Catchment-scale modelling of water harvesting structures in the Jordan Badia

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Abstract

The Badia is a dry region that covers 81% of Jordan. At the same time it is an import source for food, especially for agro pastoral communities depending of livestock farming systems. Macro scale rain water harvesting (RWH) is currently used to support the production of fodder. Vallerani structures are a promising micro RWH technique that can be applied over large areas. Micro basins from these structures retain surface water and store it in the soil profile, reducing surface runoff and land degradation. The Soil and Water Assessment Tool (SWAT) was used to assess the hydrological impacts of the Vallerani structures on a small catchment scale. A small watershed (10km^2) located near the Al-Majdiyya village and east of the Queen Alia Airport was used as study area.

An observation setup was installed to measure discharge in a sub-watershed with Vallerani structures installed and one without any RWH. Calibration of the SWAT model was based on this quantitative data from the 2018/2019 rainy season. It was evaluated based on semi-quantitative data from the local population, who indicated that there are 4-6 discharge events annually. The calibrated model showed good performance for large events, but underestimated smaller events. The number of discharge events that were modelled was lower than indicated by the local population.

Increasing the area treated with Vallerani structures decreased the number of discharge events linearly to a maximum of 45.3% (R^2=0.984). Total flow decreased linearly as well to a maximum of 36.2% (R^2=0.996). The reductions in number of events and total discharge produced by the SWAT model were lower than those observed in the field. Here they decreased by 75.0% and 61.0% respectively. The model is promising as it describes the right trends, but impact of the Vallerani structures is underestimated. A more extensive dataset is needed to reevaluate model performance. Discharge data from the recalibrated model can be used as input for other models to assess the effects of Vallerani structures on the current agricultural practices.

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1. Introduction

1.1 Background information

The Badia is a dry area in the West-Asia and North-Africa (WANA) region that receives less than 200mm of annual precipitation on average (Allison et al., 1998), while some parts receive far less than that (Freiwan and Kadioğlu, 2008). In Jordan, 81% of the land area is classified as Badia, which is divided into three geographical areas: The Northern, Middle and Southern Badia, constituting 35%, 13% and 51% respectively (Karrou et al., 2011). Oweis et al. (2006) describes several problems Jordan experiences, among which are scarce and highly variable water resources.

In dry areas 75% of the available water resources are used for agriculture (Akhtar, 2007). The increasing demand for water by other sectors, such as industry, will decrease the water allocated to the agricultural sector. In addition, the population is growing in Jordan and also in the Badia (Millington, 1999; Oweis et al., 2006). The increased population and higher demand by other sectors will increase stress on the already scarce fresh water resources (Al-Adamat et al., 2003). Projections are not promising as Jordan is estimated to be subjected to extremely high water stress by 2040 (Maddocks et al.,2015).

The Badia is an important agricultural area in Jordan. It accounts for 70% of the livestock production and is also used for crop production (Oweis et al., 2006). The main crop that is produced is barley, a grain species that can be used for making bread, but is mostly used as fodder. Some agricultural fields are irrigated, however most are based on dryland farming systems and thus rely on precipitation (Karrou et al., 2011). Rainfall in the Badia occurs in short intense storms during the winter period. High intensity rainstorms on the degraded soils of the Badia causes erosion and disruption of the soil. Breaking of the soil aggregates and depleting soil organic matter results in crusting of the soil.

Crusted soils have low infiltration rates. During intense rainstorms a significant amount of the rainfall thus becomes runoff and exits the system before it can be used for agriculture. Water further leaves the system mostly through evapotranspiration. Actual evapotranspiration in the Jordan Badia is high and can account for as much as 92% of the precipitation loss (MWI, 2015). The crusted soil in combination with high evapotranspiration rates leads to short residence times of water in the Badia. In non-desert systems water leaves the system through surface runoff, evapotranspiration or groundwater flow. Deep infiltration in the Badia is limited (Sprong, 2019). Thus groundwater flow is not a big factor for water leaving the system.

1.2 Problem definition

One solution to the lack of available water in the Badia for agriculture is water harvesting. Next to increasing the water availability it also decreases land degradation by water erosion (fig 1) and is used to reestablish the native rangeland vegetation in the Badia (Haddad, 2019). Water harvesting relies on the principle of accumulating surface water from a large area in a small area (Oweis et al., 2001). This is also known as Rain Water Harvesting (RWH). The Badia has potential for water harvesting as it requires overland flow, which is produced due to the crusted soils and intense rainstorms.

