Reducing the flash flood hazard in the Sinai

J. H. Harding

Department of Hydraulic Engineering
Delft University of Technology
The Netherlands

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Cover: Flash flood warning
Picture courtesy: M. Branch (2015)

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By

J. H. Harding

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Thesis committee:	
Ir. S.J.H. Rikkert,	Delft University of Technology, supervisor
Prof. dr. ir. M. Kok,	Delft University of Technology, chair
Ir. B. Maaskant,	HKV
Ir. M.L.E.B van der Hoeven,	The Weather Makers
Dr. ir. T.A. Bogaard,	Delft University of Technology
Dr. ir. W. Kanning	Delft University of Technology

Student information:
Name Jonas Hein Harding
E-mail harding.jonas@gmail.com
Student number 1394274

Preface

This thesis marks the end of my master degree Civil Engineering and with that the end of my time as student. As such, I would like to thank everyone who supported me in bringing this research to a satisfying end. I would like to express my gratitude to my graduation committee: Stephan Rikkert, Matthijs Kok, Bob Maaskant, Ties van der Hoeven, Thom Bogaard and Wim Kanning. Special gratitude goes out to Stephan who helped me as daily supervisor and always made time for me if I needed it. Besides my committee, I would like to thank the people at HKV and The Weather Makers who helped during the research and HKV for the opportunity to do my research there. Lastly I would like to thank everyone else who gave me advice on the subject and the research.

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J.H. Harding
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Executive summary

In 2010 a large flash flood hit El Arish City, killing at least 6 people and causing a lot of damage. This was not the first time the Sinai was affected by these flash floods, more than 40 flash floods have been recorded in the El Arish watershed in the last 100 years. The enormous amount of water and the flow velocity of these floods are a hazard to its surroundings and to the rehabilitation plan of the Weather Makers. On the other hand the water is scarce in the arid Sinai and the flash floods could contribute to the plan to create a robust water cycle. The underlying goal of this research is to investigate whether a robust water cycle can be created by reducing the flash flood hazard and increasing the available water for the creation of biomass. Measures will have to be taken to start the transition and tackle issues such as drought, unfertile soil, water regulation and to properly address the social benefits to involve the inhabitants of the area. It is therefore essential to assess the hazards of the current and future situation of the Sinai and to apply appropriate measures on the hazardous locations.

The goal of this research is to propose a strategy to reduce the flash flood hazard, by first identifying hazard prone areas and then propose measures to counter these hazards. This strategy takes into account a scenario on change in catchment hydrology, gives guidance on land use for the region and will propose feasible measures to reduce flash flood hazards. It does not involve the design of the feasible measures nor a cost benefit analysis.

To assess the hazards in the El Arish watershed, the USACE method is used. The USACE method uses HEC-HMS for the hydrologic modelling and HEC-RAS for the hydraulic modelling. With a DEM sub basins and wadi channels are delineated and measured, precipitation data is collected from the TRMM and analyzed, the retention of the soil is simulated with curve numbers and transmission losses are estimated. The sensitivity of the hydrological model is checked and is used to simulate the 2010 flash flood to compare with imagery of the event. Measures usable in arid areas like the Sinai to reduce flash flood hazards are analyzed on their feasibility and their effects are modelled with the hydrologic model.

The current flash flood hazard is assessed by simulating an extreme event and the region with the highest relative hazard is selected. Measures are proposed based on their applicability and the physical attributes of the surface with a decision tree. The following measures are suggested: spreading dams in flat wadis (<2%), impervious dams in mild sloping wadis (2-5%) and pervious dams on steep sloping wadis (>5%). The effect of these measures combined on the peak discharge is estimated to be 70-75% for an extreme precipitation event. The measures decrease the total- and peak discharge but they also spread the flash flood making the duration of the flow longer. To check whether the suggestions are future-proof a scenario of change in the hydrological cycle is considered by increasing the extreme precipitation with 15%. This causes the peak discharge to increase with 30-35% if no measures would be applied. By applying measures the peak discharge decreases with 60-65%, which is a smaller percentage then without an increase of extreme precipitation (70-75%).

Challenges of the research are that measurement data was lacking to calibrate the conceptual hydrological HEC-HMS model, the large amount of uncertain parameters therefor cause equifinality. The estimated values of the parameters and the results of the simulation are however consistent with literature and gives a good indication on the hazard.

This research shows that the flash flood hazard in the El Arish watershed can be reduced by using feasible measures. The proposed method to reduce the flash flood hazards can contribute to the plan of the Weather Makers to rehabilitate the Sinai by slowing down the flood and to enhance the infiltration. It also creates suitable locations for vegetation by capturing sediment and water this could help to create a robust water cycle.

Contents

Abbreviations

CN	Curve Number
DEM	Digital Elevation Model
ESDAC	European Soil Data Centre
FOA	Food and Agriculture Organization of the United Nations
GE	Google Earth
GEE	Google Earth Engine
GEV	Generalized Extreme Value
GIS	Geographic Information System
GLCF	Global Land Cover Facility
HAND	Height Above Nearest Drainage
HEC-HMS	Hydrologic Engineering Center - Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center - River Analysis System
IWMI	International Water Management Institute
MCA	Multi Criteria Analyses
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
QGIS	Quantum GIS
RQ	Research Question
SRTM	Shuttle Radar Topography Mission
SWAT	Soil Water and Assessment Tool model
TRMM	Tropical Rainfall Measuring Mission
UNESCO	United Nations Educational, Scientific and Cultural Organization
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WMS	Watershed Modelling System
WRRI	Water Resource Research Institute
YP	Yearly Probability

1. Introduction

On 18 January 2010, a large flash flood hit the city of El-Arish, in the Sinai province of Egypt. Killing 6 people and causing for an estimated 137 million Egyptian pounds(17,5 million euro) worth of damage it was one of the most destructive events in the region since 1925 (Maowad, 2013). Flash floods are characterized by their short duration, small areal extent, high flood peaks and rapid flows, and heavy loss of life and property. The main difference with other types of floods is the short time interval between the event that caused the flood and the flood itself, and the local aspect of the event (Lin, Yinglin, Givone, Guoqing, Bouzaine, & Ruifang, 1999).

The Sinai region is an arid region which is affected by flash floods and these are even more dangerous because people tend to live near or in the wadis. Wadis are riverbeds that are dry except in the rainy season, they are the most humid parts of the otherwise dry area and are therefore the places best fit for small-scale agriculture or grazing. Due to the nature of flash floods water flows only for a small period of time and therefore people historically tried to harvest or retain this scarce water for small-scale agriculture or (Critchly, Siegert, Chapman, & Finkel, 1991; Haiman, 2012; Bruins H. , 1986).

The Sinai is squeezed in between the African and Asian continents and the Egyptian triangular-shaped peninsula is almost completely a desert. A degraded soil surface, sand-dune expanses, salinization, and wadis are some of the characteristic traits of the region (Encyclopedia Britannica, 2012). In the southern part of the region, there is a mountain range which divides the peninsula into fragments. Several fragments form smaller catchment areas and drain in the Gulf of Suez and the Gulf of Aqaba. And one large northern fragment which forms the Al-Arish catchment that drains into the Mediterranean Sea, spanning one-third of the Sinai region. This means the catchment is more than half the size of the Netherlands. The location of the Sinai is shown in figure 1.1.

Figure 1.1: Spatial reference (Google Earth, 2017)

There are some hints that in history less-arid climatic conditions prevailed (Otterman, Manes, Rubin, Alpert, & Starr, 1990) which is demonstrated by occasional terraces of thick alluvial and lacustrine deposits (Lamb, 1977). An average precipitation of 100 mm/year falls in the Northern coastal part of the catchment and the amount decreases going South to 25 mm/year (Greenwood, 1997; El-Sayad, Risk Assesment of Flash Floods in Sinai, 2012). Most of the precipitation falls during the winter months(October, November, December, January, February and March) while there is almost no precipitation in the rest of the year (TRMM, 2016). In the Netherlands the average precipitation is 800 mm/year (KNMI, 2016).

The rainfall and soil conditions of the region inspired The Weather Makers to come up with a plan to rehabilitate the region to a fertile state which could support agriculture and an ecosystem in balance. The main contributor will be to establish a robust water cycle. This will be done by harvesting the precipitation and sediment which will enhance the natural growth of biomass. Because the amount of vegetation increases more precipitation is able to be entrenched which allows more vegetation. With more water storage and stabilization of the soil, this will cause a significant growth of biomass and a robust water cycle (The Weather Makers, 2016).

Flash floods are a danger to the plans of The Weather Makers, but at the same time, the floods are also a chance to make the plan work. If the water can be stored or harvested this would serve both: a decrease in flash floods and more water for the creation of biomass giving chance to create a robust water cycle.

1.1 Problem description

Worldwide freshwater floods are the type of natural disaster that affects the highest number of people. Between 1975 and 2001 more than 2 billion people were affected by freshwater floods. Within the freshwater flood disasters, flash floods are the type that has the highest mortality rate. In the same period, an average of 3,62% of the people affected by flash floods was killed. (Jonkman, 2005). Flash floods also cause damage to property and infrastructure and incur economic losses. With an increasing demand for housing, agricultural lands and other economic activities more flood plains are colonized and the effects of flash floods will be higher in the future (Colombo, Hervas, & Arellano, 2002).

Flash floods are frequent in arid regions where high-intensity rain falls on steep hill slopes with exposed rocks and lack of vegetation (Lin, Yinglin, Givone, Guoqing, Bouzaine, & Ruifang, 1999). These local brief spells of precipitation cause local and brief floods with a high and short peak discharge which can cause landslides and mud flows sweeping away everything before them. The combination of high discharges and landslides and the debris in flash floods magnify the damage to buildings and cause fatalities (Hapuarachchi, Wang, & Pagano, 2011; Lin, Yinglin, Givone, Guoqing, Bouzaine, & Ruifang, 1999; Cools, et al., 2012).

1.1.1 El-Arish and a history of flash floods

Since 1925 more than forty flash floods affected the city of El-Arish and probably more in the rest of the watershed. All the recorded flash floods took place in the winter months (October through March). In February 1975 an extreme flood occurred in the city of El Arish which killed 20 people (Abdel-Fattah, Kantoush, & Sumi, 2015). The Hydrological Service of Israel measured a peak discharge of 1650 m^3/s at the Ruaffa Dam 50 km upstream of the city of El Arish. At that time the flood was estimated to be an event with a return period of over 100 years and had a total outflow of $120 * 10^6\ m^3$ (Klein, 2000).

The most recent large event was on January 18th 2010, causing at least six casualties and 137 million Egyptian pounds of damage. Maowad (2013) estimated a total outflow of $124 * 10^6\ m^3$ and he assumed that the floods of 1975 and 2010 are comparable. During the flash flood of 2010 several videos and photos were made, which showed the destructive force of the flood causing houses and bridges to collapse and trucks to flow away some pictures of that flood event are shown in figure 1.2.

Figure 1.2: Flash flood 18 January 2010, left: Ruaffa Dam, right: city of El-Arish (Maowad, 2013)

To counter flash floods and to store water, the Ruaffa Dam was constructed in 1946. Its initial capacity of $3 * 10^6\ m^3$ was upgraded to $5{,}5 * 10^6\ m^3$ in 1987 (Maowad, 2013). The 1975 and 2010 flash floods showed that the capacity of the dam was too small to store all of the water from extreme flash floods. The upstream ephemeral lake is not soaked into the groundwater but instead evaporates or is used for agriculture. To store water in the soil the dam should have been placed just south of the Halal Narrows as depicted in figure 1.3, where the water would have filled the paleolakes and recharged the aquifers (El-Baz, Kusky, & Morency, 1998).

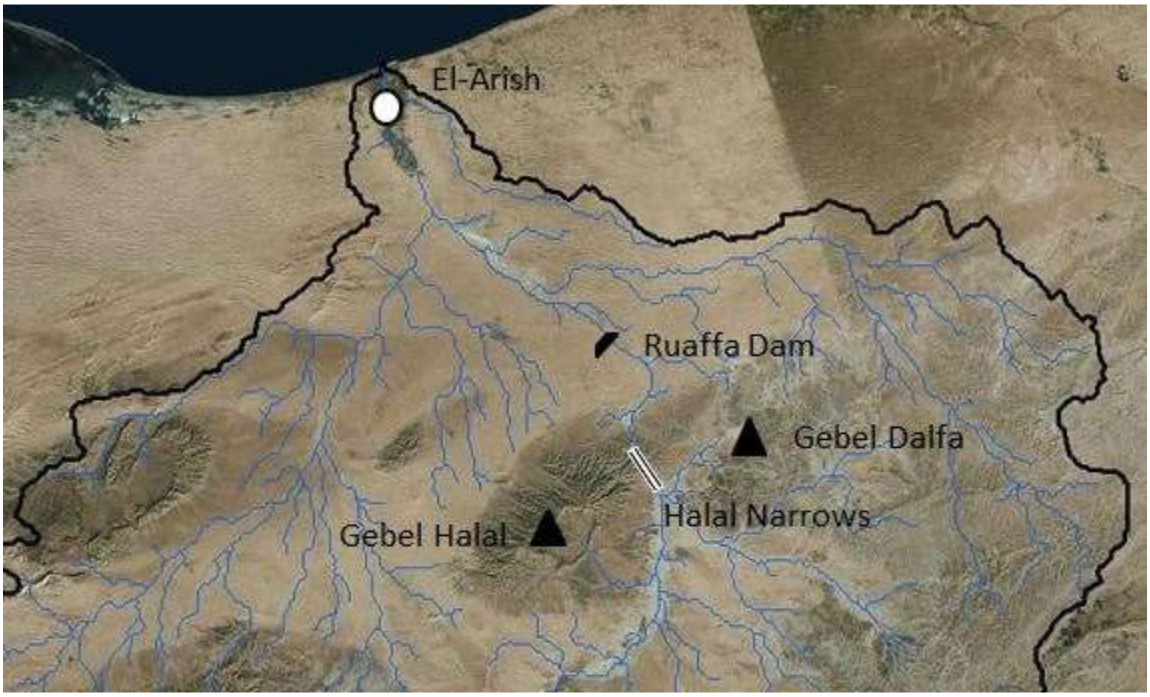

Figure 1.3: Most Northern part of the El-Arish watershed (google earth, 2017)

1.1.2 Suitability for rehabilitation

If the proposed plan of the Weather Makers is to succeed the plan will have to overcome several issues. Such as drought, unfertile soil and proper water supply but also the local disgruntled militants and bedouins. Below these issues are further addressed.

First the Sinai is an arid to hyper arid region according to UNESCO, the precipitation is only a fraction of the potential evapotranspiration. The potential evapotranspiration in the Sinai is 2500 mm/year while the precipitation ranges from an average of 25 to 100 mm/year in the region (Greenwood, 1997). The lack of precipitation is not the only problem, in arid regions like the Sinai rainfall is spatially and temporal extremely variable (Wheater, 2005). This means that heavy rainfall can fall at one place while a few hundred meters away no rainfall is measured.

Second the soil of the Sinai has a few principal soil regions, they are not ideally suited for agriculture but can be made fertile with irrigation. In the Northern part sand dunes are dominating. The Southern mountainous area the soil is dominated by a bare rock surface, the soil is shallow and never reaches more than 50 cm until bedrock. In and around the wadi beds are alluvial soils, these are predominantly made of sand and are well drained and nonsaline. Overall the soils are low in organic matter and they will not be easy to rehabilitate (Greenwood, 1997).

Thirdly earlier attempts to rehabilitate areas of the Sinai had mixed success. In the area of city El-Arish, agriculture is possible due to irrigation water which is subtracted from the aquifer or transported by pipe from the Nile (Rayan, Djebedjian, & Khaled, 2001). Another failed attempt to reclaim even more agricultural land was with the newly built El-Salam canal that is currently not receiving the 4 billion m^3/year it is supposed to. President Sisi ordered a hold on pumping water into the channel in November 2014 because of heavy pollution in the channel.

And last the willingness of the inhabitants to adapt to a different lifestyle. A large part of the inhabitants of the region reside in urban areas like Al-Arish and Nekhel, but around 40% of the 420.000 estimated inhabitants reside in rural areas predominantly as Bedouin's (Encyclopedia Britannica, 2012). These Bedouins move around through the Sinai with herds of cattle to find vegetation to graze. The overgrazing of the sparse vegetation in the area shows the long term benefits are outweighed by the short term profits. Local inhabitants need to be aware of the problems in the area and their role in the rehabilitation. The knowledge and the willingness to contribute of the Bedouins is needed for the measures and the rehabilitation of the area.

1.1.3 Problem definition

For the proposed rehabilitation project by the Weather Makers, flash floods could pose a serious problem. In the future situation more water will be able to infiltrate into the soil while more precipitation might occur (The Weather Makers, 2016). These parameters will influence the hazard of flash floods and the damage caused by them: infiltration and storage could decrease the forming of flash floods, while the extra precipitation could enhance them.

The El-Arish area is prone to flash floods as shown in the past and the current situation is not ideal for a transition to agricultural land or for other purposes. Measures will have to be taken to tackle issues such as drought, unfertile soil, erosion, water regulation and properly addressing the social benefits to involve the inhabitants of the area.

1.2 Scope

The Weather Makers proposal of making a functional ecosystem in the Sinai is focused on the rehabilitation of the region and creating a robust water cycle. In this research the scope will be more specific for the area in which the relative flash flood hazard is the highest. Therefore research will be done to locate the areas of relative highest hazard.

Flash flood hazard is the intensity of a flash flood and is expressed in depth and flow velocity. The highest depth and flow velocity depend on the peak discharge. Therefore these three aspects are being assessed. Groundwater flow will not be taken into account because it is expected that it has little to no influence on the generation of flash floods. The region with the highest relative hazard is the region with the highest peak discharge with respect to the size of the region. This region will be used in the continuation of the research.

After the area of highest relative hazard is defined the research continues by finding measures to reduce flash floods hazards. The measures that are considered are selected on their applicability in arid areas similar to the Sinai. Therefore measures for any other climates are not included except for measures that are applicable in both. The measures are all selected on their applicability and should be of a physical nature; they can decrease the velocity of the flood, prevent flash floods to form, increase the permeability of the soil or do any combinations of these.

To make the measures successful they are dependent on the input needed from local inhabitants, influence on local inhabitants, impact on environment, local materials, construction time, technology needed, skill needed and needed maintenance. These aspects provide the criteria for the Multi Criteria Analysis (MCA). From the analysis the feasibility of the measures is derived. The interests of the local inhabitants are roughly estimated so there is no study conducted amongst the locals. No attention will be given to the social resistance the construction of the measures will get. The proposed measures and their allocation will not be influenced by these social barriers. But the allocation will be considered solemnly on the reduction of flash flood hazard of the measure. Excluded from the proposed measures in this research are their design and furthermore no cost benefit analysis will be made.

This is an explorative research using a method to assess the flash flood hazards based on the available data in the area. It is in no way a conclusive solution but a guideline on how the flash flood hazard can be reduced. It does not involve the design of the feasible measures nor a cost benefit analysis.

1.3 Research question and goal

The enormous amount of water and the flow velocity of flash floods in the El Arish region are a hazard to their surroundings and to the rehabilitation plan of the Weather Makers. On the other hand the water is scarce in the arid Sinai and the flash floods could contribute to the plan to create a robust water cycle. By rehabilitating the region to a fertile state it could support agriculture, create an ecosystem in balance and make it a liveable region. To achieve this it is essential to assess the hazard in the current and future situation and to apply hazard reducing measures on hazardous locations. Therefore the research question of this thesis is:

"Which measures are feasible in the Sinai to reduce the flash flood hazard, based on the hazard assessment of the current situation and considering the future rehabilitation of the region?"

To answer this research question several sub questions have to be answered:

1) Where and what are the current flash flood hazards in the Sinai?
2) Which measures are feasible and where can they be used in the Sinai?
3) What is the effect of the measures on the flash flood hazards?

The goal of this research is to propose a strategy to reduce the flash flood hazards by first allocating hazard prone area's and then measures to counter these hazards. This strategy gives guidance on land use for sub basins and will propose feasible measures to reduce the flash flood hazard. It does not involve the design of the feasible measures nor a cost benefit analysis.

1.4 Research approach

To be able to answer the research question it is split up into three sub questions. These sub questions together will form the answer to the main research question. To be able to answer these sub questions a simple model is made which depicts how the research is set up, as shown below in figure 1.4. The research method shows that for the hazard assessment method data is needed. By conducting the flash flood hazard assessment the location with the highest relative hazard is derived. This area is used to reduce the flash flood hazard by allocating feasible hazard reducing measures which provides the input for the second hazard assessment. By conducting the flash flood hazard assessment with the allocated measures the reduction of the flash flood hazard by feasible measures is assessed.

First data will be collected from literature and open source databases: topography, precipitation, soil conditions and wadi beds characteristics. For necessary data that was unavailable estimations are made based on physical characteristics or reference projects. Second, a hazard assessment method is selected which is appropriate for the research. The selection is made on the base of the type of needed input, ability to simulate measures and possibility of calibration. The hazard assessment method is used to simulate a measured flash flood event so it can be calibrated and a sensitivity analysis is done to check the potential biases of the input parameters. Imagery of a flash flood in El Arish City is used to compare the results from the simulation by the flash flood hazard assessment with a recorded event. Hazard reducing measures which are found in literature are analysed on their applicability and feasibility. The way they can serve as input for the hazard assessment method is derived. By conducting the flash flood hazard assessment the location with the highest relative hazard is derived. This area is used to reduce the flash flood hazard by allocating feasible hazard reducing measures with support from a decision tree which is based on surface conditions of the area with the highest relative hazard and the applicability of the measures. The allocated measures and their effects on the hazard assessment method provide the input for the second hazard assessment. The applied measures are then placed back into the hazard assessment method from which the reduction of the hazard can be assessed. By allocating measures in the entire watershed the potential flash flood hazard reduction of the Sinai can be assessed.

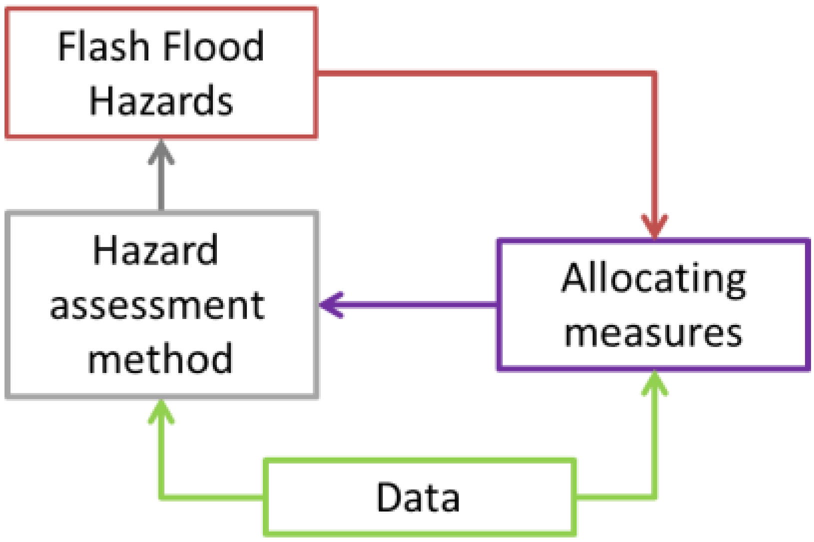

Figure 1.4: Research method (own illustration, 2017)

1.5 Structure of report

The research starts with an introduction to the area and the problem at hand. The background chapter provides the necessary context prior to the rest of this research. First an introduction to the concept of flash floods is given and then the study area is considered: the history and culture, topography, land-use, precipitation, geology and wadi beds are discussed. The third section explains the plan of the Weather Makers to rehabilitate the Sinai and the last section describes the earlier literature research about the region (Chapter 2).

The methodology describes how the research is conducted. First an overall approach of the research is presented in which will be explained how the conclusion is derived from the research question with help from three sub questions followed by a brief explanation of how these research elements come together in a model. Second, a description is given on hazard assessment and methods are considered to assess flash flood hazards followed by a brief explanation on which model is selected and why. The chapter will close of with a description on how the selected model will be applied within this research (Chapter 3).

The flash flood hazard assessment chapter first explains the USACE model itself. Describing how the hydrological HEC-HMS model works and how the results are used in the hydraulic HEC-RAS model. Secondly the background information and the data gathered is analysed and processed to fit the input needed in the USACE model. Thirdly the hydrologic model simulated in HEC-HMS is calibrated and the sensitivity is analysed. The measurement of the flash flood of 1975 is compared to the hydrograph simulated by the hydrological model. The sensitivity analysis is done by varying the values of input parameters to consider their effects on the model and will give an indication on the range of the results and the discrepancies of the input parameters. Fourth the 2010 flash flood is simulated with the same hydrological model and the discharges produced are then inserted in HEC-RAS to check whether this would give a flood of the magnitude captured on film. Fifth the current flash flood hazard is assessed for an event with a yearly probability of 2% is simulated with the USACE method. Lastly the measures that reduce flash flood are discussed and how they are simulated in the USACE method (Chapter 4).

In the reducing flash flood hazards chapter the USACE method is first used to assess the flash flood hazards for a precipitation event with a 2% yearly probability. The region with the highest relative contribution to the hazard is then used to apply hazard reducing measures in. Secondly hazard reducing measures are allocated based on their applicability and their use in the area. A decision tree is used to allocate measures to surface regions with certain soil profiles and slope. Thirdly the effect of the proposed measures is assessed for the region with the highest relative hazard. Lastly the flash flood hazard is considered that the extreme precipitation could increase due to the rehabilitation plan by The Weather Makers (chapter 5).

The discussion deliberates the results of the research. First the validity of the research is discussed. Secondly the results are interpreted by discussing what the results could mean. Thirdly the significance of the research is discussed by debating on the place of this research in literature and the applicability elsewhere. Fourth the challenges of this research are discussed. Lastly new research opportunities are discussed (chapter 6).

The conclusion provides the answers to the research question and its sub questions. The most important results to answer these questions are presented (Chapter 7).

The recommendations chapter discusses the steps that need to be taken because of this research. Practical recommendations are given and should be used to reduce the flash flood hazard in the Sinai or to increase the value of this research (chapter 8).

2 Background

This chapter provides background to the research, the necessary context prior to the rest of this research. The first section gives an introduction to the concept of flash floods. The second section considers the study area: the history and culture, topography, land-use, precipitation, geology and wadi beds are discussed. The third section explains the plan of the Weather Makers to rehabilitate the Sinai. The fourth section describes the earlier literature research about the region.

2.1 Flash floods

As the name suggest a flash flood is a rapid type of flood. It can be caused by high intensity storms, snow-ice melt water or by (ice) dam breaks. In this research the flash floods caused by high intensity storms are taken into account. The main difference between flash floods and normal river floods is the speed with which it occurs and the lack of time between the causative event and the flood itself (Lin, Yinglin, Givone, Guoqing, Bouzaine, & Ruifang, 1999).

2.1.1 Generation of flash floods

Flash floods occur in arid areas like the Sinai during high intensity storms because of a lack of retention capacity in the watershed. Precipitation is scarce and has an extremely high spatial and temporal variability in arid areas. When an extreme precipitation event happens it is not able to infiltrate into the soil. In arid areas the sparse vegetation diminishes the protection of the soil from raindrop impact. The absence of vegetation leads to increased erosion, the clogging of soil pores and a reduction of permeability of the soil. The inability of precipitation to infiltrate the soil causes the excess precipitation which runs-off unhindered over steep slopes with a lack of resistance and permeability into a wadi. Runoff accumulates in the wadi and a flood wave forms (Morin & Benyami, 1977; Lin, Yinglin, Givone, Guoqing, Bouzaine, & Ruifang, 1999; Wheater, 2005). Effects of these processes on the hydrograph of a flash flood are shown in figure 2.1.

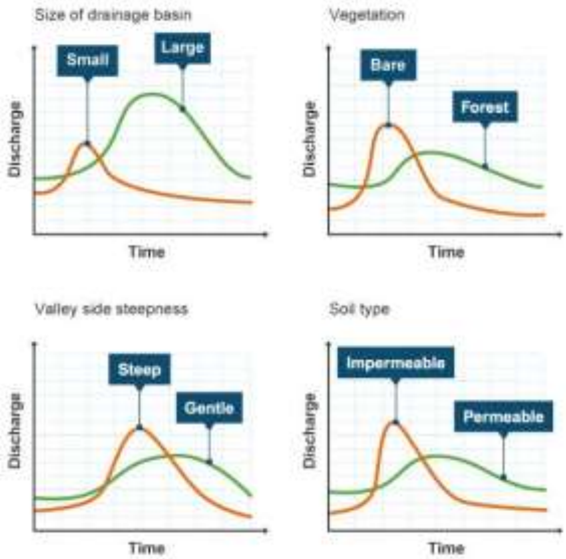

Figure 2.1: Effects of physical characteristics of a watershed on the hydrograph of a flash flood (BBC, 2014)

Flash floods move down the stream network as a flood wave over a bed that is commonly dry in arid regions. This is the main factor that reduces the flood volume as the flood moves downstream. It is common not to observe a flood downstream while upstream a flood has been generated and lost due to the bed infiltration. Although these transmission losses can be high they are frequently not large enough to completely diminish the flood wave, hence the recurrent floods in El Arish city (Wheater, 2005).

Due to the low resistance of the wadi bed the flood does not slow down and the mud-rock flow sweeps everything in its path due to the force and velocity of the flood wave. This causes the flash flood hazard and if in the path of the flood buildings, vegetation and people are at risk (Yair & Lavee, 1985; Lin, Yinglin, Givone, Guoqing, Bouzaine, & Ruifang, 1999).

2.1.2 Flash floods in history

In the El Arish watershed there are numerous recorded flash floods since 1925, because of the spatial variability, the low population density and the sometimes local nature of the floods these records are far from conclusive. In table 2.1 a summary of the recorded flash floods since 1925 in the El Arish watershed is presented with the annual amount of precipitation. In appendix B is the full list of the recorded flash floods.

Table 2.1: Summary of recorded flash floods. (a) Observed by Dr Shata (b) at Ruaffa Dam. Sources: 1. Dames & Moore (1985), 2. Klein (2000), 3. Hermas (2011), 4. Moawad (2013), 5. TRMM (2017)

Date (where if specified)	Flood magnitude	Annual rainfall at El Arish city [mm] (average causing the event [mm])	Source
Oct. 1925	Very strong	114	1
Oct. 1937	Very strong	123	1
Jan. 1945 (7 days flow at Mitmetni)	Very strong	-	1 (a)
1948	21×10^6 m^3(b)	37	1
27 Mar. 1965	30×10^6 m^3	193	4
21 Feb. 1975	120×10^6 m^3	- (40 – 50)	2
1979	30×10^6 m^3	-	4
10 Dec 2009 (Lake and/or Gaifi)	-	42 (0) [5)]	3
18 Jan 2010 (whole watershed)	124×10^6 m^3	81 (15,6)[5)]	4

The records of these flash floods and their description are based on several sources. For the flash floods earlier in history (before 1945) qualitative descriptions have been made by government officials. A strong flood has a quantity of about 20 x 10^6 m^3 or greater, which could be expected every 2 to 4 years (Dames & Moore, 1985). The magnitude of the flash floods occurring between 1945 and 1970 have been estimated with the empirical Finkel formulae by Dames & Moore (1985) and the 2010 flash flood was simulated by Maowad (2013).

The Finkel method uses the area of the basin and the probability of occurrence to estimate the total volume of the outflow in a given year. The only physical based parameter used in the Finkel method is the area of the watershed.

$$Q_{peak} = K_1 * A^{0,67}$$

$$V = K_2 * A^{0,67}$$

With Q_{peak} is the peak discharge (m^3), K_1 and K_2 are constants depending on the probability of occurrence in table 2.2, V the total discharge (1000 m^3) and A is the area of the basin (km^2).

Table 2.2: K_1 and K_2 constants for the Finkel method (Dames & Moore, 1985)

Probability of yearly occurrence	K_1 (10^{-6} m/s)	K_2 (10^{-3} m)
80%	0.01	0.168
10%	1.58	26.5
2%	4.3	72.2

Klein (2000) describes the flash flood in 1975, the volume is measured at the Ruaffa Dam and the precipitation is based on averages from five rain gauges, three in and two outside the El Arish watershed.

The estimated flood magnitudes from Moawad (2013) are based on a conceptual hydrological model using the curve number method. Moawad uses precipitation data from HYDIS and uses the curve numbers to calculate the subsequent surface runoff.

For most flash flood events precipitation measurements are missing, Dames and Moore (1985) listed the annual precipitation in El Arish for every flash flood event before 1980. But also notes that the annual precipitation data for El Arish seem to have no correlation to the hazard of flash flood generation in the rest of the watershed. Since there are no records for the rainfall events causing the flash floods before 1980 mentioned by Dames and Moore (1985), Maowad (2013) and Hermas (2011) it is assumed that there is no daily rainfall data available for that period of time.

2.2 Study area

The Sinai region in general and the El-Arish watershed in particular lacks data. The low population density, (armed) conflicts in the recent history, an unstable government and a lack of funds contribute to this. There are only a handful of rain gauges in the region which lack consistent data and there are no discharge measurement stations in the El Arish watershed. Furthermore there are hardly any soil measurements done, but the groundwater level is closely monitored. Even with these difficulties researchers have done research in this area and produced multiple papers and reports on the region.

2.2.1 History and culture

The Sinai Peninsula is part of Egypt, which it has been for the larger part since the first dynasty of ancient Egypt (3100 BC). According to the Hebrew Bible it was crossed during the Exodus by the Israelites and on Mount Sinai (Gebel Musa in Egypt) Moses received the Ten Commandments from God. On the place where supposedly Moses saw the burning bush the Saint Catherine Monastery has been built in 548 AD.

It has been under the rule of a large number of historic empires including the Assyrian-, Persian-, Hellenistic Greece, Roman-, Byzantine-, Ottoman- and British Empires. Since the 1950s it has been part of conflicts between Egypt and Israel and has been under Israeli rule for some time. After 1982 the Israeli troops retreated and the region has been Egyptian since then (Encyclopedia Britannica, 2012).

Although the Sinai is arid there are lots of remnants from ancient agriculture, this was possible due to the use water harvesting techniques. A massive system of terraced wadis and diversion systems is dated to the Byzantine and Early Islamic era in the 7th and 8th centuries AD (Haiman, 2012; Bruins H. , 1986). Haiman (2012) argues that only in these era's runoff farming systems where constructed on imperial initiative. In other era's the structures where basic and spontaneous and comparative to those of present-day Bedouins, only of secondary importance to their economy. The remnants of the Byzantine structures are scattered in the El-Arish wadi. A large terracing work of the diversion type with an estimated size of 1000 km^2 is still present in the El-Arish wadi, as well as several terraced wadis shown in figure 2.2 (Haiman, 2012).

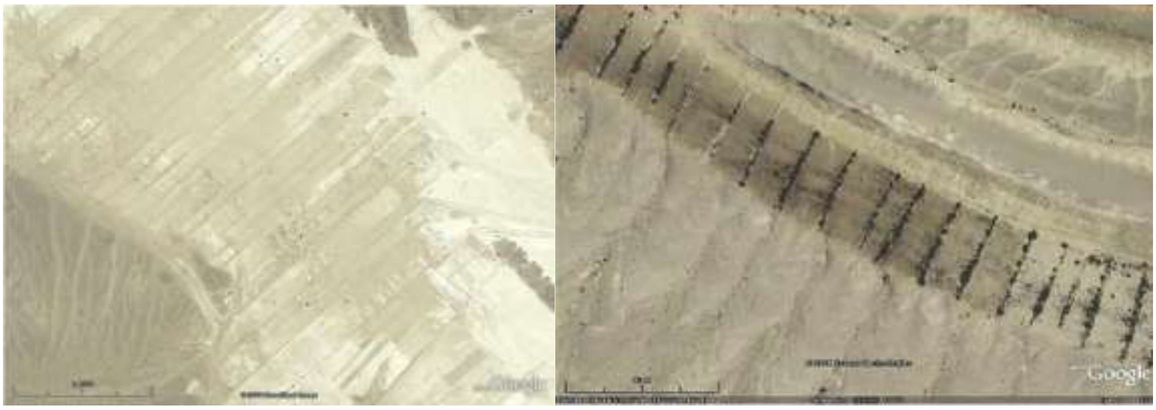

Figure 2.2: Remnants of runoff farming systems (left) terraced wadi to capture sediment and slow water down(right) (Haiman, 2012)

Present day agriculture is predominantly practised near the city of El-Arish and the rest of the coastal strip of the Mediterranean Sea. The main source of water is not storm water or water harvesting as it historically was, but is now focused on groundwater extraction and the use of Nile water transported with the Salam canal and the pipeline from Port Said to Rafah (Hassan, 2011; The Weather Makers, 2016).

Shifts of livelihood made the larger part of the inhabitants of the region reside in urban areas like El-Arish: due to the agriculture, fisheries and tourism in the region of El-Arish City. Around 40% of the 420.000 estimated inhabitants still reside in rural areas predominantly as Bedouin's (Encyclopedia Britannica, 2012). Since 2011 the region has been affected by the Sinai insurgency: a conflict between Islamist militants and the Egyptian armed forces. The militants are mostly local Bedouin's who say they are barred from joining the army or police, find it hard to get jobs in tourism and claim that many of their lands have been taken from them. As no other options where present, they joined the militants (The Economist, 2013).

2.2.2 Topography

The Sinai peninsula is 1,5 times the area of the Netherlands, it spans 60000 km2. One third of that area is part of the wadi El-Arish watershed. In figure 2.3 the important topographic places mentioned before are shown. The wadi drains into the Mediterranean Sea and the southern border is marked by the Tih Escarpment reaching 1600 m. The limestone Tih Plateau slopes gently from the most upstream part of the watershed in the south to the Insular Massif. The Insular Massif topographically divides the watershed into two parts: the mild sloping Tih Plateau to the south of the massif and the dune sheet north of the massif. The Wadi forces itself through the Insular Massif in the Halal Narrows and streams into the dune sheet. The dune sheet is only a small part of the El-Arish watershed (1000 km2), but is the most inhabited part of the watershed. The Ruaffa Dam is 10 km downstream of the Halal Narrows and 50 km to the north (and downstream) the city of El-Arish is situated.

To be able to assess the flash flood hazard with a model elevation data is needed, a so called Digital Elevation Model (DEM). The United States Geological Survey (USGS) site offers a world covering free DEM. Shuttle Radar Topography Mission(SRTM) is chosen as DEM for this study with a grid size of 30x30 m which is depicted in figure 2.3. The absolute vertical error of this DEM is less than 16 m (Ramirez, 2017). In the Philippines the mean vertical error for the 30x30 m SRTM is 6,91 m (an overestimation of the heights) and areas with dense vegetation have a higher mean error than with lower vegetation intensities (Santillan & Makinano-Santillan, 2016). The mean error in the sparsely vegetated Sinai might therefore be lower, but is considered to be around 7 m.

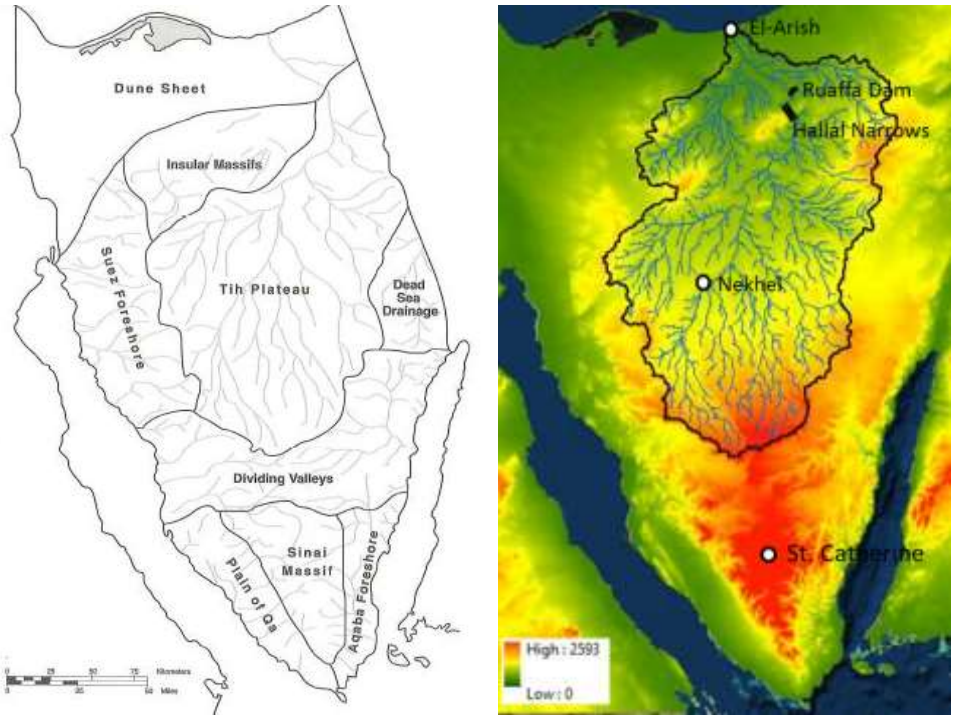

Figure 2.3: Division of topographic areas (left) (Greenwood, 1997), DEM of the Sinai with the El Arish and described watershed(right) (Lehner, Verdin, & Jarvis, 2008)

2.2.3 Land-use

Land use classification is an indirect input for a hazard assessment. Land-use classification provides information about how land is used, thus which area needs protection from hazards. It also offers information about soil coverage, making a distinction between the amount of vegetation for each land type. This information is downloaded from the Global Land Cover Facility(GLCF) website, the smallest available grid size is 1x1 km. Google Earth (GE) can also be used to manually observe the land use of the Sinai.

2.2.4 Precipitation

Precipitation is an important parameter in the Sinai area: it is the forming factor of flash floods and is essential for the plan to rehabilitate the Sinai. The average yearly precipitation in the Sinai ranges from 25 to 100 mm as depicted in figure 2.4, with a potential evaporation of around 2500 mm per year this makes the area arid to hyper arid. Occasionally an extreme perception event occurs and causes a flash flood.

Precipitation data is traditionally collected with rain gauges, while satellite radar techniques are used since a few decades. There are 16 rain gauges in the Sinai Peninsula and 5 of them are within the El Arish watershed as shown in figure 2.4. One of these stations is operated by the National Climatic Data Centre (NCDC) and the rest is operated by the Water Resource Research Institute (WRRI) in Cairo. Satellite precipitation data is available from the Tropical Rainfall Measuring Mission TRMM at the NSA website, in daily and 3-hourly intervals.

Precipitation is scarce and has an extremely high spatial and temporal variability in arid areas (Wheater, 2005). A rain gauge only measures the precipitation on a specific place and the number of available rain gauges in the region is limited, this means that precipitation data from rain gauges can give distorted results. Due to several conflicts in the region the measurements of rain are not constantly monitored, data off some periods are missing. The satellite data is measured since 1998 with a grid size of 30x30 km, the precipitation is thus an average of the grid for a certain time period. This would give a better spatial coverage of the rainfall in the area, both in time and space. However, Milewski et al.(2009) states that short extreme rainfall events can be missed by the three hourly satellite measurement and Chiu et al.(2006) shows that TRMM values could underestimate precipitation events by 15 – 30% in arid environments.

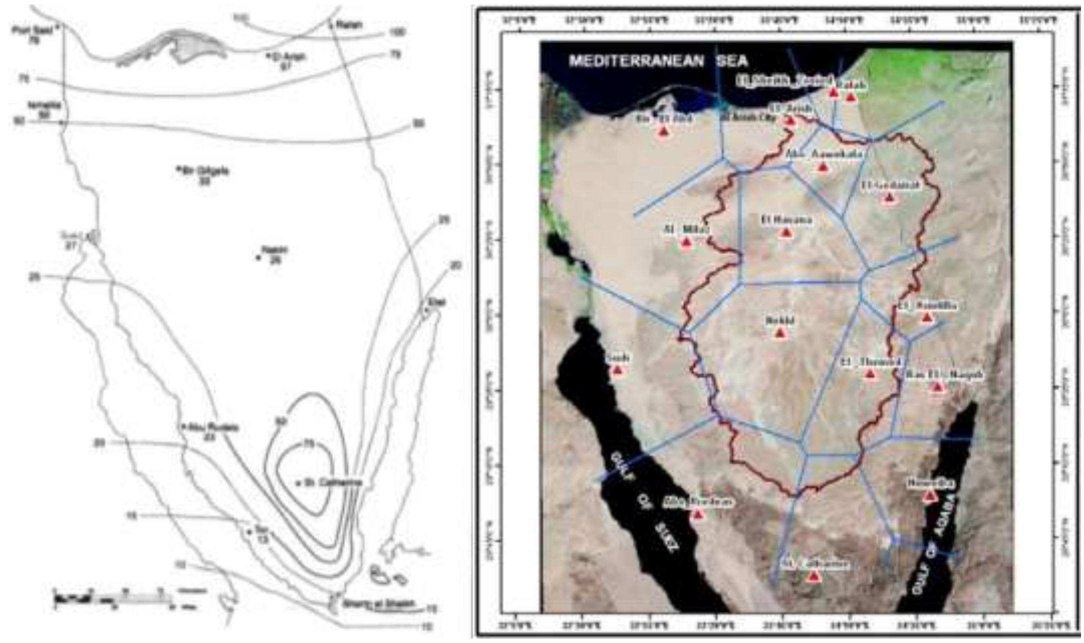

Figure 2.4: Average rainfall mm/year in the Sinai (Greenwood, 1997) and locations of rain gauges of the WRRI (Hassan, 2011)

In arid areas two different storm types are recognized: convective storms and frontal storms. Convective rainfall mainly occurs during the fall and late spring while frontal storms are mostly to occur mid-winter (Sharon, 1972). They can both cause flash floods but have a different cause and effect.

Convective storms occur in unstable conditions and are characterized by their local character, high intensity and brief duration. The cells of the convective storm are 3-10 km in diameter and have a limited life span of a few minutes to nearly an hour (Sharon, 1972). This causes a large spatial difference in rainfall amount between wetted and non-wetted areas. Because of the high intensity, small cell and rapid movement the accumulated rainfall amount is usually 1 to 5 mm. However there are exceptional cases with a far larger total precipitation was measured (Yair & Lavee, 1985).

Due to the local character of the convective storms they tend to have low impact on runoff generation in larger watersheds. This is due to the transmission losses that occur in the more downstream dry wadi beds. This means the convective storm can cause damage and thus form a hazard in the El Arish watershed, but are not taken into account in the hydrological model.

Frontal storms result from cold rainfall fronts which develop in humid areas and spread into adjacent arid areas. They are characterized by low- to medium intensity rainfall, long duration of several hours to days and the large area they can cover (up to thousands of square kilometres). This causes the total precipitation at a given location during a storm can vary between a few mm to more than 50 mm, depending on the distance from the storms centre (Yair & Lavee, 1985). Although the frontal storms cover a large area and have a long duration compared to convective storms, spatial variability of precipitation is still large because of topographical characteristics. Sharon (1972) argues that the base of the slopes collect more precipitation than the upper parts of the slope.

The large area, long duration and high total precipitation means that the frontal storm is noted by the earlier mentioned rainfall measuring methods and is thus considered in this research.

2.2.5 Geology

For the flash flood hazard assessment the interaction between water and the soil is important. There is some literature on the Sinai which describes the thickness of the top soil and a few ground samples were made to describe the soil. An aeromagnetic survey map is downloaded from European Soil Data Centre (ESDAC), which describes the surface geologic strata (or rock type). The aeromagnetic survey map together with the description of the top soil gives an indication of the infiltration capacity and -rate of the soils.

In the Northern part sand dunes are dominating, they are low in organic matter(<0,2%) and are quite thick soils reaching at least 25 cm until bedrock. In the southern mountainous area the soil is dominated by a bare rock surface, the soil is shallow (never reaches more than 50 cm until bedrock) and they are almost never moist. In and around the wadi beds are alluvial soils, these are predominantly made of sand and are well drained and nonsaline. This makes them potentially the most fertile soils of the Sinai. In the North Eastern part close to the Israeli border there are sandy soils with a high calcium content, which makes them more fertile than normal sand soils. Overall the soils are low in organic matter and they will not be easy to rehabilitate (Greenwood, 1997).

2.2.6 Geohydrology and wadi beds

Geohydrology is the movement of water below the earth surface. Soil moisture is normally the cause of runoff generation, but in dry areas soil moisture is low and does not attribute to flooding (Yair & Lavee, 1985). The water table is usually far beneath the surface (hence the low soil moisture) and therefore the wadi bed is also dry. This causes the wadi bed to subtract water from the flash flood. The wadi beds who act as shallow aquifers however subtract a considerable amount of water from the flash floods (Milewski, et al., 2009; Wheater, 2005).

Groundwater movement in an aquifer or aquitard is slow, certainly in respect to the time frame of flash floods and therefore falls out of the scope of this research. The wadi beds are however an exception, these loosely packed sandy soils are highly permeable and can act as a shallow aquifer. The hydraulic conductivity of the coarse sand of the wadi bed is in the range $10^3 - 10^5\ m/year$ m/year and the limestone bed rock beneath it in the range of $10^{-2} - 10^1\ m/year$ (Yu, Kamboj, Wang, & Cheng, 2015), this makes the wadi bed a potential sink for water during a flash flood.

Because of the difference in time scale between deeper (or slow) groundwater flow and flash floods groundwater flow is not taken into account. A flash flood moves through the El Arish watershed within days while groundwater flow reaches the Mediterranean Sea in years, decades or even longer depending on the type of aquifer. The ephemeral character of wadi El Arish shows that the groundwater flow does not contribute to the flash flood hazard. The shallow aquifers (with 'fast' sub surface flow) who subtract water from the flash flood are taken into account and are called transmission losses.

The transmission losses from the surface water system are a major source of potential groundwater recharge. In wadi El Arish the wadi bed alluvium is a thick unsorted coarse sand and gravel layer which is very permeable. The underlying bed rock is a combination of rock types with a high amount of limestone which has a low hydraulic conductivity in respect to the wadi bed material in figure 2.5 a soil profile of the main wadi and its tributary wadi just south(upstream) of El Arish City is shown (Greenwood, 1997; Wheater, 2005).

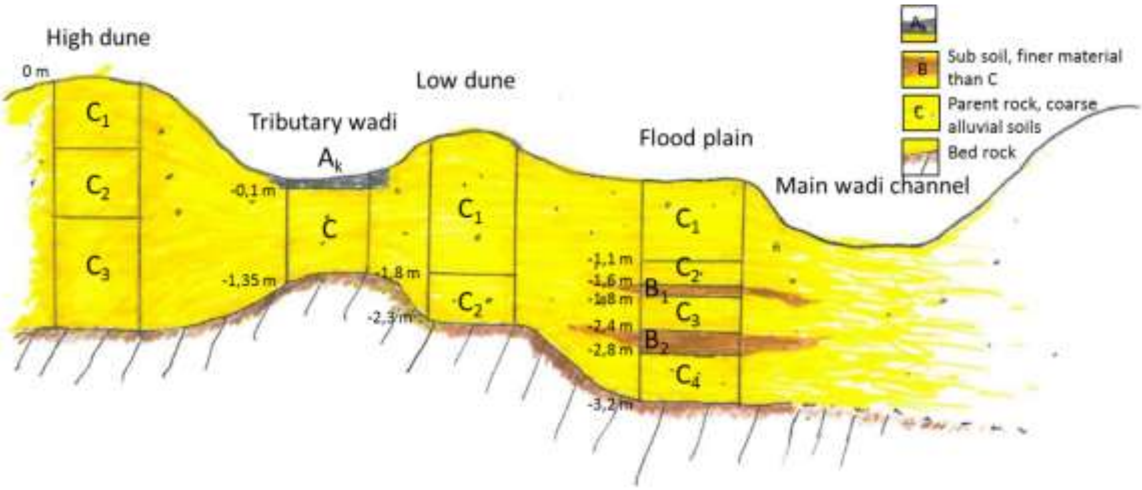

Figure 2.5: Wadi bed derived from Greenwood (1997) (own illustration, 2017)

2.3 Plans of The Weather Makers to rehabilitate the Sinai

There are some hints that in history less-arid climatic conditions prevailed and this is demonstrated by occasional terraces of thick alluvial and lacustrine deposits (Lamb, 1977). The extensive historic agricultural sites in the region described by Bruins(1990) and Haiman(2012) show that even in a climate comparable to the current state the Sinai has more potential. An average precipitation of 100 mm/year falls in the city of El-Arish, which could be larger in the local gorges (van der Hoeven M. , 2017). This could form a good basis to start the rehabilitation of the Sinai.

The potential of the region inspired The Weather Makers to come up with a plan to rehabilitate the region to a fertile state which could support agriculture and an ecosystem in balance. The main contributor will be to establish a robust water cycle: this means that more water is stored in the sub basins, more water is used by vegetation and more water is recycled before it is discharged.

In the Sinai hardly any water is stored on the surface: the small amount of precipitation in the region either evaporates into the atmosphere, infiltrates into the ground or flows into the ocean (sometimes as a flash flood) (Hassan, 2011; Maowad, 2013). This is due to the lack of biomass in the Sinai: there is sparse vegetation and the top soil does not contain living matter (Greenwood, 1997). The capability of the soil to store water is small: either not infiltrating when there is a small layer of soil until bedrock or with thick sandy soil water infiltrates deeper into the ground or evaporates into the atmosphere. Bot & Benites(2005) writes that a higher concentration of organic matter causes the soil to store more water. And with a higher amount of soil cover less water acts as runoff and more is infiltrated. See for more information on these processes appendix A. To create a robust water cycle as proposed by the Weather Makers, biomass is needed and to create biomass more water is required.

A more robust water cycle is obtained by stabilizing sand dunes with vegetation near the Mediterranean Sea, which will decrease the temperature of the soil and reduce aeolian transport. Terrace agriculture will be built to enhance the storage of water, increase sedimentation and subsequently soil depth. By using sabkah deposits natural growth of biomass in the region will be enhanced. Because of the increased vegetation and the more robust water cycle more precipitation is able to be entrenched which causes more vegetation and again a more robust water cycle. In the long run this will cause a significant return of biomass and a robust water cycle, in figure 2.6 the end result of these plans is shown (The Weather Makers, 2016).

The plan of The Weather Makers is based on the four returns of a resource based society. First the return of inspiration with new future perspectives for all involved. Secondly the return of social capital with the creation of jobs better health and social bonding, Thirdly the return of nature capital with an increase in biomass, fauna and flora, fertile land and fresh water. Fourth the return of financial capital (Ferwerda, 2015).

