DOI:10.53539/squjs.vol29iss1pp56-67

Sultan Qaboos University Journal for Science

Journal page: www.squ.edu.om/index.php/squjs/index

Preliminary Evidence for the Decline in Discharge at Falaj Daris, Nizwa, Oman

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ARTICLE HISTORY

Received 8 May 2023
Received revised 18 September 2023
Accepted 13 November 2023

ABSTRACT

Falaj Daris is one of the oldest active aflāj located in Oman and the largest in the Dakhiliyah governorate. It is a 7,999-meter long Dāwūdī-type falaj. Ninety-five percent of water drawn from falaj Daris is used for agricultural irrigation and the remaining five percent is used for domestic purposes. In this paper, we analyzed several datasets including falaj Daris discharge, borehole water levels in wadi al-Abyadh, whose aquifer falaj Daris taps, and GRACE satellite data to determine the historical trend of falaj Daris discharge during 1982-2020. A set of standard statistical methods and data visualization techniques were applied including the Mann-Kendall trend test. Preliminary evidence shows a decline of 226,000 L/day in falaj Daris discharge between 1982-2020. This finding is supported by the overall trends in borehole water levels in wadi al-Abyadh. All these trends were confirmed using GRACE satellite data which shows a decrease in water volume of 6 (WET cm) in the larger basin between 2002-2021.

Keywords: qanat; falaj Daris; wadi al-Abyadh; Nizwa, Oman; GRACE satellite.

أدلة مبدئية على نقصان تدفق فلج دارس، نزوى عُمان

زيانة الرواحي و بول آر هاوزر

الملخص: فلج دارس هو واحد من أقدم الأفلاج الحية الموجودة في سلطنة عمان والأكبر في محافظة الداخلية. يبلغ طوله 7999 مترا وهو فلج من النوع الداؤدي. يستخدم خمسة وتسعون في المائة من المياه المستخرجة من فلج دارس للري الزراعي بينما تستخدم الخمسة في المائة المتبقية للأغراض المنزلية. في هذا البحث ، قمنا بتحليل العديد من مجموعات البيانات بما في ذلك تدفق فلج دارس ، ومنسوب مياه الآبار في وادي الأبيض الذي يغذي خزانه الجوفي فلج دارس ، والبيانات المقتبسة من القمر الصناعي (غريس) لتحديد الاتجاه التاريخي لتدفق فلج دارس خلال الفترة 1982-2020. تم تطبيق مجموعة من الأساليب الإحصائية القياسية والعرض المرئي للبيانات بما في ذلك اختبار اتجاه مان كينديل. تبين الأدلة المبدئية انخفاضًا قدره حوالي 226 ألف لتر يوميا في تدفق فلج دارس في الفترة ما بين 1982-2020. ويدعم هذا الاكتشاف الاتجاهات العامة في مستويات مياه آبار حوض وادي الأبيض ، الذي يمد فلج دارس. يساند دليل هذا الاتجاه النزولي في تصريف فلج دارس البيانات المقتبسة من القمر الصناعي (غريس) للفترة 2002-2021 الذي يؤكد نقصانا في حجم المياه في الحوض الجامع لحوض وادي الأبيض بمعدل 6 (ويت) سم.

الكلمات المفتاحية: قناة، فلج دارس، وادي الأبيض، نزوى، عُمان، القمر الصناعي (غريس).

1. Introduction

Oman is a country in the south-west corner of the Arabian Peninsula astride the Tropic of Cancer. According to the Köppen-Geiger climate classification system [1], Oman is an arid country. Indeed, the World Resources Institute expects Oman by 2040 to be the tenth most water-stressed country in the world [2].

Although prehistorically Oman did have surface water flow, as suggested by its morphology [3], the country no longer has lakes or permanent rivers/streams. Thus, the country's only freshwater sources are intermittent wadi flow resulting from limited rain, and groundwater. Oman's groundwater is broadly classifiable into two categories: (1) renewable ground water replenished by rainfall via the hydrologic cycle; and (2) fossil ground water which, if abstracted, is thought to be non-replenishable [4].

Groundwater is abstracted by wells and underground aqueducts (qanats), known locally as aflāj (sing. falaj). It is believed that the aflāj were first introduced in Oman during the sixth century BCE. Some aflāj may have even been built as early as 1,200 BC [5]. Many of the original aflāj are still in use today [6]. Since their introduction, Omanis have relied on the groundwater conveyed by the aflāj for agricultural and domestic use [7-9].

Three types of aflāj exist in Oman according to their water source: (1) *ghailī*, (2) *'aynī*, and (3) *Dāwūdī*. The source of water for a ghailī-type falaj is the base flow through the surface gravel of a wadi. A ghailī-type of falaj is often seasonal as the water comes from shallow subterranean sources which may dry out during the year [10]. Natural spring water is the source of an 'aynī-type falaj.

A Dāwūdī-type falaj draws its water from a dug well reaching the aquifer. Although Dāwūdī-type aflāj represent only a quarter of Oman's aflāj, they produce half of the harvested falaj-water [11]. When compared with the other two types of aflāj, a Dāwūdī-type falaj will typically have a higher flowrate and are the steadiest.

At times, water for a Dāwūdī-type falaj will be drawn from more than one mother well depending on the falaj's size [12]. The volume of flow for a falaj is affected primarily by the lithology of its aquifer and the changes that take place due to water-recharge [13]. The mean flow rate for Oman's aflāj is between 15 and 20 liters per second [14].

Agricultural irrigation is the largest consumer of aflāj-water [12]. In Oman, agriculture is the second largest economic sector after oil, even though more than 80% of the land is desert. The main crop grown in Oman is dates from the palm tree (*Phoenix dactylifera* L.). Overall, falaj-water supplies 36% of the water to irrigate agricultural lands, the remainder 64% is coming from wells [11]. Oman's aflāj are estimated to provide about 680 MCM (million cubic meters) of water annually [15] and irrigate about 26,500 ha of land [12,15].

As a result of Oman's dependence on the aflāj, most agricultural activities in the country are concentrated in alluvium plains next to mountains [16]. As Stanger observed, "It is no coincidence that most of the large provincial towns are situated at or close to nodal points in the piedmont drainage systems where remarkably efficient groundwater interception has long utilized the piedmont storage in such a way that available resources and water use are in equilibrium" [17].

