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Assessing The Channel Design Of The Eco-Friendly 'Falaj' Water System In Meeting The Optimal Water Demand: A Case Study Of Falaj Al-Khatmain, Sultanate Of Oman

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The Falaj system, derived from natural water sources, is a man-made canal system designed to supply communities of farmers with water for domestic and agricultural purposes. For thousands of years, Falaj has served communities by harnessing the force of gravity, it persists as a vital water management system in numerous regions across the Sultanate of Oman. Remarkably, predates the establishment of many fundamental hydraulic principles used today. Al-Khatmain Falaj, with its accessibility and historical significance spanning over 2000 years, was chosen as the focal point of this study. The research aimed to investigate the efficiency of Al-Khatmain Falaj in meeting specific water demands. HEC-RAS model was utilized to visualize water flow dynamics within the Falaj channels, accompanied by graphical representations of pertinent variables. The application of HEC-RAS helped to measure different water flow scenarios within the channel, enabling a clear comparison with the demand area. The cultivated land of Al-Khatmain is 723,124 m2 and consists of 16,873 palm trees representing 91% of the total area and the remaining 9% is mixed types of trees counted 3,920 trees. The study revealed a total daily demand of 3532.85 m3 is required to irrigate the cultivated land. Through rigorous analysis, the study has proven that the Falaj system in Al-Khatmain operates with high efficiency as the average annual water supply is 9676.8 m3/day. Additionally, the channel designed at 0.6m width x 0.3m height, efficiently holds the optimal water supply, with an average flow depth of 0.21m. Also, the system includes an overflow drainage channel to mitigate floods and prevent crop damage based on the seasonal requirements. This research holds promise for examining diverse hydrological conditions and devising effective strategies to manage scenarios of both high and low flow rates in Falaj Systems.

Index Terms— Falaj Al-Khatmain, Sustainability, HEC-RAS, Water Management System

I. BACKGROUND

Oman has a dry, hot desert with a low annual rainfall of less than 60 mm and very high temperatures in summer with big difference between the maximum and minimum temperatures where it can reach over 42^{o} in some seasons [1]. These harsh environmental conditions reduce the chances of establishing stable human settlements. Oman is one of the few countries that has developed a unique hydraulic system called ‘Falaj’ to overcome the drought issues and provided Oman with water since the eighth century B.C [2]. This system enabled Oman to produce a varied type of seasonal crops and supply the global markets by many agricultural Omani products. Agricultural fields in Oman are almost fully depending on Falaj system, in which supply more than one third of irrigation water demand [3]. A falaj can be defined as a canal system that provides water to a community of farmers for domestic and agricultural use. The water flows naturally by gravity along specified slopes, generating a consistent flow speed and water depth to maintain steady motion within the channel. Hence, the operation of Falaj system is environmentally friendly as no machinery energy is used for water extraction and distribution to users. In Oman, there are over four thousand falaj, with more than three thousand active Falaj. These active falajs are categorized into three types: Ghaili, Daudi, and Aini. Ghaili falajs draw water from channels (wadis), Daudi falajs are supplied by aquifers, and Aini falajs depends on natural springs [4]. Notably, five active falajs are listed as UNESCO World Heritage sites. Collectively, the active falajs produce approximately 680 million cubic meters of water annually, with 410 million cubic meters being fully utilized to irrigate about 26,500 hectares of agricultural land [2]. The study of Falaj system concepts can be widely defined in terms of operation management, construction, maintenance, and hydraulic engineering. Still, this research will evaluate the efficiency of the channel design in achieving the required water demand. Also, this study focusses on the Daudi system due to its complexity as the water derived from aquifer through continuous underground and overground channels (Fig.1).

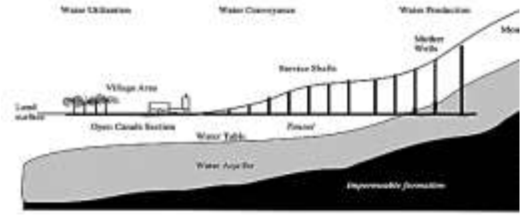


Fig. 1: Daudi Falaj System [9]

