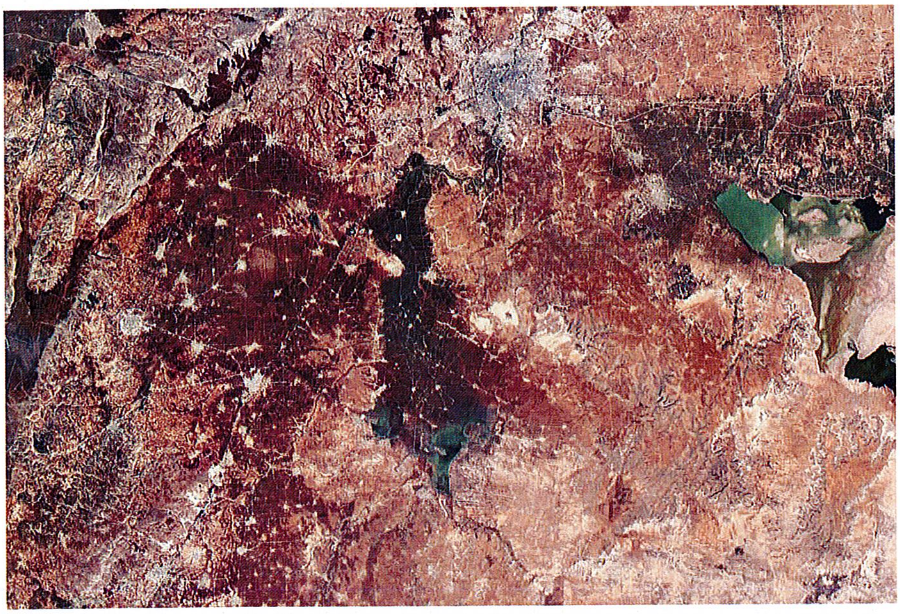
An Assessment of Wadis as Suitable for Wastewater Treatment, in a Semi-Arid Region with Limited Data Access – Aleppo, Syria



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Abstract

As a consequence of the conflict in Syria, the wastewater treatment plant in southwestern Aleppo has not been fully functioning since 2013, and wastewater is released into the Queiq River without adequate treatment. Farmers utilizing the land in the vicinity of the river have previously relied on the Queiq River water for the irrigation of their crops, now they can no longer rely on a good water quality. A Soil-Aquifer-Treatment (SAT) system, which is a managed aquifer recharge technology, would be an environmental-friendly, sustainable and cost-effective option with a low energy demand for reclaiming water quality until the wastewater plant is in commission again. SAT systems utilizes the natural filtration of water achieved by percolation through the vadose zone of permeable sediments. However, as the geology of the regions around Aleppo is mainly karstic, covered by a thin soil cover, only certain areas, such as the regions' wadis, accommodate sufficiently thick and unconsolidated sediment deposits needed for a SAT system. For this reason, an investigational study about the sedimentological nature of the wadis found in the vicinity of Aleppo has been conducted, for the intention of evaluating the possibility for introducing a SAT system into one of these.

Sammanfattning

Till följd av konflikten i Syrien har avloppsreningsverket i sydvästra Aleppo haft funktionella problem sedan 2013 och avloppsvatten släpps ut i Queiq floden utan att först genomgå en godtagbar reningsprocedur. Bönder som odlar markerna i områdena kring Queiq floden har tidigare kunnat använda flodvattnet för bevattning av sina grödor, men med den numera låga vattenkvalitén är denna vattenresurs inte längre lämplig. Ett miljövänligt, hållbart och kostnadseffektivt sätt att rena flodvatten på, tills dess att avloppsreningsverket fungerar fullgott igen, vore att använda sig av ett Soil-Aquifer-Treatment (SAT) system, vilket är en teknologi för artificiell grundvattenbildning. SAT system utnyttjar den naturliga filtrationen av vatten då det tillåts perkolera genom sediment med en relativt hög genomsläpplighet. Ett SAT system kräver alltså o-konsoliderade sedimentavlagringar för en adekvat reningsprocess, men då geologin i regionerna kring Aleppo till största del är karstisk, täckt av ett tunt jordlager, är det bara några få områden, så som regionens wadis, som uppfyller detta kravet. Där av har det i denna studie utförts en undersökning om den sedimentologiska naturen hos de wadis som finns i Aleppos närområde, i orsak av att bedöma möjligheten till att introducera ett SAT system i någon utav dessa.

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Acknowledgments

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1. Introduction

1.1 Aim and purpose

Following a request from Dresden University of Technology, this thesis has the intention to evaluate the sedimentologic and hydrogeological characteristics of wadis in the regions south of Aleppo, Syria. 'Wadi' is the Arabic term for ephemeral streams, which means that they are seasonally dry, working as drainage systems for rainwater during wet seasons (Missimer et al., 2012). The objective of the evaluation of these wadis is to assess the possibility of introducing a Soil-Aquifer-Treatment (SAT) system in this region that has suffered a decrease in water quality since the Syrian civil war.

The geology of the wider Aleppo region is mainly karstic, covered by a thin soil cover (Lucke et al., 2015). Only certain areas such as the regions' wadis, along with their associated alluvial sediments, would provide desirably unconsolidated sediment deposits that can offer a sufficient infiltration capacity for SAT. Unfortunately, there is a scarcity of sedimentological data from the region and information about wadi characteristics must be acquired from literature concerning wadis and other ephemeral streams in regions with a similar climatological and geological setting as Syria.

The aim of this study is to predict the sedimentological nature of wadi sediments found in the vicinity of Aleppo for the intention of evaluating the possibility for introducing a SAT system into one of these. The results will be based on a literature study of wadi stratigraphy and sedimentology, tectonic and climatic history of the region and through the inspection of satellite imagery and elevation data. Based on these results, areas suitable for the development of a SAT system will be designated. This is a first attempt to assess the possibility of introducing a SAT system to the region, resulting in a report that could act as a framework for further investigation in the future. The end of the report will present suggested methods for future field studies in the area.

1.2 Background

As a consequence of the conflict in Syria, the wastewater treatment plant (WWTP) in southwestern Aleppo has not been fully functioning since 2013 due to power outages and destructions of the city (Arshad and Aoun, 2017; Stevens et al., 2017). Wastewater from households and industries are released into a canal that confluence with the Queiq River in front of the WWTP, without an adequate treatment. This has resulted in poor water qualities in the river and usage of this polluted water is a health risk for both people and the environment.

The wastewater flows down the Queiq River and reaches the agricultural parts of the region (Fig. 1). Farmers utilizing the land in the vicinity of the Queiq River have previously relied on the water in the river for their irrigation of crops (Stevens et al., 2017), now they can no longer access an adequate water source. Water quality tests on the Queiq River reveal extremely high levels of Total Phosphorus, Total Nitrogen, and faecal coliform bacteria, as well as considerable concentrations of heavy metals, that are far above acceptable water-quality values according to international guidelines for irrigation (UN-ESCWA and BGR, 2013).

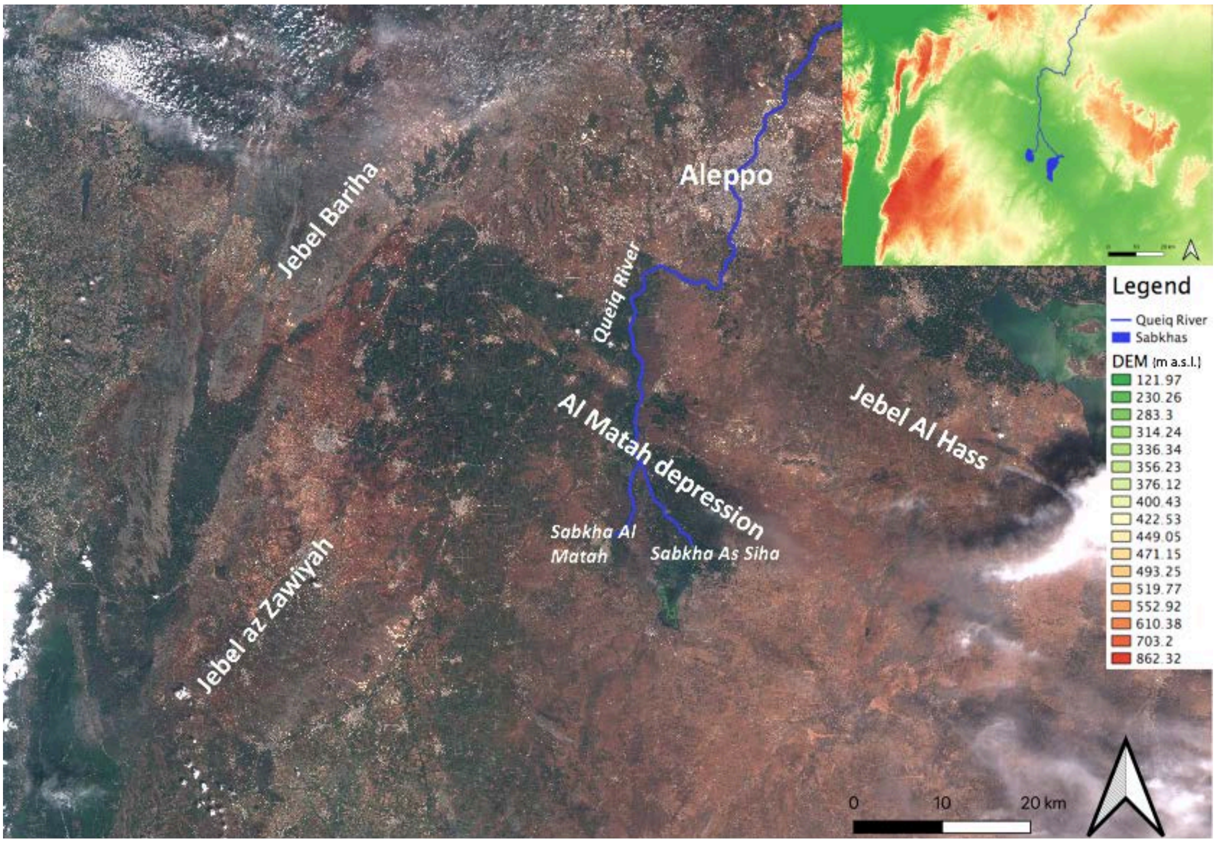

Figure 1: A satellite images (Sentinel-2) showing the Queiq River flowing through Aleppo and discharging into the Sabkha Al Matah and Sabkha As Siha, found within the Al Matah depression. (Names of geomorphological features retrieved from Stadler et al., 2012 and UN-ESCWA and BGR, 2013).

According to Prof. A. N. Aldarir (personal contact, April 16, 2020), previous resident of Aleppo and professor at the University of Aleppo, for most part of the year there is no natural waterflow in the Queiq River channel; Three dams to the north of the city hinder the flow and cause the stream to run dry. Instead, the majority of water flowing in the channel is the untreated wastewater. Drinking water is pumped from the Euphrates River, situated to the east of Aleppo, with a rate of 4 m^3/s. After usage the water ends up in the Queiq River. The latest update from 2020 says that the flow rate of wastewater in the river is about 300,000 m^3/d (A. N. Aldarir, personal contact, April 16, 2020).

A SAT system would be an environmental friendly, sustainable and cost-effective option with a low energy demand (Abel, 2014) for reclaiming water quality until the wastewater plant is up in commission again. The SAT system would also work as an important water reserve for water in a country with high evaporation rates. SAT systems utilizes the natural filtration of water achieved by percolation through the vadose zone of permeable sediments (Aharoni et al., 2011). Contaminated water is spread onto sediments that have a high infiltration capacity and sinks through the unsaturated zone. By the time it reaches the aquifer, the water has acquired an improved quality.