With respect to its groundwater, Oman suffers from three main problems. First, there is the problem of excessive abstraction of the country's aquifers to sustain increased agricultural and domestic water use. This has led to the drying of some of the country's wells and aflāj. Several regions in Oman are currently experiencing this problem, including the Interior (Dakhiliyah) governorate where the city of Nizwa is located.

Second, during drought periods, there is aquifer mismanagement [14]. With decreased rainfall due to climate change, this issue is expected to intensify [18].

Finally, in coastal areas, there is the problem of sea water seepage into deep aquifers [19]. This has damaged the prosperous date palm groves as salt water intrudes from the Gulf of Oman [20]. About 5,040 hectares in the Batinah governorate were abandoned between 1997 and 2010 due to high levels of salinity of irrigation water and consequent salinization of soils [21]. As this problem is restricted to Oman's coastal regions, it does not affect the study area (Nizwa town) which is some 160 kilometers inland from the coast.

Aside from their agricultural importance, the aflāj are also precious to the Omani people as they are an integral part of the national culture and identity. Therefore, the aflāj must be protected to ensure their sustainability for future generations.

2. Materials and methods

2.1 Study area

Nizwa is a city in central Oman situated at the foot of the western flank of the Jebel Akhdar (Aka. the Green Mountain) massif. Ibn Battuta, the famous medieval explorer, passed through the town in the mid-fourteenth century CE. He described Nizwa as "a city at the foot of a mountain, enveloped by orchards and streams, and with fine bazaars and splendid clean mosques" [22]. The streams Ibn Battuta saw are Nizwa's many aflāj. Among Nizwa's aflāj, falaj Daris is the most famous today.

Falaj Daris is one of the oldest active aflāj in Oman and the largest in the Dakhiliyah governorate. It is a 7,990-meter long Dāwūdī-type falaj, i.e., supplied by groundwater. Its two mother wells are located at the foothills of the Jebel Akhdar massif at an altitude of 559 mamsl (meters above mean sea level).

These two mother wells tap the wadi al-Abyadh aquifer. The total area of wadi al-Abyadh alluvial aquifer drained by falaj Daris is approximately 32.86 km^2 [23]. With alluvial aquifers, like that at wadi al-Abyadh, the recharge system works along the wadi's mountain boundary (here, Jebel Akhdar) and consists of two main mechanisms: (1) mountain front recharge, and (2.) channel recharge [24].

Typically, with alluvial aquifers, channel recharge is the dominant process of recharge [25]. Channel recharge results from runoff infiltration in defined and undefined channels and from mountain slopes [26]. There are four wadis (Tanuf, Swehriya, Kamah, and Sumeyt) which originate in Jebel Akhdar and flow into wadi al-Abyadh. Flooding in one or more of these wadis can result in flooding in wadi al-Abyadh. In the active wadi al-Abyadh channel, infiltration is estimated at 8 m/day. However, in the cemented alluvium, infiltration drops to 0.6 m/day [23]. Depth to the water table is shallow to moderate, ranging from < 5 m to 30 m [23].

Based on the physical position of falaj Daris with respect to the aquifer, it is assumed that falaj Daris can draw only two-thirds of the available water stored in the aquifer. As a result, the lower one-third of the aquifer cannot be dewatered by falaj Daris [23]. Falaj Daris consists of two branches: one branch 1,700 meter long at a depth of 17.5 meters; and a second branch 1,900 meter long at a depth of 16 m. The *fardh al-multaqa* is the point where the two branches meet. The first surface opening, (Ar. *sharīʻah*) is located approximately six kilometers north of the Nizwa town center at UTM 40N/ 556 315 Easting, 2 540 635 Northing [23,27,28]. Ninety-five percent of the water drawn from falaj Daris is supplied to agriculture, with the remaining five percent used for domestic purposes.

According to a remote sensing study conducted in 2008, the Nizwa oasis' entire vegetative area is 337 ha [29]. Of this area, falaj Daris supplies water to a total of 238.26 hectares [28]. Date palms represent about 90% of the agricultural production in Nizwa town [30]. Other crops grown include mangos, lemons, sugarcane, vegetables, fodder (livestock feed), and various seasonal plants. In addition to farms, residential areas and other establishments are also located in proximity of falaj Daris [31].

Falaj Daris is an outstanding example of a millennial-old cultural landscape that is still in use today. In 2006, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) selected five of Oman's aflāj to be listed on its World Heritage List (WHL). One of these was falaj Daris [32]. To commemorate the inclusion of falaj Daris on the WHL, a park was created. The falaj Daris park is a popular destination for tourists and local families.

Figure 1 is a Google Earth satellite image of the study area.

2.2 Data description

For this study, several datasets were obtained from the government of Oman. Additionally, GRACE satellite data was used. These datasets are described below.

