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A Birds Eye View: Using Google Earth to Study the Late Islamic Qanats of Sohar, Oman

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1. Introduction

Qanats have been essential to the distribution of water all across Arabia and in other regions of the world. This thesis will aim to study qanats in the area of Wadi Suq using satellite imagery, a choice for which there are three key reasons. Firstly, the geographical area chosen for study has already been researched in the past by two researchers, Costa and Wilkinson, and therefore their results will provide useful comparison to the results found within the thesis. Secondly, the previous research in the area was done without satellite imagery, which creates a gap in research that can be explored. Lastly, this research can be used as a case study to look at the utility of satellite imagery for the study of qanats, which could eventually be carried over to other areas with qanats present. To do so, this thesis will study the features that were left behind by irrigation systems located in Oman using satellite imagery.

It is important to clarify the vocabulary being used to avoid confusion: “Qanats” are the irrigation systems being studied in this thesis. However, some sources may refer to these systems as “*falaj”* or *“aflaj”* which is a word used in Oman to designate any type of irrigation system. If one of these words is used, qanats are still being referred to.

To understand the work done in this thesis, it is important to give a brief explanation of qanat systems and remote sensing in an archaeological context. To begin with, qanat systems are irrigation systems that rely on gravity to operate, bringing water down to settlements for whatever needs they might have. These needs might be agricultural, such as irrigating farmland, religious, sanitary, or simply the necessity of clean water. These qanats are going to be the focus of the thesis and will be explained in further detail later on.

Following that, remote sensing is the act of gathering information concerning an object or landscape, without having to physically touch the object (Hadjimitsis et al. 2013, 57). By this definition, it can encompass many different sensing techniques such as LiDAR, aerial photography and satellite imagery. In archaeology, remote sensing is highly valued due to the fact that information can be gathered without altering or damaging whatever is being studied, be it a feature, remains or an artefact (Hadjimitsis et al. 2013, 57-58), as well as studying landscapes that are no longer physically preserved.

This now leads to the research question of this thesis:

- To what extent can satellite imagery be reliably used to reveal and gather information concerning qanat irrigation in the area surrounding Sohar, Oman?

This can be broken down into several sub questions that will give the thesis several focus points that can easily be understood:

- What kind of information can be obtained on qanat systems using satellite imagery?
- What are the inaccuracies that come with the information gathered?
- How can the data gathered be used to identify characteristics that can help compare, categorise and date the different qanat systems ?
- How does this information compare to other research done concerning qanat systems in Sohar?

This research question is interesting for several reasons. Firstly, it is useful to research the Sohar area (Seen in Figure 1), despite the fact that the qanat systems there have been studied in the past by Costa and Wilkinson, as they were not studied using satellite imagery. This presents a new opportunity to gather information that possibly had not been found in previous research. This data would be both qualitative and quantitative and could therefore possibly give a new perspective on these qanat systems. Currently the work done by Costa and Wilkinson is seen as essential to any academic work done on the irrigation systems of Sohar. This research will help see their work through a modern perspective and add more information on the qanats found in Sohar. Furthermore, over time these irrigation systems are disappearing due to natural or anthropogenic factors, and as such it becomes necessary that a track of these systems be kept due to their archeological and cultural value. The most effective way to monitor them is using satellite imagery: by foot it is harder to spot their features, and there are no associated artefacts to qanats that would facilitate a pedestrian survey. Remote sensing can therefore be seen as a useful addition to the toolbox used for studying irrigation systems, permitting both their study and allowing also for records of their existence to be kept.

A potentially interesting aspect of this research, from a methodological point of view, is the possible insight it may give into the usefulness of manual remote sensing, as opposed to the automatic remote sensing on which newer studies focus, as the data gathering was done on a small scale by a single individual. This research therefore may provide insight into the advantages and drawbacks of doing remote sensing manually, within the specific context of studying irrigation systems.

Going over the structure of this thesis, in chapter 2 the background on qanat systems in general and in the area will be covered, followed by the background of satellite imagery and how it has been used for studying qanats in the past. In chapter 3, the methods used for the present research will be explained, starting with how remote sensing is used in archaeology, how satellite imagery was used in this research and the approaches and limitations of these methods. In chapter 4, the results of the thesis will be presented. In chapter 5, the results will be analysed and discussed. Finally, in chapter 6 a short conclusion will be made on the findings of the present research and possible future avenues for research.

Figure 1 : Map of the Sultanate of Oman with Sohar visible along the Gulf of Oman (Costa & Wilkinson, 6)

2. The Study of Qanats in Arabia

To understand the scope of the research it is essential to discuss previous research done in the area. This second chapter will be looking at the different factors that make up the research area: what qanat systems are and how they were built; a geographic description of the region of Sohar; a brief overview of the previous research done in the area concerning qanat systems, and finally a short review of other cases of remote sensing being used to spot irrigation features in other regions.

2.1. Context on qanat systems

Qanats are a form of water distribution that has been used across many different regions of the world across many different periods (Charbonnier 2015, 39). These qanats are particularly common in the Middle East, being found from Northern Iraq to South Eastern Arabia, with a higher density in the South, some of which are still in use today (Charbonnier 2015, 39). Qanat systems are very important to the well-being of countries such as Oman where qanats are responsible for 55% of the irrigation done on arable land (Charbonnier 2015, 40). These qanats are often a large undertaking by a community and would take several villages to make one qanat, each qanat would usually distribute water to multiple villages or agricultural fields (Wilkinson 2013, 74).

Qanats can be broken down into two or three parts (see Figure 2): the first part consists of the underground water system with vertical shafts and horizontal water conduits (Legend 1,2 and 4); the second part consists of outlets to the water for distribution and reservoirs (Legend 3 and 5), while the third part consists of irrigation feeding into agricultural fields (Legend 6). In some cases, the third part and the second part are one and the same, with the water directly feeding into the agricultural land. This research will specifically be looking at the first part of these qanats, the underground water systems marked by their vertical shafts since these can clearly be seen in the landscape through the use of satellite imagery.

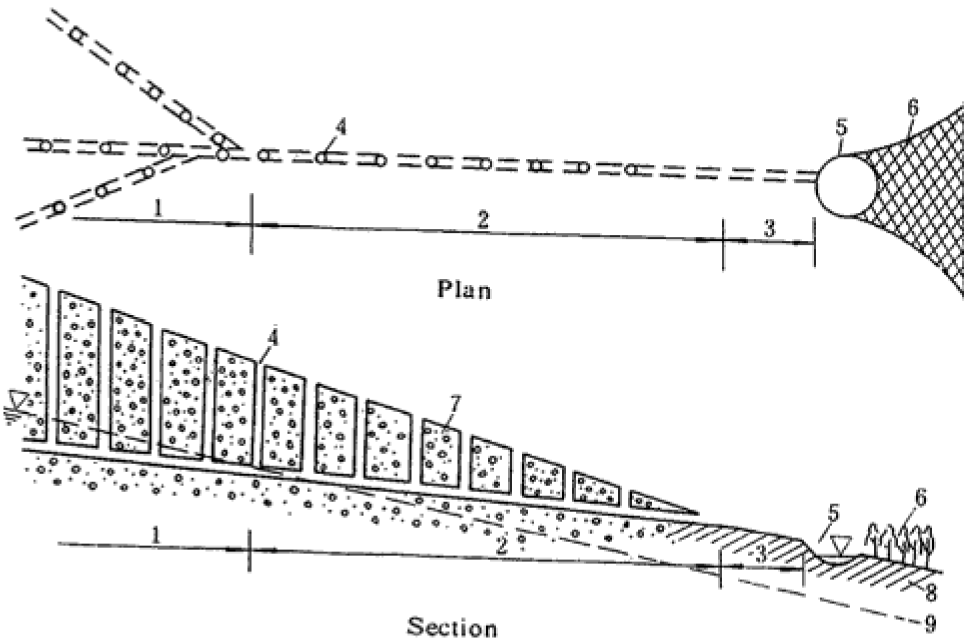


Figure 2: Structure of a Qanat (http://www.waterhistory.org/histories/qanats/)

Legend:

(1) Infiltration part of the tunnel
(2) Water conveyance part of the tunnel
(3) Open channel
(4) Vertical shafts
(5) Small storage pond
(6) Irrigation area
(7) Sand and gravel
(8) Layers of soil
(9) Groundwater surface

There are 2 types of irrigation structures commonly seen in Oman: ghalyl falaj and qanat falaj (Wilkinson 2013, 74). It is important to describe and differentiate these two structures for later on in the thesis. Ghalyl falaj tend to have a smaller structure, located close to a *wadi* (a valley), where the water is directly diverted by a small bund between the wadi and the falaj. These irrigation systems tend to travel a shorter distance compared to qanats but on occasion they can go a considerable length as long as they stay alongside the wadi; they are simply diversion channels. The second type of structure is the qanat falaj: these irrigation systems are built around having a sloped tunnel that drains groundwater up to the surface (Charbonnier 2015, 39), and these tunnels are marked at regular intervals by vertical shafts. These shafts are used for maintaining the qanats through repairs or removing spoil from the tunnel (Charbonnier 2015, 39).

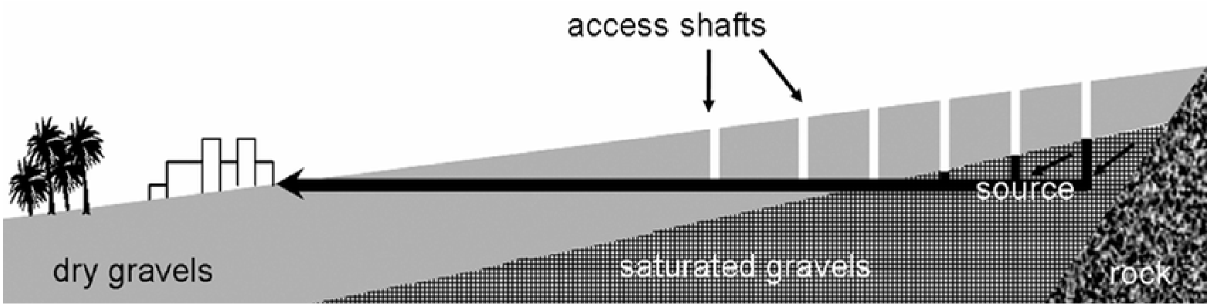


Figure 3: Diagram of a qanat (Harriet Nash 2007, 3)

The horizontal tunnels of these qanats used to be covered by *sarūj*, a strong, water resistant material that would keep these structures together. With time the material was changed to cement, even though it was acknowledged by most that *sarūj* was a stronger material (Costa and Wilkinson 1987, 221). The reasons behind this could be that the manufacturing process was either lost over time, or that it was too lengthy and cement was a cheaper alternative (Costa and Wilkinson 1987, 221).

The placement of these irrigation systems is essential for the efficiency and sanitation of the water distribution. In the case of the ghalyl falaj, as previously explained, it is simply placed next to a wadi and diverts the water from the wadi to supply it elsewhere. The interesting factor in ghalyl falaj placement is where the water heads to, as arable land might often not be close to where the ghalyl was placed, therefore requiring it to travel a greater distance. When looking at qanats the opposite is observed, as the most important factor is not the destination, but rather the starting point. The mother well is the necessary starting point for any qanat, and these wells must be placed while taking into account several factors (Wilkinson 2013, 76) These mother wells are the first shaft to be dug out when building a qanat. While it is cheaper to place the mother well at a higher point as there will be less work to excavate it, there will be a lower volume of water compared to placing it further downstream (Wilkinson 2013, 76). However, when going too far downstream the quality of the water also tends to decrease (Wilkinson 2013, 76). These factors are essential to the success or the failure of a qanat.

Qanats are believed to have emerged around the Bronze age (2300 B.C - 1200 BCE) or the Iron age (1200 B.C - 670 BCE), although the exact time period remains a topic of debate , and evidence for Bronze age qanats remain circumstantial (Charbonnier 2015, 40, 68). The irrigation systems studied in this thesis are more recent and likely date back to the Late Islamic period (1500-1750 CE) (Costa and Wilkinson 1987, 60). This period was largely characterised by a Portugese and Ottoman presence in Oman which would go on until the late 17th century (rafmuseum.org.uk).

