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Assessment of Water Resources in Sana'a Region, Yemen Republic (Study Case)

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Abstract: Yemen is a water-scarce country with inadequate fresh water and considerable groundwater depletion, as well as a lack of adequate surface water. The study region is considered an arid region, and there is insufficient water to meet the needs of the region's yearly population growth rate of 4 %. This study aims to assess the water resources in the Sana'a region and to identify the current water situation and forecast for the future. Rainfall changes spatial and temporal in very few quantities and an annual average of 267 mm. Water harvesting facilities are entirely filled by 75% of the total water facilities in the rainy seasons. The groundwater level in Sana'a Basin decreases about 6-8 meters annually due to the increase in the number of wells, the abundance of abstraction, and the lack of recharge. The amount of abstraction exceeds 400% of the recharge in the Sana'a basin. The water per capita is 70 - 85 m³ annually. It is an abstraction from the aquifers by private wells. The crop cultivated area decreased from 184217 hectares in 2007 to 122583 hectares in 2018 due to lack of water. The sewage treatment plant treats 18.25 Mm³ annually, with less than 70 % efficiency. The water deficit is about 500 to 723 Mm³ annually; it is an abstraction from the aquifers by private wells. The current water situation in the Sana'a region is catastrophic, and the planning and management must ensure a water balance in the future.

Keywords: Sana'a Region; Rainfall; Surface Water; Groundwater; Water Crisis

1. Introduction

Water is the basis of life, an essential input for social and economic development, and an essential element of environmental sustainability. The Arab region is one of the poorest regions in the world in terms of water resources, which makes most of the countries of the Arab region face significant challenges to create a water balance. Yemen is located within the arid and semi-arid region, with latitudes (12° – 19°) N, and longitude (42° – 55°) E. That is evident in the lack of precipitation and its irregularity in quantity and distribution. Yemen is considered one of the ten countries in the world that suffer water scarcity [1], especially since it does not contain perpetual rivers [2]. Yemen has a problem in the irrational use of the available water quantity, which leads to a rapid depletion of groundwater [3].

Groundwater reached 1.5 billion cubic meters (Bm³), the surface water was 1.0 Bm³, and the water demand reached 3.4 Bm³ [4]. In comparison, renewable water amounted to 2.5 Bm³, which means a deficit of 0.9 Bm³ that is to be compensated by groundwater. Currently, this deficit has increased to about 1.4 Bm³ [5] due to the current water demand reaching 3.9 Bm³ (2020) and will increase to 4.4 Bm³ by 2025. The large amount between supply and demand means withdrawal from the stored groundwater. Agricultural Production consumes about 93% of the total water resources [6]. There is no country in the world where the rate of depletion of aquifers is going as fast as Yemen [7]. In general, more than 90% of the population in Yemen uses less than 90 cubic meters annually. This decrease is considerable and shows that the per capita share in Yemen does not exceed 10% compared to other countries [7].

In Sana'a region, the recent rapid population growth and increased water consumption for the agriculture sector (especially qat cultivation) as well as a dearth of precipitation, have led to an overuse of groundwater. The amount of groundwater extracted from the Sana'a basin is about 400% of the amount of recharge [8], so most of the groundwater wells in the study area dried up due to the drop in the groundwater level, which is estimated at 6-8 meters annually [9, 10]. The increase in population with water scarcity poses significant challenges to the state economically, socially, and politically and threatens the stability of the environment [11]. Despite the shortage of water in the Sana'a region, it also suffers from rainwater drainage, especially in the capital, where the valleys in the vicinity flow into the heart of the Sana'a city (Wadi Al-Saila) due to population congestion and urban expansion. In addition, the internal migration to Sana'a Region ranks first among Yemeni cities, where the proportion of the urban population reached 7.52% of the city's total population [12]. The water problem in Yemen in general and the Sana'a region, in particular, is a big problem that is exacerbating with time, and there are no satisfactory solutions by the government, especially with the recent events that the country has witnessed. These Problems require achieving a water balance between the available water and its demand; so that it does not dry out quickly. If the water problem in Yemen is not solved, expected will deplete its groundwater reserves within two decades. This research deals with the water situation in the Sana'a region in its two parts, Sana'a city and Sana'a governorate. And aims to assess water resources in the Sana'a region by collecting previous and current information and analyzing them to display complete details about water quantity, distribution, and uses. Analyze the results, and develop proposals and solutions to reduce water problems.

2. Materials and Methods

2.1. Study Area

Sana'a Region is located in the Northern-central part of Yemen. It consists of the Sana'a governorate and Sana'a city, Sana'a city also called Amanat Alasimah, and it is the political and historical capital of Yemen. Sana'a governorate surrounds Sana'a city from all sides. Sana'a Region is located within the coordinates of latitudes ($14^{\circ}45' - 16^{\circ}5'$) N and longitudes ($43^{\circ}30' - 45^{\circ}5'$) E, as shown in Figure 1.

It is above sea level by 2200 meters. The highest area is Jabal al-Nabi Shuaib, located in the Bani Matar district, and it rises 3666 meters above sea level. It is considered the highest area in the Arabian Peninsula. The total area is 12259 km². Sana'a governorate and Sana'a city 11869 and 390 km² respectively. Based on [13], the population of Sana'a governorate and Sana'a city were 1,469,960 with a 3.2% growth rate and 3,406,643 with a 4.5 % growth rate, respectively. Sana'a governorate consists of 16 districts are (Sanhan, Khawlan, Alttayal, Bani Dabyan, Alhusn, Bilad Alrus, Hamdan, Bani Matar, Arhab, Nihm, Al-yayma 1, Al-yayma 2, Manakhah, and Sa'fan). Sana'a city contains ten districts (Bani Alharith, Alssafia, Alsabain, Old city, Ma'ain, Azal, Altahrir, Alwahdah, and Althaorah).

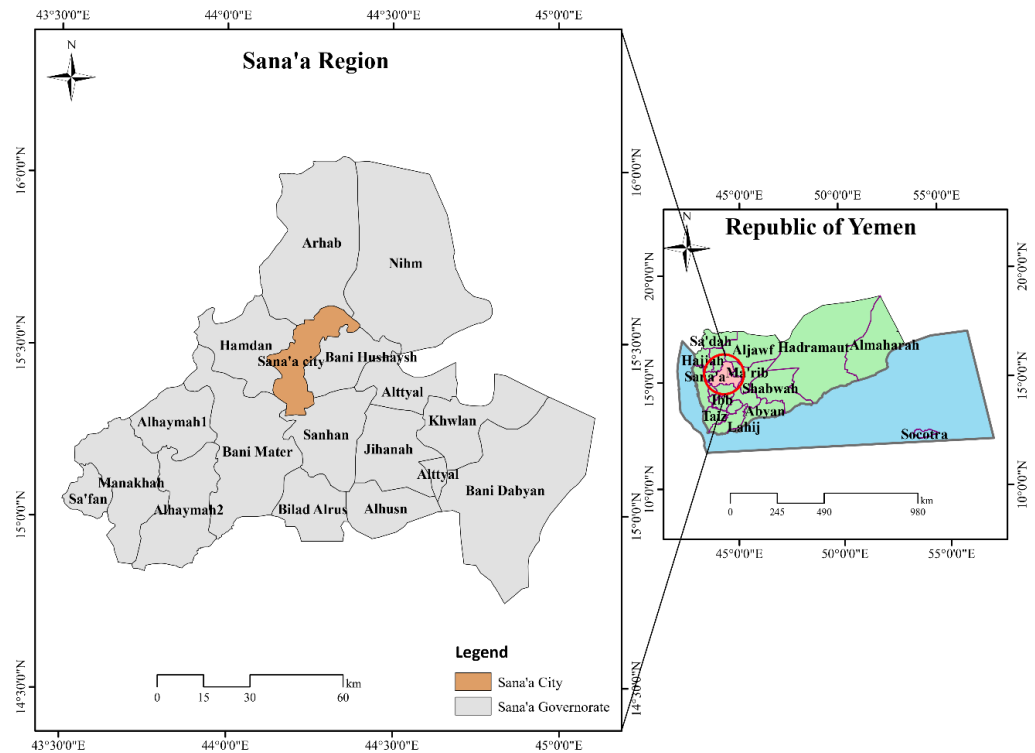


Figure 1. Sana'a Region location map.

