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**Survey and assessment
of ancient Cisterns
in the West Bank**

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Contents

1	Introduction	4
1.1	Previous Studies	4
1.2	Definition of a Cistern	5
1.3	Key Issues for Water Management	5
2	Methods	6
3	Results	8
3.1	Location	8
3.2	Age and Appereance	12
3.3	Condition	12
3.4	Size	13
3.5	Ownership	13
3.6	Catchment Area	14
4	Potential	15
4.1	Storage Capacity	15
4.2	Harvesting Potential	16
4.2.1	Rainfall Runoff Model	16
4.2.2	Model Application	17
4.2.3	Example: Al Manyia	19
4.3	The Cost of Cistern Water	20
5	Discussion	22
5.1	Representativity and Reliability	22
5.2	Pros and Cons of cistern usage	22
5.2.1	Economics	22
5.2.2	Drinking water from cisterns	23
5.2.3	System Robustness	23
5.3	Sustainability	24
6	Conclusions	25
6.1	Summary	25
6.2	Proposed criteria for restoration projects	25
6.3	The role of cisterns in integrated water management	26
6.4	Further Research	26
A	Cisterns that should be restored	29

List of Figures

2.1	Sketch of the shape of a model cistern and measured lengths . . .	7
3.1	Cisterns in Umm Salamuna and Beit Fajjar	9
3.2	Cisterns in Al Manyia and Tuqu'	10
3.3	Cisterns in and around Sa'ir	11
3.4	Condition of surveyed cisterns	12
3.5	Volumes of surveyed Cisterns	13
3.6	Catchment area sizes of surveyed Cisterns	14
4.1	Rainfall Runoff model for 2004/2005	18
4.2	Harvesting potential of surveyed cisterns	18
4.3	Relation between volume and harvesting potential	19

List of Tables

3.1	Property Status	14
4.1	Model Values	16
4.2	Harvesting Potential	17

Chapter 1

Introduction

Water management in the middle east is a business as old as civilization itself. Regardless of the struggle over land that has ever been going on, all the people that lived here struggled to obtain the water that made live possible. They came up with technologies and systems to use every drop of water they could find. Many of these ancient facilities can still be seen or are even in use. Rainwater collecting cisterns which are at the focus of this report are one of these ancient means of producing water.

Facing today's water crisis in the West Bank and considering the depressing inhibition of development due to Israel's occupation there is hope that cisterns can provide solutions. They may help to provide water in remote areas and relieve those who suffer from severe water shortage. They might improve agricultural production. They might as well be a sustainable and profitable way of producing fresh water. This report assesses the value of ancient cisterns with regard to these hopes.

1.1 Previous Studies

There are no studies known that focus merely on ancient cisterns. Related research about ancient smallscale water harvesting techniques is done whithin the project Rainkeep in Jordan [9][17]. Archaeological interest in cisterns is usually limited to those connected to great and prestigious structures like herodian castles, which are well described in the literature [5]. In the Levant cisterns are so common and abundant that they seem not worthy of being studied. However this very abundance shows that they once played an important role about which little is known.

Especially quantitative studies about cisterns and ancient rainwater harvesting are hard to find. Biswas [4] has introduced the linkage between archaeology and hydrology in 1970. Recently there has been considerable interest in rainwater harvesting as an alternative source of water. NGOs like Care International and Oxfam have implemented projects for development of new and old cisterns. Also there is hope that ancient techniques may be more sustainable than industrial systems. The open question is, is it worth to use and build onto these ancient small scale systems and how effective have they been? This report contains the results of an extensive field survey of 83 cisterns in the area south of

Bethlehem and attempts to give an answer to this question based on observation and modeling.

1.2 Definition of a Cistern

A cistern (from Greek kiste, basket) is a receptacle for holding liquids, usually water. Often cisterns are built to catch and store rainwater. They range in capacity from a few litres to thousands of cubic metres (Wikipedia).

For the purpose of this paper I define a cistern as a cavity in the ground with impermeable walls that is used to store water. More abstract, a cistern serves as a buffer that allows to meet an irregular demand with an irregular supply. Input can be harvested rainwater, irregularly delivered tap water or truck delivered water. The output of water may be used for drinking, for domestic use, for irrigation or for livestock.

1.3 Key Issues for Water Management

Water management in the West Bank is complex. There are three main issues that need to be addressed. First it is a semiarid to arid region with water scarcity and heterogenous precipitation [2]. The hydrology of the Palestinian aquifers is extremely complex and the available resources need to be shared between several countries. According to experts, the net extraction of available conventional resources is close to its sustainable maximum while the population and the demand are growing at high rates [12]. The status quo is critical, with an average Palestinian water consumption of only 55 liters per day, while the minimum recommendation of the WHO is 100 liters a day [3].

Second, in the setting of the middle east conflict and the current occupation of the West Bank, geopolitics and watermanagement are closely intertwined. This adds a layer of treaties and restrictions that have to be considered for the management of water supplies. In fact for Palestinians political and military restraints are the major cause of today's water shortage [11][3][7]. The future development of this situation is dependent on many political factors, resulting in great uncertainty for planners.

A third variable is the effect of climate change in the region, which still is quite uncertain. The Israel national report on climate change of 2000 [14] forecasts a decrease in precipitation between 4% and 8%, higher intensities of precipitation and a shortened, delayed rainy season. In a more recent high resolution study it was projected that the runoff of the Jordan river will decrease by 82%, crippling the only supply of surface water [8].

Hence we are confronted with an already tense situation which is dominated by rigid external factors that are likely to change with time, but we are unsure how. This imposes a great deal of uncertainty and any strategy should be assessed for its robustness towards a wide variety of scenarios.

Chapter 2

Methods

The survey comprises a total of 83 cisterns located in the area between Bethlehem and Hebron (Al-Khalil). 35 parameters concerning location, size, catchment area, condition, building material and property status were taken. The cisterns were chosen by local guides who knew the old cisterns of their region. Their knowledge was matched up to cisterns shown in British Mandate maps of 1944 [1]. In the field, an attempt was made to find these mapped locations, supported by the advice of locals. However, the locals pointed out many more old cisterns than there were to be found in the maps. All sites were located with a GPS Tracker, photographed and measured.

It is not trivial to measure the volume of a cistern, since they have irregular shapes, are difficult to enter and often it is impossible to see past the entrance shaft, called zinnar. On the ground of a cistern there is usually some sediment, which can take up a considerable share of the volume. For all cisterns the depth was measured, whenever possible the average width as well. Additionally, the length of the zinnar was measured and the thickness of the sediment estimated. From observations in the accessible cisterns, a rough geometric model was developed that treats a cistern as a cone on top of a cylinder as sketched in figure 2.1. The formula for the volume derived from this model is very handy:

$$V = 3/4 * (depth - zinnar + sediment) * (1/2 * width)^2 * pi \quad (2.1)$$

The width was measured with a laser meter from below the zinnar, or if accessible from inside the cistern. This measure could be obtained for 46 cisterns. For the others it was first assumed that the width depends linearly on the depth. Hence the known widths were regressed on their respective depths, providing a regression model for the cistern width. However the confidence intervals in this model's predictions were too wide and it was concluded that the depth can be very misleading when trying to estimate the volume of a cistern. Cisterns with a non-circular base area were treated individually.