2.2. Features of the region

It is important to present a general report of the geography of Oman to better understand the land surrounding these qanats, starting with a general description of Oman and progressively going more into detail about the research area.

Oman is a country with a dry desert climate, only getting on average 80-100 mm of rainfall per year (weather-and-climate.com). The terrain is generally rugged with a central desert plain adjacent to mountains in the North and the South of the country (www.cia.gov). Due to these geographical characteristics, arable land becomes hard to use as the lack of water cannot sustain all the possible land, with only 4,7% of the land being used for agricultural purposes (www.cia.gov). It is because of this climate that Oman and other middle eastern countries have such a large quantity of qanats present on their territory, tapping into the underground water and bringing it to wherever people or crops are present.

The region of Sohar (Figure 4) can be characterised by two different landscapes: a mountainous and foothill zone and a coastal plain zone (Costa and Wilkinson 1987, 23). The former of these two can be seen as a 40 - 50 km stretch of mountains and foothills. Their elevation reaches up to 1600 m above sea level and they form a belt around Sohar, separated by a 10-15 km area of coastal plains. The main geological composition of the mountains in this area is the Sumā'il igneous complex, mainly composed of ophiolite (Costa and Wilkinson 1987, 23). Copper could be mined from these mountains and worked by the people of the land, one of the facets found in the economy of Sohar (Costa and Wilkinson 1987, 23). Settlements within the mountainous area were scarce as there was a limited amount of available water for a community to be able to survive with, however it is within this area that cultivable land could be found and irrigated by open channels (Costa and Wilkinson 1987, 24). Moving away from the mountainous area of Sohar, there is a transition zone which merges the foothills and the coastal plains before finally reaching the coastal plains. These coastal plains are made up of Holocene and Pleistocene sediments washed up from the Hajar al-Gharbī mountains, which are 60-90 m in thickness (Costa and Wilkinson 1987, 24-25).

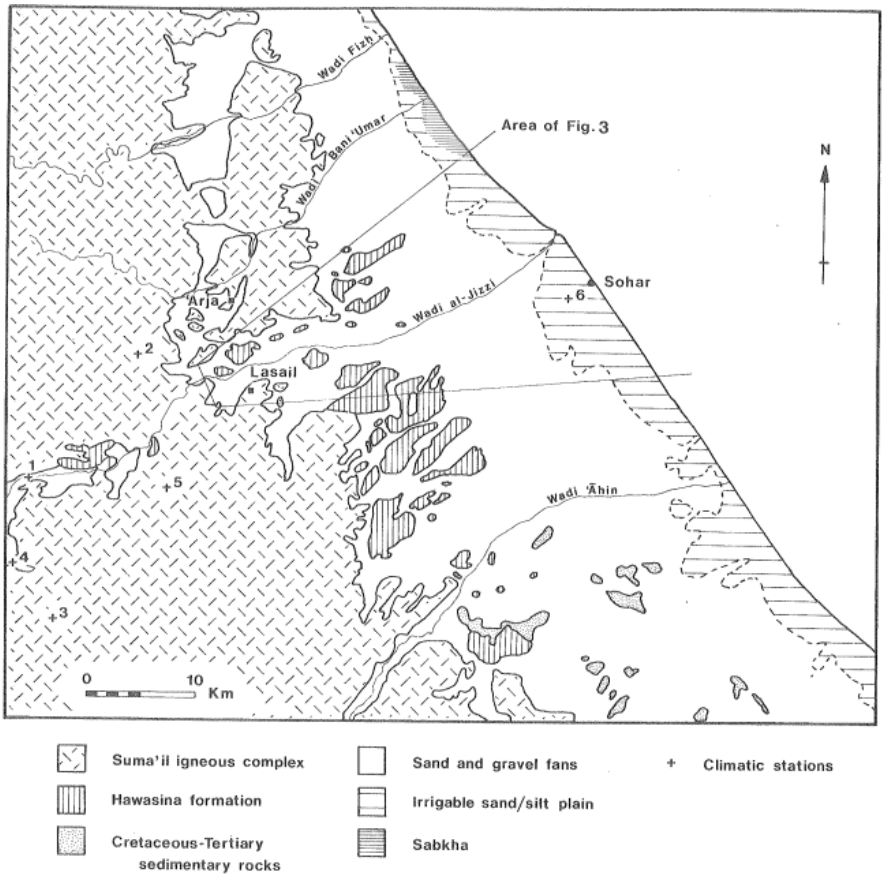


Figure 4: Geological Map of the area surrounding Sohar (Costa and Wilkinson, 24)

There are 6 different terrain types that can be seen in the coastal plains (Costa and Wilkinson 1987, 25-27):

1. High terraces covered in dark and highly weathered cobbles, within which cobble burials dating from various periods can be found.
2. Outwash deposits that are composed of massive sheets of gravel and cobble; these tend to be more recent and thus less affected by the weather.
3. A coastal accumulation plain, 2-6 km wide with a gentle slope, mainly composed of sand and silt found in between gravel fans and with active wadi channels.
4. Salt flats along the coast between modern palm gardens and strips of coastal sand.
5. A coastal sand belt constantly moving along the coast.
6. Small hills of tertiary limestone that can be found at the midway point of the coastal plain .

It is also interesting to look at the hydrology of the region as it is a key factor for the presence of qanats. The two main landscapes, being the mountainous area and coastal plains, each play a role in the hydrology of the region (Costa and Wilkinson 1987, 31).

During storms, the mountainous region experiences a large runoff of water and will also store a considerable quantity of groundwater. This storage is essential to the water supply for several qanat systems in the area of falaj al-Mutaridh (Costa and Wilkinson 1987, 32). The water from these storms eventually reaches the coastal plains where it infiltrates the gravel outwash or when the flow is too large discharges into the sea. The presence of moderately impermeable gravels barriers leads water to the hills where the water table rises (Costa and Wilkinson 1987, 32). Due to the manner in which the region was formed, open channel systems are found in the mountainous region as it is easier to divert storm runoff from the mountains into inhabited areas using these irrigation systems. Underground systems are then placed in the coastal plains as there are large quantities of groundwater that can be exploited there (Costa and Wilkinson 1987, 32). These open channels in the mountains are usually used to irrigate cultivable land, while the underground systems along the coast generally lead to fields and settlements to provide access to water for day to day needs (Costa and Wilkinson 1987, 36, 38)

The specific site studied in this thesis is located close to Wadi Suq, which can be found to the North-East of Sohar (Figure 5). In the present day, this area is covered by many roads and roundabouts. It was also part of the area studied by Costa and Wilkinson and was suitable for the present research as there was a cluster of qanats specifically in that area, allowing the research site to be kept at a manageable size for an individual to study, but with enough data for it to produce interesting and meaningful results.

2.3. Former research on qanats in Sohar, Oman.

The largest and most comprehensive archeological publication on the region of Sohar, Oman is “The Hinterland of Sohar: Archaeological Surveys and Excavations Within the Region of an Omani Seafaring City” by Costa and Wilkinson (1987). This covers not only the irrigation systems in the area but also other factors such as copper exploitation, the different settlements present and the geographical characteristics of the area.

This research by Costa & Wilkinson follows in the footsteps of past research projects concerning Sohar and its hinterland, starting with preliminary investigations in 1958 which shed light on the early Islamic period, although it was not a large-scale project (Costa and Wilkinson 1987, 19). This was followed by research conducted by Andrew Williamson in 1973, in which he defined the topography and archaeology of Sohar for the first time, emphasizing on the agricultural hinterland of Sohar (Costa and Wilkinson 1987, 19). Williamson's research led to the creation of the Sohar ancient fields project, which delved further into Sohar and presented new data on the water supply systems present in the area (Costa and Wilkinson 1987, 20). This research would later give way to the 'Arja excavation, which mainly focused on copper mining in the area (Costa and Wilkinson 1987, 21). These projects would all finally contribute to the work led by Costa and Wilkinson, which summarised all the different aspects of research done in Sohar by the Sohar Ancient Fields and 'Arja projects into one comprehensive publication, accompanied by updated information on each aspect. Their book covers most of the research on qanat irrigation in Oman up until that point and is an invaluable document for studying these qanat systems. As this thesis focusses on qanats in the Sohar area, it will only discuss the part of Costa and Wilkinson's work which concerns these irrigation systems. This includes the dating of these systems, how they were found and the reason why so many of them are found in that area.

An important contribution of the research done by Costa and Wilkinson is their mapping of qanat systems in the area surrounding Sohar, as can be seen in Figure 5. The systems found in this area by remote sensing coincide with those found by Costa and Wilkinson, and thus provide a useful point of comparison. Costa and Wilkinson mark these systems by an "I", indexed by a number between 1 and 3. (see Figure 5 and 6, below). The qanat systems found in the present research are believed to be fragments of these previous systems. From their research in chapter 4 of the book, they conclude that the qanat I_1 is still in use at the time of their research in 1987, and both I_2 and I_3 have been abandoned, with I_3 having been abandoned more recently than I_2 (Costa and Wilkinson 1987, 60). Dating qanats can be difficult as there are no associated artefacts, such as pottery, to these features. As a solution to this challenge, Costa and Wilkinson dated archaeological features that were close to the qanats, such as the bricks used to make the shafts to get an approximate age. Alternatively, they could look at the positioning of two qanats, and should one cross over another, this would provide a relative date (Costa and Wilkinson 1987, 53). From these different dating techniques, it was believed that the "I" qanats date back to the Late Islamic period (1500-1750 CE), with "I_1" being the most recent, "I_3" being the second most recent and "I_2" being the oldest (Costa and Wilkinson 1987, 60).

Figure 5: Map of the identified qanats in the area around Sohar by Costa and Wilkinson, with the red square highlighting the area covered in this thesis (Costa and Wilkinson 1987, 42)

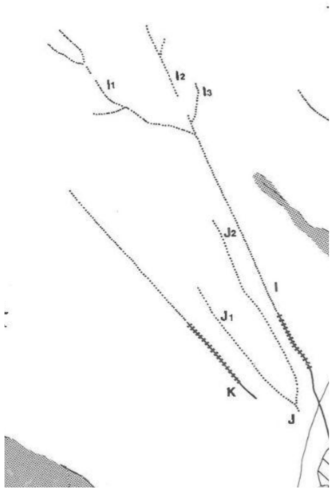


Figure 6: A map with a closer view on the area studied in this thesis (Costa and Wilkinson 1987, 42)

In Costa & Wilkinson's research, these qanats were identified using aerial photography and by searching on the ground. They were able to find 23 systems, and of these 22 were underground systems, with only one being an open channel gathering water from Wadi al-Jizzi (Costa and Wilkinson 1987, 53). They admit that not all systems could be found using aerial photography, hence the need for people to spot these systems on the ground (Costa and Wilkinson 1987, 77). This will be interesting to compare to the methods used in this thesis later on.

From their research, Costa and Wilkinson were able to show how important these water irrigation systems were for the functionality of Sohar (Costa and Wilkinson 1987, 77). It is suggested by these authors that this concentration of qanats around Sohar could be due to the large catchment of the coastal area in the region that can be exploited, and possibly also because the water table was sufficiently high for water to be easily accessible. This therefore encouraged the construction of qanats, from a hydrological viewpoint (Costa and Wilkinson 1987, 78). However, they did not believe that the construction of these qanats were based on hydrological factors alone. Socio-economic factors must have played the leading role in their construction as, regardless of the time period and location, the construction of a qanat was always a costly project (Costa and Wilkinson 1987, 78).