The four returns are created over 3 landscape zones. The first zone is a natural zone where the restoration of the ecological foundation and biodiversity takes place. The second zone is the combined or eco-argo mix zone where the topsoil is restored which can provide low economic activity. The third zone is the economic zone where a high economic productivity is possible. Those three zones are the fundamental zones in the mosaic landscape, so that ecological sustainable living is possible and in balance. The key to success for the restoration of land consists out of five main steps: co-initiating, co-sensing, co-strategizing, co-creating and co-evolving between the local communities, companies, scientists and governments (Brasser & Ferwerda, 2015).

The restoration of the landscape is based on the following principles: First capture and store rainwater as close as possible to where it falls. Water is slowed down to recharge lower terrains, avoiding flash floods and soil erosion. Secondly the soil is hold in place to develop a stable, organic and biodiverse soil environment. Thirdly a permanent biodiverse vegetation cover and wildlife adapted to the local environment is stimulated. Fourth agricultural systems to sustain the population in suitable areas are applied, without damaging the earlier mentioned principles. Lastly a buffer is needed in the natural and agricultural system so that the carrying capacity is not reached during stress periods (for example prolonged droughts). This requires a strict management of human occupation in balance with natural resources.

The principles are reached by using these methods: Terracing and water harvesting in and around the wadi streams to reduce flow and avoid erosion. Growing a permanent vegetation to improve infiltration and to reduce the impact of rain- and wind erosion. This is done by planting native trees, making small agricultural plots and preventing grazing. Develop natural zones in erosion sensitive areas (steep slopes and mountain tops) where human activity is minimized. Agriculture that is beneficial for the soil is encouraged: biological agriculture and permaculture increase soil organic matter and biodiversity. Lastly a knowledge base of hydrological processes is created to explain their relationship with the environment and human activity on different levels. This will increase the understanding of the locals and their place in the rehabilitation plan.

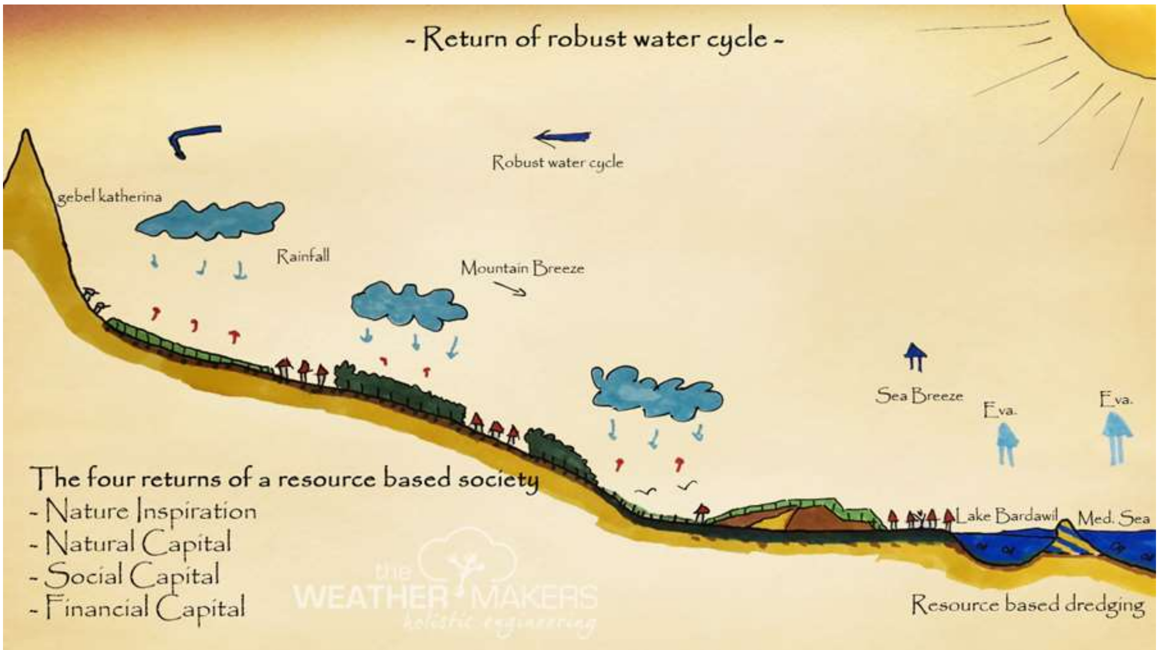

Figure 2.6: Future of the El-Arish watershed: a robust water cycle and an ecosystem in balance (The Weather Makers, 2016).

2.4 Earlier research on the El-Arish watershed

The Sinai is an arid region and agriculture is not practiced on a large scale except in the coastal strip in the most northern part of the peninsula. Here irrigation water is available from the El-Salam canal and pipelines with Nile water (Rayan, Djebedjian, & Khaled, 2001). But also groundwater is subtracted on a large scale from the coastal quaternary aquifer which causes a constant decline in water level and is therefore subject to groundwater intrusion (Hassan, 2011; Mills & Shata, 1989; Gad, Zeid, Khalaf, Abdel-Hamid, Seleem, & El Feki, 2015).

There are however regions in the Sinai which are also suitable to use for agriculture. Mainly the wadi channels with Quaternary deposits are suitable for agricultural purposes (Ghaffar, Abdellatif, Azzam, & Riad, 2015). Dames & Moore agrees with this statement but adds that the area around the Insular Massif (Gebel Maghara, Yelleq and Halal) would also have a high potential for agriculture. However all the soils in the Sinai are low in organic matter and are hard to rehabilitate and more is needed than just water but the salt content of the soil is low so that is not an issue (Greenwood, 1997; Dames & Moore, 1985).

Water is scarce in the Sinai but there are some moments that it is abundant and a hazard. Flash floods hazards in the Sinai have been studied by multiple researchers. El-Sayad (2012) used the Watershed Modelling System (WMS) to model the El Arish watershed with the curve number method and unit hydrograph transform. He estimates a peak discharge of 780,29 m^3/s and total discharge of 132 million m^3 for an event with 50-year return period. Milewski et al. (2009) used the Soil Water and Assessment Tool model (SWAT) to calculate the average yearly initial losses (CN), total discharge and transmission losses based on remote sensing data for 14 watersheds in Egypt including El Arish. The research does not calculate the discharges of extreme events but gives an estimate of the total yearly hydrological variables.

Maowad (2013) analysed the flash flood of 2010 by using an empirical black-box model that uses curve numbers (CN). Precipitation data was acquired from TRMM and HYDIS and the watershed was divided in 10 sub basins. The main contributor of the flood were the middle and north-western parts of the watershed, since the total precipitation was the highest in these regions. The total discharge of wadi El Arish for the 2010 flash flood was estimated to be 124 million m^3 but no peak discharge was estimated. The average flow velocity between the Ruaffa Dam and El Arish City was 1,6 m/s. The model could not be calibrated due to the lack of measurements but is in agreement with the measurement of the 1975 event by Klein (2000). The total discharge of the 2010 flood is 124 million m^3 in Maowad (2013) and 120 million m^3 in the 1975 event described by Klein(2000).

Klein (2000) describes the formation of a delta in front of wadi El Arish caused the sediment of the 1975 flash flood. This flood was measured at the Ruaffa Dam and therefore a hydrograph and the total- and peak discharge at the Ruaffa Dam for the 1975 flash flood is available.

The suggestion by Maowad (2013) that the 2010 flood and 1975 flood have the same magnitude seems to be premature. First the measurement in Klein(2000) are done at the Ruaffa Dam and the total discharge Maowad (2013) describes is at the outflow point of El Arish which has a difference of upstream drainage area of 6000 km^2. Secondly Maowad (2013) describes that a large part of the runoff is generated in the Hasana which is downstream of the Ruaffa Dam. Thirdly the delta formed in front of the outflow point of wadi El Arish is small according to Hermas & Bastawesy (2010). Fourth the precipitation that caused the event is not the same: Klein estimated an average precipitation for the whole watershed of 40-50 mm while the average precipitation used by Maowad was less than 30 mm. This means that the 2010 and 1975 cannot be assumed to have the same total- and peak discharges in this research.

3 Methodology

This chapter describes how the research is conducted. First an overall approach of the research is presented in which will be explained how the conclusion is derived from the research question with help from three sub questions followed by a brief explanation of how these research elements come together in a model. Second, a description is given on hazard assessment and methods are considered to assess flash flood hazards followed by a brief explanation on which model is selected and why. The chapter will close of with a description on how the selected model will be applied within this research.

3.1 General approach

First the research question and the derived sub questions will be elaborated on; how the sub questions support the main research question, how an answer is sought and how they will come together in the end. Thereafter a general approach of the research will be presented in the shape of a model. This will make clear how the various elements of the sub questions have a place within the research.

3.1.1 Answering the research question

The research question can be broken down into three pieces that translate into sub questions. These sub questions are elaborated on below. First the sub questions are explained, thereafter an insight is given one how they are answered and finally how they will come together in answering the research question.

The first sub question is: Where and what are the current flash flood hazards in the Sinai? To answer this question first a suitable hazard assessment method is needed. The flash flood hazard is expressed by the depth and flow velocity (or discharge) given a certain probability of occurrence. Data on the topography, precipitation, soils and wadis is collected and analysed to be usable as input for the hazard assessment. The method is calibrated on the retrieved flash flood events in history and analysed on its sensitivity on possible biases in the input data. By simulating an event with a low probability of occurrence the first sub question is answered.

The second sub question is: which measures are feasible and where can they be used in the Sinai? This question consists of two parts that influence each other. First measures are needed that can reduce the flash flood hazard and which are feasible and applicable in the Sinai. These measures are found in literature regarding water harvesting techniques and flash flood manuals. The measures' feasibility is analysed with criteria that relate to problems in the region and their applicability is based on physical needs of the measures. Secondly the measures are allocated based on the surface conditions in the Sinai and the feasibility of the measures.

The third question is: what is the effect of the measures on the flash flood hazards? This question is answered by using the answers of the first two sub questions. First the region with the highest relative flash flood hazard (peak discharge in respect to the area that caused it) is retrieved from the answer of sub question 1. Then the allocation of measures from sub question 2 is used in the flash flood hazard assessment method. The method is re-used with the allocated measures to calculate the effect of the feasible measures on the flash flood hazard.

These three questions together answer the main research question: Which measures are feasible in the Sinai to reduce the flash flood hazard, based on the hazard assessment of the current situation and considering future changes in the hydrological cycle? The conclusion of the research is therefore: an overview of measures that help reducing the flash flood hazard, a guideline on how to locate them, an estimate on the reduction of the hazard and an indication of the effects of the rehabilitation on the flash flood hazards in the Sinai.

3.1.2 Research method

To reduce the flash flood hazard by allocating feasible measures first an appropriate flash flood hazard assessment method is needed. The selection of this model is the starting point of the research. To be able to use the model data needs to be collected, analysed and transformed so that it can be used as input for the flash flood hazard assessment model. From the results of the flash flood hazard assessment model the area with the highest relative hazard is selected. In this area feasible hazard reducing measures are allocated and by simulating them in the hazard assessment method the effects of the measures are assessed. An overview of the feedback loop this creates for this research is shown in figure 3.1.

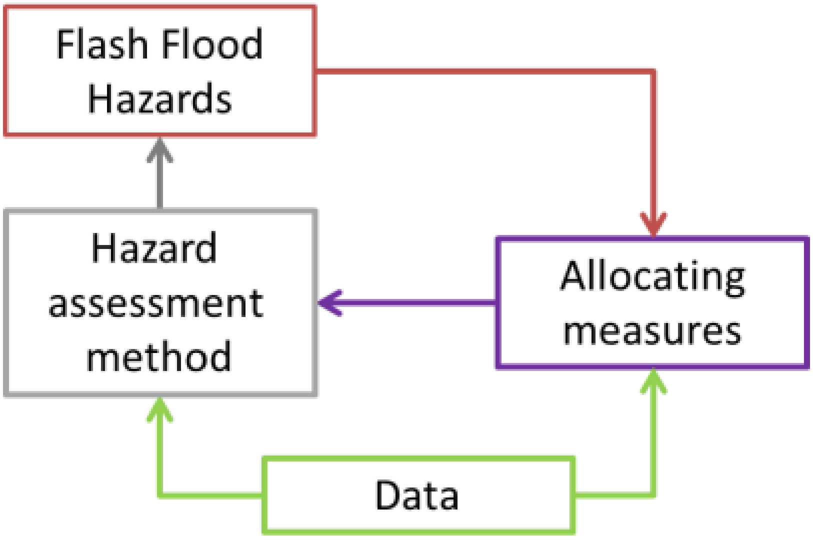

Figure 3.1: Research method (own illustration, 2017)

3.2 Selection of flash flood hazard assessment model

The city of El-Arish flooded several times in recent history, at least forty times a flood is recorded since 1900 (Maowad, 2013; Dames & Moore, 1985; Hermas, 2011). The lack of measurements and information about the flood extend together with the plan to rehabilitate the watershed grounds the need to assess the flash flood hazards.

A hazard is any source of potential damage, harm or adverse health effects on something or someone. In the case of a flash flood this means that given the probability of the occurrence of an event, what area is susceptible to be affected by the flash flood. If property or people are exposed to this hazard this could cause risk if the intensity of the hazard is high enough. The definition of hazards in connection to risk is shown in figure 3.2.

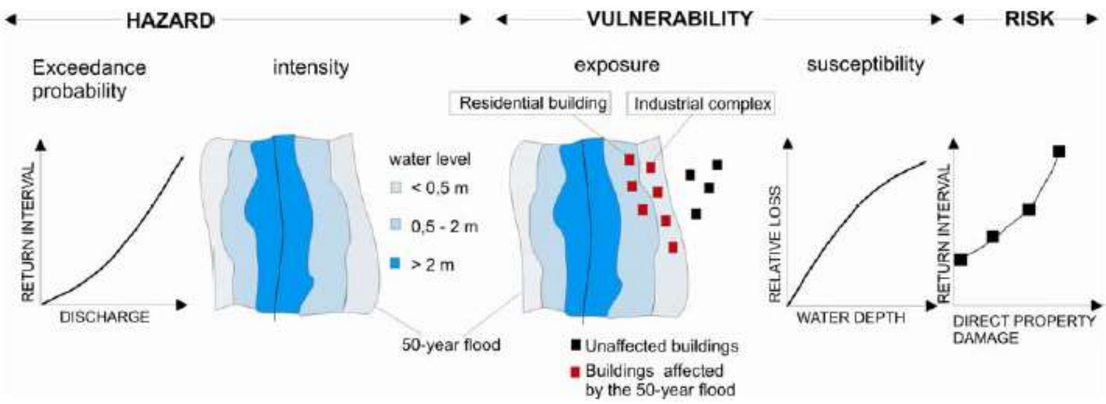

Figure 3.2: Definition of hazard in connection to risk (Thieken, 2006)

3.2.1 Possible methods to assess flash flood hazards

To delineate the area which is susceptible to be affected by the flash flood a hydrological model is needed. A hydrologic model is a mathematical generalization of hydrological processes. There are several types of models:

Probabilistic or black-box models mathematically describe the relation between inputs (i.e. precipitation) and output (i.e. area affected by flash floods) without describing the physical process but form a statistical link between in- and output (Abdelhalek, 2009).

Deterministic or physically based models are based on the physics of hydrological processes. These models are characterized by parameters that are measurable and have a direct physical significance (Wheater, 2005). There are problems with physical based models because the underlying physics are derived from small-scale laws and process observations. This means that the processes may not apply under field conditions and at the scale of the modelled watershed (Abdelhalek, 2009).

Conceptual or stochastic models depict hydrological processes in the form of a conceptual representation (Wheater, 2005). Conceptual models are characterized by parameters that usually have no direct, physically measurable identity but are estimates based on physical properties of the hydrologic processes. If the information content of the data on which the parameters are calibrated is limited, parameters are non-identifiable (Abdelhalek, 2009).

There are multiple ways to spatially represent hydrological processes. Lumped models are represented by spatially averaged watershed characteristics. Distributed models incorporate spatial variability. Semi-distributed models adopt a lumped representation for individual sub-catchments.

Savenije (2010) explains that although complex models ought to start in the most detailed level and from the most basic level, they give a wide range of possible outcomes with a lot of uncertainty. The complex models are therefor quite often outperformed by more simple simulations.

In this research the USACE method is used: The hydrologic model simulates discharges with HEC-HMS while the hydraulic model simulates the flow velocities and the depth of the flash flood with HEC-RAS. Both the HEC-HMS and HEC-RAS programs are free to use and publicly available and therefore contribute to the plan to set up a knowledge base of hydrological processes of the Sinai by the Weather Makers. To assess the hazards in the El Arish watershed the USACE-, Satellite- and Enhanced HAND method were considered. These are described and discussed in appendix C.

3.2.2 Chosen model

For this research the USACE method is chosen: The method is called that way because the programs used to do hydrologic and hydraulic model are HEC-HMS and HEC-RAS which are created by the United States Army Corps of Engineers (USACE). The model used is a conceptual semi-distributed hydrological model with in addition a two dimensional hydraulic model. The USACE method is chosen because: the needed input parameters are available, the method can be calibrated and is reusable for the assessment of the effects of hazard reducing measures. Both the HEC-HMS and HEC-RAS programs are free to use and publicly available and therefore contribute to the plan to set up a knowledge base of hydrological processes of the Sinai by the Weather Makers

3.3 The use of USACE within the research

To reduce the flash flood hazard in the Sinai multiple steps have to be taken. In figure 3.3 the selected flash flood hazard assessment model is added into the general research approach. The processes that take place within this model and how they influence each other is explained by addressing each step below.

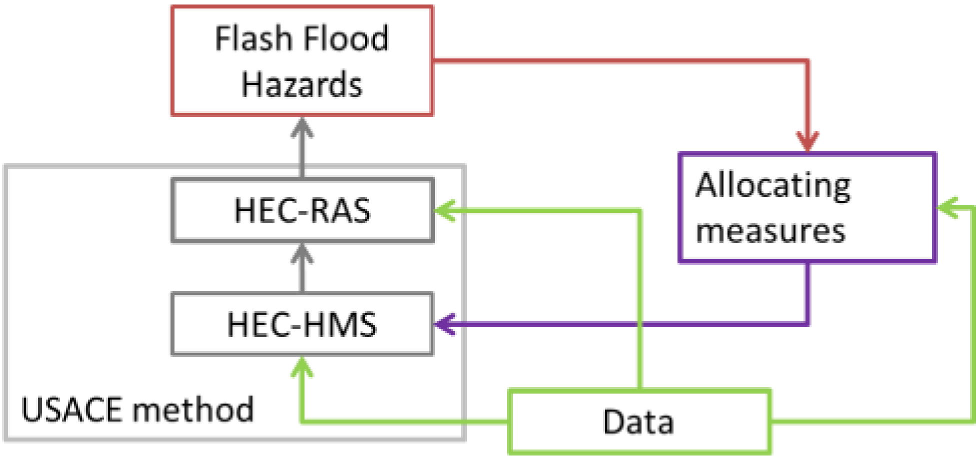

Figure 3.3: Reduction of flash flood hazard (own illustration, 2017)

First, data is gathered about the El Arish watershed to serve as input for the USACE method and to allocate measures. The background information about the study area is analysed and processed to fit the input needed in the USACE model. The scarcity of data in the Sinai often means that assumptions and estimates need to be made.

The USACE method consists of two parts: the hydrological model in HEC-HMS and the hydraulic model in HEC-RAS. The HEC-HMS simulates the hydrological processes and produces discharges as output. The discharge from HEC-HMS is the input for the hydraulic model in HEC-RAS which simulates the flow velocities and the depth of the flash floods. Because data is scarce and estimates are needed the USACE method needs to be calibrated and the sensitivity of the model is analysed.

The flash flood hazard is the depth and the flow velocity simulated by HEC-RAS in the USACE method. The depth and flow velocity depend on the discharge calculated in HEC-HMS and therefore the discharge is used as indicator for the flash flood hazard.

To reduce the flash flood hazard measures need to be allocated. The flash flood hazard assessment provides the region with the highest hazard which is used to allocate measures. By using data on the surface conditions suitable locations for the feasible measures are derived. The allocation of the measures is now the input for the USACE method to derive the new hazard.

By using the USACE method again the discharges are modelled in HEC-HMS and the flow velocities and depth of the flash flood are simulated in HEC-RAS. The difference between the first and second computation is the reduction in flash flood hazard.

4 Flash flood hazard assessment

In this chapter first the USACE model itself is explained. Describing how the hydrological HEC-HMS model works and how the results are used in the hydraulic HEC-RAS model. Secondly the background information from chapter 2 and the data gathered is analysed and processed to fit the input needed in the USACE model. Thirdly the hydrologic model simulated in HEC-HMS is calibrated and the sensitivity is analysed. The measurement of the flash flood of 1975 is compared to the hydrograph simulated by the hydrological model. The sensitivity analysis is done by varying the values of input parameters to consider their effects on the model and will give an indication on the range of the results and the discrepancies of the input parameters. Fourth the 2010 flash flood is simulated with the same hydrological model and the discharges produced are then inserted in HEC-RAS to check whether this would give a flood of the magnitude captured on film. Fifth the current flash flood hazard is assessed for an event with a yearly probability of 2% is simulated with the USACE method. Lastly the measures that reduce flash flood are discussed and how they are simulated in the USACE method.

4.1 USACE method

To assess the hazards in the El-Arish watershed its hydrology and hydraulics are modelled with the USACE method as is shown in figure 4.1. The method is called that way because the programs used to do hydrologic and hydraulic model are HEC-HMS and HEC-RAS which are created by the USACE.

Within this section it will be explained how the USACE method works and what input the method needs. First a general outline is provided on which processes are important in flash flood generation, followed by a description on how they are modelled in HEC-HMS and what data is needed. The second paragraph explains how HEC-RAS is used to make inundation- and flow velocity maps and which data is required.

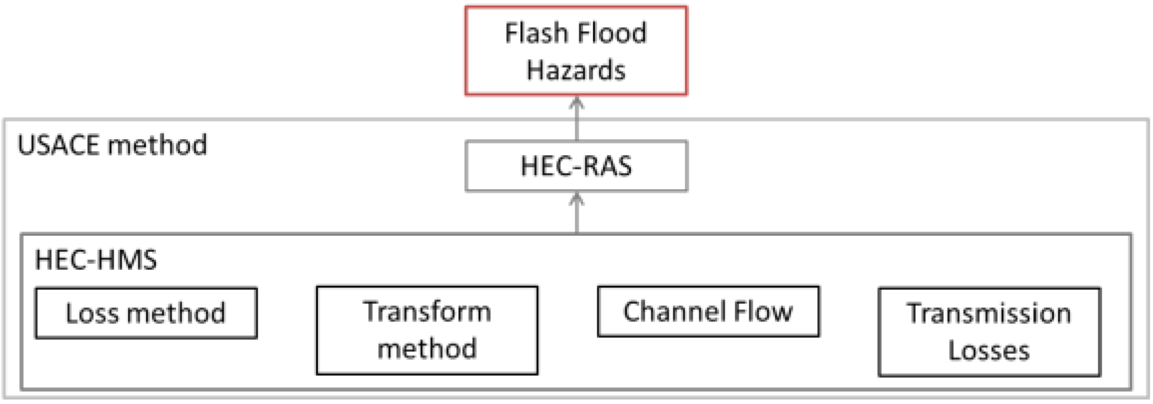

Figure 4.1 USACE method and its components (own illustration, 2017)

4.1.1 Modelling hydrology with HEC-HMS

With hydrologic modelling a water balance of a certain area is simulated, representing the hydrologic processes in a realistic way is essential for an accurate model. There are processes of the water cycle which are important and other processes are negligible or intentionally not included. The important processes are: precipitation, lack of infiltration of the soil, steep slopes, lack of resistance and the losses during the movement of the flood wave downstream.

Due to the available data in the El-Arish a semi-distributed conceptual model is used to assess the flash flood hazards in the Sinai. This means that the El Arish watershed is divided into multiple sub basins and the hydrologic processes are modelled by estimates based on physical properties. The level of distribution depends on the amount and size of the sub basins and channels between them. These are based on the topography of the El Arish watershed and the amount of detail that is needed. The conceptual parameters that are used depend on the available data.

With HEC-HMS a realistic simulation can be made of the important processes. These important processes and how they are modelled will be treated in the following order: precipitation, soil infiltration, slopes, resistance and the losses during the movement of the flood wave downstream.

First precipitation serves as causing processes in HEC-HMS and can be inputted in any way. Precipitation can be distributed uniformly, per watershed or gridded depending on the available data.

Second the infiltration of the soil is simulated by the loss method in HEC-HMS. It estimates the precipitation excess as a function of the cumulative precipitation and potential maximum retention of the soil. The potential maximum retention of the soil depends on the intermediate parameter the Curve Number(CN), which estimates the maximum retention based on: soil types, land use and treatment, surface condition and antecedent watershed moisture. The CN describe the processes of interception by vegetation, infiltration and retained water in surface depressions. To define the CN, the soil type and the land use is needed.

Third the steep slopes and the rapid floods that are caused by them are modelled within a sub basin by the transform method. It simulates the process of the transformation of excess precipitation into discharge in the outflow point of the sub basin. This means that for every sub basin the time it takes to flow from the point furthest away to the outflow point is calculated, the so called lag time.

Fourth the steep slopes and rapid flood wave that is discharged from the out flow point of a sub basin into a wadi channel is modelled with the channel flow. The channel flow is estimated with kinematic wave theory, this theory approximates the channel flow by making several simplifications. The theory involves the dimensions of the wadi channel, the slope and the roughness of the bed.

Fifth the resistance of the arid region is simulated with the transform method via the lag time and with the channel flow via the wadi bed roughness.

And the losses during the movement of the flood wave downstream are simulated by transmission losses are the losses in the wadi channels between the sub-basins. due to infiltration of water in the channel bed. The transmission losses are estimated on the Potential Water Bearing Capacity (PWBC) method and are based on the dimensions of the channel, the thickness of the wadi bed and permeability of the wadi bed.

4.1.2 Modelling hydraulics with HEC-RAS

To assess the flash flood hazard in El Arish watershed, the depth and flow velocity of the inundated area is needed. To simulate the depth, flow velocity and the extend of the flash flood the two dimensional hydraulic model of HEC-RAS is used.

To model the extend, depth and flow velocity of the flash flood HEC-RAS either uses the Saint-Vernant equation or the Diffusion wave equation to model the unsteady 2D flow. These are based on the motion of fluids described with the Navier-Stokes equations, but are simplified to the shallow wave equations. The consequence of these simplifications is that the model depends on the bed resistance and the gravitational forcing caused by the slope of the bed (U.S. Army Corps of Engineers, 2016). This means that a DEM and the wadi bed resistance is needed for the computations. From HEC-HMS the discharges are used as input.

4.2 Data input for the USACE method

To be able to assess the flash flood hazards the available data in this region needs to be considered and the right input for the models need to be found. In the previous section the methods that are used by HEC-HMS and HEC-RAS to assess the hazards are discussed and in this section the input for these methods are derived.

First the topography of the El Arish watershed is analysed. The topography influences: the loss method by the size of the sub basins, the transform method by the slope and the shape of the sub basin, the channel flow by the dimensions of the channels and the slope, and the transmission losses by the dimensions of the channel. In HEC-RAS the simulation of the flow depth and velocity with HEC-RAS also requires the DEM.Secondly the precipitation is considered this influences the amount of run off that is generated with the loss method and the transmission losses lost in the wadi channels. Thirdly the curve number is derived. The CN influences the amount of run-off generated in the loss method and depends on the geology, land-use and aridity of the region. Lastly the wadi beds are discussed. The wadi beds influence the transmission losses by estimating the thickness of the wadi bed and the soil parameters. The channel flow is influenced by the wadi bed because of the roughness of the bed. Figure 4.2 shows the hazard assessment and how data serves as input for the USACE method. Table 4.1 gives an overview of the input and output of the USACE method.

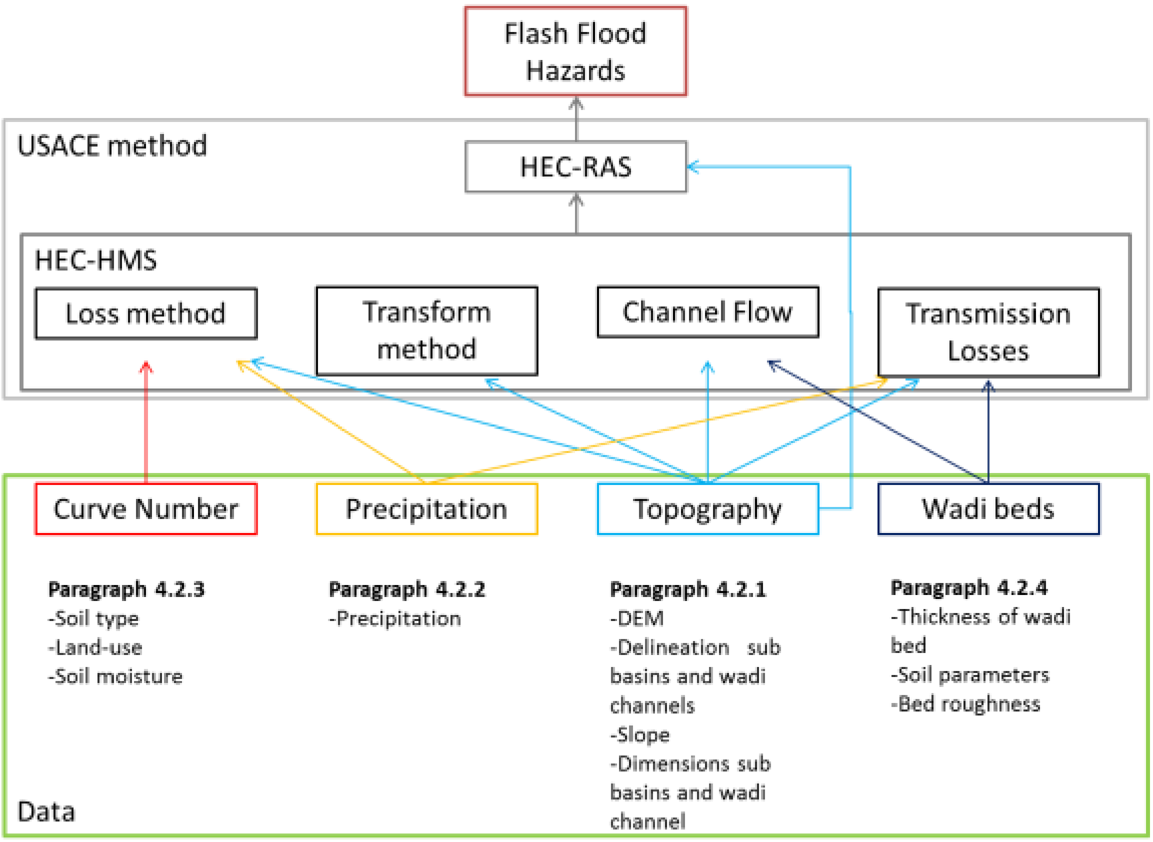

Figure 4.2 Data input for USACE method to assess the flash flood hazard in the El Arish watershed (own illustration, 2017)

Table 4.1: Overview of parameters for the USACE method (own illustration, 2017)

What	Input	Output
HEC-HMS	Precipitation, dimensions sub basins and wadi channels, loss method, transform method, channel flow and transmission losses	Discharges of sub basins
Dimensions of sub basins	DEM	Sub basins dimensions
Dimensions of wadi channels	DEM, sub basins	Channels between sub basins, dimensions wadi
Loss method	CN, precipitation	Precipitation excess(run off) and maximum retention
Curve Numbers (CN)	land-use, soil types and soil moisture	CN
Transform method	sub basin dimensions and -slope	Lag time of sub basins
Channel flow	dimensions wadi, slope, roughness of bed	Flow through the wadi
Transmission Losses	dimensions wadi, soil parameters	Amount of water subtracted by wadi bed
HEC-RAS	DEM, discharges of sub basins	Inundation maps and flow velocities
Flash flood reducing measures	Slope, soil characteristics and applicability of measures	Allocation of measures

4.2.1 Topography

To retrieve data on elevation, dimensions of the wadis and sub basins, and to assign measures DEM and shapefiles for the sub basins and wadi channels are needed which are downloaded from the USGS site and hydrosheds.org. First the delineation of the watersheds is discussed, secondly the explanation of the flow in every sub basins is given, thirdly the division of the main wadi channels and the simulation of flow through them are explained and finally the derivation of the slope for the allocation of feasible measures is discussed.

The watershed of wadi El Arish is divided into smaller sub basins. The amount of sub basins chosen decides the level of detail in the hydrological model and the amount of detail needed from the input parameters. It defines where the output of discharges is calculated and thus the amount of detail in the model. Making sub basins very small makes the model complicated and error prone. Making sub basins very large it can be become too lumped. This might cause an inaccurate flood hazard assessment and makes the assigning measures against flash floods imprecise. One of the basic principles of water harvesting is to harvest water upstream, the sub basin size is chosen so it allows flash flood assessment and measures in the upstream areas as well. Because of the spatial variability- and the size of the watershed a maximum area of 2000 km^2 is used per sub basin. By merging some small basins from the downloaded shapefiles in QGIS 38 sub basins are derived, depicted in figure 4.3. More information about the sub basins and their dimensions is in appendix D.

Within the sub basins fallen precipitation travels from every point to the most downstream point of the basin. This process is influenced by the slope in the catchment, the roughness of soil and the length of the flow lines. To simulate the time it takes for every sub basin to reach a peak discharge, a simplification is made by calculating the intermediate lag time parameter. The needed data to calculate the lag time is: the maximal channel length within the sub basin and the average slope of the channel. The method used and the lag time of the sub basins are more elaborately explained in appendix G.

To link the 38 sub basins and to simulate the flow in the main wadi channels, channel flow is modelled in HEC-HMS using the kinematic wave routing method. Because the average slope of the channels exceeds 0,004 m/m. The channel flow is based on the dimensions of the channel, the slope of the channel and an estimate of the Manning coefficient. The length of the channel and the average slope are derived from the DEM. With Google Earth the width of the channels is measured the results are in appendix D. In figure 4.3 the 30 main wadi channels which are used in HEC-HMS are shown.

With the Quantum Geographic Information System (QGIS) program a slope map for the watershed is derived, this is done with the open source program QGIS. The slope map is used to assign locations for the different measures.

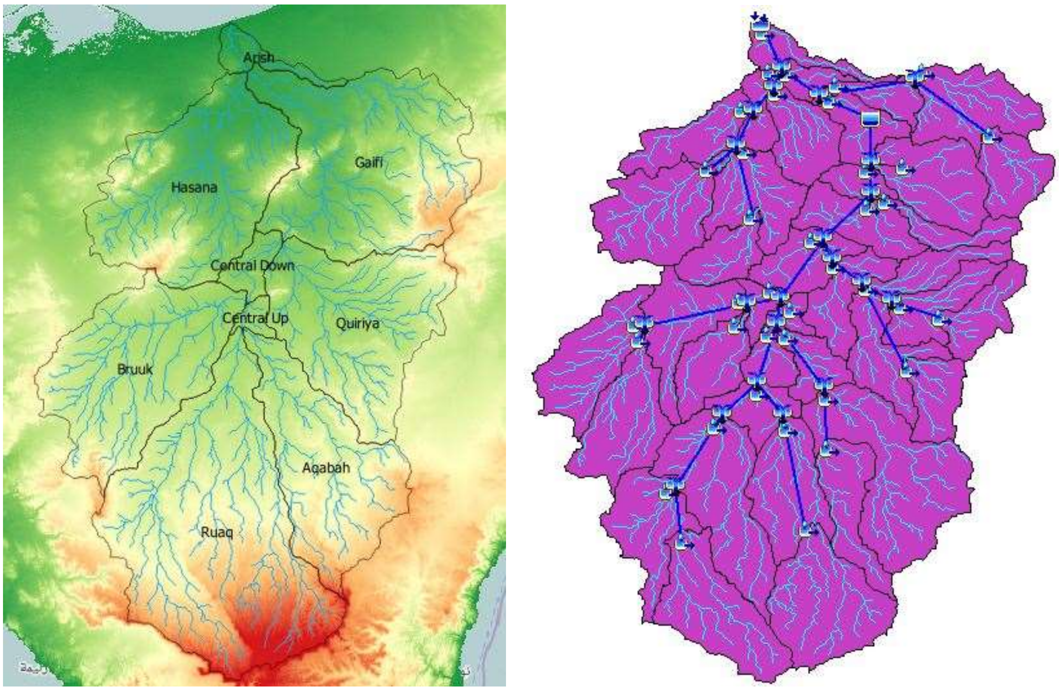

Figure 4.3: Rough level of sub-basins of the El Arish watershed with DEM (left) and finer level of 38 sub basins and 28 channels which are modelled in HEC-HMS (right)

4.2.2 Precipitation

To measure precipitation satellite data from the TRMM is used as input for the model, in appendix E is explained why and what other options were considered. Because the TRMM cells cover 30 x 30 km, data on 48 cells is needed to cover the whole extend of the El Arish watershed. The sub basins can cover multiple TRMM cells as shown in figure 4.4, when this is the case data will be used from multiple cells to describe the precipitation of a sub basin.

Satellite-based rainfall estimates tend to underestimate event-based precipitation events especially in arid areas (Morrissey & Janowiak, 1996). Chiu et al. (2006) describes that TRMM data underestimates the precipitation in arid areas with 15-30% compared to rain gauges. Milewski et al. (2009) uses a multiplication factor of 1.18 to calibrate the TRMM dataset to the rain gauges in his research about several watersheds in Egypt, including the El Arish watershed. To assess how much the precipitation data from TRMM underestimates the values that are measured rain gauges the storm causing the flash flood of 2010 is analysed in appendix E. The measured values are a factor 1,26 larger than the values TRMM provides but because this is only one event with 5 measuring points the 1,18 found by Milewski et al. (2009) is used.

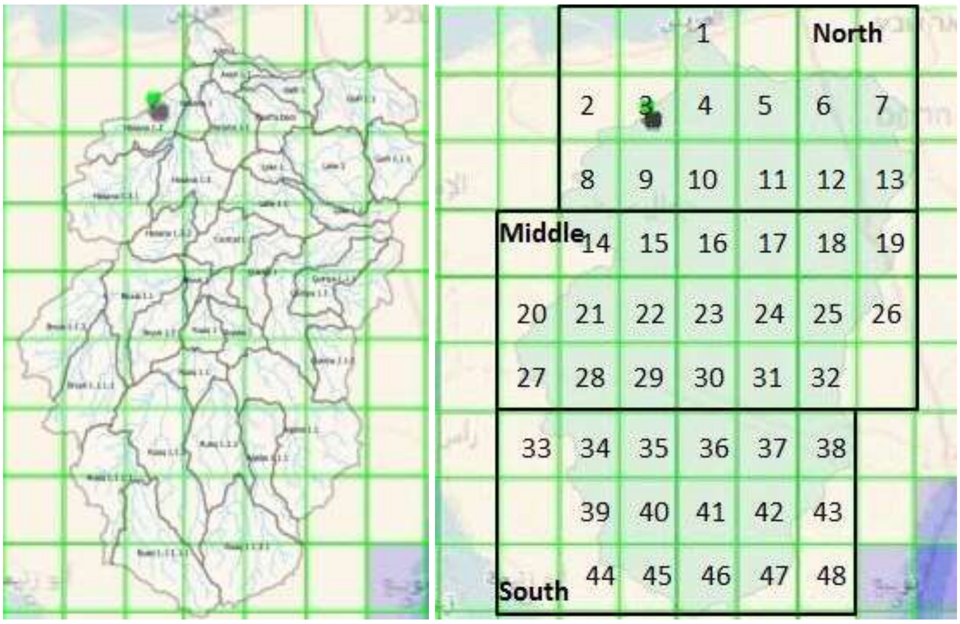

Figure 4.4 TRMM cells and sub basins used in the hydrological study(left) and the cell numbers divided over the northern-, middle- and southern part (own illustration, 2017)

The gathered precipitation data between 1998 and 2015 is used to 'create' events with a certain return period. To be able to simulate flood events with a certain return period an extreme value analysis is done with MATLAB, this gives estimates of precipitation events outside of the measured database. The analysis is in appendix E and the summery is in this paragraph.

The yearly average precipitation is highest in the northern coastal area and is gradually getting lower to southern borders of the watershed. The TRMM cells are split up into a northern-, middle- and a southern part to use in the extreme value analysis. In figure 4.4 the distribution of the cells is depicted.

Within the northern-, middle- and southern part the daily precipitation data of all the cells is averaged for every day since 1998. Because frontal storms can last more than one day the same is done for two consecutive days. This means that there is precipitation data for daily and for two consecutive days for the northern-, middle- and southern area. For every year the highest precipitation event is selected and with the MATLAB dfittool a distribution is fitted to the available TRRM data. For all three areas and for the daily and the two consecutive days the distribution is a Generalized Extreme Value(GEV) distribution. In appendix E the probability plots, the considered distribution fits and the parameters of the used GEV for every area is given. In table 4.2 the precipitation amount with a 50%, 5% and 2% yearly probability are shown.

Table 4.2: Precipitation for extreme events (own illustration, 2017)

Area		Amount of prec. with a 50% yearly probability (mm)	Amount of prec. with a 5% yearly probability (mm)	Amount of prec. with a 2% yearly probability (mm)
North	1 day	19	23,5	25,5
	2 days	20,5	31,5	40,5
Middle	1 day	11	18	21,5
	2 days	11,5	24,5	38
South	1 day	6,5	14,5	21
	2 days	7,5	18	26

In the future the precipitation process might change due to the rehabilitation of the watershed by the Weather Makers. To take this into account while suggesting flash flood hazard reducing measures, scenarios of precipitation change are discussed. These estimates are based on the precipitation increase in other rehabilitation projects and estimates of the Weather Makers.

By rehabilitating the region the average temperature of the region decreases but also increases the moisture in the air due to the vegetation and the availability of water. Studies about climate changes showed that an increase of temperature causes an increase of extreme precipitation (Trenberth, Dai, Rasmussen, & Parsons, 2003). A decrease of temperature should give an opposite effect and therefore the Sinai should have less extreme precipitation events in the future.

The total precipitation is expected to increase due to the rehabilitation of the Sinai. In the Negev (Israel) grazing was banned in certain areas and a large area was afforested which increased the average yearly precipitation by 15% (Otterman, Manes, Rubin, Alpert, & Starr, 1990). The rehabilitation of the Sinai is expected to increase the average yearly precipitation by 68% (van der Hoeven M. , 2017). If the yearly average precipitation increases with 68% the extreme precipitation might also increase. To make a conservative estimate an increase of extreme precipitation of 15% is taken into account. The forthcoming amounts for a precipitation event with a yearly probability of 50%, 5% and 2% is shown in table 4.3.

Table 4.3: Extreme precipitation with an increase of 15% from the current situation (own illustration, 2017)

Area		Amount of prec. with a 50% yearly probability (mm)	Amount of prec. with a 5% yearly probability (mm)	Amount of prec. with a 2% yearly probability (mm)
North	1 day	21,9	27,0	29,3
	2 days	23,6	36,2	46,6
Middle	1 day	12,7	20,7	24,7
	2 days	13,2	28,2	43,7
South	1 day	7,5	16,7	24,2
	2 days	8,6	20,7	29,9

4.2.3 Curve Numbers

This section describes the derivation of the Curve Numbers(CN), this is an intermediate parameter to estimate the maximum retention of the soil and thus the amount of water available to run off. The CN is based on soil types, land use and treatment and antecedent soil moisture. It is used because exact parameters are missing for the soil in the Sinai. Only a few ground samples are available for the large watershed, the available geologic aeromagnetic map is crude and the DEM will not allow detailed information about depressions or sinks in the area. The CN is a replacement of the missing data and describes the interception by vegetation, infiltration into the soil and retained water in surface depressions.

The Curve Number of a watershed can be estimated as a function of the soil type, land use and treatment and antecedent watershed moisture. Its values range from 100(water bodies) to approximately 30 for permeable soils with very high infiltration rates and capacity.

Soil type

The composition of the soil influences the capability to store water and is an important factor in the water cycle. Soil materials influence the processes of infiltration, retention, evaporation, percolation, capillary rise and the capability of storage. Data on these processes are however not available and therefore the intermediate CN is used. The composition of the soil in the Sinai is an input for defining the CN via the Hydrologic Soil Group (HSG) and can also give an indication on the capability to rehabilitate the area.

Combining the surface geology map derived from European Soil Data Centre (ESDAC) in QGIS with the information from Greenwood(1997) about the soil horizons. The Hydrologic Soil Group (HSG) is derived as described in appendix F. In figure 4.5 the created surface geology map is shown and in table 4.4 the derived HSG are presented.

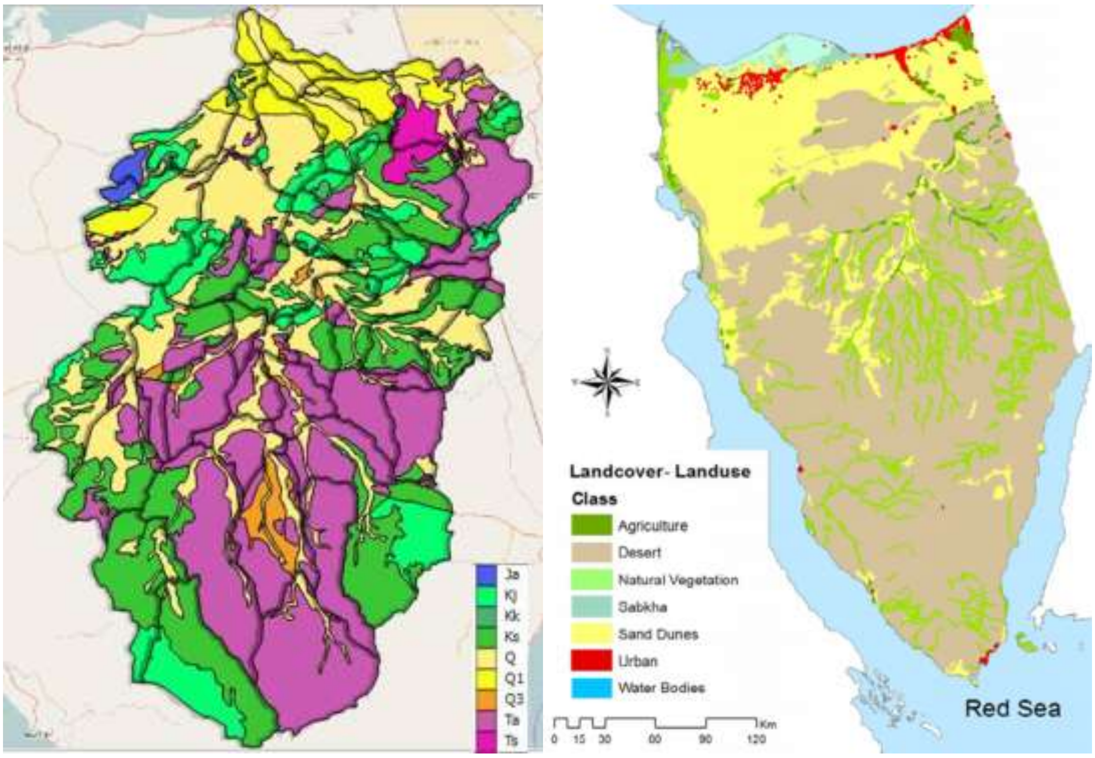

Figure 4.5: Soil map of the El Arish watershed with sub basins (own illustration, 2017) and land-use in the whole Sinai (The Weather Makers, 2016)

To summarize the derivation of the HSG: Quaternary alluvial deposits (Q and Q1) are well-drained thick layers of sand and gravel, with low runoff potential and high infiltration rates and are therefore marked as soil group A. The quaternary lake deposit (Q3) contain more clay and marl and therefor has a lower infiltration capacity, thus they are ranked as HSG B. Soil cover is generally absent on the massive limestone plateau in the middle and southern parts of the watershed, leaving the bedrock surface exposed. Infiltration capacity is extremely limited in these areas, and runoff is very high with a soil group D. These groups are in accordance with what Foody et al. (2004) and Milewski et al. (2009) used in their respective research.

4.4 Hydrologic Soil Groups per type of soil from figure 4.5. (own illustration, 2017)

Abbreviation	Description	HSG
J_A	Jurassic: Limestone, dolomite, marl, sandstone	D
K_J	Cenomanian- Turonian: Limestone, dolomite and marl	D
K_K	Lower Cretaceous: Sandstone, marl and limestone	D
K_S	Senonian – Palaeocene: Chalk, mar, clay, chert and limestone	D
Q	Quaternary: Alluvium	A
Q_1	Quaternary: Sand dunes (coastal and desert)	A
Q_3	Pliocene – Quaternary: Marl, clay, sand conglomerate(lake and wadi deposit)	B
T_A	Eocene: Chalk, limestone, chert	D
T_S	Oligocene-Miocene: Clay, sandstone, marl, gypsum, conglomerate and limestone	D

Land-use
The land-use describes what function the land has and the condition it is in. This is important in relation to the interception- and transpiration of the vegetation but also for the evaporation, permeability and infiltration capacity of the soil. Appendix A describes how the amount of soil cover and organic matter influences the infiltration and therefor the amount of runoff. The condition and the function of the land influences the CN takes this into account.

The Sinai has a barren soil, the six soil samples analysed by Greenwood (1997) contained less than 0,1 organic matter which affects the water holding capacity and fertility. Vegetation cover is very low because the sparse vegetation is eaten by overgrazing herds of livestock and the use of plants for firewood by an increasing population say Otterman et al. (1990) and Greenwood (1997).

Land-use classes are limited to desert shrubs (arid vegetation) with a low amount of ground cover(less than 30%). This is the dominant land-use and the condition of the land in the Sinai. In the wadi bed and on the stable dune landscape near El Arish city some agriculture land is used with the help of irrigation. The city itself has an urban land use, with impermeable surfaces. The land-use map is shown in figure 4.5.

Soil moisture
UNESCO considers the Sinai to be arid to hyper arid, having a potential evaporation to precipitation rate of less than 0,03 in the mayor part of the watershed (hyper arid). The amount of moisture in the soil before a rainfall event happens also influences the amount of water the soil can retain. The CN takes this into account via the Antecedent Runoff Condition(ARC), which divides the condition prior to the rainfall event into three classes: a dry condition, an average condition and a wetter condition. Because the Sinai has a very high potential evaporation rate compared to the rainfall a dry condition is assumed.

Derivation of Curve Numbers
Given the soil types, land use and treatment, surface condition and antecedent soil moisture the CN can be derived. In table 4.5 the CN for the land uses that are present in the El Arish watershed are shown. If a region has the land-use desert and has a HSG A the region has a CN of 63. To calculate the CN value for a sub basin the weighted average is used, calculated with the shape file made in QGIS. In appendix F the values for all the sub basins are shown and the curve number is derived at length.

Table 4.5: CN derived for the three land uses in the El Arish watershed for different HSG, given dry ARC conditions (U.S. Army Corps of Engineers, 2016) (Natural Resources Conservation Service, 1999).

	A	B	C	D
Desert shrubs (<30% ground cover)	63	77	85	88
Orchard or tree farm(<50% ground cover)	57	73	82	86
Residential districts (65% impervious area)	77	85	90	92

4.2.4 Wadi beds

The wadi bed is where the sediment from the bare surroundings accumulates and moves downstream when water is present. Generally speaking the wadi bed is thicker in areas with a higher yearly precipitation (Yair & Lavee, 1985). In combination with the downstream movement of sediment it is assumed that the wadi bed is thicker in the downstream northern area with higher precipitation. Just upstream of the city of El Arish, soil profiles of the wadi bed have been collected by Greenwood (1997). Because the soil profile is made in the most downstream section of the watershed, the soil thickness of the wadi bed is assumed to decrease linearly in upstream channels shown in figure 4.6. Wadi bed profiles made by Faershtein et al.(2016) in a more upstream part of the El Arish watershed confirm this hypothesis.

The thick wadi beds subtract water from the flash flood wave, this processes is called transmission losses. To calculate the transmission losses of the wadi beds the dimensions of the wadi bed are needed: the width-, length- and the thickness of the wadi bed. The material of the bed determines the amount of water that can be stored and the soils ability to transmit water (hydraulic conductivity).

The dimensions of the wadi channel measured in appendix D are used to calculate the transmission losses. However a higher magnitude flash flood will flood a wider part of the wadi bed and the discharge will therefor influence the width of the wadi bed that subtracts water from the flash flood. In appendix I the method used to calculate the transmission losses is discussed.

The roughness of the wadi bed also provides resistance for the flash flood moving downstream in the main wadi channels. The roughness of the main wadi channel is relatively low because of the sand and gravel beds and the straight channels. This is simulated in HEC-HMS with the manning coefficient in the channel flow model described in appendix H.

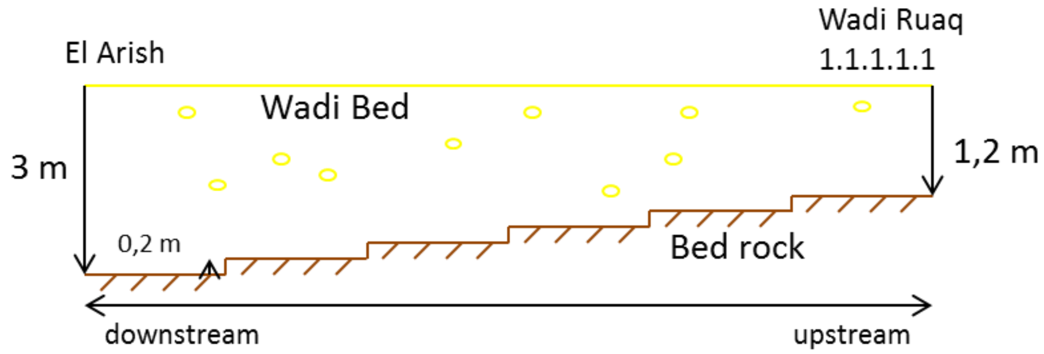

Figure 4.6 Simplification of the wadi bed thickness in the El Arish watershed (own illustration, 2017)

4.3 Calibration and sensitivity analysis of the hydrological model

The HEC-HMS hydrological model is a semi distributed conceptual model and has multiple input parameters: precipitation, sub basin- and wadi dimensions, curve numbers, lag time, channel flow routing and transmission losses. The CN, the lag time, channel bed roughness and the transmission losses have no direct, physically measurable identity but are estimates based on physical properties of the hydrologic processes. Together with the precipitation which has a large uncertainty these non-measurable parameters need calibration. The same parameters are used in a sensitivity analyses to see the effects of potential biases in the estimations.

First the hydrological model in HEC-HMS is calibrated. This is done with the only retrievable flash flood measured in the El Arish watershed in 1975. Klein (2000) shows the measured hydrograph at the Ruaffa Dam, the total measured outflow and describes the corresponding precipitation.

Second the sensitivity of the model is assessed. The values used for the parameters are estimates based on the physical properties of hydrological processes. Because they are estimates and cannot be calibrated it is necessary to assess the sensitivity of these parameters.