For each site the area, the slope and the land use of the catchment area were observed. The goal was to assess the runoff and harvesting potential of these areas. It should be noted that not all catchments were actually in use. When a cistern was operating, the obvious drainage area was measured. When it was not in use, the historic catchment area was measured whenever it could be identified by remainders of drainage ditches and channels. If this was impossible, a new

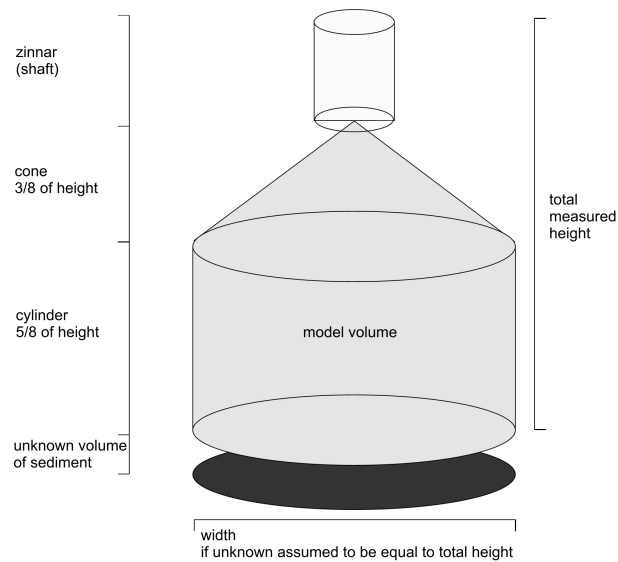


Figure 2.1: Sketch of the shape of a model cistern and measured lengths

potential catchment was measured that usually consists of roads or buildings that cut through the historic catchment area.

Natural catchments were further scrutinized, noting the fractions of the surface covered by bare solid rock, loose rocks with a diameter smaller than 25cm, rocks with a diameter smaller than 3cm, sand, earth and vegetated area. These results were later used for the estimation of runoff on the respective catchments.

Chapter 3

Results

3.1 Location

83 cisterns in the area between Bethlehem and Hebron (al-Khalil) were studied. The visited municipalities are Beit Fajjar, Umm Salamuna, Sa'ir and Tuqu'. The cisterns locations can be seen in exhibits 3.1, 3.2 and 3.3. The red dots denote cisterns that are specified in British Mandate maps. The yellow stars denote surveyed cisterns. Occasionally these two symbols overlay which means that the location in the old maps could be verified. Sometimes they are very close to each other, which allowing for some error means the same thing. Many times however, surveyed cisterns were not shown in the British maps, even though they clearly existed at the time, are operating and of large size as for instance the Sachemet system in Sair (Survey ID 50 to 52). Of 83 surveyed cisterns, 19 were previously known from the British Mandate maps. There was one instance where a cistern from the old maps could not be found. The cisterns with survey ID 49 and 63-68, are not shown in the maps because they are outside the scope of these maps. Cistern number 49 is in Bethlehem, numbers 63-68 are 3km south of Sa'ir next to Wadi Rim.

Unfortunately it is unclear, which cisterns the British included into their maps, or if it was even their aim to map them all. In the collected data no evidence is found for a systematic difference for the previously known cisterns to the newly found ones. Possibly they only mapped public cisterns, as it is well known that the majority of houses has a private cistern. If this is the case property status must have changed for some of them. The most likely assumption is that they mapped mainly public cisterns, but did not aim for completeness.

The true spatial distribution is hard to determine from the surveyed sample, because it is not complete. Also the locations from the British maps are not very useful for that, as this is not a complete collection either. It seems that a string of cisterns can usually be expected along the main roads of villages, as this is the place where the oldest houses are. In the countryside there are cisterns basically anywhere. It is not sure, if the cluster of cisterns south of Tuqu' is an exception or if this is the usual density of rural cisterns. Certainly there are many more cisterns to be found than shown in the map. An estimate to that is given in chapter 4.