2.4. Remote sensing used for similar projects

This thesis is not the first to use remote sensing techniques to observe archaeological features concerning irrigation. Costa and Wilkinson used air photographs to detect 124 different mounds (Costa and Wilkinson 1987, 53) in the landscape and 23 qanat systems (Costa and Wilkinson 1987, 45). These photos were done on a 1:20 000 scale and helped greatly in tandem with the fieldwork being done in the area around Sohar (Costa and Wilkinson 1987, 77). This research is also not the first to use satellite imagery to detect qanat features in the land. As such, it is useful to look at how these other projects were carried out using these methods to understand the current standing of satellite imagery in locating qanats.

To understand how satellite imagery is commonly used to locate these qanat systems, it is important to describe the features being searched for. When looking at satellite imagery, qanats can be identified as a series of circular indentations in the ground. Each circular indentation is separated more or less by the same distance. Each indentation is also surrounded by spoil which forms a rim. These circular structures are the shafts of a qanat system, while the rim formed by the spoil is a spoil heap and is what was generally dug out to make the hole. These features generally vary in size and clarity, however the previously explained characteristics are usually the same for each system and are what researchers will look for. Additionally, these features are much easier to detect when using satellite imagery as it gives the user a clear view of the entire landscape. An example of this can be seen with Figure 7.

Figure 7: Example of several qanat features from Anshan visible using Google Earth (livius.org)

In Figure 7, several qanats are seen crossing over one another, there being most likely 3 in total. These systems are marked by the circular shafts and there are visibly different sized ones. It seems reasonable to suppose that shafts of similar size belong to the same qanat, and considering the fact that these 3 qanats have the same orientation, it is likely that these are qanats built over several periods. Like any tool, there are drawbacks to satellite imagery, as it can be difficult to distinguish these different qanats due the image resolution and also, parts of the system of circular shafts associated with a qanat may no longer be visible because these have been covered by earth or debris over time. This especially applies to older qanats.

Two more recent research projects, based in Xinjiang, China, and in the Kurdistan region of Iraq, also use remote sensing, and in particular satellite imagery in the study of qanats.

The first publication, by Lei Luo et al., is based on using Google Earth as a remote sensing tool to detect the tops of qanat shafts. These authors argue that their research is useful in understanding water distribution in the region of Xinjiang, which could be helpful for anthropologists and agriculturalists (Luo et al. 2014, 11956-11957). Due to the large size of their research area, they propose an automated method of detecting these shafts (Luo *et al.* 2014, 11957). Up until this point, manual detection had been the standard in order to avoid the appearance of false positives but Luo et al. believe that this is too time-consuming (Luo *et al.* 2014, 11957) and propose to use the Hough transform, a technique that helps to extract imperfect versions of a shape from an image through a voting procedure, and to use this technique on the circular shapes in the landscape which indicate qanat shaft openings (Luo *et al.* 2014, 11958). This research was purely used for detecting these systems but lacks qualitative data.

The second paper, written by Mernoush Soroush et al., focuses on detecting qanats using the Cold War era CORONA Satellite Imagery (Mernoush 2020, 1-2). Their project is focused on a deep learning tool that can be taught to detect qanat features (Mernoush 2020, 2-3). Their reasoning behind the research is that with remote sensing, there are many new ways to obtain information, however as a consequence there is sometimes too much information to process and using manual checks often takes too much time, depending on the scale of the project (Mernoush 2020, 1). As such, they state that teaching a tool to automate some or all of the process is beneficial for future research(Mernoush 2020, 1-2). They argue that qanats are a useful starting point for such a tool as their features are relatively easy to recognise (Mernoush 2020, 4).

A common characteristic of these two projects is that they both seek to automate remote sensing as it is a time consuming task. While this appears to be true for these two case studies, on a smaller scale, such as the one in this thesis, manual remote sensing is adequate to handle all the data without taking too much time. Furthermore, it allows for quantitative data to be collected, such as relative dating or tracking the visibility of these systems over time, something not yet possible with an automated approach.

3. Methods

The methods in this thesis are centered around the use of remote sensing, and how this technique can be used to gather information concerning qanats. The main tool employed was Google Earth as this thesis argues that this has all the functionalities necessary to enable the quantitative measurements and comparisons of the qanats shafts of the qanat systems that were examined. The resolution was of a sufficiently high quality to be able to do these measurements (see below for further discussion of Google Earth's resolution), and the time slide function allowed for the capturing of clearer images and also for recording if these features were still present today.

3.1. Remote sensing in archaeology

Firstly, it is essential to explain what remote sensing is with regards to archaeology, and why it is potentially useful for archaeologists when looking at sites, features and artefacts. Remote sensing is a process in which the physical characteristics of an object, site or feature can be identified without having to make physical contact with the object (Hadjimitsis et al 2013, 57). Its value in archaeology is therefore extremely high due to the fact that in contemporary archaeology the aim is to study the past with as little alteration as possible. Using techniques like remote sensing allows for archaeological items to be studied without having to be concerned about anthropogenic and natural factors affecting these items. It also allows for the detection of features that would otherwise be invisible, for coverage of much larger areas of study and for the study of ancient landscapes that are no longer preserved. Satellite imagery is one possible method of remote sensing. The process involves using imaging satellites to get high resolution images of Earth. Satellite imagery is widely used as a means of locating archaeological features and monitoring cultural heritage. In the context of the present research, it can be argued that satellite imagery is employed to achieve both of these goals.

In the past, satellite imagery tended to be quite pixelated, with a single pixel representing up to 80m when it was first introduced. However, this technology has evolved significantly, and now one pixel can represent an area as small as 0.41m (Fowler 2010, 100). Despite the lack of accuracy of early satellite imagery, it could still detect archaeological features such as water management systems in Mesopotamia (Fowler 2010, 101), thus proving the benefits to archaeology of this technology, which would also see rapid improvements of the quality of information gathered by satellite imagery. Satellite imagery has become an important resource which can be used in combination with more traditional techniques of archaeological research. Furthermore, in areas where little to no aerial photographs had been taken in the past, satellite imagery archives can now show features that have otherwise been destroyed due to factors such as urban expansion (Fowler 2010, 108). Examples of this can be seen in this thesis when discussing the results.

3.2. Using satellite imagery in the research area

This thesis relied on satellite imagery to gather important information on the qanat systems found around the area of Sohar, Oman. Sohar was a center of trade during the Early Islamic period, with its hinterlands being home to extensive copper resources, water and irrigated lands (Costa and Wilkinson 1987, 9). With its rich history in irrigation and the previous extensive research done by Costa and Wilkinson in the area, the region was the ideal location to explore the research questions posed by this thesis. The data gathered is for the most part quantitative, and looks at the different measurements of the visible part of qanat systems including the diameters of the shafts and the distances between the shafts. Some qualitative factors include whether the systems are still visible in the landscape as well as how these systems can be used to relatively date one another. Due to the fact that this thesis analyses the reliability of the data gathered by satellite imagery and its potential usefulness, it is essential to take an unbiased approach (insofar as possible) when gathering these data.

As already mentioned, Google Earth was used in order to locate these qanats and gather their measurements. Satellite imagery has been used since 1959 since the CORONA program created by the United States (oneonta.edu), taking pictures of the Earth for various purposes. It has been open to the public for free use since 2005 in the form of Google Earth (livescience.com). Furthermore, in previous research archaeologists have found Google Earth is highly effective as a remote sensing tool, as the quality of the imagery is good enough to identify archaeological features in the land. For this thesis, Google Earth Pro was used, which had an image quality that could effectively show the location of the qanat systems and enable measurements to be carried out. This was all done using landsat 8. As the area size of the research was relatively small, pushing the program up to its computational limits was of little concern. The time function available with Google Earth also permitted images of a higher quality to be obtained. This is due to the fact that certain days were better lit, giving a clearer outline to the different qanat shafts. This function furthermore allowed for tracking the preservation of these systems by looking through different images to see whether these systems had disappeared or not.

The area studied in this thesis is situated to the north-east of Sohar, next to the wadi Suq. The reasoning behind this choice was that previously, research on qanats had already been conducted, as seen in the second chapter of Costa and Wilkinson (1987). However, as it was necessary to have a smaller and more manageable research area than the one covered by Costa and Wilkinson, due to the limitations of the project (which had to be carried out by a single person in a limited amount of time) it was decided to concentrate on the northeastern area of Sohar, as it had a reasonable amount of qanats to compare and contrast during the research stage of the project. These qanats were ideal for the research project as they possessed sufficiently clear satellite images to enable the desired measurements. This particular region had already been marked by Costa and Wilkinson, but one of the aims was to analyse this particular area in more depth.

In total, 10 different qanats were able to be located and measured. The characteristics that were recorded were taken to be quantifiable in a manner that could be used for comparison between qanats. These measurements were taken using the ruler and path functions of Google Earth and required the measurements to be taken manually by an individual. The measurements were made to half a meter, this is because as of now, a pixel on Google Earth represents as small as 0.41m, as such to have any measurement made with a precision of below half a meter is unrealistic. All the measurements made in the appendix were noted as they were measured but they should only be considered to be accurate to half a meter. The characteristics which were measured were: the diameter of each shaft, the width of the spoil heap rim that would form around the shaft, the interval between shaft edge, the total length of the qanat system, the number of shafts and finally also the qualitative characteristic of whether the qanat was still visible, with additional notes on the probable date and reason of it disappearance. Qanats were measured at different Google Earth dates, depending on when they were the most visible and easiest to measure. The qanats were named and ordered in the order they were located, thus Qanat 1 is the one located first and Qanat 10 is the last one found in the area.

Qanats 6 and 7 were of particular interest. When looking at the satellite imagery, they were initially considered to be from the same qanat system. However two aspects made it important to differentiate them. Firstly, when looking at the most recent Google Earth imagery of these two qanat systems, only Qanat 7 has disappeared from the landscape.

Furthermore, Qanat 7 had a slightly different orientation to Qanat 6 which suggested that these two systems were in fact different.

There are several reasons why the particular characteristics mentioned above were selected. The characteristic of the shaft diameter was chosen as a way to examine whether there was a relation between shaft holes and the construction technique of a qanat, and whether a consistent or uniform hole size for the shafts of a single qanat was apparent, which would enable to compare and distinguish different qanats: if the shafts of one qanat did not relate to those of the other qanats in a consistent manner, then it could be argued that the qanats could have been built by another group or at another point in time. It could also provide information as to the type of sediment that the qanat was built in.

A similar reasoning led to the choice of spoil heap rim width: if there was a consistent measurement for a single qanat that differed between qanats, it could be argued that they were either made by different groups or during a different time period. It might also provide information concerning the construction methods that were used in building the qanat such as the type of material used or if any notable building techniques were used. The spoil heap also provides insight into the depth of each shaft and their diameter, as a larger spoil heap indicates more was dug out from the shaft. Furthermore, it could also indicate the relative age of a shaft, as older shafts will have their spoil heap erode over time. However, it is important to note that this remains speculative when using satellite imagery alone, as there are many natural and anthropogenic factors that could have impacted the size of the spoil heaps.

The gap between each spoil heap was calculated to analyse whether qanats had a consistent construction technique, and again also to see whether it could be used to relate or differentiate qanats from one another.

The total number of shafts and the total length of one system was recorded with the intention of having a general size comparison between qanats. However, the total length was based on what was visible through the imagery and therefore is not necessarily representative of the qanat system in its entirety.

The present-day visibility of the qanat was studied in order to see if future research could be done at the location of these qanats, as well as to digitally preserve the memory of the qanats that have disappeared. In addition to this, notes were made on the date of the disappearance on what the reason for the disappearance is believed to be.

3.3. Approaches and Limitations

There were several limitations to the way the research was carried out, which was due to the limitations of the Google Earth program (software or imagery) or the fact that the measurements were carried out manually, needing to factor in human error. Regarding the limitations of Google Earth, even though the features that showed the presence of past qanats were clearly visible, it was not always possible to see detailed images of important characteristics. Whether due to the image quality or because the qanats had faded into the landscape, sometimes characteristics that were intended to be measured could not be found. This might be the spoil heap rims or occasionally entire shafts that were unable to be measured. In the case of the shafts being missing, a problem arose as despite only a few of them being missing, this would largely affect the gap measurements of the qanat in question. As such, this made it more difficult to pursue the original goal of measuring the gaps between shafts to see if there was some sort of consistency in the construction of these qanats.