Figure 1 Gullies formed as a result of water erosion in rangeland area located in the Jordan Badia

Water harvesting can be done on large (macro) and small (micro) scale. Macro scale refers to run-on areas in the order of 1-10 km^2, while these are in 10-100 m^2 for micro scale. One of the macro RWH systems currently used in the Badia is the Marab, a watershed-scale water harvesting system. In this system, farmers store the surface water in a downstream area of the watershed using a series of dams. The water is then used for Barley production. There are also small scale water harvesting sites, also known as micro-catchment water harvesting (MCWH). These structures capture overland flow from small areas and store it in the soil profile on the hillslopes, as opposed to the downstream situated Marab (Ali et al., 2010) (fig 2).

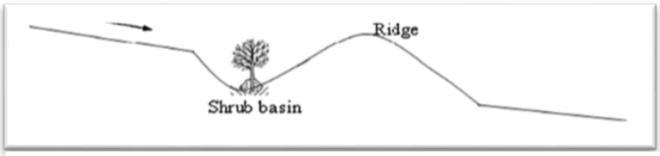


Figure 2 Typical layout of a micro catchment harvesting basin (Ali et al., 2010)

One of the most promising MCWH techniques is the Vallerani water harvesting system (Antinori and Vallerani, 1994). Vallerani structures are created by a tractor pulled plow (fig 3) that creates micro water harvesting catchments and is suitable for large scale production (Ali et al.,2006). The Vallerani system works by creating a series of micro basins that collect rainwater, overland flow and eroded sediments. By storing the water in the Vallerani structures, the residence time of water in the system increases, which enhances the potential for infiltration and provides a long term source for plant growth (fig 2). Previous studies found that by implementing Vallerani structures shrub survival rates increased form 3-6% to as much as 73% in Jordan and from

Figure 3 Plow used to make Vallerani structures

30% to 75-95% in Syria (Oweis, 2016; Ali et al., 2006).

Previous studies have focused mainly on the local hydrological effects and sediment yield of Vallerani structures (Ali et al., 2006; Al-Mahasneh et al., 2013; Karrou et al., 2011; Sprong, 2019). There is a lack of knowledge on the hydrological impact Vallerani structures have on a watershed scale. As the MCWH structures are implemented water availability and crop production potential of the upper regions of the watershed increases. The effects on the water availability and potential for Barley production in the downstream Marab are unknown. This knowledge is important to optimize barley production and prevent conflicts between upstream and downstream farmers. Field data is lacking and difficult to gather. Rainfall events are sparse and the area treated with Vallerani structures upstream of the Marab is limited. Modelling can provide the knowledge that can not be gathered in the field.

1.3 Research goals

The small and decreasing fresh water availability in the Jordan Badia requires the inhabitants to practice rain water harvesting. With different techniques available at both macro and micro scale, it is important to study their effects on water availability at a watershed scale. Research has been done on potential water harvesting locations (Ziadat et al., 2006) and on the small scale effects of these structures (Ali et al., 2010), but the effects on a watershed scale are still unknown. The aim of this research is to assess the hydrological changes caused by Vallerani structures at small catchment scale (10km^2) in the Jordan Badia. The Soil and Water Assessment Tool (SWAT) was used to assess different degrees of water harvesting implementation in the small watershed. The research goals are:

- Characterizing an experimental watershed with Vallerani RWH structures and Marab dams installed
- Calibrating the Soil and Water Assessment Tool (SWAT) for the experimental watershed
- Evaluate the effects of Vallerani structures on watershed hydrology using different treatment scenarios

2. Site description

The watershed used for this research is located just outside of Amman to the east of the Queen Alia International Airport. It is situated at the Al-Majdiyya village (fig 4), located in the middle Badia (Haddad, 2019). There are three important areas that were considered in this research. The watershed is the whole watershed with a size of 10km^2, with two experimental sub-watersheds within the watershed. These are the treated and untreated sub-watersheds.