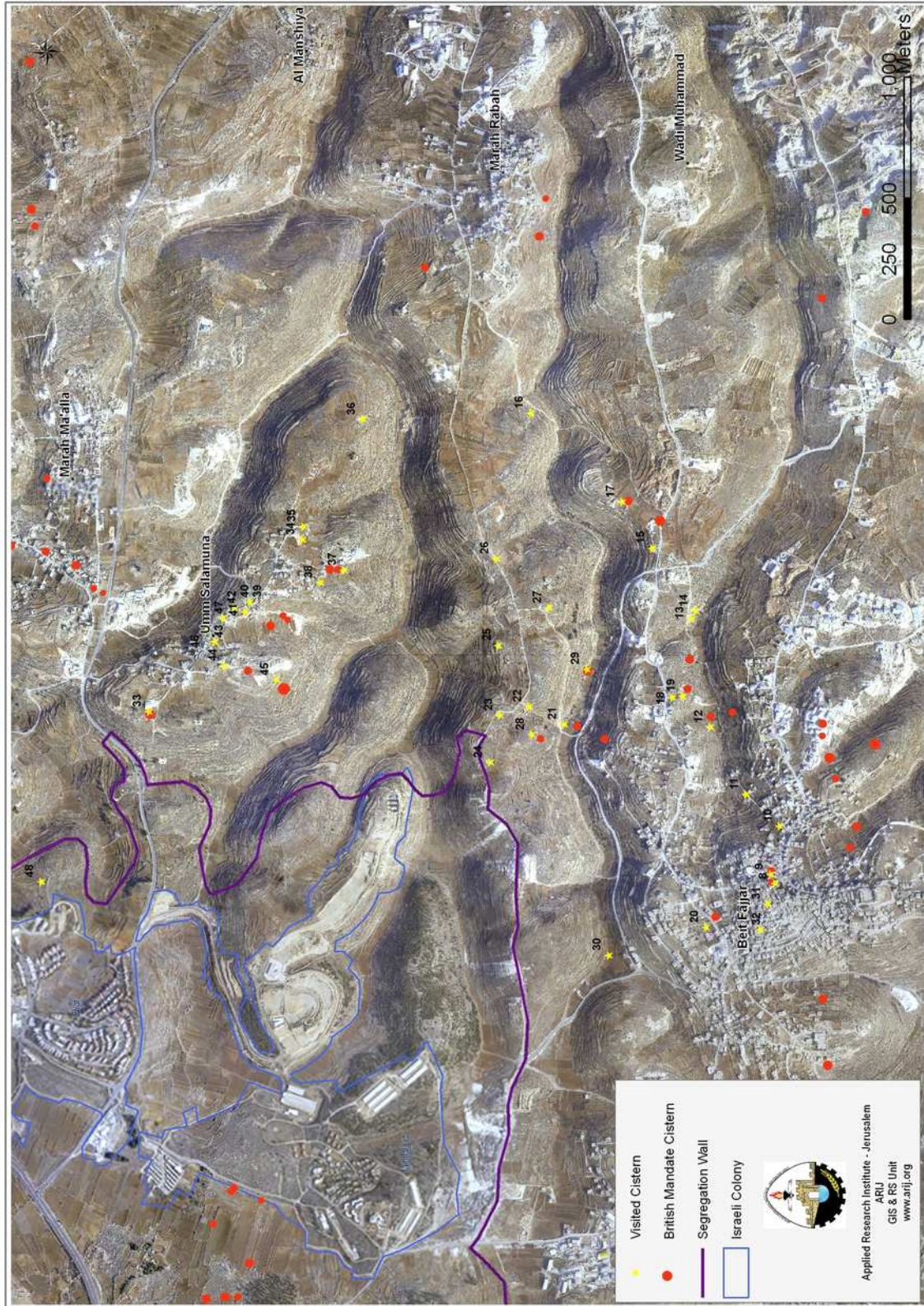


Figure 3.1: Cisterns in Umm Salamuna and Beit Fajjar

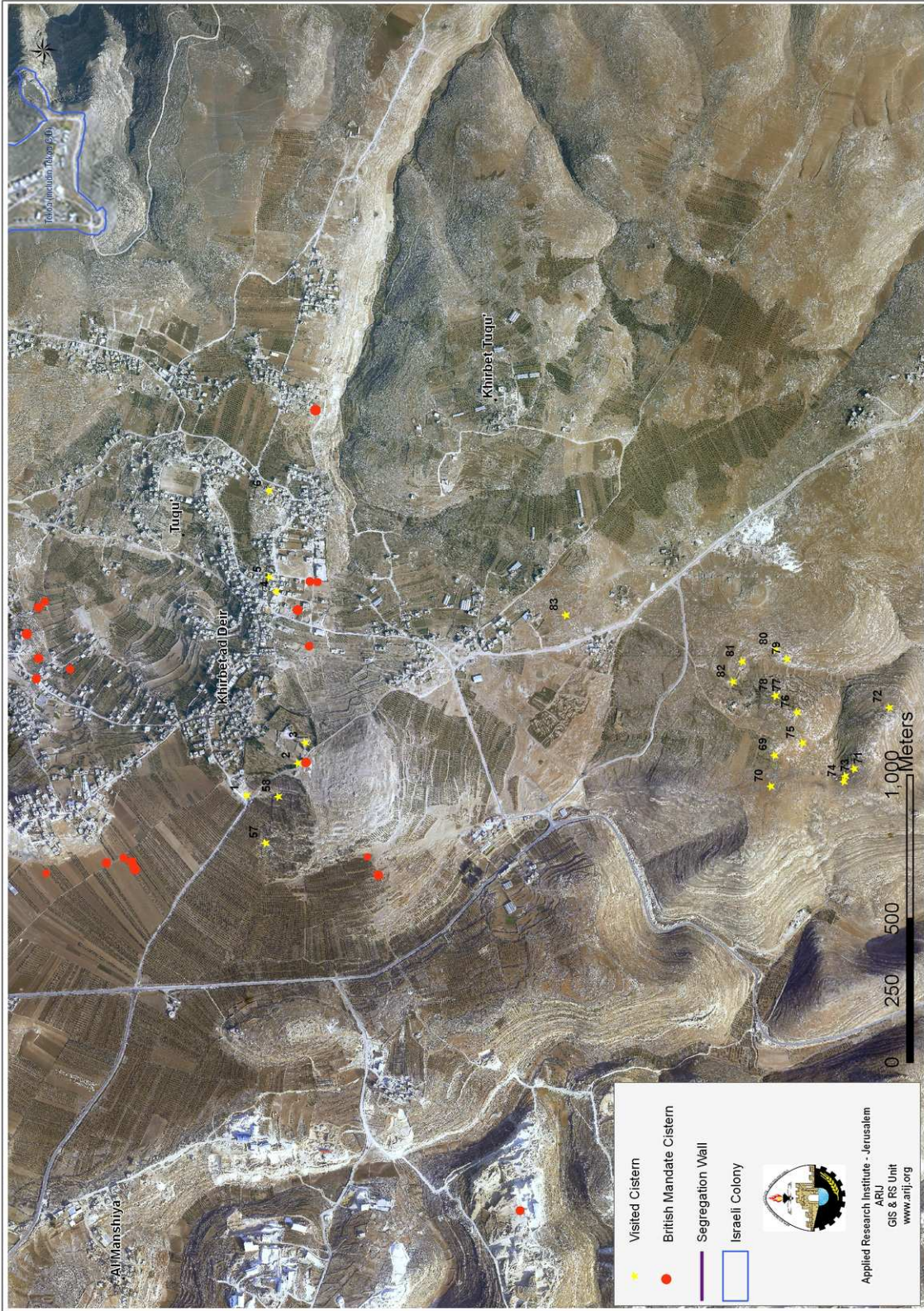


Figure 3.2: Cisterns in Al Manyia and Tuqu'

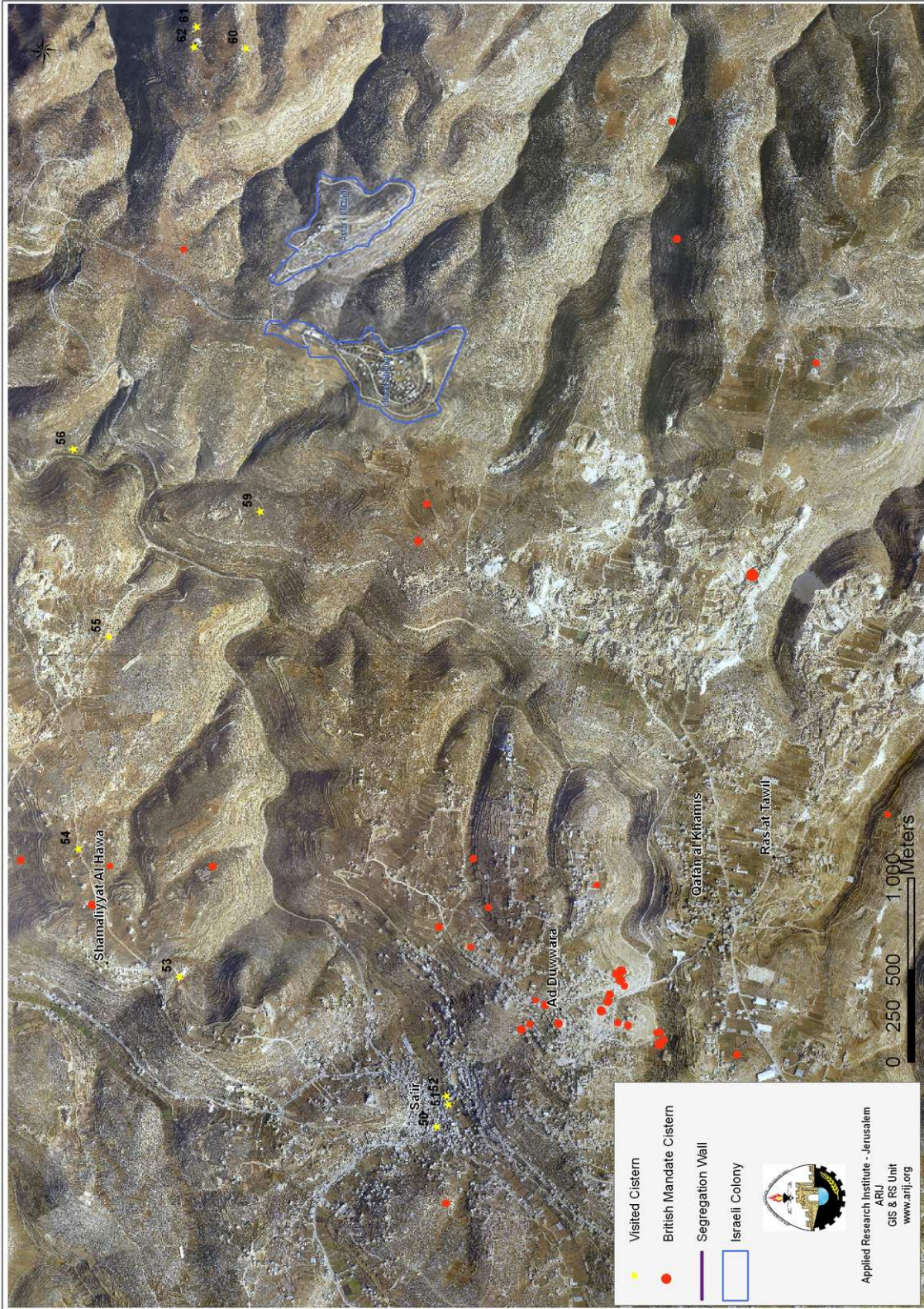


Figure 3.3: Cisterns in and around Sa'ir

3.2 Age and Apperance

The age of the surveyed cisterns is unknown, however from their apperance and from statements made by local guides they are surely more than 60 years old, with their potential age reaching several thousand years. Many for instance have their original cover ring on top, a massive hand dressed rock ring, which would in modern times have been replaced by a concrete structure. Others have several layers of different cements on the wall, suggesting that they have been used and reused during different periods in history. Also a common sight are rock hewn basins next to the cistern which provide a drinking spot for cattle. Some cisterns have rock hewn sedimentation pools prior to the inlet of the cistern to settle out particles. Contrary to the prominent pear or bell shape that is proclaimed in most literature to be typical, the studied cisterns are better characterized as having a narrow shaft that expands after 1-2m quite rapidly resulting in a cone, which is followed by a cylinder as it is shown in exhibit 2.1.