The Al Matah depression, found to the south of Aleppo (Fig. 1) is internally drained, and the wastewater of the Queiq River flows into two endorheic lakes, Sabkha Al Matah and Sabkha As Siha, found at the lowest elevation within the depression (Fig. 1). For the SAT method, water would be pumped from the lakes, additionally directly from the Queiq River, and transported through pipelines to the intended infiltration area. The goal is to find a site that offers sufficiently loose sediments, in the range of gravel to fine sand and coarse silt that could offer a combination of a sufficient infiltration capacity and an absorptive and adsorptive capability (Amy and Drewes, 2007). The only sites that may fulfil these requirements are the wadi valleys with their alluvial fill found in the vicinity of the Queiq River and the two lakes.

1.3 SAT requirements

SAT is a managed aquifer recharge system for the reclamation of water quality by geo-purification processes, designed by Herman Bouwer in 1978 (Aharoni et al., 2011). In addition to improve water quality, SAT also provides a long-term storage of water in areas where evaporation loss is extensive (Sharma and Kennedy, 2017). According to Aharoni et al. (2011), dissolved organic matter, suspended solids, microorganisms, heavy metals and other pollutants are effectively removed from the water when percolated through the vadose zone as a result of different processes like biodegradation, filtration, adsorption and chemical precipitation. When the treated water reaches the saturated zone it travels horizontally and experiences additional purification before it is recovered by recovery wells (Abel, 2014). To be able to perform purification and to control the recovery operation, the SAT system should be installed within aquifers of unconsolidated materials (Aharoni et al., 2011). Figure 2 shows a schematic figure of an SAT infiltration basin.

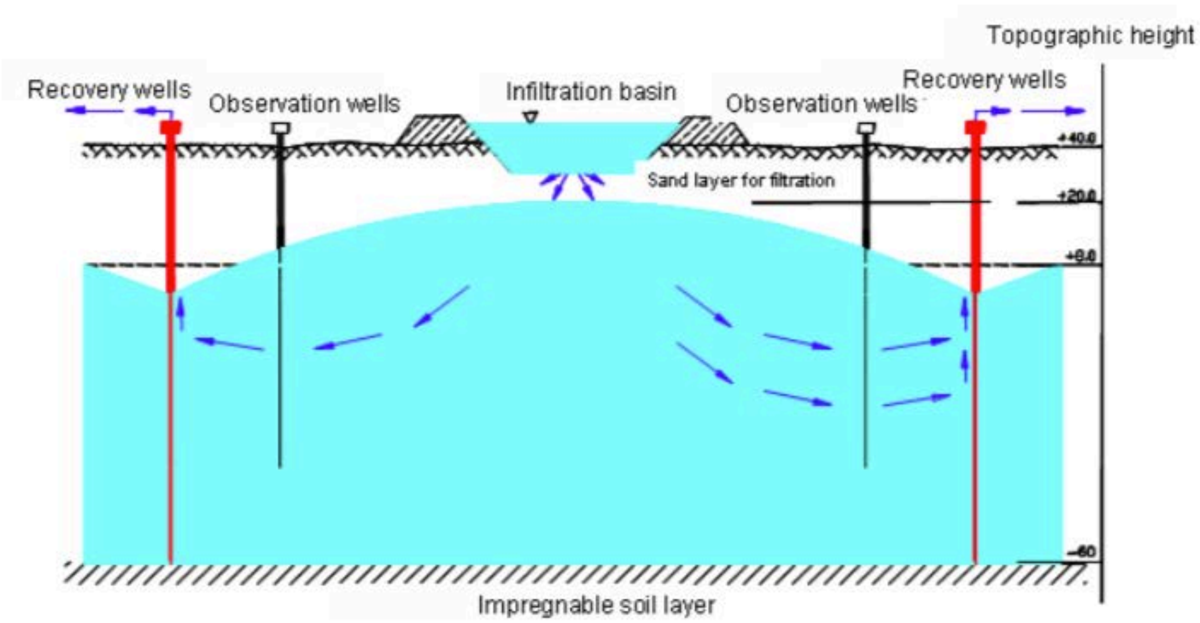

Figure 2: A schematic diagram of a Soil-Aquifer-Treatment infiltration basin. Figure retrieved from Aharoni et al. (2011).

Even though the wastewater is improved in quality, it may not reach a quality of potable use. For this reason, the treated water should not be mixed with the native water found in natural aquifers since this may entail a risk of aquifer contamination (B. Lucke, personal contact May 15, 2020). Thereby, a separate zone could be created within the regional aquifer to let the infiltrated wastewater be hydrologically separated from the rest of the aquifer by production wells surrounding the infiltration area (Aharoni et al., 2011), but in the limestone characteristic regions of Syria, a greater concern is perhaps the permeability of the underlying bedrock and risk of seepage down to the karstic aquifers. However, as many of the karstic aquifers in the regions around Aleppo are salty and the concentration of sulphur in the groundwater is very high (A. N. Aldarir, personal contact, May 10, 2020), the amount of valuable groundwater resources is rather low.

Depending on the intended use of the SAT treated wastewater, different types of pre- and post-treatments could be adapted to the process (Sharma and Kennedy, 2017). However, for irrigational purposes, the quality of the water may be good enough only after the recharge-reclamation process of the SAT itself (Aharoni et al., 2011), though it must be stressed that this depends on the type of contamination. SAT is most effective on removal of suspended solids and micro-organisms, however, for wastewater with a primary pre-treatment, it has also been proven to have a indicative removal efficiency of 57-100% on nitrogen, 4-100% on phosphates and 50-100% on heavy metals (Sharma and Kennedy, 2017). Nitrogen is removed by biological processes, whereas phosphates and heavy metals are mainly removed by adsorption onto soils (Lee et al., 2004; Crites et al., 2006, cited in Sharma and Kennedy, 2017), which means that the removal efficiency of phosphates and heavy metals may be decreased with time (Sharma and Kennedy, 2017).

Two of the main concerns regarding aquifer characteristics when choosing a SAT site are the thickness of the vadose zone and the permeability of the soils and sediments (Sharma and Kennedy (2017). Mekorot (2006, cited in Aharoni et al., 2011) claim that a thickness of 10-30 m of the vadose zone is required for a SAT system to function adequately whereas Sharma and Kennedy advocate a minimum thickness of 5 m. Pescod (1992) states that the most appropriate type of surface soils for SAT systems are in the range of fine sand, loamy sand and sandy loam, and that extensive clay layers should be absent because of its low infiltration capacity. Pescod (1992) also states that below the surface soils, deeper down in the vadose zone, the sediments should be granular and coarser. This configuration is desired for a combined action of enough retention time to improve the quality of the water and a sufficient infiltration capacity for high infiltration rates (Sharma and Kennedy, 2017). The hydraulic conductivity of these sediments, which is the ability for fluids to pass through the pore space of a material, is seen in Table 1. A high value of hydraulic conductivity indicates a good permeability of the sediment whereas a low value reflects a poor permeability. A further requirement for the development of a SAT system is distance between the infiltration site and the wastewater source. According to Sharma and Kennedy (2017), the distance between the two locations should be less than 20 km, most preferably within 5 km, to reduce the constructional costs of pipelines.

Table 1

Hydraulic conductivities for unconsolidated sediments

Material	Hydraulic conductivity (cm/s)
Clay	10^{-9} – 10^{-6}
Silt, sandy silts, clayey sands, till	10^{-6} – 10^{-4}
Silty sands, fine sands	10^{-5} – 10^{-3}
Well-sorted sands, glacial outwash	10^{-3} – 10^{-1}
Well-sorted gravel	10^{-2} – 1

Note: Loam is mostly a mixture of silt and sand and can thereby be compared to the values of silty sand and sandy silt. Values retrieved from Fetter (2018).

There are three different types of SAT systems; the infiltration basin (also called surface spreading basin), the vadose zone injection well and the direct injection well (Aharoni et al., 2011). The three systems are displayed in Figure 3. Infiltration basins may range in sizes less than 0,4 ha to more than 8 ha, however, the system requires at least two different infiltration basins (Crites et al., 2000), partly for the reason of preventing clogging issues caused by sedimentation of particles falling out of suspension from the ponded water (Bouwer, 2002). Another advantages of using two infiltration basins is the possibility of improving the treatment process. Oxygen in the vadose zone will enhance the biological activity, leading to an increased removal of organic matter from the infiltrated water (Aharoni et al., 2011). By having two basins, wet/dry cycles of each basin can be adapted, which allows oxygen to enter the soil during drying periods and thereby augment the reclamation process.

A vadose zone injection well is preferably used where the requirements of permeable surface soils cannot be fulfilled (Bouwer, 2002) or if the land availability is scarce, though in this case a relatively deep vadose zone of 15-30 m is required since the surface layers do not partake in the reclamation process (Aharoni et al., 2011). Direct injection wells are used for water that has already experienced an advanced treatment and is injected directly into deep aquifers.

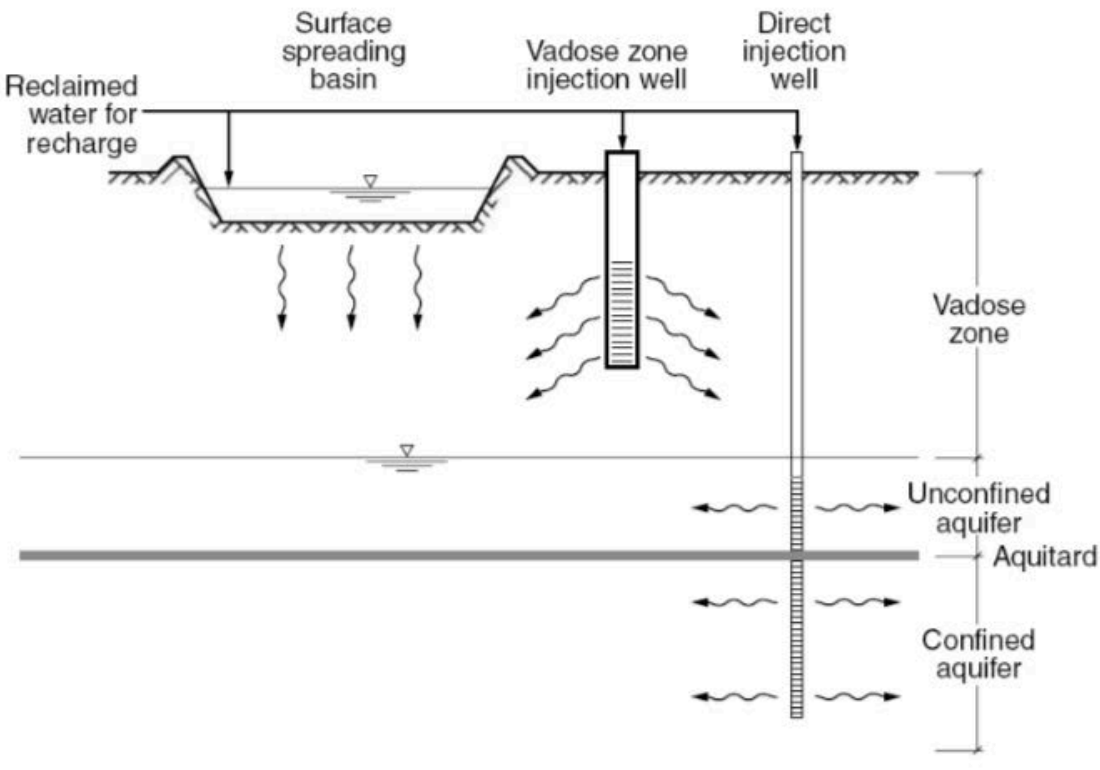

Figure 3: A schematic diagram of the three different SAT system. Figured retrieved from UESPA (2004).