II. MOTIVATION

The falaj system is a vital water source in Oman that has served the community for a long time. Unfortunately, this system lacks technical information and has rarely been analyzed or presented in hydraulic engineering studies. Today, new irrigation techniques pose a significant challenge to the reliability of falaj system designs. Over time, only minor improvements have been made, such as the use of concrete for the channels [5]. However, this change has inadvertently blocked the direct infiltration of rainwater into the underground channels. Therefore, the development of the falaj system is relatively slow and appears to be without considering modern engineering techniques, remaining almost unchanged since it was first made. In other words, falajs were designed and constructed before the introduction of contemporary hydraulic principles, and their efficiency has yet to be proven. Furthermore, the complexity of the falaj system requires high accuracy in hydraulic parameters such as slope, water flow rate, coefficient of friction, channel cross-sectional area, and demand area. Any alteration in these parameters will directly impact the water flow system, disrupting the allocation cycle for farms and likely causing fluctuations in the water supply. Still, no previous simulations of Falaj systems incorporating their reliability and efficiency have been established, making this application unique. Thus, this evaluation will aid in future development plans by spotting any design weaknesses in the system and providing the opportunity to examine various hydraulic parameters.

The selected Falaj has been in operation for more than two thousand years without any documented improvements in channel design. This raises a substantial question regarding their design effectiveness in meeting optimal water demand and whether it is critical to adopt modern water supply techniques as a replacement for better efficiency. The main aim of this study is to evaluate the sufficiency of the Falaj's channel design to meet the optimal water demand in Al-Khatmain area. Therefore, the total water demand in Al-Khatmain area has been evaluated in addition to analysing the physical hydraulic processes in Al-Khatmain Falaj system through the applied HEC-RAS model and indicate if any further modifications are needed.

III. METHODS

This research provides a hydraulic study of a typical selected location of Daudi Falaj system by using the HEC-RAS software to physically represent the hydraulic processes of the falaj based on the available measured data from Falaj Al-Khatmain. It assesses Falaj efficiency and determines its ability to supply specific area (total demand volume) via varied discharge (Q) scenarios and corresponding irrigation times. HEC-RAS is a hydraulic model originally designed to assist hydraulic engineers in floodplain determination and channel flow analysis that can be applied in flood insurance studies and floodplain management. The program has been established by the United States Army Corps of Engineers (USACE) where the aim of HEC-RAS is to manage the rivers, and other public works. The fundamental procedure of HEC-RAS is to compute water surface profiles assuming a gradually varied flow (GVF) and steady scenario, this method is called the Direct Step Method [6]. Basically, the computational procedure is mainly based on iterative solution of energy equation which states that the total energy (H) at any given location along the stream is the sum of kinetic energy ($\frac{av^2}{2g}$) and potential energy (Z+Y) as indicated below:

$$H = Z + Y + \frac{av^2}{2g} \qquad (1)$$

Where (Z) is elevation of water at cross section, (v) is average velocity, (a) velocity weighting coefficient and (g) is the gravitational acceleration.

The HEC-RAS model is typically accurate for open channels such as rivers. Although, the Daudi Falaj features an underground channel that is enclosed at the top, the model's functionality remains unaffected, as the water flow in the Falaj channel is considered open-channel flow where the only driving force is gravity, and the water surface is under the impact of the atmospheric pressure. This is because the water level within the channel does not reach the maximum channel height, and there are service shafts along the channel.

Hence, using HEC-RAS can offer valuable insights for improving water systems. It provides a detailed analysis of the system with minimal errors, allowing for the comparison of various modification proposals. These improvements can be implemented in a more cost-effective, efficient, safer, and faster manner. Therefore, HEC-RAS software will be useful in evaluating the current efficiency of the falaj system and determining its capacity to supply a specific area. Also, varied discharge (Q) values can be used to estimate the time required to fully irrigate the demand area. Additionally, the water demand is calculated based on the typical trees number per m^2 and irrigation requirements according to the local farmers and the literature review.

IV. STUDY AREA SELECTION

Falaj Al Khatmain has been selected as the following criteria has been considered:

i. Accessible location.
ii. Maintained in 2006, and still operating.
iii. Availability of input data required, including flow rate; channel slopes; channel cross-sections; channel route, elevation, and length.
iv. Age of the Falaj as listed in UNISCO heritage.

Falaj Al Khatmain is Daudi Falaj in the Al-Dakhiliyah region (Fig. 2). The total length from the mother well to Sharia, the first point where the water appears on the surface, is approximately 2,200 meters (section 1). The mother well, or main well, has a depth of 17.5 meters underground. It has no subbranches (i.e. water flows direct to the point of use) and is fed by Wadi Al Maiden, one of the most important wadis which springs from the foothill of Al Jebal Al Akhdar (Fig. 3). At the Sharia junction stage, the water flows past the Fort, Masjid, and public bath, all within a 300-meter stretch (section 2) before reaching the irrigation distribution junction. The overground section has a smaller depth compared to the underground section, which was designed to allow the maximum demand to enter the demand area. Still, the purpose of this study is mainly to evaluate the efficiency of this design.