Despite this setback, there are still enough gap measurements that this avenue of research is still worth exploring, although any result obtained from such measurements must be very carefully considered, due to the previously mentioned shortcomings. Regarding the missing spoil heaps, that also caused an issue as four of the ten qanat systems were not clear enough to gather spoil heap data for. This therefore limited the utility of making these spoil heap rim measurements. Additionally, when using solely satellite imagery it becomes difficult to study natural or anthropogenic factors that could have caused changes in these systems as only sight can be relied upon when using satellite imagery. This is something to be wary of when drawing any sort of conclusion from the data. Another limitation posed by Google Earth is related to the dates of disappearance which were attempted to be recorded. The earliest date from which these qanat systems would have disappeared and not be present in the landscape anymore has been marked, however this date cannot be considered 100% accurate. This is due to the fact that rather than having the actual date on which the qanat disappeared, only the date where Google Earth first took an image after the qanat system had disappeared is available. This however does not affect the results significantly.

Moving onto human limitations, there is the problem of human error. Because all of these measurements were done manually by a human looking and measuring qanats on a screen using Google Earth software, there are bound to be errors present in the measurements. Even when zooming in to get a clear picture of a spoil heap rim's edge or a shaft, it will eventually become so pixelated that the human eye will have difficulty differentiating the different characteristics. As such, the measurements are only approximate though the margins of error are minor (within pixel precision). This problem could have been fixed using an automated program such as those discussed in chapter 2. However the primary advantage of doing everything manually is that it avoids the occurence of false positives which can obscure the data.

From this, it can be evaluated that the methods used, while not absolutely accurate due to the human factor involved and the limitations of Google Earth, are still adequate to produce valid, workable results. The human error was minimal, especially when considering the small research area of only 10 qanat systems, while the program limitations are mitigated by having multiple measurements that lead to the same information. The conversion of raw raster datasets to human-readable images will always lead to a certain loss of information (Verschoof-van der Vaart and Landauer 2021, 151). This is something that must be taken into account when using satellite imagery or any kind of remote sensing technique.

The methods used in this thesis have been proven to be effective in the past. Remote sensing as a whole is a valuable tool when studying any kind of archaeological object due to the implications of being able to study something without at all physically altering it. In the case of this thesis, satellite imagery was a well suited approach to studying qanats. This is because they represent a landscape feature that sometimes is difficult to see on the ground since it has no consistently associated artefacts, which means getting an entire view of the landscape makes them easier to spot with little information is missed in comparison to on the ground. Google Earth is an easy open access tool to use, which also made it a good fit for this research. Due to the limitations of Google Earth and the physical condition some of these qanats were in, drawbacks were suffered with two of the intended measurements, that of the width of the rim and the gaps between the shafts. These measurements could not be used with complete trust in any conclusions drawn from their use. However, these two measurements are not absolutely essential to the research aim of trying to distinguish qanats by their physical characteristics as seen from space: other measurements such as shaft diameter could in principle also be used. It is still important to present the results of all the measurements which were performed, including the compromised ones, as will be done in the next part, as it is interesting to see if any insights can be drawn from them.

4. Results

This section presents the numerical and other data which was collected for the qanats which were studied. Table 1 below summarizes these data, listing the average shaft diameter, rim heap width (were applicable) and shaft gap for each of the ten qanats, together with their respective standard deviations in parenthesis. The table also includes additional information, such as whether the qanat is still visible and the date of its disappearance if not. The map of Figure 8 below shows the location of each qanat. Following that, there will be a more in-depth overview of each individual qanat. Additional information that could help clarify the results will be added, as well as any missing details.

Table 1: Summary of data gathered from all 10 qanats

Qanat Number	**Qanat 1**	**Qanat 2**	**Qanat 3**	**Qanat 4**	**Qanat 5**	**Qanat 6**	**Qanat 7**	**Qanat 8**	**Qanat 9**	**Qanat 10**
Shaft diameter (m)	11 (2.5)	8.5 (1)	11.5 (2)	10 (2.5)	8 (2.5)	8.5 (2)	10.5 (1)	11(2.5)	9.5 (1)	12 (2.5)
SH Rim Width (m)	Not clear enough	Not clear enough	Not clear enough	3 (0.5)	3 (1)	3 (0.5)	3 (0.5)	3 (0.5)	Not clear enough	Not clear enough
Shaft Gap (m)	8 (2.5)	10 (2)	4 (1.5)	9 (3)	8 (4)	8 (2)	15.5 (3)	17.5 (3)	6 (2.5)	22.5 (11)
Total Length (m)	372	164	395	681	611	930	108	172	224	176
Number of visible Shafts	20	9	19	33	24	48	5	6	11	4
Still visible ?	No	Yes	Partial	Partial	Yes	Yes	No	No	No	Yes
Date of Disappearance	15/04/2013	-	-	-	-	-	30/10/2016	20/06/2016	20/06/2016	-
Additional Notes	Built over constr.		Built over partial.	Built over constr.				Built over constr	Built over constr	Barely visible
	Road		House	Road				Road	Road	Only traces

Figure 8: Map showing the 10 qanat systems in the research area, all numbered correspondingly

In this first table, there are a few details that should be clarified. Firstly all numbers shown are marked in meters (m) and rounded off to the half meter, for reasons explained before. Additionally, as already mentioned, the measurements in the first three rows show the mean and in parentheses the standard deviation for each qanat. The standard deviation provides an indication of the variability of the individual shaft measurements for a given qanat. In the second row, the abbreviation 'SH' stands for Spoil Heap, while 'Not clear enough' was used in the row whenever the width of the spoil heap rim could not be identified as it was not clear enough. In the "Still visible?" row there are 3 possible markings: "yes", "no" or "partial". "Yes" means that the qanat system is still visible in the most recent images of Google Earth, "No" means that the qanat system is no longer visible in the most recent images of Google Earth and finally "Partial" means that some of the qanat system is still visible in the most recent images of Google Earth but not in its entirety. An "-" entry in the "Date of Disappearance"-row means that the corresponding qanats has not yet faded away from the landscape. The final row, marked "Additional Notes", is intended to record anything that was deemed of interest concerning the disappearance of the qanat system or the general state of the qanat.

The results for each row varied in efficacy to study qanats. As previously mentioned, the measured shaft diameter does not necessarily represent the original diameter of the shafts, as these have most likely collapsed over the years. Measurements of the width of the spoil heap rim met with varying success, for even though consistent measurements were obtained for the shafts for which this width could be measured, the measurement itself was not always available. The shaft gap was difficult to measure consistently as some qanat shafts had completely faded into the landscape over time, thus making some of these distances between gaps appear larger than they are in reality. It is important to be aware of these issues when interpreting the measurements, in order to avoid basing any later conclusions on possible inaccuracies in the data. As for the shaft diameter and the total number of shafts, these two categories were not as useful as anticipated, again because certain shafts and thus certain parts of the systems were no longer visible. As a result, an accurate reading on the entirety of a qanat system was not possible. Both the date of disappearance and a qanat's visibility in the landscape are useful data to monitor these systems and preserve their place in the landscape. The next section will provide an overview for each individual qanat.

4.1. Qanat Results

The tables recording the measurements for each individual qanat can be found in the appendix, and are numbered as Appendix 11 - 20, Appendix 1-10 being some aerial photos of the qanats. The numbers recorded there are the ones as provided by Google Earth software to dm-precision, but for the discussion below they have been rounded off to 5 dm to take into account pixel size (see the discussion on page 23 of section 3.2)

As regards the average shaft diameters found in this thesis, it is interesting to note that they tend to be relatively large, ranging anywhere from 8 - 12 m, and therefore much larger than the average shaft diameter of 1 to 2 meters reported for example in (Beaumont, 1971, 40). This brings up questions as to the validity of the results reported here. This difference can however could be explained by the fact that these shafts date back to the Islamic period and have most likely collapsed inwards on themselves, thus creating larger shaft holes. Another possibility is concerning the terrain in which these qanats were made. The ground in Sohar consists of cobbles, gravel and sand which is less stable thus perhaps necessitating larger shaft holes or continued maintenance on the collapse of these shafts holes. This would also explain why we can still observe a spoil heap rim despite these shafts having collapsed.

4.1.1. Qanat 1

This first qanat has a total of 20 identified shafts and a total length of 372 meters. All measurements were made using the imagery collected by Google Earth on 27/5/2009. The shaft diameter had a range of 6,5 - 15 meters and the shaft gap a range of 4 - 12,5 meters. A measurement on the spoil heap rims was unavailable as these were not clear enough to get reasonable lengths. The qanat is no longer visible from Google Earth starting from 15/04/2013. The reason for this appears to be that a new roundabout was built just over where the qanat was located.

4.1.2. Qanat 2

Qanat 2 is a smaller feature, comprising just 9 different shafts with a total length of 164 meters. All measurements were made using the imagery collected by Google Earth on 27/5/2009. The length varies between 7- 9,5 meters, with the gap ranging from 7 - 14 meters. As with the previous qanat, a measurement of spoil heap rims was unavailable. However, the qanat is still visible in present-day when using Google Earth.

4.1.3. Qanat 3

Qanat 3 has 19 shafts in total and a length of 395 meters (m). All measurements were made using the imagery collected by Google Earth on 27/5/2009. The shaft diameter varies from 8 - 14,5 m, while the gap length varies from 2,5 - 7,5 m. In this qanat there were some shafts that were too faded out leaving large gaps between shafts. As a result, some measurements were left out as it would have made too much of an inconsistent impact on the average gaps. Measurements for the spoil heap rims were not clear enough on the imagery to record. This qanat was partially built over by a house, however most of the qanat is still visible.

4.1.4. Qanat 4

Qanat 4 has 33 shafts and a total length of 681 m. All measurements were made using the imagery collected by Google Earth on 27/12/2010. The shaft diameter ranges from 4,5 - 15 m and the gap varies from 6 - 14 m. Measurements from some of the spoil heap rims were available and ranged from 2 - 4 m. There was a gap that could not be measured due to the fact that some of the shafts had faded into the landscape. The qanat has been partially built over by a road.

4.1.5. Qanat 5

Qanat 5 has 24 shafts and a total length of 611 m. All measurements were made using the imagery collected by Google Earth on 27/12/2010. The shaft diameter varies from 4,5 - 13,5 m and the gap length varies from 3 - 10 m. Some distinguishable spoil heap rims were available and ranged from 1,5 - 4,5 m. There were some gaps that could not be measured due to the previously mentioned circumstances. The qanat is still visible in Google Earth's most recent images.

4.1.6. Qanat 6

Qanat 6 is the largest qanat that was found and the best preserved, with 48 visible shafts and a total length of 930 m. All measurements were made using the imagery collected by Google Earth on 27/12/2010. The shaft diameter varies from 5 - 14 m and the gap measurements range from 3 - 12,5 m. The spoil heaps were also well visible and ranged from 1,5 - 4,5 m. The qanat can still be seen in present-day from Google Earth.

4.1.7. Qanat 7

Qanat 7 has only 5 shafts in total with a length of 108 m. All measurements were made using the imagery collected by Google Earth on 27/12/2010. The length varies from 10 - 11,5 m. Spoil heap rims were also present and ranged from 3 - 4 m. This qanat is no longer visible, having completely faded away from the landscape and was last visible on Google Earth on 30/10/2016, however there is no clear reason as to why it disappeared from sight.

4.1.8. Qanat 8

Qanat 8 has 6 shafts and a total length of 172 m. All measurements were made using the imagery collected by Google Earth on 27/12/2010. The shaft diameter is between 7,5 - 14,5 m and the gap varies from 14,5 - 22,5. Rims were also present ranging from 2,5 - 4 m. The qanat is no longer visible and was last seen on Google Earth on 20/06/2016, due to the fact that it has been built over by a road.