1.4 Description of the study area

1.4.1 Climate

The regions south of Aleppo where the study area lies, is situated in northwest Syria where the climate is of semi-arid Mediterranean type with hot, dry summers and cool, wet winters (Abo and Merkel, 2015). Precipitation varies between 240 – 350 mm/year and is restricted to a single rainy season starting in October and extending through the spring (Farahani et al., 2009). The mean annual temperature is 18°C and the potential evapotranspiration ranges between 1,200 and 1,400 mm/a (Abo and Merkel, 2015). South of Aleppo, the land is highly cultivated. Wheat and barley are two of the most commonly grown crops during winter (Abo and Merkel, 2015) and potatoes, sugar beets, cotton, corn and fresh vegetables are grown in the summer (A. N. Aldarir, personal contact, April 16, 2020).

1.4.2 Geomorphology and geology in the region

The Queiq River originates from the mountain areas in southern Turkey, flows through a length of 155 km through the Syrian territory and discharges into the Al Matah depression (Fanack, 2019; UN-ESCWA and BGR, 2013). The Queiq River Basin is a closed drainage basin where the dammed water that does not infiltrate will evaporate (UN-ESCWA and BGR, 2013). The average daily discharge in the Queiq River is ~440,000 m^3 (Fanack, 2019), of this about ¾ constitutes the wastewater coming from the city (A. N. Aldarir, personal contact, April 16, 2020).

The area south of Aleppo has a relatively flat topography and an altitude of 250-500 m a.s.l. (Abo and Merkel, 2015). The Jebel al Hass, a basaltic plateau at about 600 m a.s.l., is the topographic boundary to the east and two limestone ridges, Jebel Bariha and Jebel az Zawiyah, with altitudes of 650-850 m a.s.l., confine the basin to the west (Stadler et al., 2012). See Figure 1 for location.

According to the geological map of Syria (1:1,000,000) by Ponikarov (1964) (Fig. 4), the dominant type of bedrock in the study area are the Helvetian limestones, the Paleogene soft chalky limestones and the Neogene basalts. The Al Matah depression, found at the lowest elevation within the basin, is mapped as filled with Quaternary deposits (recent and upper Pleistocene). The type of sediments of the Quaternary deposits are identified as pebble beds, sands, sandy loams, loams and clays (Ponikarov, 1964), however, the cartographer does not specify the distributional occurrence of these sediments on the map and instead, equates all areas covered by unconsolidated material as Quaternary sediments. For this reason, the actual type of sediment to be found in the Al Matah depression is hard to determine. However, Luijendijk and Bruggeman (2008), who studied groundwater resources in the Jebel Al Hass region, found that the Al Matah depression mainly is covered by lacustrine deposits, which implies clay and silt as the major type of sediments.

A soil map of Syria (1:1,000,000) produced by Ilaiwi (1985) reveals five main soil types found in the area; Calciorthids, Gypsiorthids, Petrocalcic Xerochrepts, Vertic Xerochrepts and Calcixerollic Xerochrepts. These soils, derived from the local bedrock and alluvium, are dry-land soils, often with calcium carbonate accumulations. According to the Illustrated Guide to Soil Taxonomy by the U.S. Department of Agriculture, USDA (2015), the Calciorthids and Gypsiorthids belongs to the Aridisols group of soils, meaning that they are dry desert soils. Xerochrept soils are found in regions with a Mediterranean-type climate of cool, moist winters and warm, dry summers. They belong to the Inceptisols group, meaning that they are slightly developed soils (USDA, 2015). The occurrence of these soils, even though very general, is seen in Figure 5 and the potential infiltration capacity of these will be discussed in section 3.3.

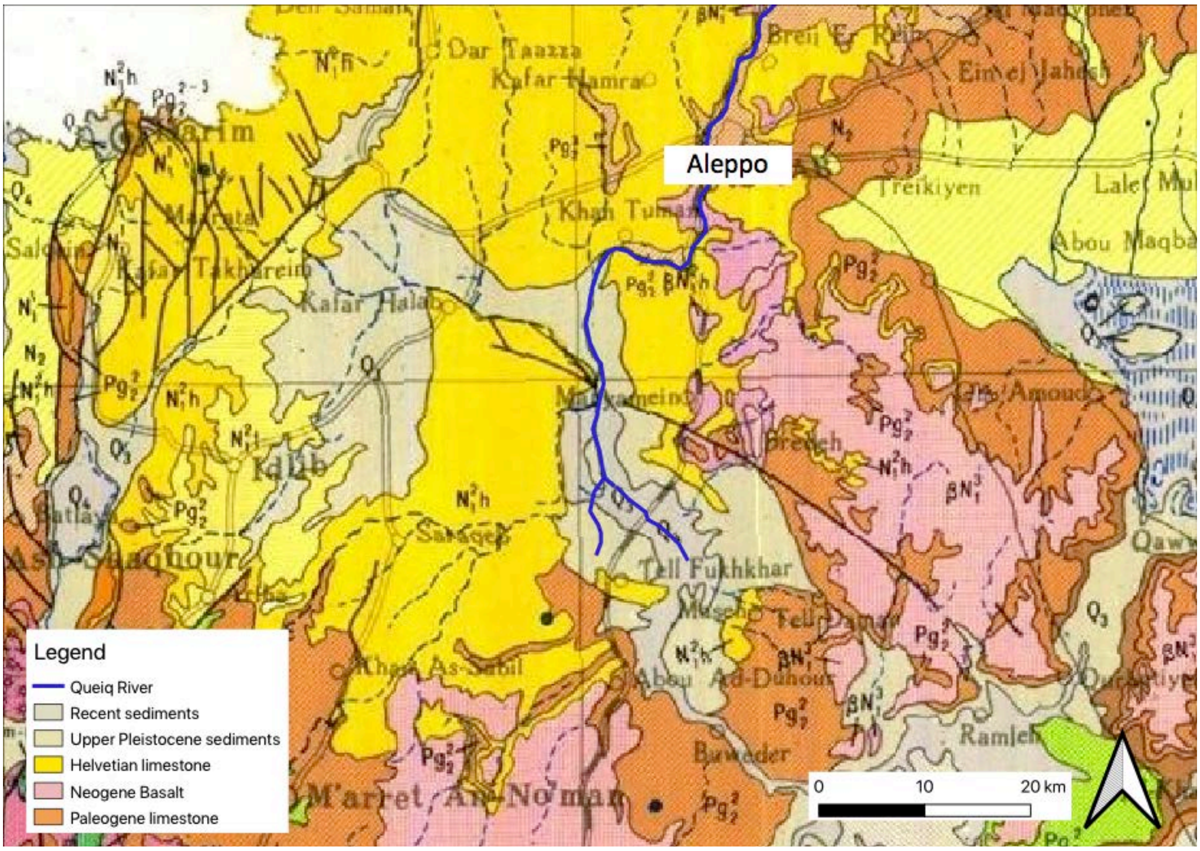

Figure 4: A geological map showing the geological formations found in the area south of Aleppo. (Edited figure from original map by Ponikarov, 1964).

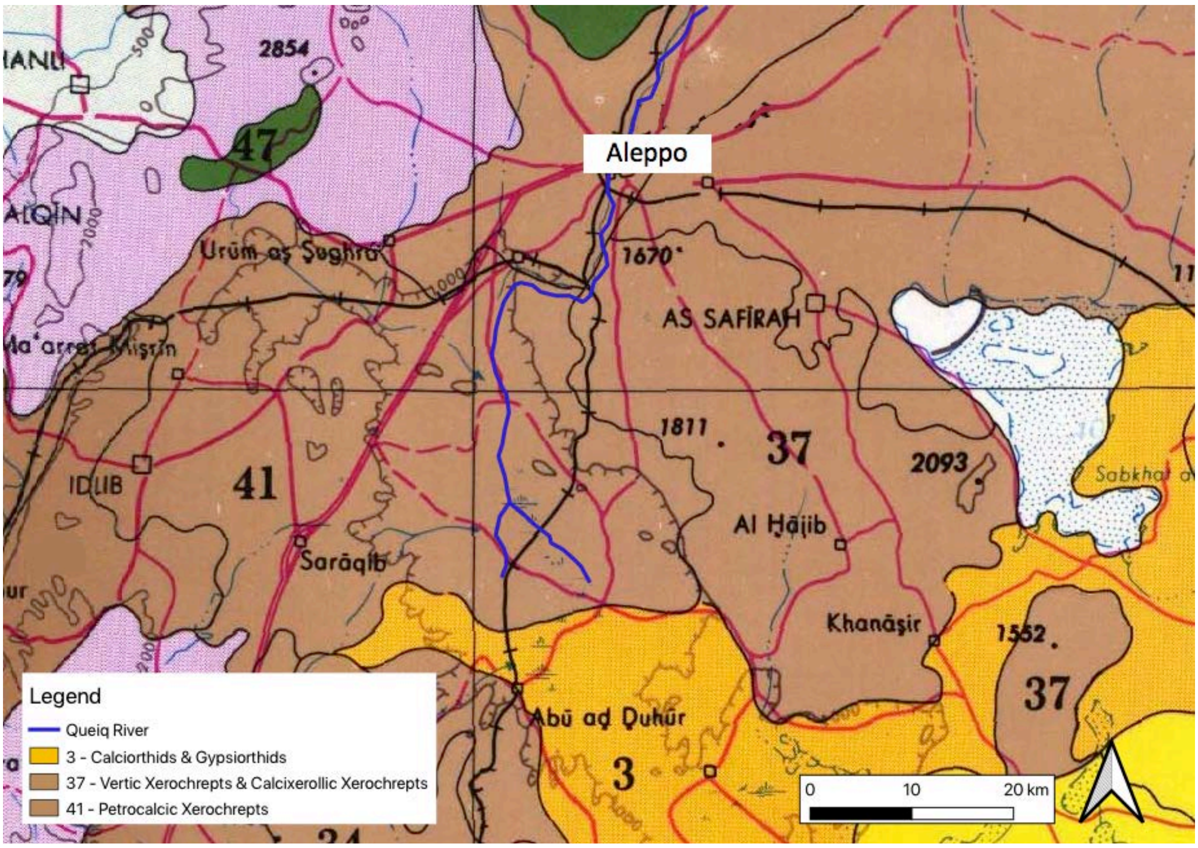

Figure 5: A soil map showing the soil types found within the area south of Aleppo. (Edited figure from original map by Ilaiwi, 1985).

1.4.3 Tectonic history

Syria is close to the leading edge of the N-NW directed collision of the Arabian and the Eurasian Plates; a plate boundary that has controlled most of the Cenozoic tectonics of Syria (Brew et al., 2001). According to Al Abdalla et al. (2010), a NNW-SSE directed regional compression has influenced the Syrian landscape since the end of Miocene until present. There is also evidence of an E-W trending compression related to the Dead Sea Fault system (Al Abdalla et al., 2010). These neotectonics have resulted in a quite rapid uplift of Syria since the Late Quaternary (Bridgland et al., 2017). The Al Matah depression (Fig. 1), also a result of tectonic activities, is part of a large syncline that belongs to a gentle anticlinal and synclinal system in the region (Wagner, 2011). Tectonic activity during the Quaternary may have affected sedimentation patterns within the wadis of the study area, however, there is no published work yet that has confirmed this.