2.2. Data and method

Climate, population, agriculture, dams, and wells data were collected from various sources such as Civil Aviation and Meteorology Authority [14], Ministry of Agriculture and Irrigation [15], Ministry of Water and Environment [5], National Water Resources Authority [16]. Previous studies were also presented, analyzed, reviewed, and compared with the current situation. And predicting the future water situation in the study area. The geographic information systems (GIS) program was used to determine the study area and the locations of the water facilities. Digital Elevation Model (DEM) and the Arc Hydro software integration were used to derive water flow networks and direction and identify watersheds. Digital elevation data were obtained from the NASA website and the USGS Geosciences Observation Center (DAAC) archive.

3. Results

3.1. Surface water

3.1.1. Rainfall

The average annual rainfall ranged from 130 mm in the eastern coastal areas to more than 600 mm in the southwestern highlands [16]. According to studies conducted by [17], the average rainfall amounted to 200 mm annually in the Sana'a Basin that representing 30% of the total study area, while [8-11, 18-23] mentioned the annual rainfall ranged between 100 and 350 mm. [12] indicated that the average rainfall ranged between 250 to 300 mm annually.

Recorded rainfall data began in the 1970s for different private goals and projects to study the Sana'a Basin and Wadi Siham [16] and then stopped working after that. About 56 stations have been established throughout the study area, distributed between 12 meteorological stations and 44 rainfall stations distributed in different places, as shown in Figure 2. Various authorities are responsible for these stations, such as (CAMA), (MAI), (MWE), (NWRA). Currently, most of these stations discontinued work because they were

established to achieve private projects; thus, many of the data were missed in these stations for many years.

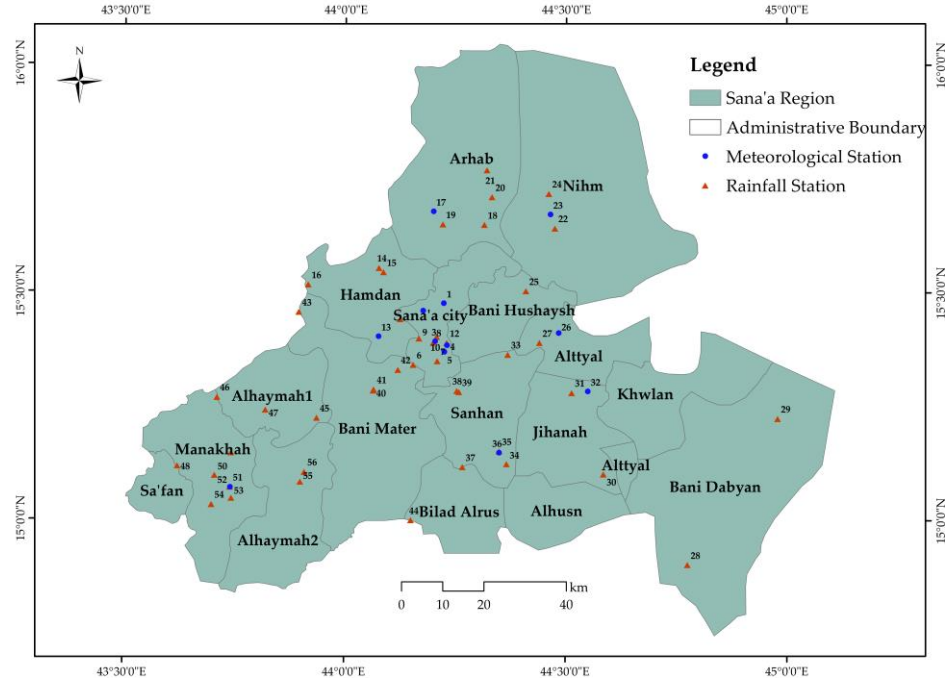
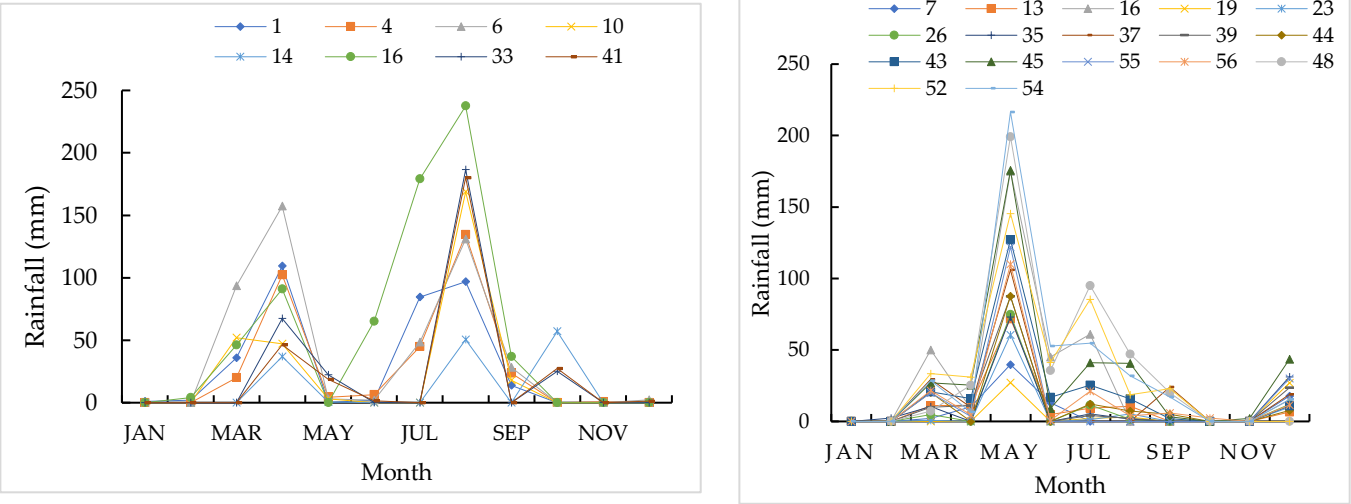


Figure 2. Meteorological and rainfall stations distribution map in the Sana'a Region

Also, the difficulty obtaining data for all stations and unavailability for researchers make the vision incomplete for the current situation. In 1975 the number of stations was eight stations, then the number increased to 17 and 18 stations in 1984 and 1996, respectively. In 2006 and 2020, the stations decreased again to 11 and 6 stations, respectively Figure (4). According to the available and recorded data, the operating stations are currently six Stations (1, 4, 7, 10, 36, and 38). Stations (1, 4, and 36) are metrological stations, while stations (7, 10, and 38) are rainfall stations. Stations (1 and 7) are managed by CAMA, while station (4) are managed by NWRA, and MAI manages stations (10, 36, and 38).

In 1975, the behavior of rainfall recorded was the same in all stations, but the monthly rainfall amount was different, as in Figure (3a). The rainfall occurred in March, April, July, and August, while the rest of the months were dry. Rainfall station (16) recorded the highest rainfall during July and August, 179 and 237.5 mm, respectively. The total maximum annual rainfall for this station amounted to 659.6 mm. The lowest annual total rainfall was in a station (14), which amounted to 144.8 mm.