3.3 Condition

55% of the surveyed cisterns are operating in the sense that they do harvest some water and there are people that actually use it. Few are conveniently connected to a pump, but almost half of the operating cisterns suffer from leakage. The other 45% are out of use for a variety of reasons, half of them because they are filled with rocks or trash. Figure 3.4 shows the condition of the cisterns in a graph.

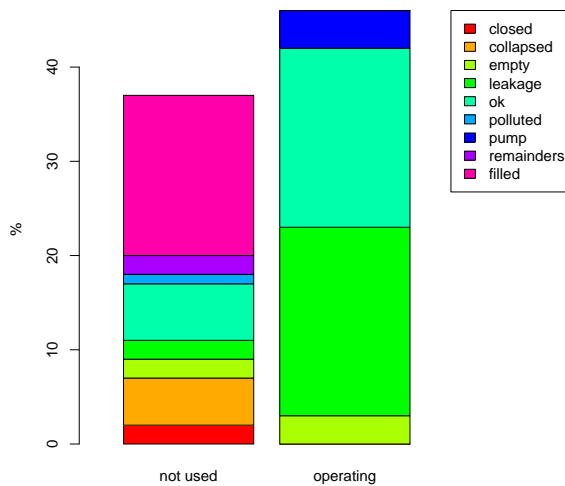


Figure 3.4: Condition of surveyed cisterns

3.4 Size

The volumes of the 46 measured cisterns are shown in figure 3.5. The volumes range from 3m^3 to 428m^3 , the mean is 92m^3 and the median 58m^3 . This means that most cisterns are smaller than the average. Clearly the sample is dominated by 11 large cisterns with over 100m^3 that make up 60% of the total volume. On the other hand there is a large number of cisterns evenly distributed around 60m^3 . The biggest cisterns were found in Khirbet Tuqu', an ancient Roman settlement and in the area of Al Maniya. Unfortunately some of these big cisterns have collapsed.

The volume bars are coloured according to the land use of the catchment of the respective cistern. The very big cisterns are those with a catchment on bare or agricultural land, therefore rural cisterns. The smaller part below 150m^3 is a mixture of rural and urban cisterns. There is no significant difference in size for other factors like ownership or condition.

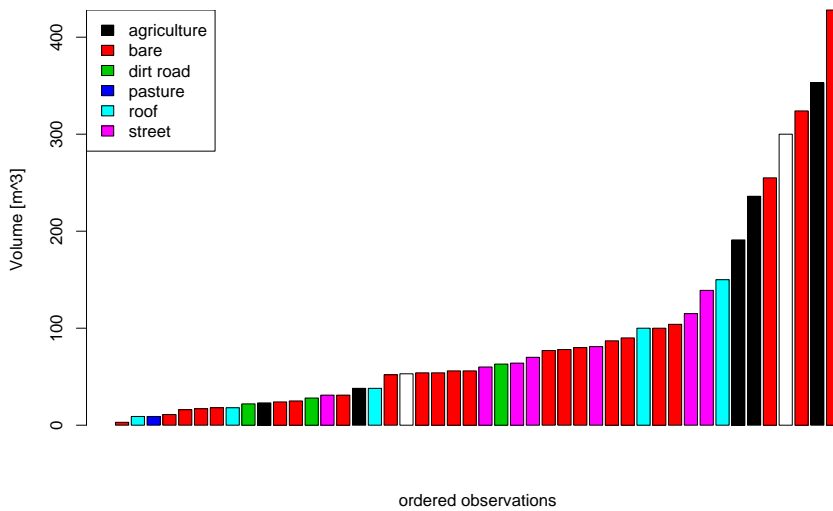


Figure 3.5: Volumes of surveyed Cisterns

3.5 Ownership

Ownership is an important parameter, especially concerning restoration of cisterns. There are three types of ownership: privately owned cisterns, publicly owned cisterns, and private cisterns, that are nevertheless open to anybody. During the field trips it became very clear that privately owned cisterns have the best chance of being maintained. Only private cisterns for instance had a pump connected to it. Most cases of leakage were found among the public cisterns. About half of the private and private-open cisterns did not suffer any major problems (condition = "ok"), for public cisterns this fraction is only 1/5.

Table 3.1 shows the relationship between ownership and status of the surveyed cisterns. It is obvious that those privately owned are more often operating than the others.

Table 3.1: Property Status

	not used	operating	
private	7	19	73% operating
private, but open	10	11	52% operating
public	9	14	60% operating

3.6 Catchment Area

The sizes of the catchment area are similarly distributed as the volumes of the cisterns, shown in figure 3.5. The mean is 413m^2 and the median 200m^2 . Again the bars are coloured with respect to land use and similarly as for the size distribution there is a couple of large catchments dominating the sample. However these large catchments are not identical with the large cisterns. There is no urban cistern with a roof catchment larger than 900m^2 .

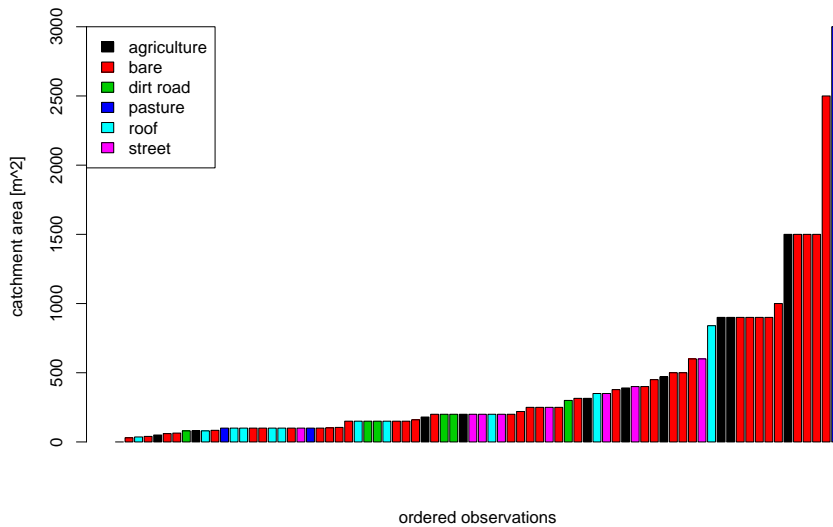


Figure 3.6: Catchment area sizes of surveyed Cisterns

Chapter 4

Potential

One question of great interest is the potential of cisterns to contribute to a general water supply. Depending on the answer to this question it will become clear to what extent a restoration of cisterns will have benefits. The total storage capacity must be estimated, the harvesting potential and the price of the water produced in this way.