4.3.1 Calibration with the 1975 event

For the simulation of the flash flood of 1975 the HEC-HMS model used the parameters that are in appendix J. Klein (2000) estimated an average precipitation of 40-50 mm for the whole El Arish watershed starting in the evening of 19 February and continuing through the whole 20th of February of 1975. A 40 mm precipitation is assumed in 30 hours uniformly distributed over all the sub basins. The measurement from Klein(2000) and the simulated hydrograph are shown in figure 4.7.

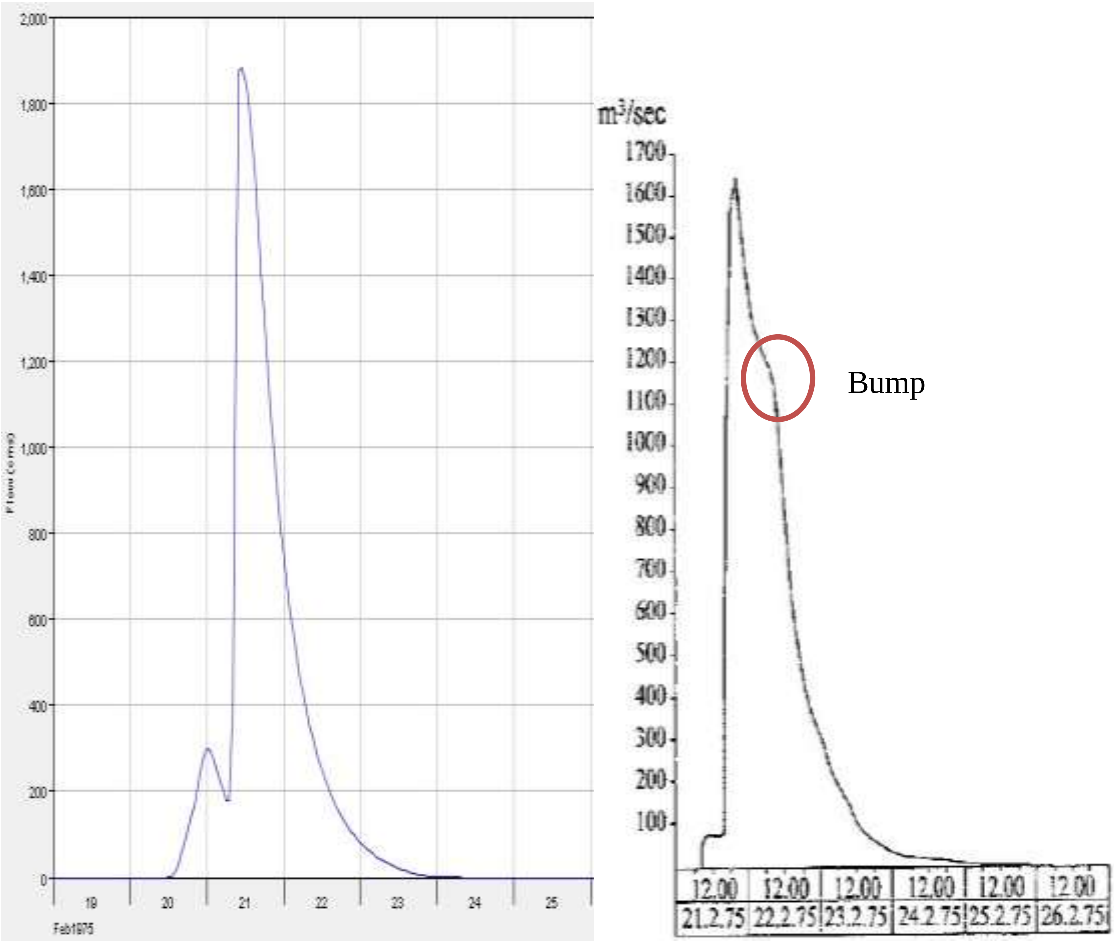

Figure 4.7: Results from the HEC-HMS simulation (left) and the measured event at the Ruaffa Dam(right) (Klein, 2000)

The two hydrographs look similar in most aspects, there are however some noticeable differences: the peak flow is somewhat higher in the modelled hydrograph, the flow in the simulation starts and stops a day earlier, and there is a bump in the tail of the measured hydrograph. The total discharge in the simulation is $121 * 10^6 m^3$ while the measurement had a total discharge of $120 * 10^6 m^3$, which sounds too good to be true.

The lack of discharge measurements in the El Arish watershed makes it impossible to identify the parameter that causes the differences between the measured and the simulated hydrographs. Therefore many combinations of the CN, bed roughness of the wadi, lag time and transmission losses parameters values may give a similar performance and these parameters cannot be calibrated. This means that the whole hydrological model cannot be calibrated. For a conceptual hydrological model applies that if the information content of the data on which the parameters are calibrated is limited, the parameters are non-identifiable. With only one event measured on one location it is not possible to calibrate the model for the whole watershed or to give more than an indication on the quality of the hydrological model.

The precipitation event that caused the flash flood is given as a bandwidth of 40-50 mm in Klein (2000) and this means that even if the model would be physical based the model could not be calibrated as well. The lack of data in the El Arish watershed does not allow any hydrological model to be calibrated.

Even with the uncertainties the comparison between the simulation and with the measurement gives results. The hydrograph produced with the simulation has the same shape as the measurement and the duration of the flow at the Ruaffa Dam is consistent. The rapid accumulation of water in the Ruaffa Dam is comparable, the steepness of the hydrograph is similar and the small bump before the flow is visible in the simulation as well.

To investigate how the model reacts to the input parameters this is discussed further in the sensitivity analyses of the hydrological model.

4.3.2 Sensitivity of hydrological model

To simulate the flash flood in 1975 available information was used to estimate the parameter values. There is uncertainty in these estimates and they cannot be calibrated because of the lack of measurements. The sensitivity analysis shows the influences of these uncertainties on the hydrological model. Different values of input parameters are used to test their influence on the outflow at the Ruaffa Dam in the hydrological model.

A bandwidth of the potential bias of the non-measurable and measurable parameters is established in this sensitivity analyses. The lag time, wadi bed roughness, CN and transmission losses are tested because they are non-measurable and are estimates based on physical properties. Because they are estimates they potentially cause a large bias. Measurable parameters like slope, precipitation or width of the wadi are not taken into account in the sensitivity analysis. Precipitation is a measurable parameter but because of the uncertainty in the measurement and the large bandwidth given for the 1975 flash flood event by Klein(2000) its sensitivity also analysed.

The roughness of the wadi bed, the CN, the lag time, transmission losses and precipitation are tested on their influence. The values from the 1975 flash flood simulations are used as initial values in the test. The sensitivity of the hydrologic model for the CN and the estimation of the HSG are shown in table 4.6 and figure 4.8. The sensitivity analysis of the parameters earlier mentioned is in appendix L.

The sensitivity analysis shows that the CN and precipitation are important parameters for the accuracy of the model. An increase of 5% of the CN would cause an increase of around 50% of peak discharge. If the precipitation would 45 mm in 30 hours instead of the 40 mm assumed to simulate the 1975 event the peak discharge would increase with more than 50%. With a northward moving storm the peak discharge would increase with 20%.

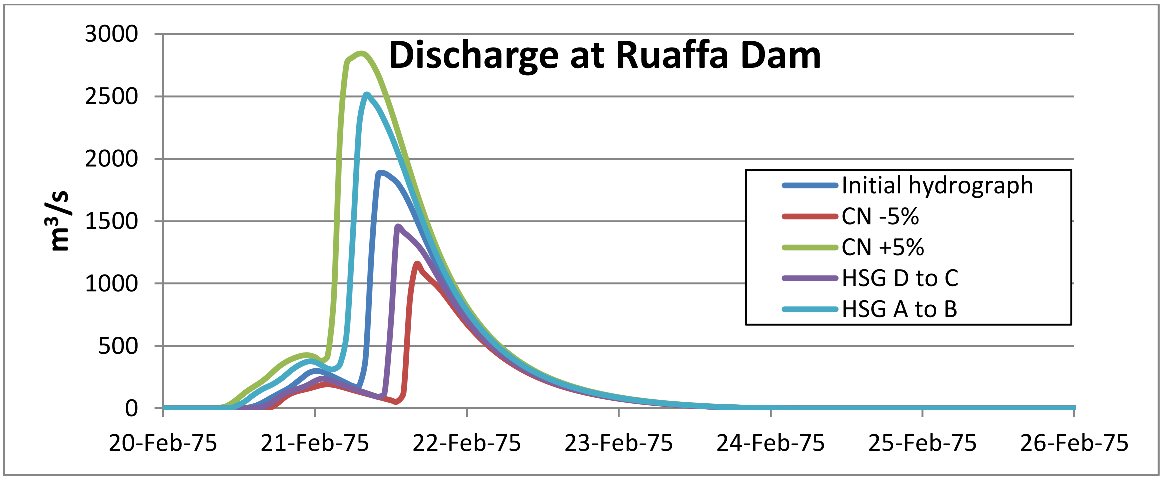

Figure 4.8: Hydrograph at the Ruaffa Dam showing the effects of the CN (own illustration, 2017)

Table 4.6: Influence of changes of the CN and in HSG (also effects the CN)

	Initial	CN -5%	CN +5%	HSG D to C	HSG A to B
Whole watershed trans losses (%)	10,5	9,4	11,4	9,8	11,4
Whole watershed discharge (%)	13,5	7,0	22,8	9,5	20,2
Whole watershed losses due CN (%)	76,0	83,6	65,8	80,7	68,4
Peak discharge at Ruaffa Dam(m^3/s)	1880	1150	2840	1450	2510
Change peak discharge (%)	-	-38,8	+51,1	-22,9	+33,5
Total discharge at Ruaffa Dam(m^3)	1,21E+08	6,77E+07	1,98E+08	8,68E+07	1,60E+08
Change total discharge (%)	-	-44,1	+63,2	-28,3	+32,5

4.4 Hydraulic model check

The simulation of the hydrologic model gives an estimate on the discharges during flash floods in the El Arish watershed. To check whether these discharges would cause a similar flood as was witnessed in 2010 they are used as input in a HEC-RAS simulation. First the hydrological model is used to calculate the discharges in the 2010 flash flood. Then these are used as input for the 2-D hydraulic flow model downstream of the Ruaffa Dam to simulate the extend-, depth- and flow velocity of the flash flood. Finally these results are compared to the pictures and video's made of the flash flood of 2010.

4.4.1 Simulation 2010 event in hydrologic HEC-HMS model

The difference between the 1975 event and the 2010 is the smaller amount of precipitation (even with the multiplication factor of 1,18) and a smaller contributing wadi bed for the transmission losses (to ratio with the amount if precipitation). The CN, dimensions of the sub basins and –main wadis, and parameters to calculate the channel flow stay the same. The result is a flash flood smaller in magnitude than the 1975 event. Figure 4.9 shows the 2010 flash flood event.

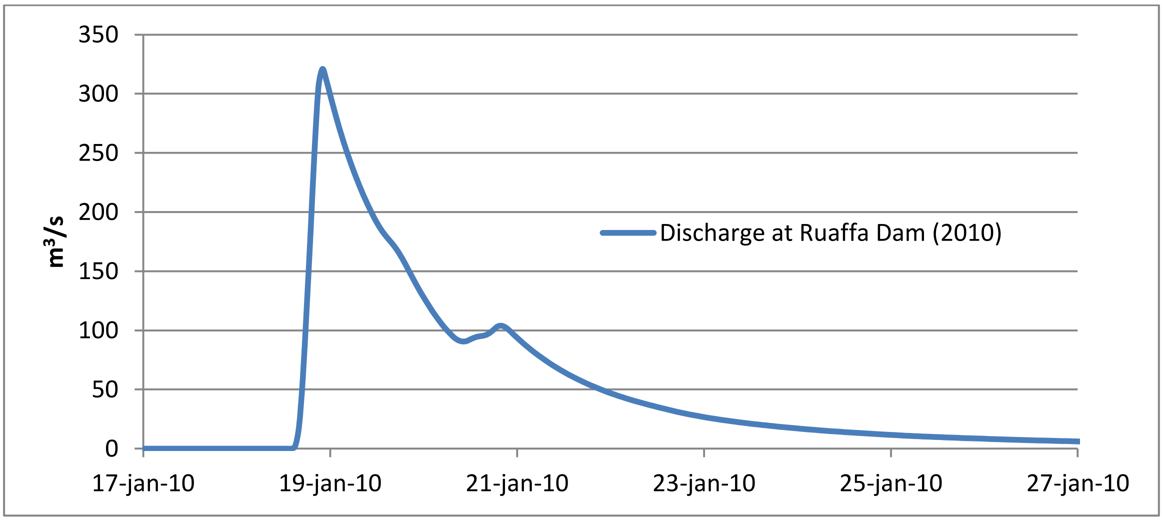

Figure 4.9: Simulation of the 2010 flash flood with HEC-HMS (own illustration, 2017)

4.4.2 Simulation by HEC-RAS of 2010 event

The results from the HEC-HMS are used as input for the HEC-RAS 2D flow model. Because the video footage and the pictures from the 2010 flash flood are taken between the Ruaffa Dam and the outflow at the Mediterranean Sea, only that area is simulated in HEC-RAS. In figure 4.10 the extend-, depth- and flow velocity of the flash flood are shown.

The simulation shows that the main wadi channel overflows the banks and that the flash flood surges through the city center of El Arish. The inundated area resulting from the simulation is not continuous from the wadi channel into the city. This could be because the city has some elevated parts or because of an error in the DEM.

The maximum flow velocity during the simulated event can reach velocities up to 8 m/s. The maximum flow velocity of the 2010 event through the city of El Arish is shown in figure 4.10. In Klein (2000) an average velocity of 1 m/s was measured for the 1975 flood at the Ruaffa Dam. The simulation of the flood of 2010 is smaller in magnitude and therefore the average velocity should be lower and this seems to be consistent with the velocities of figure 4.10.

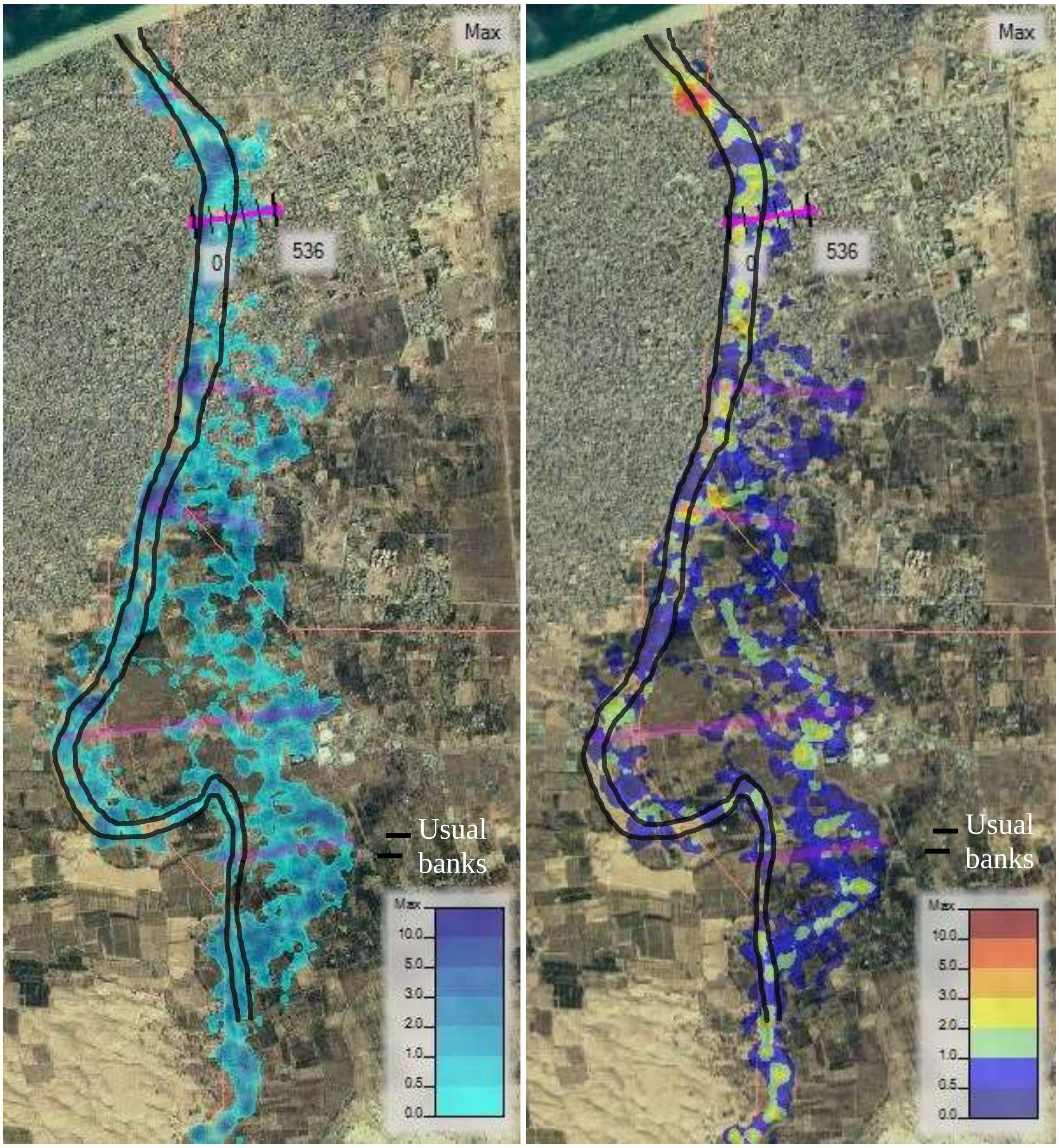

Figure 4.10: Results of the flow depth(left) and -velocity (right) in the city of El Arish for the 2010 flood event (own illustration, 2017)

4.4.3 Comparison with the imagery of the 2010 event

Pictures and videos from the 2010 flash flood are compared to the simulation of HEC-RAS by deriving their location with Google Earth. This is done by looking up notable buildings or vegetation from the pictures on Google Earth. These derived locations are an estimate of the place where the pictures where taken but the landmarks seem to be coherent. The extend of the flood in the pictures seem to correspond well with the simulation. The flow velocity in the videos is in the same order as HEC-RAS simulates. In appendix M the pictures and their estimated location in El Arish city is shown with a description of the comparison.

The result from the comparison of the simulation of the 2010 flash flood is that the simulation is similar to the imagery of the event. However the imagery cannot be exactly located and pictures might be not be taken at peak discharge. The results of the simulation are the maximum extend and flow velocity of the 2010 flash flood. Therefore the results from the USACE method should be used as an indication for the flash flood hazard. The flash flood flow velocity, the depth and the extend of the flood are giving likely results based on the imagery of the flash flood. It should be noted that the simulation even gives a no flow depth in the wadi channel and this is clearly not the case in the pictures. The spottiness in the results of the simulation is therefore the result of errors in the DEM and not due to actual hills in the wadi channel. Outside the wadi channel in the flood plain this could also partly explain the spottiness of the simulation although hills can be present there.

4.5 Current flash flood hazard assessment

To assess the current flash flood hazard a precipitation event with a yearly probability of 2% is used. First the hydrological model is used to calculate the discharges which are caused by such a precipitation event. Then these are used as input for the hydraulic model downstream of the Ruaffa Dam to simulate the extend-, depth- and flow velocity of the flash flood. The current flash flood hazard is later compared to the hazard with measures.

The peak and total discharges at the Ruaffa Dam are higher than the discharges caused by the 2010 flash flood as shown in figure 4.11. This causes the flow depth and velocity in figure 4.12.

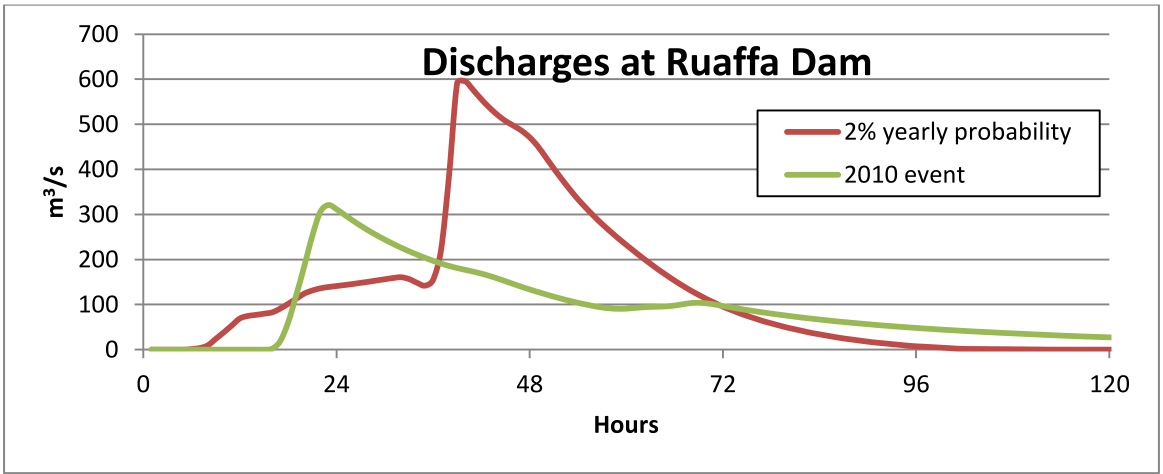

Figure 4.11: Simulation of the discharges at the Ruaffa Dam for the 2010 event and an event with a yearly probability of 2% (own illustration, 2017)

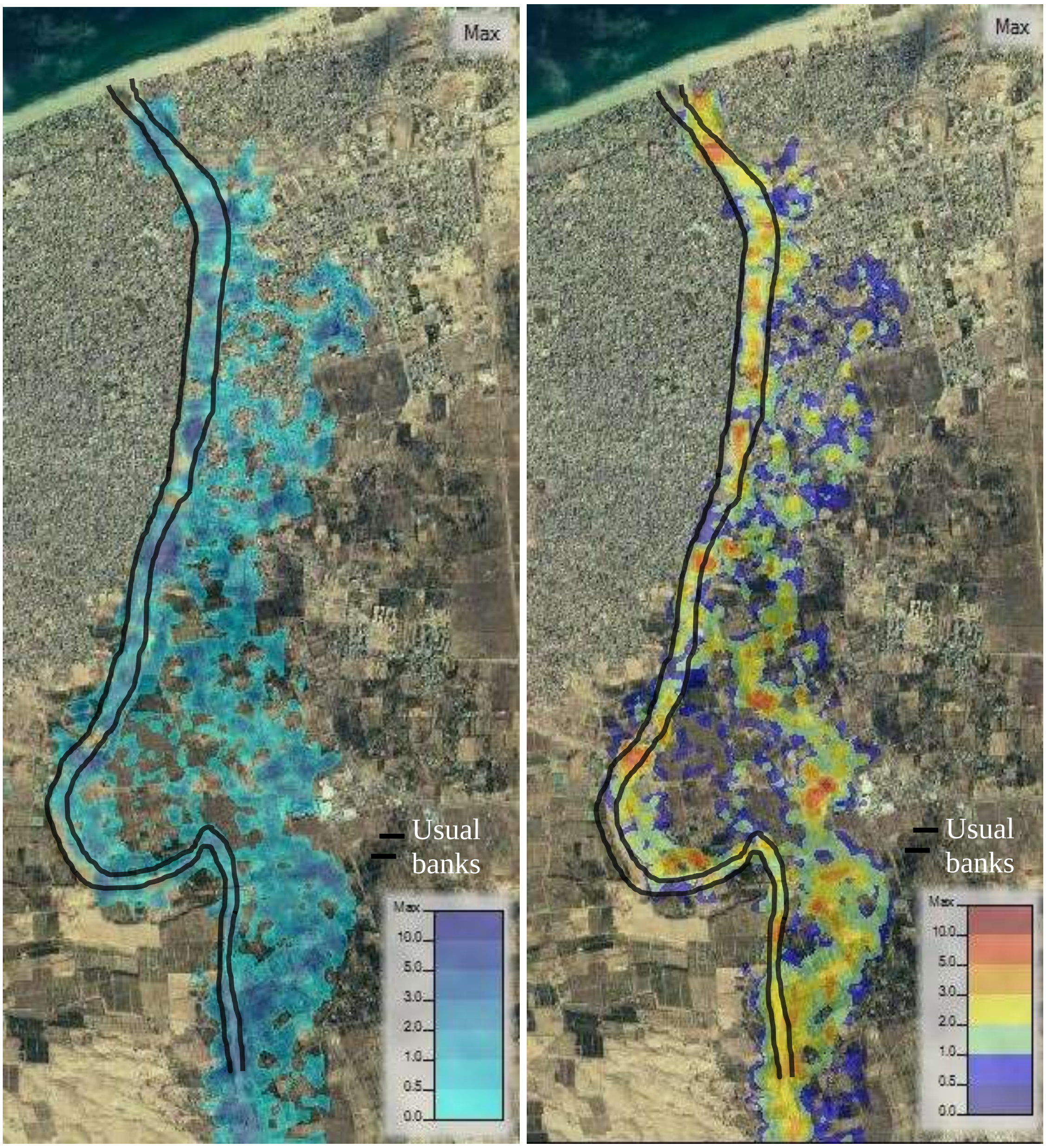

Figure 4.12: Flow depth(left) and -velocity (right) for an event with a 2% yearly probability (own illustration, 2017)

4.6 Measures in the USACE method

To be able to reduce the flash flood hazard in the Sinai feasible measures are used that can reduce the amount of total- and peak discharge. These measures are physical and applicable in climates like the Sinai, they can decrease the velocity of the flood, prevent flash floods to form, increase the permeability of the soil or do combinations of these.

An example are the spreading dams in figure 4.13, this measure is built in the wadi bed and spreads the water of the entire wadi bed width. This causes a decrease in flow velocity and therefore allows water from the flash flood to infiltrate into the thick alluvial soils. It is only applicable on HSG A or B and in flat areas (slope < 2%). The spreading dams are simple stone structures which are easy to build but need a lot of maintenance because they are in the main wadi channel. The effect they have on the USACE method is that they spread the water over the entire wadi bed and thus increase the contributing wadi bed this increases the transmission losses. The spreading of the water and the dam structures also increase the Manning coefficient to 0,05 in the main wadi channels this slows the flood wave down.

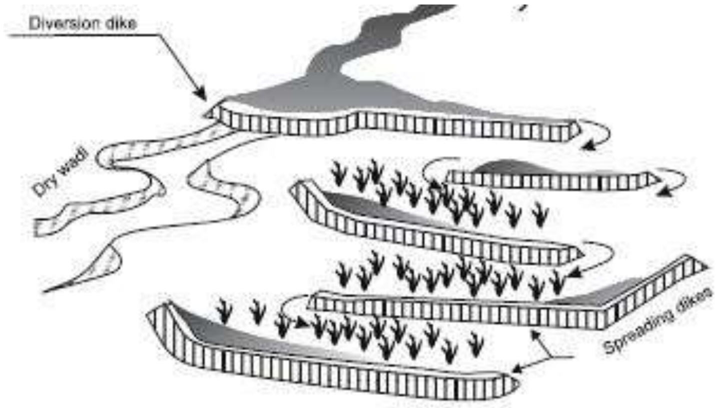

Figure 4.13 Percolation pond or diversion dikes (Oweis, Hachum, & Kijne, 1999)

The measures that are used in this research are listed below in the left column of table 4.7. A more elaborate explanation of these measures can be found in appendix N. Their applicability is defined and their feasibility is tested with a Multi Criteria Analyses. To model the flash flood hazard reducing measures in the HEC-HMS model their effects on the CN, lag time, channel flow and transmission losses is also discussed. The hazard reducing measures are assumed to be in full effect. Terraced wadis are less effective just after they are constructed since no sedimentation on the upstream side of the measure has taken place. The effect described in the table is the effect when the terraced wadis reached their full potential.

Table 4.7: Summary of the measures that are considered in this research, where they are applicable and the effects on the hydrological model in HEC-HMS

Measure	Function	Slope	HSG	Effect on HEC-HMS
Check dams	Retainment in the wadi	Any	Any	Increase of lag time of 30%, decrease of CN of 5%
Terraced wadis	Retainment in the wadi	< 12 %	Any	Increase of lag time of 30%, decrease of CN of 5%
Jessour and Tabia	Retainment in the wadi	Any	Any	Increase of lag time of 30%, decrease of CN of 5%
Sand dams	Retainment in the wadi	Any	Any	Increase of lag time of 30%, decrease of CN of 5%
Percolation or spreading dams	Spreading of water	<2%	A, B	Increase of contributing wadi bed width B, increase of Manning coefficient n to 0,05
Obstacle dams	Slowing down water in channels	<2%	Any	Increase of manning coefficient n
Storage dams	Storage of water	<10%	Any	Reservoir addition, dependent on reservoir size
Underground reservoir	Storage of water	Any	Any	Reservoir addition, dependent on reservoir size
Contour ridge	Harvesting measures around the wadi	< 5%	A,B	Increase of lag time of 30%, decrease of CN of 5%
Diamond shaped bunds	Harvesting measures around the wadi	< 5%	A,B	Increase of lag time of 30%, decrease of CN of 5%
Semi-circular bunds	Harvesting measures around the wadi	< 5%	Any	Increase of lag time of 30%, decrease of CN of 5%
Conservation bench terrace	Harvesting measures around the wadi	1 - 50%	Any	Increase of lag time of 30%, decrease of CN of 5%
Meskat and Manka	Harvesting measures around the wadi	Differs	C, D	Increase of lag time of 30%, decrease of CN of 5%
Afforestation	Afforestation	<20%	A, B	Decrease of CN for HSG A: 55, HSG B: 72
Eye brow terraces	Afforestation	1 - 50%	A, B	Decrease of CN for HSG A: 55, HSG B: 72

5 Reducing flash flood hazards

In this chapter the USACE method is first used to assess the flash flood hazards for a precipitation event with a 2% yearly probability. The region with the highest relative contribution to the hazard is then used to apply hazard reducing measures in. Secondly hazard reducing measures are allocated based on their applicability and their use in the area. A decision tree is used to allocate measures to surface regions with certain soil profiles and slope. Thirdly the effect of the proposed measures is assessed for the region with the highest relative hazard. Lastly the flash flood hazard is considered that the extreme precipitation could increase due to the rehabilitation plan by The Weather Makers.

5.1 Current situation

The current situation is that steep slopes and a lack of resistance cause high velocity flows in wadis. The high velocity flows in combination with the lack of permeability of the soil cause a low infiltration rate. The combination of the lack of infiltration and the flow velocity cause the flash floods in arid regions like the Sinai. The physical processes in the wadi that influence the three regions and which need to be altered are described in short.

Region 1 has steep slopes (>5%) and shallow soils until bedrock (HSG type C and D) cause high flow velocities and a lack of infiltration. To decrease the velocity of the flow more resistance is needed and therefore the surface roughness needs to be increased. To increase the infiltration the flow velocities need to be decreased and the permeability of the soil needs to be increased.

Region 2 has mild slopes (2- 5%) and thicker soils until bedrock than region 1(HSG type A, B, C and D). The flow velocity inside the wadi is still high due the accumulation of runoff despite the milder slopes. The infiltration is medium due to the high flow velocity and the medium permeability. To decrease the flow velocity the amount of runoff from the upstream areas should be decreased and the surface roughness needs to be increased. The infiltration increases by lowering the flow velocity and/or by increasing the permeability of the soil.

Region 3 has nearly flat areas (<2%) with thick soils. Water accumulates from the upstream steeper slopes. The flow velocity is medium because of the large amount of water, this limits the infiltration but the permeability of the soil is high. If the flow velocity is reduced the infiltration increases. A schematization of the current processes in the three regions is shown in figure 5.1.

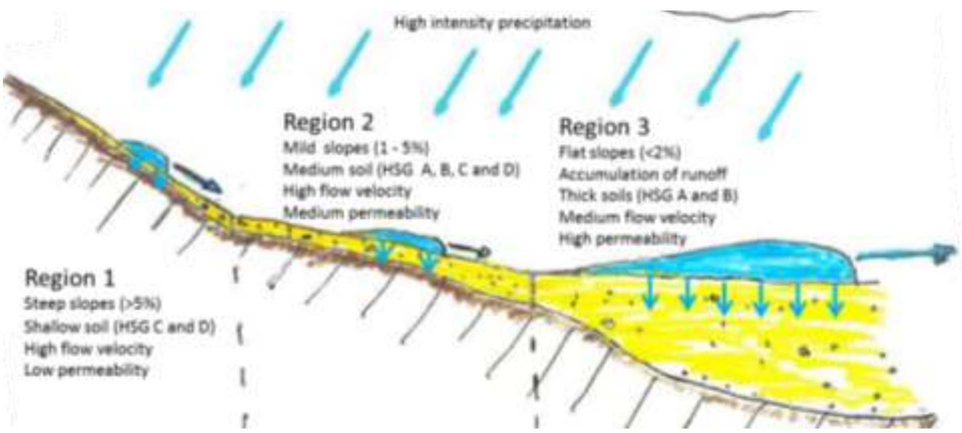

Figure 5.1: Schematic representation of the current situation of flash flood generation divided in regions 1 till 3 (own illustration, 2017)

The flash flood hazard in the current situation is assessed for a precipitation with a yearly probability of two- and five percent. The area with the largest relative contribution to the hazard in the city of El Arish is the area with the highest discharge per km². This is the area containing the Gaifi 1.1.1 and Gaifi 1.1 sub basins and in these basins the effect of feasible measures on the flash flood hazard is assessed. The hydrographs of a precipitation with a yearly probability of 2 and 5% in point A and B (outflow points of the two sub basins) of figure 5.3 are shown in figure 5.1.

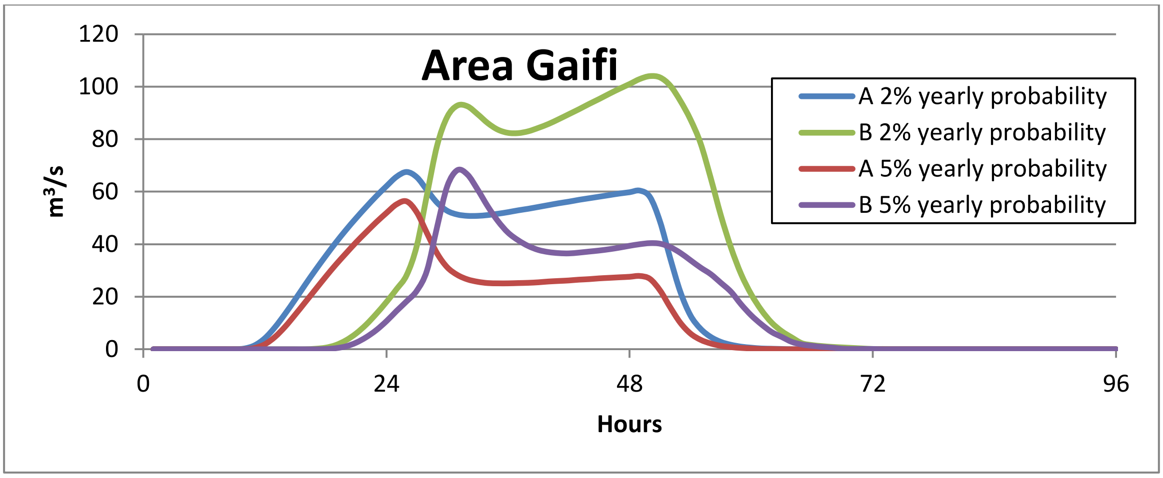

Figure 5.2: Hydrographs of point A and B shown in figure 5.3 (own illustration, 2017)

To reduce the flash flood hazard, measures are suggested in the Gaifi 1.1.1 and Gaifi 1.1 sub basin at the applicable areas. The movement of a flash flood downstream in a wadi provides the division in the sub basin. The division in the sub basin is therefore based on the soil profile and the slopes around the wadi channels, as is shown in figure 5.1. The following regions are derived:

1. Shallow soils until bedrock (HSG C and D and steep slopes >5%.
2. Thicker soils (HSG A, B, C and D) until bedrock and mild slopes (2 – 5%).
3. Thick soil until bedrock (HSG A and B) and slopes less than 2%.

In the region Gaifi 1.1.1 and Gaifi 1.1 the surface regions are divided as is described in table 5.1. There is a small areal extend of region 2 and 3 in sub basin Gaifi 1.1.1., region 1 is dominating. In Gaifi 1.1 the regions described above do not make up for the entire sub basin. The missing 17% is a region with sand dunes who does not contribute to the flash flood hazard. The soil in the region consists of thick sandy deposits before bedrock, is therefore very permeable and does not generate runoff. Because these sand dunes are not near wadis it does not receive upstream water and therefore measures do not have an effect on the flash flood hazard. This region is therefore not taken into account.

Table 5.1: Division of regions in the Gaifi area (own illustration, 2017)

	Region 1	Region 2	Region 3	Total
Gaifi 1.1	15%	42%	25%	83%
Gaifi 1.1.1	83%	10%	7%	100%
Whole Gaifi area	41%	30%	18%	89%

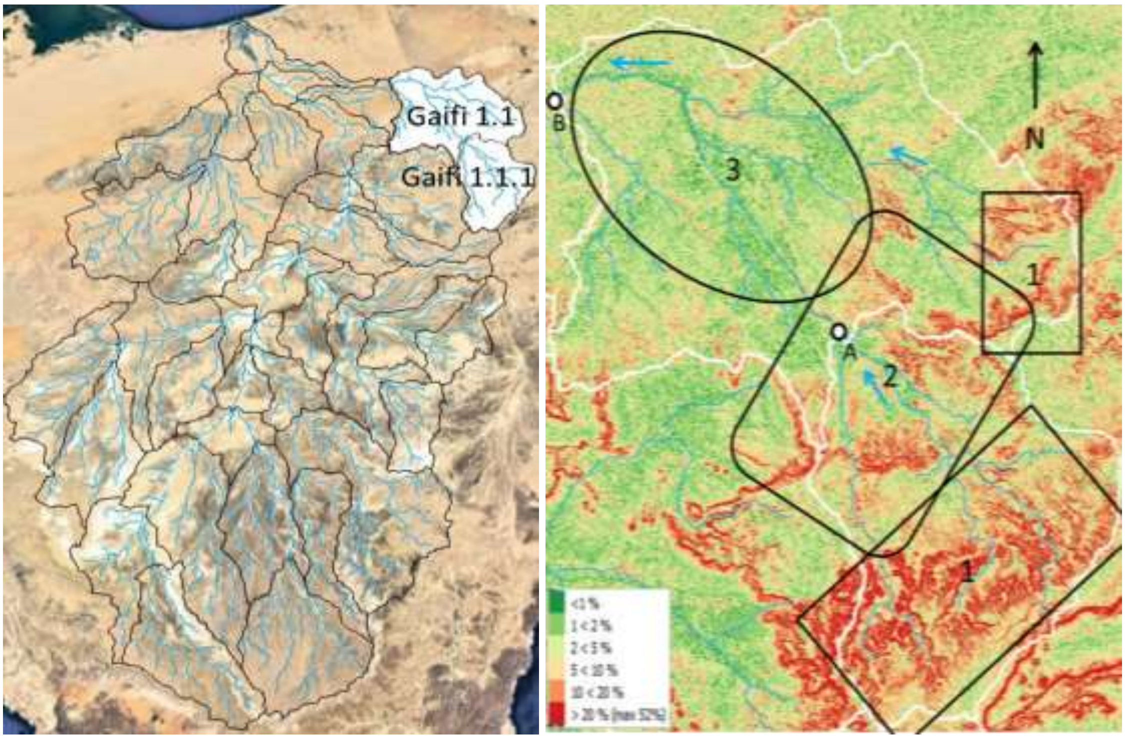

Figure 5.3: The location of region Gaifi (left) and the slope map with soil groups of the Gaifa 1.1.1 and Gaifi 1.1 sub basins(own illustration, 2017)

5.2 Allocating measures to reduce flash flood hazard

Hazard reducing measures described in appendix N influence processes that cause the flash flood. Their use and the way they influence these processes decide for which slope and soil group they are applicable. The allocation of measures for a region is based on whether the location is in- or outside the wadi. First the allocation of measures in wadi channels is discussed and secondly the measures outside the wadi are deliberated.

5.2.1 Inside the wadi

Wadi channels receive water from their surroundings through overland flow and gullies or from other wadi channels upstream. The measures in wadi channels in region 1 till 3 are allocated in the following way:

In region 1 pervious sediment catchers are used to slow down and filter runoff. This captures sediment and increases infiltration capacity. Because the slope and flow velocity is high the sediment catchers in this area are pervious. The sediment catchers are placed in the gullies and wadis that are caused by the drainage pattern to have effect.

In region 2 impervious sediment catchers are used. Region 2 receives runoff from the upstream steeper region 1. Because of the milder slope the water flows slower than in region 1 and therefore impervious sediment catchers can be used. These impervious sediment catchers will block the groundwater flow downstream which will increase the period of available soil moisture for vegetation at the upstream side of the measure.

Region 3 is the downstream part of the wadi where the soil is thick before bedrock. To make use of this natural reservoir (the transmission losses) the large amount of water streaming here needs to be slowed down. This is done by spreading dams: by redirecting the water from the main channel over the entire wadi bed the water travels a longer path and thus the average slope is lower and flow velocity smaller which in turn increases the infiltration.

For example check dams are small pervious wooden or stone dams which slow down water while it streams down a slope. Slowing down the water causes sedimentation at the upstream side of the small dams and sedimentation gives an increase in infiltration capacity in the long run. Because they are pervious they are less likely to fail in case of an extreme event and applicable on steep slopes. Because of these characteristics check dams are applicable on any kind of slope on any kind of soil group but because they do not block the water they have less effect in the larger wadis and regions with a milder slope.

To allocate hazard reducing measure the decision tree in figure 5.4 is used. This decision tree combines the applicability and feasibility of the measures with the regions described.

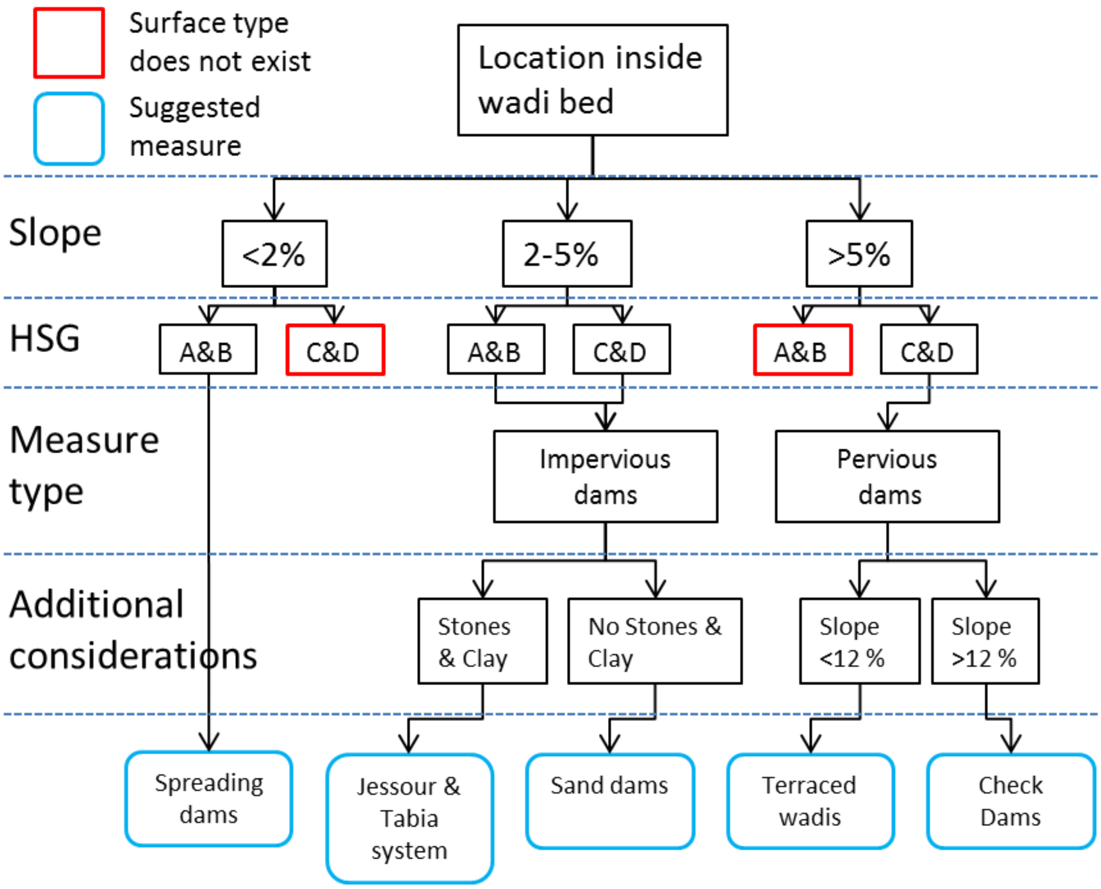

Figure 5.4: Decision tree for measures suggested in the wadi (own illustration, 2017)

The decision tree works as followed: the slope comes first, followed by the soil group. From here a measure type is proposed which can be further detailed. For example if the slope of the wadi considered is 4% and the soil group of the considered location is B, impervious dams are proposed. If stones and clay are available for the construction in the area a Jessour and Tabia system is preferred. If there are no such local buildings materials available sand dams are suggested. Sand dams require expertise from the engineer that designs them and are difficult to repair if they are damaged (Ertsen & Hut, 2009). Jessour and Tabia systems are preferred due to the relative easy construction and repair.

The flash flood moves downstream in the wadi therefore the measures in region 2 are influenced by the region 1 measures. The amount of discharge that flows in region 3 depends on the region 1 and 2 measures. This is shown in figure 5.5 which also shows the suggested measures for every region.

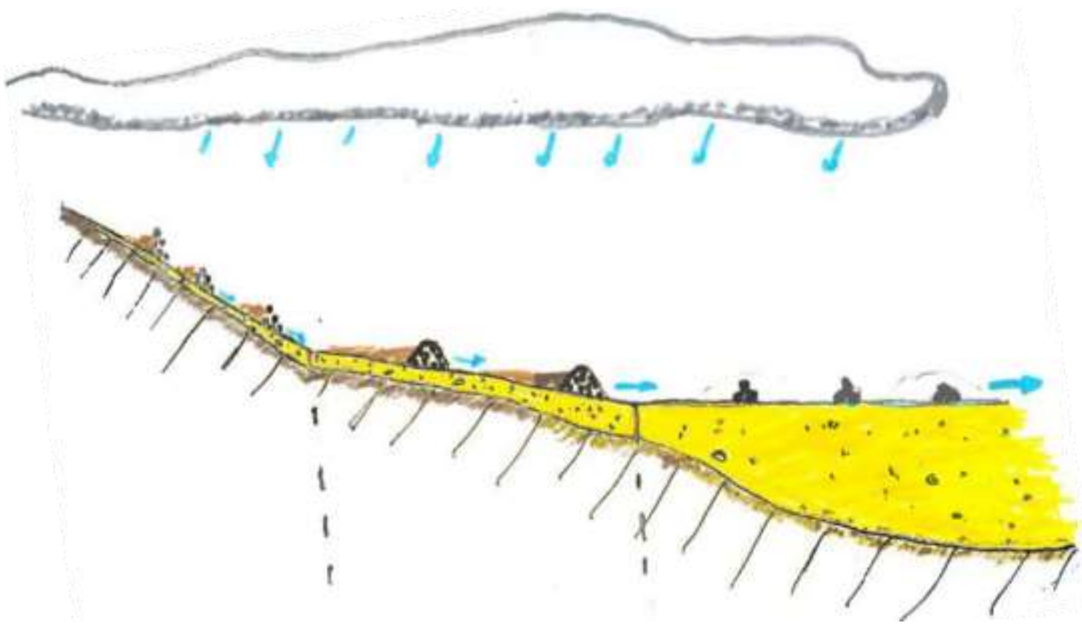

Figure 5.5: Schematic representation of the proposed measures in regions 1 till 3 in the wadi channels (own illustration, 2017)

5.2.2 Outside the wadis

In locations outside the wadi channel the excess precipitation causes overland flow, this will sooner or later reach a gully or wadi and thus add to the generation flash flood. To reduce the amount of overland flow that reaches the wadi measures are suggested for locations outside the wadi channel. The measures outside wadi channels in region 1 till 3 are allocated in the following way:

In region 1 pervious bunds are used to slow down and filter runoff. This captures sediment and increases infiltration. The bunds are pervious to minimize damages on the steep slopes. In region 2 bunds are used. The bunds slow down the generated runoff, capture sediment and increase the infiltration. This will decrease the total amount of water that flows into the wadi. Region 3 surface areas do not need measures because they do not generate runoff themselves and do not receive runoff from upstream. An example is the sand dunes in the most northern part of the watershed: they do not generate runoff because of their high permeability and low slopes and do not receive any upstream runoff because water runs off via the wadi bed.

The decision tree works in the same way as the decision tree for measures in the wadi. If the location of interest has a 2% slope and a HSG B, bunds are proposed. The easiest way is to use a mechanized process to construct earthen bunds, these are however susceptible to damage during extreme precipitation events. If the bunds are not repaired the downstream bunds are more likely to be damaged. Therefore it is essential to have the machinery and the knowledge to use these in the area where the measures are used. Or have a local community that can and sees the use of repairing these structures by hand. If the construction cannot be mechanized and there are stones in the area stone contour ridges can be applied. These are easier to repair and less likely to be damaged by an extreme event. The decision tree is shown in figure 5.6.

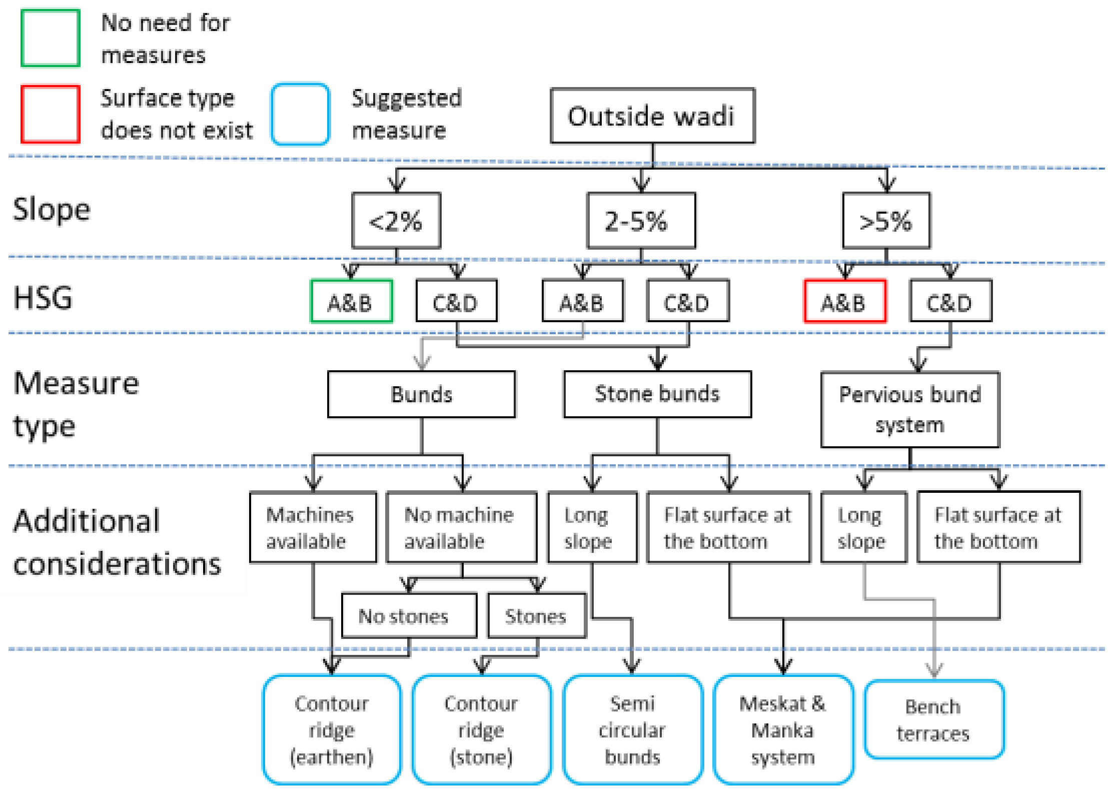

Figure 5.6: Decision tree for measures suggested outside the wadi (own illustration, 2017)

5.3 Hazard after applying measures

With the measures suggested in the previous section the hazard reduction of the measures can be assessed. This is first done by applying the measures in the region with the highest flash flood hazard. Then an estimate is made on the change in flash flood hazard for the El Arish City if the measures would be applied for the whole watershed.

5.3.1 Effect on the region with the highest flash flood hazard

The regions and the measures are discussed one by one to see the effect each measure has for each region and what kind of effect they have combined. This means that in total eight scenarios are considered, for each scenario the hydrograph of points A and B in figure 5.3 are shown for a precipitation event with a yearly probability of 2%. The peak discharge and total discharge for points A and B for precipitation event with a yearly probability of 2 and 5% are shown in a table as well. The hazard is assessed assuming that the hazard reducing measures reached their full effect. These eight scenarios are being discussed:

0. Current situation
1. Measures applied in region 1
2. Measures applied in region 2
3. Measures applied in region 3
4. Measures applied in region 1 & 2
5. Measures applied in region 1 & 3
6. Measures applied in region 2 & 3
7. Measures applied in region 1 & 2 & 3

Scenario 0: the current situation

In the current situation none of the suggested measures are present and this is the base case. In figure 5.7 the hydrographs of point A and B are shown for a precipitation event with a 2% yearly probability.

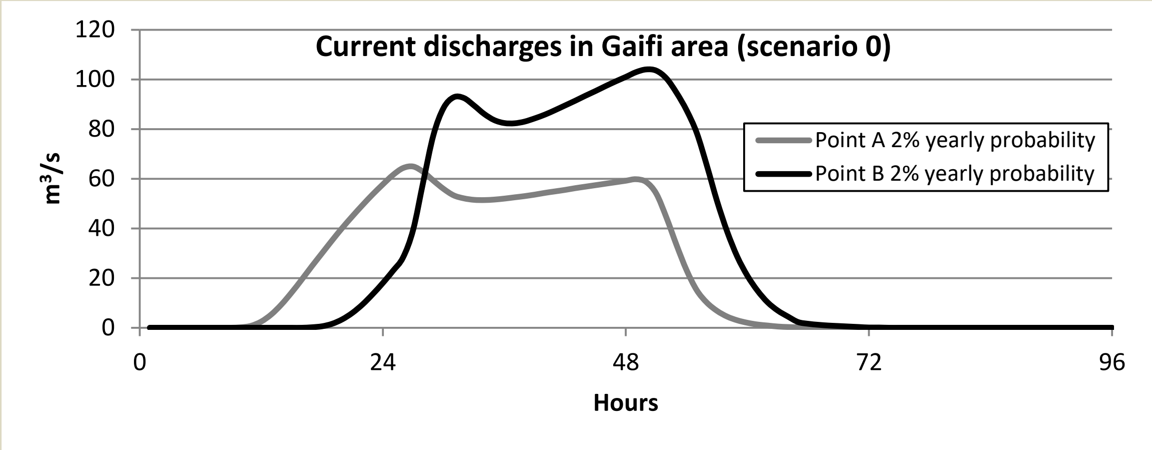

Figure 5.7: Hydrographs at point A and B for the current situation, scenario 0(own illustration, 2017)

Scenario 1: applying measures in region 1 only

In this scenario measures are only applied in the region with the steep slopes (>5%) and shallow soils (HSG D) as can be seen in figure 5.8. This causes a reduction in flow velocity and an increase of infiltration and thus a smaller peak discharge and total volume of flow is expected. In the hydrological model this is simulated by an increase in lag time and a decrease of the CN. The effects of these measures as is shown in figure 5.9 and table 5.2.