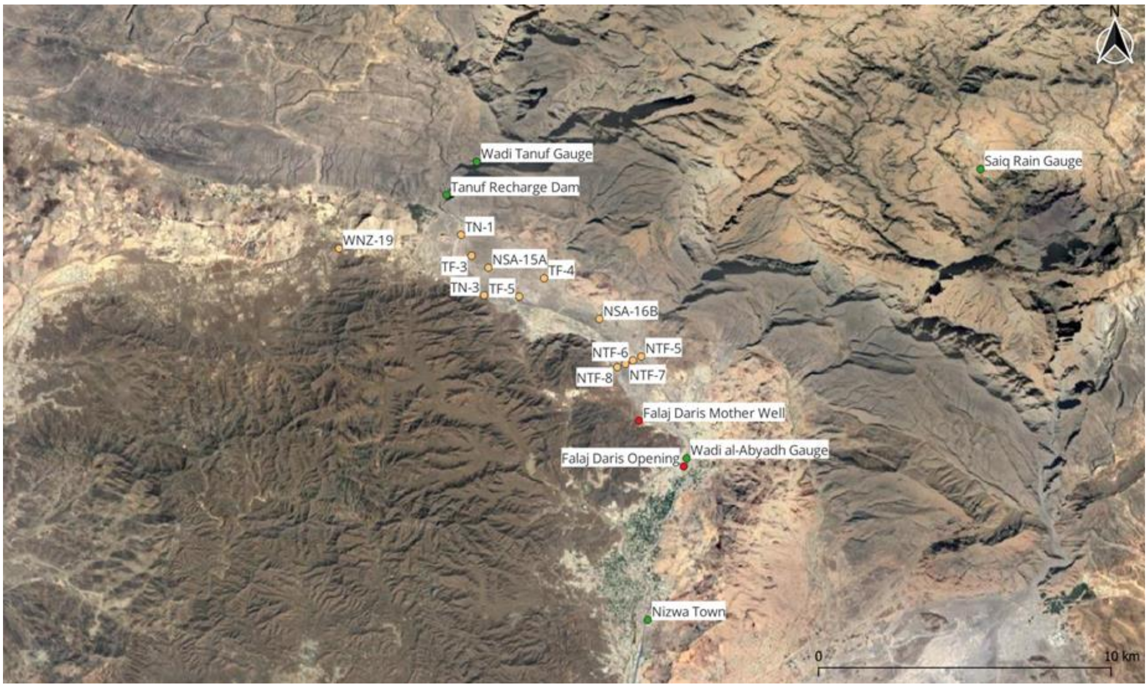

Figure 1. Locations of falaj Daris and the boreholes. Locations associated with falaj Daris are indicated by red circles. Yellow circles are boreholes in wadi al-Abyadh. All other locations are represented by green circles. The green region (center bottom) represents Nizwa town farms irrigated by falaj Daris and other aflāj. (Satellite image source Google Earth.)

2.2.1 Falaj Daris discharge dataset

The falaj Daris discharge dataset was obtained from the Omani Ministry of Agriculture, Fisheries and Water Resources. It consists of an irregularly sampled time series of n = 409 observations taken between March 2, 1982, and July 7, 2020. Unfortunately, there is a large gap in this dataset, consisting of two years (1987-1988) with no observations, followed by a year (1989) when only a single measurement is reported. Moreover, on four dates (January 8, 2006; August 11, 2009; July 2, 2011; and August 7, 2013) no measurements were reported. This data gap was partially completed with data published by al-Habsi [23] resulting in a dataset n = 446 observations. The mean frequency of these 446 samplings is 31.2 days. Although the mean frequency of samplings is monthly, the time series remains irregular. Figure 2 highlights the monthly gaps in the dataset where no data was recorded.

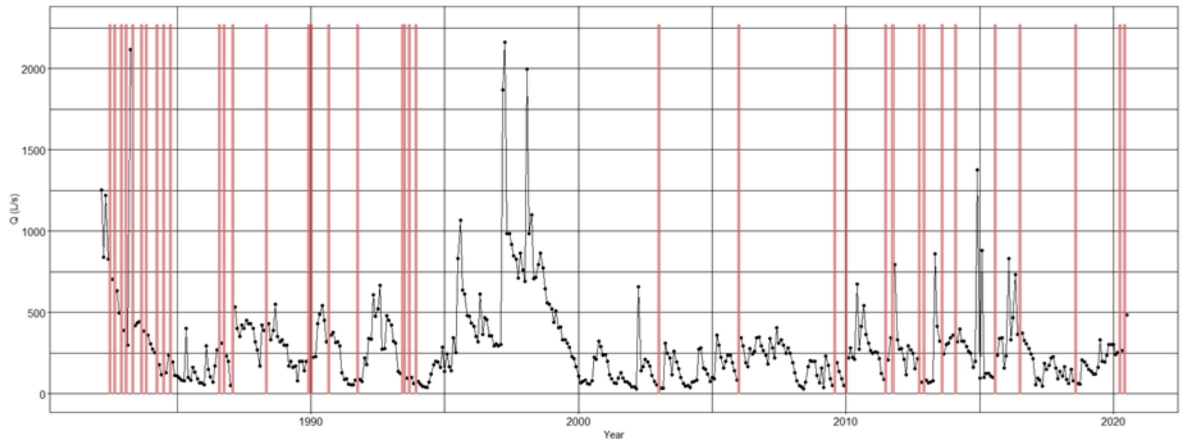

Figure 2. Falaj Daris hydrograph (n = 446 observations). Months with no data represented by red vertical lines.

2.2.2 Wadi al-Abyadh boreholes dataset

Data for twelve boreholes in wadi al-Abyadh whose aquifer feeds falaj Daris were also provided by the Ministry of Agriculture, Fisheries and Water Resources. The location of these boreholes with respect to Nizwa town is indicated in Figure 1 (above) by yellow circles. The data consists of water levels in the twelve boreholes taken between the years 1982-2019, with most of the data points from 1992-2019.

2.2.3 Wadi al-Abyadh flash flood dataset

The wadi al-Abyadh flood dataset provided by the Ministry of Agriculture, Fisheries and Water Resources consists of 12,851 daily measurements of flood volume taken between October 1, 1984, to December 7, 2019. Of these 12,851 observations, there are 389 nonzero measurements (flood events), which is approximately 3% of the dataset. The gauge which measures flood volume is about 200 meters above the falaj Daris first surface opening in Nizwa town [23]. The dataset, thus, represents wadi flash flood (WFF) volume at the terminus of wadi al-Abyadh, as it enters Nizwa town. The true flood volume of any WFF event in wadi al-Abyadh would be the volume gauged at Nizwa in addition to any transmission loss occurring, as the flood passed through the wadi.

2.2.4 Saiq airport precipitation data

Rainfall measurements at the Saiq meteorology station (1,986 mamsl) were obtained from Oman's Directorate General of Civil Aviation and Meteorology. The Saiq precipitation dataset consists of monthly precipitation amounts (mm) for a twenty-seven-year period (1979-2005).

2.2.5 GRACE and GRACE-FO satellite data

Finally, GRACE and GRACE-FO (hereinafter GRACE) satellite data for mascon block 1420, where Nizwa town is located, were downloaded using the Mascon Visualization Tool at the Colorado Center for Astrodynamics Research [33].