Fig. 2: Falaj Al Khatmain location [10]

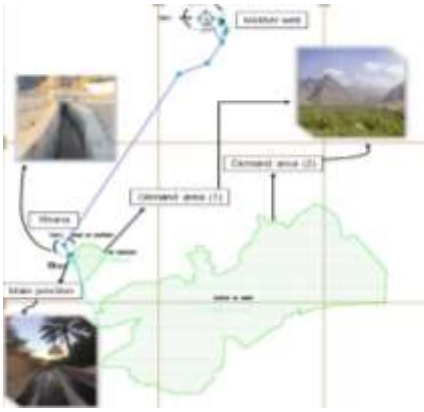


Fig. 3: Falaj Al Khatmain map

V. HEC-RAS MODEL APPLICATION

In this research, the 1D model of HEC-RAS is deemed sufficient for conducting the necessary efficiency evaluations. Consequently, the input data is tailored to the requirements of the 1D HEC-RAS simulator, encompassing channel cross-sections, flow rate, slope, and surface roughness. Each input parameter can be adjusted within the model for further evaluations and assumptions. However, in this study, all inputs will remain constant except for the flow rate, which will be tested at various levels. The channel design will then be assessed based on its capacity to hold water and meet demand. The purpose is to determine the Falaj's capacity to supply the demand area under varying rainfall conditions, whether low or high. Then, the implementation of 1D HEC-RAS in Falaj system will state the maximum and minimum flow limits in term of required volume (V) and needed time to fully irrigate the farms (t).

The 1D HEC-RAS modeling stage requires the following input parameters: the mother well (main well) as the upstream position, and uniform values for slope, flow rate, Ground level elevation, Upstream depth, Manning's value, and cross-section as the water flows downstream for 2,500 meters (see Table I).

Table I: Measured input Parameter

Data	Value
Ground elevation at mother well	610 m
Mother well depth	17.5 m
Flow rate (Q)	0.112 m^3/s
Underground Length (Section. 1)	2,200 m
Overground length (Section. 2)	300 m
Underground channel slope	0.0081
Overground channel slop	0.0028
Underground cross-section dimension	0.6 width x 1.2 height (m)
Overground cross-section	0.6 width x

dimension	0.3 height (m)
Underground & overground Manning's value	0.015 (rough cement)

The second stage involves designing the Falaj system in HEC-RAS software. It begins from the mother well, extends to the Sharia station (the junction connecting the underground and overground channels), and continues for 300 meters before the water enters the Falaj distribution network. At this stage, the channel slope decreases at Sharia station, and water depth increases with steady flow rate between both sections. Even though the channel has only two sections (Fig. 4), the model considered eight stations to accurately represent the channel's direction (Fig. 5). The underground section divided into six stations at 500 m, and the overground had two sections at distance of 300 m.

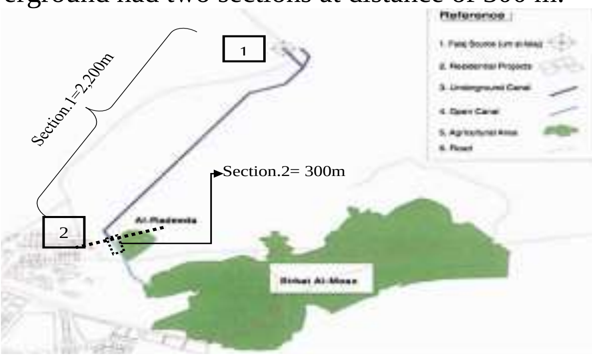


Fig. 4: The identified falaj channel sections

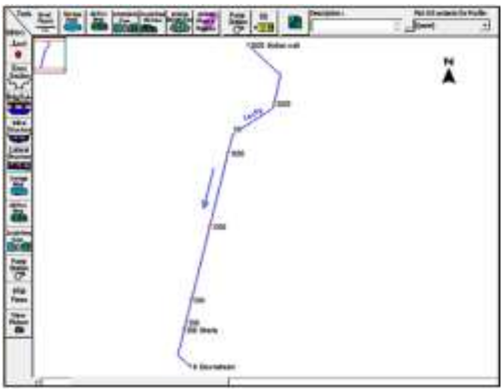


Fig. 5: Falaj channel direction.