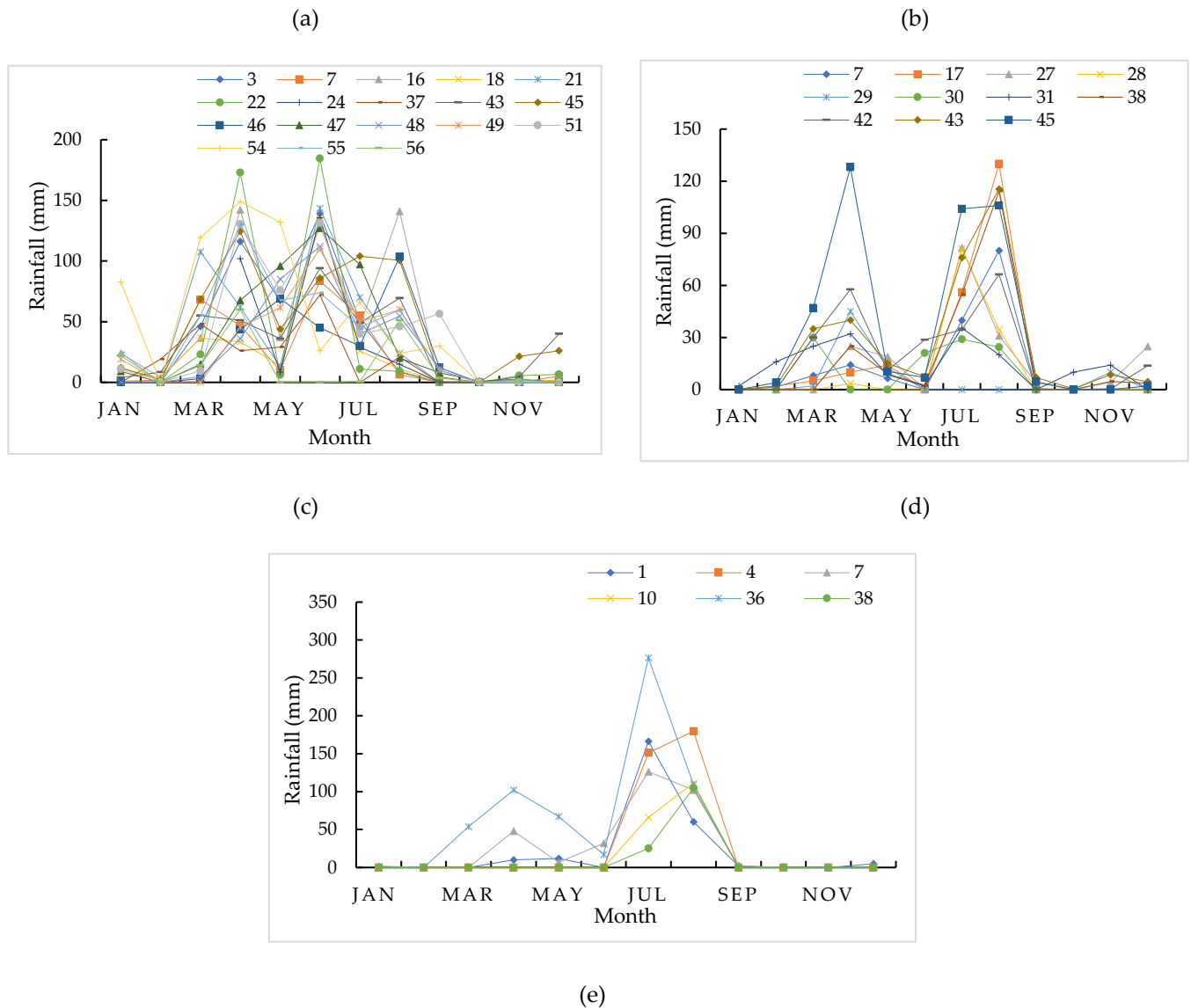


Figure 3. Rainfall records for the stations in some selected years: (a) 1975; (b) 1984; (c) 1996; (d) 2006; (e) 2020; (Numbers in legend refer to rainfall recorded stations numbers)

Also, in 1984, the behavior of rainfall was the same for all stations, and the rainfall months were March, May, June, and August; during the year, most of the precipitation was in May, as shown in Figure (3b). In May, the maximum monthly rainfall was at Station 54, which amounted to 216.5 mm. The maximum total in the station (48) was 429.8 mm, and the lowest total amounted was 59.2 mm at the station (19). In Figure(3c), in 1996, the precipitation behavior is varied and reached a maximum monthly rainfall of 184.5 mm in June, which was recorded by the station (22). The precipitation period starts from March to August. Station (54) recorded a total maximum of 629.3 mm, while station (56) recorded a minimum of 153 mm. In 2006 Figure (3d), the amount and behavior of precipitation were the same; the maximum rainfall was recorded in June, which amounted to 130 mm in August by a station (17). The maximum total rainfall was 413 mm by station (45), while the minimum total rainfall was 69.5 mm station (29). For 2020, as shown in Figure (3e), the rainfall months were March, April, May, June, and August. The station (36) recorded maximum monthly rainfall, which amounted was 276.5 mm in Jul. In contrast, the maximum total rainfall amounted was 625.7 mm in the same station, and the minimum total rainfall reached 130 mm at the station (38).

In general, through the available data for several stations from 1972 to 2020, the study area can be divided into five areas:

1. In eastern and southern highlands include the districts of Sanhan, Bani Hushaysh, Khwlan, Al-ttyal, Bani Dabyan, Al-Husn, and Bilad Al-Rus. The range of rainfall is between 130 and 320 mm annually, a maximum of 827 mm in 1981 by the station (44) and a minimum of 47 mm 2008 by the station (31).
2. In southern highlands include the districts of Bani Matar and Hamdan, with ranges of annual rainfall between 160 and 450 mm, a maximum of 685 mm in 1998 at Station 16, a minimum of 62 mm in 2003 at a station (43).
3. In southwestern highlands, which include the districts of Al-Haymah (1 + 2), Manakhah, and Sa'fan, annual rainfall ranges between 250 and 520 mm, a maximum of 887 mm in 1997 at a station (54), and a minimum of 142 mm in 1992 by a station (48).
4. In the northern highlands, which include the districts of Nihm and Arhab, the ranges annual rainfall varies between 150 and 235 mm, a maximum of 419 mm in 1996 at Station 22, a minimum of 59 mm in 2004 at a station (19).
5. The central region, which includes the Sana'a city, ranges annual rainfall between 130 and 350 mm, a maximum of 655 mm in 1979 at a station (6) and a minimum of 83 mm in 2002 by a station (7).

The data acquired through the research revealed that precipitation in the studied area fluctuated both temporally and geographically. Rainfall periods can be divided into two seasons, the first season from March to May and the second season from July to August. Because of the geographical location and its influence, the convergence between the Red Sea and the tropics [24]. Generally, the annual Rainfall in Sana's region varies between 160 and 375mm, with an average of 267 mm/year.

The lack of climate-related data is a significant challenge in Yemen to reach hydrological models that represent reality and seek better manage water resources [25]. The climate change phenomenon is one of the most important topics that should receive significant attention due to its relationship with natural resources. Because the Sana'a region is considered a dry area according to the UNESCO classification in 1979, the evapotranspiration exceeds the amount of rainfall, where the annual average for evapotranspiration is between 2000 and 2500 mm [18, 21]. Climatic phenomena (floods - drought) and their relationship with weather phenomena such as rainfall, relative humidity, wind speed, and temperature are essential to know the causes of current climate change and future expectations. These weather phenomena depend on the region's topography and height above sea level. It is noted that the temperature is lower in the eastern, western, and southwestern highlands, while the amount of rainfall is more than in the central regions of the study area.

The average temperature ranges (12 – 25°C) [5, 16, 19, 22, 26]. In contrast, the average maximum annual temperature ranges between 23 and 30 °C with an average of 26°C by analyzing all data obtained (1972-2015) [16]. The average yearly minimum temperature ranges between zero and 17 °C, with an average of 9°C, and it decreases in some winter nights to below zero in December and January, causing frost in the highlands of the Sana'a region. The frost phenomenon is classified as a dangerous factor that threatens some crops and destroys them. In January 1986, the lowest temperature was recorded in the region reached -9°C [16]. The temperature is considered very low and close to the high mountainous areas south of the Sana'a region, which recorded in the same period reached -12° in Dhamar Governorate [27]. In general, the mountainous heights in the Sana'a region are considered one of the coldest regions in Yemen during the winter and the most moderate during the summer. The average monthly relative humidity in the range of (38 - 58) %, wind speed is 2 - 3.1 m/, sunshine 7 – 11 hr/day from 1972 to 2014 [16].