GRACE data capture gravitational anomalies relative to a 2004-2010 time-mean baseline. The data is available for discrete cells known as mascons (mass concentrations). There are 4,551 equal-area 3-degree spherical cap mascons across the Earth's surface.

When viewed individually, each mascon cell represents the gravity signal for that particular area on the Earth's surface. Because these mascons represent discrete locations, regional studies of water storage changes are calculatable. The units for GRACE data are water equivalent thickness (WET) measured in centimeters. WET values represent the deviations of mass in terms of vertical extent of water in an area. Thus, a decrease of one WET centimeter is like saying that mass has been lost to the mascon equal to water spread out over the entire mascon one centimeter deep.

2.3 Data integration

The primary dataset used in this study is the falaj Daris discharge dataset. The other datasets described were selected to confirm the results obtained from the trend analysis of the falaj Daris dataset. As a Dāwūdī-type falaj, falaj Daris taps the wadi al-Abyadh aquifer. Any change in falaj Daris discharge rates should therefore also be reflected in borehole water levels in wadi al-Abyadh. Water level data from twelve boreholes in wadi al-Abyadh were used to capture changes in the water volume of the aquifer.

Because the falaj Daris and borehole datasets are irregular sampled time series', the daily measured wadi al-Abyadh flood dataset may show trends obscured in the falaj Daris discharge and borehole water level datasets. However, as only one of the four wadis which flow into wadi al-Abyadh is gauged (wadi Tanuf), it is almost impossible to determine the actual volume of a flood event in wadi al-Abyadh prior to transmission loss (recharge). As a result, the amount of measured rainfall at Saiq (elevation 1,986 mamsl) can be used as a check for the flash flood volume gauged in wadi al-Abyadh. The Saiq rainfall dataset should therefore correspond to any trend seen in the wadi al-Abyadh flood dataset.

Finally, wadi al-Abyadh is part of the larger wadi al-Halfayn basin. GRACE satellite data was used to determine if the trend seen in wadi al-Abyadh is observed throughout wadi al-Halfayn.

The datasets used in this study do not cover the same time frame (Table 1). This is because different entities of the Omani government collect different data. As these data were collected for different purposes, they were measured at different time periods and frequencies. Integrating these datasets is a complex task when studying the interaction between the various components of the recharge system. However, since here we are only looking at overall trends, the problem is greatly simplified.

Table 1. Datasets used.

Dataset	Period Collected
Falaj Daris discharge	1982-2020
Wadi al-Abyadh flooding	1985-2019
Borehole NSA-15A water levels	1982-2021
Borehole NSA-16B water levels	1982-2021
Borehole NTF-5 water levels	1992-2021
Borehole NTF-06 water levels	1992-2021
Borehole NTF-07 water levels	1992-2020
Borehole NTF-08 water levels	1992-2020
Borehole TF-3 water levels	1992-2021
Borehole TF-4 water levels	1992-2021
Borehole TF-5 water levels	1992-2021
Borehole TN-1 water levels	1992-2021
Borehole TN-3 water levels	1992-2021
Borehole WNZ-19 water levels	1993-2021
Saiq airport precipitation dataset	1979-2005
GRACE, GRACE-FO mascon 1420	2002-2021

3. Results and Discussion

To determine the thirty-nine-year trend in the falaj Daris discharge rate Q (L/s), a set of standard statistical methods and data visualization techniques were applied. Table 2 presents summary statistics for falaj Daris Q.

Table 2. Summary statistics for falaj Daris discharge rate, Q (L/s), between 1982-2020.

Statistic	Falaj Daris Q
n	446
Minimum	29 (L/s)
1st Quartile	121 (L/s)
Median	238.5 (L/s)
Mean	298 (L/s)
3rd Quartile	350 (L/s)
Maximum	2,160 (L/s)
Interquartile range	229 (L/s)
Standard deviation	278 (L/s)
Coefficient of variation	93.2%
Skewness	3.04
Kurtosis	13.78

Table 2 indicates that over the thirty-nine-year time series Q_{min} = 29 (L/s), while Q_{max} = 2,160 (L/s). Since falaj Daris is a Dawūdī-type falaj, it is therefore supplied by groundwater flow from the wadi al-Abyadh alluvial aquifer.

As a result, there are no Q = 0 (L/s) observations in the dataset.

Falaj Daris sample median is 238.5 (L/s). As an alternative to the point estimate, a confidence interval (CI) was calculated which has a 95% probability of containing the true population median. The approach adopted for determining the confidence interval is through the use of bootstrapping [34]. However, when there is a high positive skewness, as is often the case with the hydrologic data, the upper confidence limit (c_{up}) will often be too low [35]. To compensate for this, bias-corrected and accelerated (BCa) bootstrap intervals will shift and scale the percentile intervals [36]. For the falaj Daris Q dataset, based on a thousand bootstrap replicates, the BCa 95% CI for the median Q_{50}, is (218, 261) (L/s).

3. 1. Falaj Daris hydrograph

In Figure 3 below, the 446 observations comprising the falaj Daris Q time series are plotted as a hydrograph.

The falaj Daris hydrograph shows considerable variability across the time series. Because of this temporal variability for falaj Daris Q, we cannot rely on the long-term median discharge range, Q_{50} = (218, 261) (L/s), to be available all the time. Rather, to determine the Q at which falaj Daris is ordinarily available, we should select a rate occurring at large percentage of the time, such as 95%. For the falaj Daris dataset Q_{95} = 50 (L/s). Recall Q_{min} = 29 (L/s) (Table 2 above).

Conceptually, the determination of the Q at which falaj Daris is ordinarily available is best visualized by the use of a flow-duration curve [37]. A flow-duration curve is a graph showing the percent of time a particular Q observation equaled or exceeded a given magnitude. Figure 4 is the flow-duration curve for falaj Daris. It shows both the point median Q_{50} = 238.5 (L/s) and Q_{95} = 50 (L/s) which are represented by the dashed lines.