In HEC-RAS, each cross-section had a different elevation, initially based on the ground elevation of 610 meters and a main well depth of 17.5 meters. The elevation decreased progressively from the mother well, determined by the channel slope and the channel cross-section.

- ➢ Elevation input equations as following:
- ⇒ Station (1) at 2500m: Top of channel = Ground surface elevation – mother well depth; Bottom of channel = top of channel – channel depth

⇒ Station (2 to 8): Top of channel = top of previous channel – (Distance (m) × Slope); Bottom of channel = top of channel – channel depth

VI. RESULTS

A. Demand volume:

In this study, the latest statistics on the number of trees are represented as a percentage, with date palms constituting 91% and other fruit trees and vegetable crops, such as mango, lemon, and tomato, making up the remaining 9% [4]. The typical number of trees was determined based on these given percentages. The calculated values would have enough accuracy to find the typical required demand that Falaj most delivers [7] (see Table II - IV).

Table II: Date palm irrigation requirement

Factor	Value
Total area of data palms	723,124 m^2 × 91% = 658,043 m^2
Typical radius	3.5 m
Typical area	$\pi(3.5)^2$ = 39 m^2
Total number of palms	$\frac{658043}{39}$ = 16,873 palms
Total demand per year	2.3647 m^3/m^2/year
Irrigations per year	73 times
Per irrigation demand	0.0324 m^3/m^2
Irrigation demand per palm	0.0324 × 39 = 1.263 m^3
Total demand (m^3)	1.263 x 16,873 = 21,320

Table III: Average irrigation requirement for other trees

Factor	Value
Total trees area	723,124 × 9% = 65,081 m^2
Typical average radius	2.3 m
Typical average area	$\pi(2.3)^2$ = 16.6 m^2
Total number of trees	$\frac{65,081}{16.6}$ = 3,920 trees
Irrigation demand	0.87 m^3
Total demand (m3)	0.87 x 3920 = 3,410

Table IV: Summary of total demand

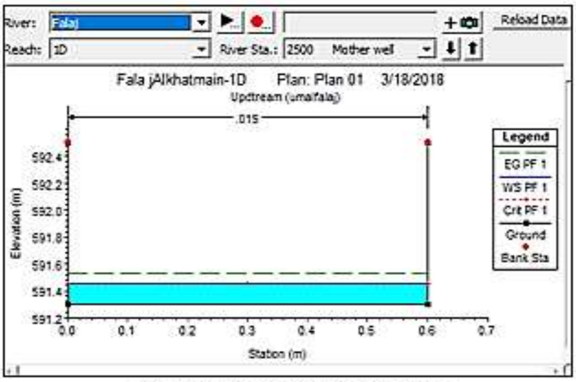
Type	Total number	Demand (m^3)
Date Palms	16,873	21,320
Other	3,920	3,410
Total demand		24,730 m^3/per time

The agriculture water demand calculations indicate that the Falaj system of Al Khatmain must supply at least 24,730 m^3 to fully irrigate the demand area. However, this value is not the actual daily demand volume, because Falaj system doesn't irrigate the whole area in daily phase. The farm owners have developed a minimum Falaj shares system for water allocation, typically ensuring a routing time of 7 days for each farm [8]. The HEC-RAS model was used to evaluate various discharge values by applying the irrigation time into two different phases scenario:

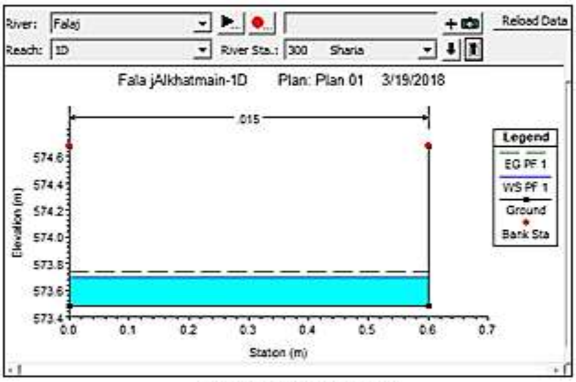
- Phase (1): Full crops supply at once
- Phase (2): Seven days allocation system