3.1.2. Stream flow

There is no permanent surface runoff except the runoff due to floods. These floods occur due to heavy rainfall in some years. The site's topography makes most of the valleys

pass from Sana'a's center, causing floods. Flood damage increases with time due to urban expansion and the increase in population, specifically in the Sana'a region. Sana'a city is considered one of the cities most affected by floods, as rainwater collects from the hills and heights to valleys and sewers to form the flow [24]. Most of the valleys surrounding Sana'a city flow through the wadi (Al-Sailah) (Figure.4). It is the city's only outlet for floods drainage, which is 30 km long and 15 to 16 m wide, with a height ranging between 1.4 and 3.6 m; on the other hand, wadi Al-sailah is a major corridor for vehicles.

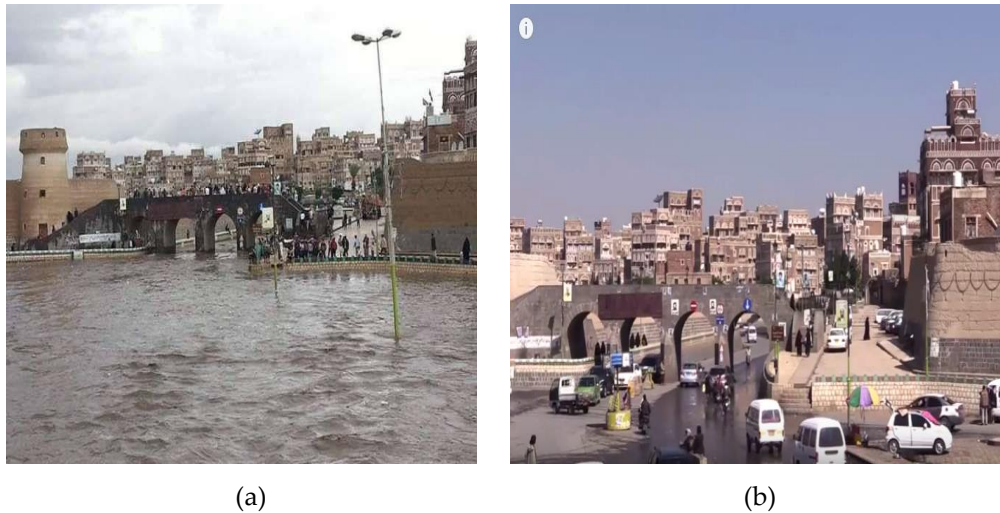
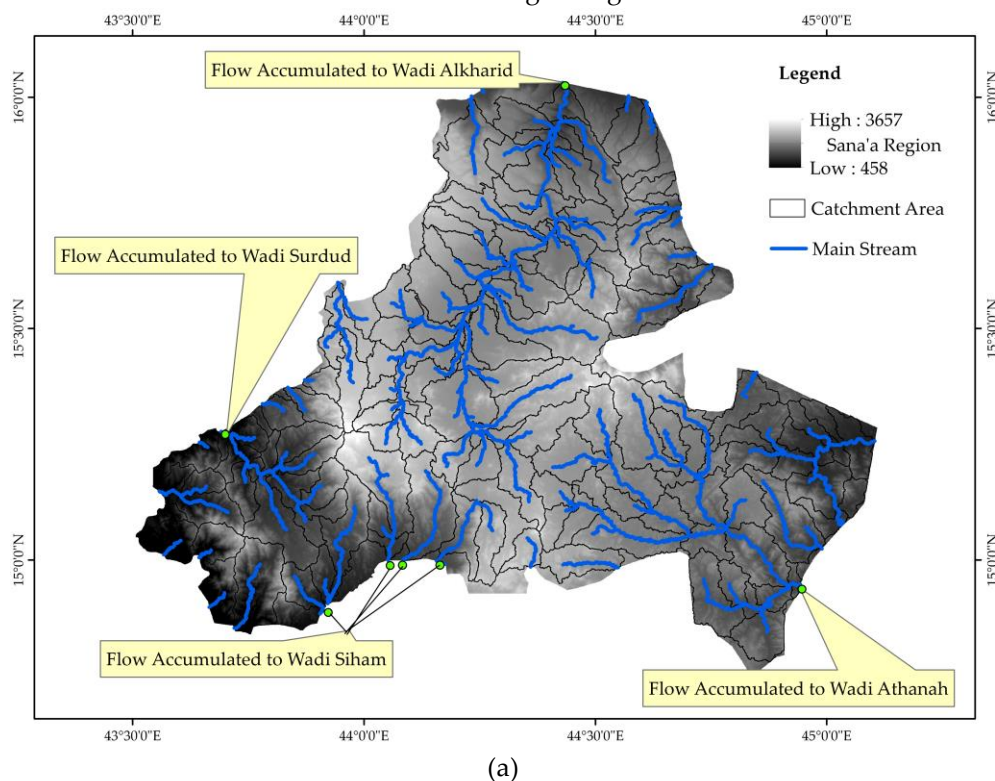


Figure 4. Flood effect on Sana'a city in wadi Alsailah: (a) Sana'a city with flood; (b) Sana'a city without rains

The water collects to wadi Alsailah then to north-east of the Sana'a region to wadi Al-kharid in Aljawf governorate. Wadi Al-kharid is considered a significant watershed in Sana'a. Some springs feed the area, estimated at $0.2 \text{ m}^3/\text{s}$ [28]. Other springs within the region have an estimated flow of about $17.2 \text{ (Mm}^3\text{)}$ annually [29]. Two maps were created by GIS 10.3 with arc Hydro to determine the Main and sub-streams flow directions with catchment area in the Sana'a Region Figure 5.



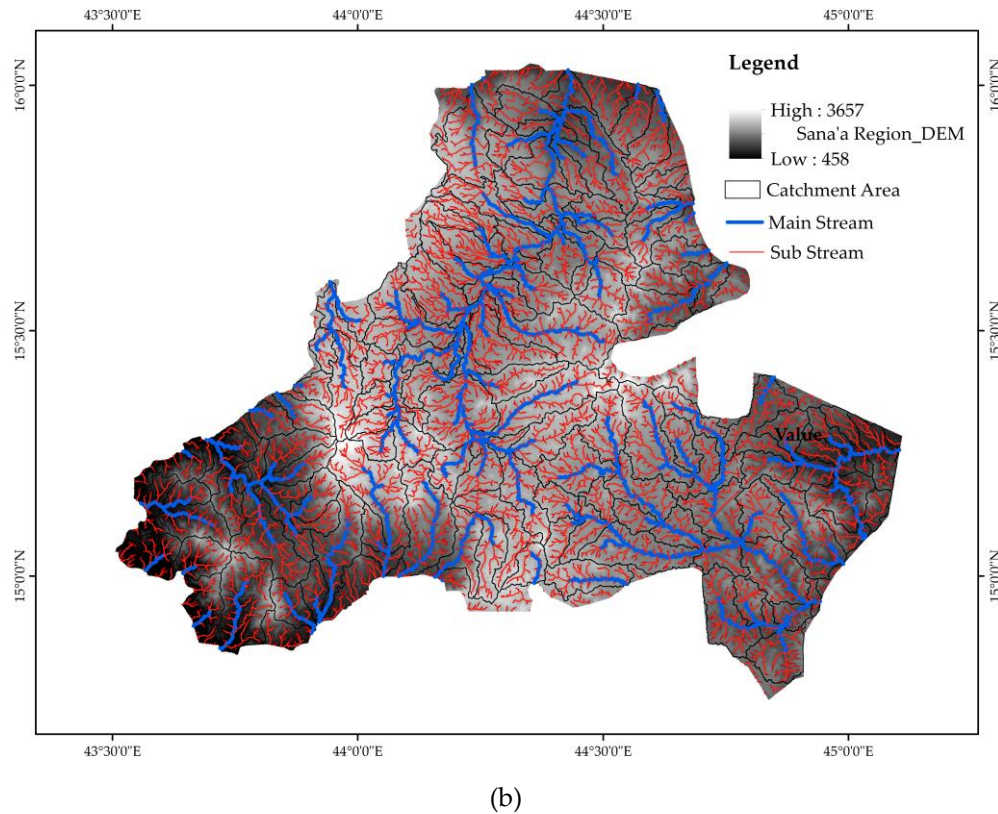


Figure 5. Main and sub-streams flow directions in the Sana'a Region: (a) Main stream with catchment area; (b) Main and sub stream with catchment area