1.4.4 Aquifer systems

Karst aquifers are the predominate aquifer type in Syria and are one of the main reasons for ancient settlement in the region (Burdon and Safadi, 1965). By providing a fresh water source in a region characterized by high evaporation losses, the karst system may have been decisive for the development of societies. Bakalowicz (2015) argues that carbonate sedimentation started to develop on the continental margins of the Mediterranean Sea during the Late Triassic. Periods of tectonic uplift have resulted in the exposure of carbonate bedrock, eventually leading to karst formations being widespread over the regions around the Mediterranean Sea today (Bakalowicz, 2015).

As stated in section 1.4.3, the nature of the Syrian landscape has been altered by tectonic activities throughout the history, leading to fractures, joints and fissures in the bedrock. Burdon and Safadi (1965) conclude that jointing is one of the two main criteria for karstification to develop, which partly explains the extensive distribution of the karst in the region. The second requirement for karstification to occur is that precipitations must be able to infiltrate and circulate through the joints and fractures of the carbonate bedrock. By solution, the joints enlarge and forms great karst systems (Burdon and Safadi, 1965). It is well known that mature karst systems have very high values of transmissivity and can carry large amounts of groundwater.

In the area south of Aleppo, the Helvetian and Paleogene limestones are the two most common rock types. These rocks may accommodate significantly large karst system that can hold great amounts of groundwater, however apparently at rather great depths. The wadis in the area are ephemeral and clearly loosing streams, and seemingly, the Queiq River is a losing stream as well as the piezometric heads are drastically decreasing when moving away from the Queiq River channel. At a distance of 150 m from the riverbed, the groundwater table is found at depths of less than 5 m, but within 2 km away from the river, the water table is located at a depth of 150 m (A. N. Aldarir, personal contact, May 10, 2020), this without any drastic changes in ground level. However, as many of the karstic aquifers of the Aleppo region are salty and have high concentrations of sulphur, only some of these resources have qualities good enough for utilization (A. N. Aldarir, personal contact, May 10, 2020).

2. Method

This thesis has been completed fully remotely and with usage of available literature and data sources. To be able to assess the suitability for introducing a SAT system, knowledge of the intended area's sedimentological characteristics is of utmost importance. Unfortunately, there is a scarcity of sedimentological data from the region. Instead, knowledge of wadi characteristics had to be achieved through a literature study of wadis in general, and of wadis and other ephemeral streams in areas with similar climatic and geologic conditions as northwestern Syria since the depositional and stratigraphic characteristics of these perhaps are comparable with the ones found in northwestern Syria. The interpretation of wadi settings in the study area was, except based on information gained from the literature, also formulated through the inspection and integration of Google Earth, satellite imagery and elevation data in QGIS, and available soil and geology maps.

2.1 Literature study

Available sedimentologic data from the study area is scarce and the current situation in the region has hindered any field studies. Instead, reports, articles and other scientific papers about the sedimentology of wadis and other ephemeral streams in areas with similar characteristics as northwestern Syria have been analysed and summarized. A literature study about sedimentation patterns and fluvial response to tectonic and climatic changes has also been conducted since this may give some clues about the possible sediment type and thickness of the wadis in the study area. Information about Syria's climate, tectonic history and geology as well as information about SAT requirements were also found by reading scientific papers. In addition to using literature as a source of information, personal contact with scientists within the field has been very helpful.

The main online source for information has been the GeoRef database. The possibility of using Boolean search operators such as "OR" and "AND" has helped to find available and relevant research. Some of the key terms used as search criteria has been "wadis", "ephemeral streams", "soil aquifer treatment" and "artificial recharge". Other databases used are Scopus, Google Scholar and Gothenburg University's library resource "Supersök".

A broad source of information is desired for a comprehensive research and was for that reason the aim for each approach in the report. Usage of several different authors and publications provides an objective view as well as confirmation of knowledge. Examples of types of references used are journal articles, reports, conference papers and doctoral theses. Interesting secondary sources were further investigated to find additional articles that could be useful for the research.

2.2 Interpretation and integration of satellite images and available maps

Wadi channels and floodplains in the study area were found through the inspection of satellite images. As stated in section 1.3, the infiltration site should not be located further than 20 km from the wastewater source to reduce pipeline costs. For this reason, a buffer zone of the desired radius was produced along the Queiq River and the lakes to know which wadis in the area that are within the possible reach. For each wadi valley found within the range of 20 km, measurements of the width, relief, gradient and length were completed since this says something about the sedimentology of the wadis. To measure the change in width and relief along the valleys, transverse cross sections were drawn through digital elevation models (DEMs) in QGIS and on Google Earth data. For each value to be measured, 4-5 measurements were taken to get a range and an average. Stream gradients along the wadis were measured on longitudinal cross sections and are expressed in elevation change/km. The lengths of the wadis were measured on satellite images.

The type of soils and bedrock found in the study area have a great influence on wadi characteristics. Using QGIS, the wadis suggested as suitable for a SAT system were marked by polylines, and two maps, one about the geology of Syria and one about the soils of Syria, were georeferenced. By then integrating the wadi vector data with the georeferenced maps it was possible to get an idea of what type of conditions to except in each wadi valley.

Sources of satellite imagery were the United States Geological Survey's (USGS) EarthExplorer and the European EO Browser, which provides satellite images from the Landsat 8 program and Sentinel-2. Elevation data were retrieved from USGS EarthExplorer which maintains DEMs produced by NASA's Shuttle Radar Topography Mission (SRTM).

3. Wadi sedimentology, stratigraphy and soil development

In arid regions, important potential recharge zones are confined to certain geomorphological landscapes such as alluvial fans, sand dunes and wadis (Missimer et al., 2012). In the regions around Aleppo, wadis are quite common and are suggested to accommodate the desired sedimentology of a SAT system.

3.1 A general description of deposition

3.1.1 Sediment fractionation

The fluvial dynamics of wadis are similar to other fluvial stream in the way that alluvial sediments of different grain sizes are deposited in certain parts of a stream depending on the fluvial regime and the gradient of the longitudinal channel. However, wadis are still quite different from a typical stream as they undergo transmission losses and that they often accommodates a rather thick vadose zone (Missimer et al., 2012).

The general configuration of wadis is explained by Missimer et al. (2012), who argues that a wadi stream can be divided into different segments. Wadis, like all ephemeral streams, occur in topographically low areas, initially incised into the underlying bedrock. The stream originates from the most elevated part of a wadi catchment were the channel is narrow and steeply dipping, mostly containing boulders and a very low content of fine-grained sediments. Flash floods caused by heavy rainfalls erodes the channel and transports sediments downstream to the flattened part of the area where the wadi broadens. When the stream slows down, sedimentation occurs. The middle segment of the wadi, adjacent to the hills, will be characterized by a mix of boulders, cobbles and coarse sand, while some parts of the channel may have been scoured down to the bedrock by the flood. Further downstream, close to the point of discharge, the slope of the channel becomes significantly low causing the stream to slow down and allow thick layers of sediments with a lower average grain size to accumulate and the width of the channel tends to increase. Stratified deposits of pebbles, coarse sand, medium to fine sand and mud layers are found in the channel that reflects alternations in the fluvial regime (Missimer et al., 2012). Missimer et al. (2012) suggest the lower segment of a wadi for installation of any artificial recharge system since this part normally offers a thick deposit of sediments compared to the upper and middle segments.

In the American southwest, the ephemeral streams are referred to as arroyos. These are dry creeks, temporarily or seasonally flowing, very similar to the Arabian wadis. The American southwest has a similar semi-arid to arid climate as Syria and a similar geology of sedimentary bedrock. Nelson and Rittenour (2014), who documented the alluvial deposits of Kanab Creek arroyo in southern Utah, explain how a low vegetation density and a weak, rather easily eroded bedrock are two fundamentals for a high sediment production, conditions that are fulfilled in a region with a semi-arid to arid climate and a sedimentary geology.

Nelson and Rittenour (2014) study revealed, just like Missimer et al. (2012) that the stream could be defined by three distinct reaches, even though in another manner; the upper reach, the middle canyon part and the basin-fill. Even though Nelson and Rittenour (2014) included the very basin fill in their division, the different reaches were distinguished on the basis of the same type geomorphic characteristics as Missimer et al. (2012) divided the stream; valley width, bedload and stream gradient. Nelson and Rittenour (2014) found that the upper segment of the channel is broad and shallow with gravel- and boulder-sized clasts derived from the local bedrock. Downstream, approaching the middle canyon part, the general slope decreases, and the authors observed a shift in sedimentation from gravel-boulder sized deposits towards a sandier character. At the transition of the middle canyon to the lower reach, the stream is discharging into a 2 km wide basin where the slope is decreasing (Nelson and Rittenour, 2014). According to a drill core drilled by Wright Drilling (Nelson and Rittenour, 2014), a fill of approximately 60 m thick alluvial sediments has accumulated in this basin.

3.1.2 Terrace formation

In response to changes in stream discharge and sediment supply, which in turn are related to climatic and tectonic forcing (section 3.2), ephemeral streams may go through numerous phases of aggradation and erosion, leaving a potentially complex set of valley fills and terraces. An example of this was described by Wedel and Stevens (1990), who performed a sedimentological investigation of an ephemeral stream in southeastern Cyprus. According to their study, the initial phase of channel formation was a time of incision into the bedrock and formation of a broad valley, followed by a period of aggradation, resulting in a 14 m thick fill of fluvial sand and gravel. Following periods of incision into this valley fill resulted in the abandonment of previous floodplains, forming terraces, left above the present stream bed (Wedel and Stevens, 1990). The purpose of the sedimentological investigation was for potentially using the recent and former stream beds for artificial recharge and storage of captured stream water. Figure 6 shows an example of a wadi stream that displays terraces.

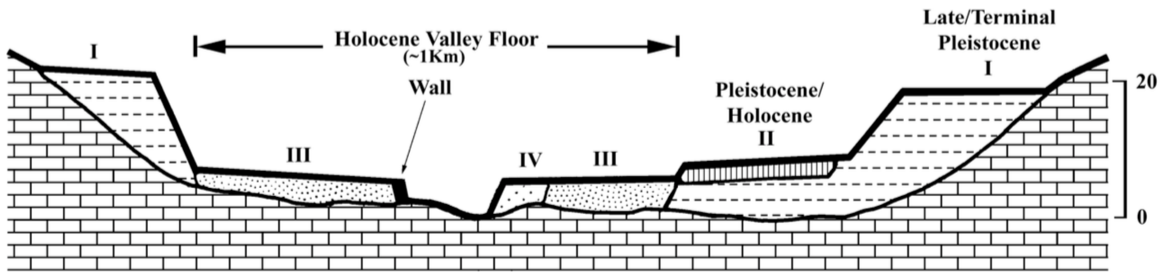

Figure 6: A schematic model of a wadi in northern Jordan showing 4 different terrace fills found above the recent channel. (Figure retrieved from Schuldenrein, 2007. Version is based on final terrace chronology (Copeland and Vita-Finzi, 1978: Figure 1b), which was modified from the original (Vita-Finzi, 1966: Figure 1b)).