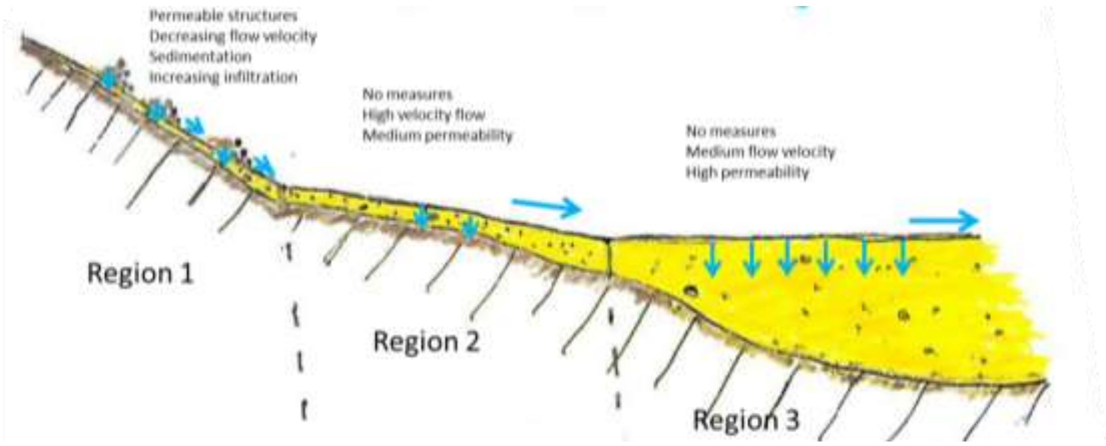

Figure 5.8: Region 1 measures are applied (own illustration, 2017)

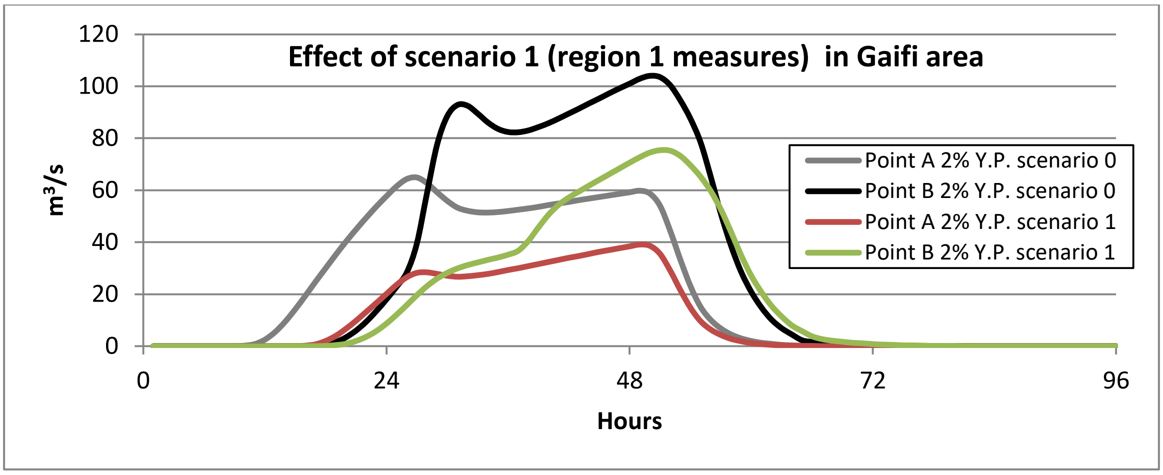

Figure 5.9: Hydrographs at point A and B for scenario 1(own illustration, 2017)

Because of the reduction of the flow velocity the hydrograph takes longer to peak and due to the increased infiltration the peak is lower as well. Upstream of point A soils are shallow and the terrain is steep, to reduce the discharges here has a direct effect on the downstream hazard as can be seen in the discharges in point B. This is also caused by the decrease of the discharge in point A which decreases the flow velocity in the main wadi channel and thus more water can infiltrate into the thick alluvial soils of region 3.

Table 5.2: Effects scenario 1 (own illustration, 2017)

Point A	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	56	20	-64	68	39	-42
total discharge ($1000m^3$)	4382	1741	-60	7403	3672	-50

Point B	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	68,2	23	-66	104	75,4	-28
total discharge ($1000m^3$)	5100	2476	-51	10459	6550	-37

Scenario 2: applying measures in region 2 only

This scenario only applies measures in region 2: the mild sloping (1 – 5%) region with shallow soils (HSG D) as shown in figure 5.10. The measures decrease the flow velocity and increase the infiltration. In the hydrological model this is simulated by an increase in lag time and a decrease of the CN which causes the discharges downstream decreases. Because there is relative low amount of region 2 soils upstream of point A the effects are small in that region. Downstream in point B the effect is larger, due to the larger amount of region 2 area upstream of point B and the amplified effect of the effects of the upstream: when the water slows down in region 2 the infiltration in region 3 increases. The effects are shown in figure 5.11 and table 5.3.

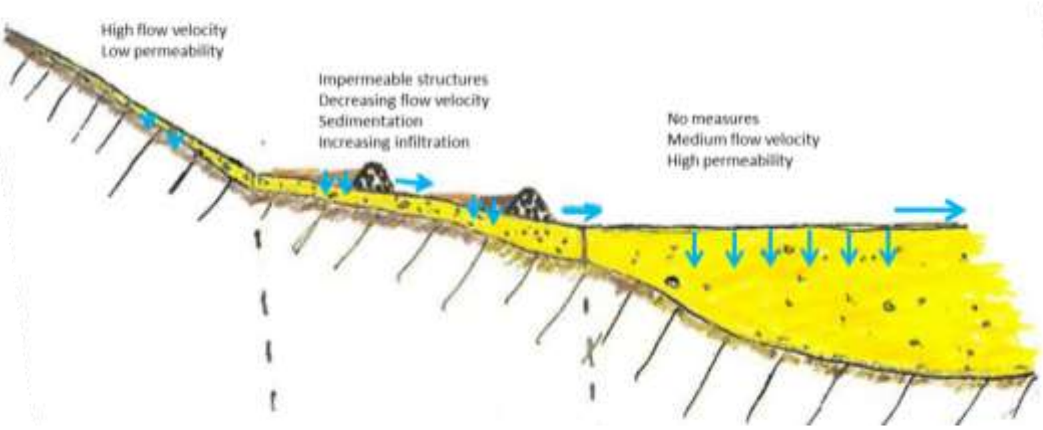

Figure 5.10: Region 2 measures are applied (own illustration, 2017)

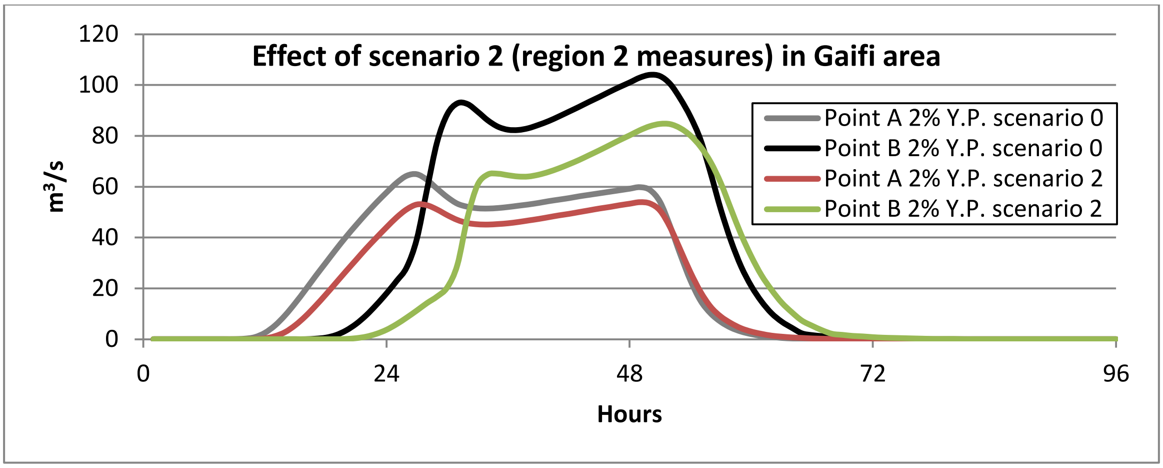

Figure 5.11: Hydrographs at point A and B for scenario 2(own illustration, 2017)

Table 5.3: Effects of scenario 2 (own illustration, 2017)

Point A	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	56	43	-25	68	54	-20
total discharge ($1000m^3$)	4382	3558	-19	7403	6290	-15

Point B	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	68	43	-37	104	85	-19
total discharge ($1000m^3$)	5100	3448	-32	10459	7880	-25

Scenario 3: applying measures in region 3 only

This scenario only applies measures in region 3: spreading dams are used to decrease the velocity of the flow and to increase the contributing width of the main wadi depicted in figure 5.12. In the hydrological model this is simulated by increasing the contributing width in the transmission losses calculations (see appendix I) and an increase of the Manning coefficient in the wadi channel flow (see appendix H). This increases the infiltration in the thick soils in region 3. Upstream of point A there is a negligible amount of region 3 type surfaces and therefore the discharge does not change in point A. In point B the effects are visible, due to the large runoff amount reaching region 3 the flow velocity is still high and the relative effect would be higher in combination with measures in other regions. The effects of the measures in region 3 are shown in figure 5.13 and table 5.4.

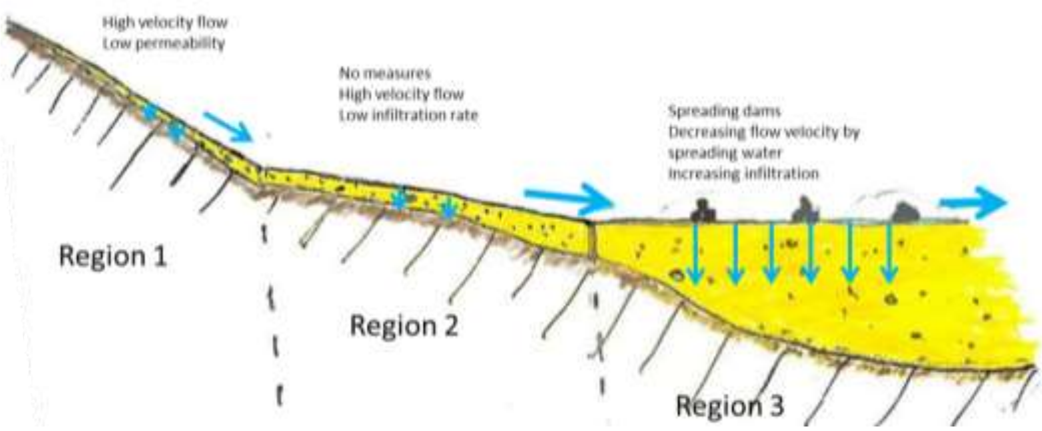

Figure 5.12: Region 3 measures are applied (own illustration, 2017)

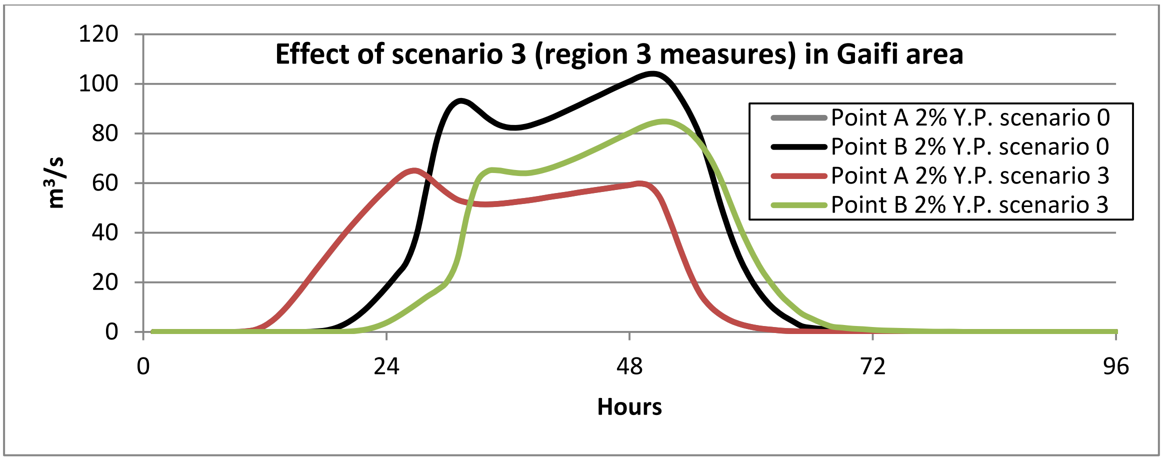

Figure 5.13: Hydrographs at point A and B for scenario 3, in point A there is no difference between the current and the situation with measures (own illustration, 2017)

Table 5.4: Effects of scenario 3 (own illustration, 2017)

Point A	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	56	56	0	68	68	0
total discharge ($1000m^3$)	4382	4382	0	7403	7403	0

Point B	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	68	26	-62	104	76	-27
total discharge ($1000m^3$)	5100	2009	-61	10459	6799	-35

Scenarios 4: applying measures in region 1 and 2

This scenario applies measures in the regions with shallow soils. The measures decrease the flow velocity and increase the infiltration. Therefore the discharges downstream decreases and this is shown in figure 5.14 and table 5.5. Because region 1 and 2 surfaces are widespread throughout the sub basins the effect is large.

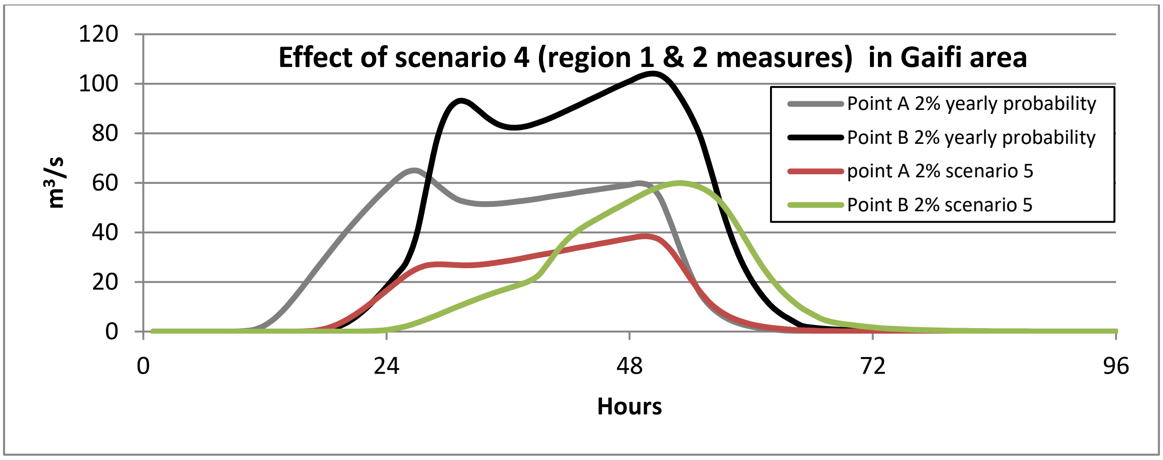

Figure 5.14: Hydrographs at point A and B for scenario 4 (own illustration, 2017)

Table 5.5: Effects of scenario 4 (own illustration, 2017)

Point A	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	56	19	-67	68	38	-43
total discharge ($1000m^3$)	4382	1741	-60	7403	3672	-50

Point B	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	68	15	-77	104	60	-42
total discharge ($1000m^3$)	5100	1401	-73	10459	4705	-55

Scenario 5: applying measures in region 1 and 3

This scenario applies measures in region 1(with steep slopes and HSG C&D) and region 3 (flat slopes and HSG A&B) but does not considers changes in region 2. The total and peak discharges downstream decrease as can be seen in figure 5.15 and table 5.6.

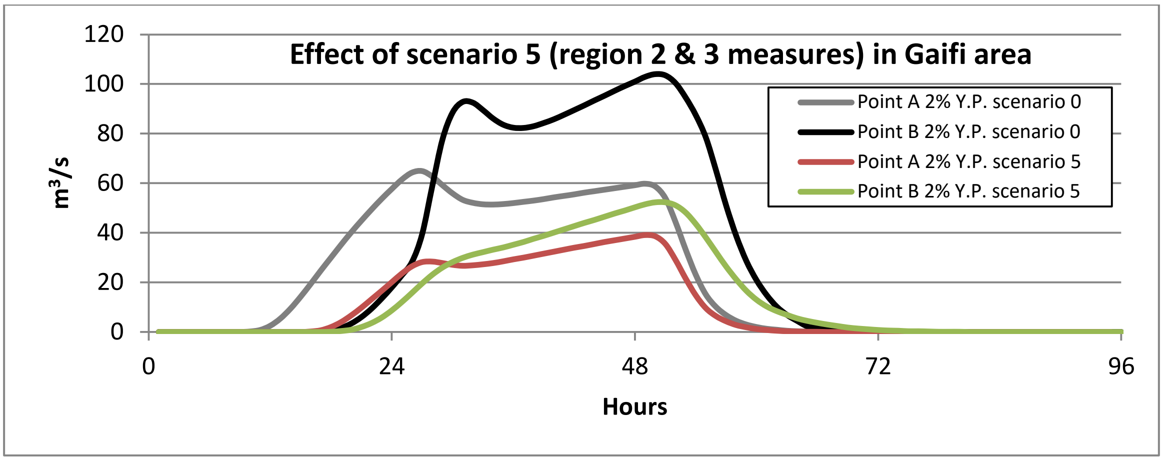

Figure 5.15: Hydrographs at point A and B for scenario 5 (own illustration, 2017)

Table 5.6: Effects of scenario 5 (own illustration, 2017)

Point A	5% Y.P.	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	56	20	-64	68	39	-42
total discharge ($1000m^3$)	4382	1741	-60	7403	3672	-50

Point B	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	68	20	-70	104	52	-50
total discharge ($1000m^3$)	5100	2135	-58	10459	4898	-53

Scenario 6: applying measures in region 2 and 3

This scenario applies measures in the regions with milder slopes(<5%). These regions are easier to reach, better fitted to work on, better habitable and therefore attractive to construct measures. The measures decrease the flow velocity and increase the infiltration. Therefore discharges downstream decrease which is shown in figure 5.16 and table 5.7. In point A the decrease is relative small due to the low amount of region 2 surface and the negligible area of region 3 type surfaces.

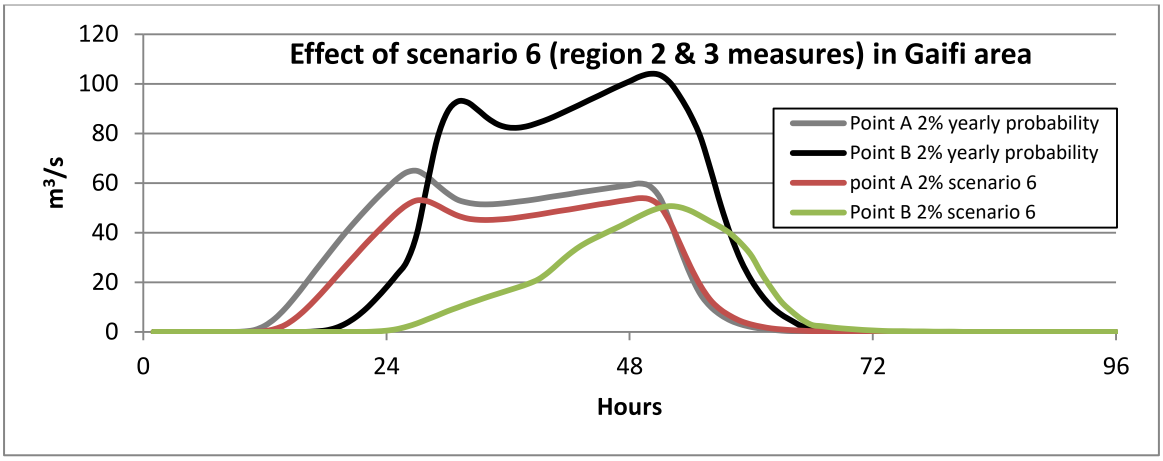

Figure 5.16: Hydrographs at point A and B for scenario 6(own illustration, 2017)

Table 5.7: Effects of scenario6 (own illustration, 2017)

Point A	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	56	43	-25	68	51	-25
total discharge ($1000m^3$)	4382	3557	-19	7403	3956	-47

Point B	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	68	11	-84	104	53	-49
total discharge ($1000m^3$)	5100	863	-83	10459	4046	-61

Scenario 7: applying measures in region 1, 2 and 3
This scenario applies measures in all three regions, the measures are shown in figure 5.17. This is the scenario that causes the biggest reduction of the flash flood hazard as can be seen in figure 5.18 and table 5.8.

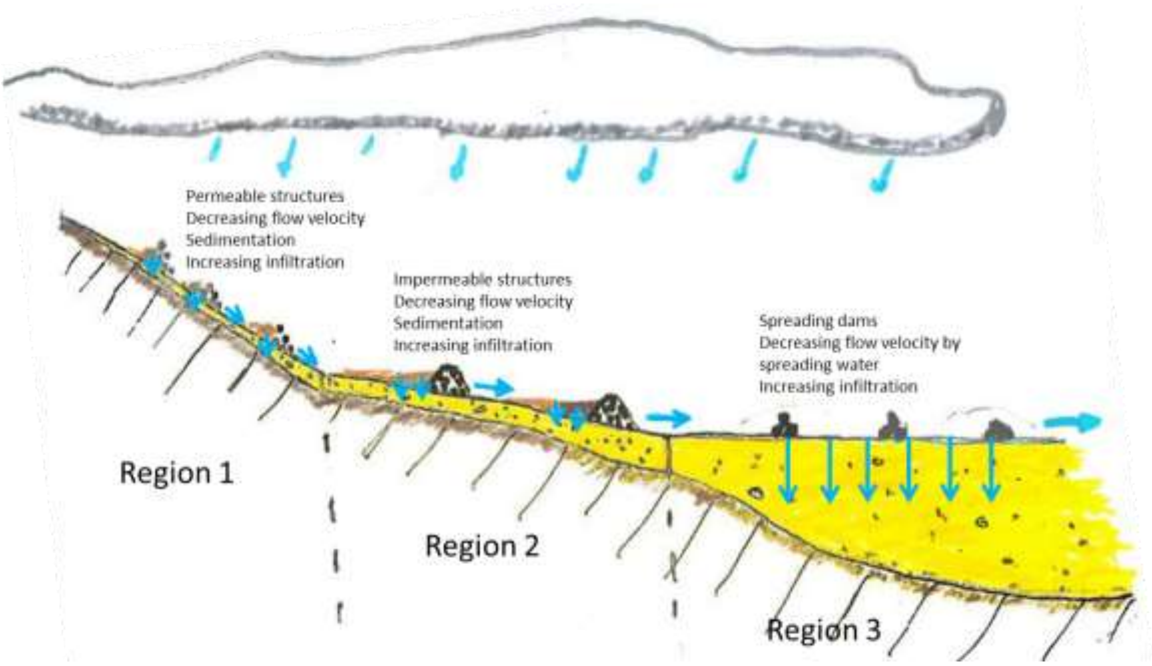

Figure 5.17: Measures in all regions are applied (own illustration, 2017)

The measures in region 1 and 2 make the total discharge smaller and slow down the water before it reaches region 3. This causes the measures in region 3 to have more effect, the spreading of the already slowed down water decreases the flow velocity even more and thus the infiltration in region 3 becomes higher. The effect is that the downstream peak discharge and total discharge in point B is lower than in the upstream point A. The flood 'disappears' due to the infiltration moving down the sub basin.

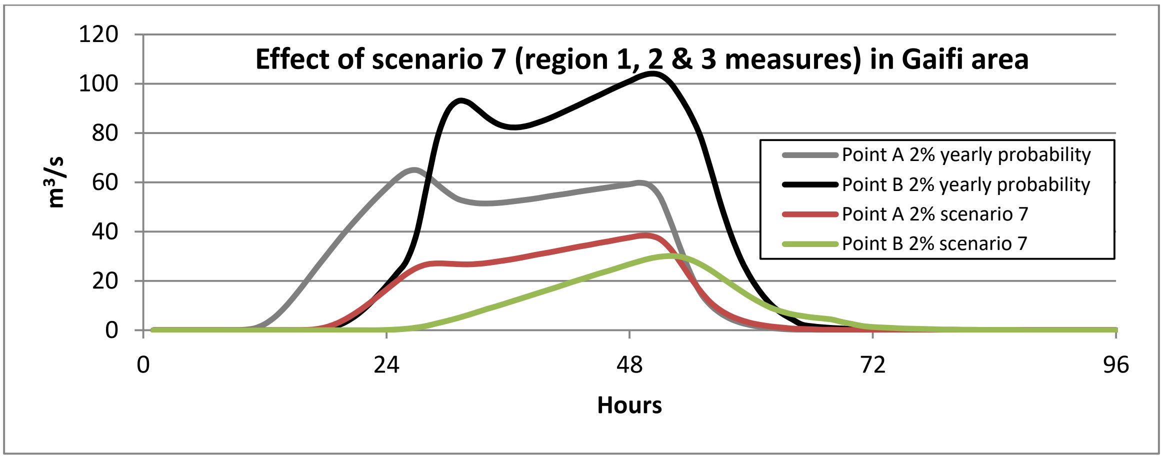

Figure 5.18: Hydrographs at point A and B for scenario 7(own illustration, 2017)

Table 5.8: Effects of scenario 7 (own illustration, 2017)

Point A	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	56	19	-67	68	38	-43
total discharge ($1000m^3$)	4382	1741	-60	7403	3672	-50

Point B	5% yearly probability	5% with measures	change %	2% yearly probability	2% with measures	change %
peak discharge (m^3/s)	68	9	-87	104	30	-71
total discharge ($1000m^3$)	5100	682	-87	10459	2375	-77

Relative effect of hazard reducing measures in region 1, 2 and 3

The effect of measures in surface region 1, 2 and 3 are described in scenario 1 till 3. The results show the decrease in total- and peak discharge due to the hazard reducing measures. Region 1 surface areas dominate Gaifi 1.1.1 and therefore the effect of applying measures in this region is high. In table 5.9 the relative effect of the measures is discussed. The change in percentage of the peak discharge due to the application of measures in a surface region divided by the percentage area in the Gaidi area is the relative effect.

Table 5.9: Relative effect of hazard reducing measures in region 1,2 and 3 (own illustration, 2017)

Point B – event with 2% yearly probability	Decrease in peak discharge (%)	Total area of region (%)	relative effect factor (-)
Region 1	28	41	0,68
Region 2	19	30	0,63
Region 3	27	18	1,50

5.3.2 Effect on flash flood hazard for El Arish

In the previous paragraph the reduction of the total- and peak discharges is assessed for the region with the highest relative hazard. Following up, the effect this has on the hazard downstream in El Arish City is assessed. The total area of the Gaifi area that was assessed in is 5,8% of the entire El Arish watershed. The effect on the total hazard of the watershed is therefore limited (although relative to its area highest).

The downstream point B had an assessed reduction of its peak discharge of 71% and the total discharge decreased with 77%. This gives an indication on the change these measures could provide if considered for the whole watershed. A conservative estimate of a reduction of 50% for the total- and peak discharge is used to see the potential reduction of the hazard in El Arish City. In figure 5.19 the effect of scenario 7 on the extend and depth of the flash flood is shown, compared to the current hazard.

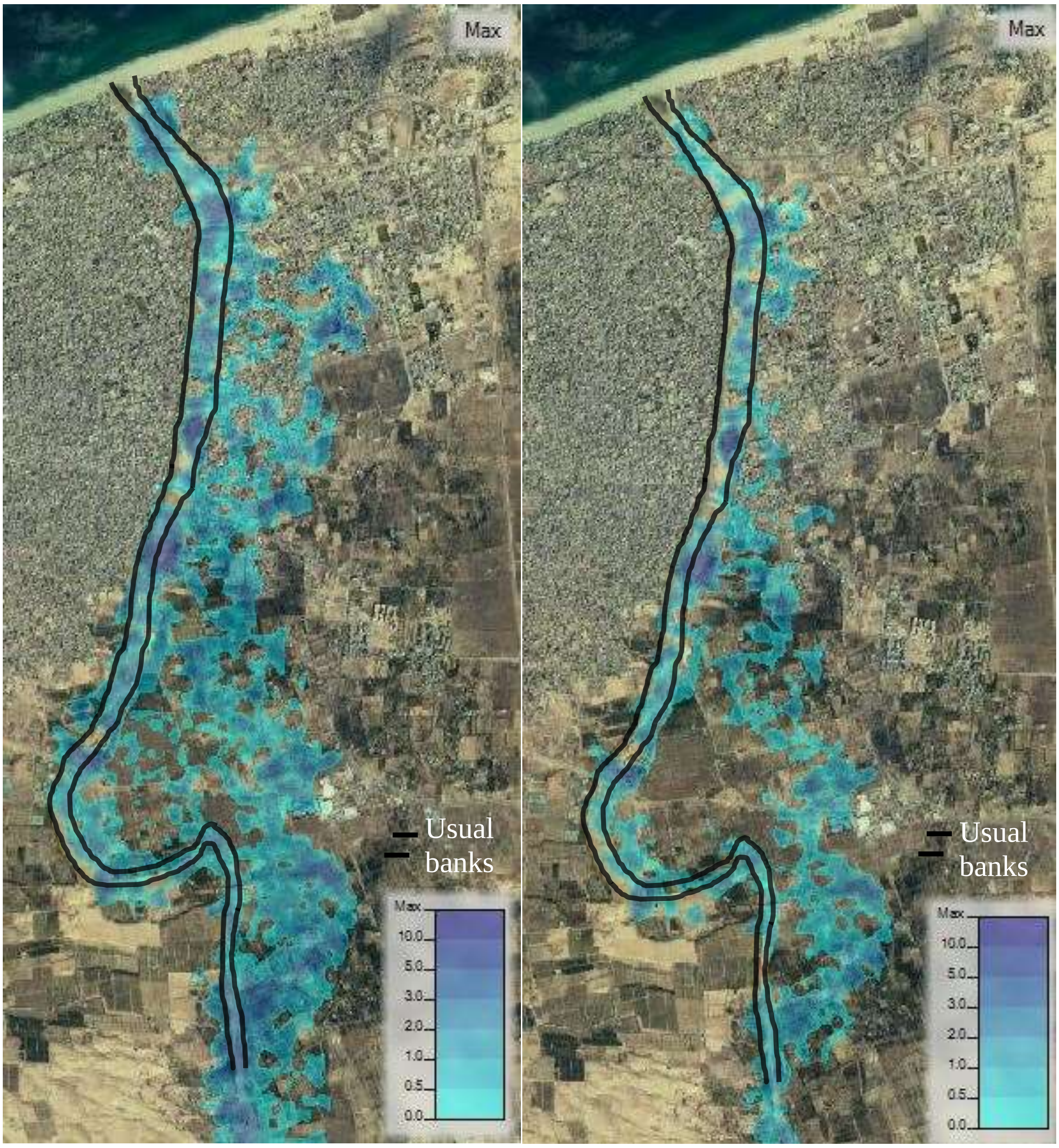

Figure 5.19: The current depth and extend of a flash flood with a 2% yearly probability (left) and the situation if measures would be applied in region 1, 2 and 3 for the whole watershed (own illustration, 2017)

5.4 Scenario of change in extreme precipitation

The hazard reducing measures will cause sedimentation at the upstream side. In time the sedimentation cause a thicker soil and therefore more water can infiltrate. This thicker soil and the water that is stored in it can be used by vegetation. An increase of vegetation will cause more organic matter and the associated soil fauna lead to greater pore space. Greater pore space is a consequence of the bioturbating activities of earthworms and other macro-organisms and channels left in the soil by decayed plant roots. Greater pore space leads to increased storage capacity and increase of ease of access in the soil. Thicker soils before bed rock and water availability are important factors for an increase of vegetation and vegetation and an increase in organic matter increases the infiltration capacity.

The rehabilitation plan of The Weather Makers creates a robust water cycle and this is based on the increase of biomass and the availability of water. The measures proposed to reduce the flash flood hazard can enhance the rehabilitation of the Sinai by creating favorable places for vegetation. The increase of biomass and the availability of water in the watershed will increase the amount of precipitation. The large reforestation and grazing ban in Israel caused an increase of average yearly precipitation by 15% (Pernil & Alpert, 2001; Otterman, Manes, Rubin, Alpert, & Starr, 1990). While the increase of yearly average precipitation is estimated to be 68% in the Sinai for large scale reforestation with a soil cover of 40% (van der Hoeven M. , 2017).

The suggested increase yearly average precipitation could also increase the extreme precipitation events. The effect of increasing the extreme precipitation with 15% without measures for point B is shown in table 5.10 and figure 5.20.

To check the effects of the suggested measures for the possible extremer precipitation events in the future the flash flood hazard is assessed for the Gaifi area with measures. With the extreme precipitation increasing with 15% scenario 7 would still reduce the peak- and total discharge compared to the current situation. The peak discharge reaches point B later than in the current situation, the measures have the desired effect even with an increase of 15% as can be seen in figure 5.20.

In Table 5.11 the total- and peak discharges of the situation with an increase extreme precipitation of 15% are shown in a situation with and without measures for B. The relative effect of the measures is lower than in the situation without the increase in extreme precipitation. The change of peak discharge in point B is -71% without taking the increase of extreme precipitation into account and -64% if the increase of precipitation is assumed. The peak discharge is reduced with 74 m^3/s without the assumption and 88 m^3/s with making the assumption of an increase of extreme precipitation. The relative effect of the measures is less with an increase of extreme precipitation while the absolute effect is larger.

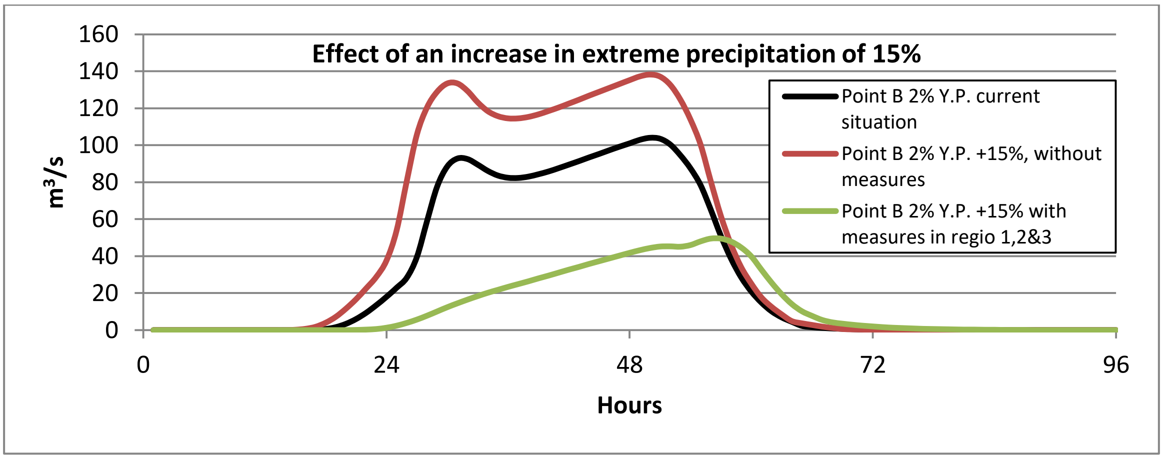

Figure 5.20: Hydrographs at point A and B for an increase of extreme precipitation of 15% with measures in regions 1, 2 and 3(own illustration, 2017)

Table 5.10: Effect of an increase of extreme precipitation of 15% in point B (Gaifi area) (own illustration, 2017)

Point B	5% Y.P. current situation	5% Y.P. with 15% increased prec	change %	2% yearly probability	2% yearly probability with 15% increased prec	change %
peak discharge (m^3/s)	68	103	51	104	138	33
total discharge ($1000m^3$)	5100	7967	56	10459	14991	43

Table 5.11: Effect of measures with an increase of extreme precipitation of 15% in point B

Point B with a 15% increase of extreme precipitation	5% Y.P.	5% Y.P. with measures	change %	2% Y.P.	2% Y.P. with measures	change %
peak discharge (m^3/s)	103	16	-85	138	50	-64
total discharge ($1000m^3$)	7967	1445	-82	14991	4491	-70

6 Discussion

This chapter discusses the results of the research. First the validity of the research is discussed. Secondly the results are interpreted by discussing what the results could mean. Thirdly the significance of the research is discussed by debating on the place of this research in literature and the applicability elsewhere. Fourth the challenges of this research are discussed. Lastly new research opportunities are discussed (chapter 6).

6.1 Validity of research

To assess the flash flood hazard the 1975 event described in Klein (2000) is simulated. The hydrologic model simulates a total discharge with a small deviation (14%) of the peak discharge and the form of the hydrograph is the same. The percentage of the precipitation that is discharged, abstracted due to the curve number and infiltrated into the wadi bed due to transmission losses is similar to the percentage found by Milewski et al. (2009). The inundated area and the velocities of the simulated 2010 flash flood by HEC-RAS correspond with the pictures and movies made of the event. Based on these results the hydrological- and hydraulic models seem valid or at least give an indication of the flash flood hazard of the El Arish watershed.

The water harvesting structures around the wadi are used in arid regions around the world to make agriculture possible. The structures to reduce flash flood hazards in the wadi are based on structures which were used on a large scale in history combined with modern day solutions. Because these structures are used worldwide and throughout history their applicability is described in detail in literature, making the allocation of these measures valid. Based on literature from Colombo et al. (2002) , Lin et al. (1999), Chritchly et al. (1991), FAO (2010), Oweis et al.(1999) and Prinz (1996) the feasibility of the measures is analyzed which makes the resulting decision tree valid.

The measures to reduce the flash flood hazard are modelled by increasing the lag time, decreasing the CN, increasing the contributing width of the wadi and an increase of the roughness coefficient. The pervious and impervious sediment catchers that are suggested in region 1 & 2 are similar to measures used by El-Weshah & El-Khoury (1999) to mitigate flash floods in the Petra area in Jordan. The results of applying measures to reduce flash flood hazards are comparable for an event with a 2% yearly probability. In this research the change of peak discharge is -43% and the reduction in the research by El-Weshah & El-khoury (1999) is around -50%. Because these are both indicative studies the results should be treated likewise making it a valid estimate.

6.2 Interpretations of results

This section discusses how the results can be interpreted and what new insights can be derived.

6.2.1 Measures to reduce flash flood hazards

This research assumes fully functional hazard reducing measures for the hazard assessment in scenario 1 till 7. For a pervious sediment catcher this means that the structure did capture sediment and thus the lag time increased and CN decreased. The time it takes for measures to become fully functional depends on the type of measure, where it is build and the precipitation upstream of the measure.

The strategy to allocate hazard reducing measures based on the three surface regions is consistent with the goal of the Weather Makers to use water closest to where it falls. The proposed measures reduce the hazard before it forms, this implies that the hazard is reduced everywhere where the measures are applied. This is also the reason that no large reservoirs are proposed: large reservoirs only reduce the flash flood hazard downstream but leave the upstream part unchanged and do not contribute to the rehabilitation of the Sinai.

Large reservoirs are not used in the allocation of the measures. This does not mean the measure should not be used. The measures suggested in region 1 till 3 are relative local hazard reducing measures and their effect is largest if applied in the whole watershed. To construct measures in the whole watershed will probably take a long time. During which the hazard is only reduced a little and water is still discharged into the sea without being used to rehabilitate the Sinai. There are multiple locations that are suitable to capture a large amount of discharge that seem to be fit to construct a dam, these locations should ofcourse first be researched on their suitability for construction. Dams however do not contribute to an overall reduction of flash flood hazard: they only decrease the hazard downstream. They also cause a hazard themselves: a dam flash flood. In figure 6.1 four dam locations are proposed to capture discharge.

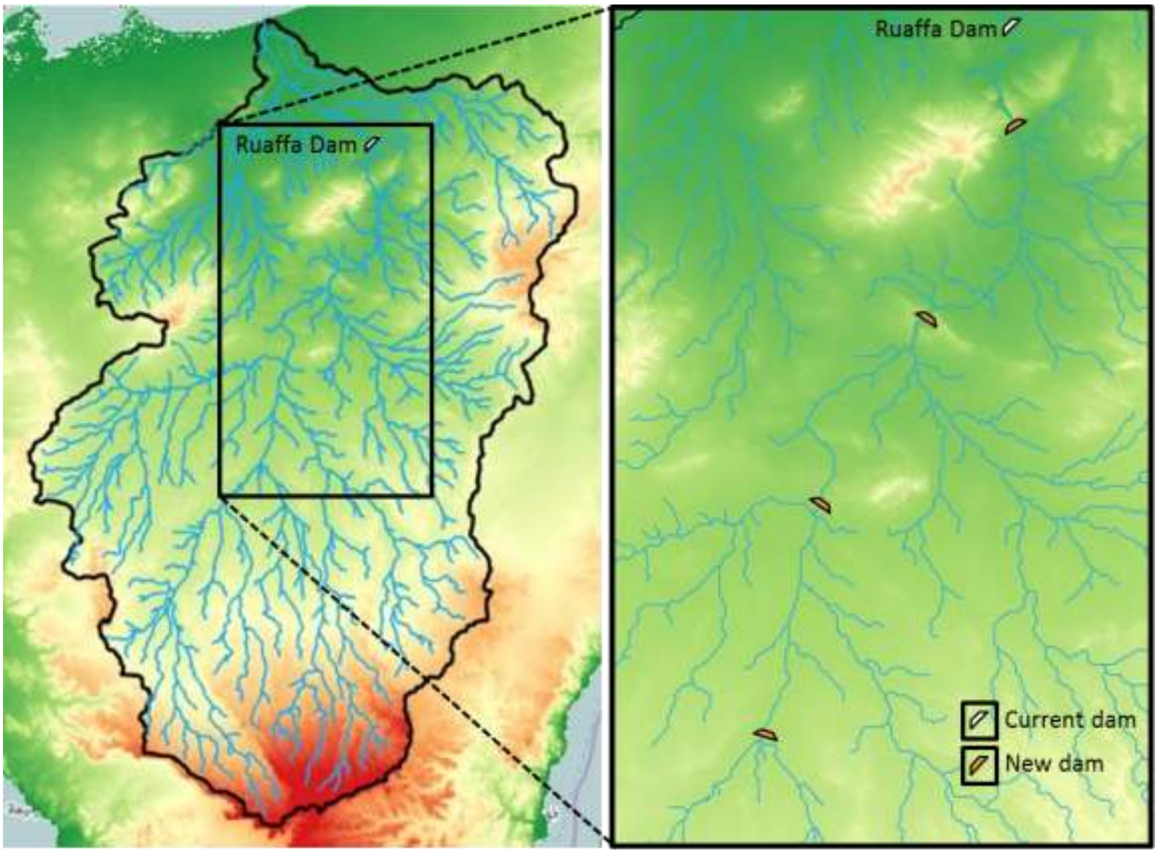

Figure 6.1: Possible new locations for dams

6.2.2 Reducing the flash flood hazard

The measures in region 3 (with HSG A or B and <2% slope) spread the water by redirecting it from the wadi channel onto the flood plain. This causes a higher roughness and thus slows down the water which is taken into account in the model. The spreading of the water however also increases the length of the flow path of the water and thus the slope. This is not taken into account in the model. The effect of the region 3 measures is therefore likely a underestimation of the real effects these measures have. From the results region 3 measures already are the measures that have the largest relative effect (percentage change of peak discharge to area applied) on the flash flood hazard. This was to be expected because water streams down into region 3 from region 1 and 2.

To reduce the flash flood hazard the region with the highest relative hazard was used. The Gaifi region has the highest peak discharge to area ratio. This makes the effect of applying measures highest but also harder to achieve. Other regions in the El Arish watershed are estimated to reduce the flash flood hazard with roughly the same percentage as the Gaifi region. For the simulation of the flash flood hazard in El Arish City in HEC-RAS a reduction of 50% is used for the discharge.

The results from the hazard assessment at El Arish City after measures are applied provide the extend and the depth of a flash flood. El Arish city is still flooded by the event and thus someone could conclude that the measures did not have the desired effect. This is however not necessarily true. First of all this research aims to reduce the hazard for the whole area and not only for El Arish city, because flash floods are not only a hazard to people and buildings in El Arish City but also to the rehabilitation project of The Weather Makers. Secondly because the DEM has a 30x30 m grid with a relative error of 7 m which does not take into account the dykes build around the wadi after the 2010 flash flood.

Measures in surface type region 3 cause the highest relative flash flood hazard reduction of the three regions. This was to be expected because this is where the water accumulates and the soil is most permeable. If however only measures are applied in surface region 3 the amount of water that accumulates will not decrease and thus the chance that the measures be damage is higher. Furthermore by constructing measures in region 3 only, rehabilitation will be limited because erosion will continue in other regions and no new usable soils will form (Which will form if region 1 and 2 measures are applied).

6.2.3 Effect of rehabilitating the Sinai on the hydrological cycle and the flash flood hazard

This research increases the extreme precipitation due to the rehabilitation of the Sinai and test the effect of the measures with this increase. The measures contribute to the rehabilitation of the Sinai, without these measures an increase of precipitation due to afforestation is hard to achieve. Without capturing sediment and runoff by the measures afforestation and agriculture is only possible on a small scale in the Sinai (Dames & Moore, 1985; Dames & Moore, 1981; Greenwood, 1997).

By increasing the extreme precipitation with 15% the peak discharge increases with 30-55% in the Gaifi area. This shows that the precipitation has a big factor on the flash flood hazard and that if the rehabilitation of the Sinai would cause an increase of extreme precipitation flash flood reducing measures are even more important than they are now.

In the USACE method ground water is only modelled as a sink where water is lost due to the flood wave moving over the bed or as one of the factors in the CN. In reality this water is not lost and can either recharge the underlying aquifer, used by vegetation or evaporate. All these processes would contribute to the rehabilitation of the Sinai.

The proposed method to reduce the flash flood hazards contributes to the plan of the Weather Makers to rehabilitate the Sinai by slowing down the flood and to enhance the infiltration. It also creates suitable locations for vegetation by capturing sediment and water this could help to create a robust water cycle. In figure 6.2 the plans of the Weather Makers incorporating the measures found in this research with the rehabilitation of the Sinai.

Figure 6.2: Measures in region 1 till 3 suggested by this research (left) and the combination with the plans of the Weather Makers (left) (van der Hoeven & Harding)

6.3 Significance of the research

6.3.1 Compared to other research of the area

This research combines a flash flood hazard assessment with a plan to reduce those hazards and quantifies the effects of the measures taken. In other researches about the area flash flood hazard are also assessed: Maowad(2013) simulate the flash flood of 2010 and El-Sayad(2012) calculates the extend of the flooding in El Arish City. Researchers provide strategic places for dam construction or places to harvest water: Elewa et al. (2013) describes places best fit for water harvesting and building dams while Dames & Moore (1985) provides areas best fit for agriculture in combination with spreading dams. This research introduces a plan to integrate the two separate topics and combines them with a strategy to rehabilitate the Sinai.

The flash flood hazard in the Sinai was researched earlier by using the CN, however these studies did not take into account transmission losses. For the flash flood hazard assessment in this study transmission losses are important because of the goal of the research; to propose a strategy to reduce the flash flood hazards, by first allocating hazard prone area's and then measures to counter these hazards. Therefore the flash flood hazard is needed in the entire watershed and to simulate that the large losses in the main wadis are taken into account. If this wasn't done the CN (which describes losses before runoff) would encompass the transmission losses (that are actually during the downstream movement of the flood wave). This also explains the difference in used CN between the study of Maowad (2013) and this research.

Allocating measures and assessing the reduction in flash flood hazard by an hydrological model has been used by Al-Weshah & El-Khoury(1999) in Petra, Jordan. This was also indicative research and the results of the research are used for this sudy. The research did not take into account the surface conditions of the watershed and did not allocate different measures but used the same measure everywhere. This research assigns measures to reduce the flash flood hazard based on the applicability of the measures and the surface conditions in the Sinai. The measures also have to serve the goal to rehabilitate the Sinai.

6.3.2 Applicability of the research elsewhere

The flash flood hazard assessment using the USACE method could be used in all data scarce arid regions. Due the use the conceptual parameters (CN, lag time, bed roughness with the Manning coefficient and transmission losses) in combination with physical measured parameters (precipitation) all data can be gathered with remote sensing techniques. Since the data that influences these parameters is globally available this method can be used everywhere where the same dominant hydrological processes apply.

The allocation of measures with the decision trees can be used in arid areas with a yearly precipitation of around 200 mm or less. With a higher yearly precipitation other water harvesting techniques can be used and thus other measures would be advised. A higher yearly precipitation also changes the surface conditions due to a change in sedimentation, vegetation and water availability.

The results from this research will be similar in other arid areas. After applying hazard reducing measures the flash flood hazard will decrease. The percentage will differ depending on the surface conditions of the soil and the extreme precipitation. The basic processes that are caused bythe hazard reducing measures are: reducing the high velocity flows, increase the permeability and thus increase the infiltration. Changing these processes will reduce the flash flood hazard in any arid region and thus the results of this research are not transferable one on one but will give a similar reduction in other arid regions.

6.4 Challenges

In this section the challenges during this research are discussed this is done with a reflection on the research.

6.4.1 Methodology

Due to the availability of data a conceptual hydrologic model was chosen to simulate the El Arish watershed. Parameters are non-identifiable in a conceptual model if the information content of the data on which the parameters are calibrated is limited, therefore many combinations of parameter values may give a similar performance in the model used in this research. This gives the limitation that the parameters cannot be uniquely identified and they cannot be linked to catchment characteristics and therefore the hydrological model cannot be calibrated. This can be solved by measuring discharges caused by flash floods at multiple locations in the watershed or to use a physical based hydrological model. Because of the large watershed and the data needed for such a model the measuring of discharges is the best option to solve this challenge.

If a physical based type of method would have been used to assess the flash flood hazard the lack of measured discharges in the Sinai would still cause problems. Due to the size of the watershed, the many different types of soils and numerous processes that need to be simulated the model would also need to be calibrated. Due to the availability of data and the size of the watershed, the methodology used fits the goal of this research. In hindsight there is still no more accurate method to assess the hazard.

6.4.2 Flash flood hazard assessment

The direct runoff or lag time is calculated with the Kirpich method. This method is based on the longest channel in the sub basin, the averaged channel slope and fixed values to describe the overland flow. The lag-time gives an indication of how long the time difference is between precipitation falling and the peak of the discharge at the outflow point of the sub basins. This approximation gives a standard shape of the hydrograph, based only on the earlier mentioned parameters. This research is therefore not able to encompass delaying factors in the physical features of the sub basin. However the lag time gives a satisfactory indication on the time it takes to travel downstream for the accuracy of this research.

Transmission losses are modelled as an average amount of flow subtracted from the flash flood per second in HEC-HMS. Due to taking an average value for transmission losses over time, the physical processes are not represented anymore. If the discharge is at its peak, the flow velocity is generally high as well. A high flow velocity decreases the infiltration rate, while slow moving water is infiltrated more easily. This suggests that an average subtraction over time is overestimating the subtraction at time of the peak discharge while the subtraction is underestimated during the rest of the flash flood. The peak discharge also causes the widest contributing channel width and the flow over the 'flood plain' is slower and causes a higher transmission loss at the peak discharge. These processes could cancel each other out and therefore gives a good estimate on the transmission losses. However the physical processes in the calculation of the transmission losses on the flow velocity and the varying contributing width is absent. Therefore the transmission losses are a good indication on the average losses in the wadi bed but could under- or overestimate the losses at the peak discharge and lower discharges.

Transmission losses are estimated for the main channels between the sub basins. Smaller wadis within a sub basin have a thick alluvial soil as well. Partly their transmission losses are included in the CN, but some smaller wadi channels could have transmission losses as well. This is taken into account by the allocation of measures by not only applying spreading dams in the main wadi channels but on every region 3 surface area.

Convective storms are intense and small in size. These types of storms are usually missed by satellites and precipitation gauges. Due to the local character of the convective storms they tend to have low impact on runoff generation downstream in larger watersheds. This is due to the transmission losses that occur in the dry wadi beds. Convective storm can cause damage and thus are a hazard in the El Arish watershed but are not taken into account in the hydrological model nor in the hazard assessment.

The research done by Klein (2000) describes the measurement of the flash flood in 1975, but no information on the measuring devices and methods is given. Flash floods have a destructive power which makes it hard to do a correct measurement and therefore it is hard to say what accuracy the hydrograph and measurement has. The precipitation event that caused the flash flood in 1975 is given as a bandwidth of 40-50 mm and this means that the measurement has to much uncertainty to use for calibration.

The sensitivity analysis shows that the values estimated for the parameters in this research have a big impact on the flash flood hazard. By increasing and decreasing the values it is shown that the parameters could be estimated wrong but the shape and the time a flood is noted in the Ruaffa Dam stays roughly the same (except for the sensitivity of the Manning coefficient). The hydrograph at the Ruaffa Dam with the estimated values for all the parameters is consistent with the measurement of the 1975 flash flood of Klein (2000). This means that the flow pattern of the hydrological model is reliable even if the values of the parameters are over- or underestimated.

The simulation of the 2010 flash flood and the flood with a yearly probability of 2% with the USACE method has as output the depth and flow velocity at El Arish City. The simulation shows that the main wadi channel overflows the banks and that the flash flood surges through the city center of El Arish. The inundated area resulting from the simulation is not continuous from the wadi channel into the city. This could be because the city has some elevated parts or because of an error in the DEM. The depth of the simulated flood can reach up to 20 m in and around the wadi channel which seems an overestimation. This is probably because of errors in the DEM, the mean error is around 7 m as described in section #. These errors could also cause a bias in the extend and the flow velocity resulting from the simulation.