The primary cause for falaj Daris discharge variability, observed in Figures 3 and 4, or for that matter the discharge variability with any Dawūdī-type falaj, is the amount of recharge resulting from transmission loss as a flash flood passes through wadi al-Abyadh. A flood event in wadi al-Abyadh will often immediately boost falaj Daris discharge rate. Because rainfall in semi-arid regions displays great temporal and spatial variability [38], flooding in wadi al-Abyadh will consequently display a great deal of variability in the number and magnitude of flooding events per hydrologic year. This variability in flood frequency and volume results in falaj Daris discharge variability. Figure 5 shows the variability in total annual volume of wadi al-Abyadh flash flood events.

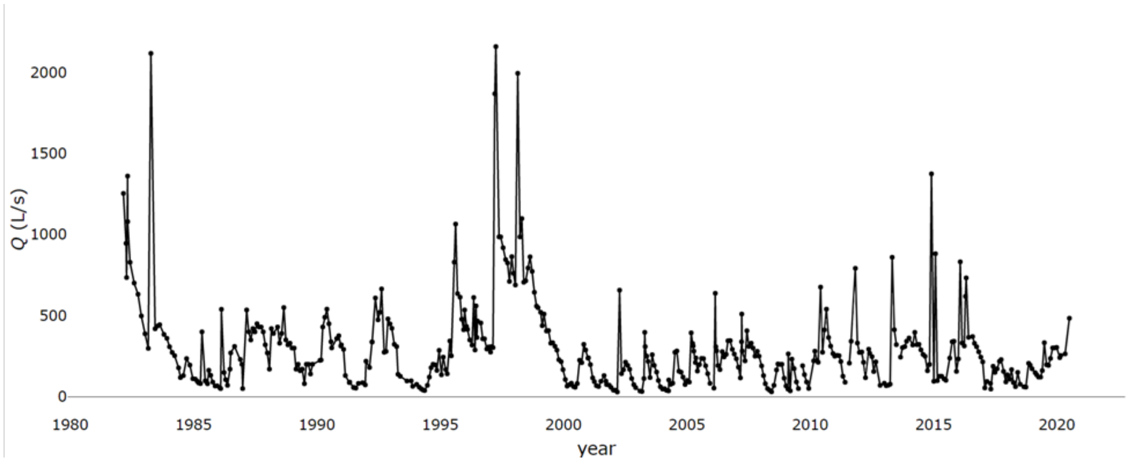

Figure 3. Falaj Daris Q hydrograph (1982-2020).

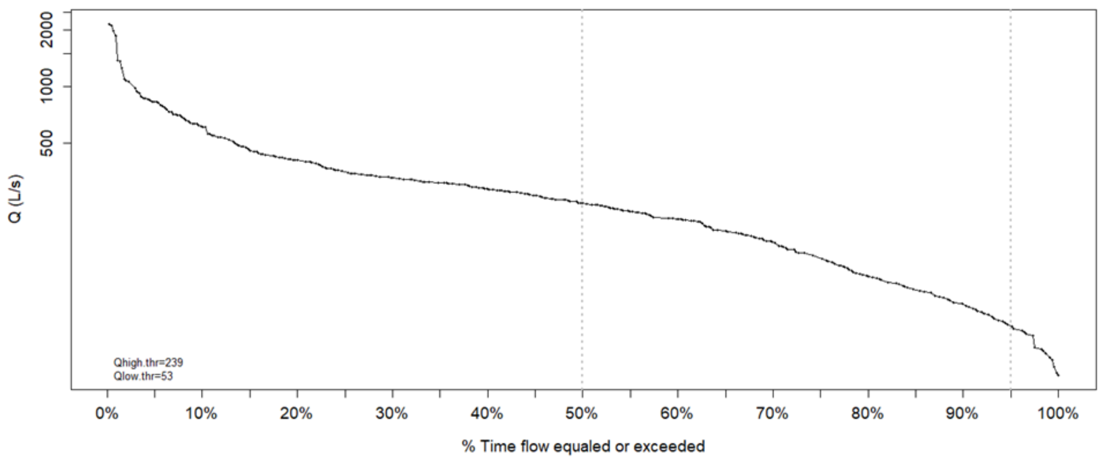

Figure 4. Flow-duration curve for falaj Daris (1982-2020). Vertical dashed lines represent Q_{50} (the median) and Q_{95}.

Those years in Figure 5 with large flood volumes measured at wadi al-Abyadh (mamsl 543) are typically reflected in heavy rainfall amounts measured at the much higher elevation Saiq (mamsl 1,986). The Pearson correlation between Saiq rainfall and the amount of flash flood in wadi al-Abyadh is 0.87 which tells us the two variables are highly correlated (Figure 6).

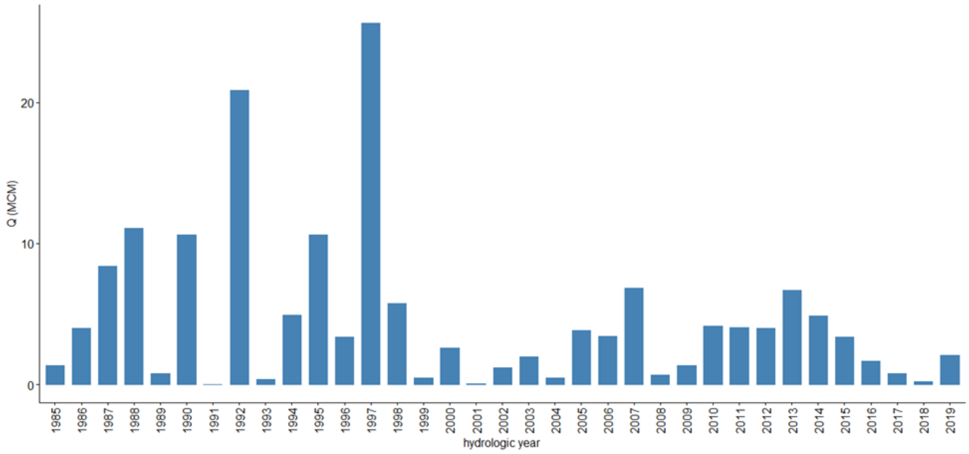

Figure 5. Annual wadi al-Abyadh flash flood volume between 1985-2019 in million cubic meters.