In Sana'a basin, the outflow is 27 Mm³ annually [29], while inside the Sana'a basin, the total flow is estimated at 40 Mm³ annually [19, 22, 29]. The valleys of the southwestern study area flow towards wadi Siham and wadi Surdud to Al Hudaydah governorate. [30] mentioned the average surface runoff in wadi Siham is 82.92 Mm³ annually, while [31] noted the runoff in wadi Siham and Surdud are 73 and 82 Mm³/year, respectively, with rainfall between 80-597 and 50-400 mm for wadi Siham and Surdud, respectively [31, 32]. Additional study [33] indicated the surface runoff in the wadis of Al-kharid, Siham and Surdud was 35, 89, and 69 Mm³/year, respectively. In contrast, the valleys southeastern Sana'a region flow out of the area towards wadi Athanah, with the area is 11500 km² to Ma'rib governorate, the rainfall ranges between 100-400 mm annually, and the runoff is estimated at 5.9 Mm³/year [32].

Because the floods caused substantial human and economic losses reported. The government is represented by the Ministry of Agriculture and Irrigation (MAI). Some external donors to Yemen, such as the Social Fund Development (SFD), Agriculture and Fisheries Production Promotion Fund (AFPPF), European Union, and the United States Agency for International Development [34], to create a set of programs to develop dams and water barriers to alleviate floods as well as to recharge groundwater that helps and supports agriculture. The idea of dams and barriers dates back to thousands of years ago when man invented the method of harvesting water through collect it by barriers and dams; over the past years and up to the present, new technologies and unique innovations have appeared in dam construction [35]. The number of dams and reservoirs constructed are 168 dams, and 65 reservoirs, as shown in Figure 6, with a storage capacity of 64,656,651 and 238,983 m³, respectively. About 32% of them are located within the Sana'a basin. Most dams and reservoirs are used for irrigation and domestic uses as one of the water sources, serve the purpose of its establishment about 80%, and 20% do not fulfill the purpose of its establishment for various reasons, such as the remoteness of the site on the beneficiaries and the lack of water transfer techniques or high leakage rates; thus, the water does not stay in it

for long, or the sediment rises in some dams. In rainy seasons, filled dams are about 74 % of total dams, while the rest are partially filled 26 %, which means the number of dams is insufficient to harvest water and meet water demand.

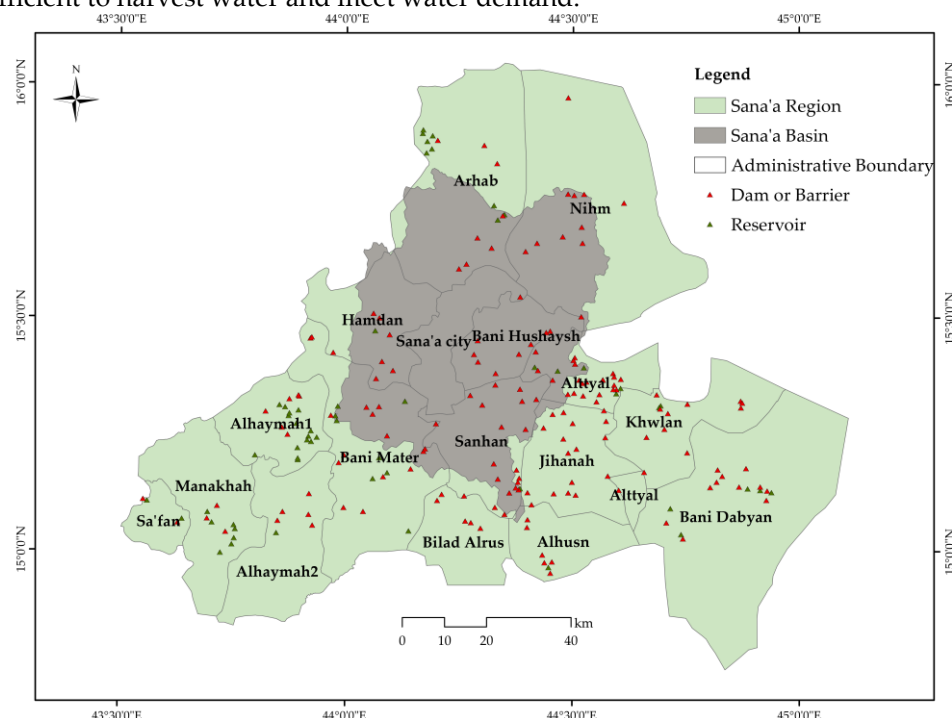


Figure 6. Dams and reservoirs distribution in the study area with Sana'a basin boundary

3.2. Groundwater

People currently depend mainly on groundwater for irrigation and domestic uses, and in some rural areas, rainwater is collected by traditional methods such as basins, ponds, and small dams [5, 36]. In Sana'a city, there are approximately 198 wells supervised by the government to meet the needs of the people. Currently, many wells have stopped working due to the low water level. The number of wells operating in Sana'a city is about 70 out of 196 wells, and their depths range between 200 m to more than 1000 m. Sana'a city currently has more than 3 million people. These quantities of water do not meet the needs of people, so it depends on people buy water from private sources, which increases the cost, As some families are not able to meet the needs of family members, which leads to a decrease in the per capita of water [37]. There is no complete data on wells' number and productivity in the Sana'a governorate. The reason is the government's inability to impose laws and reduce random drilling that threatens to deplete water. In addition, the people have the idea that whoever owns the land has the right to dispose of it, which justifies the owners of the land their right to dig Wells [8]. The number of wells in the Sana'a governorate is estimated at more than 20,000; most of these wells are concentrated in the Sana'a basin with about 13000 wells [17, 23, 38], representing about 30% of the total area of the Sana'a region. People cannot meet the drilling requirements; therefore, the daily consumption per capita decreases.

3.2.1. Sanaa Basin

The Area of the Sana'a Basin is about 3240 km² [19, 22]; most of the population of the Sana'a region is concentrated in the Sana'a Basin region, which is estimated at 80% of the total population of the Sana'a region due to the presence of water and urban areas compared to the rest of the areas that are considered mountainous heights. Figure. 8 shows the location of the Sana'a Basin, which most previous studies indicated that the water table declined due to the lack of other sources of water. The Sana'a Basin is the upper part of wadi Alkharid, which is considered one of the catchments of wadi Al-Jawf north of Sana'a. The average annual rainfall ranges between 100 and 350 mm [8, 19, 20]. The Sana'a

Basin is fed by 22 sub-basins [24, 29]. These sub-basins have an estimated surface runoff due to seasonal rains of 40 Mm³ [19, 22].

As shown in Figure 7, In 1985, the amount of abstraction was equal to the recharge in the Sana'a Basin [38], which means a water balance. Still, the amounts of abstraction increased to 300-330 Mm³ (2019-2021) and decreased recharge to 80 Mm³ [5, 23]. The increased drilling of wells in the basin leads to large amounts of groundwater withdrawal. There is no strong governorate management, which means it is considered a traditional local system, increasing the pressure on the government [8, 39, 40].