4.1.9. Qanat 9

Qanat 9 has 11 shafts for a total length of 224 m. All measurements were made using the imagery collected by Google Earth on 27/12/2010. The shaft diameter is between 8,5 - 11 m and the gap varies from 4,5 - 12 . The rims were not clear enough to make a defined measurement. The qanat is no longer visible and was last seen on Google Earth on 20/06/2016, the same date as the previous qanat, due to the fact that it was also built over by a road.

4.1.10. Qanat 10

Lastly, Qanat 10 has 4 shafts and is the smallest of the 10 qanats, with a total length of 176 m. All measurements were made using the imagery collected by Google Earth on 27/12/2010. The shaft diameter varies from 9 - 14,5 m and the gap length ranges from 10 - 30. The spoil heap rims were not clear enough to measure. The qanat is still present but is starting to fade away, leaving only partial visible shafts the last time Google Earth took an image of the area.

4.2. The positioning of the qanats

This section goes over the orientation of certain qanats relative to others, as this is important for the analysis later on. Specifically, this concerns Qanats 4 through 8, as these are the qanats that crossover or are present alongside one another. Qanats 1, 2, 3, 9 and 10 do not present such characteristics, and as such they will be left out of this part. At the very end of what is visible from Qanat 4, on the most Eastern point of the qanat, it overlaps with Qanat 5, as can be seen in Figure 9. Qanat 4 also runs parallel to Qanat 6, and at the most southwestern point of Qanat 4, it can be seen overlapping with Qanat 8, as shown in Figure 10. Finally, Qanat 6 runs parallel to Qanat 7 which can be seen at the most Southwestern point of Qanat 6, see Figure 11.

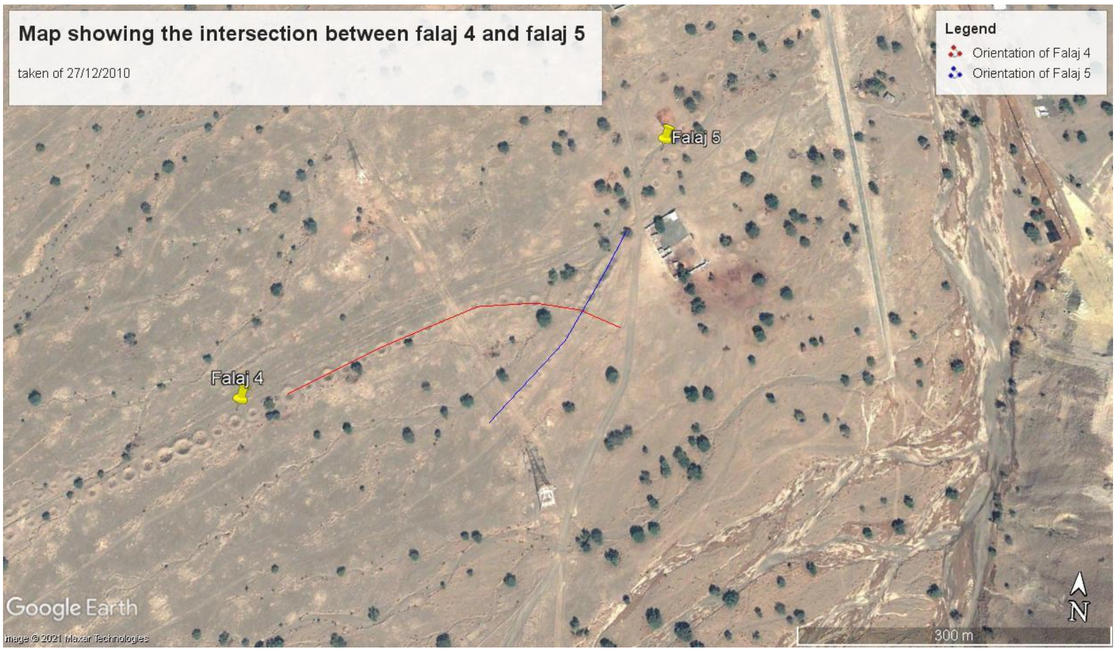


Figure 9: Map showing the intersection between Qanat 4 and Qanat 5, taken through Google Earth.

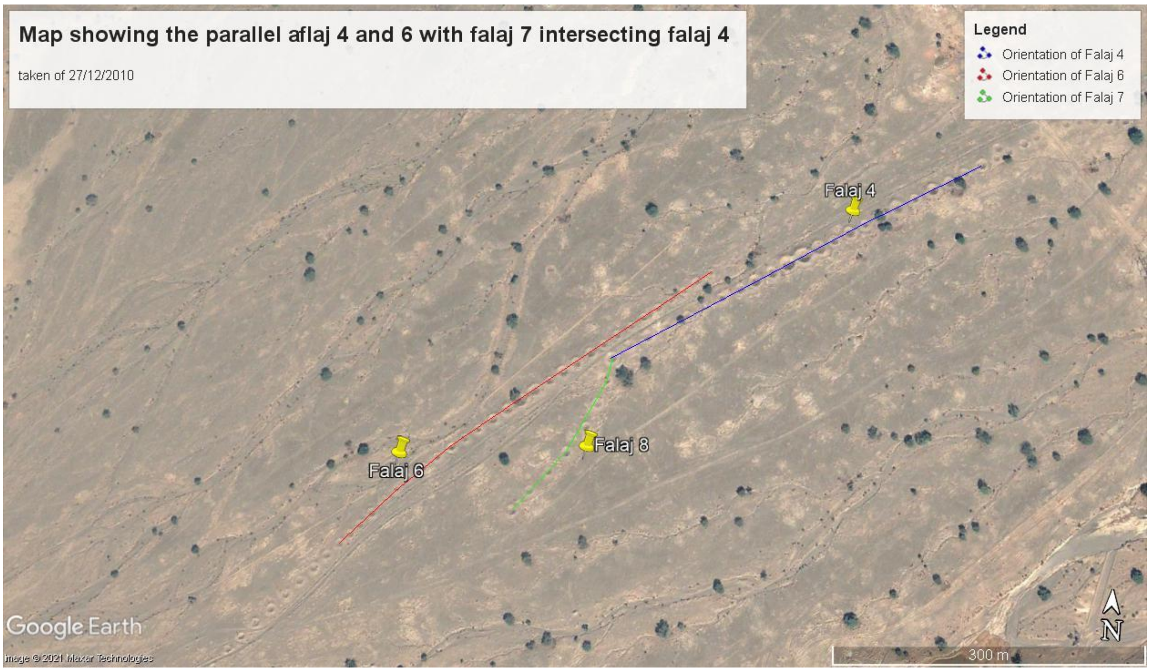


Figure 10: Map showing the parallel between Qanats 4 and 6 with Qanat 8 intersecting Qanat 4, taken through Google Earth

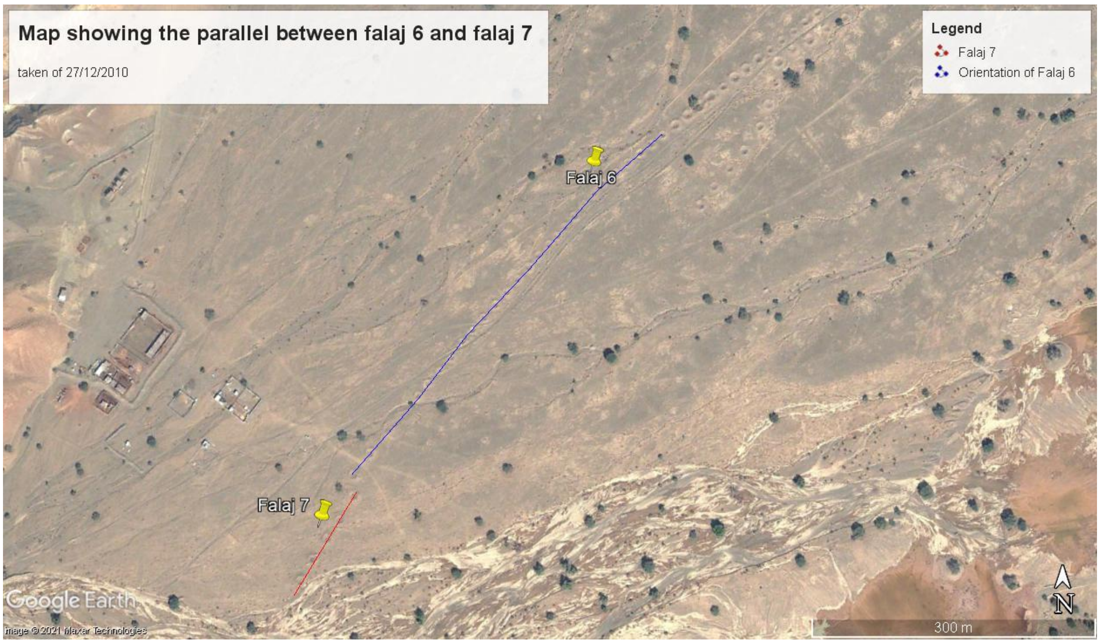


Figure 11: Map showing the parallel between Qanat 6 and Qanat 7, taken through Google Earth

5. Discussion

Now that the results have been presented, they will be analyzed in this section and it will be determined whether, and if so, how, they can be used to deduce useful information about the qanats which were studied. .

Information was collected on different proportions of each qanat shaft and on entire visible qanat systems using Google Earth. The original goal for these measurements was to analyse whether sufficiently consistent measurements could be performed for each qanat for the different qanat systems to be comparable based on such data. These data are summarised in Tables 2 - 4 in the form of bar charts for the mean shaft diameters, shaft gaps and spoil heap rims. However, once the results are reviewed, this goal appears unlikely. On average, the shaft diameter varies from 8 - 12 meters (see Table 2), with only a variation of 4 meters in the most extreme of cases and mostly amounting to a variation of 2 meters between qanat systems. This therefore makes differentiation between these qanats based on average shaft diameter an unreliable method, especially when standard deviations are taken into account. For example, for qanats 1, 3, 4, 7, 8, 9 and 10 the difference between average diameters is smaller than the largest of the two standard deviations. The variability of diameters within any of these qanats is therefore bigger than the difference between the averages, implying that these averages cannot be used to distinguish between them. Similarly, the biggest difference in average shaft diameter, 4m for qanats 2 and 10, is of the same order as the sum of their respective standard deviations (1 + 2.5 = 3.5).

A similar reasoning can be employed for the spoil heap rim measurements, which only range from 3 - 3,5 m (see Table 3). The shaft gap is the measurement with the most variation, ranging from 4 to 22,5 m(see Table 4), but as aforementioned, these measurements are not reliable due to not all shafts being visible, leading to a certain degree of error. Even though the shafts may have collapsed, because of their similar average diameters, it is likely that they previously had similar sizes back when they were intact. It would then be interesting to compare this group of qanats to other areas in Oman, or the Near East as a whole. In the research done by Costa and Wilkinson, the qanats in the research area were all found to be dating back to different times of the Late Islamic period (1500-1750 CE), with some being abandoned more recently, and others having been abandoned some time ago (Costa and Wilkinson 1987, 60). In their research, they identified 3 feeder channels that all fed water to the same settlement and garden. As stated, they all dated back to different times during the Late Islamic period (1500-1750 CE), with the one being the longest abandoned noted as “I_2”, a more recently abandoned channel being noted as “I_3” and one that was still in use at the time of Costa and Wilkinson’s research being noted as “I_1”(Costa and Wilkinson 1987, 60). From this information, it is possible that these qanats would have been rebuilt over time in order to gain access to the same water supply.