The total discharge in the simulation of the 2010 flash flood event was $46,8 * 10^6\ m^3$ which is lower than the $124,6 * 10^6\ m^3$ estimated by Moawad (2013). The difference can be explained by the precipitation taken into account: Moawad (2013) used a total precipitation of $665 * 10^6\ m^3$ while this research used a total precipitation over the El Arish watershed of $575 * 10^6\ m^3$ (including the TRMM factor of 1,18). The difference is also enhanced by the curve numbers used: for a type D soil this research used a CN of 88 while Moawad used a CN of 94 and thus generating more run-off. The model by Moawad did not take into account the transmission losses, which means that he assumed no losses while the flood wave was travelling downstream. Both models could not be calibrated, but Moawad assumed that the 2010 flood was of the same magnitude of the 1975 flood described by Klein (2000) which is doubted in this research by comparing the sediment deltas of the 1975 event in Klein (2000) and the 2010 event in Hermas et al. (2011).

6.4.3. Reducing the flash flood hazard

The values used to simulate the measures in the research are indicative and are used to estimate what the different types of measures could change in the sub basins and for the overall hazard in the city of El Arish. The literature on changes caused by these measures in climatic circumstances like the Sinai and for the use of such a model is limited. This is consistent with the indicative nature of the semi-distributed conceptual hydrologic model, which offers an estimate on the hazards in the El Arish watershed and particular in the city of El Arish. This research should not be used as design or definitive strategy but as an indication on how measures can be used to reduce the flash flood hazard.

Because the hydrological model is semi-distributed the measures in the wadi that are divided into region 1 till 3 are not placed in sequence as in reality but averaged over the sub basin or the main wadi bed. For example: If measures are applied in region 3 that would mean that the transmission losses and roughness of the wadi bed are increased. This means that the amount of discharge in the outflow point in point B is decreased, but no conclusion can be done on whether the hazard upstream in region 1 is reduced.

6.5 Further research

Flash floods in the El Arish watershed have been recorded for almost 100 years. The first mention of these flash floods was in 1925. Since then the magnitude was estimated using observations of first hand witnesses, simulated in a hydrological model or in one instance measured. The peak discharge and total discharge in combination with precipitation data is needed for calibration hydrologic models. The size of the sediment delta after a flash flood in front of the wadi El Arish outlet is a good indication of the total- and peak discharge. Precipitation data can be retrieved from the WRRI or TRMM. Coupling this data to satellite images of the sediment delta from just after the floods allows the researcher to estimate the magnitude of a flash flood following a precipitation event by comparing it to the sediment delta and flood measurement of Klein (2000).

Satellite imagery can also be used to assess the wetted perimeter of the wadi bed. After a flash flood wet soil can be distinguished on satellite imagery but even if there is no imagery available just after the flash flood event the new sediment on the wadi bed has other reflective characteristics than the 'old' sediments. With the wetted perimeter the peak discharges at every point in the watershed can be assessed due to the slope and DEM. By coupling these peak discharges with precipitation events the flash flood hazard is assessed. This research is comparable to the satellite method considered in this research but was not used because it cannot simulate the effects of flash flood hazard reducing measures.

The three different surface regions that are used to assign hazard reducing measures can also be used to create a physically based spatially distributed hydrologic model. A cell of a certain size is divided into one of the surface regions and whether it is inside or outside a wadi. The cells are linked to each other and with the characteristics of the soil the infiltration rate of a given moment is simulated. The thickness and material the soils consist of are averaged. This will improve the spatial distribution of the hydrological model and thus the allocation and effect of the hazard reducing measures can be more precise. The lack of data in the region can cause a large bias and is presumably larger than the method used now.

When the region is rehabilitated and a robust water cycle is established a continuous hydrological model should be used instead of an event based model. The assumption of a dry soil is not applicable anymore and this causes a different run-off generation. In a more humid environment the runoff generation is caused by high soil moisture while in an arid region the soil lacks infiltration capacity or the infiltration rate is not high enough for precipitation to infiltrate (Yair & Lavee, 1985). The need for a continuous hydrological model is also influenced by the ground water flow. Currently the wadis are ephemeral and no ground water flow into the wadis is safe assumption to be made. When the region is rehabilitated this is not the case and groundwater flow has to be taken inot account. This can be combined with the hydrological model based on the three surface regions.

Measures to reduce the flash flood hazard are assessed on their feasibility. The criteria to do this which are influenced by- or influence locals are: input needed from local inhabitants, influence on local inhabitants, local materials, impact on environment and needed maintenance. These criteria describe the important role local inhabitants have within the feasibility of the strategy to reduce the flash flood hazards. To incorporate Bedouins and other local inhabitants more research is needed on their possible motives to take part in the rehabilitation of the Sinai (and thus to reduce the flash flood hazard). A start can be made by doing a stakeholder analysis, but it should also be considered to apply a kind of joined ownership. This gives an incentive to maintain the hazard reducing measures and also makes reducing flash flood hazard a social interwoven cause. In short research needs to be done on the impact of flash flood reducing measures on the local inhabitants and a plan should be made to incorporate them into the plan.

The effect of spreading dams on the transmission losses and thus the flash flood hazard is not described in literature. This is because the focus lies on the agricultural uses and the benefits it has on vegetation. To assess the effects of spreading dams on the flash flood hazard a scale model can be made. The TU Delft has a testing flume where the role vegetation plays in the development of riverbanks is tested. This flume could also be used to assess the effects of the spreading dams on flash floods in arid areas (dry soil conditions).

In this research the effects of the hazard reducing measures is assumed to behave as fully developed measures. However hazard reducing measures take time to reach their full effect and a strategy to implement the measures is needed. Further research is therefore recommended about the effects of the hazard reducing measures over time. The result of this research is a strategy that takes into account the hazard reduction over time and combines this with the allocation of hazard reducing measures. This could mean using reservoirs to (temporarily) reduce the flash flood hazard.

The flash flood hazard is assessed in this research but the risk this causes is however not discussed. With the discharges, flow velocities and flow depth calculated in this research a study can be done about the risk in the Sinai. The values of the things exposed, the susceptibility of the exposed (fragility curves) and a model (QGIS) to link the parameters is needed to assess the risks. The results from the flash flood hazard assessment show that a DEM with a higher accuracy is needed.

When the risk of the flash flood is assessed and a strategy is proposed to apply hazard reducing measures in time these can be used to evaluate the need for reservoirs upstream of cities in the El Arish watershed. Because the risks are known a cost benefit analysis can be made for the dams.

This research proposes hazard reducing measures in the Sinai. These measures are relative simple to construct and consist of basic building materials. By using Critchly et al. (1991) and other literature on water harvesting structures an estimate can be made on the materials that are needed and the amount of work that is needed to construct these. This allows a cost estimate to be made. The benefits however are harder to assess because the rehabilitation of the Sinai is caused by a combination of factors and not only the flash flood hazard reducing measures.

To account for the potential increase of extreme precipitation caused by the rehabilitation of the Sinai a 15% increase is used. This is an estimate based on the increase of yearly precipitation in the Negev and is thus used to test the effect of the hazard reducing measures with an increase in extreme precipitation. To be able to assess the flash flood hazards for a rehabilitated region the change in extreme precipitation is needed. Only by coupling the extreme climate events with the land degradation that impacted them can we make useful predictions for the future. The systematic monitoring of extreme event impacts presents a major challenge for future work (Clarke & Rendell, 2007). Regions that are effectively rehabilitated in the world are rare but there are many regions that have degraded over the past 50 years. An analysis of the change in extreme precipitation of these degraded regions gives an estimate on the change that can be expected in the Sinai after rehabilitation.

7 Conclusion

Flash floods are historically a problem in the Sinai and have caused damages and casualties in the El Arish watershed. The floods are a danger to the plans proposed by The Weather Makers to rehabilitate the Sinai but are also an opportunity to enhance them. This grounds the need to assess the current hazards caused by flash floods, to consider the future changes due to the rehabilitation and to propose measures which are feasible in the Sinai.

To assess the current flash flood hazard the USACE method is used, this method is a semi-distributed conceptual hydrologic model. With the USACE method the 1975 flash flood is simulated and the results are compared to the measurement of that event at the Ruaffa Dam. A sensitivity analysis is done and this shows that a 5% increase of the CN would increase the peak discharge with 50%. Precipitation causes an increase of peak discharge of more than 40% if the estimated average was not 40 but 45 mm. These are both important parameters for the accuracy of the model. The USACE method was also used to simulate the 2010 flash flood event to compare the results to imagery of that event. The extend and flow velocity of the simulated event is comparable to the imagery of the 2010 flash flood. Because the pictures only cover a small part of the city(and an even smaller part of the wadi) and the timing in respect to the flood peak is not clear, no definitive conclusions can be given on the accuracy of the USACE method. The model provides the total- and peak discharges of all the 38 sub basins in the El Arish watershed for an extreme event. The flow velocity and depth of the flow depend on the discharges and therefore the current flash flood hazard is assessed.

The measures to reduce the flash flood hazard used in this research are selected based on their proven use in areas with similar aridity and surface conditions. These measures have been subjected to a multi criteria analyses to assess their feasibility in the Sinai. The surface conditions of the Sinai were used to assign feasible measures to suitable locations. This was done with a systematic approach which differentiates three regions based on the slope of the surface and the hydrologic soil group. A decision tree was made which is able to apply a feasible measure to any location that contributes to the flash flood hazard.

Eight different scenarios were used to decrease the flash flood hazard in the area that causes the highest relative flash flood hazard for the El Arish city. The feasible measures used in these scenarios are able to reduce the peak discharge of a flash flood with a yearly probability of 2% up to 75% in the Gaifi region. The combinations of measures used to do this are: pervious sediment catchers in- and outside the wadi for the region with a slope of more than 5%, impervious sediment catchers in- and outside the wadi in the region with a slope less than 5% and a HSG C or D and spreading dams in the wadi for flat (<2%) regions with a HSG A or B. The decrease of total discharge is 75-80% for a flash flood with a 2% yearly probability. Spreading dams that are suggested in surface region 3 are estimated to have the highest relative effect on the flash flood hazard. The relative effect is the decrease in peak discharge relative to the area they are applied on. An anticipated effect of the rehabilitation of the Sinai is an increase in precipitation and this could also mean an increase in extreme precipitation. This is taken into account by testing the measures on their effect with an increase of 15% in extreme precipitation. An increase of 15% would give an increase of peak discharge of around 30-50% without measures (current situation) in the Gaifi area for an extreme event. With measures in surface regions 1,2 and 3 in the Gaifi area the peak discharge would be reduced with 60-85%.

In short, this research shows that the hazards caused by flash floods in the El Arish watershed can be reduced by using feasible measures. The strategy to reduce the hazard by flash floods can contribute to the plan of the Weather Makers to rehabilitate the Sinai by increasing the infiltration by the wadi bed (transmission losses) and increase the interception by vegetation, infiltration and retained water in surface depressions (CN).

8 Recommendations

The steps that need to be taken because of this research are discussed in this chapter. The recommendations that are given are practical and should be used to reduce the flash flood hazard in the Sinai or to increase the value of this research.

8.1 Assessing the flash flood hazard

From the research it is reasonable to suggest that the USACE method in its current form still has some room for improvement. The sensitivity analysis shows that the method is sensitive to most of the parameters used in the hydrologic model. To further increase the accuracy of the model some steps can be taken to collect data:

Building two flood recording stations in the same wadi relative near each other improves the transmission losses estimates, the manning coefficient is estimated more accurately and the model itself is calibrated. These two locations should be chosen so that there is no lateral inflow from other wadis. The difference in total discharge is the transmission losses. The manning coefficient is calculated with the average flow velocity and the slope at the measuring station. The calibration of the model is done by measuring floods following a precipitation event and combining the new more accurate estimates of parameters.

By setting up a systematic approach for keeping records of flash floods in the El Arish watershed at chosen points in the wadi the reason of the discrepancies between the precipitation and flash flood events can be derived. A simple application for mobile phones provides all the needed input: a person spotting a flash flood opens the app after he sees the flash flood, provides an indication on the magnitude and by using the GPS of the phone the location is sent to the database of flash floods.

Using cameras in several wadis could also increase the accuracy of the USACE method. Instead of measuring stations or relying on observations of locals, cameras are used to derive the discharges at multiple locations. The width, depth and velocity of the flash flood can be estimated and by using multiple cameras in the same wadi (downstream of each other) the parameters can be derived accurately. With an accurate measurement of precipitation this would mean the CN(water that streams into the wadi), transmission losses (due to multiple cameras in a row), lag time (time between precipitation and peak discharge) and Manning coefficient (flow velocity of the flood)could be estimated accurately. Flash floods are however infrequent and together with their spatial variability this would mean either a lot of cameras are needed or a lot of patience.

The USACE method only uses programs that are free and publicly available. This means that the results and the methods are transferable to anyone who has interest in flash flood hazard. This is in line with the goal of the Weather Makers to set up a knowledge base for hydrological processes.

8.2 Reducing the hazards of flash floods

There are remnants of Byzantine era water harvesting structures according to Haiman (2012) and Bruins (1986). There are large systems of spreading dams still visible with satellite and seemingly still working terraced wadis are also present in the El Arish watershed. The first thing to do to reduce the flash flood hazard and to harvest water and sediment is to analyse these structures on their state and to repair them if possible. Because most of them have been out of use for a long period of time the wadi scoured around the terraced wadis and diversion dams as is shown by Al Qudah et al. (2016) in Jordan. This makes the structures useless in their current state but easy to repair and to integrate them into a plan to reduce the flash flood hazard and to rehabilitate the Sinai.

When started with the rehabilitation of the Sinai and the hazard reducing measures are build, a strategy to construct the structures should be considered. If construction starts with measures in region 3 and no structures are applied in region 1 & 2 the structures in region 3 should have larger dimensions than when measures in region 1 & 2 would be build first. The safest sequence for construction is when measures are built in the most upstream sub basins first. And within these sub basins region 1 & 2 should be the first priority (after the repair of the old structures). This would reduce the flash flood hazard locally but also everything downstream.

To make the measures work a strategy to keep them working is needed, this means that the local community needs to be incorporated. This could be reached by making the people who maintain and use the measures for agriculture co-owners. This would stimulate people in the cities to move to these rural areas and that these hazard reducing structures keep maintained.

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A.Hydrological Cycle

The concept of the water cycle is important throughout the research: the concept will be used to explain the problems of the area and the effect measures have. Every problem and measure will influence the water cycle in a way and therefore the concept is explained.

The water cycle or the hydrologic cycle describes the continuous movement of water in solid, liquid or gas form. The water moves between reservoirs due to hydrological processes under the influence of solar energy or gravity. The largest part of the total amount of water is saline water, only 2,5% of the available water on Earth is fresh water (Schiklomanov, 1993).

Water reservoirs are every physical place where water can be stored. There are several types of water reservoirs, from large to small in total volume: oceans, glaciers and permanent snow cover, ground water, ground ice and permafrost, lakes, soil moisture, atmospheric water, rivers and biological water. The water stored on local scale can be altered by for instance subtracting ground water or to create a storage dam. For every water reservoir a water balance can be made, the in- and outflow of the water balance are called hydrological processes.

Hydrological processes move the water in and out of reservoirs and are forced by solar energy and gravity, the main processes are: precipitation, snowmelt, infiltration, percolation, capillary rise, overland flow, evaporation, transpiration, ground water flow, channel flow and condensation. These processes are sometimes caused by local events like transpiration from a tree. While precipitation can be caused by evaporation (liquid to vapor) of ocean water which then condensates far away to precipitation (vapor to liquid state) (USGS, 2016).

Water is stored above(atmosphere), below(ground) and on(snow, surface water) the Earth surface. These reservoirs can be natural or man-made and can store water in solid, liquid and gas state.

Hydrologic processes move water in and out of reservoirs and can change the state of the water.

In the next section the interaction between reservoirs and processes are explained, using a schematization of the water cycle shown in figure A.1. The effect of every process and reservoir has on the Sinai, and in which way those processes and reservoirs can be changed for a more robust water cycle is discussed below .

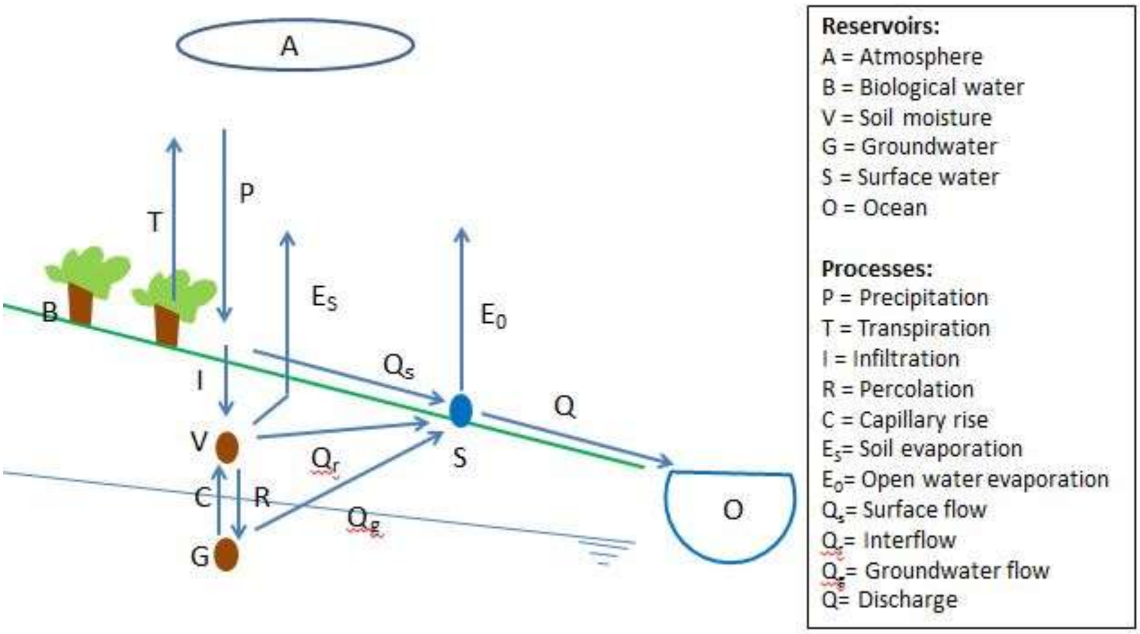


Figure A.1: Schematization of the water cycle (own illustration, 2017)

Water reservoirs

The water reservoirs are addressed in order of total volume of water on earth, from largest to smallest. Explanation on how they affect the Sinai, what changes can be made in the Sinai and their effect on the region.

Oceans and seas are the largest reservoirs of water, they are saline and make up 96,5% of the total available water on the Earth. The reservoir itself does not influence the Sinai, the evaporation of the water and the (under the right circumstances) precipitation that follows from it above the Sinai does. The majority (> 70%) of the precipitation in the Sinai comes from oceans and seas (Ent, Savenije, Schaefli, & Steele-Dunne, 2010). There are no measures to alter the reservoir in the scope of this research.

Glaciers and permanent snow cover is solid water above the ground. They are concentrated around the poles and on high altitudes. The Sinai has some snowfall but no permanent snow cover and thus this reservoir falls out of the scope of this research.

Ground water can be both fresh and saline. Fresh groundwater reserves are 30% of all the fresh water available on earth (Schiklomanov, 1993). Fresh water has a lower density than saline water, causing a fresh water bubble on top of saline water. Groundwater near the seas is saline in the Sinai and become less saline land inwards and near fresh water sources like wadis. Due to the increasing groundwater extraction the water level in the aquifers(water transporting ground layer) is lowered in the Sinai. This can lower fresh water pressure and saline water from the sea is able to infiltrate into the aquifers (Gad, Zeid, Khalaf, Abdel-Hamid, Seleem, & El Feki, 2015; Hassan, 2011).

To store more (fresh)water as groundwater, more water should be recharged into the aquifer or less water should be subtracted. More water can be recharged by building for example new dams (El-Baz, Kusky, & Morency, 1998), using percolation ponds (Oweis, Hachum, & Kijne, 1999) or Aquifer Storage Recovery (ASR) by injecting water with hydraulic barriers (The Weather Makers, 2016). Less subtraction is possible when alternatives for groundwater abstraction are present, for instance if the El Salam canal would be used or when precipitation could be stored and used when needed.

Ground ice and permafrost is ground water in solid form. It is concentrated around the (North) pole and on high altitudes. In the Sinai no ground ice or permafrost is found.

Lakes are water bodies surrounded by land and can be fresh or saline. In the Sinai Lake Bardawil is the only lake, by artificially opening it to the Mediterranean Sea it became a lagoon. In history (at least 5000 years ago) large lakes where present in the Sinai (El-Baz, Kusky, & Morency, 1998; AbuBakr, Ghoneim, El-Baz, Zeneldin, & Zeid, 2013). Upstream of the El Ruaffa Dam an ephemeral lake forms every few years due to precipitation events.

Placing dams in the wadi bed can create artificial lakes and thus storage for water. Creating these lakes will increase the groundwater infiltration due to the low velocity of the water behind the dam. The dam will also decrease the channel flow or stop it entirely if the volume of the basin upstream of the dam is larger than the discharged water.

Soil moisture is the water that is stored in the soil above the ground water table. The water is used by plants, evaporated into the air, or percolated further into the ground. When soils are wet plants require no suction to draw water into its roots, when the moisture content in the soil goes down (due to evaporation etc) plants need more suction to use the water. When the soil gets dry, roots need a lot of suction to extract water. Cactus plants can produce a higher suction than the average tree. If the suction needed is too high for plants soil moisture becomes unavailable for plants to use. The concentration this happens is called the Wilting coefficient (Wadleigh, 1957). The type of soil influences the amount of water it is able to hold, the finer the soil the more water it can hold and the slower water moves in it. Finer soils are able to retain water longer while sandy soils are dried up faster but take water in faster as well (Donahue, Miller, & Shickluna, 1977).

To increase the soil moisture storage capacity, the volume of organic matter in the soil should be increased. This is because the addition of organic matter increases the amount of pores in the soil either by creating better living conditions for soil organisms or the gluing of soil particles to create more pores. The moisture holding capacity can be increased by mixing organic matter with mineral soil materials. In the top soil this effect is the largest because the organic matter content is greatest (Bot & Benites, 2005). All the soils in the Sinai have a low amount of organic matter (Greenwood, 1997), thus the soil needs more organic matter to increase the soil moisture storage capacity.

> To increase the soil moisture storage capacity, an increase in organic matter is needed.

Atmospheric water is the water in vapor state in the air, it can become precipitation through condensation of water vapor to liquid water when the concentration is high. Water in the atmosphere comes from the evaporation of open water bodies or the transpiration of soils and plants.

In the El-Arish watershed the dominant northern winds carry water in the form of clouds from the Mediterranean Sea, providing a relative high humidity in the city of El Arish. Due to the hot land mass the air warms up above the peninsula and air with a higher temperature requires a higher water concentration to trigger precipitation (Millán, 2012). If vegetation and soil transpire or open water evaporates these can provide the needed extra concentration of water to trigger precipitation. In the Sinai these sources of water are not present, to increase atmospheric water more vegetation (biomass) is needed.

Rivers are marked as a reservoir because at any time there is water somewhere in a river. Rivers also function as a process in the form of runoff, which is described later in this section. Rivers are fed by groundwater, surface runoff and precipitation. In the Sinai there are only wadis which are an ephemeral river. To become rivers wadis should maintain streaming water for the biggest part of the year. This might be possible if there would be more water available in the water cycle.

Biological water is the water stored in all life forms, including all vegetation and animals. Vegetation provides soil cover, which decreases soil temperatures. Soil temperatures over 35° restrict water abstraction of vegetation (Bot & Benites, 2005). And thus vegetation is needed to allow other vegetation. In the Sinai there is almost no vegetation, by planting forests and agriculture the biological reservoir is enlarged and temperature goes down.

One of the goals of rehabilitating the Sinai is to create a ‘robust’ water cycle, for all the different reservoirs this means that more water needs to be stored.

Hydrological processes

A hydrologic process moves water from reservoir to reservoir, they are the active component in the hydrological cycle and can cause water to change state. A hydrological process interacts with water reservoirs as in- and out flow and are forced by solar radiation and gravity. A relevant example for the Sinai area is the processes precipitation can undergo: where rainfall(process) lands on the soil surface, a fraction infiltrates(process) into the soil to replenish the soil water(reservoir) or percolates(process) to recharge the groundwater(reservoir). Another fraction may run off as overland flow(process) and the remaining fraction evaporates(process) back into the atmosphere(reservoir) directly from unprotected soil surfaces(reservoir) and from plant leaves(reservoir). These and other relevant processes for the Sinai are discussed below, in no particular order.

Precipitation is condensed water vapour that falls onto the Earth. Precipitation comes in the form of rain, snow, hail, fog drip, graupel and sleet. Precipitation occurs when the atmosphere becomes saturated with water vapor, this causes the water to condensate and then precipitates. Two processes can lead to air becoming saturated: cooling the air or adding water vapor to the air. In the Sinai the dominant wind direction is a northern in the winter which causes the humid air from the Mediterranean Sea to drift south up the mountains. The air is cooled due to the upward forcing of the winds and mountains and this is the reason why in the winter months the biggest part of the precipitations falls in the Sinai region (Greenwood, 1997). At the same time this is also the reason why there is so little precipitation, the air heats up above the warm landmass and the initial humidity is not enough to cause precipitation (Millán, 2012).

To trigger more precipitation over the Sinai, the temperature should drop or the concentration of water vapor in the atmosphere should be increased. To realize both will have the most effect. An increase of water vapor can be caused by transpiration of vegetation and evaporation from open water bodies and soil moisture. More transpiration by vegetation and evaporation by soils requires more biomass (Millán, 2012). Open water bodies can be created by capturing run-off. While even change of land-use and land-cover has an impact on rainfall amounts (Pielke, et al., 2007). A decrease of temperature can be achieved by soil cover, a decrease from 55° to 35° is caused by soil cover in the tropics (Bot & Benites, 2005). The way soil cover influences the temperature of the soil is shown in figure A.2.

More biomass in the form of vegetation is decreasing the soil temperature and increasing the water content of the atmosphere which could cause more precipitation.

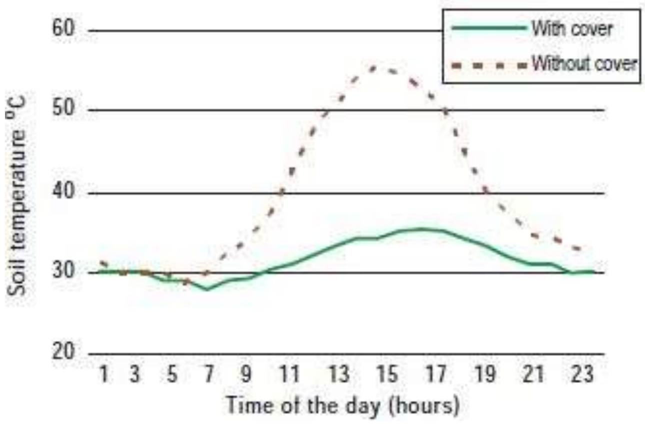


Figure A.2: Soil temperature influenced by soil cover in tropical Brazil (Bot & Benites, 2005)

Evaporation is the transformation of water from liquid- to gas phase as it moves from the ground or water bodies into the atmosphere. The amount of evaporation is influenced by: the concentration of water vapor in the atmosphere, the flow of air and the temperature.

If evaporation could be reduced, more water is stored in the soil or in open water bodies. To reduce the amount of evaporation: the concentration of water vapor in the atmosphere could be increased, the flow of air reduced or the temperature reduced. Concentration of water vapor in the air is increased due to an increase of biomass. Wind is decreased by trees and soil cover to provide more shelter to the soil and other vegetation. Temperature is decreased by soil cover. Conserving vegetation as a cover on the soil surface reduces evaporation, this results in 4 percent more water in the soil. This is roughly equivalent to 8 mm of additional rainfall (Bot & Benites, 2005).

Transpiration is the process of water sucked up from the moisture of the soil by the plant roots through a plant and its evaporation into the atmosphere. It is influenced by humidity, wind and temperature in the same way as evaporation. An increase in vegetation will lead to an increase in transpiration.

Infiltration is the flow of water from the ground surface into the ground. Once infiltrated, the water becomes soil moisture (in the unsaturated or vadose zone)or groundwater (below the groundwater level). Infiltration rate is the amount of water a soil can absorb, which decreases when the soil is saturated. If the amount of precipitation exceeds the infiltration rate, water will run off. The infiltration rate is influenced by the ease of entry, the soil texture and structure, vegetation types and cover, water content of the soil, soil temperature, and rainfall intensity.

A large part of the Sinai soil is bare rock, which does not allow much infiltration of water into the soil. Soils around the wadis and in the dune area are barren, sparsely vegetated and unprotected from sealing and crusting by raindrop impact. Figure A.3 shows the relation between the amount of organic matter and the infiltration capacity. An increase of vegetation will cause more organic matter and the associated soil fauna lead to greater pore space. Greater pore space is a consequence of the bioturbating activities of earthworms and other macro-organisms and channels left in the soil by decayed plant roots. Greater pore space leads to increased storage capacity and increase of ease of access in the soil (Bot & Benites, 2005).

Infiltration capacity/rate increases due to an increase of organic matter. Organic matter is the remains of organisms such as animals or plants, which enhances due to an increase of vegetation.

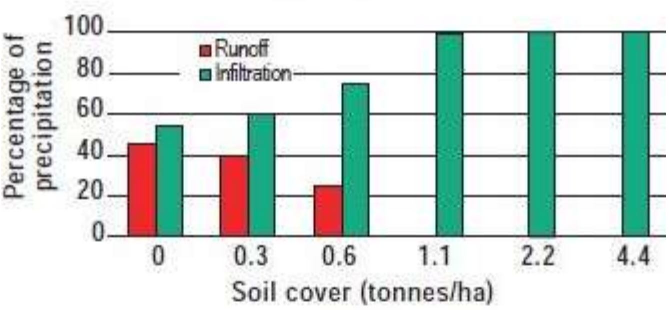


Figure A.3: Soil cover influences the amount of runoff (Bot & Benites, 2005)

Subsurface flow is the collective term for interflow (above ground water table in the vadose zone) and ground water flow (below groundwater table). Vegetation usually subtracts water from the vadose zone while abstraction for human consumption usually comes from the aquifers beneath the groundwater table. Subsurface flow may return to the surface in springs or can flow into rivers, if neither happens it will eventually seep into the ocean.

In the Sinai the groundwater table is usually not near the surface. There are several springs and oasis where subsurface water flows to the surface, these are near mountains and in the dune area in the north. The amount of subsurface flow is not enough to feed into a steady river or stream.

Surface flow is the excess of water from precipitation or other sources which cannot infiltrate into the ground, evaporate into the atmosphere nor be stored by organic matter. This happens when the ground is saturated or water arrives more quickly than the water can be absorbed. When then water reaches a channel the flow becomes **channel flow**, which will eventually flow into the ocean and will be 'lost'. The sources of channel flow are surface flow, groundwater flow and interflow.

Due to the low infiltration capacity of the soils in the Sinai, a large part of the precipitation is not used and lost as outflow. By increasing the infiltration capacity, the storage capacity and/or the usage of water in the watershed of El-Arish the outflow of water should be decreased. The goal to minimize loss of water due to outflow is aligned with the goal to decrease hazards caused by flash floods.

Precipitation is 'lost' due to channel flow into the ocean because it cannot be used for other purposes

B. Flash floods in history

All the recorded flash floods in the El Arish watersheds

Date (where if specified)	Flood magnitude	Annual rainfall at El Arish city [mm] (average causing the event [mm])	Source
Oct. 1925	Very strong	114	1
Dec. 1928	Strong	64	1
Dec. 1930	Strong	110	1
Oct. 1931	Medium	69	1
Dec. 1933	Strong	82	1
Oct. 1935	Strong	37	1
Oct. 1937	Very strong	123	1
Oct. 1938	Medium	126	1
Oct 1940	Medium	94	1
Dec. 1942	Strong	98	1
March 1943	Weak	121	1
Jan. 1945 (7 days continuous flow at Mitmetni)	Very strong	-	1 (a)
1948	21×10^6 m^3(b)	37	1
Dec. 1949	$0,5 \times 10^6$ m^3	80	4
1950	18×10^6 m^3(b)	127	1
Mar. 1951	3×10^6 m^3 (b)	45	1
Dec. 1951	$0,43 \times 10^6$ m^3	-	4
Feb. 1952	$0,4 \times 10^6$ m^3	-	4
1953	$0,8 \times 10^6$ m^3	126	1
1954	$0,5 \times 10^6$ m^3	113	4
17 Nov. 1964	$4,4 \times 10^6$ m^3	128	4
11 Dec. 1964	2×10^6 m^3	128	4
14 Dec. 1964	$3,45 \times 10^6$ m^3	128	4
12 Jan. 1965	$0,5 \times 10^6$ m^3	193	4
27 Mar. 1965	30×10^6 m^3	193	4
1965/1966	1×10^6 m^3 (b)	-	1
21 Feb. 1975	120×10^6 m^3	- (40 – 50)	2
1979	30×10^6 m^3	-	4
1980	Large Flood	-	1
25 Apr.1984 (Lake and/or Gaifi)	-	-	3
07 Apr. 1986 (Lake and/or Gaifi)	-	-	3
23 Mar. 1991 (Lake and/or Gaifi)	-	- (21)[3)]	3
2 Nov. 1994	3×10^6 m^3	-	4
01 May 2001 (Lake and/or Gaifi)	-	100 (0,6)[5)]	3
29 Jan. 2004 (Lake and/or Gaifi)	-	162 (9)[5)]	3
27 Oct. 2005 (Hasana)	-	95 (0,3)[5)]	3
20 Jan. 2007 (Hasana)	-	85 (0,41)[5)]	3
10 Dec 2009 (Lake and/or Gaifi)	-	42 (0)[5)]	3
18 Jan 2010 (whole watershed)	124×10^6 m^3	81 (15,6)[5)]	4
16 Feb. 2010 (Quiriya)	-	81 (0,25)[5)]	3
26 Feb. 2010 (Bruuk)	-	81 (6)[5]	3

Table B.1: A strong flood has a quantity of about 20×10^6 m^3 or greater, which could be expected every 2 to 4 years (Dames & Moore, 1985). (a) Observed by Dr Shata (b) at Ruaffa Dam. Sources: 1. Dames & Moore (1985), 2. Klein (2000), 3. Hermas (2011), 4. Moawad (2013), 5. TRMM (2017)

C. Methods to assess flash flood hazards

USACE method

This method combines a hydrological- and hydraulic model to assess the flash flood hazards. The hydrological model describes the processes affecting the water moving from precipitation down to the outflow. These processes are described by intermediate parameters or simplifications because data is missing for some processes in the El Arish watershed. The hydraulic model uses the results from the hydrologic model to create the inundation maps for several probabilities of occurrences, the method is shown in figure C.2.

As input for the USACE model the processes of precipitation, infiltration, evaporation, transpiration and groundwater flow can be used. These are described by intermediate parameters which are based on decades of testing and fieldwork of the United States Army Corps of Engineers (USACE). Together with the topographic elements slope, resistance and basin area to calculate the runoff of a certain area. The hydraulic model uses the hydrological process channel flow together with the topographic elements elevation, slope, resistance and channel dimensions to calculate where the water will flow.

The output of the hydrological model is the amount of water flowing out of the watershed or sub basins or cells (depending on the spatial distribution chosen). The hydraulic model provides inundation maps and flow velocities.

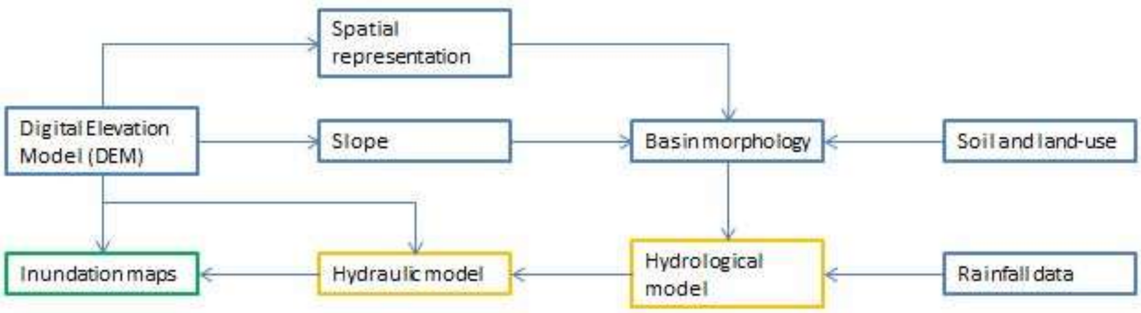


Figure C.1: Methodology for the USACE method

The measured discharge and the estimated rainfall from the 1975 flood event described in can be used to calibrate the hydrological model. For the hydraulic model the video footage of the 2010 flood event can be used to calibrate the flood extend. The data from 1975 is measured at the Ruaffa Dam and the 2010 videos are made in El Arish City. If the model is calibrated to those events the discharges, velocities and flood extends calculated with the model will be assumed correct for upstream parts of the watershed.

This model is useable for simulating the current hazards, given input from the current situation. Considering proposed measures and changes in ecology the future hazards can also be assessed.

This is a conceptual model with several spatial representations possible. The spatial representation depends on where the focus of the research is. If the discharges are only needed in El Arish a lumped model is sufficient. A semi distributed model is applicable if the model needs to assess the discharge on specific places. While a distributed model is possible when a grid size is chosen which makes the parameters within these cells uniform. The TRMM precipitation data is spatially uniform distributed within the cells in example.

Satellite method

This method uses satellite images from LandSat and Sentinel satellites and the open source web based platform Google Earth Engine(GEE) to make inundation maps. With GEE a large amount of satellite images is assessed on surface water: water absorbs most radiation at near-infrared wavelengths and beyond which makes water bodies recognizable with satellite camera's (McFeeters, 1996). Satellite images on the days of known historic flash floods in appendix B will be checked for surface water. Images with surface water will be detected by the script and if one of the satellites passed by at the day of the flood this will show the extend of the flood or inundated area. The probability of the precipitation event preceding the flash flood coupled to the inundated area gives the hazard area for several return periods. Using a DEM the wet perimeter and the water level per cross section can be calculated as shown in figure C.2. With the help of the slope, the wet area and the roughness of the bed the discharge can be calculated with the Chezy or Manning equations. The method used is described in figure C.3.

The method relies on the availability of satellite images of the region. Currently there are several satellites providing the needed images: Landsat 7&8 both having a repeat interval of 16 days and the Sentinel 1A, 1B, 2A and 3A a repeat interval of 12 days. During the flood event of 2010 only Landsat 5 and Landsat 7 were available, which both take a picture every 16 days of the Sinai. Further back in history even less satellites where available and not all the images are (still) available.

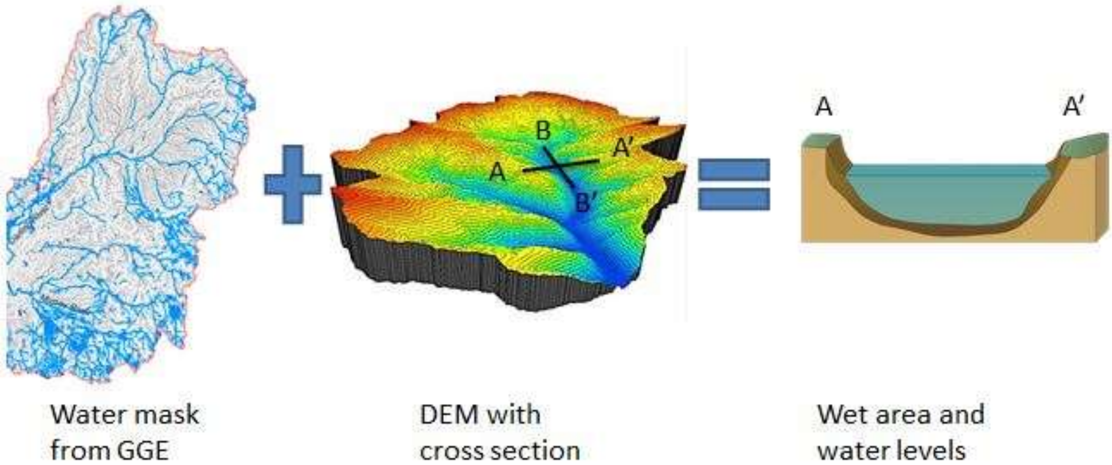


Figure C.2: Satellite image methodology

The input for this method are satellite images from flood events and a digital elevation model (DEM).

Outputs of this method are discharges, inundation maps and water levels for different return periods.

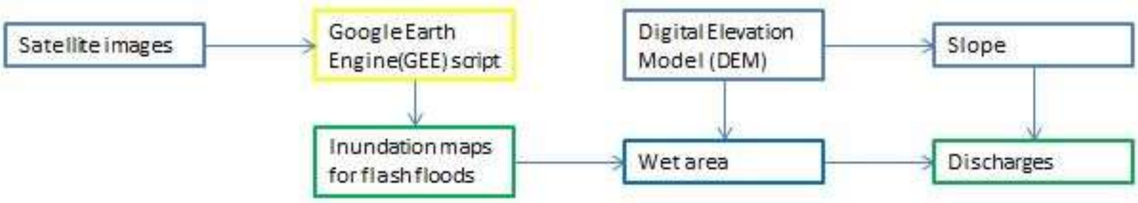


Figure C.3: Methodology for the satellite method

Because the method uses inundation images from past floods, the method does not need validation or calibration.

This method can only be used to assess the current hazards and is not suitable to predict the hazards after applying measures against flash floods. Reusing the method to assess the hazards after applying measures is not possible until a new rainfall event occurs above the rainfall threshold for flash floods. This means that only when a rainfall event which would normally cause a flash flood happens, the satellite method could assess where and how much was flooded.

The Satellite method is a black box model which is spatially distributed. The internal process is not described or modelled but the hazard area can be derived from the amount of precipitation that preceded the flash flood.

Enhanced HAND-method

This method uses a combination of the HAND model, soil maps and slope of the wadi to assess the hazards caused by flash floods in a qualitative way. To the HAND hazard map, soil hazard map and slope hazard map weight is assigned and with a GIS program the final hazard map is created.

The Height Above Nearest Drainage(HAND) is a topographical based qualitative hydrological model. The HAND model uses a Digital Elevation Model (DEM) to analyse the hazard of flooding. Every cell of the DEM flows to the lowest of the 8 bordering cells, creating a flow pattern. The user defines the number cells need to drain into a cell before it is called a drainage, a threshold for drainage channels. The drainage network created is then compared to satellite images to check whether the right threshold is chosen. With the DEM and the flow patterns the HAND grid is calculated, giving the height above the nearest drainage for every cell of the watershed as shown in figure C.4 (Renno, et al., 2008; Nobre, et al., 2011).

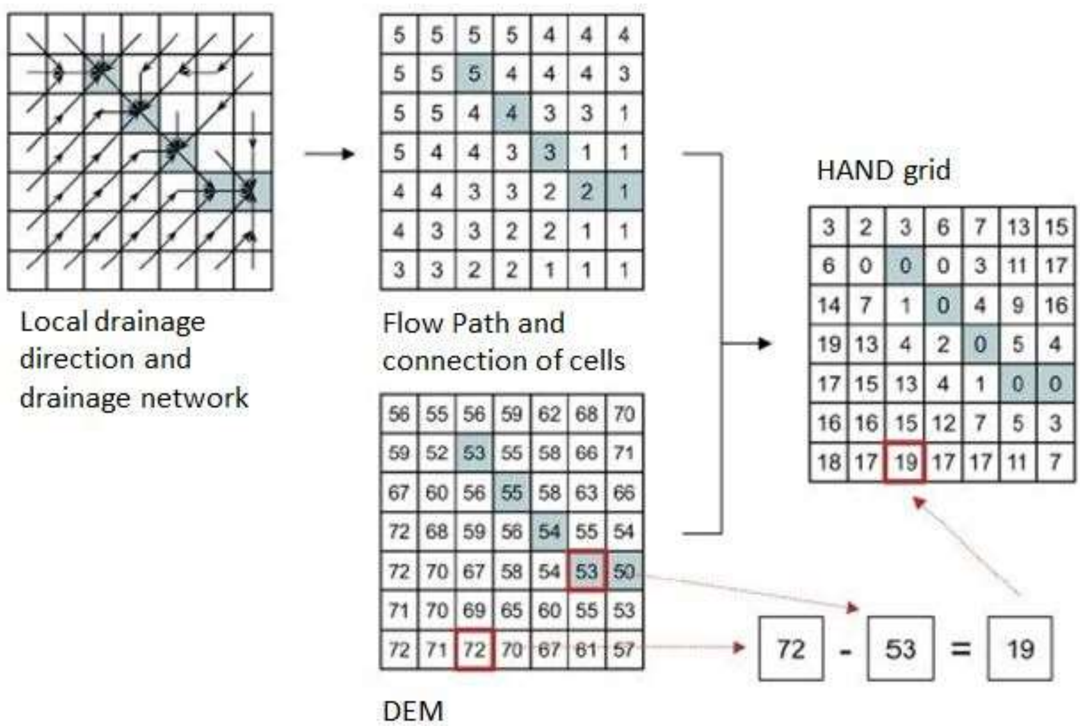


Figure C.4: Procedure to calculate HAND grid, blue squares are drainage networks and black arrows are the flow paths (Renno, et al., 2008)

To assign hazard zones to the calculated HAND grid values, the drainages are separated into drainages with a large amount of cells upstream(>100.000), medium amount of cells upstream (>1000) or a small amount of cells upstream (<1000). The grid cells near the drainages are assessed on their height above the nearest drainage. A cell near a drainage channel with a large amount of cells upstream needs to have a higher HAND value than a cell near a smaller drainage. This classification results from the validation process, the areas with hazard derived from the HAND method need to be compared to known flood extends these are shown in table C.1 (HKV, 2015).

Table C.1: Potential HAND hazard classification used for the hazard assessment (own illustration, 2017)

Type	Amount of cells	High HAND hazard	Medium HAND hazard	Low HAND hazard
Large drainage	>100000	<3	3 - 5	5 - 10
Medium drainage	>1000	<2	2 - 4	4 - 8
Small drainage	<1000	<1	1 - 3	3 - 5

Mechanisms that cause the flash flood phenomena are: high intensity storms, steep slopes in the catchment, poor vegetation cover, high velocity flows and lack of permeability. Without considering the precipitation these are affected by the type of soil and the slope. Areas with bare rock have a smaller infiltration capacity and a larger overland flow velocity then a well-drained sand soil. Wadis near bare rock soils have a higher hazard on flash floods than a wadi surrounded by sand dunes or forests.

With the slope maps the velocity of overland- and channel flow are categorized, with a steep slope water will have a higher velocity and less time to infiltrate or evaporate. A higher slope around- and in the wadi means a higher hazard for flash floods (El-Sayad, Sanad, Kotb, & Eltahan, 2012).

The input for the enhanced HAND method are soil maps and a DEM. The HAND model is used to deduce a HAND grid and a GIS based program for the slope map. The HAND hazard classification, slope hazard map and soil maps are used as input for the final hazard map.

Output of this method are qualitative hazard maps, it assigns hazards based on threshold values chosen by the user.

Threshold values for the HAND hazard classification chosen by the user needs to be calibrated and validated by inundation maps from the satellite method or by the output from HEC method.

This method can only be used to assess the current hazards and is not suitable to predict the hazards after applying measures against flash floods.

The HAND method is a conceptual model which is spatially distributed. The hydrological process are not described by physical measurable parameters but by the enhanced HAND hazard intermediate parameter. The method is distributed.

Selecting a method to assess the flash flood hazards

Now that the methods are described a method is selected to assess the flash flood hazard. First an overview of the methods and their in and output is given in table C.2.

Table C.2: Overview of methods to assess hazards caused by flash floods

	USACE method	**Satellite method**	**Enhanced HAND**
Input needed	Precipitation, land use- and soil maps, DEM.	Images of flood events, precipitation data and DEM.	DEM, soil maps
Output generated	Discharge, flow velocity and flood maps	Discharge, flow velocity and flood maps	Hazard maps
Calibration and Validation	Calibration hydrologic model: flood 1975 Calibration hydraulic model: flood 2010 No validation options	Not a simulation, so no calibration needed. No validation options	Calibration with satellite flood maps or HEC method.
Prediction	Able to predict changes in hazard caused by change in ecology and by including measures	Not able to predict changes in hazard, only evaluate the change in hazards	Not able to predict changes in hazard

To choose a method for the hazard assessment the methods themselves need to be evaluated to find a suitable method. The methods are evaluated by:

- The availability of the input parameters
- The possibility of calibration and validation
- Reusable for prediction due to changes

In the previous paragraphs every method was described by means of their in- and output, calibration and validation options, and the ability to re-use the method to assess hazards including change of ecology and –measures as is shown in table C.3.

Table C.3: Review of methods to assess hazards

	USACE method	**Satellite method**	**Enhanced HAND method**
Availability of input parameters	Transpiration, evaporation and infiltration data is not available. But can be predicted by intermediate parameters	No images available from known flood events.	Available
Possibility of calibration and validation	Calibration possible, validation not possible for this area	No need for calibration	Calibration with help of other methods
Reusability for predictions	Reusable	Not reusable	Not reusable

The USACE method to assess the hazards is the only method which satisfies all criteria and is therefore chosen to assess the flash flood hazard in the El Arish watershed.

Because the watershed of El Arish is large (2/3 of the area of the Netherlands) a lumped model is not applicable, the parameters in the whole area are not uniform and thus this would give biased results. Furthermore the discharges at multiple points in the watershed is needed to propose measures and this is not possible with a lumped model

A distributed model in the watershed would give the spatial variability to propose measures, however the grids of the model should be chosen a size it can follow the topographic boundaries of the watershed. This is possible if a small grid size is chosen, which would make the model very large and impractical.

A semi-distributed model is the only option which is suitable for this watershed. The physical characteristic topography and the needed amount of detail decides the boundaries of a sub basin. The sub basins are connected with the natural course of the wadi stream, which form a drainage network.

D.Dimensions of sub basins and main channels

This appendix provides the results of the division and the measurements of the dimension of the sub basins and wadi channels.

The sub basins division is downloaded from the hydrosheds.org website, the sub basins in the downloaded files are divided in different size categories. To be able to assess the hazards even in the upstream parts of the El Arish watershed a small size of sub basins is chosen. But because the corresponding shapefiles give very small sub basins downstream, some small sub basins are merged with QGIS. This provides the 38 sub basins shown in figure D.1. Dimensions of the basins are derived with QGIS and shown in table D.1.

Sub basins are named after the regions they are situated in for example Ruaq 1 till Ruaq 1.1.1.1.1 are situated in the Ruaq region. Ruaq 1 is the most downstream sub basin and Ruaq 1.1.1.1.1 is the most upstream region (3 sub basins are between them). If a sub basins have multiple sub basins upstream in their number changes as well. For example Bruuk 1 has two direct upstream sub basins: Bruuk 1.1 and Bruuk 1.2. Bruuk 1.1 has an upstream sub basin as well called Bruuk 1.1.1 if Bruuk 1.2 had an upstream sub basin it would be called Bruuk 1.2.1.

The main wadi channels are the channels connecting the sub basins to the sub basin downstream. 30 of these channels are derived and they are named after the sub basin upstream of the channel. For example the main wadi channel that connects the sub basins Ruaq 1.1.1.1 (upstream) to the downstream part of Ruaq 1.1.1 is called Wadi Ruaq 1.1.1.1. The length-, width- and slope of these channels are derived with Google Earth and with QGIS. The dimensions are input for the channel flow in appendix H and are shown in table D.2.

The input for the direct runoff method in appendix G is also derived: the longest channels within the sub basin and the average slope are measured with Google Earth and QGIS. In table D.1 the results are shown.