Signs of incision and abandonment of floodplains within ephemeral streams were not only observed in Cyprus. Alford (1982), who performed a stratigraphic study in the San Vicente Arroyo, southwestern New Mexico, found the arroyo to be cut into a complex of Pleistocene fan deposits of sand and cobbles. Today, the ephemeral stream is flowing on bedrock at its headwaters, however, immediately downstream the valley floor is characterised by a sandy wash. Terraces were also observed in the arroyo in southern Utah; Nelson and Rittenour (2014) documented three alluvial terraces above the recent channel that holds a variety of grain sizes ranging from fine-grained silty sand in the upper terraces and gravel and boulder dominance in the lower terrace.

In another study by Stevens and Wedel (1995), facies sequences in terraces, found above the present floodplain of three different valleys in southeastern Cyprus, were related to different fluvial processes. The provenance of the sediments was found to be mafic, including basalt, diabase, gabbro and ultra-mafic rocks, and sedimentary of chalky and marly limestone.

Stevens and Wedel (1995) observed the grain size of both the mafic and limestone components to generally range from gravelly to fine grained fractions, however the marls were stated to be too soft to be preserved as grains of the coarser fractions. According to the authors, two of the most frequently occurring transitions within the most well-developed terrace in the study area, are between sandy gravel and sandy silt facies, respectively clast-supported gravel and clayey silt facies. Each transition is interpreted to reflect aggrading axial-streams respectively fan systems. Stevens and Wedel (1995) also observed a general stratigraphic trend of axial-stream deposits to be followed by floodplain and then fan deposits in the terraces.

In addition, Stevens and Wedel (1995) found caliche (a carbonate-cemented soil horizon) to occur within both the coarse- and fine-grained facies. Caliche is formed as calcium carbonate is leached from the upper soil layer to lower horizons where it is precipitated as small fragments or thin coatings on sediment grains. As the coatings thicken, adjacent grains will be cemented together, eventually forming a continuous, hard and impermeable subsurface in the soil (King, 2005). The Petrocalcic Xerochrepts, found in the study area, may be similar to the caliche, however this will be further discussed in section 3.3.

3.2 The influence of tectonics and climatic cycles

Sedimentation within wadis, like any fluvial system, is highly affected by tectonic activities and climatic changes, (Macklin et al., 1995), causing the depositional and erosional characteristics of a stream to be complex. Even though it may be difficult to interpret fluvial response to tectonic or climatic changes or to relate certain facies to specific processes, many scientists have agreed on some correlations between these mechanisms that could explain some of the patterns within fluvial systems.

Syria has experienced rapid uplift since the Late Quaternary due to neotectonics influencing the region (Al Abdalla et al., 2010; Bridgland et al., 2017). Uplift will cause streams and rivers to down-cut and get incised into the underlying material (Bridgland et al., 2017) but will also lead to an increased exposure of bedrock, setting the principal condition for erosion (Stevens and Wedel, 1995). A superimposed period of climatically induced runoff may lead to an increase in sediment yield to streams and rivers, leading to times of aggradation within fluvial valleys (Stevens and Wedel, 1995).

According to Bridgland et al. (2017), there is a growing consensus that tectonic uplift but more so climatic fluctuations are influential on base level changes within fluvial systems. The authors claim that glacial and interglacial induced climatic changes had the primary control on incision and aggradation within fluvial systems in the NE Mediterranean regions, throughout the Quaternary. However, McLaren et al. (2004) and Bridgland et al. (2017), point out a division between scientists who argue that glacial and interglacial cycles correlates with dry and cool respectively wet and warm periods in the lower latitudes, such as in the study area, and those who advocate wet and cold during glacials and dry and warm during interglacials. There may even be those who doubts whether these relations between glacial-interglacial and pluvial-interpluvial can be connected whatsoever. This does not make it an easy task to try to connect paleo fluvial behaviour to glacially/interglacially induced climate changes.

According to Robertson (1977, cited in Stevens and Wedel 1995), Cyprus has experienced tectonic uplift since the early- to mid-Quaternary, leading to the exposure and weathering of sedimentary, mafic and ultra-mafic rocks. Even though this sets the basic conditions for erosion, the climatic influences during the Late Pleistocene and Holocene were interpreted by Stevens and Wedel (1995) to have a greater control on the depositional characteristics in the stream valleys of the island. Interglacials, suggested to be associated with a wetter climate in the Mediterranean regions, is proposed by the authors to have favoured axial stream deposition, while drier climates during glacials, related to a lowering of the sea level, led to incision and abandonment of flood plains which enhanced soil and caliche development on the terrace surfaces. Alford (1982) on the other hand, who found the arroyo in southwestern New Mexico to be incised into a complex of Pleistocene fan sediments, assumed these deposits to be associated with pluvials related to continental glaciation and that future interpluvial periods caused down-cutting into the Pleistocene deposits.

In a study much closer to the study area, Maher (2011) completed a survey about the changing paleolandscape of Wadi Ziqlab in northern Jordan to try to understand the sedimentologic history of the wadi valley. Radiocarbon dating was used to determine age of deposits found in the valley. According to Maher, the change of the landscape in Wadi Ziqlab is highly affected by the local response to regional climatic change. Maher concludes, based on regional paleoclimatic reconstructions by e.g. Bar-Matthews and Ayalon (2003), that prior to the Last Glacial Maximum, LGM, during the upper Pleistocene, the climate was warm and moist, resulting in the thick alluvial gravel deposits found in the valley today. Maher implies that a wet climate, resulting in an increased runoff and sediment yield, had a great control on the grade of aggradation. According to Maher, the wadi valley was at this time shallow and flat, characterized by broad flood plains.

Maher also documents incision, extensive erosional episodes, and a depositional hiatus within the wadi, that she suggests is a result of the initiation of the LGM. However, Maher highlights that the change in base level at this time may also have been connected to tectonic activity in the Jordan valley during the Pleistocene (Field, 1994, cited in Maher 2011). Post LGM, Maher argues that there was a shift from erosion to resumed deposition, coinciding with an increase in annual rainfall (e.g. Bar-Matthews and Ayalon, 2003 cited in Maher, 2011). Unlike Stevens and Wedel (1995), Maher (2011) suggests strong soil development during wetter climates rather than during dry climates. However, it should be noticed that Stevens and Wedels (1995) suggestion is stressed on the stability of the abandoned terraces surfaces caused by terminated flood plain sedimentation during glacials, whereas Maher (2011) put emphasis on the increased availability of moisture during interglacials, necessary for soil development.

The Younger Dryas, which occurred at the end of the last ice age, came with an increase in aridity and a widespread erosion in the valley (Maher, 2011). Deposits from the succeeding warmer period in the early Holocene display fluctuating changes in precipitation by the presence of alluvial gravels unconformably overlying paleosols. The remainder of the Holocene is interpreted by Maher to be characterized by alternating cycles of deposition and erosion, with a tendency towards increased intensity in both aridity and rainfall. Today, weak soil formation is found in the wadi, though farming and grazing have hindered any strong pedogenesis. Maher concludes that changes in the flow regime, in turn controlled by e.g. tectonics and climate change, appear to be the primary cause of landscape change in Wadi Ziqlab.

As mentioned earlier in this section, there is a division between scientist regarding the climatic characteristics of glacial cycles in the lower latitudes, however both McLaren et al. (2004) and Bridgland et al. (2017) concludes that most scientist agree on a drier climate during glacials and wetter during interglacials in the Mediterranean and Middle East regions. A conclusion confirmed by two studies performed in the area (Stevens and Wedel, 1995; Maher 2011). The interpretation of the past depositional and erosional characteristics of the wadis found in the area south of Aleppo may therefore be based on these statements. Tectonics has also been suggested to be influential on sedimentation within fluvial valleys (Bridgland, 2017; Maher, 2011; Stevens and Wedel 1995), and will also be taken into account for the interpretation of wadi characteristics in the study area.

3.3 Soil development

Since the permeability of the materials in the wadis is crucial for the possibility to introduce a SAT system, we also need to know about the character of the soil development in the area. Lucke et al. (2015), who performed a soil survey in the areas around the Dead Cities of Syria, situated in the vicinity of Idlib, southwest of Aleppo, showed that the distribution of soils in the region is mainly affected by the local geological patterns. As stated in section 1.4.2, the three main rock types found in the area south of Aleppo are the Helvetian limestone, the soft chalky Paleogene limestones and the Neogene basalts. Because soils and sediments are derived from the local bedrock these rocks will have a great influence on the regions soil characteristics and sediment thickness.

Bernhard Lucke (personal contact May 15, 2020), who partook in the soil survey southwest of Aleppo, explains how the valleys that are incised into the Helvetian limestone, which is quite hard and not easily eroded, normally holds quite little soil and sediment. According to B. Lucke, the only way for greater amounts of sediment to accumulate within these valleys would be connected to some major event such as an earthquake or periods of heavy rainfall. “The soft, chalky limestones on the other hand are rather easily eroded and valleys incised into this bedrock may accommodate quite larger amounts of soil and sediment”, states B. Lucke.

As mentioned in section 1.4.2 are the five types of soils found in the study area: Vertic Xerochrepts, Calciorthids, Gypsiorthids, Calcixerollic Xerochrepts and Petrocalcic Xerochrepts. Vertic Xerochrepts are dry soils which have a clayey texture. Because of their low moisture content, they have mud cracks often formed in the dry season (USDA, 2015). According to USDA (2015), Calciorthids, Gypsiorthids and Calcixerollic Xerochrept develops as calcium carbonate or gypsum accumulates within the upper 100 cm of the surface soil, forming a calcic or gypsic horizon. These soils are formed in areas where the extent of ions that are leached from the parent material, and that is necessary for the reprecipitation of calcite and/or gypsum, is higher than what the rate of precipitation is able to remove from the upper horizon.

Petrocalcic Xerochrepts also have a calcium carbonate horizon, but here the layer is cemented (USDA, 2015). The infiltration possibility of this soil may be considerably reduced, however the occurrence of the soil in the study area may not be as widely distributed as what is suggested from the soil map by Ilaiwi (1985) (Fig. 5). The map is rather general, and it cannot be assumed that all geomorphological features in the area, mapped as being covered by Petrocalcic Xerochrepts, do accommodate this soil. Instead, by comparing the geological map by Ponikarov (1964) with Ilaiwi’s soil map, it is seen that the major part of the Quaternary sediments in the region are covered by the Calciorthids and the Gypsiorthids (Fig. 7). This suggests that the sediments found in the wadi valleys in the study area have soils similar to the soils found on the Quaternary sediments and that they likely lack a petrocalcic, or caliche, horizon. In fact, as was shown in Wadi Ziqlab by Maher, only weak soil development occurs in the wadi, which suggest that similar conditions are found in the wadis of the study area.