Table 2: Graph comparing the shaft diameter between each qanat

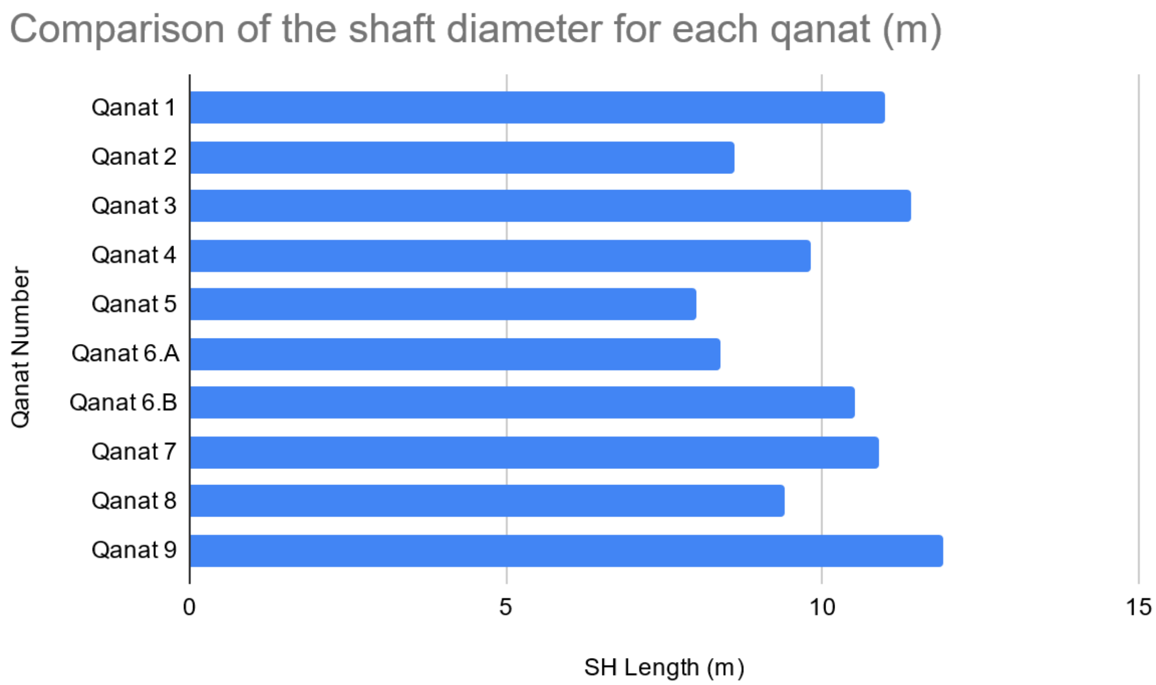


Table 3: Graph comparing the spoil heap rim between each qanat

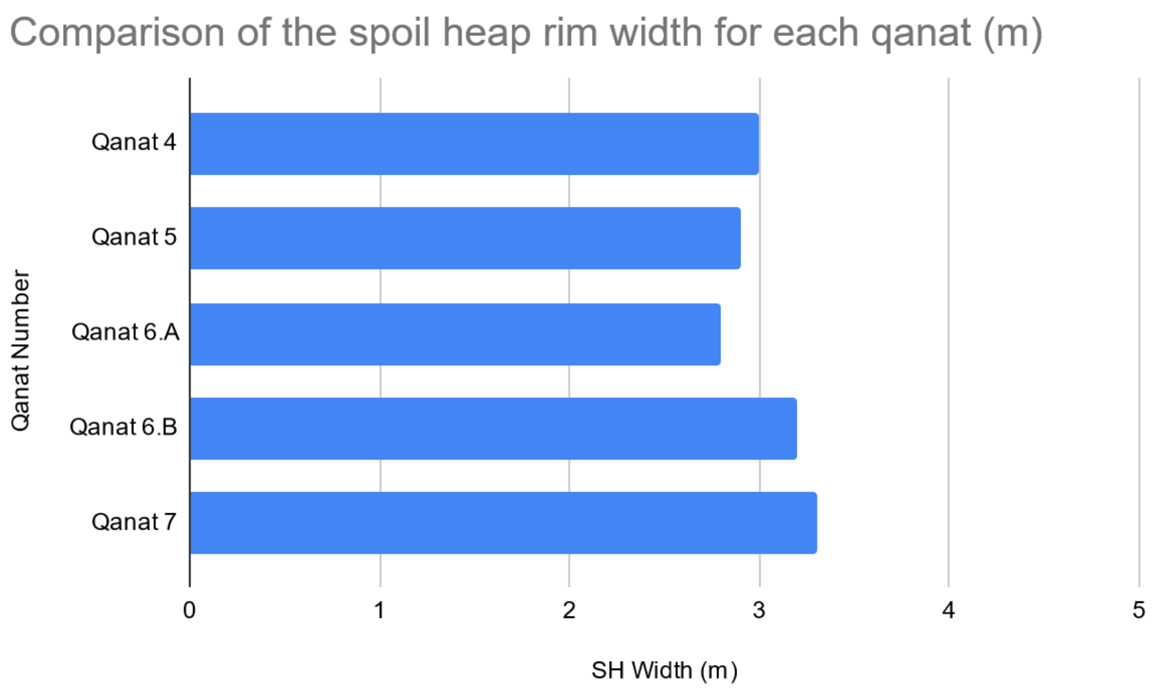
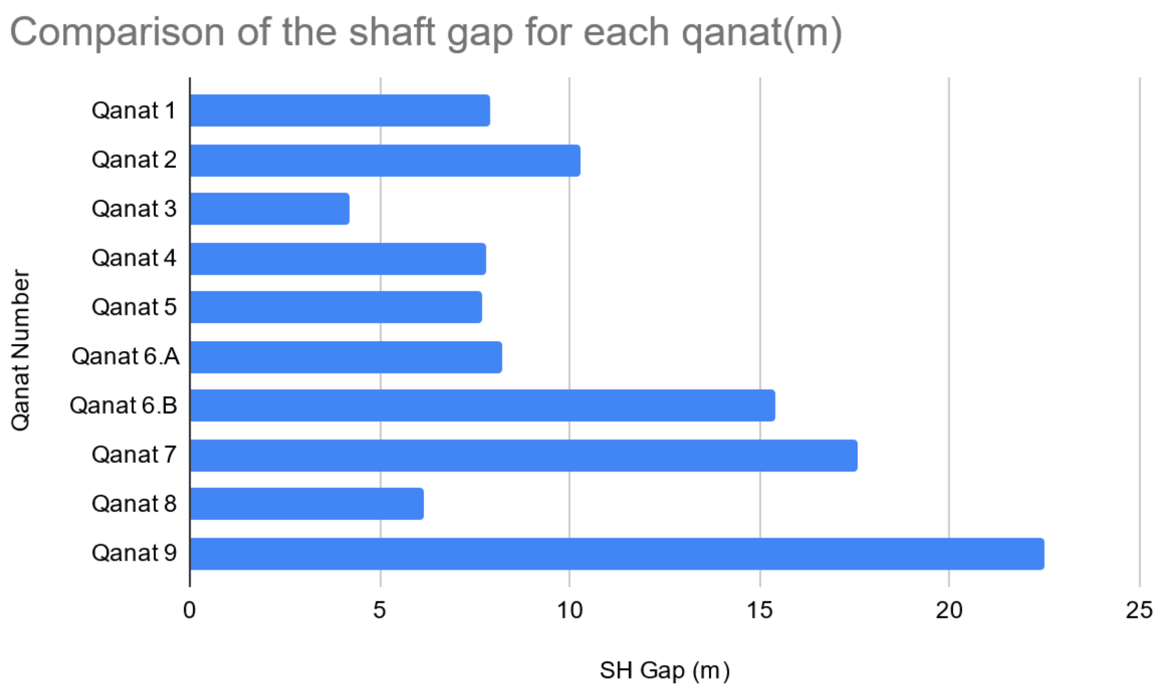


Table 4: Graph comparing the shaft gap between each qanat



The positioning of the different qanats and the clarity with which the systems can be seen (as discussed in chapter 4) can also play an important role, as it helps provide information on the relative dating of these systems. While finding a precise date using satellite imagery from Google Earth is not possible, there are ways to chronologically date these systems relative to one another. To begin, it is important to observe the positioning of Qanats 4, 5, 6, 7 and 8. Qanat 5 cuts above Qanat 4, and therefore by employing the law of superposition, it can be confirmed that Qanat 5 is more recent than Qanat 4. Qanat 4 also appears to be above Qanat 8, and as such it is likely that Qanat 8 is older than Qanat 4. Qanat 4 and 6 run alongside one another; logically speaking, there would be no reason for two parallel qanats to be active at the same time, and as such, there has to be a difference in dating. Qanat 6 is a more complete qanat showing a large part of the system, whereas Qanat 4 can already be seen to start fading away at its most Eastern point. It can therefore be deduced that Qanat 4 is older than Qanat 6. Finally, Qanat 6 and 7 are again parallel to one another. However Qanat 7 appears more faded than Qanat 6, suggesting that Qanat 7 is older.

Regarding the qanats for which spoil heap rim measurements were unable to be taken (Qanats 1,2,3,9 and 10), it is worth noting that their spoil heap rims are likely to be older than those of the qanats with visible spoil heap rims (Qanats 4,5,6,7 and 8). This is because these spoil heap rims were difficult to distinguish in the landscape from satellite imagery, indicating that they were more eroded and hence more ancient. There are no indications of human interference on these systems (which might have been another explanation for the missing spoil heaps) that can be spotted from satellite imagery. Qanats that do not have spoil heap rim measurements therefore will be assumed to date back further than the qanat systems for which spoil heap rim readings were able to be taken.

From these observations, the following tentative relative dating of these qanat systems is formed: Qanats 1, 2, 3, 9 and 10 are the older systems, with no way to differentiate the dating between each one. Qanat 8 is the oldest of the remaining qanats, followed by Qanats 4 and 7, while the most recent qanats are Qanat 5 and 6. This timeline is summarised in Figure 12. There is no way to see an age difference between Qanat 4/7 and Qanat ⅚. All of this has been visualised in Figure 13. If the work by Costa and Wilkinson is referred to, it is possible that qanats would date back to the Late Islamic period (1500-1750 CE) (Costa and Wilkinson 1987, 60).
Although satellite imagery can provide some insight into how these systems are dated relative to one another, it is impossible to use it to provide specific dates or to estimate the amount of time that has passed between the different systems. If this relative timeline is compared to the dating done by Costa and Wilkinson, in which they made out 3 different

feeder channels of varying ages then Qanat 1, 2, 3, 9, 10 would be a part of “I_2”, Qanat 4 and 7 would have been a part of “I_3” and lastly, Qanat 5 and 6 would have been a part of “I_1”. With the knowledge that Qanat 8 was more recent than the qanat from the oldest period but younger than Qanat 4 and 7, it is difficult to place it in either “I_2” or “I_3”, and as such it is better to leave it out of this comparison.