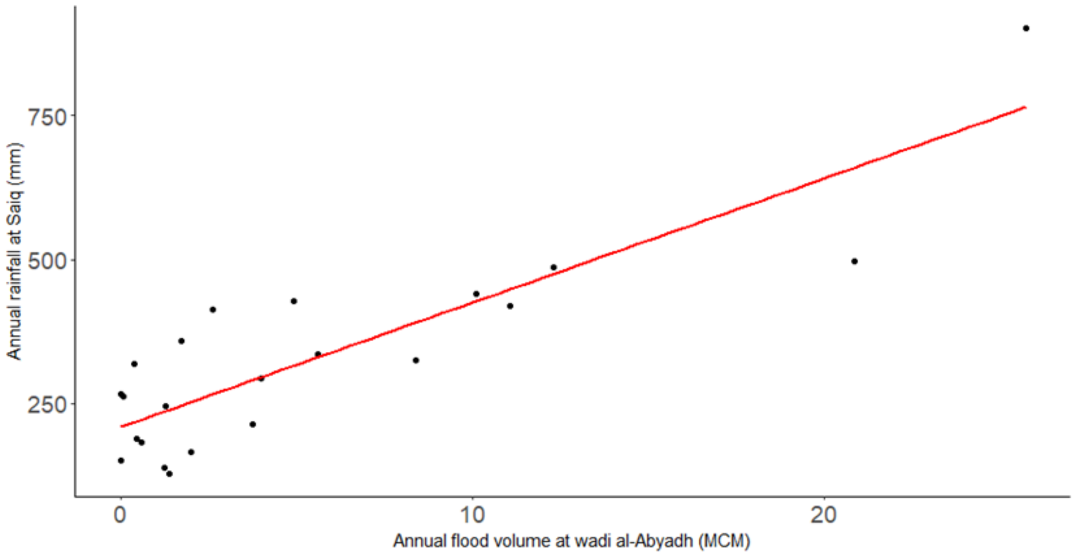

Figure 6. High correlation between annual flood volume at wadi al-Abyadh (mamsl 543) and annual rainfall total at Saiq (mamsl 1,986).

3.2. Falaj Daris trend analysis

The annual variability in falaj Daris Q discharge (Figure 3 above) makes it impossible to visually determine any long-term trend. As a result, a Mann-Kendall trend test was applied to the falaj Daris Q dataset. The Mann-Kendall trend test is a nonparametric test. It answers the question if the central tendency of the variable of interest (here, falaj Daris discharge Q) changes in a monotonic fashion with the time variable [39]. Moreover, the Mann-Kendall test is not adjusted to exogenous variables, such as wadi flash flood volume, which boosts falaj Daris Q. H_0 is rejected if the value of S is statistically significantly different from zero.

The selected α level for the Mann-Kendall test was 0.05. The z-score = -3.63 and the p-value < .001, with τ = -0.115. The Thiel slope $\hat{b}_1$ = -2.6 (L/s), the 95 % CI on $\hat{b}_1$ is [-4, -1] (L/s). Thus, we can reject H_0 and conclude that there is an overall trend in falaj Daris discharge, and that trend is slightly negative. This slight downward trend, approximately 226,000 (L/day), for falaj Daris Q is illustrated in Figure 7.

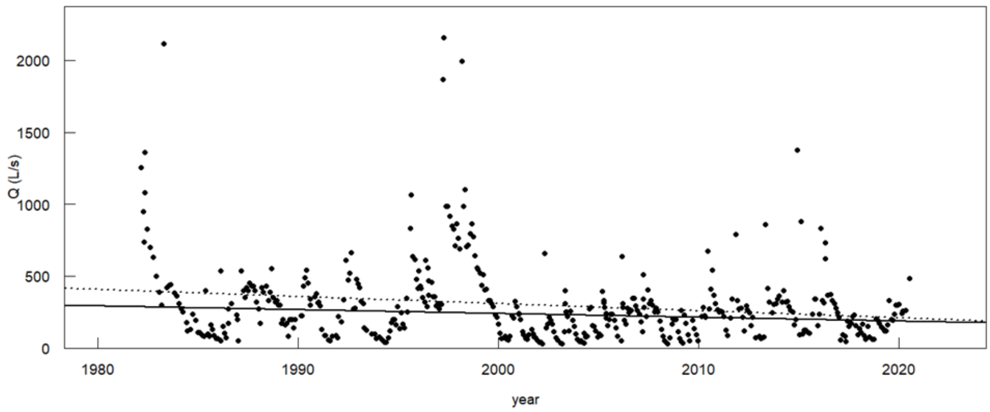

Figure 7. Slight downward trend of falaj Daris Q between 1982-2020. The Theil-Sen robust line is solid; the regression line is dashed.

3.3. Water table levels in wadi al-Abyadh

To confirm the slight downward trend in falaj Daris Q, the water levels of twelve boreholes in wadi al-Abyadh were then investigated. The wadi al-Abyadh aquifer feeds falaj Daris. Thus, an overall downward trend in borehole water level across the time series would support the finding of a slight decrease in falaj Daris Q between 1982-2020.

In Figure 8, each boxplot represents a borehole. The line within a boxplot is the median water level for that borehole. The lower and upper edges of each boxplot are the first and third quartiles, respectively. The vertical dots across a boxplot are the observations made at that borehole. Not all boreholes are measured with the same frequency, nor were all these boreholes measured throughout the time period from 1982 to 2019. As mentioned, most of the borehole data points are from 1992-2019.

The boxplots in Figure 8 show that there is considerable variability in water levels across the twelve boreholes. To see if this variability is seasonal, the mean monthly water level for the years 1992-2019 for the twelve boreholes were calculated and plotted (Figure 9).