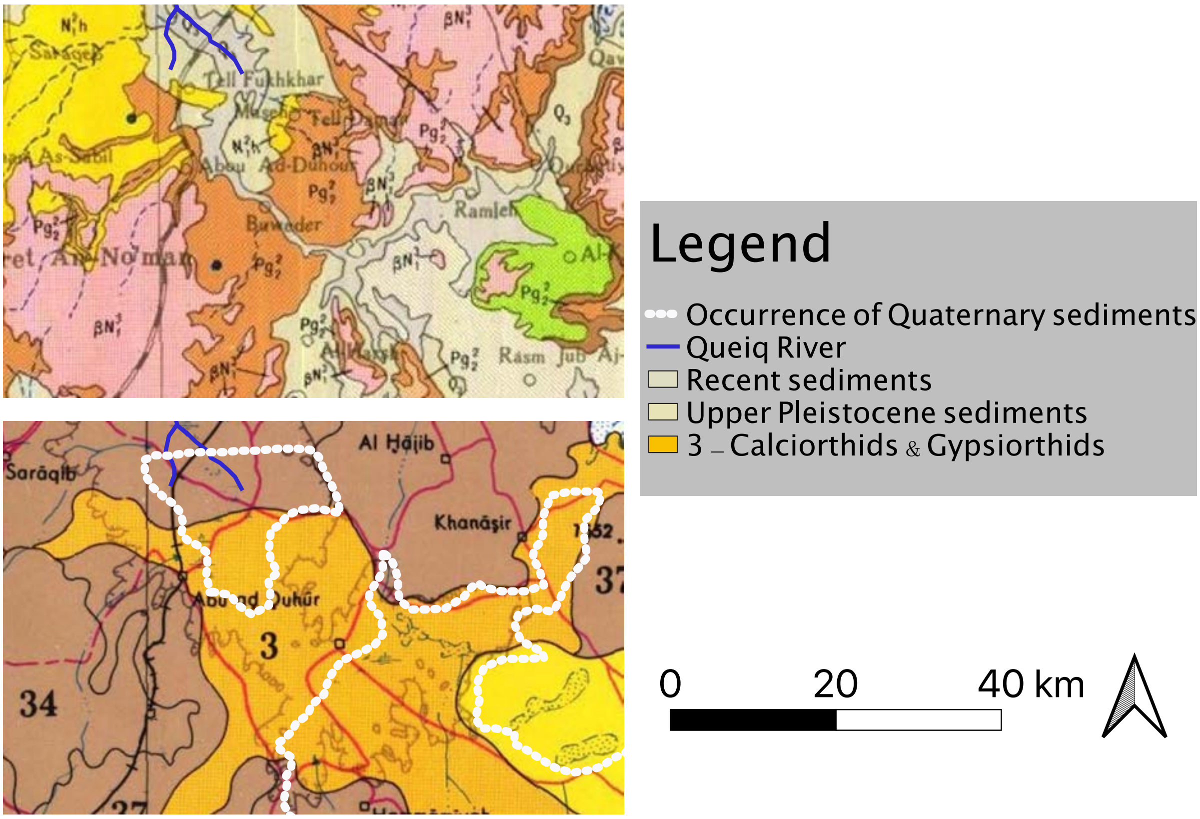

Figure 7: A comparison between the geological map by Ponikarov (1964) (above) and the soil map by Ilaiwi (1985) (below). It is seen how the Quaternary sediments are dominantly covered by Calciorthid and Gypsiorthid soils. (Edited figure from original maps by Ponikarov, 1964 and Ilaiwi 1985).

4. Site Selection

Based on the geography, geomorphology and geology of the region, four sites are designated as suitable for a SAT system (Fig. 8). Each site is found within the lower segment of four different wadis. The interpretation of the characteristics of the wadis is based upon visible inspection on Google Earth, geomorphological values measured on satellite images and cross sections through elevation data, and by the integration of wadi locations to the georeferenced geology map. Geomorphological characteristics of each wadi valley are seen in Table 2. The division of the wadi segments were based on the characteristic of different parts of a wadi stream as explained by Missimer et al. (2012), being the width and gradient (and bedload). The length of the wadi is an indication of its catchment area and the degree of valley incision reflects the amount of sediments that has been eroded and transported downstream.

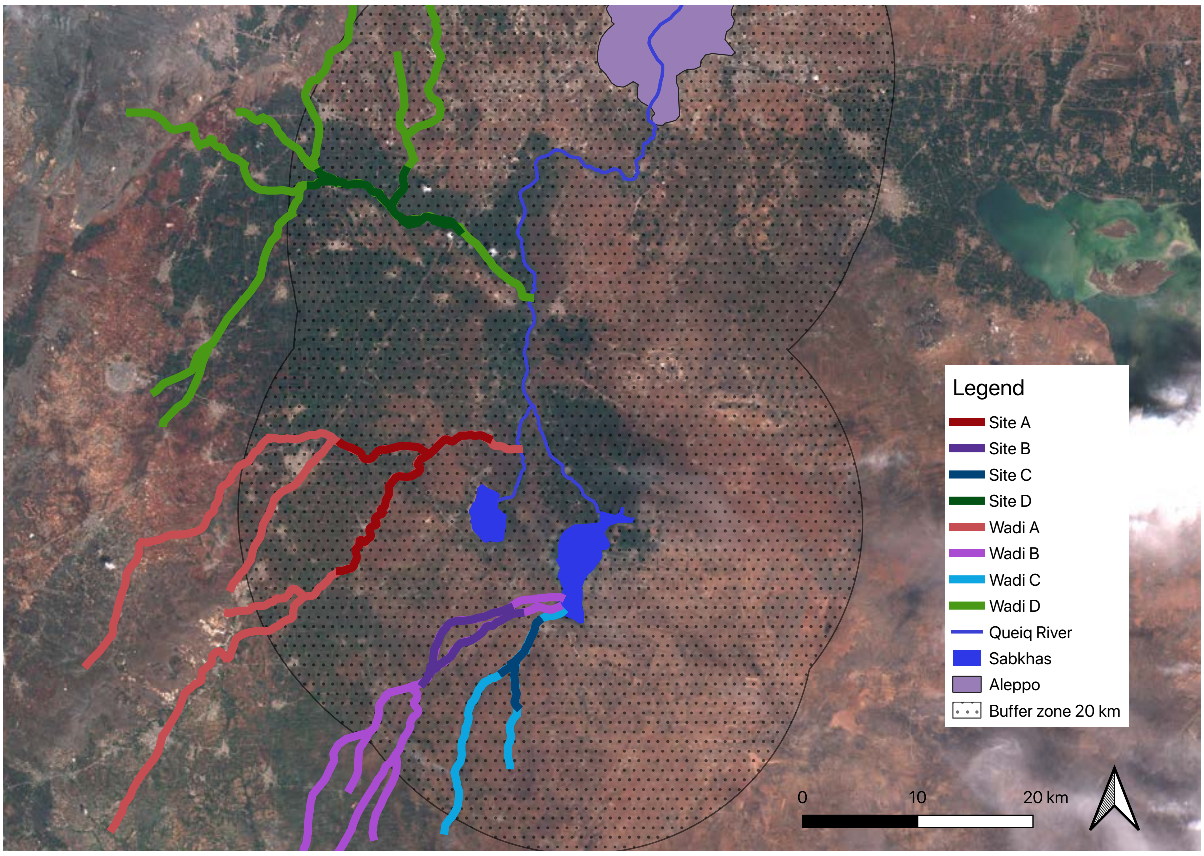

Figure 8: Location of potential sites for the development of a SAT system. All sites are found within the lower segment of wadis, found in the vicinity of the Queiq River and the two Sabkhas.

Table 2
Geomorphological characteristics of the four wadis suggested as suitable for SAT

Wadi	A	B	C	D
Approximate wadi length (km)	107.6	77.3	32.4	152.0
Range of relief* (m)	9-32	17-54	20-49	14-71
Range of valley bottom width (m)	32-66	73-138	42-136	32-432
Upper segment average stream gradient (m/km)	7.0	7.4	9.2	11.2
Middle segment average stream gradient (m/km)	4.6	4.8	8.8	2.1
Lower segment average stream gradient (m/km)	3.5	4.3	6.4	1.1

Note. *Difference between the level of the wadi and the surrounding uplands.

To assess the possibility to introduce a SAT system into one of the wadis the knowledge of what type of sediments that are deposited is central. It has been shown by Missimer et al. (2012) and Nelson and Rittenour (2014) that sedimentation is related to the slope of the stream. Also, it has been shown that grain size distribution is not only affected by stream gradient but also parent material (Stevens and Wedel, 1995). More easily eroded bedrock may result in a smaller average grain size found within the valley fill. Therefore, a compilation of stream gradients in ephemeral streams with a known sedimentology, found in other areas with similar geology and climate as Syria, has been conducted and can be seen in Table 3. As one can see, lower gradient ephemeral streams tend to be finer grained than steeper ones.

Table 3
Stream Gradient and Documented Grain Size for Different Ephemeral Streams

Ephemeral stream	Whitewater Draw	Rio Puerco	Kanab Creek arroyo	Wadi Madoneh	San Vicente Arroyo	Wadi Ziqlab
Location	Arizona	Northern New Mexico	Southern Utah	Northern Jordan	Southwestern New Mexico	Northern Jordan
Average stream gradient (m/km)	1	2	6	7	17	45
Documented grain size	Sandy clay and clayey sand	Clay, silt and sand	Sand	Silt, coarse sand and gravel	Sand	Gravel
Source	Waters (1985)	Friedman et al. (2014)	Nelson and Rittenour (2014)	de Laat and Nonner (2012)	Alford (1982)	Maher (2011)

Note. These ephemeral streams have relatively small drainage basins in semi-arid to arid regions with a sedimentary bedrock geology.

4.1 Sites suggested as suitable for a SAT system

The Al Matah depression, being the area where the Queiq River and the wadis discharges, may accommodate a tremendous sediment thickness, as was similarly shown by the core drilled in the basin where the Kanab Creek arroyo is discharged (Nelson and Rittenour, 2014). However as explained by Luijendijk and Bruggeman (2008) these deposits are mostly lacustrine, which implies that the dominant sediment type is within the range of clay to silt. Cross sections drawn through the Al Matah depression show that the gradient is very low (~0,5 m/km), and with comparison with Table 3, this confirms the interpretation of clay as the main size fraction, which is undesirable for a SAT system. Also, considering the lakes, it is likely that the water table is found quite near the surface in this area, which implies a rather thin vadose zone. Instead, the wadis originated from the hilly parts of the area are by comparison with Table 3 expected to accommodate a wider range of sediments and a thicker vadose zone than the Al Matah depression and would therefore be more suitable for a SAT system. Figure 9 and 10 are two maps that repeatedly will be referred back to in the following sections. Figure 9 shows the location of the wadis on the georeferenced geology map and figure 10 is a DEM that shows the location of cross profiles through the wadi valleys.