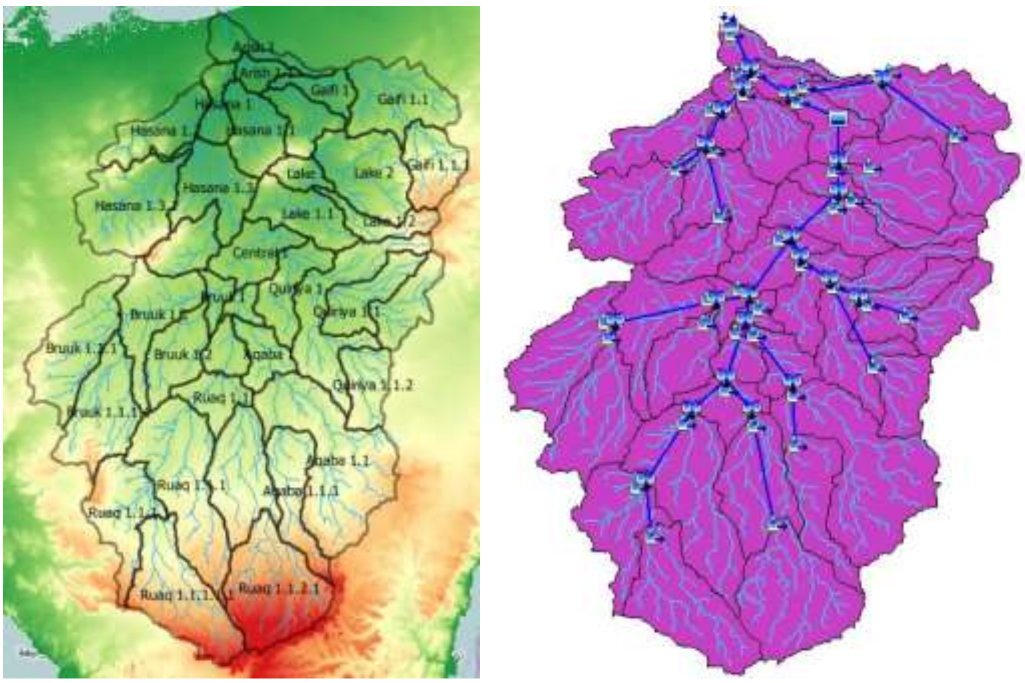


Figure D.1: Sub-basins of the El Arish watershed with DEM (left) and finer level of 38 sub basins and 28 channels which are modelled in HEC-HMS (right) (own illustration, 2017)

Table D.1: Dimensions of the sub basins

Sub basin	Area(km^2)	Maximal channel length (km)	height difference (m)	Average slope(m/m)
Aqaba 1	338,6	28	100	0,0036
Aqaba 1.1	1763	69	400	0,0058
Aqaba 1.1.1	632,9	57	450	0,0079
Arish 1	308,9	43	120	0,0028
Arish 1.1	184,3	16	30	0,0019
Bruuk 1	158,4	20	40	0,0020
Bruuk 1.1	770	50	150	0,0030
Bruuk 1.1.1	920,2	43	150	0,0035
Bruuk 1.1.1.1	903,2	41	160	0,0039
Bruuk 1.2	554,8	41	140	0,0034
Central 1	501,2	30	70	0,0023
Central 1.1	136,9	12	30	0,0025
Gaifi 1	269,5	30	65	0,0022
Gaifi 1.1	854,8	40	220	0,0055
Gaifi 1.1.1	524,4	30	450	0,0150
Hasana 1	268,9	30	40	0,0013
Hasana 1.1	554,2	33	140	0,0042
Hasana 1.2	560	45	100	0,0022
Hasana 1.3	745,6	38	130	0,0034
Hasana 1.3.1	1058,6	49	270	0,0055
Hasana 1.3.2	425,5	37	200	0,0054
Lake 1	202	21	140	0,0067
Lake 1.1	595,7	28	50	0,0018
Lake 1.2	305,2	54	600	0,0111
Lake 2	866,7	38	360	0,0095
Quiriya 1	503,8	34	140	0,0041
Quiriya 1.1	1034,7	50	200	0,0040
Quiriya 1.1.1	521,1	34	260	0,0076
Quiriya 1.1.1.1	444	30	250	0,0083
Quiriya 1.1.2	442,1	30	150	0,0050
Ruaffa Dam	398	34	85	0,0025
Ruaq 1	256,5	23	100	0,0043
Ruaq 1.1	372,1	22	90	0,0041
Ruaq 1.1.1	1411,4	75	560	0,0075
Ruaq 1.1.1.1	792,1	46	430	0,0093
Ruaq 1.1.1.1.1	1139,5	60	670	0,0112
Ruaq 1.1.2	875,8	49	325	0,0066
Ruaq 1.1.2.1	1262,4	56	640	0,0114

Table D.2: Dimensions of the main wadi channels

Main wadi channel	Through sub basin	length(m)	average slope (m/m)	bottom width(m)
DR A 1.1	Aqaba 1	28200	0,0035	600
R A 1.1 & H1	Arish 1	20000	0,0025	500
R A 1.1.1	Aqaba 1.1	18600	0,0043	500
R B 1.1	Bruuk 1	11700	0,0009	800
R B 1.1.1	Bruuk 1.1	33000	0,0021	700
R B 1.1.1.1	Bruuk 1.1.1	5700	0,0026	500
R C 1	Lake 1.1	23200	0,0017	400
R C 1.1	Central 1	31400	0,0019	2000
R G 1.1	Gaifi 1	29700	0,0027	400
R G 1.1.1	Gaifi 1.1	33700	0,0062	200
R H 1.1	Hasana 1	10100	0,0020	700
R H 1.2	Hasana 1	8800	0,0011	700
R H 1.3	Hasana 1	12800	0,0023	600
R H 1.3.1	Hasana 1.3	4700	0,0032	600
R H 1.3.2	Hasana 1.3	24300	0,0037	500
R L 1.1	Lake 1	11500	0,0022	2000
R Q 1	Central 1	8600	0,0023	2000
R Q 1.1	Quiriya 1	12500	0,0024	1000
R Q 1.1.1	Quiriya 1.1	10500	0,0029	700
R Q 1.1.1.1	Quariya 1.1.1	16800	0,0042	700
R Q 1.1.2	Quiriya 1.1	35800	0,0039	400
R R 1.1	Ruaq 1	21600	0,0032	600
R R 1.1.1	Ruaq 1.1	15000	0,0033	600
R R 1.1.1.1	Ruaq 1.1.1	32900	0,0027	500
R R 1.1.1.1.1	Ruaq 1.1.1.1	15500	0,0039	400
R R 1.1.2.	Ruaq 1.1	13200	0,0053	600
R R 1.1.2.1	Ruaq 1.1.2	44000	0,0055	500
R R&A 1	Central 1.1	9400	0,0032	600
R Ruaffa 1	Arish 1.1	15400	0,0019	1000
R Ruaffa Dam reservoir	Ruaffa Dam	36800	0,0024	300

E. Precipitation

There are three sources of precipitation data considered. The first is the Water Resources Research Institute (WRRI) which has a total of 18 rain gauges on the Sinai Peninsula and 6 in the El-Arish watershed since 1990 (Hassan, 2011; El Afandi, Morsy, & El Husseiny, 2012), the locations are shown in figure E.1. The second source is the National Climatic Data Center (NCDC), which has only one measuring station in the city of El Arish recording precipitation since 2000. The third option is satellite data from the Tropical Rainfall Measuring Mission(TRMM) which extracts precipitation data since 1998.

The WRRI precipitation data is not publicly available and thus the full data set since 1990 is not available for this research. There are however a few researchers who used data from the WRRI and whose research are publicly available. In Hassan (2011) and El Afandi et al.(2012) the precipitation of the six rain gauges within the El Arish watershed is used to describe the 2010 flash flood event, the results are shown in figure E.1. El-Sayad(2012) used the WRRI data to estimate rainfall extremes with the Generalized Extreme Value (GEV) distribution, for the six measuring stations in the El Arish watershed. Because the precipitation data is not available for this research the before mentioned literature is used to compare the data that is available.

The NCDC is the old name of the National Oceanic and Atmospheric Administration (NOAA) which collects climatic data all around the world. In the Sinai they have a measuring station in El Arish city since 2000. Since the average annual precipitation of El Arish city is considerably higher than the rest of the watershed, this measuring station is not representable for the rest of the watershed. It also does not allow spatial coverage of the entire watershed, but usable if nothing else is available to give an indication.

The TRMM is a joint US–Japan satellite mission launched on November 1997. It has been designed to monitor tropical precipitation using the Precipitation Radar (PR) and gives coverage extends from 50° south to 50° north latitude. The daily accumulated rainfall product is derived from a three-hourly product and is available in a 30 x 30 km grid cell. The data is publicly available and downloaded with DELFT-FEWS from Deltares for this research. The TRMM database offers data from 1998 to 2015 with a grid size of 30 x 30 km for the Sinai. Because of the long time span and the spatial distribution of the data the TRMM is used for this research.

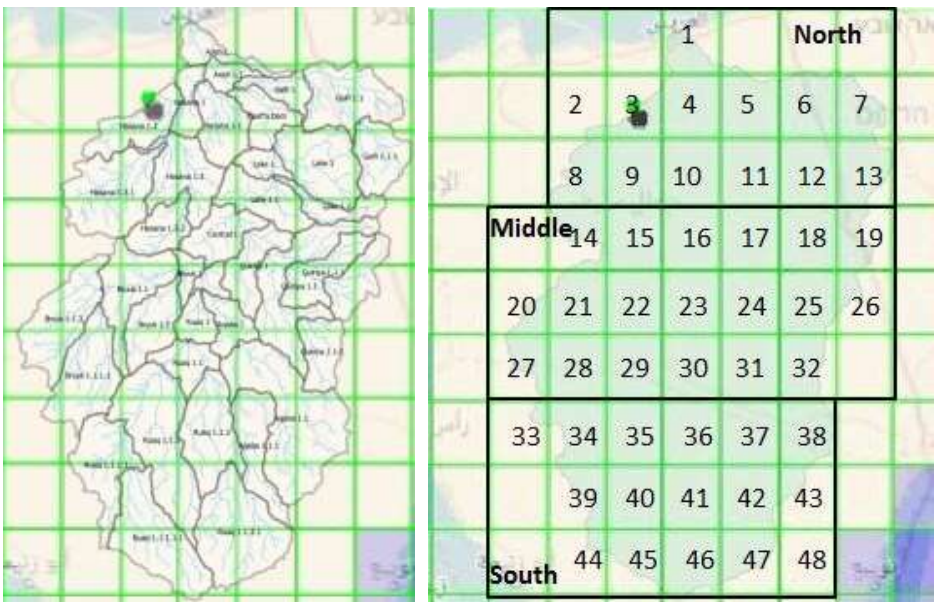


Figure E.1: TRMM cells and sub basins used in the hydrological study(left) and the cell numbers and (own illustration, 2017)

Every flash flood happened after 1998 and on record from appendix B can now be coupled to a rainfall event. The average rainfall of all the 48 cells is noted and the value of the cell with the highest rainfall intensity that day in table E.1. At a first glance the flash floods in modern times are not preceded by a large precipitation event.

From table E.1 it is derived that sometimes a flash flood is recorded while no or a very low precipitation is registered by the TRMM satellites and that can have three reasons. The first is that the TRMM registers measurements every three hours, short intense rainfall events that start and end between two TRMM acquisitions can go undetected (Milewski, et al., 2009). The second reason is that convective storm cells have a diameter of 3-10 km (Sharon, 1972) and because of the grid size of 30x30 km of the TRMM these might go unnoticed as well. Thirdly the record of the flash flood could be false. A systematic approach of keeping records of flash floods in the El Arish watershed could help identifying the reason of the discrepancies between the precipitation and flash flood events.

Date	Flood magnitude	Average and (highest) rainfall before event [mm]	Source of record
21 Feb. 1975	120 x 10^6 m^3 [2)]	40 – 50 [2)]	2
23 Mar. 1991 (Lake and/or Gaifi)	-	21 [3)]	3
01 May 2001 (Lake and/or Gaifi)	-	0,6 (5,6) [5)]	3
29 Jan. 2004 (Lake and/or Gaifi)	-	9 (40) [5)]	3
27 Oct. 2005 (Hasana)	-	0,3 (1,2) [5)]	3
20 Jan. 2007 (Hasana)	-	0,41 (11,2) [5)]	3
10 Dec 2009 (Lake and/or Gaifi)	-	0 (0) [5)]	3
18 Jan 2010 (whole watershed)	124 x 10^6 m^3 [4)]	15,6 (31,2) [5)]	4
16 Feb. 2010 (Quiriya)	-	0,25 (11,2) [5)]	3
26 Feb. 2010 (Bruuk)	-	6 (22,8) [5)]	3

Table E.1: Flash floods since TRMM started. Sources: 1. Dames & Moore (1985), 2. Klein (2000), 3. Hermas (2011), 4. Moawad (2013), 5. TRMM (2016)

Analysis of underestimation of extreme precipitation by TRMM

Satellite-based rainfall estimates tend to underestimate event-based precipitation events especially in arid areas (Morrissey & Janowiak, 1996). Chiu et al. (2006) describes that TRMM data underestimates the precipitation in arid areas with 15-30% compared to rain gauges. Milewski et al. (2009) uses a multiplication factor of 1.18 to calibrate the TRMM dataset to the rain gauges in his research about several watersheds in Egypt, including the El Arish watershed. To assess how much difference the precipitation data from TRMM and the rain gauges and provide for an extreme event, the storm causing the flash flood of 2010 is analysed.

Figure E.2: rainfaill gauges in the Sinai (Hassan, 2011)

In figure E.3 the precipitation measured by five WRRI rain gauges is shown, the location of these gauges are depicted in figure E.2. The total rainfall of the 2010 event per gauge is noted in table E.2, together with the values of the corresponding TRRM cells for the same period.

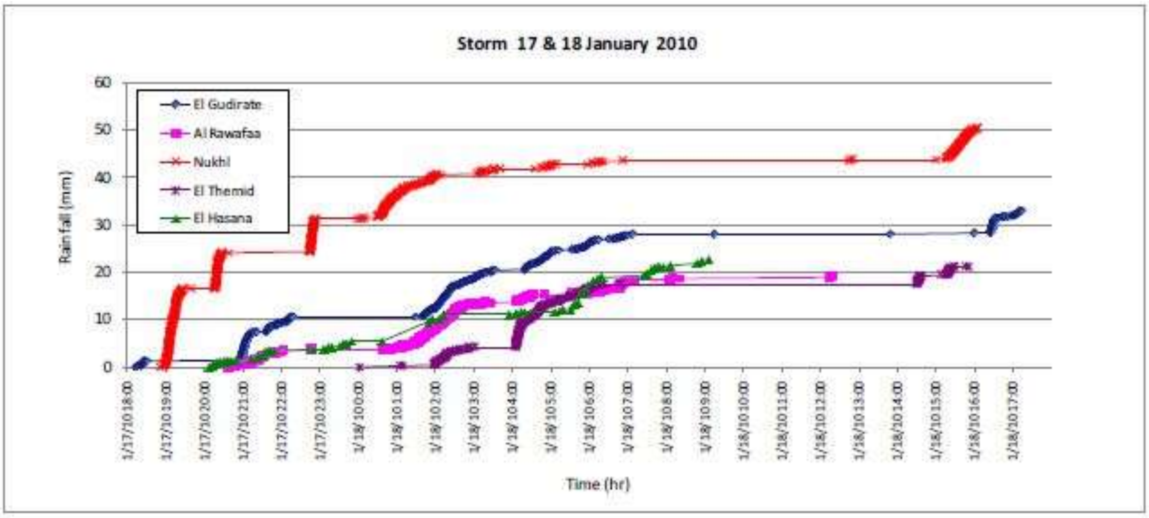


Figure E.3: Precipitation data of five rain gauges in the El Arish watershed causing the 2010 flash flood (Hassan, 2011)

The result of this analysis is that the average difference between the measured rain gauge data and the estimate by the TRMM for the precipitation at 17 and 18 January 2010 is a factor 1,26. This is consistent with the value Chiu et al. (2006) found and is in the same order of magnitude as Milewski et al.(2009) used. Because this is only one event based on five points of measurement, the value suggested by Milewski et al.(2009) will be used to describe the underestimation of TRMM values: 1,18.

Rain gauge (cell number in TRMM)	Total precipitation measured by gauge (Hassan, 2011)(mm)	Total precipitation estimated by TRMM satellite on same location (mm)	Multiplication factor (-)
Godairat (12)	32	24,8	1,29
Ruaffa Dam (5)	19	26,6	0,71
Nekhl (29)	50	24,2	2,07
Themed (38)	21	17,4	1,21
Hasana (16)	22	21,6	1,02
Average	**28,8**	**22,92**	**1,26**

Table E.2: Difference between estimated TRMM- and measured rain gauge precipitation data, which caused the flash flood of 2010.

Extreme value analysis

As input for the hydrological model precipitation data is needed and to be able to indicate the chance that a certain precipitation event occurs the available data needs to be analysed. The available TRMM data from 1998 till 2015 is used with a multiplication factor of 1,18 to estimate the chance of a certain precipitation event to happen during a given year.

Because the yearly average precipitation is highest in the northern coastal area and is gradually getting lower to southern borders of the watershed the TRMM cells are split up into a northern-, middle- and a southern part.

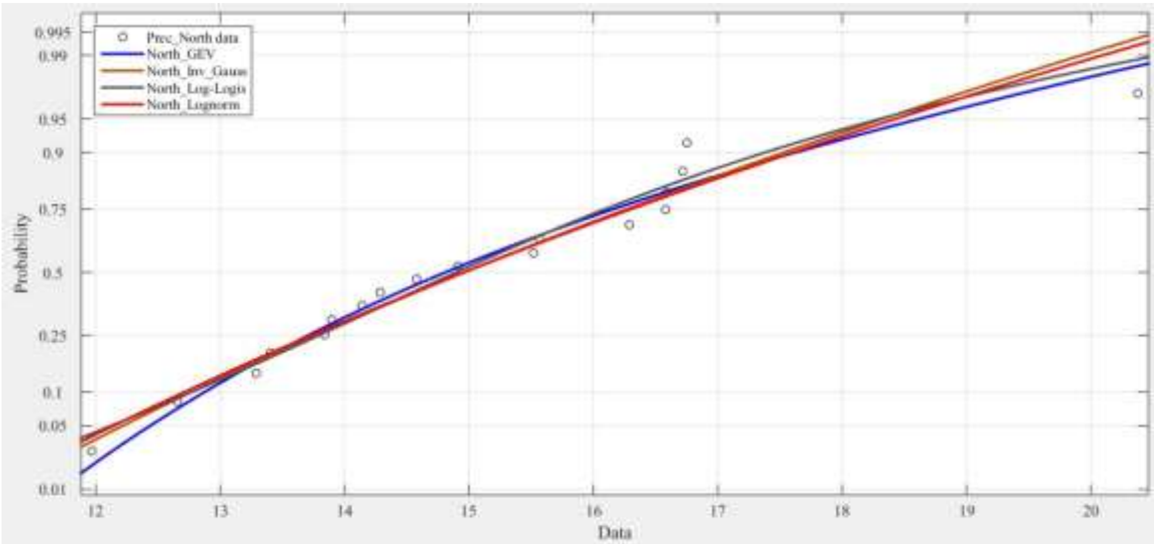
The daily precipitation data of all the cells in the three areas is averaged for every day since 1998. Because frontal storms can last more than one day the same is done for two consecutive days. This means that there is precipitation data for daily and for two consecutive days for the northern-, middle- and southern area. For every year the highest precipitation event is selected and with the MATLAB dfittool a distribution is fitted to the available TRRM data. For all three areas and for the daily and the two consecutive days the distribution is a Generalized Extreme Value(GEV) distribution. In the figures at the end of this appendix the probability plots, the considered distribution fits and the parameters of the used GEV for every area is given.

With the GEV distribution the amount of precipitation for a certain return period is simulated for all the areas for the one day and two day event using a MATLAB script. The results are in table E.2.

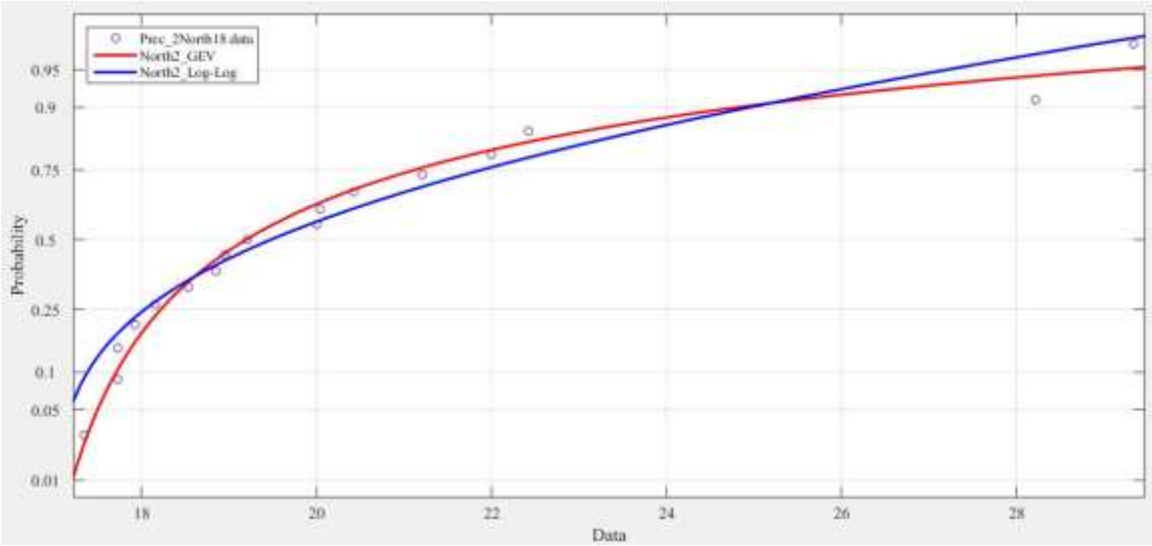
The flash flood of 1975 had an estimated average precipitation of 40-50 mm in two days and over a 100 year return period. From the values in table E.2 this lies in the range of possibility.

Table E.2: Amount of precipitation for 1 day event and 2 day event, for certain probabilities

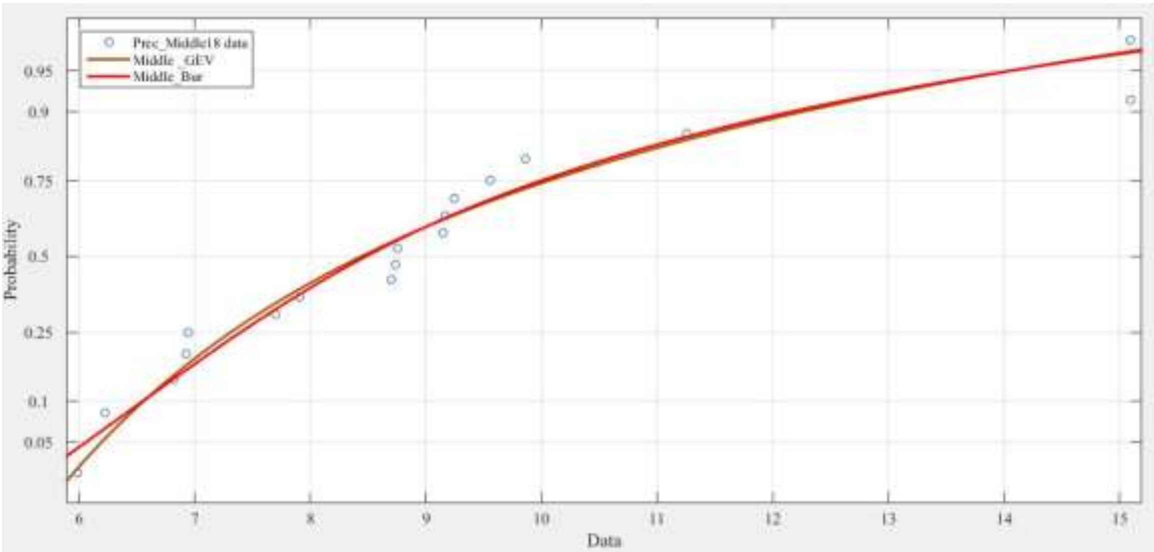
Area		Amount of prec. with a 0,5 yearly probability (mm)	Amount of prec. with a 0,05 yearly probability (mm)	Amount of prec. with a 0,02 yearly probability (mm)
North	1 day	19	23,5	25,5
	2 days	20,5	31,5	40,5
Middle	1 day	11	18	21,5
	2 days	11,5	24,5	38
South	1 day	6,5	14,5	21
	2 days	7,5	18	26



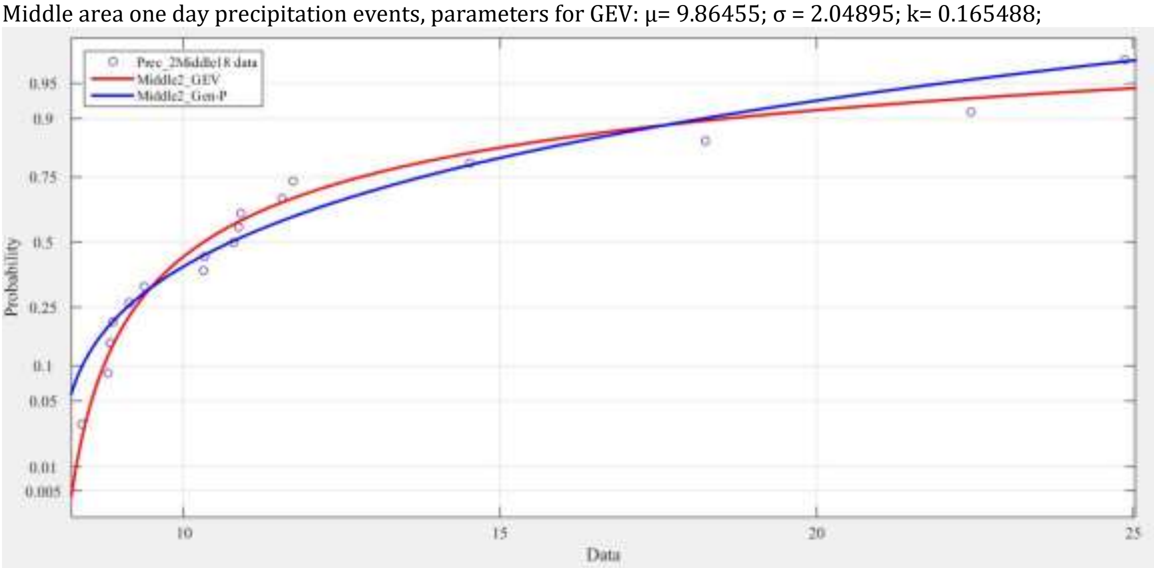
North area one day precipitation events, parameters for GEV: μ= 17.9345; σ= 2.00568; k= 0.05;



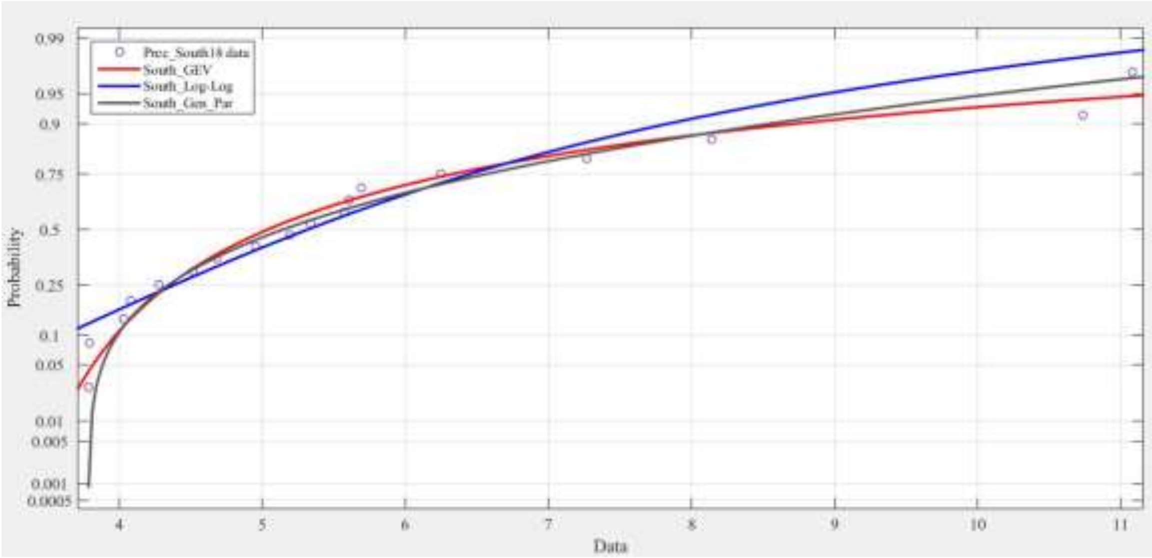
North area two days precipitation events, parameters for GEV: μ= 19.8955; σ= 1.47462; k = 0.556684;



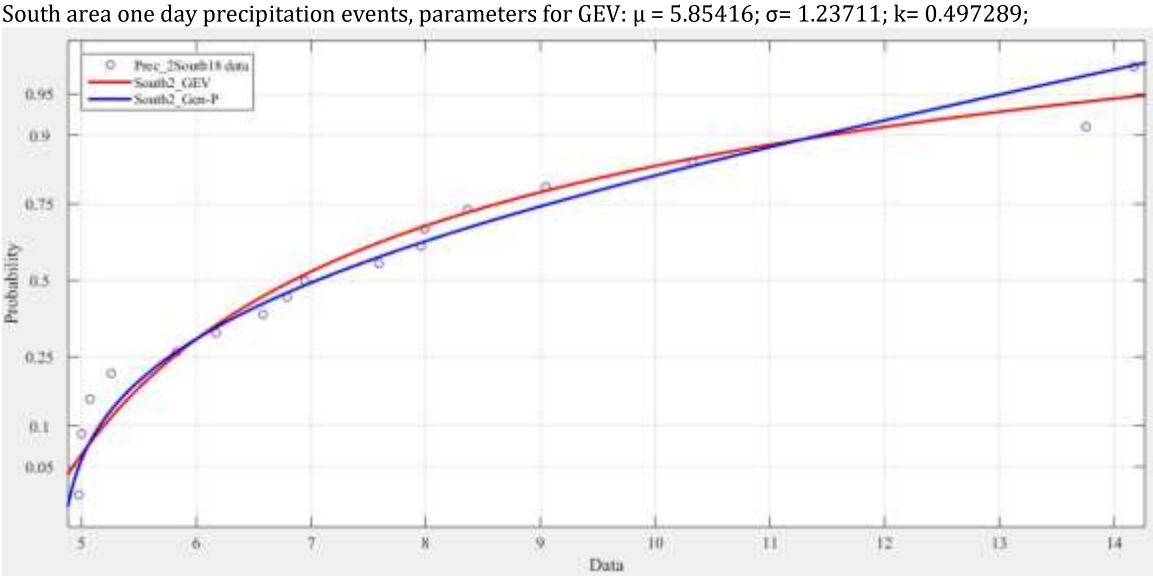
Middle area one day precipitation events, parameters for GEV: μ= 9.86455; σ = 2.04895; k= 0.165488;



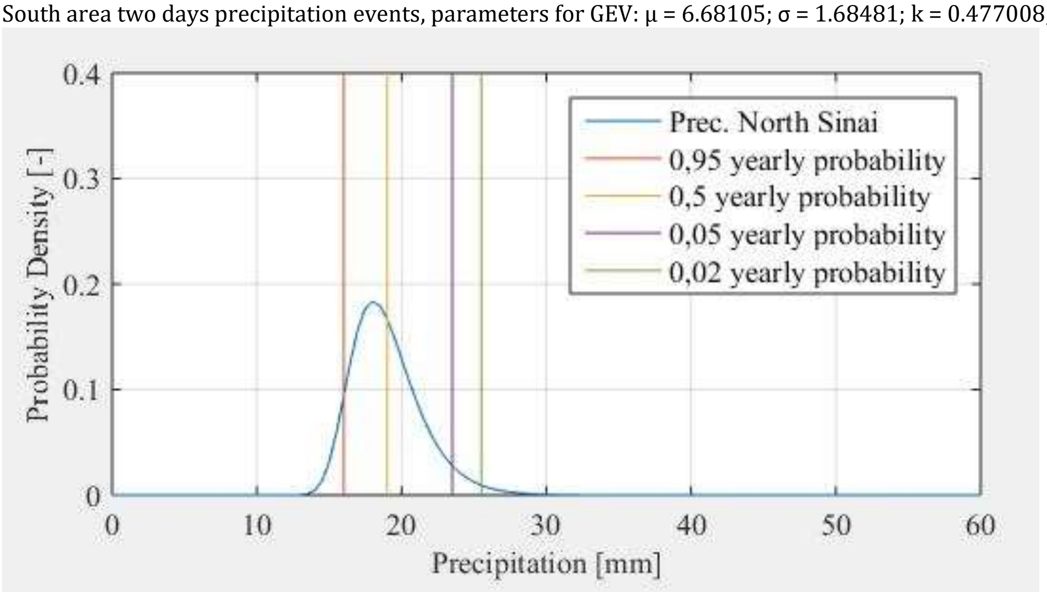
Middle area two days precipitation events, parameters for GEV: μ = 10.3326; σ = 1.51493; k = 0.652081;



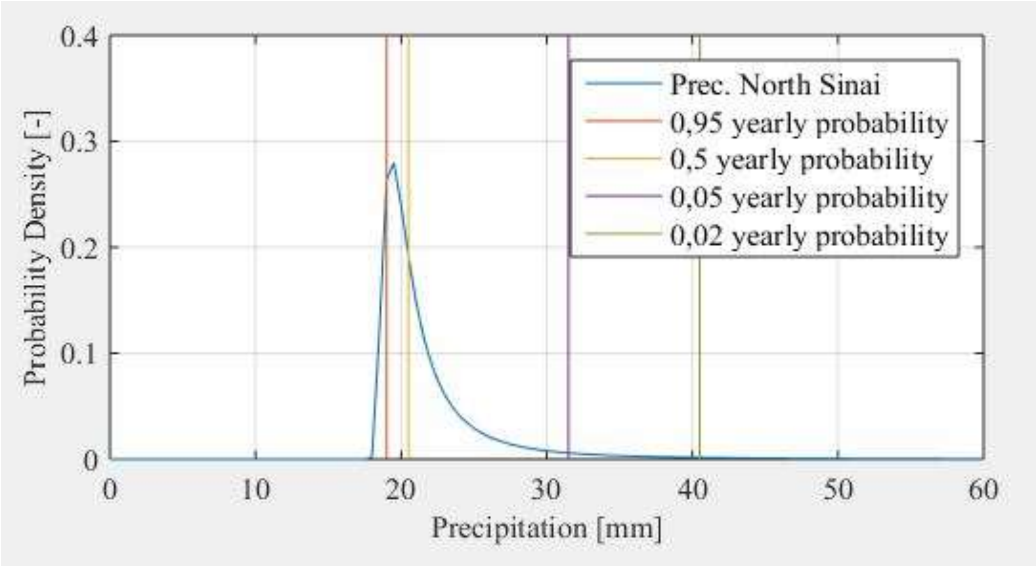
South area one day precipitation events, parameters for GEV: μ = 5.85416; σ= 1.23711; k= 0.497289;



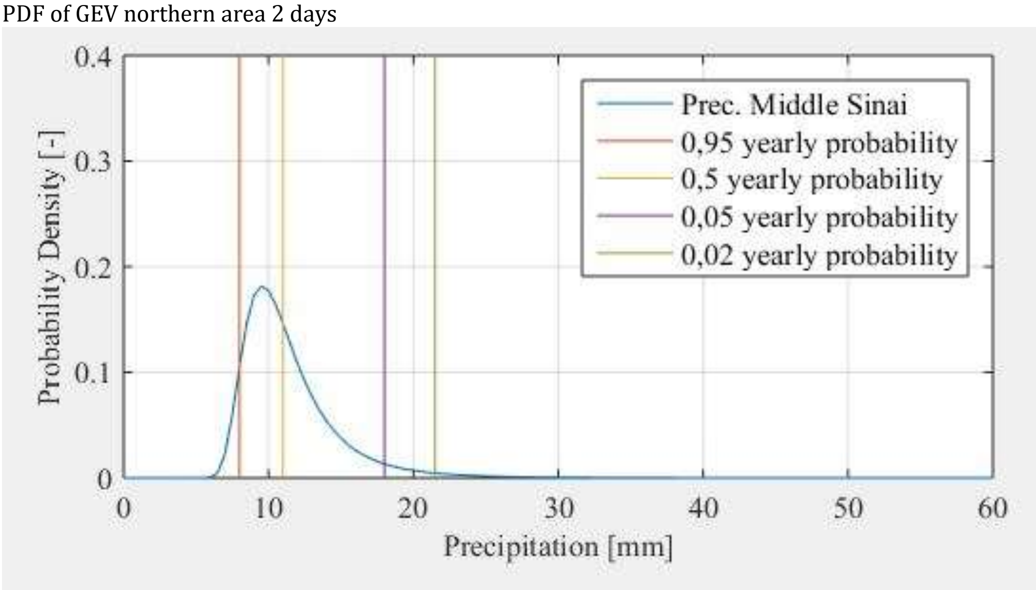
South area two days precipitation events, parameters for GEV: μ = 6.68105; σ = 1.68481; k = 0.477008;



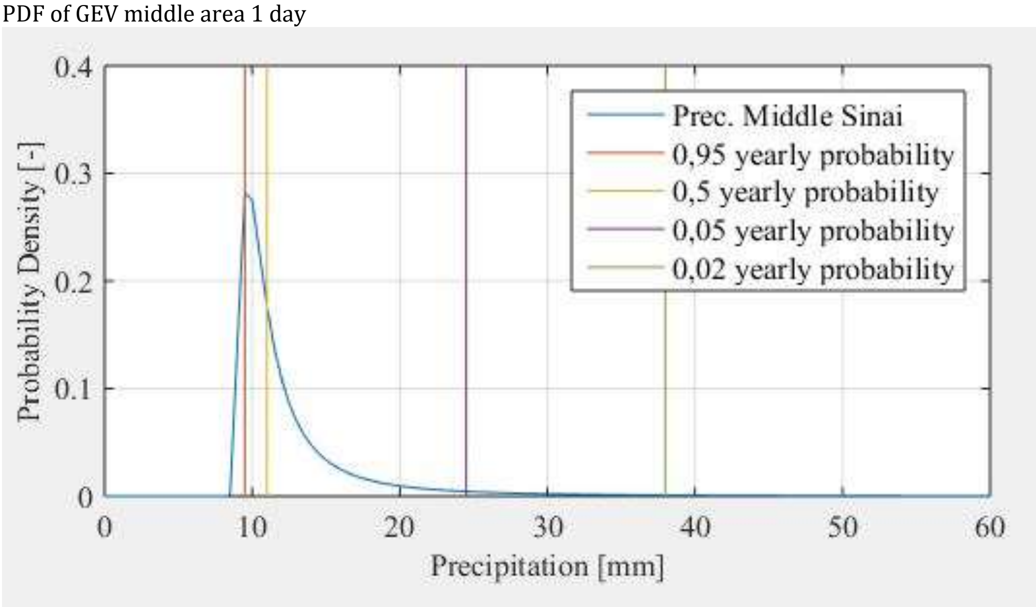
PDF of GEV northern area 1 day



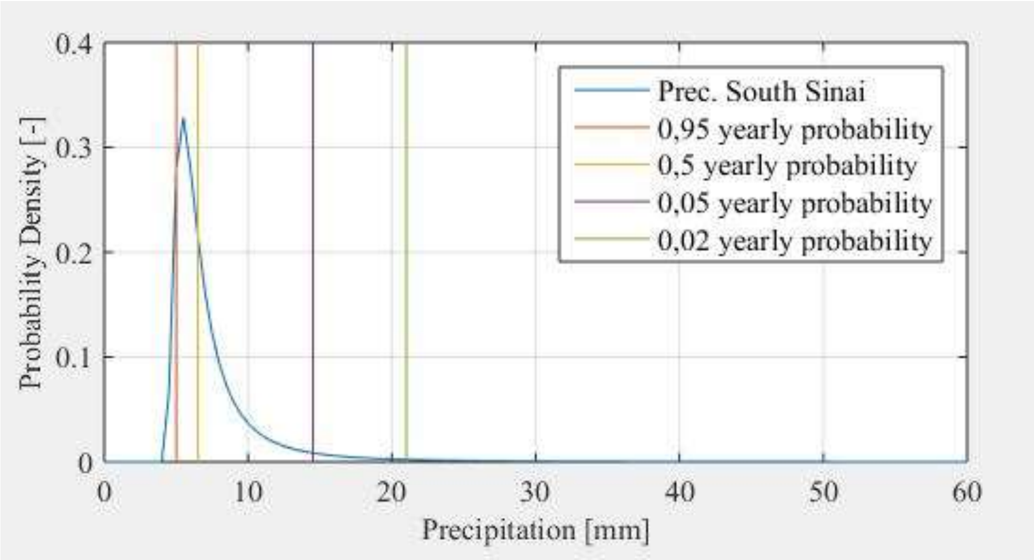
PDF of GEV northern area 2 days



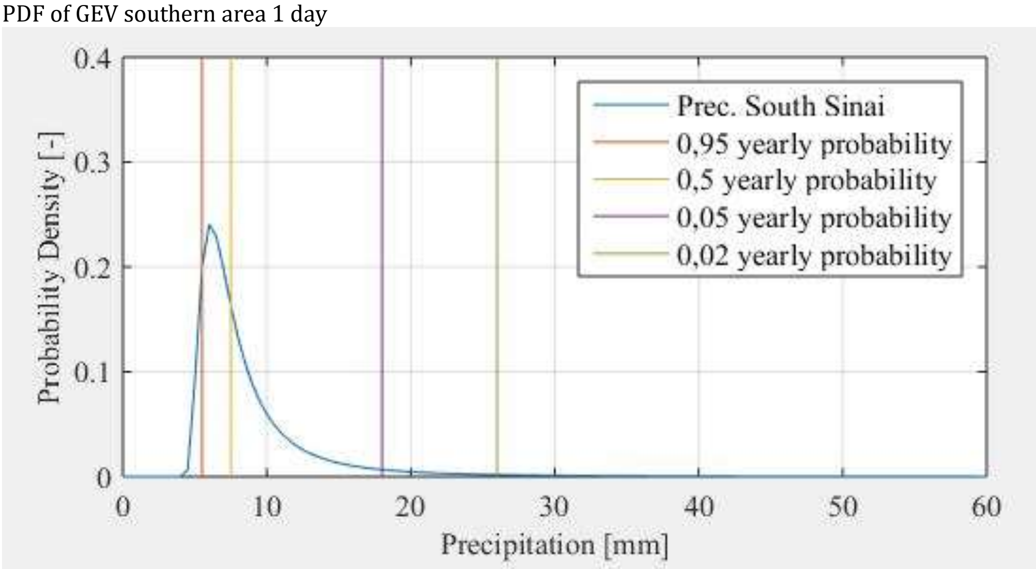
PDF of GEV middle area 1 day



PDF of GEV middle area 2 days



PDF of GEV southern area 1 day



PDF of GEV southern area 2 days

F. Loss method

The loss method is the method the HEC-HMS program uses to estimate the precipitation excess as a function of the cumulative precipitation and potential maximum retention of the soil.

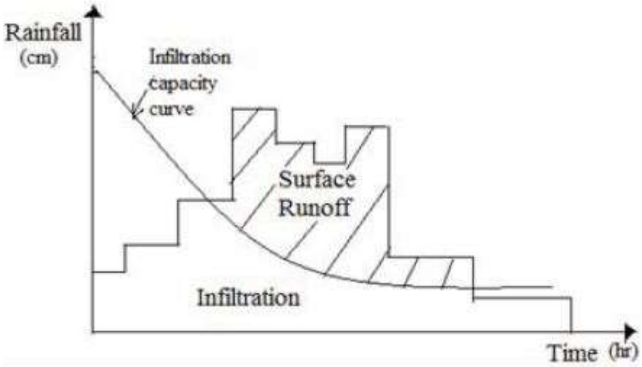


Figure F.1: Relation between precipitation, infiltration and surface runoff in the loss method (El-Sayad, Risk Assesment of Flash Floods in Sinai, 2012)

$$P_e = \frac{(P - 0{,}2S)^2}{P - 0{,}8S}$$

With P_e is the precipitation excess(mm), P is the cumulative precipitation(mm), S is the potential maximum retention(mm), the relation is showed graphically in figure E.1. The maximal retention includes all losses before overland flow begins: water interception by vegetation, infiltration and retained water in surface depressions. Water starts flowing when $P > 0{,}2*S$. The maximal retention is calculated through an intermediate parameter, the Curve Number (CN).

$$S = \frac{25400 - 254CN}{CN}$$

Curve Number

Curve Number values range from 100(water bodies) to approximately 30 for permeable soils with high infiltration rates and capacity. The CN of a watershed can be estimated as a function of the soil type, land use and treatment and antecedent watershed moisture.

Curve Numbers (CN) are intermediate parameters to estimate the maximum retention based on soil types, land use and treatment, surface condition and antecedent soil moisture. And describe the processes of interception by vegetation, infiltration and retained water in surface depressions

The surface geology of the El-Arish watershed can be divided into two regions: the lower Northern part and the Southern elevated part. The Northern part consists mostly of sand dunes, wadi deposits and some outcrops of basalt rocks. The Southern part of the watershed is characterized by large limestone formations, wadi deposits and again outcrops of basalt rock. In figure E.2 the surface geology map created for this research is shown, this map is made with QGIS and it is based on the aeromagnetic map downloaded from the European Soil Data Centre (ESDAC).

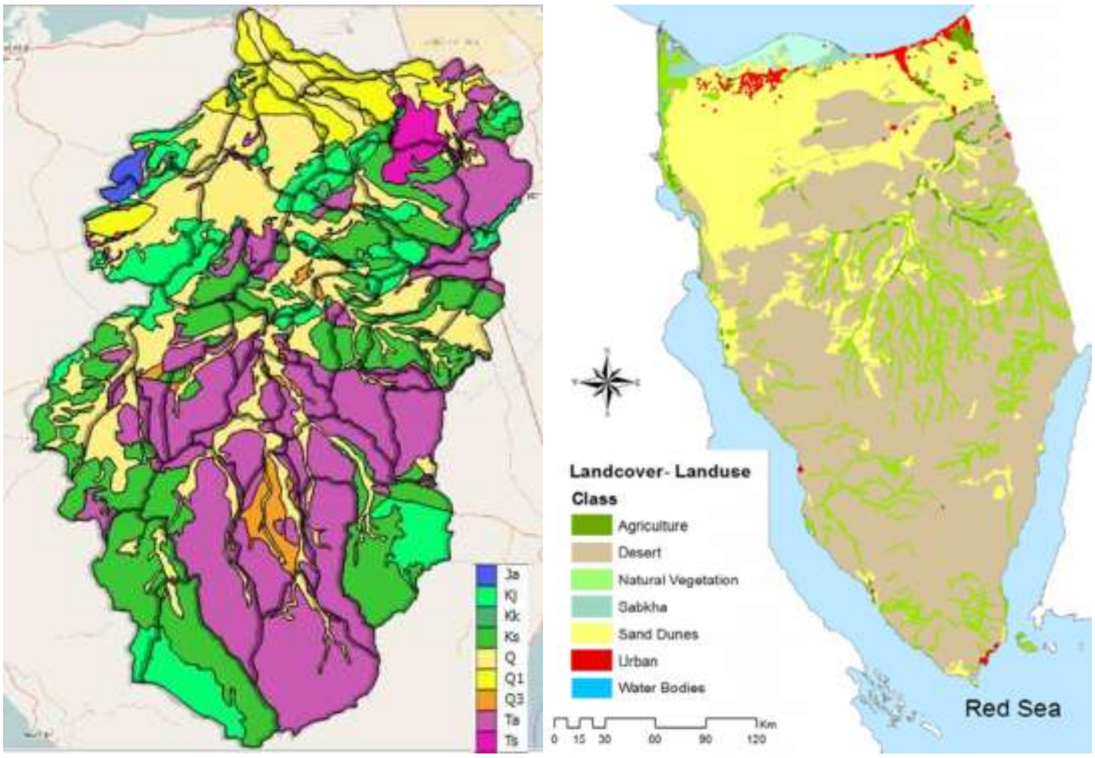


Figure F.2: Soil map of the El Arish watershed with sub basins (own illustration, 2017) and land-use in the whole Sinai (The Weather Makers, 2016)

The surface geology does not tell the whole story, the infiltration capability of soils is also depends on the thickness of the soil layer until bedrock and the type of rock beneath it. Because the Sinai is arid the landscape is rugged with steep rocky slopes, covered at their bases with colluvial or alluvial deposits. With more precipitation the sedimentation is generally higher and therefore the thickness and extend of the soil cover is higher. With a low yearly precipitation the rocky slopes increase and the alluvial and colluvial soil cover is lower (Yair & Lavee, 1985). In the El Arish watershed the northern part receives a higher yearly precipitation and is also downstream, the soil on top of the bed rock is therefore thicker than in the upstream and more arid part of the watershed.

The hypothesis that soil cover is shallower in the southern area is confirmed by research done by Greenwood (1997). The different soils are described as follows: Dunes (Q1) in the northern part of the watershed have no shallow lithic contact, they have a low carbonic content (less than 0,2 percent) and a sand fraction of more than 95%. Alluvial soils of Quaternary origin (Q and Q_3) are well drained and non-saline soils, there is no shallow lithic contact and the top soil is disturbed frequently because of flooding. The rest of the soil in the El Arish watershed is from older geologic periods with the common denominator that lithic contact(bedrock) is reached within 50 cm of the surface. In the eastern part of the watershed more clay is present and therefor are more fertile (still less than 0,6 percent organic carbon) than its western counterpart with a dominating calcareous soil surface.

The soil types are divided into four Hydrologic Soil Groups(HSG) based on their minimum infiltration capacity. The way the Soils Conservation Service(SCS) classifies the soils is described in table F.1. The geological surface map and the description of the soils provides the input to assign HSGs to each geologic type described. In table F.1 the types are related to HSGs.

Table F.1: Hydrological Soil Groups, their description and the soils in the Sinai associated with them (U.S. Army Corps of Engineers, 2000; Natural Resources Conservation Service, 1999; Natural Resources Conservation Service, 2009).

HSG	Description	Associated soils in the Sinai
A	Soils which have low runoff potential and a high infiltration rate even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (i.e. deep sand, deep loess, aggregated silts)	- Quaternary(Q): Alluvium - Quaternary(Q1): Sand dunes (coastal and desert)
B	Soils with moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures (i.e. shallow loess and sandy loam)	- Pliocene – Quartenary(Q3): Marl, clay, sand conglomorate(lake and wadi deposit)
C	Soils with low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture(i.e. clay, loams, shallow loams, soils low in organic content, and soils usually high in clay content)	None
D	Soils with high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material.	- Oligocene-Miocene(Ts): Clay, sandstone, marl, gypsum, conglomerate and limestone - Eocene(Ta): Chalk, limestone, chert - Senonian – Paleocene(Ks): Chalk, mar, clay, chert and limestone - Cenomanian- Turronian(Kj): Limestone, dolomite and marl - Lower Cretaceous(Kk): Sandstone, marl and limestone - Jurassic(Ja): Limestone, dolomite, marl, sandstone

The land use and treatment provides information on what is done in- and on top of the soil, which influences the amount of water which can be retained. Most of the El Arish watershed is a desert with sparse vegetation, however in the downstream northern part of the watershed there is agriculture in the wadi bed and in the most downstream part the city of El Arish is situated. For the three types of land use and treatment the SCS propose estimates of the CN described in table F.2.

Table F.2: CN derived for the 3 land uses in the El Arish watershed for different HSG

	A	B	C	D
Desert shrubs (<30% ground cover)	63	77	85	88
Orchard or tree farm(<50% ground cover)	57	73	82	86
Residential districts (65% impervious area)	77	85	90	92

The Antecedent Runoff Condition(ARC) describe the variability in the CN resulting from rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature. ARC is divided into three classes: II for average conditions, I for dry conditions, and III for wetter conditions. For the above CN values the dry condition is used, because the area is arid to hyper arid. Dry soil conditions can be assumed before every precipitation event.

The sub basins of the El Arish watershed have different soil types and uses within every sub basin. With the soil maps and land uses CN is calculated for every sub basin (U.S. Army Corps of Engineers, 2000):

$$CN_{comp} = \frac{\sum A_i CN_i}{\sum A_i}$$

Positive aspects of the SCS CN loss model are that is simple and stable. It relies on one parameter and is a well-established method used all over the world (Ponce & Hawkins, 1996).

Negative aspects are that the predicted values are not in accordance with classical unsaturated flow theory. Developed with small agricultural watersheds, applicability elsewhere is based on empirical small scale research. Precipitation intensity is not considered, same loss for 25 mm storm in 24 hours or in 2 hours (Ponce & Hawkins, 1996).

Sub basin	CN
Aqaba 1	81
Aqaba 1.1	86
Aqaba 1.1.1	87
Arish 1	69
Arish 1.1	60
Bruuk 1	78
Bruuk 1.1	80
Bruuk 1.1.1	78
Bruuk 1.1.1.1	80
Bruuk 1.2	85
Central 1	76
Central 1.1	77
Gaifi 1	66
Gaifi 1.1	77
Gaifi 1.1.1	86
Hasana 1	67
Hasana 1.1	68
Hasana 1.2	75
Hasana 1.3	71
Hasana 1.3.1	75
Hasana 1.3.2	85
Lake 1	82
Lake 1.1	82
Lake 1.2	88
Lake 2	85
Quiriya 1	79
Quiriya 1.1	83
Quiriya 1.1.1	82
Quiriya 1.1.1.1	74
Quiriya 1.1.2	86
Ruaffa Dam	72
Ruaq 1	79
Ruaq 1.1	80
Ruaq 1.1.1	86
Ruaq 1.1.1.1	85
Ruaq 1.1.1.1.1	87
Ruaq 1.1.2	81
Ruaq 1.1.2.1	86

G. Direct runoff

Direct runoff simulates the process of the transformation of excess precipitation into discharge in a chosen point. There are two options in the HEC-HMS program to model direct runoff: empirical- and conceptual models.

Empirical models establish a link between runoff and excess precipitation without detailed considerations of the internal processes of the sub-basin. The equations and parameters do not refer to the physical attributes but are selected through optimizations of a goodness of fit criterion.

Physical based models represent all physical mechanisms that influence the movement of excess precipitation. Overland flow and channel flow in the small channels of the watershed.

For the sub basins in the El Arish an empirical method is used to calculate the lag time without detailed considerations of the internal processes of the sub-basin. The equations and parameters do not refer to the physical attributes but are selected through optimizations of a goodness of fit criterion. This is done because the available DEM is not precise enough to distinguish small channels and their dimensions which is needed for a physical based model. For this method the slope of the sub basin and the length of the main channel is needed.

The size of the El Arish watershed makes the need of a detailed conceptual model unnecessary.

In HEC-HMS the SCS Unit Hydrograph(SCS-UH) model is used. The SCS-UH uses the lag time to define the time it takes for precipitation to get from the farthest point in the sub basin to point of outflow. The lag time is calculated with the Kirpich or Haktanir–Sezen methods provide reliable estimates of mean values of T_{lag} for large watersheds (Fang, Thompson, Cleveland, Pradhan, & Malla, 2008):

$$T_{Lag,Kirpich} = 2{,}387 * L_c^{0{,}77} * S_c^{-0{,}385}$$

$$T_{Lag,Hak-Sez} = 26{,}85 * L_c^{0{,}841}$$

Where T_{lag} is the lag time in minutes, L_C channel length over land(km)and S_C the averaged channel slope(m/m). Where the Haktanir-Sezen method is only a function of Channel length, the Kirpich method takes the averaged channel slope into account. Sub basins have a large deviation in channel slopes and it is an important parameter for generating flash floods. The Kirpich method for calculating the lag time is therefore used.

The Kirpich method is based on the longest channel in the sub basin, the averaged channel slope and fixed values to describe the overland flow. The lag-time gives an indication of how long the time difference is between precipitation falling and the peak of the discharge at the outflow point of the sub basins.

Name	Maximal channel length(km)	height difference(m)	Average slope (m/m)	Kirpich Lag time (minutes)
Aqaba 1	28	100	0,003571	271,84
Aqaba 1.1	69	400	0,005797	451,78
Aqaba 1.1.1	57	450	0,007895	346,26
Arish 1	43	120	0,002791	415,93
Arish 1.1	16	30	0,001875	226,42

Bruuk 1	20	40	0,002	262,27
Bruuk 1.1	50	150	0,003	454,33
Bruuk 1.1.1	43	150	0,003488	381,69
Bruuk 1.1.1.1	41	160	0,003902	352,40
Bruuk 1.2	41	140	0,003415	370,99
Central 1	30	70	0,002333	337,73
Central 1.1	12	30	0,0025	162,41
Gaifi 1	30	65	0,002167	347,50
Gaifi 1.1	40	220	0,0055	302,97
Gaifi 1.1.1	30	450	0,015	164,98
Hasana 1	30	40	0,001333	418,92
Hasana 1.1	33	140	0,004242	288,72
Hasana 1.2	45	100	0,002222	470,23
Hasana 1.3	38	130	0,003421	349,65
Hasana 1.3.1	49	270	0,00551	353,96
Hasana 1.3.2	37	200	0,005405	287,23
Lake 1	21	140	0,006667	171,30
Lake 1.1	28	50	0,001786	354,99
Lake 1.2	54	600	0,011111	291,19
Lake 2	38	360	0,009474	236,23
Quiriya 1	34	140	0,004118	298,85
Quiriya 1.1	50	200	0,004	406,69
Quiriya 1.1.1	34	260	0,007647	235,48
Quiriya 1.1.1.1	30	250	0,008333	206,88
Quiriya 1.1.2	30	150	0,005	251,84
Ruaffa Dam	34	85	0,0025	362,15
Ruaq 1	23	100	0,004348	216,59
Ruaq 1.1	22	90	0,004091	214,27
Ruaq 1.1.1	75	560	0,007467	437,01
Ruaq 1.1.1.1	46	430	0,009348	275,08
Ruaq 1.1.1.1.1	60	670	0,011167	315,19
Ruaq 1.1.2	49	325	0,006633	329,57
Ruaq 1.1.2.1	56	640	0,011429	296,23

H. Channel flow

Channel flow between the sub basins can be simulated with different models in HEC-HMS. With a channel slope averaging 0.004, the simplification of the kinematic-wave is used because of its simplicity.

