حسب مصادر الري ليس فقط في سهل ذمار ولكن في جميع المحافظات في عام ٢٠١٣ حوالي ٢٧ و ٧٣٪ من المياه الجوفية والمياه السطحية على التوالي، والتي تغيرت في عام ٢٠١٥ إلى ٣٩ و ٦١٪ على التوالي . وهذا يعني أن هناك احتمالاً للضغط على المياه الجوفية في المستقبل في قطاع الزراعة. من المهم جدا تطبيق إدارة أفضل للمصادر المائية والحفاظ عليها بالتخطيط في المحافظة من أجل حل مشكلة نقص المياه في المستقبل والحفاظ على المصادر المائية غير المتجددة. من هذه الدراسة، اقترحت سيناريوهات مختلفة لتبنيها مع ندرة المصادر المائية.