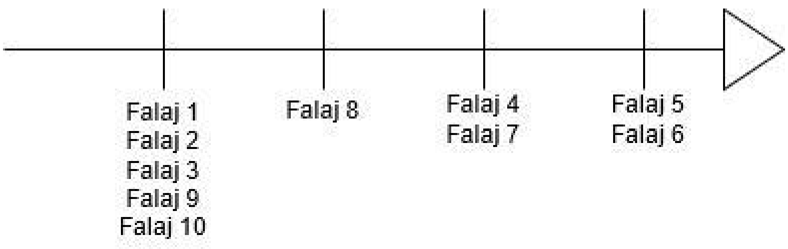


Figure 12: Relative timeline of the qanats

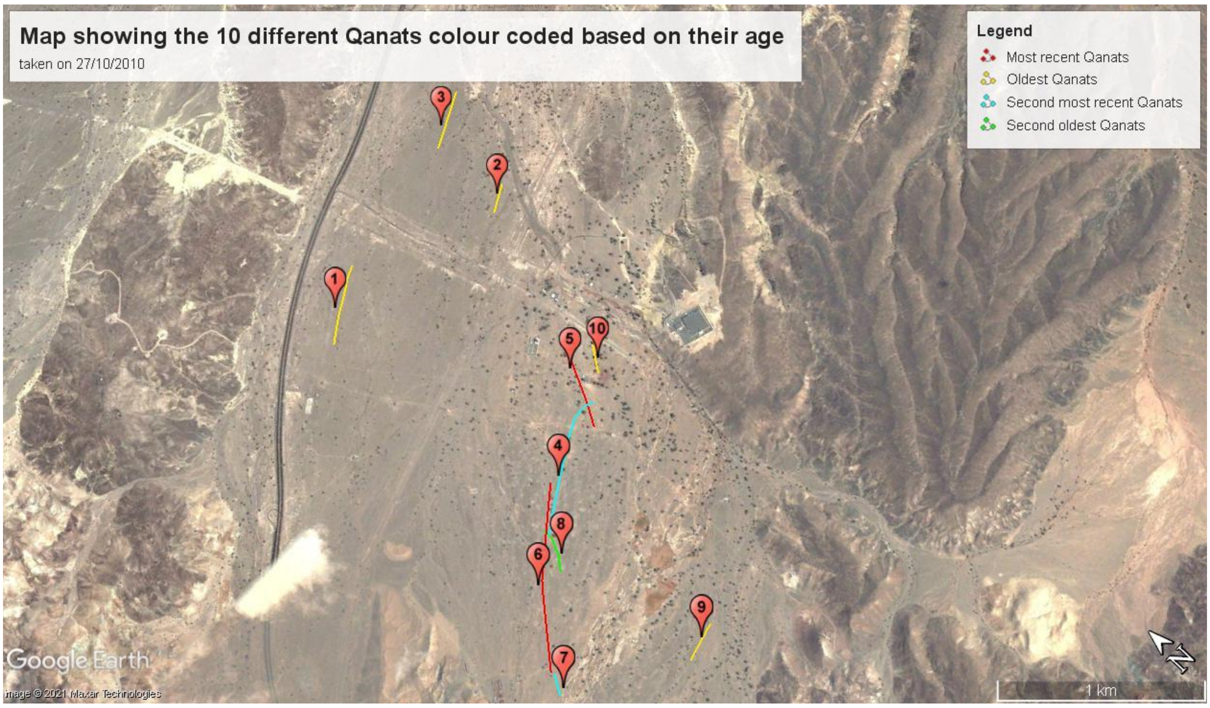


Figure 13: Map Showing the 10 different qanats organised according to where they stand on the relative timeline

From the results presented it can be seen that there are a number of problems that arose with the remote sensing method used, notably that of measurements not necessarily being complete or leading to the desired information. Nonetheless, valuable information was still found for the qanats in general, along with a relative dating system. When comparing remote sensing tools, it is obvious that there are some with a higher performance than satellite imagery such as LiDAR or using pictures taken by drones at a lower altitude which can provide the user with more accurate detail. However, considering the scale and scope of the project, satellite imagery was adequate for the qanat shaft measurements the thesis set out to do. Lastly, it is important to note that it is unlikely that the full irrigation system was able to be studied. This is because parts of the systems are not visible in the landscape, bearing in mind that these qanats are underground irrigation systems and therefore not everything can be discovered simply from above-ground remote sensing. Additionally, this research only focused on one part of qanats, the part marked by the vertical shafts.

Despite its shortcomings, satellite imagery nevertheless allowed to gather some important information on the qanat systems which were studied. Firstly, it allowed for gathering data on the dimensions of qanat shafts and the qanat shaft system as a whole, and provided a clear picture of the visible part of each qanat. Satellite imagery also provided information concerning the orientation and position of these irrigation systems in the landscape, which facilitated the creation of a relative timeline of the different systems, by comparing the positioning and how clearly an irrigation system could be seen in the landscape. Lastly, satellite imagery offers a means of monitoring these archaeological features across time using tGoogle Earth's time function, which permits the preservation of images of qanats across time, and shows whether they are still preserved in the landscape to this day or have disappeared.

There were, however, some disadvantages to using satellite imagery. Firstly, as the measurements were taken manually, it naturally creates a source of error, thus not every measurement can be accepted as being completely consistent or accurate no matter how carefully they are taken. Secondly, the timeline that was created for these irrigation systems was only a relative one. As a result, there are no precise dates for any of the qanats, and it is impossible to deduce the distance in time between two qanats using solely on satellite imagery. Lastly, the measurements of the diameter of each qanat shaft was skewed, due to the shafts being old and collapsing, making them appear bigger than they actually are when they were in use.

With the data gathered on the different measurements, position and degree of preservation for each qanat, these different systems can be categorised based on date The dating is possible due to their position and degree of preservation. Whilst the measurements of these qanats did not give us as much information as anticipated it did show that in this aspect the qanats were quite similar to one another. Assuming that the data can serve to categorize these qanat systems and given that the measurements of shaft diameters are quite close alongside the previous research of Costa and Wilkinson, it is possible that these systems were made by a same group of people living in the area over multiple periods.

These findings are important as they provide new data on a previously researched area from several decades ago. They also prove the utility of satellite imagery in gathering information concerning qanats, as both a relative dating timeline and a data range were created from the findings. The data range created could be used to look at other concentrations of qanats in Oman, in order to see if similar results are shown thus potentially demonstrating a cultural tie to the way qanats are made in Oman. This research therefore aids in updating the work done by Costa and Wilkinson by using satellite imagery.

It is interesting to observe what was achieved in this research with satellite imagery, and compare it to the possibilities offered by other forms of remote sensing. There are two other techniques in particular that could produce interesting results when compared to satellite imagery, techniques that could possibly counterbalance its drawbacks. These two techniques are aerial photography and LiDAR. In the case of aerial photography, this is mainly done by taking pictures above the ground with an overhead or,in more recent times, by using drones (Hadjimitsis et al 2013, 57). This becomes an advantage when detail is required for pictures, allowing for measurements to be made with greater precision, while the oblique pictures can offer alternative angles from which other features may appear more clearly. However, there are of course separate limitations; aerial photography cannot cover the same area as satellite imagery and requires specific actions to be taken that are not necessary when using satellite imagery, for example manual programming. LiDAR is another, more modern, remote sensing technique, which uses lasers to calculate the time it takes for a laser to go from the machine to the ground and back, and subsequently using that calculation to produce a precise 3D map (Simon Crutchley 2018, 1). The advantages of LiDAR are that it goes through foliage, thus removing any interference that may occur when looking at a normal satellite image. It is also an extremely precise method, thanks to the pinpoint accuracy of the lasers used. The primary disadvantage, however, of LiDAR is its high cost, which makes it inaccessible to those with smaller research budgets.

In a broader academic context, the present research contributes to the body of knowledge on irrigation systems in the region surrounding Sohar by providing a more detailed view on qanat systems in part of the research area studied by Costa and Wilkinson. Additionally, when compared to similar and recent studies on qanat irrigation detection such as those by Lei Luo et al. and Mernoush Souroush et al., the advantages and disadvantages of using satellite imagery manually become clearer. Despite a smaller number of qanat systems having been detected than would have been possible with automatic remote sensing, quantitative and also qualitative aspects of these systems that would have otherwise been passed over by an automatic process were able to be recorded and analysed. The qualitative aspects of these qanat systems helped create a relative timeline and associate this research to that of Costa and Wilkinson. It is therefore important to still have a manual process in satellite imagery to observe the qualitative aspects of qanats.

Satellite imagery is an essential tool in archaeology and is well suited to the study of irrigation systems, despite presenting some limitations. It must be noted that this is only one method to study irrigation systems and no tool is perfect on its own, particularly in a multidisciplinary subject like archaeology, and therefore satellite imagery must be used in tandem with other practices in order to work effectively. It allows for the gathering of data concerning measurements and aids in the dating of these systems. Satellite imagery also allows to monitor existing features and keep a record of features that have disappeared from the landscape, making these to some extent still accessible for quantitative study.

6. Conclusion

This thesis aims to study the reliability of satellite imagery in archaeology when used for the study of irrigation systems known as qanats present in the area around Sohar, Oman. Previous research in this area by Costa and Wilkinson identified the qanats to be dating back to the Late Islamic period (1500-1750 CE), and showed how important qanat systems were to the functionality of the region. Their research however was more of a general overview of the area. Other studies using satellite imagery focused around the automation of remote sensing when studying irrigation systems, but it is arguable that on a smaller research area and for a smaller scale project, using manual methods can be just as effective. For this thesis, Google Earth was the satellite imagery tool used to gather data on 10 different qanat systems in the area next to the Wadi Suq. Some limitations arose concerning the manual recording of the data that was found and Google Earth's limits to what could be shown as there is always going to be a certain degree of error from manual recording and Google Earth image quality was not always sufficient to record all the necessary data. These issues lead to some of the measurements being compromised and not being necessarily useful to draw any kind of insights from. Despite this, the remainder of the data gathered did not have as many problems and proved useful for analysis and producing a relative timeline. Each of the four key research questions posed in the introduction will now be evaluated and discussed.

6.1. What kind of information can be obtained on qanat systems using satellite imagery?

The present research shows that satellite imagery can provide both quantitative and qualitative information concerning qanats. The quantitative information is based around the different measurable shaft features left in the landscape by the qanats. With such measurements, qanats can potentially be compared to one another. However in this case, the measurements did not allow for a clear distinction to be made between the qanats. In terms of quantitative data, satellite imagery facilitated the analysis of the orientation and positioning of these qanats, which provided the possibility of creating a relative timeline that could put the landscape and these qanats into perspective. When this research is used in tandem with the research by Costa and Wilkinson, it can be deduced that these qanats all date back to different stretches of time across the Late Islamic period (1500-1750 CE).

6.2. What are the inaccuracies that come with the information gathered?

Satellite imagery as a tool for the study of qanats can provide data concerning their visible features, for example different measurements, and data on the relative positioning of these qanats, while qualitative information can be lacking when using this type of remote sensing such as not being able to see the composition of the soil or the specific construction material of these qanats; these limitations make it all the more important to correctly interpret the obtained data. In this case, the diameter of the qanat shafts were much larger than usual due to them collapsing or due to the composition of the terrain and previous knowledge is required on these systems to be able to recognise these possibilities. There is also the possibility of the images taken by satellites not being clear enough to show the exact features of what is being studied (with limited resolution due to pixel size). This in combination with the measurements being taken manually leads to margins of errors, thus the measurements were not always taken completely accurately. Additionally, it was not possible to get any direct dating for the timeline due to the limitations of remote sensing. Therefore to gain a meaningful understanding of any archaeological landscape, remote sensing techniques work best when combined with data from fieldwork, laboratories, and archival sources (Harmon et al. 2006, 668). Moreover, it cannot exclusively be used to understand archaeological landscapes, as many anthropogenic and natural occurrences can go unnoticed when solely looking through the scope of satellite imagery.

6.3. How can the data gathered be used to identify characteristics that can help compare, categorise and date the different qanat systems ?

Originally, the intention of this research was to use the measurements of visible qanat features to date and categorise these systems. However, the measurements taken ultimately did not suffice to make such a distinction. The orientation of some of these qanats could however be used to help date them.Thus through the data it was possible to categorise these qanats through their relative age

6.4. How does this information compare to other research done concerning qanat systems in Sohar?

The research by Costa and Wilkinson had identified the qanat systems which are studied here, among others across all of Sohar. They had categorised the qanats in the research area of this thesis into three different groups: I_1, I_2 and I_3 and were able to assign each qanat to one of these three categories. Through the research done in the present thesis it was possible to associate the qanats that were found with those found by Costa and Wilkinson with those found in this thesis. This helped verify the effectiveness of satellite imagery in the study of qanats. The research done by Costa and Wilkinson was done on a much larger scale and covered more aspects than was possible in this thesis as one of the goals of this thesis was to primarily use Google Earth and examine its effectiveness as an archaeological tool. As such, whilst the present research was not able to cover to the extent of other research it was able to study some of the same aspects that would be found in other research on a smaller scale.