As the study was limited to a selection of ancient cisterns within a limited area, some assumptions will be necessary. However, compared to other estimations of cistern potential in the literature, numbers and assumptions are presented in a way that anyone with additional information can make his improvements [the author highly appreciates these comments, please do not hesitate to send them]. As described in chapter 2, the survey was carried out based on both maps from the British mandate period as well as guidance from locals. In this chapter, the total abundance and volume of ancient cisterns is estimated, the amount of rainwater they can potentially harvest and the cost of this water.

4.1 Storage Capacity

The most conservative statement sticks to the surveyed cisterns. Between Bethlehem and Sair there are 83 verified ancient cisterns with a total volume of 6400m^3 , thereof 2900m^3 operating. Concerning restoration, the cost will differ depending on the condition of the cistern, especially for the collapsed ones, but for now it is assumed that all of them would be restored, hence yielding 6400m^3 of cumulative storage volume. The British maps show 1709 cisterns in the entire West Bank, some of them west of the green line and 230 in the study region. For every cistern previously known from the British maps there were 3 newly found during field trips. A reasonable estimate is therefore that there are at least 4 times more cisterns than shown in the maps. Using the 58m^3 median this would result in roundly 7000 cisterns and a total cistern storage capacity to 400.000m^3 for the entire West Bank and almost 1000 ancient cisterns with 58.000m^3 for the study area.

Comparison to other numbers The Humphrey Report of 1936 [6] casts a harsh light on these estimations. In a report concerning the water supply of Bethlehem, Humphrey estimated that there are 1300 cisterns of average 60m^3

in Bethlehem and Beit Jala. While the volume is in good accordance with the obtained results, the British Mandate maps show for these two municipalities not a single cistern. According to Wahlin [17], a census from 1921 reported 7000 rainwater harvesting cisterns in Jerusalem. The British maps show about 10 cisterns in the greater Jerusalem area. The conclusion that there are more cisterns in reality than shown in the British maps remains. However compared to these numbers it seems they are off not by a factor of 4, but rather by 3 orders of magnitude. Therefore, to estimate the total abundance of cisterns, the British mandate maps are not useful. Also as a proxy for only ancient or public cisterns they do not serve well.

Just in order to get a rough idea of the impact of cisterns, it is possible to scale up the results of a questionnaire study that ARIJ conducted in Beit Sahour in 2005 revealing that 34% of households own a cistern. According to the PA census of 2007 there are 427'097 households in the West Bank. If we suppose the cisterns have a volume of 58m³ as it was observed in this study, it results in a total storage capacity of 8.7MCM. The total water demand in the West Bank in 2005 was 323MCM [7]. The main uncertainty in this estimation is, if Beit Sahour is representative in terms of household cisterns for the entire region. Also this estimate includes old and new cisterns.

4.2 Harvesting Potential

4.2.1 Rainfall Runoff Model

The best way to gain information about the potential of cisterns is a direct measurement of harvested water in a cistern. Unfortunately no data records were found for that. To circumvent this lack of knowledge, a rainfall runoff model was used that gives estimates of harvest potential based on precipitation and the properties of the catchment area. Therefore data on precipitation, runoff characteristics and the catchment itself is needed. Jens Lange et al. [10] conducted sprinkler experiments 10km west of Ramallah in order to study runoff characteristics of a catchment plot in the Judaeen hills. The following values were used to determine the runoff characteristics needed to estimate the harvesting potential of rainwater cisterns in the Westbank.

Table 4.1: Model Values

roof / street	immediate runoff with 95% conversion
rock surface	2mm of rain within 1 hour before runoff starts, conversion 90%
other surfaces	16mm of rain within 1 hour before runoff starts, conversion 30% after 50mm within 24 hours 90% conversion

The model was written in the open source statistics software "R" [15] and fed with hourly rainfall data measured at Birzeit university for the rather wet rainy season 2004/2005 and the rather dry rainy season 2007/2008. The data was kindly provided by Clemens Messerschmid and contains hourly rainfall intensities. The model takes into consideration the specified cutin values and antecedent wetness from the previous hour and from the previous day. Infiltration rates are assumed to be constant within the different regimes. For further details on the model please contact the author.

From the model table 4.2 and figure 4.1 could be derived. Table 4.2 shows the total runoff produced according to the model in two different years on three different surfaces. It shows that the harvesting potential on permeable surfaces is clearly inferior to solid rock or street surfaces. The total harvested amount is of course much lower in the dry year, but the respective percentage runoff coefficients are only slightly smaller. The magnitude of the runoff coefficients for permeable surfaces call for catchment areas of considerable size, or technological improvement. Figure 4.1 shows the cumulative harvest compared to the cumulative rainfall. It becomes clear that the main part of runoff is created by a few heavy rain events regardless if the year has been dry or wet. All rain that fails to exceed a certain intensity is lost.

Table 4.2: Harvesting Potential

Year	total rainfall	roof/street	rock	other surface
04/05	840mm	719mm (86%)	490mm (58%)	160mm (19%)
07/08	510mm	432mm (85%)	264mm (52%)	81mm (16%)

The obtained model values can now be applied to the observed median cistern with a volume of 58m^3 and a catchment area of 200m^2 where 35% of the natural catchments are made up of solid rock. The interplay within a catchment between impermeable and infiltrating patches is neglected. Also the differences in median size for the different catchment types are neglected because they are tiny. Following these specifications, the median cistern with a natural catchment would have harvested 55m^3 in the wet year and 29m^3 in the dry year, using only a fraction of its storage capacity. The cistern that is connected to a street or a house roof would have harvested 144m^3 and 85m^3 respectively. Coming the other way, the catchment for a cistern in order to be filled full even in a dry year should be $2.3\text{m}^2/\text{m}^3$ if it is fed by a roof or a street and between 4m^2 and 12m^2 per m^3 for a natural catchment, depending on its fraction of impermeable rock surface. This however is valid for areas with rainfall comparable to Ramallah, a region with comparably high rainfall in the Westbank.

4.2.2 Model Application

Figure 4.2 shows the harvesting potential for the survey sample as derived from the model for the wet year of 2004/2005. Unlike in the figures displaying volume and catchment area the large values stem not exclusively from rural cisterns. This is of course due to the higher efficiency of roof and street catchments. The median of harvesting potential is 89m^3 , the mean is 154m^3 and 49m^3 and 84m^3 for the dry year respectively. The relation between harvest and volume is further investigated in figure 4.3. Figure 4.3 displays the relation between harvesting potential and cistern volume in a wet year. All dots below the diagonal represent cisterns that will never be filled, because their volume exceeds their harvesting potential even in a wet year. These cisterns again belong to the group of very big rural cisterns. The dots above the diagonal represent cisterns that will be filled more than once during a rainy year and some of them will still be filled full when the year is dry.