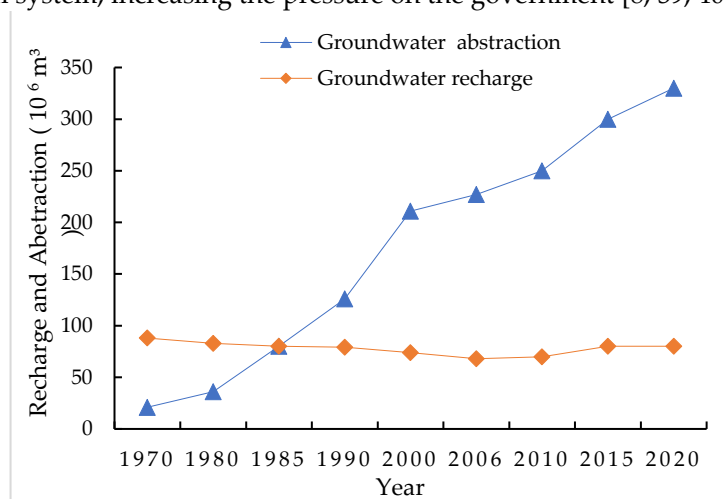


Figure 7. Abstraction and recharge for groundwater in the Sana'a Basin

3.3. Water demand

3.3.1. Domestic water

Yemen is one of the most water-depleted countries in the Middle East [41]. Food security is alarmed a disaster in Yemen [8]. Reports indicate that more than 45% of public facilities are in a state of collapse [22]. Due to the target of some vital facilities or the lack of its needs [42]. Because of the current situation in Yemen, millions of Yemenis suffer from a loss of access to clean drinking water. Most of the farmers lost their agricultural activities. The Sana'a region is considered one of the most water-scarce regions globally, so researchers anticipate a drought in the coming years due to the current water situation. Urban areas depend on groundwater, while rural areas rely on wells and traditional water harvesting methods such as small dams and ponds [24]. Water is sometimes brought by women from far away, which may put them at risk in a socially diverse society.

The beneficiaries of the water and electricity networks are only 10% of the population because of the conflict, so people turned to alternative solutions such as solar energy [22]. With the increase in the population and the lack of solutions to recharge the groundwater, the groundwater level continues to decline if the excavation depth reaches more than 100 m in 2000 [37], while in 2020, depth reaches more than 1000 m [5]. In Sana'a region, the availability of water depends on the location of the family and the percentage of income [37].

Sana'a governorate relies on other means such as rainwater harvesting and digging personal and participatory wells among people. These installations reduce the amount of water demand, but it is still unsatisfactory and insufficient. On the other hand, some people use cars and donkeys to serve them in collecting water for free from places far from their locations [43]. [7] indicated the renewable water resources in Yemen decreased from 246 to 130 m³/capita/year from 1980 to 1997, respectively. While in 2018 the renewable water resources were 73.69 m³/capita/year [44], On other hand the ministry of water and environment has shown that the renewable water resources is 85 m³/capita/year in 2019 [5], and by 2025 and ,2026 it will reach to 66 m³/capita/year [5, 33]. No accurate statistic represents the per capita of water annually, but it can currently range from 70 to 85

m³/capita/year. This quantity is considered very small and almost negligible in other countries and regions. In 2015, the percentage of families benefiting from the public network in Sana'a city was 44%, while it decreased to 28 % in 2017 because of the conflict in the country "study conducted for a sample of families" [45]. The wells operating in Sana'a city in 2021 controlled by the government were about 70 wells in the Sana'a city out of 196 wells, working weekly 25 to 112 hr with productivity range between 17 and 82 M³/hr. The annual production is about 11.5-14 Mm³, respectively. This quantity is considered minor and insufficient to meet the people's water needs, so people buy water from private sources. Currently, the public network does not cover the needs of 10 % of the population of the city Sana'a city, which increases the demand for water from private sources and puts the government in a difficult situation. The Figure. 8 shows the water demand of current and expectations for water demand in future, according to usage between 70 and 85 m³/capita/year in the study area.

There is a significant deficit between the current supply and demand. The deficit is gradually increased by predicting the water quantities required for domestic use. In (2019-2020), the public water network produced about 11.5-14 Mm³ in Sana'a city; while the estimated water demand is between (106-128,124-151,145-176,170-206,199-241 Mm³) in Sana'a governorate Figure (8a), while in Sana'a city Figure (8b) the estimated water demand is between (249-302, 312-378, 389-472, 486-590, 607-737 Mm³) for 2020, 2025, 2030, 2035, 2040 respectively. This means that the region withdraws large amounts of groundwater through private wells. The deficit is significant and requires great efforts to achieve water balance by establishing dams and reservoirs for rainwater harvesting and rational water consumption. The water demand for the industrial sector ranges between 4.8 and 16 Mm³ (2004-2020), while the estimated Touristic water demand is 0.36 Mm³ in 2005 and 7.12 Mm³ in 2020 [29].

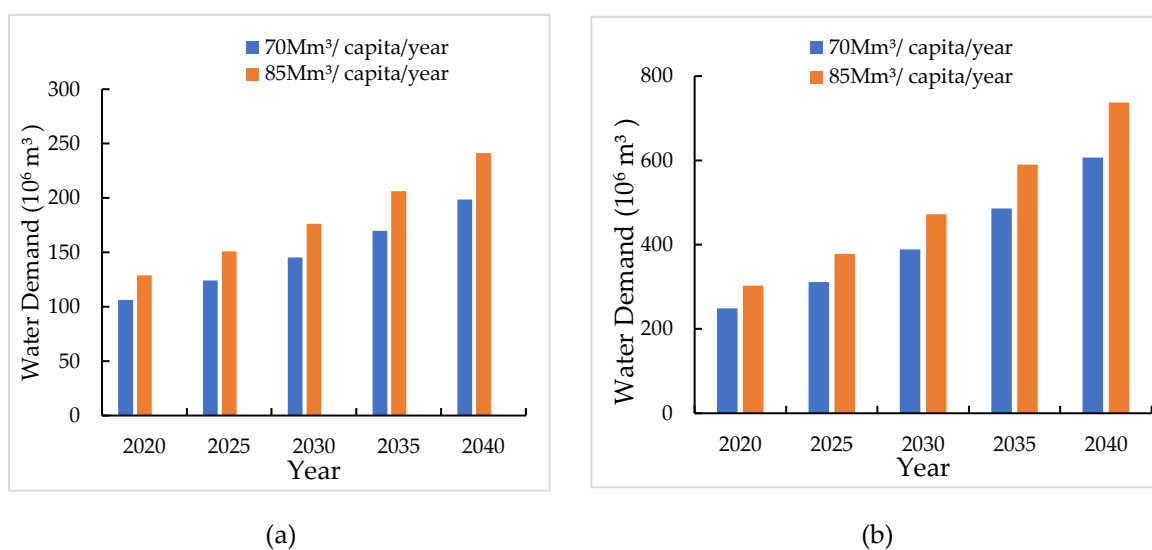


Figure 8. Domestic water demand expectation for Sana'a Region: (a) Sana'a governorate with a population growth rate 3.2 %; (b) Sana'a city with a population growth rate 4.5 %

3.3.2 Agriculture Water Demand

Sana'a region is considered one of the largest regions in Yemen in terms of agricultural crops areas, representing 11-13% of the total agricultural crops areas in Yemen (2011-2018). The cultivatable area in the Sana'a region is about 145321hectares, representing 11.9% of the total area .The water demand for the agricultural sector is significant for future planning and sustainable water management. The water needs of different crops show the amount of water needed for agriculture and forecasts of water demand for agriculture.

Significantly since recent years have decreased the cultivated area due to water depletion and scarcity, the cultivated area decreased from 184217 hectares to 122583 hectares

(Figure. 9b). Most crops have decreased the cultivated area, while some have the same cultivated area. The only crop that increases in the area annually is the qat crops, as shown in (Figure. 9a). Qat is the only crop whose area is increasing with time. In 2007, the area of qat represented 19.4% of the total cultivated areas, while in 2018, it reached 33% of the total area.