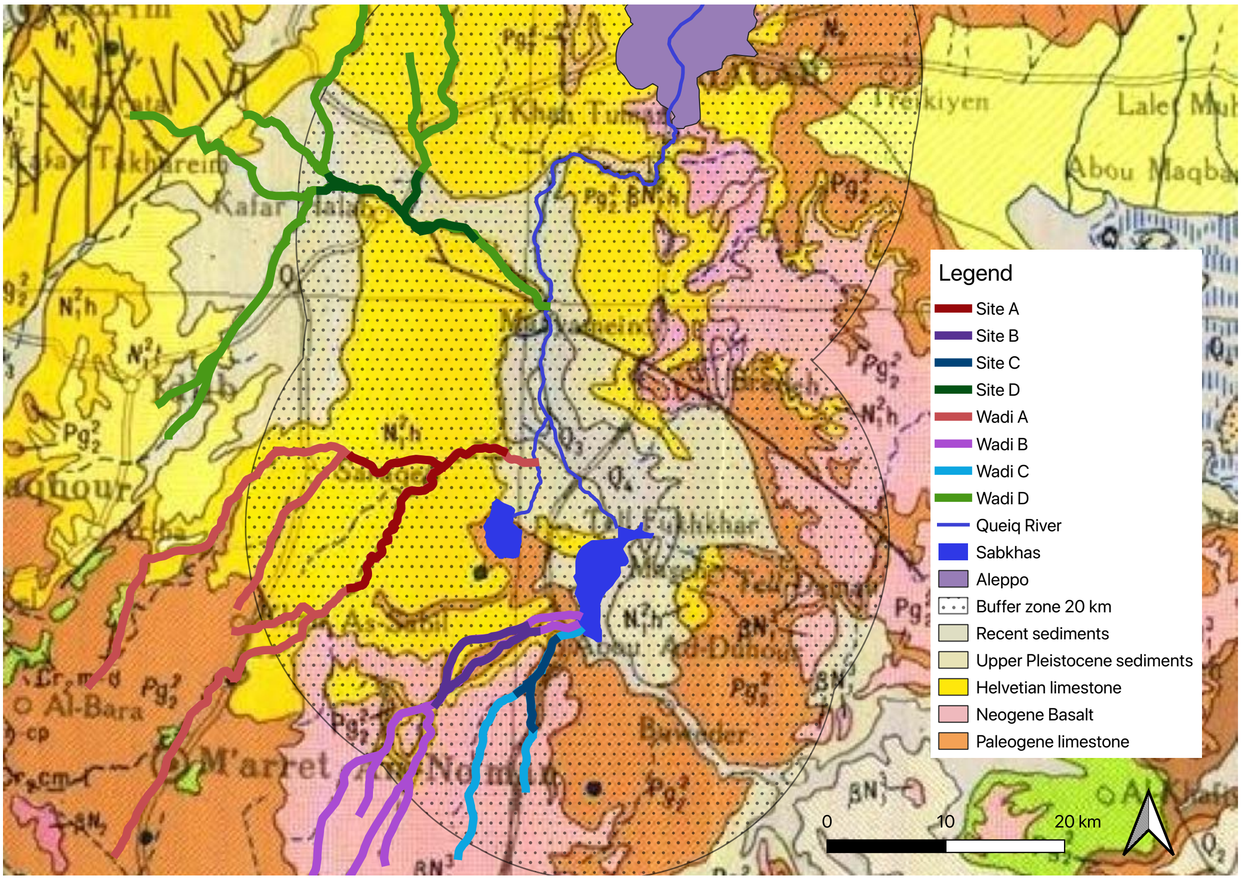

Figure 9: Location of the wadi valleys on the georeferenced geology map by Ponikarov (1964).

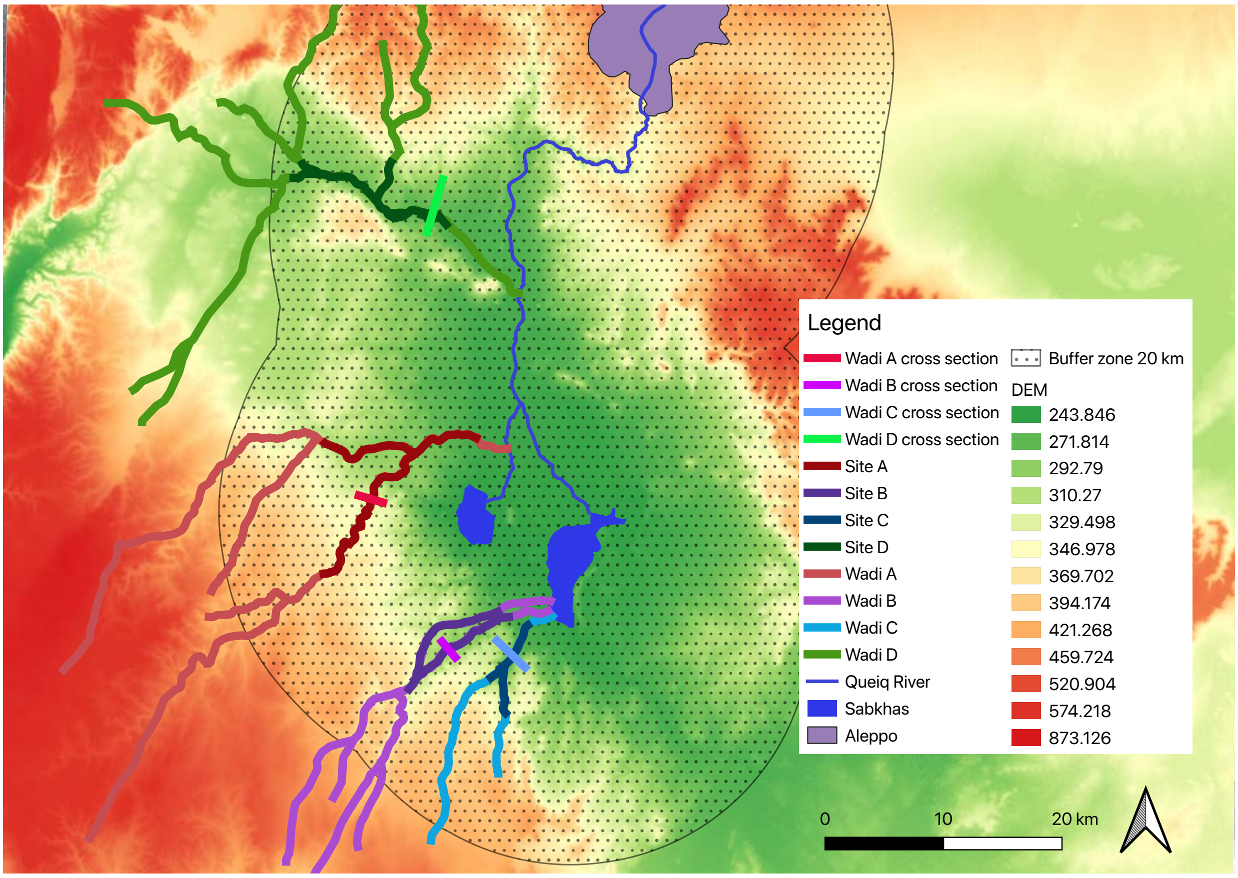

Figure 10: Location of transverse cross sections through the wadi valleys.

4.1.1 Site A/Wadi A

Wadi A is 107,6 km long in total; however, the length is contributed by several tributaries that join into one major drainage closer to the outlet in the Al Matah depression. The streams originate from the Paleogene limestone, however, downstream, the valleys are incised into the Helvetian limestone (Fig. 9). The relief within the valleys ranges from ~9-32 m, being most incised upstream and less so as approaching the outlet. Figure 11 is a transverse cross section through one of the valleys and figure 10 shows the location of the profile. The stream gradient ranges from about 7 m/km in the upper segments from where the wadis originate to about 3,5 m/km at the lower segment, closer to the outlet. By comparison with the values in Table 3, the range of sediments to be expected ranges from gravel to silt and perhaps clay. The width of the valley bottoms varies between ~32-66 m with a trend towards a broader width downstream.

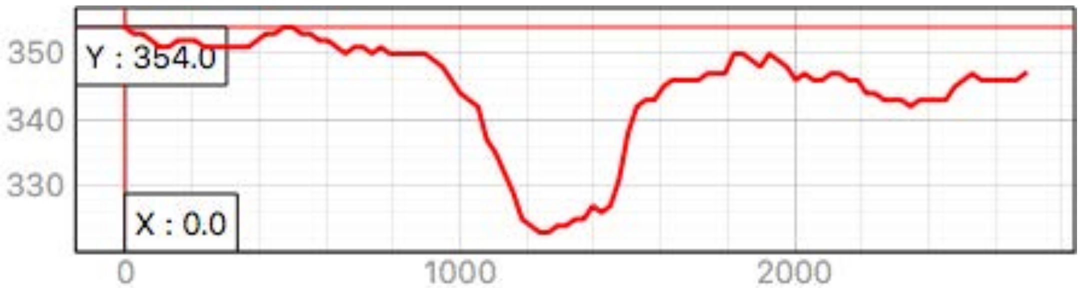

Figure 11: A transverse cross section of Wadi A. The length of the cross section is ~2,7 km and the vertical axis show a height difference of ~28 m between the level of the wadi and the uplands. Vertical exaggeration is x20. Location of the cross section is seen in figure 10.

4.1.2 Site B/Wadi B

Wadi B is approximately 77,3 km long with two wadi valleys joining as one at places. The wadis originate from an area characterized by Neogene basalt, however, downstream the valleys are incised into the Helvetian and the Paleogene limestones (Fig. 9). Figure 12 is a transverse cross section through one of the valleys being incised into the Paleogene limestone. Location of the profile can be seen in figure 10. The width of the valley bottom varies between ~73-138 m with a general trend of valley widening downstream. The relief between the level of the wadis and the surrounding uplands varies between ~17-54 m, which indicates a varying degree of valley incision. At its upper segments, the slope of the wadis is about 7,4 m/km and close to the outlet the stream gradient decreases to about 4,3 m/km. With comparison with Table 3, it is expected to find sediments in the range of gravel to silt.

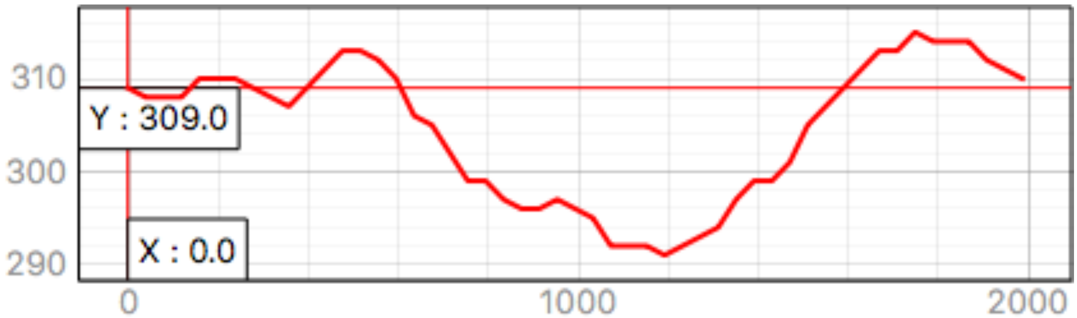

Figure 12: A transverse cross section of Wadi B. The length of the cross section is ~2,0 km and the vertical axis show a height difference of ~22 m between the level of the wadi and the uplands. Vertical exaggeration is x20. Location of the cross section is seen in figure 10.

4.1.3 Site C/Wadi C

Wadi C is approximately 32,4 km long and thereby the shortest wadi stream selected in the area. Two wadis join into one near the sabkha depression. The gradient along the streams is relatively steep and even at its lower segments, close to the outlet, the average slope is about 6,4 m/km. At its upper and middle segments, it has an average slope ranging from ~9,2-8,8 m/km. Comparing these values with the ones found in Table 3, the range of sediments to be found in the wadi are sand to gravel. The width of the valley bottoms varies between 42-136 m, becoming wider at its lower segment. The wadis originate from the same area of Neogene basalt as does Wadi B. Downstream, the valley is quite incised into the Paleogene limestone (Fig. 9), probably explained by the softness of this limestone. The degree of incision varies along the valley between ~20-49 m. Figure 13 is a transverse cross section through the Paleogene part of the valley. Figure 10 shows the location of the profile.