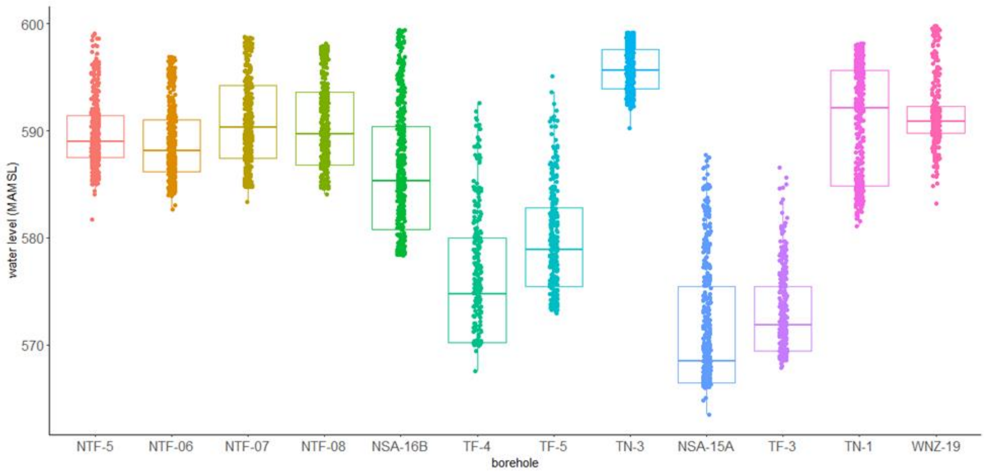

Figure 8. Boxplots for twelve boreholes in wadi al-Abyadh. The mean elevation at wadi al-Abyadh is 601 mamsl.

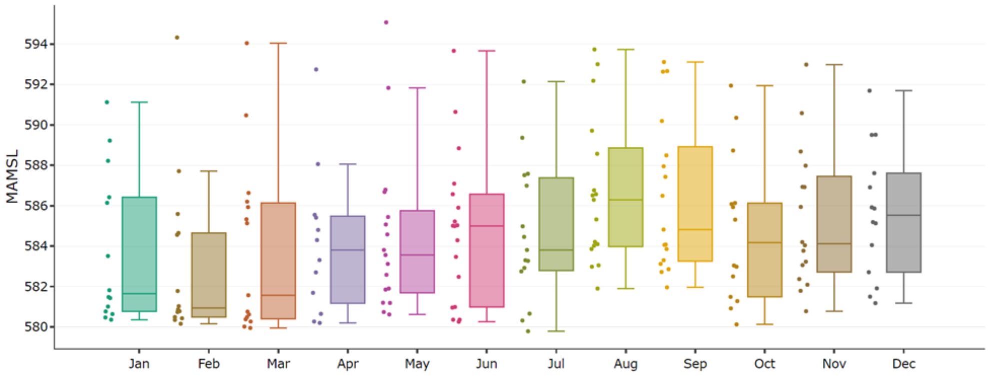

Figure 9. Monthly wadi al-Abyadh median water level as measured by twelve boreholes for years 1992-2019. Average altitude 601 mamsl.

Table 3 lists each monthly median in the boxplots of Figure 9. Generally, the medians for the summer rain season are greater than those for the winter rain season indicating that most recharge in wadi al-Abyadh occurs during the summer.

Table 3. Monthly median water levels for twelve boreholes at wadi al-Abyadh.

Month	Median Water Level (mamsl)
January	581.43
February	580.95
March	581.57
April	583.82
May	583.56
June	585
July	583.81
August	586.29
September	584.82
October	584.18
November	584.12
December	585.53

It is notable that most recharge seems to take place in the summer since rain falls in Oman during two different seasons, each linked to a different climatic system. During winter months, the Arabian Peninsula is affected by the westerlies from the mid-latitudes [20]. The summer rain season is linked to surface flow over the Arabian Sea. The flow is dominated by the strong south-westerly current that feeds the south Asian monsoon circulation and brings frequent drizzle and fog to Oman's southern Dhofar coast and its nearby mountainous areas. Occasionally penetrations of the monsoon current can trigger scattered convective showers in the country's interior affecting the Nizwa area [40,41].

To confirm that most recharge in wadi al-Abyadh occurs during summer months, wadi al-Abyadh flood data was analyzed by season. For the purposes of this study, winter rain months are December through March, and summer rain months are June through September. Between 1985-2019, the median annual flood volume at wadi al-Abyadh was 2.12 MCM. For summer months the median annual flood volume was 0.487 MCM, while the median winter flood volume was 0.224 MCM. In terms of rainfall measured at Saiq, between 1979-2005, the median annual rainfall at Saiq was 294.2 mm. Of this amount, the median annual summer rain was 114.5 mm, while the median winter rain was 80.31. Both the flood volume measured in wadi al-Abyadh and the rainfall measured at Saiq support that most recharge in wadi al-Abyadh occurs during summer months. See Table 4.

Table 4. Wadi al-Abyadh flood volume and Saiq rainfall by season.

Location	Measurement	Period	Annual median	Summer median	Winter median
Wadi al-Abyadh	Flood volume (MCM)	1985-2019	2.12	0.487	0.224
Saiq	Rainfall (mm)	1979-2005	294.2	114.5	80.31

3.4. Trend analysis of water table levels in wadi al-Abyadh

Trend analysis (Mann-Kendall test) for each of the twelve borehole water levels at wadi al-Abyadh confirms the negative trend seen in falaj Daris Q. Except for one borehole (NSA-15A), all boreholes showed a decrease in water levels. All trends were statistically significant (Table 5 and Figure 10).

Table 5. Borehole water level trends in wadi al-Abyadh.

Borehole	Period	Mann-Kendall Test		
		n	*z*-score	*p*-value
NSA-15A	1982-2021	490	2.22	0.026
NSA-16B	1982-2021	485	-3.60	< .001
NTF-5	1992-2021	433	-8.96	< .001
NTF-06	1992-2021	431	-7.35	< .001
NTF-07	1992-2020	434	-8.14	< .001
NTF-08	1992-2020	435	-7.63	< .001
TF-3	1992-2021	286	-3.50	< .001
TF-4	1992-2021	288	-4.22	< .001
TF-5	1992-2021	283	-4.4	< .001
TN-1	1992-2021	454	-10.56	< .001
TN-3	1992-2021	437	-10.26	< .001
WNZ-19	1993-2021	299	-8.66	< .001

3.5. GRACE, GRACE-FO satellite data for the study area

Wadi al-Abyadh is a part of the larger wadi al-Halfayn basin. To see if the decrease in wadi al-Abyadh aquifer volume is part of an overall trend in the wadi al-Halfayn basin, GRACE satellite data (JPL RL06M v02 Mascons) were investigated. The downloaded GRACE data confirm an overall decrease in water volume in the larger Halfayn basin, as visualized in Figure 11.