In the Sana'a region, crops' water needs for vegetables, cereals, fruits, legumes, and sesame in a range between 464-841, 380-761, 892-956, 360-420, and 401-502, respectively, while coffee needs 1111 mm, [46]. The fodders 1300-1440 mm [24]. While qat needs about (6028 -12500) m³/hectare annually [47-49]. The average evapotranspiration of qat cultivation ranges between 786.7-602.8 mm for irrigated method, and 412.8-506.2 mm for the rainfed method [49].

Through estimates of crops' water needs, annual water estimates were made from 2007 to 2018 based on the cultivated area due to the yearly decrease in the total cultivated areas, as shown in Figure 9. Annually the estimated water needs of crops for cereals, vegetables, fruits, sesame, legumes, fodder, and qat is about (162-607, 33-58, 119-186, 0.18-0.2, 37-59, 73-108, 178-518 Mm³, respectively). Through the need crops for water, the annual needs for crops were estimated coordinated of the cultivated areas, which turned out to be estimated as shown in table 1.

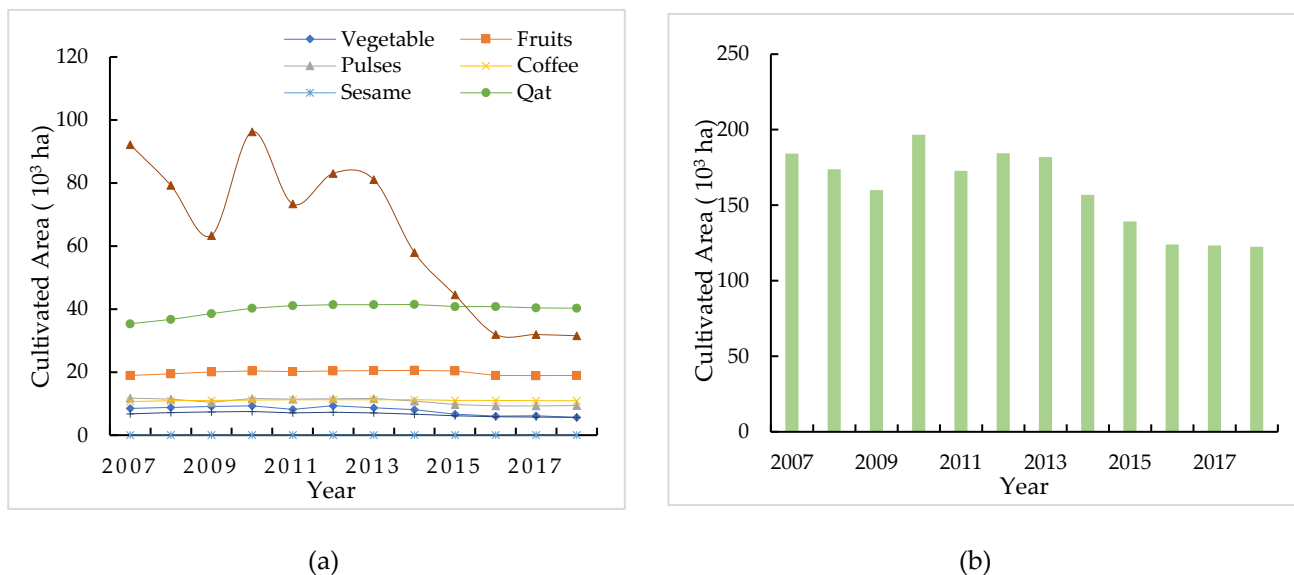


Figure 9. The cultivated area for all crops in Sana'a region (2007 - 2018): (a) The crops area; (b) Total cultivated area

Table 1. Total expected agriculture water demand for crops

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Min (10 ⁶ m ³)	1140	1091	1023	1211	1083	1145	1132	996	902	812	808	801
Max (10 ⁶ m ³)	1526	1475	1403	1644	1496	1572	1556	1395	1276	1172	1165	1158

The amount of water consumed for various crops decreased in 2007 was between 1.14 and 1.53 billion cubic meters (Bm³), while in 2018, it declined to 800 Bm³ and 1.16 Bm³. This decrease is attributed to people's lack of interest in agriculture due to the lack of water sources and the lack of alternative solutions to find water. The situation of people has become difficult, and they cannot provide private water for agriculture, forcing farmers to leave farming and stabilizing in the city to search for work. Therefore, crops' water needs are enormous compared to the total water in the area. In comparison, qat crop

increased from 19 % of the total cultivated areas in 2007 to 33% of the total cultivated areas in 2018. Irrigation sources are different, whether surface water such as rain and spate irrigation or groundwater such as wells and others. Figure. 10 shows the various irrigation sources for the cultivated areas. The cultivated areas that depend on rainwater represent 64, 66, 53, and 63 percent for the years 2011, 2013, 2015, and 2018, respectively, while the wells are 29, 27, 39, and 31%, respectively. In 2015, the percentage of dependence on wells increased to 39% due to increased drilled wells and a lack of other sources. In 2018, it decreased to 31% due to depletion of groundwater, the inability to provide fuel pumps. The qat crop is the most consumed crop and often depends on wells water, while other crops mainly depend on rainwater. Figure. 10 shows the classification of areas according to the Sana'a region's irrigation sources in 2011 was about 67 and 33% of surface and groundwater. In 2013 it was about 69 and 31% of surface and groundwater. In 2015 it was about 56 and 44% of surface and groundwater, while in 2018, it was 66 and 34 of water surface and groundwater, which means that reliance on irrigation of crops is more from surface water than from groundwater. In 2015 the withdrawal of groundwater increased but decreased in 2018. The reason is not the availability of surface water but the inability of people to pay the costs of drilling new wells.

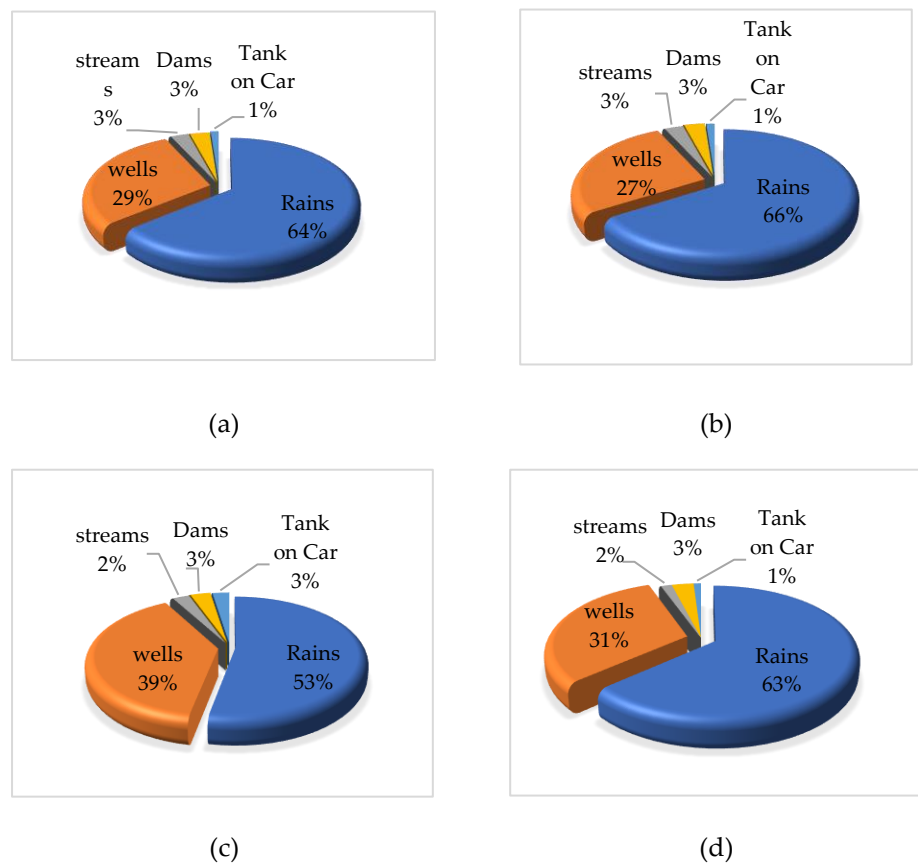


Figure 10. Sources irrigation for a cropped area: (a) 2011; (b) 2013; (c) 2015; (d) 2018

The decrease in the agricultural area for crops and the increase in the qat crop means that most people have replaced crops with qat, which is the primary source of income for most families. Qat consumes large amounts of water. In 2007, qat consumed about 15 to 29 % of the total water used for agriculture, it increased every year, as shown in Figure 11 until it reached about 25 - 43 % of the total water used for agriculture in 2018.