B. Model Output

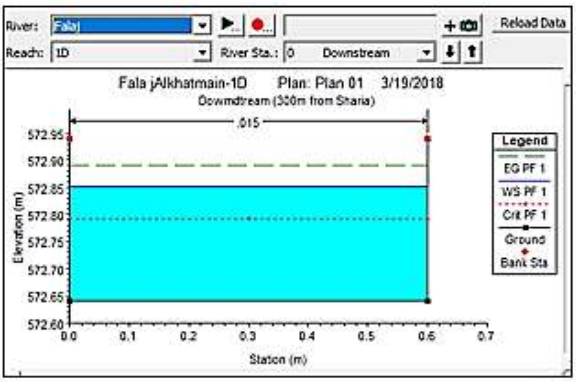
The HEC-RAC validated the data and worked in simulating the water motion within Falaj Al Khatmain based on 0.112 m^3/s flow rate value. The results showed that the water levels did not exceed the channel depth at the average flow rate, even at the Sharia station where the velocity and slope were reduced. The underground section has a water depth of 0.15 meters, which increases to 0.21 meters at the Sharia point due to the reduced slope, generating a hydraulic jump (Fig. 6 - 8). Therefore, the given average flow rate is acceptable in terms of channel capacity.



(a) the underground channel



(b) Sharia station



(c) the overground channel

Fig. 6: The simulated flow at different channel sections. (a) underground. (b) Sharia. (c) overground.

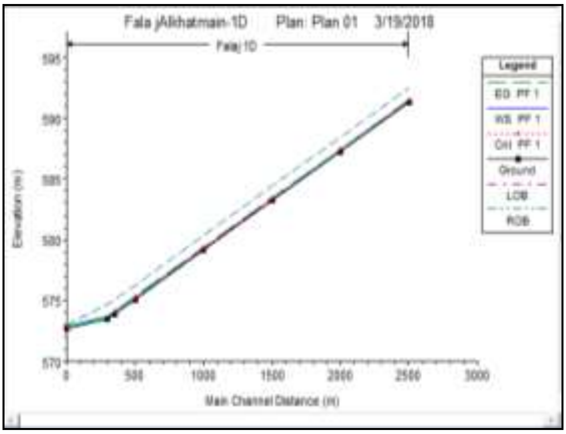


Fig. 7: Side view of Falaj Al Khatmain channels

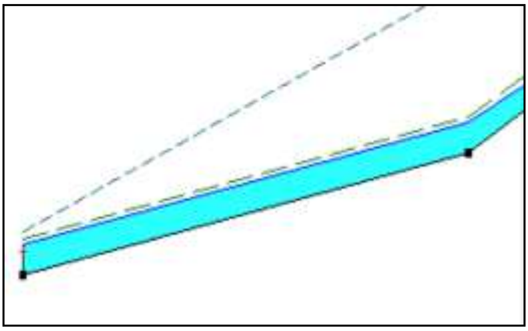


Fig. 8: Hydraulic jump at Sharia due to slope decrease, causing water depth increase.

Where EG PF: energy grade line Profile, WS PF: water surface profile, Crt PF: critical flow profile

C. Water demand analysis

The channel design efficiency in meeting the optimum water demand will be determined by applying various flow rates value in the HEC-RAS model with respect to the required volume and the channel depth level (i.e., not exceeding 0.3 m). The required time to irrigate the entire area can be calculated using the following formula:

$$\text{Time} = \frac{\text{Volume}}{\text{Flow rate}} = \frac{\text{V (m}^3)}{\text{Q (m}^2/\text{s)}} \text{ (s)} \quad (2)$$

Table V: Irrigation flow rate requirements based on time

Full irrigation demand = 24, 730 m^3/day			
Flowrate (m^3/s)	Water depth (m)	Time (s)	Time (days)
0.286	0.47	86,400	1
0.179	0.30 (max)	138,156	1.59

0.168	0.29	147,202	1.7
0.112 (Avg)	0.21	220,803	2.55
0.041	0.11	604,800	7

The results have shown the efficiency level of Falaj Al Khatmain in accommodating various amounts of water within the channel depth limits. It was noted that no more than 0.168 m^3/s can be hold by the Falaj channel, as the maximum allowable water depth should remain below 30 cm (Fig. 9). However, the research shows that Falaj Al Khatmain is not designed to irrigate the entire demand area on a daily basis, as it would require a water depth of 0.47 meters at a flow rate of 0.286 m^3/s. Therefore, the allocation cycle and water demand work perfectly with the channel design, where a water depth of 0.11 meters is sufficient to meet the daily requirement. Additionally, the optimal water depth flows at 37% of the channel's capacity, leaving an additional 63% allowable depth for higher flow rates. In other words, the channel was mainly designed to supply water at maximum of 1.7 days frequency.