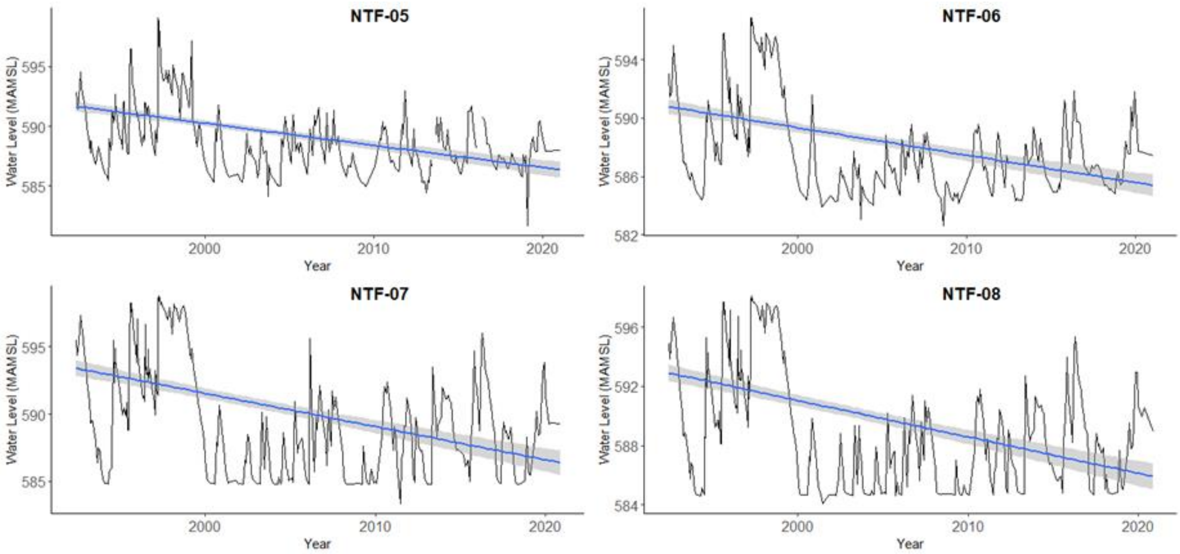

Figure 10. Water level trends for boreholes NTF-5, NTF-06, NTF-07, and NTF-08. Blue lines are the regression lines with 95% confidence level shaded grey. These four boreholes are closest in proximity to the falaj Daris mother well.

Figure 11. Declining trend in GRACE, GRACE-FO water equivalent thickness (cm) time series (2002-2021) for mascon number 1420 where Nizwa town is located. (Data source NASA JPL RL06M v02 Mascons.).

3.6. Future studies

Numerical analyses of Omani aflāj are limited due to data quality and availability issues. To allow for more robust studies on Omani aflāj, we propose several recommendations. First, regularly scheduled monitoring of the aflāj streamflow. Currently falaj Daris is monitored on average monthly. However, the measurements are not taken on the same date each month. In neighboring Iran, qanats appear to be measured twice monthly on the same date [13]. Bi-monthly, regular measurements of falaj Daris will allow researchers to better understand the dynamics of recharge in wadi al-Abyadh and falaj Daris flow.

Additionally, it is important that the government of Oman establish a central repository for the country's environmental data. At present, Oman's environmental data are held by various government entities. It is often unclear what data are available and exactly who holds that data. Moreover, once a dataset is identified there does not exist a standardized procedure to access the data collected by the government of Oman.

Finally, there needs to be improved data curation. In the datasets received, several omissions and errors were found. For example, the falaj Daris discharge dataset sent as an Excel spreadsheet was missing two years of data. However, these data were previously published [23] and thus, at some point in time, were available.

4. Conclusions

This study sought to determine the historical trend in falaj Daris discharge between 1982-2020. The dataset used consisted of 446 observations of falaj Daris discharge rate taken between 1982-2020. In addition to the falaj Daris dataset, this study used several other datasets, including, borehole water levels in wadi al-Abyadh's aquifer, which falaj Daris taps, and GRACE satellite data for the larger basin. Data analysis included the Mann-Kendall trend test along with several standard statistical methods and data visualization techniques.

When applied to the thirty-nine-year record (1982-2020) of falaj Daris discharge rates, the Mann-Kendall trend test showed that falaj Daris experienced a slight decline in discharge of approximately 226,000 (L/day). Additionally, for the thirty-nine-year period, falaj Daris discharge rates were also found to fluctuate considerably. Hence, the total volume of water available for farming at Nizwa will also vary annually.

This fluctuation is a consequence of the amount of recharge occurring in wadi al-Abyadh. With alluvial aquifers like wadi al-Abyadh, recharge primarily occurs by wadi flash flooding. Since in arid regions, rainfall (and hence wadi flooding) displays great temporal and spatial variation, the annual amount of recharge in an alluvial aquifer will also greatly vary. The annual wadi al-Abyadh flash flood volume between 1985-2019 displayed this variation. Thus, the amount of recharge in wadi al-Abyadh will vary annually and thereby affect the amount of water available for falaj Daris to tap.

The overall decline in the falaj Daris discharge rate was also reflected in the overall trends in borehole water levels in wadi al-Abyadh. Data from twelve boreholes in wadi al-Abyadh were obtained. Most measurements were made between 1992-2021, although two boreholes had data from as early as 1982. Mann-Kendall trend tests showed that eleven of the twelve boreholes had a decline in water levels, thus corroborating the declining trend seen in falaj Daris discharge.

Since the wadi al-Abyadh aquifer is part of the larger Halfayn basin, to understand the overall trend in the basin, GRACE satellite data was investigated. GRACE satellite data showed a decrease in water volume (WET cm) between 2002-2021 for the larger basin. Thus, it can be assumed that the declining volume in the wadi al-Abyadh is symptomatic of a general decline in water volumes in the larger Halfayn basin.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgment

We thank Ms. Shaikha Al-Malki from Oman's Ministry of Agriculture, Fisheries and Water Resources and Dr. Humaid Albadi from Oman's Directorate General of Civil Aviation and Meteorology for providing the necessary data sets.

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