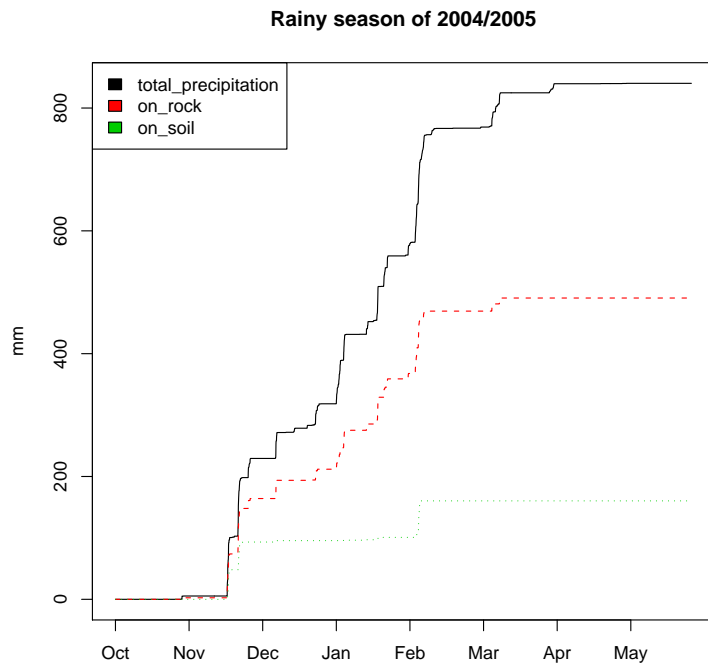


Figure 4.1: Rainfall Runoff model for 2004/2005

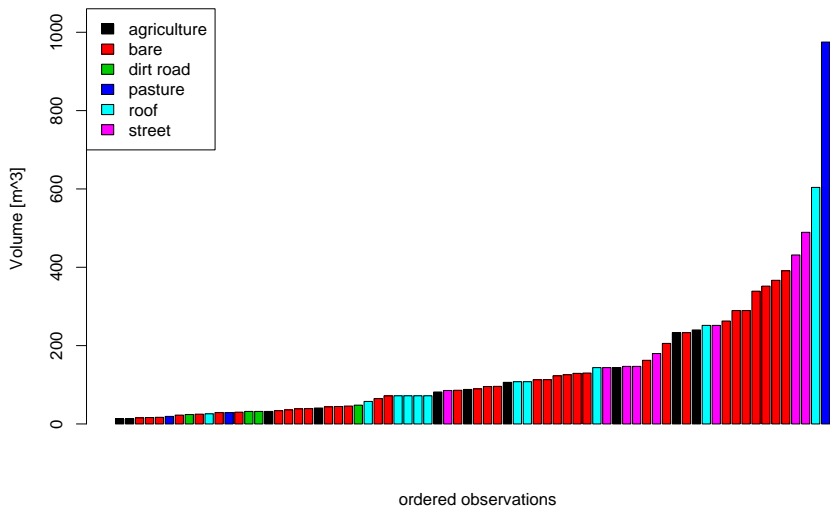


Figure 4.2: Harvesting potential of surveyed cisterns

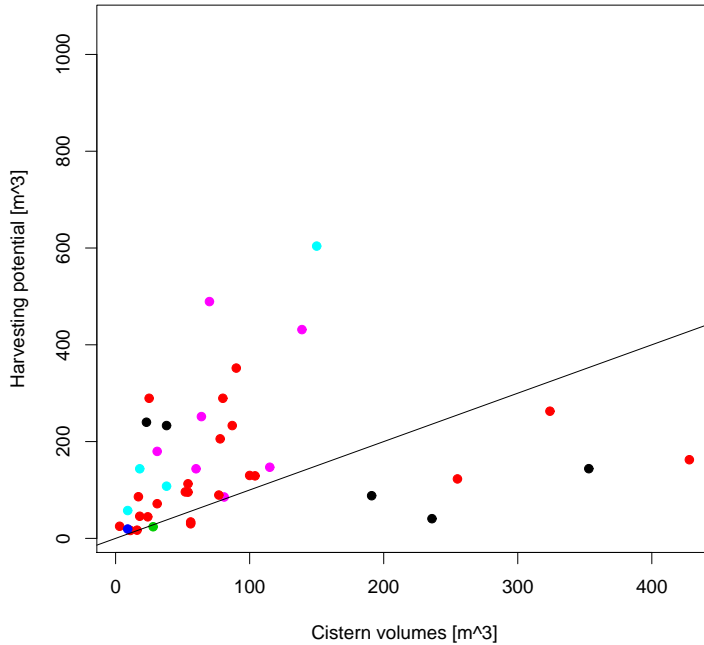


Figure 4.3: Relation between volume and harvesting potential

4.2.3 Example: Al Manyia

2km south of Tuqu' there is a valley with a lot of big old cisterns that was intensively surveyed. The locals call it Al Manyia. It is a very remote location at the northern end of Wadi Sair without connection to the pipe water system. There are a few people living close by who have to use mobile toilets. The land is owned by several large families from Sair by the names of Melat, Ngattar, Shamamia, Jabbrin, Fruch, and Shalalda. They used to come out here in the summer to take care of their fruit and olive trees. Water from the cisterns was used for drinking and irrigation of the trees.

Precisely there are 9 cisterns in one particular valley which have been surveyed. They have the IDs 76 to 83 and are shown in exhibit 3.2. Together these cisterns have a volume of 783m^3 and a harvesting potential between 1820m^3 (wet year) and 960m^3 (dry year) as derived from the model explained in chapter 4. The cultivated area down in the valley is approximately 7500m^2 . If the water from the cisterns is used for irrigation, additional 240mm of water for the crops are obtained in a wet year and more interestingly, additional 128mm in a dry year. These are significant amounts that can support a rainfed agriculture with supplemental irrigation. At the least this amount of supplemental irrigation can guard farmers against harvest losses caused by droughts. It would also be possible to keep the cisterns full over the summer and prepare in doing so for the next year in case it will be dry. In this way a delay of the rainy season can be tackled with 104mm of supplemental irrigation. This example shows

the effectiveness of ancient water supply systems. Of course these amounts are by no means comparable to the yearly yield of a well. But in ancient times the technology to drill deep wells was not available. And this system provided people with a livelihood and most importantly ensured it in dry years.

Nowadays half of these cisterns are out of use and none of them is properly maintained. The reason for that is most likely a change in lifestyle of the owners. Maybe these are relatively rich people that do not find it appropriate any more to live out in the country for several months every year. Or they do not think that it is worth to maintain the cisterns, because it will not pay off, or they lack the capital to make this investment. The people who actually live close to these cisterns are not their owners, so they do not have the right to alter them. The problem is that those people who are in the most desperate need of water do not own the cisterns whereas the owners live in the city of Sair and are connected to the pipe system.

More research should be done to find out what used to be the crops and techniques that were applied in this valley in the past. These and the migration of city population to the countryside is a cultural heritage that should not be forgotten altogether. Most definitely this farming system does not excel with extremely profitable yields as the land is problematic to be worked on with machinery. But cooperation between the owners and the local population and technological improvement of the existing structures could actually develop this weak region in a sustainable way.

4.3 The Cost of Cistern Water

The preceding chapters gave an estimation of how much water could be produced with rainwater cisterns. To make this source of water comparable to others, its cost must also be known. The cost varies depending on the state and capabilities of the cistern and therefore an example is presented from which a more general estimation is derived.

The engineer Mohamed Shalalkeh in Bethlehem has done a cost estimation for the restoration of the cistern in the SOS childrens village (ID 49, see appendix). The total cost is estimated to be 9172\$. This includes a concrete wall at the northern side for reinforcement, 4 layers of plaster and a final layer of watertight material. The harvesting potential is on average between the wet and the dry year 480m^3 . However the volume is only 150m^3 . For the optimal case that the cistern is emptied 2 times during the rainy season the effective yield is 450m^3 per year.

Since the proposed restoration activities involve 4 layers of plaster and a final layer of watertight material as well as the removal of adjacent trees there should not be a lot of maintenance necessary apart from sediment removal and roof cleaning, which is easily done for 100\$ a year. After 10 years it may be necessary to add a new layer of cement and watertight material at the cost of 1400\$. So eventually, for a lifetime of 25 years the cost of 1m^3 will be 1.27\$, after 50 years only 0.86\$.

According to the engineer office the choice of a site to build a cistern is actually quite tricky. If the soil is too soft a lot of reinforcement is needed. Rock hewn cisterns are the best but also the most expensive to dig. Supposedly a rock hewn cistern can work for up to a 100 years without constructional

maintenance. One factor to make this happen is to make sure it is never empty, as the constant moisture prevents cracks. Hence it has a great impact on the price of the water if a cistern is restored in a professional way. Especially if the cistern is restored within an aid project it makes sense to do it properly for once as the presence of the donor organization 10 years later is unsure.