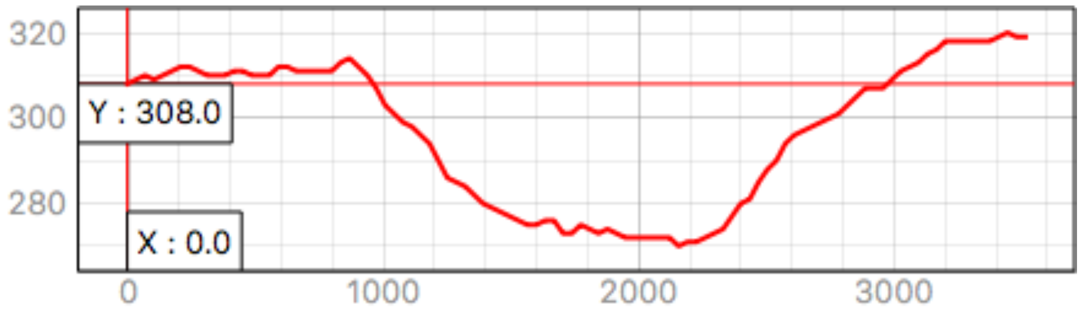

Figure 13: A transverse cross section of Wadi C. The length of the cross section is ~3,5 km and the vertical axis show a height difference of ~40 m between the level of the wadi and the uplands. Vertical exaggeration is x20. Location of the cross section is seen in figure 10.

4.1.4 Site D/Wadi D

Over its full length, Wadi D is about 152 km long, however several tributaries that join with the main channel contribute to this length. Still, all these streams should be taken into account since they contribute to the sediment supply to the main channel. In general, this wadi valley is broader than the ones already presented, with a range in width of ~32-432m, being wider at its lower segments. Figure 14 is a transverse cross section through the valley and figure 10 shows the location of the profile.

The range in relief between the level of the wadi and the surrounding uplands varies between ~14-71 m. The wadis originate from the Helvetian limestone (Fig. 9) where the average slope is 11,2 m/km, though downstream the streams are suddenly flattening out and the slope of the stream is decreasing to 2,1-1,1 m/km. According to the geological map by Ponikarov, this flat area is characterized by Quaternary sediments, though the question remains how thick these deposits are and what type of sediments there may be. When comparing to Table 3, it is suggested that this area accommodates mostly clay and silt.

Figure 14: A transverse cross section of Wadi D. The length of the cross section is ~4,9 km and the vertical axis shows a height difference of ~27 m between the level of the wadi and the uplands. Vertical exaggeration is about x30. Location of the cross section is seen in figure 10.

5. Discussion

The lower segment of a wadi valley, where the slope of the stream is at its lowest, is predicted to accommodate the absolute thickest sequence of sediments and is therefore suggested as being the most suitable site for a SAT system. An infiltration basin could be installed within the channel where the wastewater would be ponded and allowed to infiltrate, however, minding the high evaporation rates of the region and the relatively limited area of infiltration of the wadis, a vadose zone injection well could perhaps be more suitable.

As stated by Sharma and Kennedy (2017) and Aharoni et al. (2011), the most crucial requirements for efficient removal of effluents in SAT systems are the thickness and the permeability of the sediments in the vadose zone. Although there are no studies of the wadi sediments among the sites chosen, one may get an idea of the potential grain size by measuring the average stream gradient since this will say something about the carrying capability of the stream.

All the wadis suggested originate from the hilly parts of the area where the slope is relatively steep and the range of grain size, as compared to Table 3, may be from sand to gravel. Further downstream all wadis flatten out, which implies that grains within a finer range are deposited. The gradient of the lower segment of both wadi A and B implies sand and silt, perhaps even clay, as being the major type of sediments to be found here. Wadi C has a rather steep slope even at its lower segments which suggests that gravel and sand are able to be transported to this part of the wadi. Wadi D is different from the other ones by having a quite abrupt change in slope from the upper to the middle and lower segments. Also, the width of this valley is wider in average than the other ones. This broad valley could perhaps accommodate a great amount of sediments due to its broadness; however, the average slope suggest that clay and silt are the main sediment of the valley.

According to Pescod (1992), SAT systems demand sand and loams within the upper section of the vadose zone and coarser sediments below to permit a combined practice of sufficient infiltration capacity and fair retention time. This implies that a fining upward sequence, formed by an aggrading system, would be the optimal configuration. At least three of four sites, found in the lower segment of the wadis, seem to fulfil the sedimentologic requirement of sand and loam in the upper section of the vadose zone and since the wadis were initially formed by incising, erosive streams (Wedel and Stevens, 1990), more permeable sediment (sand and gravel) may be expected at the bedrock contact below each wadi. Though the question remains how thick these deposits may be.

Wagner (2011) states that the Al Matah depression is a result of tectonic activities in the region. As observed from satellite images and elevation data, this tectonic depression is a large fluvial basin, even though the wadis found within it only flow occasionally. Wahib Sahwan (personal contact May 13, 2020), who performed his PhD on geomorphologic and tectonic evolution of Syria, explained how the fluvial processes in the valley were active in the late Quaternary. This implies that the wadis during this time were not ephemeral streams, but rather perennial. Maher (2011) interpreted a period of increased deposition within Wadi Ziqlab in northern Jordan to be connected to a warmer and wetter climate post LGM and Stevens and Wedel (1995) suggested interglacials to favour axial stream deposition. Perhaps an increased activity of the fluvial regime in the valley of the study area is related to a similar response. A phase of increased runoff would have allowed streams and rivers to carry more material, resulting in a rather voluminous yield in sediments to the streams in the area. Also, since the fluvial activity within the valley was higher during the late Quaternary, perhaps coarser materials would have been able to be carried further downstream to the lower segments. As the Al Matah depression would have been filled up with sediments during this time the base level would have been raised. This could have caused the streams discharging into the area to aggrade and flatten out their slope, resulting in sedimentation of finer grain sizes. If the interpretation of aggrading systems within the wadis in the study area is found to be true, the possibility of introducing a SAT system would be rather high.

Al Abdalla et al. (2010) explained that Syria is quite recently affected by neotectonics and is experiencing uplift which one would expect to have caused incision within fluvial systems situated upon moving ground. Uplift, causing streams to cut down into the valley fill, leads to the abandonment of previous flood plains and the creation of terraces (Bridgland et al., 2017). If terraces are present in the wadi valleys of the area, infiltration could be allowed not only in the recent channel, but also in the abandoned flood plains found above (Wedel and Stevens, 1990). However, no terraces could be observed from the inspection of satellite images or elevation data. Instead, the absence of clear terraces suggests that the wadis have been aggrading for a long time.

The wadis found in the study area may hold a sufficient amount of loose sediments able to act as an aquifer for reclaimed wastewater. However, it is important that the water does not continue to percolate down through joints and fissures of the underlying bedrocks, perhaps leading to larger karst system that would disable the recovery process and induce a risk of native aquifer contamination (B. Lucke, personal contact May 15, 2020). Some of the wadi valleys are found to be initially incised into the hard Helvetian limestone, while others are established above the softer, chalky Paleogene limestone. B. Lucke (personal contact May 15, 2020), who performed a soil survey in the regions around Aleppo, explained how fractures were more commonly found within the hard and firm Helvetian limestones than the soft rocks of the Paleogene period. This implies that wadis found above Helvetian bedrock are at greater risk of having water seeping down to the deeper karst aquifers.

5.1 Suggested sites in context of their reliability

To suggest any wadi to be more suitable than another is impossible without a comprehensive field study. However, each wadi has properties that may be more or less appropriate for SAT.

At least one of these sites (site A) is initially incised into the Helvetian limestone, which may possess a lot of fractures and fissures and hold a risk of seepage down to deeper karst aquifers. Also, according to B. Lucke (personal contact May 15, 2020), the amount of sediments found within valleys of Helvetian limestone normally accommodates rather thin sediment sequences. However, this is a question in need of further investigation through a field study.

Site D, found within a broad valley, has a low average stream gradient which implies clay and silt to be the main sedimentology. However, with the fluvial history of the area in mind, there may be coarser materials found below these sediments. Also, as the valley floor is rather broad, one could expect a rather extensive and thick sediment sequence. Depending on the thickness of the clay, a vadose zone injection well could be used to overcome the low infiltration capacity of this layer.

Sites B and C are similar in the way that they are both found within wadi valleys incised into the Paleogene limestone. As informed by B. Lucke (personal contact May 15, 2020), the amount of sediments within this type of valleys may be rather high. Also, for site C, the slope of the lower segment suggests that rather coarse sediments are transported to this part of the wadi. This implies that site C would be most suitable for SAT. Regarding the SAT system type, a vadose zone injection well would be the most appropriate option, minding the relatively limited land availability of wadis. Also, as the evaporation rates of the region is rather high, water ponded in infiltration basins may be at risk of evaporation losses.

5.2 Proposed field work

The wadis suggested as potential sites for a SAT system likely hold the type of sediments desired for a sufficient reclamation process. However, questions, impossible to answer without enough field data, remains to be answered. One of the most essential questions regarding the possibility to introduce a SAT system is the question about the sediment thickness, as indicated above. In this case, geophysical measurements would be the best option. A seismic investigation is recommended since this method can distinguish between unconsolidated and consolidated materials. Seismic waves move faster within solid rock than loose and unlithified materials, resulting in a signal that indicates the depth to the bedrock. Even though limestone, being a sedimentary rock, may not show as distinct difference in wave velocity as a magmatic or metamorphic rock would do, it should still mark a rather abrupt change in wave phase that would result in a confiding signal.

To be found suitable as a host for a SAT system, not only the thickness but also the infiltration possibilities of the wadi sediments must be sufficient. The Quaternary sediments within in the valley are suggested to be within a range of pebbles to clay. To know the stratigraphic occurrence of these deposits the best option would be to take a drill core through the sediment sequence. The auger would also be able to tell the depth to the consolidated surface and would thereby perhaps be a more effective way of achieving information about both sediment characteristics and thickness.

Finally, even though previous measurements have shown that the native ground water is found at rather deep depths when moving away from the Queiq River, (A. N. Aldarir, personal contact May 10, 2020), an investigation about the depth to the water table should be conducted. Observation wells would be one option but perhaps a more cost-effective way would be to use transient electromagnetic measurements (TEM). TEM is geophysical method, very commonly used in groundwater explorations, where electric and magnetic fields induced by transient pulses are used to locate the depth to the groundwater.

6. Conclusion

Four sites, found in the vicinity of the intended pumping source, are suggested to accommodate sufficiently thick and permeable sediment deposits. All sites are found in the lower segment of a wadi as this part normally holds the thickest sequence of sediments. The climatic changes during the Quaternary have most certainly affected the past fluvial activity and sedimentation pattern of the region and are suggested to have caused aggradation within the wadis of the study area. Aggrading systems implies rather thick deposits and fining upwards sequences, desired for a SAT system. If this interpretation is true, the possibility of introducing a SAT system in the area is rather high.

Even though the sites may be suitable for a SAT system, there are some potential limitations, such as thick layers of sediments with a low infiltration capacity. However, in this case a vadose zone injection well could be adopted that would overcome this issue. A vadose zone injection well could also prevent evaporation losses, which would be a complication for water ponded in infiltration basins, and is a good option for a relatively small infiltration area.

Some sites have certain characteristics that may be more favourable for the development of a SAT system than others; such as the broad width of site D, which implies a rather extensive and thick sediment cover, or the quite steep gradient of site C that suggest coarse sediments to be transported to this part of the wadi. However, a comprehensive field study is needed before a confident statement about any site being more suitable than another can be made.

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