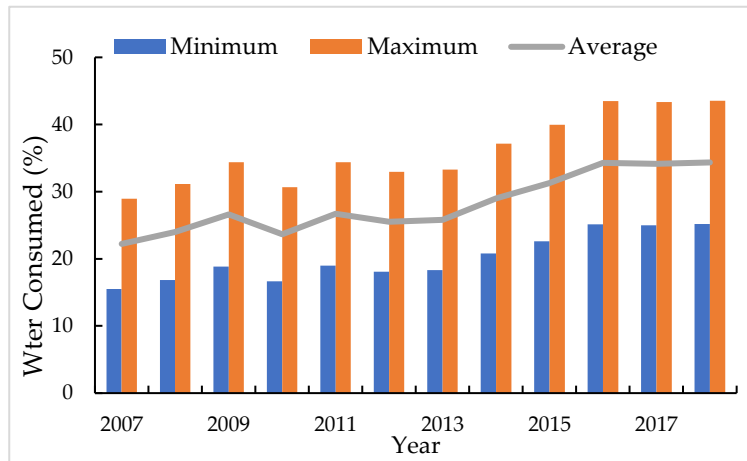


Figure 11. Water consumed for qat of the total water used in agriculture (in percent)

3.4. Wastewater reuse

The reuse of sewage water is considered a solution to the problem of water shortage in arid and semi-arid areas. This water is used for various purposes such as irrigation and agriculture. The areas near the plant benefit from it, as the dependence on the water produced from the sewage treatment plant reaches 95% for irrigation and 5% comes from wells [50, 51]. [52] indicated that sewage water benefits agriculture and plants greatly because it contains organic molecules that help plant growth. On the other hand, researchers [53, 54] reported that bacterial diseases are caused by vegetables and fruits irrigated with wastewater. Also, the intrusion of wastewater into the aquifers negatively impacts the water's properties. The sewage treatment plant was designed in the Sana'a region in 2000 and is called Sana'a wastewater treatment plant (WWTP) and is located in the north of Sana'a city and was designed to serve 450,000 people [55]. The station aims to use the resulting water for irrigation, reduce groundwater withdrawal, and protect surface and groundwater sources from deteriorating quality [56]. and since its establishment, it has faced major technical and operational problems. This station was designed to treat 50,000 m³/day. After five years of construction and operation of the plant, the plant reached its capacity, which was expected to reach its maximum capacity after 15-20 years of the design age of the plant. In 2000, the plant started treating 19000 m³/day. In 2011 and 2014, Its productivity increased to 50,000 and 55,000 m³/day, respectively, which means that in 2011 it was operating above its design capacity. This is considered one of the plant's problems and poor the outflow water's quality. The treatment efficiency does not exceed 70% compared to neighboring countries such as Oman and Tunisia, which The treatment efficiency reaches more than 90%, using the same treatment method " activated sludge" [57]. Due to the low efficiency of the treatment, it was proposed to establish a new plant in the Sana'a area, where the Canadian company Tecsalt and Hydrosult conducted a feasibility study for the plant, and due to the difficulty of acquiring the land area, the project faltered [55]. In the recent events that the country witnessed after 2015, the plant stopped working altogether, due to the interruption of electricity and essential services, after which other sources of funds were searched, such as UNICEF and the Red Cross to operate the plant, which continued to work at 50% of the entire operational departments, Despite these measures to alleviate the station's problems, there are still many administrative and technical problems. The importance of treatment plants is no less paramount than water projects, as water treatment is a new science that contributes to the irrigation of agricultural crops in large proportions and maintains the quality of surface and ground water [58].

4. Discussion

The rainfall is low, the water harvest in dams, barriers, and reservoirs is insufficient, only one treatment plant is available, the area of crops has decreased, and the municipal and industrial need is increasing with time. Table 2 shows the water supply and demand.

Table 2. Water supply and demand estimated for Sana'a Region. units: million cubic meters (Mm³)

		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
supply	Crops Rains	890	812	830	900	825	897	887	678	577	635	625	617
	Dams and barriers	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7
	Treatment plant	18.25	18.2	18.2	18.25	18.2	18.25	18.25	18.2	18.2	18.2	18.2	18.2
			5	5		5			5	5	5	5	5
	Streams or Springs	47.3	47.3	46.3	44.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3
	Public water network	18.5	19	19	17	15	14	15	12	10	9	12	11
Demand	Total	1038.75	961.25	978.25	1044.25	964.25	1035.25	1026.25	814.25	711.25	768.25	761.25	752.25
	Domestic water (80 m ³ /capita/year)	240.7	250.6	260.9	271.6	282.7	294.3	306.4	319	332	345.8	360	374.8
	Industrial water	5.3	5.8	6.4	7.12	7.9	8.6	9.1	9.9	10.6	11.2	12.3	13.4
	Agriculture water (average)	1333	1283	1213	1427.5	1289.5	1358.5	1344	1195.5	1089	992	986.5	979.5
	Touristic water	0.56	0.69	0.8	0.98	1.2	0.4	1.8	2.3	2.63	3.4	4.6	5.2
	Total	1579.6	1540.1	1481.1	1707.2	1581.3	1661.8	1661.3	1526.7	1434.4	1352.4	1363.4	1372.8
	Water deficit	540.8	578.8	502.8	662.9	617.09	626.6	635.1	712.5	723.2	584.1	602.1	620.6

The deficit between water supply and demand is enormous, is about 500 to 723 Mm³ annually. It is an abstraction from the aquifers by private wells. Abstraction is about 300 Mm³ annually in the Sana'a Basin, while the recharge is 80 to 100 Mm³. Similar quantities are also abstracted from areas located within the borders of other basins. Because of the large deficit and insufficient supply, the percentage of per capita water use decreases annually, and the cultivation of area reduces. The proposed solutions are to establish sewage treatment plants in Sana'a to support agriculture and maintain groundwater quality due to the excavations in which sewage waste is placed. Also, establish more dams and barriers to harvest rainwater because of the region's terrain; most rainwater flows outside the region. Re-running the meteorological and rainfall stations and establish stations in places that don't have.

5. Conclusions

In this study, the water resources in the Sana'a region were evaluated through past, current, and expected in the future. The rainfall was found in the 160 and 367 mm annually range between as well as the total of the rainfall and meteorological stations was 56

stations currently which operate within only six stations as well as determined the location of water facilities were 233 dams and barriers, with a storage capacity of 64,656,651 and 238,983 m³, respectively. The public water network pumps about 9 – 18.5 Mm³/year, while the private wells are about 500 – 723 Mm³/year (2007-2018). the cultivated area was decreased from 184217 hectares to 122583 hectares in 2007 to 2018, respectively. In contrast, qat crop increased from 19 to 33 % of the total cultivated areas in 2007 and 2018, with an annual water need of about 15 - 29 % and 25 - 43 % of the total water used for agriculture in 2007 and 2018, respectively. The sewage treatment plant treats 18.25 Mm³ annually, with less than 70% efficiency. With the large of groundwater abstraction, the water level decreases. Thus, the amount of water decreases, leading to a decline in the per capita share of water and a decrease in interest in agriculture. The water deficit ranges between 500 and 723 Mm³ during the period from 2007 to 2018, and it is an abstraction from the aquifers by private wells.

As these findings are obtained from analysis the collected data from government agencies and previous studies, further studies, additional field studies that could collect the private wells productivity and properties are warranted.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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