The cistern number 49 in Betlehem's SOS children's village is not an average case. It is very large, it has a very productive catchment and is located in a region with comparably high precipitation. However we can remove some items from the cost estimate like the concrete reinforcement at a cost of 2600\$, the removal of trees for 400\$ the firefighting accessories for 875\$ and the installation of pipes from the roofs for 1250\$. With these deductions the pure cistern restoration costs about 4000\$ and the achievable price for cistern water will come down to 0.39\$/m³. This estimation considers the safe yield of 450m³ per year, an initial cost of 4000\$ and only an annual 100\$ of maintenance cost during a lifetime of 50 years. This beats by far the price most consumers have to pay for tap water in the West Bank, which is something between 1\$ and 3\$ [16]. But clearly this price of 0.39\$/m³ must be regarded as the lower achievable bound.

The critical figure in this example is the yearly yield of 450m³. A look at figure 4.2 reveals that this exceeds the harvesting potential of most cisterns, keeping in mind that figure 4.2 shows the situation for a wet year in Ramallah. Also it will not always be possible to empty the cistern 2 times during the rainy season. Hence the calculation shall be limited to cisterns that are only filled once every year. Figure 4.3 shows that this is possible for many of the surveyed cisterns. After this adjustment the price goes up from 0.39\$/m³ to 1.20\$/m³. For the less optimistic calculation of a renewal of plastering every 10 years and a lifetime of 25 years the price is 2.40\$/m³. Only considering the first 10 years it is 3.30\$/m³. To keep cistern water in this pricerange it should always be ensured that the catchment is large enough to fill the cistern full even in a dry year. Chapter 4.2.1 can give reference on how large the catchment should be. If this cannot be achieved, restoration will become very expensive as the cistern volume is not fully exploited.

The price of 2\$ per m³ can serve as a basis. If the cistern is actually in good shape and in use, just suffering from some leakage 0.5\$/m³ is achievable. If there is reinforcement or catchment development necessary the price can rise up to 4\$ per m³.

Chapter 5

Discussion

5.1 Representativity and Reliability

I would like to stress that this study is based just on a sample and quite a few assumptions. It should be seen as a first step into a field of research that has mostly been treated qualitatively. The measured data in chapter 3 is reliable. It should be representative for the region between Bethlehem and Sa'ir, but not for the entire West Bank. The projected and modelled data in chapter 4 must be handled with care and should whenever possible be matched against other data that can be found. Therefore I attempted to make every assumption comprehensible. As I have a genuine interest in the matter, anyone is welcome to contribute data that might help to make the estimations more precise. They will be treated confidential and hopefully compiled into a follow-up report.

5.2 Pros and Cons of cistern usage

5.2.1 Economics

Based on the presented results it can be concluded that cisterns are a feasible source of water. They can contribute to the general supply at a competitive price. One question that immediately arises is if those that are out of use simply are not profitable? Firstly this is a common good problem which is proven by table 3.1. Private cisterns are mostly in use whereas for public cisterns and also private open cisterns there is a lack of incentive to maintain them. Secondly restoration requires an investment which some owners actually cannot pay, especially because the price of cistern water only becomes interesting in the long run. Thirdly the possibility of being connected to pipewater discourages cistern usage, because this is easier, safer, provides unlimited supply all year round and is also cheaper in the short run. Especially for the individual it is cheaper, because the pipes are usually paid for by the municipality, which is actually appropriate.

5.2.2 Drinking water from cisterns

One issue that has not yet been addressed yet is the quality of water from cisterns. According to a study from northern China, rainwater harvested from roofs and controlled artificial catchments is able to meet international standards for drinking water. Rainwater collected from open land and especially roads was found to exceed many parameters of organic, inorganic and bacterial pollution [18]. However it can be used for irrigation or domestic use, if managed properly. The quality of drinking water from cisterns depends on the knowledge and ability of the people who maintain it. From the field studies I must conclude that people's knowledge about hygiene of drinking water is not sufficient. Several times there were catchments polluted with trash and animal excrements even though people drank from these cisterns. To foreclose the risk of spreading diseases by promoting the use of cisterns, only roof catchments should be used for drinking water and the users must be carefully educated on how to clean their roofs.

It should be noted that many people prefer to cook their tea with cistern water and not with pipe water because of the taste. This may be nostalgic or due to the chlorine in the pipe water, it shows that there is some interest to keep drinking water cisterns, even when there is plenty of tap water.

5.2.3 System Robustness

As outlined in section 1.3 the resilience of any development action should be assessed towards a variety of scenarios. With respect to the political environment there are mainly two options. The positive option is an end of the occupation and free development of economy and infrastructure. In that case operating cisterns provide an additional source of water that will vanish or prevail, depending on the price that is charged for water. House cisterns may be kept operating for reasons of taste but are likely to be forgotten if the price for water does not increase sharply. If there is an increase in price they will be kept running. Rural cisterns for irrigation have the same price dependency, but for ecologically oriented farming they will always be an important asset.

For the more pessimistic scenario that the occupation prevails, maybe even wars flare up, cisterns are a very good option. As they are not dependent on a central supply they endow their owners with independence and resilience towards crisis. They are exempt from shutdowns and destruction of the general water supply and in that context building and restoring cisterns is really a safeguard against rough times, because it reduces the vulnerability of the civilian population.

Regarding climate change cisterns are a good option. For the business as usual scenario it was proven that ancient cisterns can harvest substantial amounts of water. For climate change scenarios that predict a decrease in precipitation the effect may not be as harmful as it seems at first sight. As seen in chapter 4 the bulk runoff is created by just a few extreme events. If precipitation hence becomes less but more intense [14] there is a good chance that cisterns will yield a good harvest still. This property makes cisterns a key solution to save rainfed agriculture into the future. Even when rainfed agriculture is considered a low tech enterprise without high margins, it is possible that drinking water will become too costly to use it for irrigation and force many farmers to operate in a rainfed mode or shut their business down.

5.3 Sustainability

Are ancient cisterns a sustainable method of producing water? Is the way the ancient people lived more sustainable than ours? This question opens up a wide field but some comments shall be made. Ancient civilizations had two major advantages to our modern civilization: Their standard of living was low and the population was small. Nevertheless they managed to inflict severe damage onto the environment such as the deforestation of most of the mediterranean forests.

To achieve sustainability the triple bottom line of environmental, social and economic yields must be positive. Based on this study it is not yet possible to assess if the community of the example of Al Maniya in section 4.2.3 has lived sustainable in that sense. It is for instance not known, if this type of agriculture could support the entire population that depended on it. For sure the water consumption per person was very low which goes along with a little impact on the environment. However a water consumption below the WHO recommendation of 100 l/c/d is not desirable nowadays.

So far it has been argued that cisterns are resilient. Together with the estimations to the cost in section 4.3 this translates into a long term economic benefit. Cisterns as an additional source of drinking water can be sustainable. Cisterns as a sole source of drinking water however will result in an insufficient supply that can give great relieve in emergencies but cannot be labeled as sustainable. The case is different for irrigation water. Supplemental irrigation can result in very sustainable farming systems [13], if managed correctly and embedded into the community. The fact that ancient cisterns are part of the history of the people the chance of introducing sustainable systems is much higher, because people can identify with the technology.