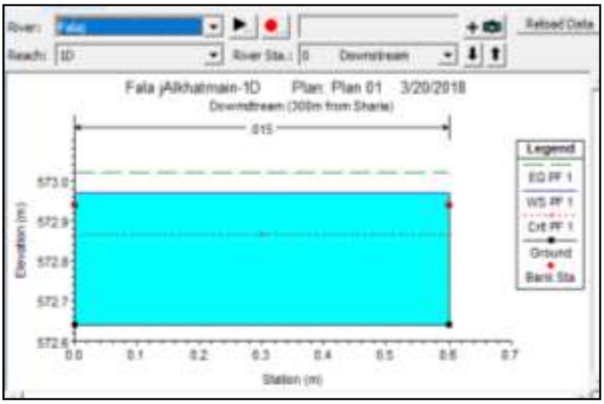


Fig. 6: Water exceeding channel depth at > 0.179 m^3/s.

At this stage, it can be argued that phase (2) (using water allocation system) is one of the main criteria that has been taken during the Falaj design stage. Hence, the following calculation represent the theoretical daily demand:

Actual demand per day = $\frac{24,730}{7}$ = 3532.85 m^3

However, it can be observed that the average flow rate is almost three times the actual need for 7-day water cycle, which supplies up to 9,676.8 m^3 per day. This indicates a highly efficient channel design, as the water cycle could be reduced to 2.55 days, or the excess water could be stored by the owners. The first option, however, may not be suitable for all seasons and all types of crops, making the second option more practical. Consequently, most farms typically have storage pools to preserve excess water when the land is fully irrigated. Storing water is common in farms using the Falaj system, especially for crops such as vegetables that require more frequent irrigation cycles, unlike palms and some fruit trees. Furthermore, the channel is designed to prevent more than 0.168 m^3/s of water flow from entering the Falaj system, likely because the demand area can only accommodate water under these boundary conditions. Higher flow rates might harm people, crops, farms, and nearby properties. This aspect should be considered in a separate study to evaluate the drainage channel design in Falaj systems.

D. Study Limitation

This research provides a detailed analysis of the Falaj cross-section design with maximum accuracy through using HEC-RAS. However, the results might be slightly affected due to the following limitations:

1. Input data were not measured as part of this research, because it requires advanced equipment and tools, expertise, and long-term monitoring and recording.
2. The study did not account for the impact of high temperatures and domestic use on the total water supply, as these factors were considered negligible.
3. HEC-RAS modelling stage extend from the mother well to a few meters before the distribution junction. The falaj network within the demand area is more complex and falls outside the scope of this study.
4. The drainage channel is not included in this research evaluation because flooding events are infrequent in this falaj system. Additionally, evaluating the drainage channel would require a 2D HEC-RAS model, which can provide accurate insights into the channel design by incorporating the land geometry.

CONCLUSIONS

Falaj systems are environmentally friendly, utilizing gravity to supply communities with clean, fresh water. They have played a crucial role in human settlement in Oman by providing essential needs such as food security. This research is essential to ensure the sustainability and potential development of falaj systems. The implementation of HEC-RAS has been found to be useful in providing a detailed analysis of hydraulic behavior along the system and evaluating the design efficiency by adjusting various variables to assess performance. Additionally, Falaj systems use fundamental hydraulic engineering principles predating modern equations. Therefore, the system is unique and unexplored in terms of design effectiveness and the underlying basis for stating these conditions. In Falaj Al Khatmain, the overground channel has the ideal capacity to manage water flow rates effectively throughout the year.

Finally, establishing a measurement station within the Daudi Falaj, especially in its underground section, poses challenges due to the small channel size that cannot accommodate station equipment. Therefore, utilizing HEC-RAS would be more cost-effective, efficient, safer, and practical. The benefits of using HEC-RAS in the Falaj system can be summarized as follows:

a) Flood Prediction: By analyzing the relationship between rainfall amount and Falaj discharge, the required size, and direction of drainage system can be obtained.

b) Design improvements: Evaluating potential adjustments in the system design such as slope, channel size, flow rate, Manning’s value (if different materials other than concrete are used)

c) Water Allocation: Establishing a suitable allocation system by applying the measured flow rate and assessing the required time for irrigation within the channel.

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