The kinematic-wave approximation is a function of the momentum equation in one dimension that is simplified to the Manning equation.

$$Q = \frac{R^{2/3} * S^{1/2}}{n} * A$$

With Q is the flow (m^3/s), R the hydraulic radius (m), S the slope (m/m), A the cross sectional area (m^2) and n the manning coefficient($s/m^{1/3}$).

The channels between the sub-basins are modelled as a trapezoidal shaped section. The dimensions and slope of all the channels are in appendix D. Channel flow modelled by the kinematic wave approximation depends on the slope and resistance of the channel bed. Because the wadi beds are relatively uniform of shape, non-vegetated and contain coarse sand to gravel the resistance is small and a Manning coefficient of 0,035 is used for all the channels of the El Arish watershed. This value falls in the range of 0,02 – 0,04 considered for arid areas in research by Milewski et al. (2009)

I. Transmission losses

Transmission losses are the losses in the channel due to infiltration of water in the channel bed. In the El Arish watershed there is thick layer of coarse material in the wadi beds, which subtract water from the flash flood when it moves down the channels. This is a reason floods can be noticed upstream but cause no effect downstream. In paragraph 2.2.6 a cross section of a wadi bed is given, showing a wadi bed which is thick and wide. These wadi beds act as a shallow aquifer and can store a lot of water in their pores, in this chapter the volume of the losses are estimated using methods from literature and making them usable for the HEC-HMS model.

There are several methods considered to calculate the total water bearing capacity of the wadi bed: the first is the standard method of the NRCS to calculate the transmission losses, the second method is an approximation based on the physical properties of the wadi bed and the third and fourth are formulas derived from measurements in the south western part of Saudi Arabia. In all the methods it is assumed that there is no lateral in and outflow at the sides of the wadi bed and only vertical flow occurs.

The NRCS method is based on numerous observed inflow-outflow events in the arid to semi-arid southwestern US. A regression equation is fitted on the data, creating the threshold volume calculation. Multiple differential equations are used to approximate transmission losses observed in the inflow-outflow events and with a least-squares analysis the parameters in the transmission loss equations are estimated (Natural Resources Conservation Service, 2007).

The Potential Water Bearing Capacity (PWBC) approximation is based on the assumption made about physical attributes in paragraph 4.2.4. The wadi bed thickness is assumed to be linearly decreasing from downstream to the upstream channels, which together with the wadi bed dimensions and the effective porosity determines the amount of water which can be stored in the wadi bed. The method assumes that the whole wadi bed is saturated at the end of the flash flood.

The south western Saudi Arabia (SWSA) method is based on observed losses between measuring stations in Saudi Arabia. Wheater (2005) combined research of Walters (1990) and Jordan (1977) to derive relationships between the upstream discharge, the slope and the transmission losses.

Natural Resources Conservation Service (NRCS) transmission losses method

The NRCS method uses a soil parameter, the channels dimensions and discharge parameters of the upstream sub basin. The soil parameter of effective hydraulic conductivity (K) is estimated with the help of table I.1. The parameters needed from the discharge of the upstream sub basin are the total amount of water streaming into the channel (V_{in}) and the duration of the flow into the channel (T) which are both calculated in the hydrological model without transmission losses in HEC-HMS. The channel dimensions needed are the length of the channel (L) and the width of the channel which contributes to the flash flood (B). The equations used to calculate the transmission losses with the NRCS method:

$$V_{tot} = \frac{-a(L,B)}{b(L,B)}$$

$$a(L,B) = \frac{a}{1-b} * \left(1 - b(L,B)\right)$$

$$a = -0{,}116 * K * T$$

$$b(L,B) = e^{-k*0.621L*3{,}281B}$$

$$k(D,P) = -1{,}09 \ln\left(1 - 6{,}72 * \frac{K * T}{V_{in}}\right)/1000$$

With

K	= Effective hydraulic conductivity (mm/h)
T	= Duration of the stream event (hour)
V_{in}	= Inflow volume into channel (m^3)
k(D,P)	= Decay factor (m^{-2})
b(L,B)	= Regression slope for a channel of length L and width B
a (L,B)	= Regression intercept for a channel of length L and width B (m^3)
a	= Regression intercept for unit channel (m^3)
V_{tot}	= Total capacity threshold volume (m^3)
L	= Length channel (km)
B	= Contributing width of the wadi channel (m)

Table I.1: Relationship between material characteristics and effective hydraulic conductivity (Natural Resources Conservation Service, 2007)

Bed material group	**Bed material characteristics**	**Effective hydraulic conductivity K (mm/h)**
Very High loss rate	Very clean gravel and large sand	>125
High loss rate	Clean sand and gravel, field conditions	50 to 125
Moderately high loss rate	Sand and gravel mixture with low silt clay content	25 to 75
Moderate loss rate	Sand and gravel mixture with high silt clay content	6 to 25
Insignificant to low loss rate	Consolidated bed material; high silt clay content	0,0025 to 2,5

The effective conductivity is assumed to be 50 mm/h for all wadi channels in the El Arish watershed.

The duration of the flash flood in a wadi channel depends on the amount of water that streams through the channel, the slope of the channel and the sub basins that are upstream (their size, distance from the channel and discharge they produce). In general flash floods in a wadi channel with a smaller upstream drainage area are shorter in duration than the wadi with a bigger drainage area. In figure I.1 the duration of the flow with a discharge of more than 4 m^3/s is plotted against the drainage area for all 28 main wadi channels for the 1975 and 2010 flash flood events without taking transmission losses into account. If transmission losses are taken into account the duration of the flow for every main wadi channel would be shorter.

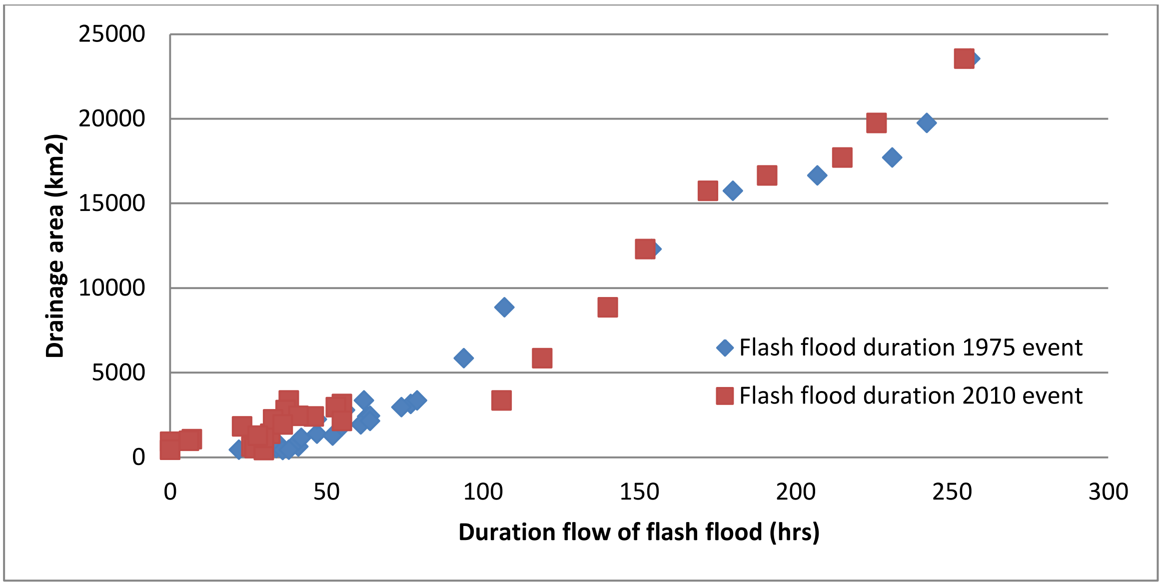


Figure I.1: Duration of flow higher than 4 m³/s due to the 1975 and 2010 flash floods without transmission losses (own illustration, 2017)

Potential Water Bearing Capacity (PWBC) transmission losses method

This method uses the soil thickness, the channels dimensions and the type of soil to estimate the total infiltration capacity of the wadi bed. This means that the calculated capacity is an estimate of the possible retention in the wadi bed under the contributing channel. The wadi bed thickness (D) is estimated using the thickness of the downstream wadi bed in section #. The dimensions needed are the length of the channel (L) and the width of the channel contributing to the flash flood (B). The effective porosity (p_e) is used to estimate the ratio of the total volume of the pores contributing to the water flow to the total ground volume.

$$V_{tot} = L * B * D * p_e$$

With

p_e = Effective porosity (-)

V_{tot} = Total capacity threshold volume (m^3)

L = Length channel (m)

B = Contributing width of the wadi channel (m)

D = Thickness channel (m)

The effective porosity (p_e) of coarse sand is 0,3 according to (Morris & Johnson, 1967), 0,22 according to (Heath, 1983) and 0,2 to 0,35 according to (Yu, Kamboj, Wang, & Cheng, 2015). A value of 0,27 is used in this research. The total capacity calculated is an indication of the water storable in the wadi bed which acts as a shallow aquifer.

Duration of wadi bed saturation

In the PWBC method it is assumed that the total wadi bed is saturated after a large flash flood event. Wheater (2005) describes field test that showed that wadi beds with depths between 2-20 m were saturated within 10 hours of flow. To check whether this also applies for the wadi beds in the El Arish watershed the Darcy equation is used to estimate the time it takes to saturate the entire wadi bed.

$$v = q/p_e$$

$$q = -K_{sat} * i$$

$$i = \Delta H / D$$

$$\Delta H = D + h$$

With

v	= Seepage velocity (m/s)
p_e	= Effective porosity (-)
q	= Water flux (m/s)
K_{sat}	= Saturated hydraulic conductivity (m/s)
i	= hydraulic gradient (-)
ΔH	= hydraulic head (m)
D	= Thickness of wadi bed (m)
h	= Water depth of flash flood (m)

Conservative estimates are made for every parameter, which will probably overestimate the time that it takes to the wadi bed to be saturated. Because the bed material is heterogeneous and air pockets can be present the hydraulic conductivity is estimated lower than in homogenous sand. The hydraulic conductivity is assumed to be saturated because figure I.2 shows that the infiltration rate becomes steady fast in similar conditions and thus $K_{sat} = 1 * 10^{-5} m/s$. This is an overestimation and figure I.2 shows that a dry soil infiltration rate is initially higher. The wadi bed thickness used for the calculation is the observed soil sample just south of El Arish City (3m), the water depth of the flash flood is assumed to be 0,5 m and the effective porosity is assumed to be 0,27. This gives a velocity of $4{,}3 * 10^{-5} m/s$ and within 20 hours the entire wadi bed is saturated, which is in the same order as suggested by Wheater (2005).

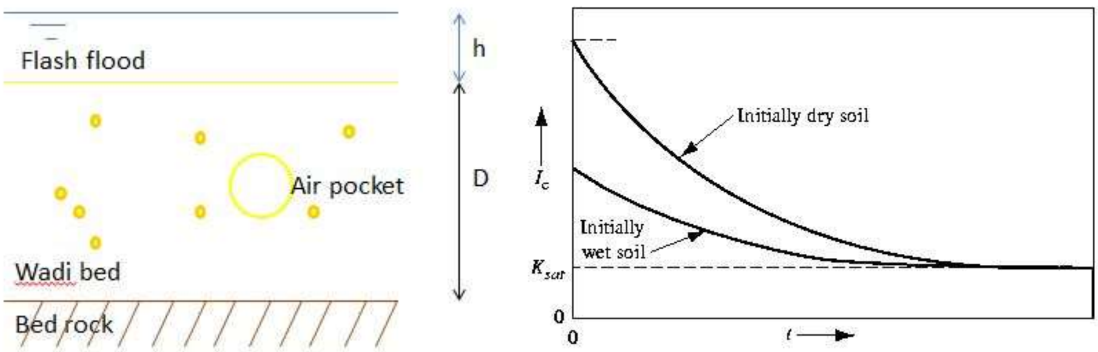


Figure I.2: Wadi bed simplification for the Darcy equation (own illustration, 2017) and the infiltration rate (Bear, 2000)

South Western Saudi Arabia(SWSA) transmission losses method

Wheater (2005) combined several observations in the south western part of Saudi Arabia to derive three simple equations. The two equations which can be used due to the needed input are described. These equations depend on the inflow volume of the wadi channel (V_{in}), the slope of the reach(s), the length of the channel(L) and the contributing channel width(B). Because these equations are fitted on the measurements from two measuring stations the lateral in- and outflow is included.

$$V_{tot} = 3{,}75 * 10^{-5} * V_{in}{}^{0{,}698} * s^{-0{,}865} * B^{0{,}497} * L$$

$$V_{tot} = 5{,}7 * 10^{-5} * V_{in}{}^{0{,}968} * s^{-1{,}049} * L$$

With

V_{tot}	= Total capacity threshold volume (m^3)
L	= Length channel (m)

B = Contributing width of the wadi channel (m)
D = Thickness channel (m)
V_{in} = Inflow volume into channel (10^3* m^3)
s = Slope of channel m (m/m)

The flash floods observed for the study of Wheater are mostly very low flows and were in small wadi channels and medium catchments (FAO, 2010). Thus the author warns that the calculated values cannot be generalised because of the limited experience with these equations.

Comparison between the methods

All the methods give an estimate on the total amount of the transmission losses threshold volume during a flash flood, based on the dimensions of the wadi channel which contributes to the flash flood. The main differences of the methods are the input parameters. The NCRS and both SWSA methods are dependent on output parameters of the HEC-HMS while the PWBC only depends on the characteristics of the contributing wadi bed. For a large flash flood as happened in 1975 for the same channel the results are of a similar order as seen in table I.2.

When a flash flood has a small magnitude the difference between the methods is profound: the results of the PWBC method stays the same (if the dimension of the contributing wadi channel stays the same) while the NRCS method gives a result which approaches infinity. The SWSA methods and the total transmission losses are larger than the wadi bed can store. This means that the amount of water that is needed before there is any flow downstream (the threshold value) of the wadi channel is out of proportion large. Consistent with the remark of FAO (2010) that the SWSA methods are suitable for smaller flash floods the methods give a low transmission loss for the event following 20 mm rainfall. In table I.2 the difference between the methods is shown for two different flash flood events in a channel with the same contributing wadi channel dimensions.

Table I.2: Transmission losses in channel Hasana 1.3.2 while the contributing channel stays the same and the duration is 48 hours (own illustration, 2017).

Method	V_{tot} (m^3) for 40 mm precipitation	Vtot (m^3/s) for 40 mm prec	V_{tot} (m^3) for 20 mm precipitation	V_{tot} (m^3/s) for 20 mm precipitation
NRCS	5.469.023	31,65	752.384.212	4354
PWBC	3.693.600	21,4	3.693.600	21,4
SWSA 1	9.304.476	53,85	644.619	3,73
SWSA 2	7.617.185	44,08	506.024	2,93

The large difference between the transmission losses of the NCRS method during the two events can partly be explained by the total inflow of the channel which determines the speed of the flash flood. When a large amount of water travels simultaneously through the wadi this will make the flow velocity high and this decreases the capability of the wadi bed to subtract water. When a flash flood is small and water travels slowly through the wadi the infiltration of the wadi bed will be larger. However the SWSA methods both depend on the inflow of water as well but are not as sensitive as the NCRS method.

In the two events from table I.2 the duration of the flash flood was both 48 hours, this is a realistic estimate for a flash flood in wadi Hasana 1.3.2. If the duration would have been shorter for example 4 hours, the methods would give the results shown in table I.3.

Table I.3: Transmission losses in channel Hasana 1.3.2 while the contributing channel stays the same and the duration is 4 hours (own illustration, 2017).

Method	V_{tot} (m^3) for 40 mm precipitation	Vtot (m^3/s) for 40 mm prec	V_{tot} (m^3) for 20 mm precipitation	V_{tot} (m^3/s) for 20 mm precipitation
NRCS	4.445.848	308,74	552.402	36,28
PWBC	3.693.600	256,5	3.693.600	256,5
SWSA 1	9.304.476	646,14	644.619	44,77
SWSA 2	7.617.185	528,97	506.024	35,14

Table I.3 shows that the capacity threshold parameter in the NRCS method depends on the amount- and duration of the inflow calculated in the HEC-HMS. The input parameters from the flash flood of 20 mm from HEC-HMS give a disproportional high threshold. The PWBC method estimates the storage in the wadi bed under the contributing width which is assumed to be filled during the flash flood event. This gives high values of the losses per second for flash floods with a short duration. The SWSA methods also give a total amount of water subtract from the flash flood, this causes a relative high loss per second. Because the SWSA methods depend on the inflow in the wadi the transmission losses per second in the small event is relatively small even with the small duration.

In table I.4 the contributing channel of the wadi is relative to the amount of precipitation that caused the flash flood while the duration is 48 hours.

Table I.4: Transmission losses in channel Hasana 1.3.2 with the contributing channel varying relative to the precipitation and a duration of 48 hours (own illustration, 2017).

Method	V_{tot} (m^3) for 40 mm precipitation	Vtot (m^3/s) for 40 mm prec	V_{tot} (m^3) for 20 mm precipitation	V_{tot} (m^3/s) for 20 mm precipitation
NRCS	5.469.023	31,65	61.564.887	356,28
PWBC	3.693.600	21,4	2.363.152	13,68
SWSA 1	9.304.476	53,85	510.335	2,95
SWSA 2	7.617.185	44,08	506.024	2,93

Results from table I.4 shows the effect of making the contributing channel relative to the precipitation preceding the event causes all the transmission losses to be smaller than if no variation is taken into account. The total transmission losses in the NRCS method for the smaller flash flood are still very high and thus the NRCS method seems not to be applicable for these. The addition of the varying contributing channel relative to the precipitation gives results that have a small effect on the SWSA methods and provides the necessary difference between the large and small flash flood transmission losses in the PWBC method.

The SWSA methods and NRCS method give a higher total transmission loss than is estimated to be the total storage capacity of the wadi bed for the larger flash flood. The SWSA methods are normally used for smaller flash floods and the overestimation of the total losses for the larger flash flood confirms this.

The assumption of no lateral in- or outflow could be the cause of (a part of) the difference. The SWSA methods are based on the fitting of losses between two measuring stations and lateral outflow is possible between these stations. A second reason might be that the PWBC uses the thickness of the wadi to calculate a maximum amount of water subtracted from the flash flood while the SWSA and NCRS methods do not take wadi thickness into account.

The PWBC method is the most stable if the flash flood has a longer duration while the SWSA methods can be used for a smaller flash flood. The duration of the flash floods in the main wadis can be assumed to last long because the hydrological model will be used to simulate large flash floods and the El Arish watershed is big. Therefore the PWBC method will be used to simulate the transmission losses.

Input in HEC-HMS

In HEC-HMS the transmission losses are simulated with the constant loss rate, which specifies a constant amount of water subtracted by the wadi bed per second (m^3/s). The capacity threshold (V_{tot}) is however a total volume (m^3) that can be subtracted from a flash flood. To be able to simulate the transmission losses in HEC-HMS the capacity threshold needs to be divided by the total time water is subtracted from the flash flood to get the constant loss rate. It is estimated that the wadi bed downstream near El Arish is fully saturated within 20 hours. In table I.2 a 48 hour abstraction time was used to get an average transmission loss of 21,4 m^3/s in wadi Hasana 1.3.2. If this is used as input in the HEC-HMS model the transmission losses for wadi Hasana 1.3.2 would give the results from figure #.

The modelled transmission loss is the difference between the discharge with and without transmission losses in figure I.2. The peak of the modelled transmission losses in HEC-HMS is larger than the input given by the calculated transmission losses. This is because the results in the figure are the discharges at the end of the wadi. The wadi is 24 km long and water is subtracted over the whole length of the wadi this means that the wadi bed upstream already subtracts water and the flood wave takes more time to reach the end of the wadi channel.

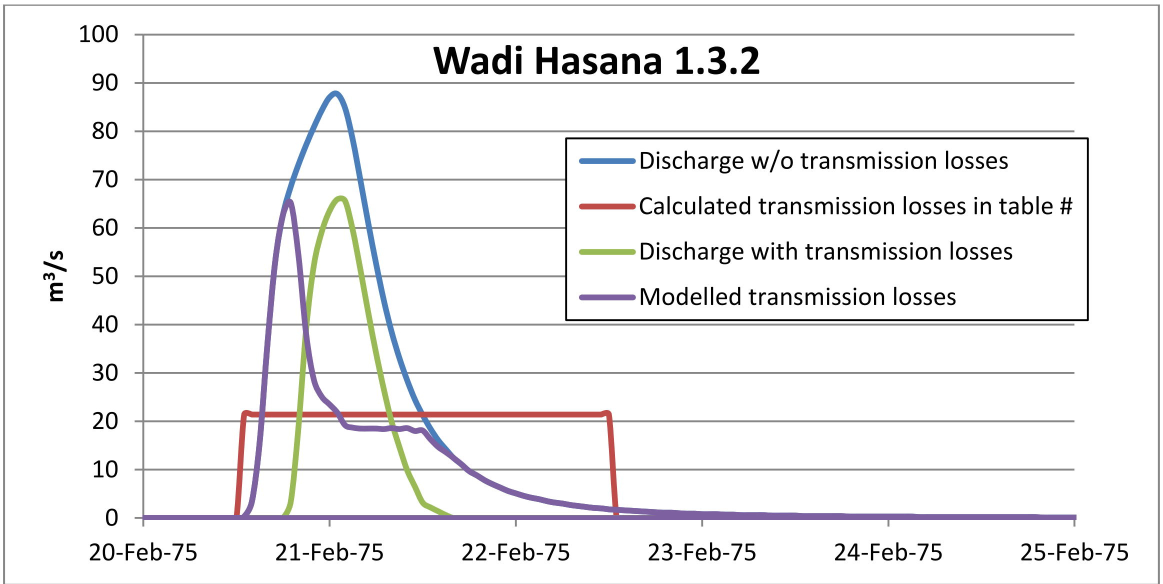


Figure I.2: Transmission losses calculated with the PWBC method in wadi Hasana 1.3.2 and how this is simulated in HEC-HMS (own illustration, 2017).

The duration of flow through the main wadi channel depends on the amount of upstream area which drains though the wadi channel as is shown in figure I.1 but is reduced due to the transmission losses as shown in figure I.2. The duration of the flow through a wadi channel is estimated by first simulating the 1975 flash flood without transmission losses. And then using that duration to calculate the transmission losses per second as is needed for the input for HEC-HMS.

In the downstream wadi channels the duration of the flow will be much longer than the calculated 20 hours it takes to fill the entire thickness of the wadi bed. Because the input of HEC-HMS is a constant rate this will cause an underestimation of the transmission losses at the beginning of a flash flood. While it will overestimate the transmission losses later on because the wadi bed is filled and only lateral outflow and seepage into the bed rock causes losses. This means that the hydrograph of downstream channels in HEC-HMS will have a higher peak discharge than realistically can be expected and that the flood will be there earlier than is expected. The total transmission losses of the wadi bed will however be the same if the assumed: bed thickness, contributing wadi bed width and duration are correctly estimated.

Per wadi channel the constant transmission losses are calculated. The contributing width and the duration of the flood depend on the magnitude of the flood. For a small flood the contributing width is smaller: the contributing width is in ratio with the precipitation intensity which caused the flash flood. The length of the channel, effective porosity and the depth of the wadi bed are constant regardless of the magnitude of the flood.

To account water already infiltrated in the wadi bed due to the precipitation, the initial loss (V_{loss}) of the wadi bed is subtracted from the transmission losses threshold.

$$V_{constant} = V_{tot} - V_{loss}$$

$$V_{loss} = P * B * L$$

V_{loss} = Initial loss (m^3)
L = Length channel (m)
B = Contributing width of the wadi channel (m)
P = Precipitation (m)

Results for different flash floods
In table I.5 the transmission losses for multiple events in the main wadi channels are shown.

Table I.5: Transmission losses for the 1975 and 2010 flash flood event

Wadi downstream of subbasin	Depth wadi bed (m)	contributing width 1975 (m)	duration 1975(hours)	transmission losses 1975 (m3/s)	Contributing width 2010 (m)	duration 2010 (hours)	transmission losses 2010 (m3/s)
Aqaba 1.1	2	300	63	18,7	188	46	16,4
Arish 1.1 & Hasana 1	3,2	250	256	4,5	156	254	2,9
Aqaba 1.1.1	1,8	250	41	14,1	156	26	14,8
Bruuk 1.1	2	400	77	8,4	250	55	7,5
Bruuk 1.1.1	1,8	350	55	26,0	219	23	40,4
Bruuk 1.1.1.1	1,6	250	34	4,6	156	0	0
Central 1	2,4	200	180	4,4	125	172	2,9
Central 1.1	2,2	1000	154	31,4	625	152	20,4
Gaifi 1.1	2,8	200	47	25,1	125	32	23,5
Gaifi 1.1.1	2,6	100	34	18,2	63	27	14,8
Hasana 1.1	3	350	62	12,2	219	38	12,8
Hasana 1.2	2,8	350	56	10,9	219	37	10,7
Hasana 1.3	2,6	300	47	15,0	188	33	13,8
Hasana 1.3.1	2,4	300	30	7,9	188	7	21,8
Hasana 1.3.2	2,4	250	48	21,4	156	48	13,7
Lake 1.1	2,6	1000	207	10,2	625	191	7,0
Quiriya 1	2,2	1000	74	17,9	625	53	16,0
Quiriya 1.1	2	500	64	13,6	313	41	13,5
Quiriya 1.1.1	1,8	350	41	11,1	219	6	48,7
Quiriya 1.1.1.1	1,6	350	22	29,1	219	0	0
Quiriya 1.1.2	1,8	200	38	23,3	125	0	0

Ruaq 1.1	1,8	300	94	8,5	188	119	4,3
Ruaq 1.1.1	1,6	300	79	6,2	188	106	3,0
Ruaq 1.1.1.1	1,4	250	61	12,7	156	36	14,5
Ruaq 1.1.1.1.1	1,2	200	42	5,8	125	30	5,7
Ruaq 1.1.2	1,6	300	64	6,7	188	55	5,1
Ruaq 1.1.2.1	1,4	250	52	19,9	156	28	25,1
Ruaq & Aqaba 1	2	300	107	3,7	188	140	1,8
Ruaffa 1	3	500	242	6,8	313	226	4,7
Ruaffa Dam	2,8	150	231	4,8	94	215	3,2

J. Input and results of the hydrological model

This appendix summarizes all the input from the loss method in appendix F, direct runoff in appendix G, the channel flow in appendix H and the transmission losses in appendix I. This input is used in the hydrological HEC-HMS method and the results from the HEC-HMS model for an event with a 2% yearly probability are shown. The input and results for the sub basins is shown in table J.1 for and table J.2 shows the input and results for the main wadi channels.

Table I.1: Input and output of the sub basins in HEC-HMS

Sub basin	Area(km^2)	Maximal channel length (km)	height difference (m)	Average slope(m/m)	Curve Number	Kirpich Lag time (minutes)	Peak discharge (m^3/s)
Aqaba 1	338,6	28	100	0,0036	81	272	2689,3
Aqaba 1.1	1763	69	400	0,0058	86	452	9381,0
Aqaba 1.1.1	632,9	57	450	0,0079	87	346	3805,5
Arish 1	308,9	43	120	0,0028	69	416	732,4
Arish 1.1	184,3	16	30	0,0019	60	226	46,1
Bruuk 1	158,4	20	40	0,0020	78	262	931,2
Bruuk 1.1	770	50	150	0,0030	80	454	5550,3
Bruuk 1.1.1	920,2	43	150	0,0035	78	382	5410,0
Bruuk 1.1.1.1	903,2	41	160	0,0039	80	352	6510,5
Bruuk 1.2	554,8	41	140	0,0034	85	371	6332,7
Central 1	501,2	30	70	0,0023	76	338	2365,2
Central 1.1	136,9	12	30	0,0025	77	162	722,7
Gaifi 1	269,5	30	65	0,0022	66	348	381,2
Gaifi 1.1	854,8	40	220	0,0055	77	303	5417,9
Gaifi 1.1.1	524,4	30	450	0,0150	86	165	7403,5
Hasana 1	268,9	30	40	0,0013	67	419	458,3
Hasana 1.1	554,2	33	140	0,0042	68	289	1121,1
Hasana 1.2	560	45	100	0,0022	75	470	2873,6
Hasana 1.3	745,6	38	130	0,0034	71	350	2355,1
Hasana 1.3.1	1058,6	49	270	0,0055	75	354	5432,1
Hasana 1.3.2	425,5	37	200	0,0054	85	287	4856,8
Lake 1	202	21	140	0,0067	82	171	478,9
Lake 1.1	595,7	28	50	0,0018	82	355	6029,1
Lake 1.2	305,2	54	600	0,0111	88	291	4484,5
Lake 2	866,7	38	360	0,0095	85	236	11287,6
Quiriya 1	503,8	34	140	0,0041	79	299	3285,5
Quiriya 1.1	1034,7	50	200	0,0040	83	407	9896,1
Quiriya 1.1.1	521,1	34	260	0,0076	82	235	4547,4
Quiriya 1.1.1.1	444	30	250	0,0083	74	207	1648,1
Quiriya 1.1.2	442,1	30	150	0,0050	86	252	5497,6
Ruaffa Dam	398	34	85	0,0025	72	362	1433,0
Ruaq 1	256,5	23	100	0,0043	79	217	1672,7
Ruaq 1.1	372,1	22	90	0,0041	80	214	2682,2
Ruaq 1.1.1	1411,4	75	560	0,0075	86	437	7508,0
Ruaq 1.1.1.1	792,1	46	430	0,0093	85	275	3715,5
Ruaq 1.1.1.1.1	1139,5	60	670	0,0112	87	315	6851,5
Ruaq 1.1.2	875,8	49	325	0,0066	81	330	2358,3
Ruaq 1.1.2.1	1262,4	56	640	0,0114	86	296	6715,1

Table J.2: Input and output of the main wadi channels in HEC-HMS

Main wadi channel	Through sub basin	length(m)	average slope (m/m)	bottom width(m)	Depth Wadi Bed (m)	Upstream drainage area (km2)	Transmission losses (m^3/s)	Peak discharge(m^3/s)
DR A 1.1	Aqaba 1	28200	0,0035	600	2	2395,9	16,9	113
R A 1.1 & H1	Arish 1	20000	0,0025	500	3,2	23547,2	6,9	660
R A 1.1.1	Aqaba 1.1	18600	0,0043	500	1,8	632,9	10,3	37
R B 1.1	Bruuk 1	11700	0,0009	800	2	3148,2	9,3	186
R B 1.1.1	Bruuk 1.1	33000	0,0021	700	1,8	1823,4	20,5	114
R B 1.1.1.1	Bruuk 1.1.1	5700	0,0026	500	1,6	903,2	2,8	70
R C 1	Lake 1.1	23200	0,0017	400	2,4	15733,8	6,3	611
R C 1.1	Central 1	31400	0,0019	2000	2,2	12286,9	38,6	427
R G 1.1	Gaifi 1	29700	0,0027	400	2,8	1379,2	21,3	82
R G 1.1.1	Gaifi 1.1	33700	0,0062	200	2,6	524,4	11,2	55
R H 1.1	Hasana 1	10100	0,0020	700	3	3343,9	13,6	109
R H 1.2	Hasana 1	8800	0,0011	700	2,8	2789,7	11,1	117
R H 1.3	Hasana 1	12800	0,0023	600	2,6	2229,7	12,7	101
R H 1.3.1	Hasana 1.3	4700	0,0032	600	2,4	1058,6	4,3	57
R H 1.3.2	Hasana 1.3	24300	0,0037	500	2,4	425,5	14,8	32
R L 1.1	Lake 1	11500	0,0022	2000	2,6	16634,7	17,0	625
R Q 1	Central 1	8600	0,0023	2000	2,2	2945,7	19,0	176
R Q 1.1	Quiriya 1	12500	0,0024	1000	2	2441,9	12,5	165
R Q 1.1.1	Quiriya 1.1	10500	0,0029	700	1,8	965,1	6,5	43
R Q 1.1.1.1	Quariya 1.1.1	16800	0,0042	700	1,6	444	11,5	13
R Q 1.1.2	Quiriya 1.1	35800	0,0039	400	1,8	442,1	12,7	40
R R 1.1	Ruaq 1	21600	0,0032	600	1,8	5852,4	8,2	369
R R 1.1.1	Ruaq 1.1	15000	0,0033	600	1,6	3342,5	5,0	69
R R 1.1.1.1	Ruaq 1.1.1	32900	0,0027	500	1,4	1931,5	8,4	595
R R 1.1.1.1.1	Ruaq 1.1.1.1	15500	0,0039	400	1,2	1139,5	3,8	637
R R 1.1.2.	Ruaq 1.1	13200	0,0053	600	1,6	2137,8	6,2	246
R R 1.1.2.1	Ruaq 1.1.2	44000	0,0055	500	1,4	1262	19,7	156
R R&A 1	Central 1.1	9400	0,0032	600	2	8843,4	3,5	117
R Ruaffa 1	Arish 1.1	15400	0,0019	1000	3	19750,1	11,9	86
R Ruaffa Dam reservoir	Ruaffa Dam	36800	0,0024	300	2,8	17703,4	8,4	74

K.HEC-RAS model

The hydraulic model uses the runoff calculated in the hydrologic model to simulate the hydrologic process channel flow. A hydraulic model represents the channel flow processes by mathematical generalizations, depending on the used spatial model.

In a **1D** hydraulic model the water level and velocity are calculated for each cross section of a channel. The channel is modelled as multiple cross sections in subsequence, linearly connecting the cross sections to one another. Due to elevation differences and the distance between the cross sections the channel flow can be calculated. The user defines the places where the cross sections are made and thus the amount of cross sections. This is a relative fast way to model the water levels and velocities. However for large complex watersheds the model needs a large amount of cross sections and a detailed flow route.

A **2D** hydraulic model calculates the water depth and the depth averaged velocity. It uses cells to spatially distribute the area of interest. Elevation of every cell is provided by a Digital Elevation Model (DEM) and with the elevation differences between cells the flow of water is modelled. By using a 2D model the flood maps are a direct output. The flow routes of water do not need to be known with this model, but need more computation power.

3D hydraulic model calculates the water depth and the velocity for every depth. This is used for sediment modelling, flows around structures and for studies that need high amount of detail.

The 2D hydraulic model is best fit to model the El Arish watershed because it answers the research question: where are the current hazards.

The 2D flow area is chosen by the user and defines the boundary for which 2D computations will be done. The flow area is given a bed resistance parameter, which is defined with the Manning coefficient. This coefficient is assumed to be uniform in the flow area and consistent with the value used for channel flow in HEC-HMS. For the flow area a grid size is chosen for which every computation is made, which decides the precision of the results and the computation time of the model. The flow area is based on the area where flow is expected to be, thus by the DEM. 2D boundary conditions describe the inflow (or outflow) of the 2D flow area. This means that at the edge of the 2D flow area data of the discharges into the area are needed. The input needed is the output of the HEC-HMS.

The computation interval of the Saint Vernant and Diffusion wave depend on the chosen grid size. For the Saint Vernant or full momentum equation simulation to be stable, the computation interval needs to be:

$$\Delta T \leq \frac{\Delta x}{v}$$

For the diffusion wave equation simulation to be stable, the computation interval needs to be:

$$\Delta T \leq \frac{2\Delta x}{v}$$

Where ΔT is the computation time step (s), Δx is the average cell size (m) and v the flood wave velocity (m/s). Larger computation steps can be used with the diffusion wave. The diffusion wave however does not take local acceleration (changes in velocity with respect to time) and convective acceleration (changes in velocity with respect to space) into account. Terms which are important for rapidly rising flood waves like flash floods.

L. Calibration and sensitivity analysis of the hydrological model

A short description of the attempt to calibrate the hydrological model is done in paragraph 4.3.1 in this appendix the results are shown more extensively. The conceptual hydrological model and the lack of measurements mean that the model cannot be calibrated, but the calibration attempt gave input for the sensitivity analysis.

The sensitivity of the hydrological model is summarized in paragraph 4.3.2 while the analysis and more extensive results are discussed in this appendix. Table L.7 at the end of this appendix shows all the results from the sensitivity analysis.

The parameters that are used in the hydrological model and for the analysis are divided into the measurable and the non-measurable parameters. Measurable parameters are length of the wadi channel, width of the wadi bed, average slope of the wadi channel and precipitation. In this appendix only the precipitation is analysed for the measurable parameters because of the high uncertainty it has. The non-measurable parameters used in the hydrological model are the curve numbers, lag time, wadi bed roughness and the transmission losses.

Calibration of the hydrological model

The hydrological model cannot be calibrated because of the lack of measurements: there is only one flash flood measured and the precipitation that caused that event is a bandwidth of 40-50 mm. The measurement of this event is shown in figure L.1.

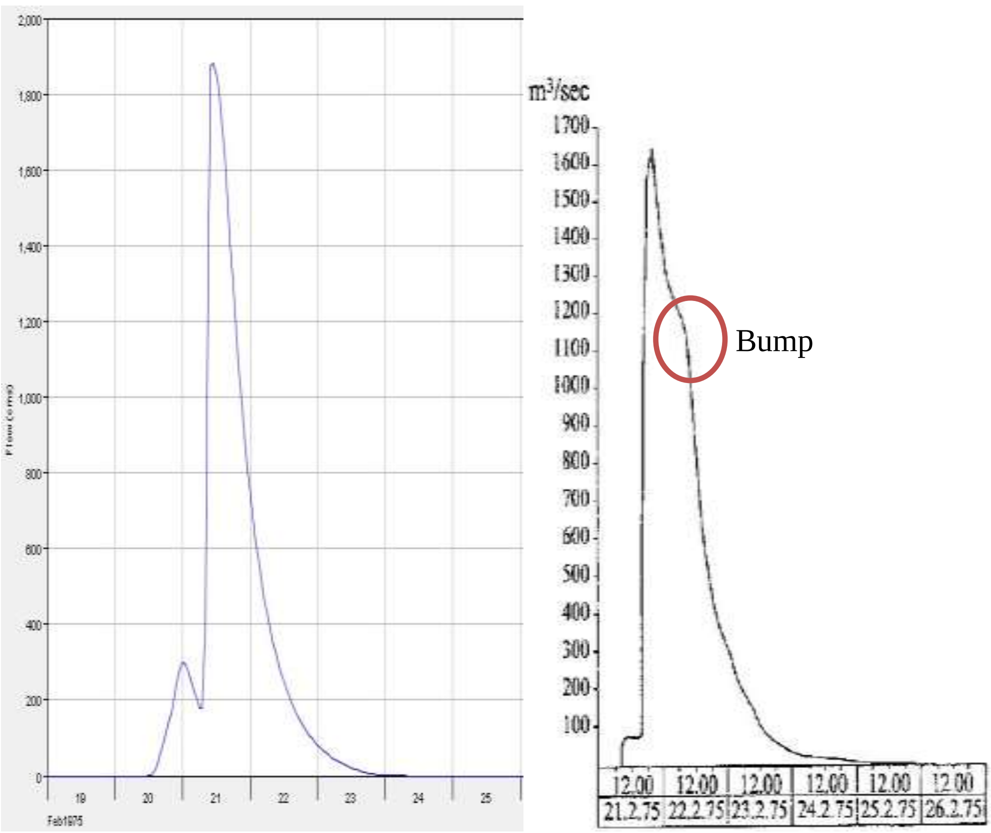


Figure K.1: Results from the HEC-HMS simulation (left) and the measured event at the Ruaffa Dam(right)

The earlier start- and earlier end of the discharge (the duration of the flow at the Ruaffa Dam is similar) in the simulated event could have a very simple reason: the storm moved from the south to the north. Klein (2000) describes that the storm advanced from the southern Sinai to the northeast towards Eilat and gained in strength throughout the 20^{th} of February. This means that the assumption of a uniform distribution over time and space could cause the shift of the hydrograph.

The bump in the tail of the measured hydrograph could be caused by the uniform distribution of the rainfall as well. The measured event had a different rainfall pattern and can therefor cause the bump flood wave to arrive a little later than the other parts of the watershed. However this could also be caused by the narrow gorges upstream acting as a natural barrier slowing down the flood wave.

The peak discharge is higher in the simulation than in the measurement which could be caused by the rainfall being uniformly distributed in the simulation as well. If the flood wave bump in the measured hydrograph arrives at the Ruaffa Dam in the simulation at the same time as the rest of the peak this could explain the higher peak discharge and the lack of the bump in the simulation. However the low assumed precipitation for the simulation (40 mm) compared to the estimated average precipitation of 40-50 mm by Klein (2000) would suggest a higher peak discharge in the measurement. The peak discharge can also be influenced by the lag time or wadi bed roughness.

The total discharge in the simulation and measurement is almost the same, a negligible difference given all the uncertainties. This could indicate a correct estimate of the CN, the bed roughness of the wadi and the transmission losses. But because the assumed precipitation is the lowest value of the 10 mm range proposed by Klein (2000) this could also cause an underestimation of the CN and/or the transmission losses.

Sensitivity analysis of the hydrological model

To assess the influence of the potential bias in the estimated values of the parameters in the hydrological model the sensitivity is analysed. This is done for measurable parameter precipitation and for the non-measurable parameters roughness of the wadi bed, lag time, curve number and transmission losses.

Roughness of the wadi bed is expressed with the Manning coefficient. Initially a value of 0,03 was used, to analyse the influence the roughness coefficient has on the hydrological model a simulation is done with 0,02 (lowest value for natural channels) till 0,1 (highest value for natural main channels which are very weedy with deep pools).

The higher Manning coefficient causes the water to slow down, causing more transmission losses, a longer flow of water at the Ruaffa Dam and a lower total discharge. The lower Manning coefficient decreases transmission losses, decreases the amount of time water flows at the Ruaffa Dam and gives a higher total discharge. In figure L.2, the initial (0,03), lowest possible (0,02) and highest possible (0,1) Manning coefficient are used to show the effect of the roughness of the wadi bed has on the hydrograph. In table L.1 results from the sensitivity analysis on the bed roughness are depicted.

Reasonable estimates for wadi bed roughness are Manning coefficient values around 0,035 - 0,04 (FAO, 2010) and 0,015 and 0,05 according to Milewski et al.(2009). The main wadis valleys have a lower n value (Milewski, et al., 2009) and therefore the value of 0,035 is used for simulations in the rest of the research.

Table L.1: Influence of change of roughness

	Initial n=0,03	n=0,02	n=0,035	n=0,1
Whole watershed trans losses (%)	10,5	9,6	11,3	14,4
Whole watershed discharge (%)	13,5	14,3	12,6	9,4
Whole watershed losses due CN (%)	76,0	76,2	76,2	76,2
Peak discharge at Ruaffa Dam(m^3/s)	1880	2126,6	1737,7	886,5
Change peak discharge irt initial value (%)	-	13,1	-7,6	-52,8
Total discharge at Ruaffa Dam(m^3)	1,21E+08	1,26E+08	1,14E+08	8,44E+07
Change total discharge irt initial value (%)	-	4,3	-5,7	-30,2

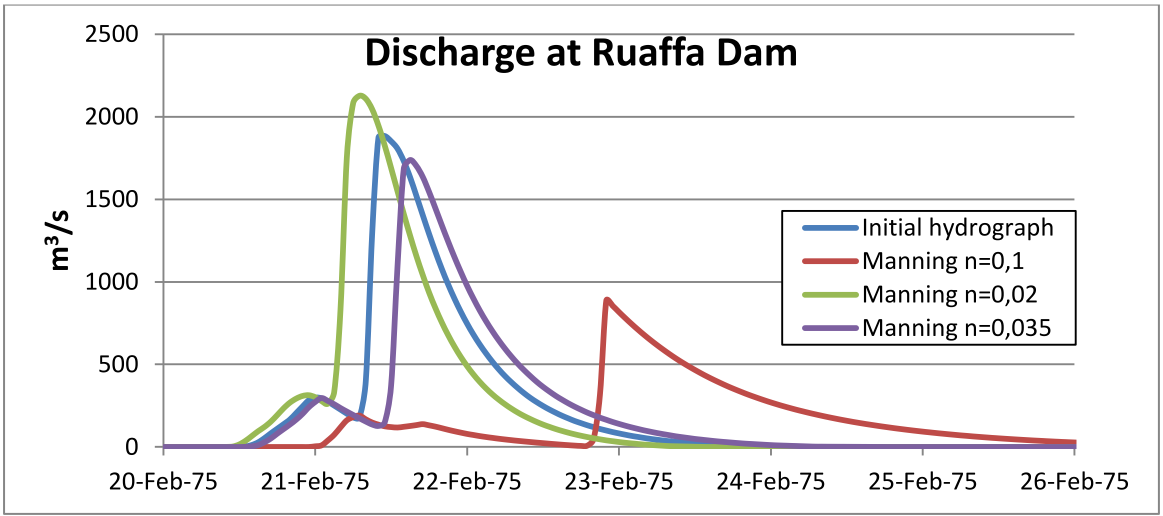


Figure L.2: The initial (0,03), lowest possible (0,02), highest possible(0,1) and adapted (0,035) Manning coefficient for natural main channels.

The lag time is based on the empirical Kirpich method describing the time it takes precipitation to fall until reaching the outflow of a sub basin. The lag time depends on the longest channel in the sub basin and the average slope of that channel as described in appendix G. The initial values are increased by 20% and 100% and decreased with 20% to see the effect it has on the hydrograph at the Ruaffa Dam.

With a higher lag time the hydrograph gets flatter: a lag time increase of 100% causes a peak flow decrease of 18% while the total discharge decreases with 7% and the time of peak is later as shown in figure L.3 and table L.2. A lower lag time shows a contrary but equal change. The lag time has a small influence on the hydrograph and is not altered because of the sensitivity analysis.

Table L.2: Influence of change in lag time

	Initial	Lag time +20%	Lag time -20%	Lag time +100%
Whole watershed trans losses (%)	10,5	10,3	10,7	11,4
Whole watershed discharge (%)	13,5	13,6	13,2	12,4
Whole watershed losses due CN (%)	76,0	76,2	76,2	76,2
Peak discharge at Ruaffa Dam(m^3/s)	1880	1987,2	1822,8	1537,2
Change peak discharge irt initial value (%)	-	5,7	-3,0	-18,2
Total discharge at Ruaffa Dam(m^3)	1,21E+08	1,21E+08	1,19E+08	1,13E+08
Change total discharge irt initial value (%)	-	0,3	-1,9	-6,9

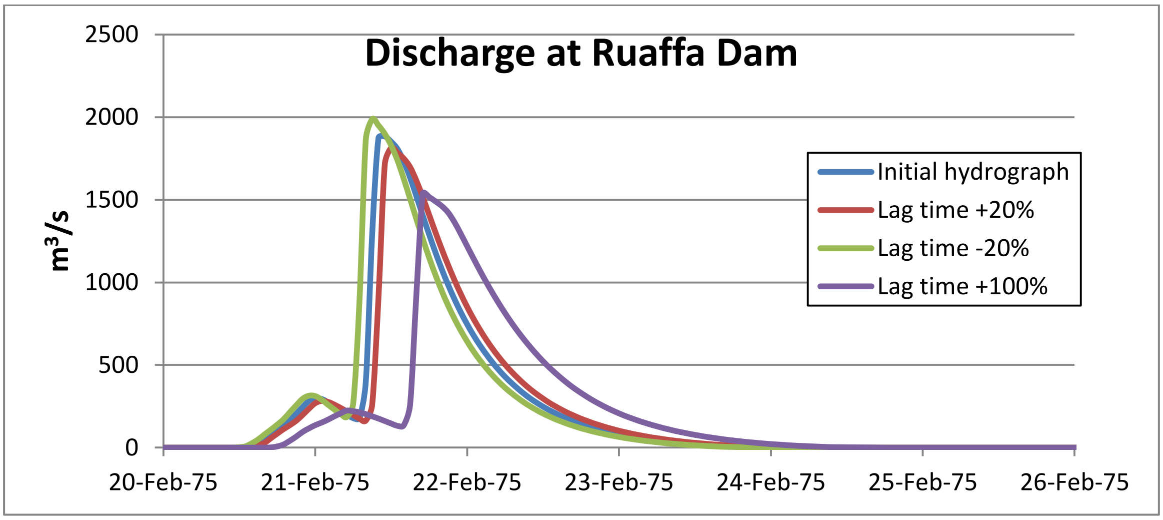


Figure L.3: Hydrograph of different lag time values

Curve numbers are based on soil type, land use and treatment, and antecedent watershed moisture. The values are averaged over a sub basin and are based on the classification of the different soil types and land use (dry conditions are assumed in the Sinai) as discussed in appendix F. These classifications are based on guidelines and can be rough estimates, to test the effect of the possible mistakes in estimating the CN of sub basins a 5% in- and decrease is used. To show the effect of a different soil group, the soil groups which were initially group D (lowest infiltration capacity) are changed to group C (somewhat better infiltration capacity) and another shows the changes caused by the shifting HSG from A (best infiltration capacity) to B (less infiltration capacity).

Another classification of HSGs for the soils in the El Arish watershed would have a big influence on the hydrograph in the Ruaffa Dam. A higher CN will cause a faster runoff of a larger part of the precipitation. The change of the wadi deposits and sand dunes from HSG A to HSG would increase the average CN of the sub basins and therefore would increase the peak discharge, the total discharge and the flow would reach the Ruaffa Dam earlier. A change of classification of the (almost) bare rock dominating the largest part of the watershed from a D type soil to type C soil would do the opposite. The results of the changes in CN and HSG for the hydrograph are in figure L.4 and in table L.3. The influence of the CN on the hydrological model is high and therefore it is sensitive to the derivation of the soil type and land-use.

The sensitivity of the model due to the CN does not cause any need to change the CN or its derivation. The HSG seems to be chosen correctly and the derived CN seems to be in the right range to simulate the conditions in the El Arish watershed. The range of the CN and the derived HSG is in accordance with similar studies from Milewski et al. (2009), Foody et al. (2004), El-Sayad (2012) and El-Washah & El-Khoury(1999).

Table L.3: Influence of changes in HSG and thus CN and CN

	Initial	CN -5%	CN +5%	HSG D to C	HSG A to B
Whole watershed trans losses (%)	10,5	9,4	11,4	9,8	11,4
Whole watershed discharge (%)	13,5	7,0	22,8	9,5	20,2
Whole watershed losses due CN (%)	76,0	83,6	65,8	80,7	68,4
Peak discharge at Ruaffa Dam(m^3/s)	1880	1150	2840	1450	2510
Change peak discharge (%)	-	-38,8	+51,1	-22,9	+33,5
Total discharge at Ruaffa Dam(m^3)	1,21E+08	6,77E+07	1,98E+08	8,68E+07	1,60E+08
Change total discharge (%)	-	-44,1	+63,2	-28,3	+32,5

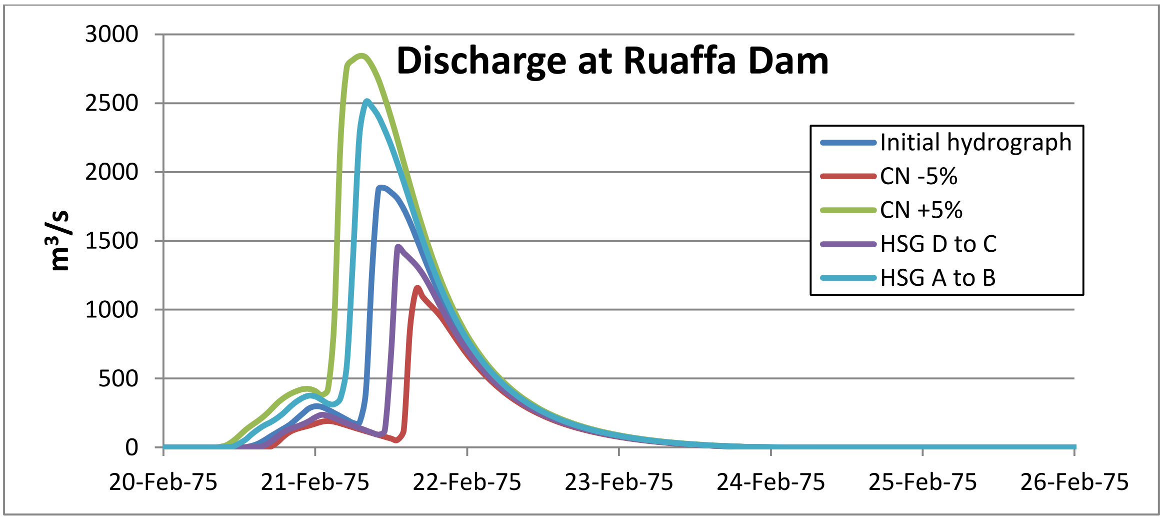


Figure L.4: Hydrograph of different CN at the Ruaffa Dam

Transmission losses are the losses in the main wadi channels due to the infiltration in the thick alluvial wadi beds. These main wadi channels connect the sub basins of the El Arish watersheds and they subtract a constant amount of water from the flood in the channel based on the thickness of the wadi bed, the width of the wadi, the length of the channel, the duration of the flow and the intensity of the flash flood. These parameters are merged to the contributing wadi bed and the duration of the flow as is described in appendix I. To assess the sensitivity of the hydrological model due to the transmission losses the contributing wadi bed and the duration are in- and decreased by 20%.

Changing the contributing wadi bed with 20% has small influence on the discharge at the Ruaffa Dam. Therefore an increase of 50% and 100% is also applied as can be seen in figure L.5. The large bandwidth used in the simulation is fitting for the multiple estimates made considering the contributing wadi bed parameter. The increase of the contributing wadi bed with 100% decreases the total discharge with 22% as can be seen in table L.4 and thus bias in transmission losses do not have a large impact on the hydrologic model.

If the duration of the flow in the wadi decreases the total discharge decreases as well as is shown in figure L.6 and table L.4. This is counter intuitive because it might be expected of a shorter flash flood to decrease the transmission losses and thus increasing the total discharge. This is however not the case because of the method used to estimate the transmission losses. The PWBC estimates the potential water bearing capacity of the wadi bed and uses the duration of the flow to calculate the average losses (m3/s). The duration is estimated by using the hydrological model without transmission losses as is explained in appendix I.