Chapter 6

Conclusions

6.1 Summary

According to the field survey a median ancient cistern has a volume of 58m^3 with the large ones having over 400m^3 . About half of them is operating, and again half of those suffer from leakage leaving a quarter that is in good condition. Private cisterns are more often operating than public ones. Catchment areas are at a median of 200m^2 . The area of al Manyia shows that with the ancient system of rainwater collection a supplemental irrigation of 128mm to 240mm is possible, depending on the rainfall. The storage volume is so large that 100mm could in theory even be released in the next rainy season to encounter a delayed rainy season.

Ancient cisterns but also cisterns in general have a good record when it comes to being robust towards future scenarios in the West Bank, especially the pessimistic ones. They limit civilians' vulnerability in times of crisis and they serve as adaptation measure to climate change. It is obliged to the decision-makers, if they prefer to invest in fail-safe basic technologies or rather work towards a more optimistic scenario featuring recognition of Palestinian water rights and fighting climate change. For civilians on the ground there is no doubt that cisterns can relieve some of the from a very tense situation.

6.2 Proposed criteria for restoration projects

In order to select a cistern for restoration the following criteria are recommended.

- The catchment must be large enough to fill the cistern at least once a year. If possible, rainfall data should be found and analyzed. If this is not available, nearby cisterns should be scrutinized to obtain an estimate of the available runoff.
- Cisterns that are currently used as a source of drinking water must be considered first. It must be ensured that the water comes from a clean catchment and the users are informed about basic hygiene.
- A committed owner must be found for any restored cistern. Without a good ownership arrangement maintenance will fail. For public cisterns a

functioning group of stakeholders must be built. In cases where the owner lives far away a leasing of the cistern could be considered.

- Agricultural cisterns of large size are good objects to be restored as this is the option has benefits for all scenarios.
- Cisterns that are objects of cultural heritage as they for instance make up the center of a village are worth being restored.
- Cisterns that will be put out of use because of construction of houses and roads should be connected to the drainage of these structures.

6.3 The role of cisterns in integrated water management

Estimations in this report state that between Bethlehem and Sa'ir there are about 1000 ancient cisterns with a total storage of 58.000m³ per year. This amount of water could be produced at a price of around 2\$/m³. According to other estimations the total number of ancient cisterns may be even much higher exceeding 100'000 in the entire West Bank. Neither the amount nor the price make cisterns the only solution for present and future water scarcity. Other options, most importantly ground water extraction on Palestinian territory must be developed as well. But if selected carefully cisterns can contribute an important share.

6.4 Further Research

Many interesting research questions spring up from the presented material. The estimations concerning total abundance and cost need to be matched up against more data. A meta study of restoration projects and more field surveys can contribute to this question. The archaeology and anthropology of ancient cisterns should be unravelled. It would be interesting to know, how exactly farming worked at different times, how the water was used and what crops were planted. To get direct data on cistern potential it would be great to set up a measurement campaign that includes cistern owners in different areas that are trained to take measurements.

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Appendix A

Cisterns that should be restored

- Bir el Jamal (4), Tuqu': catchment of 350m³ on the roof of the mosque and many families that use it in the summer when there is no water. Suffers from leakage.
- Bir Altawal (5), Tuqu': water collected from the roof flows through polluted and illdesigned catchment. Transmission loss and hygienic problems. A direct pipe would be better. The cistern is 7 meters deep and might be quite large.
- Bir Arweheed (6), Tuqu': Very big catchment with 2500m² and 80% solid rock giving a possible harvest of 500m³ to 1000m³. The owners claim that the cistern is very big. Currently the water is used only for domestic purposes, not for drinking or agriculture. The cistern is operating fine but it would be interesting to study it.
- Bir Abu Kes (9), Beit Fajjar: The owner of this well is very committed and he plans to increase catchment by another roof. He claims that this cistern is completely filled every year in march with a catchment area of just 36m².
- Bir Musallam (10), Beit Fajjar is used for emergency drinking water by many families even though the water tastes bad and is flowing from the road through an uncontrolled catchment. It is usually only filled to midheight. Lack of money is said to be the reason that no maintenance is carried out. It is public.
- Bir Zahra (11), Beit Fajjar: The owner lives far away and has sealed his cistern. The nearby road is to be reconstructed soon and could be used as catchment. 10 years ago, neighbours took water from this cistern. The ancient collection channels can clearly be seen in the rock.
- Bir Jabr (12), Beit Fajjar: located in area without tap water; probably leakage. There is a lot of potential to optimize the catchment.

- Bir Nasser (15), Beit Fajjar: Private open agricultural well. Catchment about 900m³. Channel in soil directs water, no settling tank, sediment removal necessary every 3-5 years, catchment design improvable. New plastering and concrete layer on base needed.
- Bir Abdel Fatah (22), Beit Fajjar: Inlet covered by soil, catchment probably destroyed by new road project, probably leakage. This well was famous and used to produce very good water for the people who walked to Umm Salamuna. The newly constructed road could be the new catchment, yielding 90 to 180 m³ if the road is paved.
- Bir Abu Atef (27), Beit Fajjar: Very committed owner. He closed the inlet to protect the well during construction of his new house. Will be opened, when the house is ready. The owner of this well seems to know what he is doing. In this area, there is no tabwater, so the well is needed. This one is worthy of support but maybe even unnecessary.
- Bir Abdi Jalil (32), Beit Fajjar: Central cistern that could easily be used by many people. Runoff from surrounding roofs would have to be collected.
- Bir ed Dankur (36), Umm Salamuna [36] planned for use for 2 new houses in the vicinity. Shape not spherical, the upper 2 m are only 2m wide. The man working next to it plans his own cistern close-by. Perfect rock catchment.
- Bir Mohammed Takatka (37), Umm Salamuna: Even though the water is bad, Mohammed and his family drink it. Snakes prevented him from cleaning it. Neither him nor the neighbours have the money to fix it. A big roof from the company nearby could also be used as catchment. Beautiful rock channels.
- Bir SOS (49), Bethlehem: Cistern in the SOS children's village. Half of it is below neighbour's land. Towards the end, there is a built arch and a second outlet. Treeroots are penetrating the plastering, which has many cracks and holes. It is surprisingly warm inside of the well. One of the ideas to use it is to take water during fire emergency from this well. The rainwater they collect in their other, new cistern, is used for drinking.
- Sachment System (50-52), Sa'ir apparently this well is connected below ground to two channels that receive groundwater / rainwater. These channels are said to be arched and 1.5m wide. It very much sounds like a Roman cloaca. Th well is furthermore connected to a storage inside the village by a 12 inch pipe. Polluted water from cesspits is entering the canals, making the water undrinkable. Runoff from the street clearly pollutes the water. Also, the bir was almost empty, so maybe the groundwater level has dropped, putting this well out of use. 51 is possibly just a maintenance manhole for the channel . 52 has another outlet for the school at 5m depth. This reservoir was the main source for many people from other villages for irrigation. About 10 years ago, the concrete roof was built, the cave below is much older. For irrigation the farmers take turns in pumping, 1h hour each. I suppose that the project was halted because all the aid was stopped, bc. of Hamas council members.

- Bir Joret el Khil (59), Sa'ir: Agricultural cistern with very committed owners that have already taken some action. The zinnar was enlarged, in order to make a digging machine fit in, so that the well can be enlarged. This shows, that the owner community takes interest into this well. (Samir, who showed me around in Sair, is one of the owners)
- Bir Unengil (60), Sa'ir: A family of Bedouins depends on this It has two entrances and is lengthy in shape. 5 years ago, the family living close to it has renewed the covers with concrete. The well is filled with delivered water in years w/o rain, as it has been the case this and last year. At a certain height there is leakage, so some of the delivered water is lost. There is good commitment to the bir.