From the research carried out in this thesis, it can be concluded that satellite imagery can be a reliable tool that can be used in archaeology to reveal and gather information when studying qanat irrigation in the area of Sohar, Oman. It can most likely also be used in other areas as qanats as their features are not exclusive to Oman, and satellite imagery is a tool well suited to the study of these ancient systems. However, the qualitative data gathered ultimately proved to be more useful than the quantitative data. The manual remote sensing of these systems has also shown to provide good quality information as through this process it is easy to collect both quantitative and qualitative data. This data has been useful in the study of these systems

The research conducted for this thesis suggests several opportunities for future research. Regarding satellite imagery, it would be interesting to do a comparative study in the area with the same objectives in mind. However, rather than using manual remote sensing, an automated version could be employed to detect qanat shafts. This would be helpful to compare the time needed to obtain the results, as well as the quality of the data obtained. If this research was continued specifically in the same area, it could be a valuable opportunity to use other remote sensing techniques in the area to observe what results could be obtained from the same type of study and whether they counteract the disadvantages of satellite imagery. It would also be interesting to compare the group of qanats found within this area to other areas in Oman, in conjunction with in depth study of the area's historical and cultural background, in order to investigate as aforementioned whether the qanats were made by the same, local group of people and whether different areas had different methods of construction linked to different communities or cultures.

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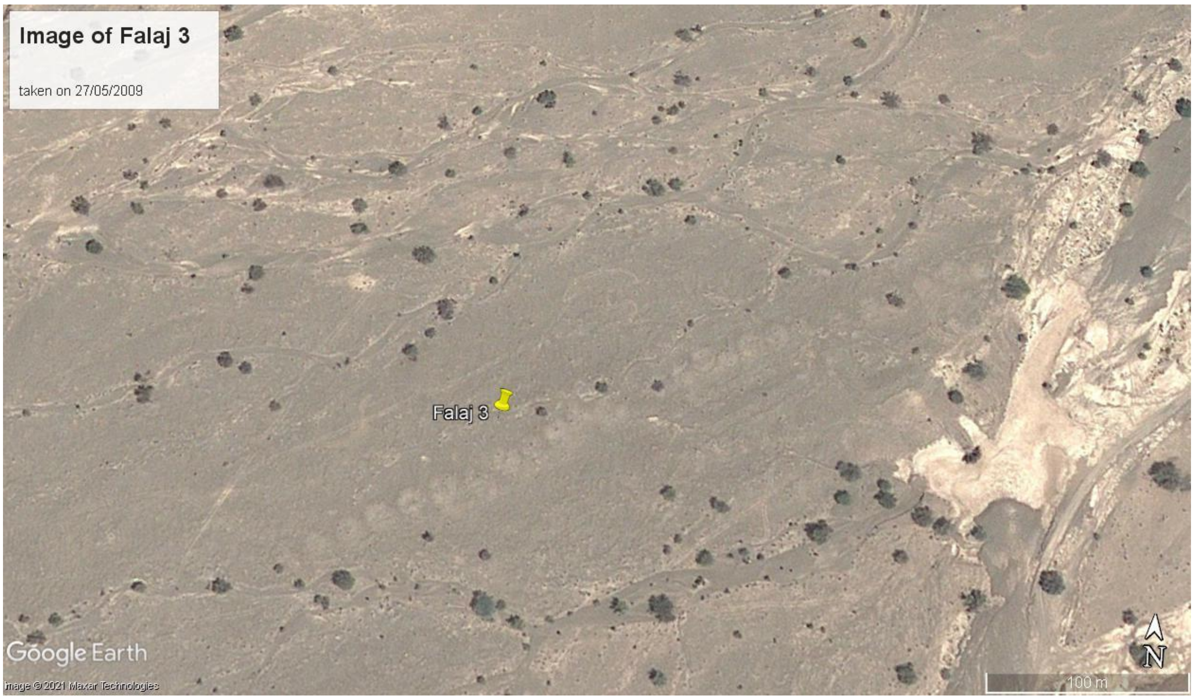
Appendices

Appendix 1: Photograph taken via Google Earth of qanat 1

Appendix 2: Photograph taken via Google Earth of qanat 2

Appendix 3: Photograph taken via Google Earth of qanat 3



Appendix 4: Photograph taken via Google Earth of qanat 4

Appendix 5: Photograph taken via Google Earth of qanat 5

Appendix 6: Photograph taken via Google Earth of qanat 6

Appendix 7: Photograph taken via Google Earth of qanat 7

Appendix 8: Photograph taken via Google Earth of qanat 8

Appendix 9: Photograph taken via Google Earth of qanat 9

Appendix 10: Photograph taken via Google Earth of qanat 10

Appendix 11: Size measurements for qanat 1

qanat 1 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
1.1	6.7	9.0	
1.2	12.0	7.9	
1.3	7.8	7.8	
1.4	13.4	6.8	
1.5	8.1	10.3	
1.6	10.7	12.5	
1.7	15.0	12.9	
1.8	11.8	7.9	
1.9	11.9	4.1	
1.10	13.5	5.6	
1.11	10.8	8.9	
1.12	12.2	4.5	
1.13	10.8	5.5	
1.14	11.7	7.5	
1.15	11.3	5.4	
1.16	9.8	7.5	
1.17	12.5	6.8	
1.18	11.1	8.6	
1.19	7.5	10.2	
1.20	7.0		

Appendix 12: Size measurements for qanat 2

qanat 2 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
2.1	7.7	11.4	
2.2	9.6	13.8	
2.3	8.7	10.9	
2.4	8.7	11.0	
2.5	9.5	7.9	
2.6	8.4	10.1	
2.7	9.6	10.1	
2.8	8.3	7.0	
2.9	7.2		

Appendix 13: Size measurements for qanat 3

qanat 3 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
3.1	12.1	7.4	
3.2	11.0	4.2	
3.3	13.5	4.0	
3.4	11.0	3.1	
3.5	14.3	3.9	
3.6	14.4	5.4	
3.7	10.5	4.1	
3.8	11.7	3.9	
3.9	11.3		
3.10	8.4	4.0	
3.11	8.1	3.4	
3.12	9.7	3.8	
3.13	11.4	3.3	
3.14	11.3	2.6	
3.15	11.8		
3.16	12.9	7.5	
3.17	9.6	4.0	
3.18	13.4	3.3	
3.19	10.2		

Appendix 14: Size measurements for qanat 4

qanat 4 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
4.1	10.1	5.6	2.5
4.2	10.6	6.1	
4.3	7.6	8.1	3.2
4.4	10.3	6.3	2.8
4.5	7.6	5.9	2.8
4.6	8.0	8.7	
4.7	5.9		
4.8	8.6	5.7	
4.9	8.3	6.3	2.4
4.10	7.0	9.9	
4.11	11.3	8.1	
4.12	9.6	6.6	
4.13	8.3	9.8	
4.14	12.5	7.7	
4.15	9.0	7.9	3.2
4.16	13.7	8.1	1.9
4.17	13.1	9.5	3.5
4.18	6.8	7.2	
4.19	11.5	7.1	
4.20	10.2	3.6	3.5
4.21	14.2	2.3	
4.22	15.0	4.3	3.1
4.23	14.0	5.9	4.2
4.24	11.0	5.2	4.0
4.25	12.3	8.9	3.5

4.26	11.5	10.0	
4.27	7.0	13.9	
4.28	4.4	14.1	
4.29	7.2		
4.30	6.7	12.9	
4.31	9.5	9.9	
4.32	9.8	9.5	
4.33	11.4		3.8

Appendix 15: Size measurements for qanat 5

qanat 5 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
5.1	8.4	4.9	1.6
5.2	5.3	6.5	1.7
5.3	4.8	8.4	1.8
5.4	5.0	6.4	
5.5	6.4	9.9	
5.6	4.6	10.0	
5.7	6.2	3.0	
5.8	10.7	2.8	4.2
5.9	11.6	2.4	3.6
5.10	7.2		2.5
5.11	13.3		2.3
5.12	11.3		4.0
5.13	7.1		2.6
5.14	6.4		
5.15	8.5	6.6	2.9
5.16	6.6	7.8	
5.17	10.9	9.9	
5.18	9.9		
5.19	7.4		
5.20	8.6	19.1	
5.21	8.8		3.9
5.22	9.6	8.6	4.6
5.23	5.1	9.3	
5.24	8.9		

Appendix 16: Size measurements for qanat 6

qanat 6 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
6.1	6.2	5.8	
6.2	5.1	6.8	
6.3	6.1	7.9	
6.4	8.0		
6.5	6.4	7.3	
6.6	6.2		
6.7	6.3	9.9	
6.8	7.0	10.9	
6.9	9.7	6.3	
6.10	8.8	8.4	2.8
6.11	7.9	10.5	3.0
6.12	8.1	9.2	3.0
6.13	7.1	10.0	3.4
6.14	6.8	8.6	2.7
6.15	9.2	7.3	3.3
6.16	10.7	6.3	4.2
6.17	12.7	5.7	4.3
6.18	10.0	7.6	3.5
6.19	8.3	7.6	3.5
6.20	12.2	3.3	3.8
6.21	14.7	5.5	3.0
6.22	9.9	6.7	3.0
6.23	9.8	8.9	2.6
6.24	8.2	9.6	2.6
6.25	8.1	7.1	3.1

6.26	7.8	9.7	3.2
6.27	8.0	8.9	2.5
6.28	8.2	12.0	3.4
6.29	6.5	7.5	2.9
6.30	7.9	7.2	2.3
6.31	9.6	8.6	
6.32	8.4	7.2	2.8
6.33	7.8	5.7	2.5
6.34	7.9	5.1	2.0
6.35	8.8	7.4	3.6
6.36	8.0	8.9	2.8
6.67	8.8	7.2	2.8
6.68	10.4	10.1	2.7
6.39	7.6	10.1	2.8
6.40	9.3	10.3	2.5
6.41	8.7	9.6	2.3
6.42	7.2		1.5
6.43	8.5	10.9	2.6
6.44	5.9	12.5	1.7
6.45	7.8	8.9	2.2
6.46	8.1		2.0
6.47	11.6		3.5
6.48	9.4		2.9

Appendix 17: Size measurements for qanat 7

qanat 7 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
7.1	9.9	19.4	4.0
7.2	10.9	13.0	2.8
7.3	10.0	15.2	2.9
7.4	10.4	14.2	3.5
7.5	11.4		

Appendix 18: Size measurements for qanat 8

qanat 8 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
8.1	14.4	14.5	3.9
8.2	10.5	22.5	3.6
8.3	12.0	17.5	3.8
8.4	7.6	17.4	2.4
8.5	10.0	16.2	2.9
8.6	11.4		3.2

Appendix 19: Size measurements for qanat 9

qanat 9 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
9.1	8.4	6.4	
9.2	10.3	4.4	
9.3	8.5		
9.4	10.8	5.1	
9.5	8.1	4.6	
9.6	9.0	6.9	
9.7	10.9	3.3	
9.8	9.8	6.5	
9.9	8.7	6.5	
9.10	8.8	11.7	
9.11	10.3		

Appendix 20: Size measurements for qanat 10

qanat 10 Measurements			
Shaft Number	Shaft diameter	Shaft Gap	Spoil Heap Rim
10.1	12.3	27.2	
10.2	14.4	30.2	
10.3	12.3	10.2	
10.4	8.8		

Appendix 21 : Standard Deviation (Screenshot taken from a separate Word document as Google Docs was unable to write down the formula)

If d_1 , … , d_N is a sequence of numerical data, for example the shaft diameters of a qanat with N being the number of shafts, their mean m is given by

$$m = \frac{d_1 + d_2 \ldots + d_N}{N}$$

and their *standard deviation s* by

$$s = \sqrt{\frac{(d_1 - m)^2 + (d_2 - m)^2 \ldots + (d_N - m)^2}{N}} \, .$$

The standard deviation s can be interpreted as the mean distance of the data to their mean m. A small standard deviation means that the data are concentrated around their mean, and a large standard deviation means the data are very spread out (see for example https://en.wikipedia.org/wiki/Standard_deviation).