Table L.4: Influence of the contributing wadi bed and the duration of the flow

	Initial	CW -20%	CW +20%	CW +50%	CW +100%	Duration -20%	Duration +20%
Transmission losses (%)	10,5	8,5	10,7	12,1	14,3	10,9	8,8
Discharged (%)	13,5	15,5	13,3	11,9	9,7	13,1	15,2
Losses due CN (%)	76,0	76,0	76,0	76,0	76,0	76,0	76,0
Peak discharge (m^3/s)	1880	1963,8	1832,2	1739,2	1573,9	1829,6	1956,4
Change peak discharge (%)	-	4,5	-2,5	-7,5	-16,3	-2,7	4,1
Total (m^3)	1,21E+08	1,36E+08	1,21E+08	1,10E+08	9,43E+07	1,19E+08	1,35E+08
Change total discharge (%)	-	12,2	0,0	-9,2	-22,1	-1,8	11,2

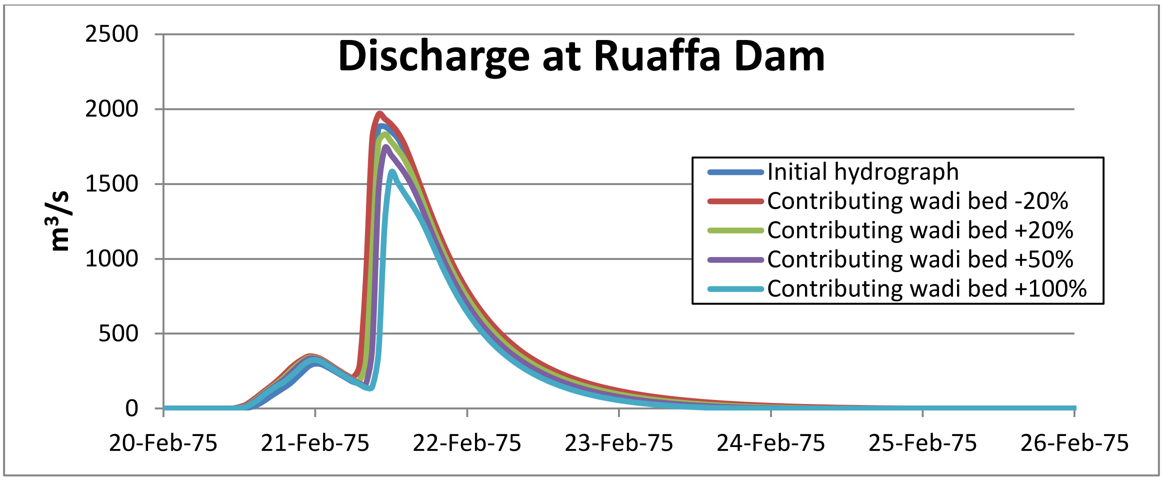


Figure L.5: Hydrograph of different contributing wadi beds for the transmission losses

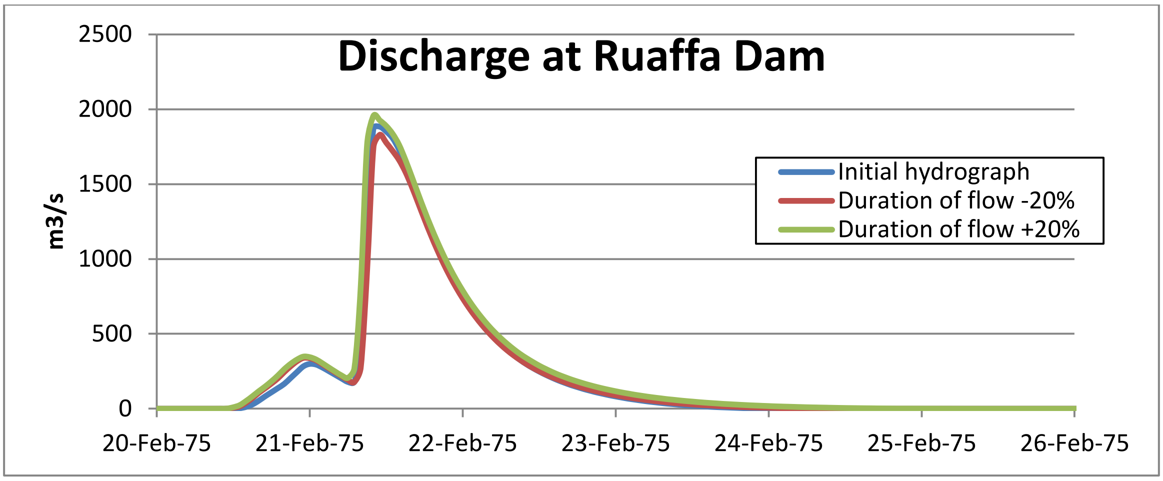


Figure L.6: Hydrograph of different duration of flow for the transmission losses

Precipitation is a measurable parameter but due to the low amount of rain gauges and the underestimation of the TRMM is still affected by uncertainty which is discussed in appendix E. The precipitation that caused the flash flood in 1975 was estimated to be between 40 and 50 mm on average in the El Arish watershed. To simulate the event 40 mm of precipitation is assumed in 30 hours and with the sensitivity analysis the potential bias is tested. Totals of 35, 45 and 50 mm in 30 hours are used to assess the sensitivity of the model on precipitation amounts.

Duration of 24 and 36 hours is used with the initial 40 mm to analyse the effect of the precipitation time on the model. This does implicate that the precipitation intensity is higher in the 24 hour test than in the 36 hour test.

The main drainage direction of wadi El Arish is northward, to assess the impact of the storm movement a norward- and southward moving storm is simulated. The northward moving storm begins 6 hours earlier in the southern precipitation region than in the middle precipitation region. The northern region begins 6 hours later than the middle region. For the southward moving storm the opposite is used.

Change in the amount of precipitation has a large influence on the hydrograph at the Ruaffa Dam. With a higher amount of precipitation the peak- and total discharge increases. The flood is also earlier at the Ruaffa Dam because the velocity of the flood wave is higher with more water. But also because of the mechanism of the CN: the loss rate gets lower when more water is already lost. The results of the sensitivity analysis for the amount of precipitation are shown in figure L.7 and table L.5.

The duration of the precipitation influences the hydrograph as well, with a shorter duration and thus a higher intensity the water will reach the Ruaffa Dam faster. And causes a more peaked hydrograph, the reverse is true for a longer duration. The difference between the total discharges is small and is caused by the lower velocity of the water and thus the increase of transmission losses. The results of the change in duration of the precipitation are shown in table L.6 and figure L.8

The effects of the direction of the storm are clear from figure L.9: the storm moving in the same direction as the main drainage direction of wadi El Arish causes an increase of peak discharge of around 20%. The difference of total discharge is caused by the flow velocity in the wadi beds. With a higher discharge the flow velocity is higher than with a lower discharge and a lower flow velocity causes a higher transmission loss.

Table L.5: Effects of the use of different precipitation amounts

	Initial (40 mm)	35 mm in 30 hrs	45 mm in 30 hrs	50 mm in 30 hrs
Whole watershed trans losses (%)	10,5	10,9	9,9	9,3
Whole watershed discharge (%)	13,5	9,2	17,7	21,6
Whole watershed losses due CN (%)	76,0	79,9	72,4	69,1
Peak discharge at Ruaffa Dam(m^3/s)	1880	1289,6	2600	3364,1
Change peak discharge (%)	-	-31,4	+38,3	+78,9
Total discharge at Ruaffa Dam(m^3)	1,21E+08	7,64E+07	1,72E+08	2,27E+08
Change total discharge (%)	-	-36,9	+42,0	+87,6

Table L.6: Effects of the duration (intensity) of the precipitation and the direction of the storm

	Initial	40 mm 24 hrs	40 mm in 36 hrs	North to South	South to North
Whole watershed trans losses (%)	10,5	10,3	10,6	11,0	10,3
Whole watershed discharge (%)	13,5	13,7	13,4	13,0	13,7
Whole watershed losses due CN (%)	76,0	76,0	76,0	76,0	76,0
Peak discharge at Ruaffa Dam(m^3/s)	1880	2100,7	1704,3	1726,7	2272
Change peak discharge (%)	-	11,7	-9,3	-8,2	20,9
Total discharge at Ruaffa Dam(m^3)	1,21E+08	1,23E+08	1,21E+08	1,18E+08	1,23E+08
Change total discharge (%)	-	1,4	-0,1	-2,2	1,8

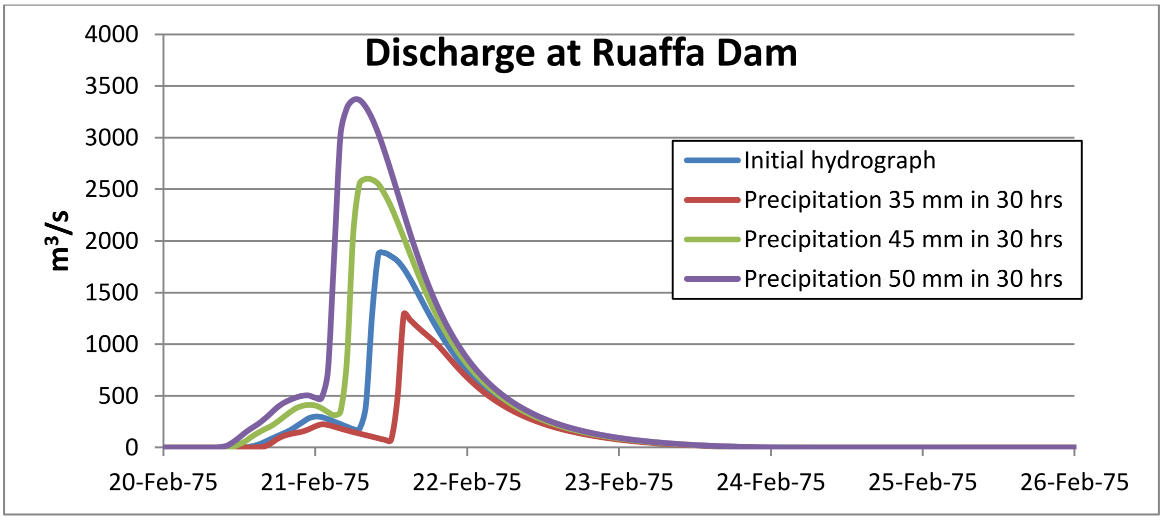


Figure L.7: Hydrograph of different precipitation amounts at the Ruaffa Dam

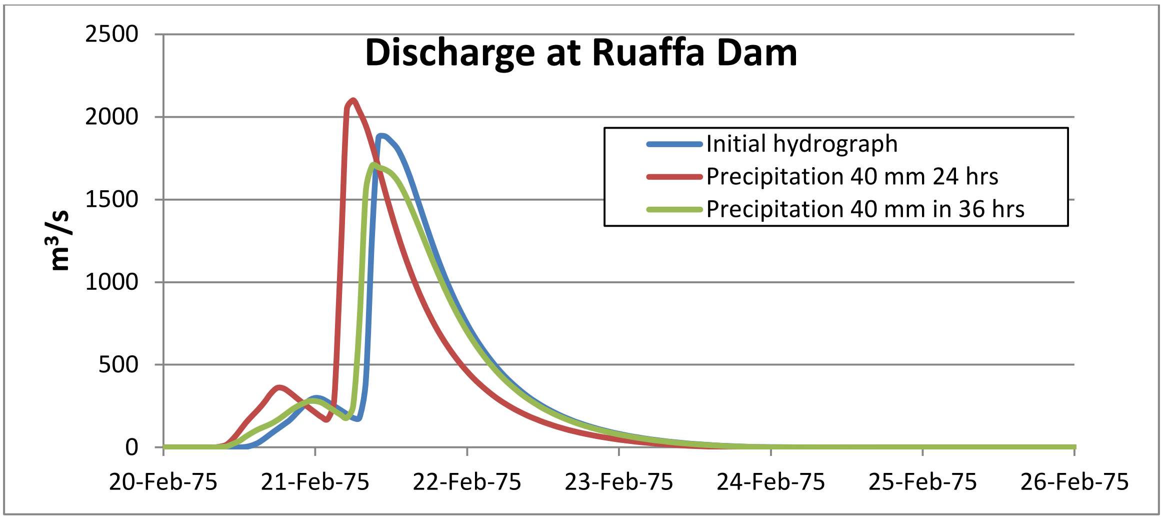


Figure L.8: Hydrograph of different precipitation duration and intensity at the Ruaffa Dam

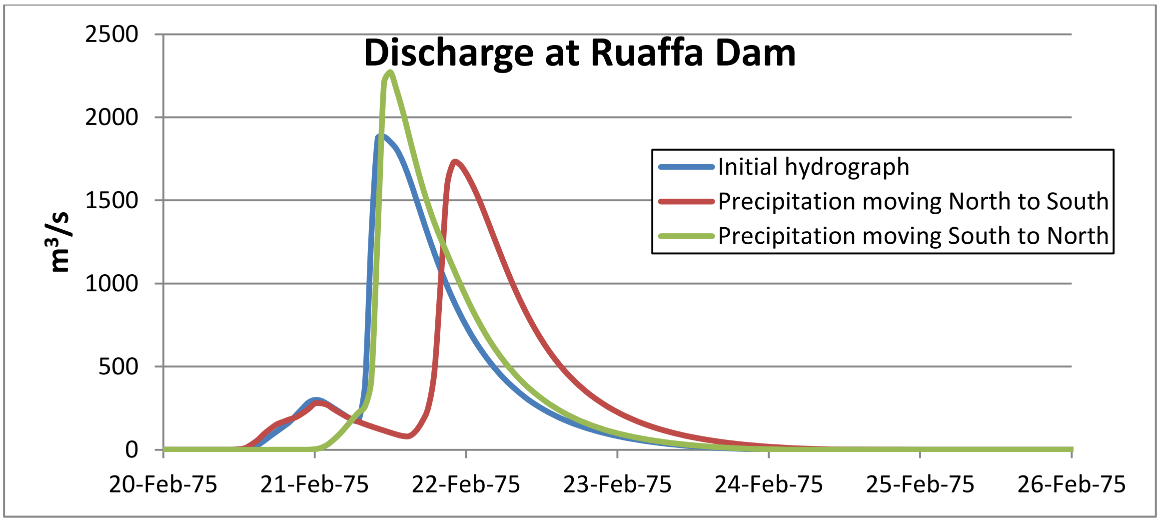


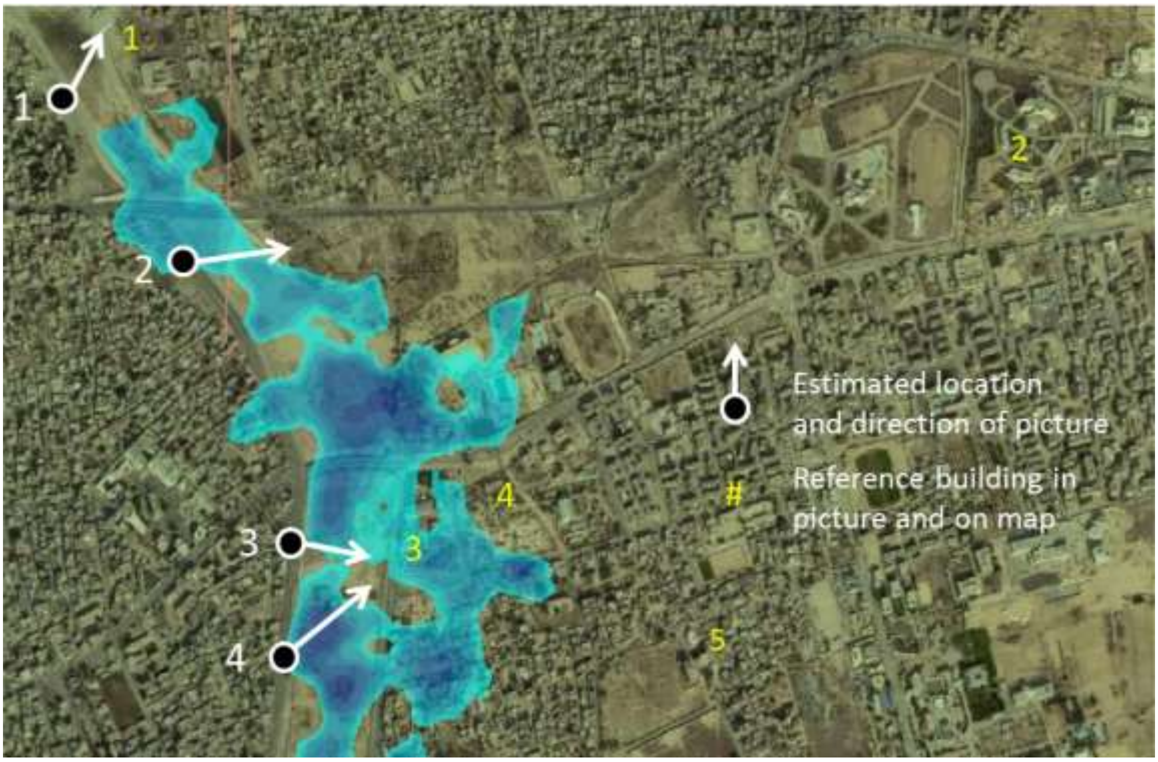
Figure L.9 Hydrograph of the effects of different storm directions at the Ruaffa Dam

Table L.7: Results from the sensitivity analysis

	Whole watershed transmission losses (%)	Whole watershed discharge (%)	Whole watershed losses due CN (%)	Peak discharge at Ruaffa Dam(m3/s)	Change peak discharge irt initial value (%)	Total discharge at Ruaffa Dam(m3)	Change total discharge irt initial value (%)
Initial	10,5	13,5	76,0	1880	-	1,21E+08	-
Manning n=0,02	9,6	14,3	76,2	2126,6	13,1	1,26E+08	4,3
Manning n=0,035	11,3	12,6	76,2	1737,7	-7,6	1,14E+08	-5,7
Manning n=0,1	14,4	9,4	76,2	886,5	-52,8	8,44E+07	-30,2
Lag time +20%	10,3	13,6	76,2	1987,2	5,7	1,21E+08	0,3
Lag time -20%	10,7	13,2	76,2	1822,8	-3,0	1,19E+08	-1,9
Lag time +100%	11,4	12,4	76,2	1537,2	-18,2	1,13E+08	-6,9
CN -5%	9,4	7,0	83,6	1150	-38,8	6,77E+07	-44,1
CN +5%	11,4	22,8	65,8	2840	51,1	1,98E+08	63,2
HSG D to C	9,8	9,5	80,7	1450	-22,9	8,68E+07	-28,3
HSG A to B	11,4	20,2	68,4	2510	33,5	1,60E+08	32,5
CW -20%	8,5	15,5	76,0	1963,8	4,5	1,36E+08	12,2
CW +20%	10,7	13,3	76,0	1832,2	-2,5	1,21E+08	0,0
CW +50%	12,1	11,9	76,0	1739,2	-7,5	1,10E+08	-9,2
CW +100%	14,3	9,7	76,0	1573,9	-16,3	9,43E+07	-22,1
Duration -20%	10,9	13,1	76,0	1829,6	-2,7	1,19E+08	-1,8
Duration +20%	8,8	15,2	76,0	1956,4	4,1	1,35E+08	11,2
Precipitation 35 mm in 30 hrs	10,9	9,2	79,9	1289,6	-31,4	7,64E+07	-36,9
Precipitation 45 mm in 30 hrs	9,9	17,7	72,4	2,60E+03	38,3	1,72E+08	42,0
Precipitation 50 mm in 30 hrs	9,3	21,6	69,1	3,36E+03	78,9	2,27E+08	87,6
Precipitation 40 mm 24 hrs	10,3	13,7	76,0	2100,7	11,7	1,23E+08	1,4
Precipitation 40 mm in 36 hrs	10,6	13,4	76,0	1,70E+03	-9,3	1,21E+08	-0,1
Prec N to S	11,0	13,0	76,0	1726,7	-8,2	1,18E+08	-2,2
Prec S to N	10,3	13,7	76,0	2,27E+03	20,9	1,23E+08	1,8

M. Comparison with the imagery of the 2010 flash flood event

In this appendix pictures and stills from the 2010 flash flood are compared to the simulation of the 2010 event in HEC-RAS in section 4.4.



M.1 Estimated locations of pictures in El Arish City and buildings in pictures (own illustration, 2017)

The map the results of the HEC-RAS simulation are shown on is a Google satellite image from 2015. Some of the buildings seen in the pictures from the 2010 flash event are destroyed since then and the other way around some buildings in the overview in figure M.1were not build in 2010.

First estimated location of the picture is in figure M.2, the buildings in the pictures are next to the beach and are marked with a 1 in the overview and in the picture. The flow in the video this image was taken from shows a flow velocity of around 1 m/s derived from the matrasses that were floating by.

The second picture in figure M.2 has a large amount of palm trees in the front of the picture and two large white buildings in the back of the picture. The buildings that fit this description are marked with a yellow 2 in the overview. The picture shows that the flash flood breeched the embankments of the wadi and flows between the palm trees consistent with the simulated event.

Picture 3 in figure M.3 shows a building still under construction marked with a 3, this is the same construction site as is depicted in picture 4. The white minaret in the picture is marked with a 5, but cannot be distinguished in the overview picture, the large building next to the 5 in the overview figure is not in figure M.3 because it was not build in 2010. The large transmission tower in picture 4 falls just out of the picture. This picture shows that the flash flood streamed into the city of El Arish, in the overview of the simulation the flood indeed inundated the city at the same point as on the picture.

Picture 4 in figure M.3 shows the same building as picture 3 from another angle. This picture was taken at the end of the day because the shadows are long and the sun comes from the behind the photographer (south west) explaining the colour difference in the two pictures. The transmission tower marked with a 4 in the picture and the overview is seen in the overview because of the long shadow it casts.

The four pictures/video stills that can be located show great similarity with the simulated flash flood event. However the simulation shows the maximal extend of the flash flood while the pictures can be made on another moment. Most probable pictures are taken on the moment that the flood was most impressive and thus at its peak, except if this happened during the night. The average flow velocity in the videos and simulation are of the same order.

Figure M.2: Pictures of the 2010 flash flood event from location 1 (left) and location 2 (right) (Choudhary, 2010)

Figure M.3: Pictures of the 2010 flash flood event from location 3 (left) from (Maowad, 2013) and location 4 (Gettyimages, 2010)

N.Measures to reduce flash floods

In this appendix measures to reduce flash floods are discussed. First the possible measures in the Sinai are researched from literature and projects in arid areas are used as reference. Secondly these measures are subdivided based on their applicability and the measures will be subjected to a Multi Criteria Analyses (MCA). Lastly the way these measures are modelled in HEC-HMS is discussed.

Possible flash flood reducing measures in the Sinai

This appendix describes possible measures which reduce the flash flood hazard. The measures which are considered need to be physical structures which can increase infiltration, by increasing vegetation cover, decrease velocity of flows and/or increase permeability. This can be in the form of structures to obstruct the flash flood in the wadi or water harvesting structures that prevent the hazard to form. There are numerous measures to reduce the flash flood hazard in the world, but not every measure is applicable in the Sinai. The Sinai is arid and thus another approach is needed than a flash flood in mountainous or humid environment. Therefore this research focuses on literature about similar arid regions around the world, as depicted in figure N.1. Studies of the Food and Agriculture Organization of the United Nations(FAO), International Water Management Institute (IWMI), and multiple individual research papers are used to create a composition of water harvesting measures. Water harvesting structures need to be applicable for an average yearly precipitation of 200 mm or less.

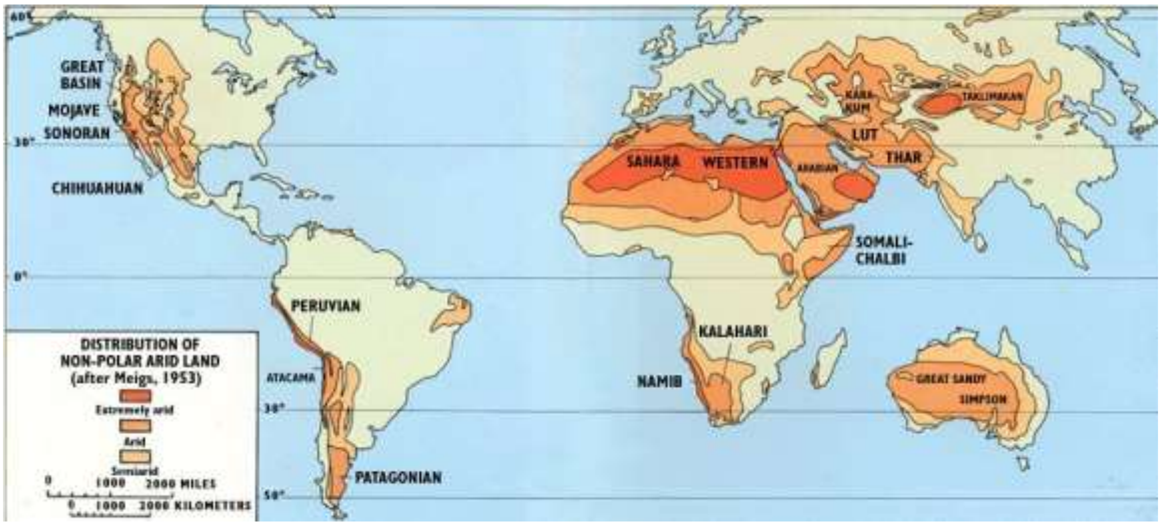


Figure N.1: Arid land world-wide or potential reference projects (USGS, 1997)

There are numerous historic and current practices of flash floods mitigation and water harvesting documented. In the rest of this appendix the measures considered for this research are discussed, given the requirements mentioned earlier.

The measures are divided into three categories based on the site of possible application: measures applicable in the wadi, measures appropriate for the land surrounding the wadi and measures that are non-structural.

Sediment catchers in the wadi

There are multiple measures considered which are applicable in the wadi bed and are all perpendicular to the wadi bed. The measures are used to capture sediment on the upstream side of the structure gradually filling the reservoir with sediment. This allows water to be stored beneath the soil which cause lower evaporation losses and risks of contamination of stored water are reduced. Direct contact with the air and animals is minimized and parasites cannot breed underground (Ertsen & Hut, 2009). Because of the lower evaporation, water can be stored for a longer period of time and could sustain agriculture even in very dry areas. The siltation upstream of the structures forms a thick layer of soil which becomes flat and is better suited for agriculture than its steep sloped counterparts. Soils reaching 1 m upstream of a sediment catcher would enable trees to survive a 2-3 years drought (Haiman, 2012).

Pervious sediment catchers are measures which trap sediment at the upstream side of the structure while allowing water to seep through. This allows the structures to be repaired and not cause a dam break in case of an extreme event. These measures are usually simple of design and are used frequently in history. The following measures are all of the pervious sediment type but used on a different scale and applied on different slopes and soil types.

Check dams are small stone or wooden dams usable on any kind of slope and soil type. Because of their small size they can only be used in small wadi channels. (Al Zayed, Ribbe, & Al Salhi, 2013; Critchly, Siegert, Chapman, & Finkel, 1991; Colombo, Hervas, & Arellano, 2002).

Terraced wadi system are used in mild sloped to flat wadis(<12%) in the El Arish watershed and in the Negev (remains of) these byzantine era terraces can be found. The whole width of the wadi is blocked by stone walls 1-2 m high. The terraced part of the wadi acts as a water harvesting area in a dry period and as a retention basin in case of a flash flood (Haiman, 2012).

Impervious sediment catchers are measures that block the natural stream of subsurface water and stores water underground for a longer period of time than its pervious counterpart. Because they are impervious they affect the downstream groundwater system and they need a spillway to allow an overflow of flood water to protect the structure from failure.

Jessour and Tabia systems are used for wadis with slopes of any steepness, the earthen 'tabia' dikes block the entire width of the wadi and are reinforced by stone 'sirra' walls made of stacked stones. This system was used extensively by the Romans in Libya on locations with an annual precipitation below the 50 mm, which makes the nickname of the 'granary of Rome' an even bigger accomplishment. When several Jessours are used in sequence over time a kind of terraced wadi is formed as shown in figure N.2 (Al Zayed, Ribbe, & Al Salhi, 2013; Prinz, 1996).

Sand dams are concrete, stone-masonry or clay dams and can be described as the modern version of the other sediment catchers mentioned before. The dams range from 1-4 m high and are used in relative small wadis. Recently they have been implemented frequently in Kenya and in other sub-Saharan counties with mixed succes. Falkenmark et al.(2001) says that the construction might be easy, but they relative complicated to design. This is because the location of the site, the design to avoid wrong siltation and leakages requires technical knowlegde and gives no room for trail-and-error. This caused an expert to claim that 80% of the sand dams are not preforming as they should, due to poor design (Ertsen & Hut, 2009).

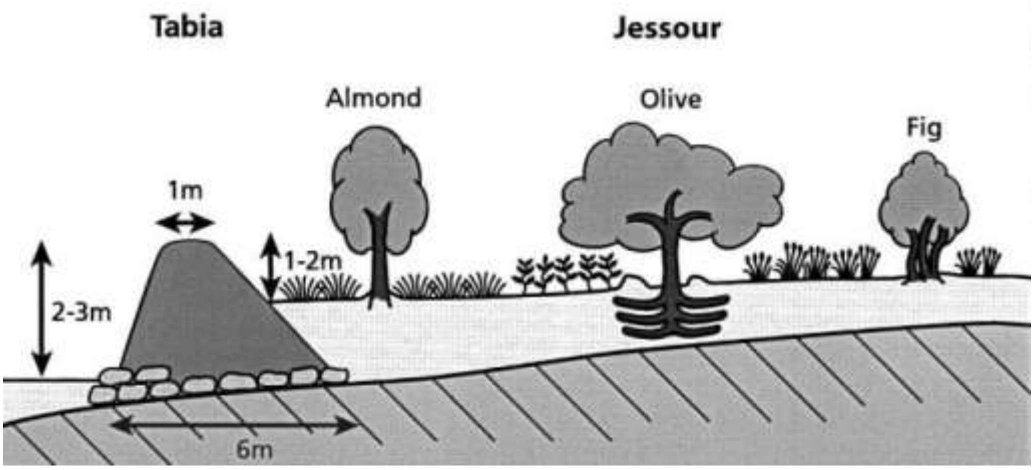


Figure N.2: The Tabia and Jessour construction (Hill & Woodland, 2003)

Water managing measures in the wadi
This paragraph describes measures that are used in the wadi to manage water on the upstream side of the measures. The measures are thus focused on stopping, slowing down or redirecting water preventing the water to flow downstream unhindered.

Percolation ponds or spreading dams divert water from the main wadi channel with large walls. These are 3-4 m thick and up to 5 m high because they need to withstand the force of the flash flood. When the water is diverted from the main channel smaller dams are used to spread the water over the rest of the wadi bed, slowing down the water (and thus the average slope is reduced) and allowing the water to infiltrate in the soil to recharge the groundwater as shown is figure N.3. The spreading of the water allows a larger area to benefit from the water which serves the vegetation, by spreading the water the water will evaporate quickly in the arid area of the Sinai. These spreading dams are frequently used in the El-Arish watershed throughout history (Haiman, 2012) and in Pakistan the same kind of spreading systems have been in use since ancient times (Prinz, 1996). A pervious soil and a relative flat bed (<2%) is needed for these spreading dams (Al Zayed, Ribbe, & Al Salhi, 2013; Critchly, Siegert, Chapman, & Finkel, 1991; Oweis, Hachum, & Kijne, 1999).

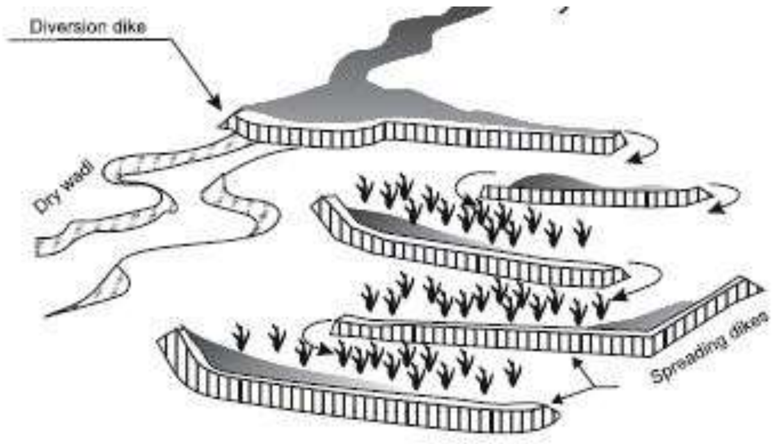


Figure N.3: Percolation pond or diversion dikes (Oweis, Hachum, & Kijne, 1999)

Obstacle dam are impervious low dams (less than 6 m) made of concrete which reduces the velocity of the flash flood allowing the water to infiltrate and is used in Egypt frequently. This measure is only usable when the wadi is flat to very mildly sloping and there is no space or reason to store water upstream. Because of the smooth surface of the dam and the mild slopes siltation will not occur upstream of the dam, a large discharge will erode the collected sediments (Abdel-Fattah, Kantoush, & Sumi, 2015).

Storage dams are impervious dams usually made out of concrete or bricks and the Ruaffa Dam is an example of a brickwork dam in the El Arish watershed. Due to the large amount of stored water upstream room is needed and some kind of spillway if the amount of water of a (flash) flood is larger than can be stored. An area should be chosen with a small slope upstream of the dam, making the dam more effective. The water stored upstream of the structure evaporates fast or is soaked into the ground depending on the soil. These dams provide an extra hazard: they can fail and cause a non-natural flash flood. These structures are therefore complex structures and need engineering expertise. (Abdel-Fattah, Kantoush, & Sumi, 2015). The scale of the dams can be chosen, Al-Weshah (1999) discusses that smaller dams have an higher impact on flash flood reduction.

Underground reservoirs store water beneath the surface to minimize evaporation, the soil or material which it is stored in should be as impermeable as possible to reduce losses. Cisterns are used since historic times while the modern equivalent is built from concrete or plastic. These underground reservoirs are frequently used in combination with water harvesting techniques or other water managing tools (Abdel-Fattah, Kantoush, & Sumi, 2015).

Measures appropriate around the wadi

These measures do not allow precipitation to reach the wadi itself, decreasing overland and channel flow and thus not allowing a flash flood to form. These measures work best in combination with small scale agriculture or planting of vegetation to retain soil and water. Usually these measures are referred to as water harvesting (WH) structures.

Contour ridges are small stone or earthen bunds slowing and filtering the runoff. Spacing the ridges some distance from each other on certain heights, contours are made hence the name. The ridges trap sediment but are only applicable on a soil that is at least 1,5 m thick to store enough water and allow plants to grow. These can be constructed on a slope ranging from 0 to 5% but are labour intensive if not mechanized. The needed earthwork depends on space between the ridges and the tie spacing as seen in figure N.4, but small compared to most of the multi shaped bunds. The contour ridges can be made with a large ploughing machine if made of earth this makes the construction fast and cheap. But because the machinery is expensive it also causes neglect if the local community does not have the tools or considers maintaining the ridges by hand useful. The contour bunds are usable with agriculture, but the picking cannot be mechanized and should be done by hand. The hazard of contour ridges is that with an extreme precipitation event the downstream contour ridges may be damaged or destroyed. (Critchly, Siegert, Chapman, & Finkel, 1991) (Prinz, 1996).

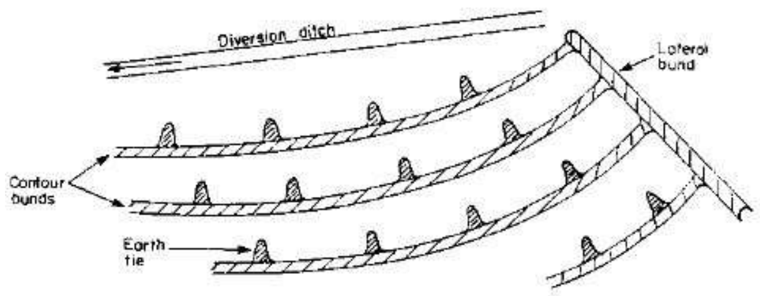


Figure N.4: Contour ridges (Critchly, Siegert, Chapman, & Finkel, 1991)

Multi shaped earthen bunds that are considered are diamond- or semi-circular shaped bunds creating micro catchments for the use of agriculture. The rainfall and runoff are captured and will infiltrate into the ground that will allow the micro catchment to sustain a small amount of agriculture. Only possible in mild sloping (<5%) terrain, diamond shaped (or frequently called Negarim) bunds need thick soils (>1,5 m) and semi-circular bunds can do with 'not to shallow' soils. The difference is caused because the semi-circular bunds trap sediment eroded upstream as shown in figure N.5, while the diamond shaped bunds are micro catchments which are closed off that do not allow sedimentation as shown in figure N.5. Both bunds are not mechanised yet and especially the diamond shaped bunds need a lot of earthwork. The maintenance of the bunds is high because of heavy rain that can overtop the structures and therefore social acceptance by local users should be high (Critchly, Siegert, Chapman, & Finkel, 1991; Prinz, 1996).

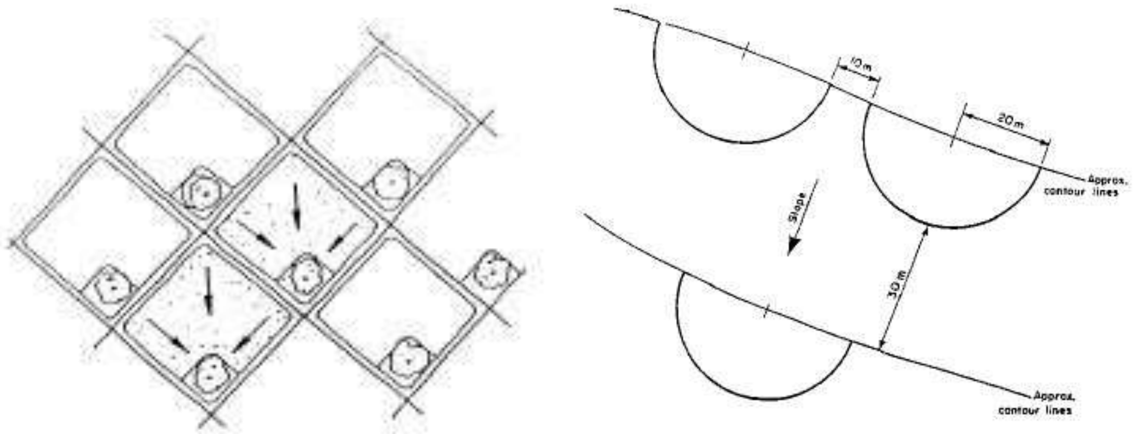


Figure N.5: Diamond shaped earthen bunds on the left (Prinz, 1996) and semi-circular bunds in the right (Critchly, Siegert, Chapman, & Finkel, 1991)

Conservation bench terrace are used on any kind of sloping surface up to 50%. They are used to conserve the soil and counter erosion on steep slopes. The thick soil layer that is created can store water and sustain agriculture therefore this strategy is used on a large scale on the Loess Plateau. To create these conservation bench terraces the soil thickness needs to be high (> 2 m) or a long period to catch the sediments is needed. Because of the steep slopes the terraces need to be combined with vegetation to hold the soil in place, if this is not done properly the terraces could fail and cause a chain reaction downwards. The FAO advices to plant a protection forest above the conservation terraces because this will minimize sedimentation from the top of the slope as is shown in figure N.6 (Prinz, 1996).

Meskat and Manka systems capture rainfall for a small cultivated area in the steep slopes above (Meskat) and trapping it in the soil at the bottom to be used as cropping area (Manka). The Meskat soil is barren and sloping (2 to 15%) while the Manka soil is thick and flat (<2%). The amount of yearly precipitation determines the ratio between the sizes of the Meskat and the Manka. To create a mini catchment and to trap sediment buns can be constructed around the Meskat system as shown in figure N.6 but if the natural form of the slope allows it this is not necessary. The system uses spillways in the Manka area for extreme precipitation events and usually several Manka areas are constructed subsequently to minimize runoff 'losses'. The bunds are mode of stones or earth and are created manually. The stone bunds allow water to flow through but resist the fast streaming water better than the earthen bunds (Prinz, 1996).

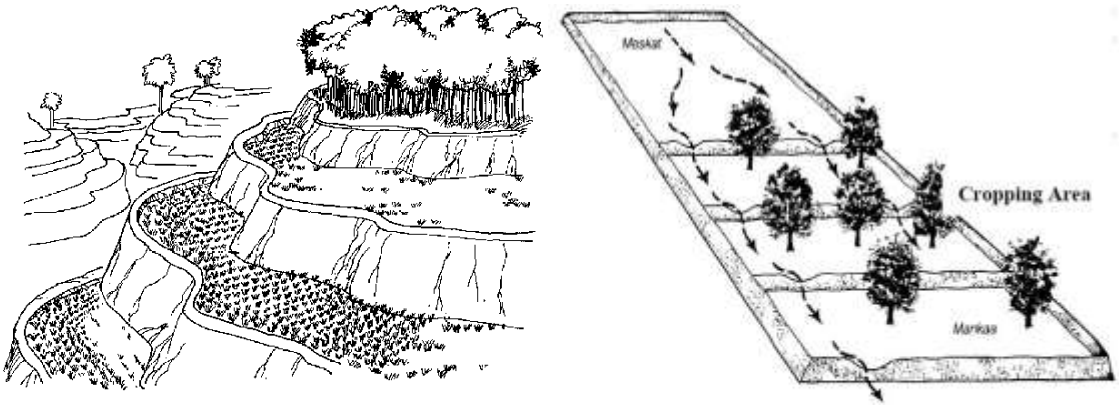


Figure N.6: Conservation bench terrace on the left (Prinz, 1996) and a Meskat system on the right (Prinz, 1996).

Non-structural measures to reduce the effect of flash floods

Measures are considered which can be applied in- and outside the wadi and do need to be constructed like the measures mentioned in the previous paragraphs.

Afforestation decreases the flash flood intensity because it increases infiltration capacity and -rate of the soil and makes the soil rougher and therefore the response gets slower. Trees can be planted on slopes with a varying steepness but needs soils of at least 1 m thick and depends on the water availability (Critchly, Siegert, Chapman, & Finkel, 1991). The plan of the Weather Makers to rehabilitate the area has a standard distance of 5 m between trees.

Eye brow terraces are a tree planting method for on hillslopes which makes a hole in the soil where the tree is planted. To prevent water from flowing out of the hole (or eye) a small brow is made at the downhill side of the eye. This method was used in the 100.000 trees project in the Negev (southern Israel). The trees are planted in a pattern which does not hinder the downhill trees as shown in figure N.7. To plant these trees and to make the eye brow terraces a soil thickness of minimal 1 m is necessary (Prinz, 1996).

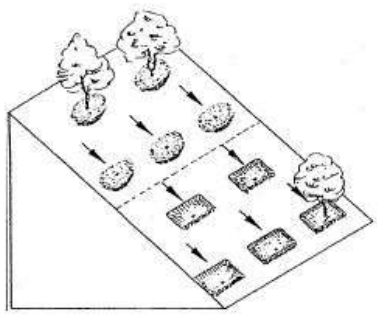


Figure N.7: Eye brow terraces (Prinz, 1996)

Feasibility of measures

To be able to assign measures in the El Arish watershed, they need to be assessed on their feasibility. This section discusses what feasibility means and which measures are feasible in the Sinai.

First the measures found in the literature are subdivided into classes based on their applicability. Secondly the measures will be subjected to a Multi Criteria Analyses(MCA) which will decide whether they are feasible in the Sinai.

Applicability of measures

The measures found are subdivided into classes based on their applicability: the function of the measures, the slope the measures is applicable in, the position of the measure in respect to the wadi and the material every measure can be made off. The applicable measures described in table N.1 give an indication on which measures are suitable on what location in the Sinai. This serves as tool to determine which measures should be located where to reduce the hazard caused by flash floods.

Table N.1: Overview of measures applicable in the arid Sinai

Measure	Function	slope	Where	Material
Check dams	Pervious sediment catchers	Any	Small Wadi	Stone or Wood
Terraced wadis	Pervious sediment catchers	< 12 %	Any Wadi	Stone
Jessour and Tabia	Impervious sediment catchers	Any	Wadi	Earth and stone
Sand dams	Impervious sediment catchers	Any	Wadi	Concrete, stone-masonry or clay
Percolation or spreading dams	Spreading water	<2%	Wadi	Stone or earthen
Obstacle dams	Slowing down water	<2%	Wadi	Concrete
Storage dams	Storing and retaining water	<10%	Wadi	Concrete, stone-masonry
Underground reservoir	Underground storage of water	any	Anywhere	Cavity in soil, concrete or plastic
Contour ridge	Soil & water harvesting	< 5%	Around wadi	Earth or stone
Diamond shaped bunds	Soil & water harvesting	< 5%	Around wadi	Earth
Semi-circular bunds	Soil & water harvesting	< 5%	Around wadi	Earth or stone
Conservation bench terrace	Soil & water harvesting	1 - 50%	Around wadi	Earth or stone
Meskat and Manka	Soil & Water harvesting	differs	Around wadi	Earth or stone
Afforestation	Stabilization of Soil & water	any	Anywhere	
Eye brow terraces	Stabilization of Soil & water	1 - 50%	Anywhere	

MCA on feasibility

In this section measures will be subjected to a Multi Criteria Analyses(MCA) which will decide whether they are feasible in the Sinai. The results of the MCA do not decide whether the measures are used or not but do give the preferred measure if multiple measures could be applied for a certain area. The measures considered have already been selected on their applicability in the Sinai and their relevance to reduce flash floods. The criteria which are used to do the MCA are: input needed from local inhabitants, influence on local inhabitants, impact on environment, local materials, construction time, technology needed, skill needed and needed maintenance.

Input needed from local inhabitants is the degree of effort needed from the locals to make the measure usable. This can be in the use of the measure or on the construction of it. For a large construction the local inhabitants will probably not be responsible for the use or construction of the measure. If however the measure is smaller small repairs and a part of the construction could be dependent on the help of local inhabitants.

Influence on local inhabitants is the degree of strain the measure give the locals, this indicates how they have to change their ways for the measure to be a success.

Environment impact describes the positive or negative impact the measures have. This can mean impact on the groundwater availability downstream, the use of natural resources or the increase of biomass due to the measures.

Local materials discuss the availability of the needed building materials in the Sinai.

The construction time discusses the amount of work a measure needs to be constructed. Some measures can be applied relatively fast while others need a lot of time to be constructed and then even longer to work in a proper way.

Technology needed describes the machinery and the complexity of that machinery needed to construct and maintain the measure. If for instance complex and expensive machinery are needed for a measure this could decrease the chances of success in the long run.

Skill needed is the amount of expertise needed for a measure to be built and maintained. When a measure is constructed the success on the short term is dependent on the skill of the engineer and the construction worker. On the long run the success depends on the skill of the people that use and maintain it. Some ancient flash flood reducing measures are still in use while recent projects fail because the skill is missing to use or maintain it.

Maintenance gives an indication on how much care is needed for the measures. Measures with a low need for maintenance have a better chance to become successful in the large El Arish watershed.

All the criteria are rated from 1 to 5: one being very negative and five being very positive. The influence on local inhabitants for instance gives a 1 if the measure has a very negative influence on the local inhabitants, a 5 if it has a positive effect and a three if there is no difference. The results of the MCA are given in table N.2.

The overall scores give an indication on how feasible measures are in the Sinai. The measures discussed in the analysis are already selected to be usable in arid areas comparable to the Sinai and on their ability to reduce the slope, increase vegetation cover, decrease velocity of flows and/or increase permeability of the soil. The overall scores of the MCA therefore provide an indication on feasibility of measures in the Sinai.

Table N.2: Scores of the Multi Criteria Analysis for feasibility in the Sinai of the hazard reducing measures

	Input local inhabitants	Influence on local inhabitants	Impact on environment	Local materials	Construction time and time till effect	Technology	Skill	Maintenance	Overall score
Check dams	2	4	4	4	2	5	4	3	28/40
Terraced wadis	3	4	4	4	2	5	4	4	30/40
Jessour and Tabia	3	4	2	4	3	5	3	4	28/40
Sand dams	3	4	2	2	4	3	1	4	23/40
Percolation or spreading dams	2	3	4	4	3	5	4	2	27/40
Obstacle dams	5	4	2	1	4	2	1	3	22/40
Storage dams	5	1	2	2	3	2	1	3	19/40
Underground reservoir	2	3	2	3	3	3	3	2	21/40
Contour ridge	2	2	3	4	3	4	3	1	22/40
Diamond shaped bunds	1	2	3	4	1	4	3	1	19/40
Semi-circular bunds	2	2	3	4	2	4	3	1	21/40
Conservation bench terrace	2	2	3	4	1	4	3	1	20/40
Meskat and Manka	3	2	3	4	2	5	3	3	25/40
Afforestation	2	1	5	2	3	5	5	5	28/40
Eye brow terraces	2	1	5	2	2	5	5	5	27/40

Input for the hydrologic model

The USACE method uses a semi-distributed conceptual hydrologic model which means that within the sub basins and channels average values are used for the hydrological parameters. And that the hydrological processes are simulated with intermediate parameters such as the CN.

To be able to quantify the effect feasible measures have on the hazard they are simulated in the hydrological model with HEC-HMS. This can be done with multiple intermediate parameters: curve numbers (CN), lag-time, roughness of the wadi bed and transmission losses. The CN estimates the maximum retention of the soil described in appendix F, the lag time estimates the time it takes for the transformation of excess precipitation into discharge in the sub basins outflow point described in appendix G, the channel flow estimates the flow velocity in the channel between the sub basins described in appendix H, the transmission losses estimate the water lost in the channel between the sub-basins described in appendix I and the basin storage is an estimate of the amount of water that is subtracted in a channel because some sort of storage is constructed (for instance the Ruaffa Dam).

The measures are divided based on their function and the quantitative effect is based on available literature or physical characteristics. Per function the effects on the HEC-HMS parameters is discussed and quantified below.

The first function considered is the soil retaining measures in the wadi: check dams, terraced wadis, Jessours and Tabias, and sand dams. They have in common that they block sediment and slow down water which enhances infiltration. Thus the lag time is increased and the CN is decreased. Al Qudah et al. (2016) reports that the surface runoff decreases by 28% by terrace structures on average and that the time to equilibrium increases with an average of 85%. Al-Weshah & El-Khoury (1999) describes the effect of check dams and terraced wadis with a decrease of the CN of 10% and a lag time increase of 30%. The values used in this research are 5% decrease for the CN and a lag time increase of 30% within a sub basin.

Second is the spreading of water function, they spread water over a larger part of the wadi bed when a flash flood happens. The spreading of the water forces water to take a longer route, decreasing the average slope of the wadi bed, decreasing the flow velocity which increases the infiltration and might enhance the growth of vegetation. The transmission losses are therefore increased due to the slower flow velocities and the expanded width of the contributing wadi channel and the channel flow is slowed down because the roughness of the bed increases. In HEC-HMS spreading dams are simulated by an increase of the Manning coefficient n in the channel flow and increases the contributing wadi bed width (B) in the transmission losses to the total width of the wadi bed.

Third is slowing down water with obstacle dams, these slow the water and thus could enhance infiltration. To simulate the decrease in flow velocity the Manning coefficient of the channel increases. The infiltration of water is not considered to be increased significantly and is therefore not accounted for in HEC-HMS.

Fourth is the storage of water by a storage dam or underground reservoir, these subtract water from the flash floods. In HEC-HMS these are simulated by a reservoir with a maximum capacity, when the reservoir is full the rest of the flood continues downstream.

Fifth are the soil and water harvesting structures around the wadis are considered: contour ridges, diamond shaped bunds, semi-circular bunds, conservation bench terraces, and Meskat and Manka systems. These measures decrease the sedimentation and the surface runoff by slowing down the water to enhance infiltration. This causes the lag time to increase and the CN to decrease as is discussed for the soil retaining measures in the wadi: a 5% decrease for the CN and a lag time increase of 30%.

Lastly the afforestation is considered, afforestation increases the infiltration rate and capacity. In the HEC-HMS the CN will decrease based on the soil type the afforestation is planned for and the associated values found in the Technical Reference Manual of the U.S. Army Corps of Engineers (2000).

An overview of the different measures mentioned above, where they are applicable and how these are used as input for the HEC-HMS model is shown in table N.3.

These values are indicative and are used to estimate what the different types of measures could change in the sub basins and for the overall hazard in the city of El Arish. The literature on changes caused by these measures in climatic circumstances like the Sinai and for the use of such a model is very limited. This is consistent with the indicative nature of the semi-distributed conceptual hydrologic model, which offers an estimate on the hazards in the El Arish watershed and particular in the city of El Arish.

Table N.3: Summary of the measures that are considered in this research, where they are applicable and the effects on the hydrological model in HEC-HMS

Measure	Function	Slope	HSG	Effect on HEC-HMS
Check dams	Pervious sediment catchers	Any	Any	Increase of lag time of 30%, decrease of CN of 5%
Terraced wadis	Pervious sediment catchers	< 12 %	Any	Increase of lag time of 30%, decrease of CN of 5%
Jessour and Tabia	Impervious sediment catchers	Any	Any	Increase of lag time of 30%, decrease of CN of 5%
Sand dams	Impervious sediment catchers	Any	Any	Increase of lag time of 30%, decrease of CN of 5%
Percolation or spreading dams	Spreading of water	<2%	A, B	Increase of contributing wadi bed width B to entire wadi bed, increase of Manning coefficient to 0,05
Obstacle dams	Slowing down water	<2%	Any	Increase of manning coefficient n
Storage dams	Storing and retaining water	<10%	Any	Reservoir addition, dependent on reservoir size
Underground reservoir	Underground storage of water	Any	Any	Reservoir addition, dependent on reservoir size
Contour ridge	Soil & water harvesting	< 5%	A,B	Increase of lag time of 30%, decrease of CN of 5%
Diamond shaped bunds	Soil & water harvesting	< 5%	A,B	Increase of lag time of 30%, decrease of CN of 5%
Semi-circular bunds	Soil & water harvesting	< 5%	Any	Increase of lag time of 30%, decrease of CN of 5%
Conservation bench terrace	Soil & water harvesting	1 - 50%	Any	Increase of lag time of 30%, decrease of CN of 5%
Meskat and Manka	Soil & Water harvesting	Differs	C, D	Increase of lag time of 30%, decrease of CN of 5%
Afforestation	Afforestation	Any	A, B	Decrease of CN for HSG A: 55, HSG B: 72
Eye brow terraces	Afforestation	1 - 50%	A, B	Decrease of CN for HSG A: 55, HSG B: 72

Overview of measures and their effect on the hydrologic model in HEC-HMS