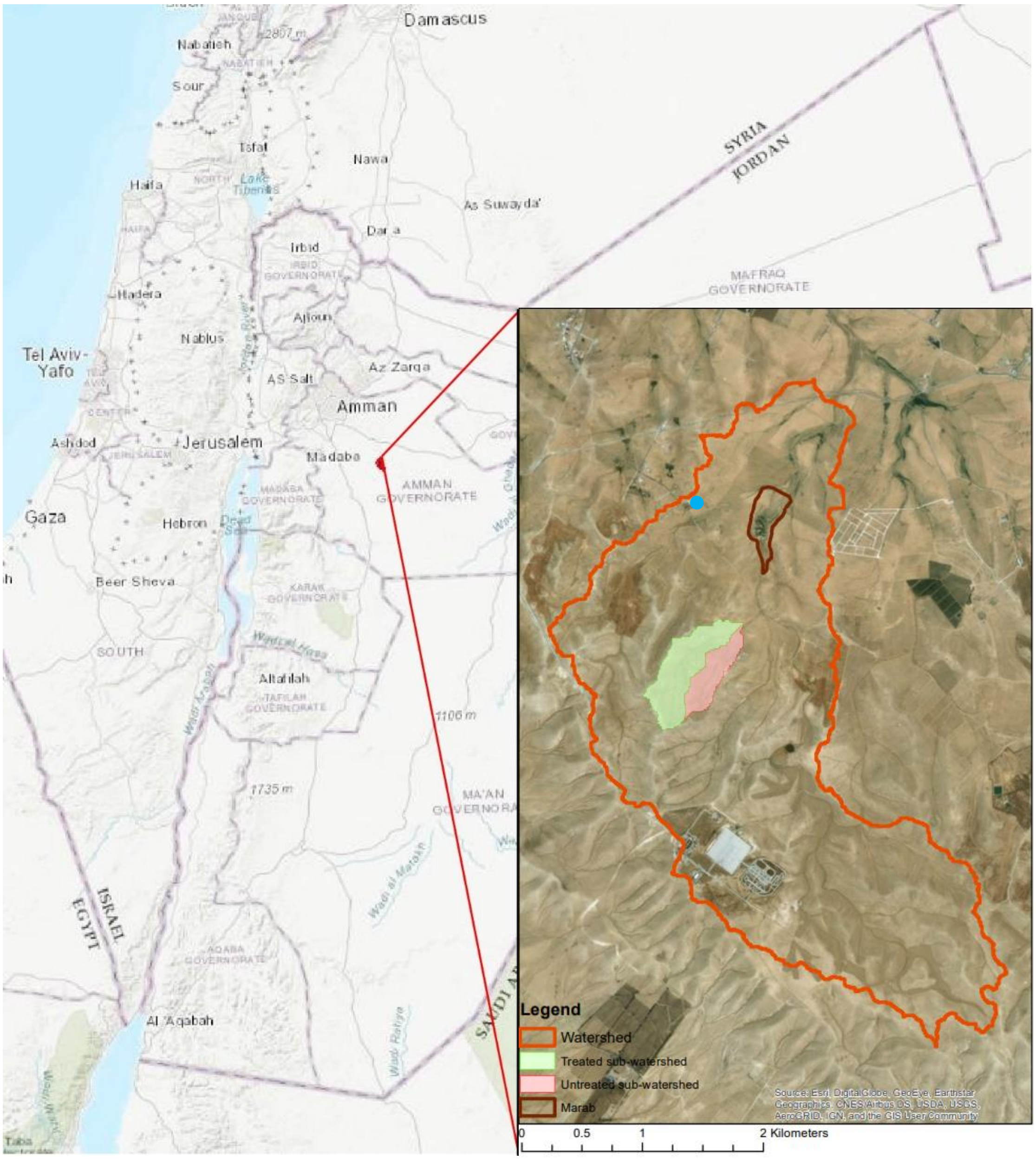


Figure 4 Location of Al-Majdiyya and the research site in the Jordan Badia. Orange outline is the study area. Green indicates the treated sub-watershed, Red the untreated sub-watershed. Brown is the Marab

In the treated sub-watershed Vallerani structures have been placed throughout. These structures encompass 35m^2 each and support the shrub Atriplex Halimus. The treated site has an area of 30ha of which 12ha have been used for Vallerani structures, due to the presence of hilltops and gullies. The untreated site has a size of 14.5ha. This site represents the natural environment that is currently dominant in the Badia (Appendix 1). Cipoletti weirs have been placed in the treated and untreated watersheds for runoff measurements (USBR, 1997). The Marab is located downstream of the treated and untreated sub-watersheds. It has a size of 12ha and can store 5400m^3 of water. The water is stored by a series 12 earth dams that have been constructed in the main channel. The earth dams have a height of 1m with overflow sections that are 10cm high (fig 5).

The elevation in the study area ranges from 780 to 940 metres, with slopes from 2 to 30%. The top of the hills are generally covered by stones and have shallow soils. Slopes are gentle in the downstream area and become steeper streamupward. There are three dominant types of soils in the Badia (Karrou et al., 2011). All soils in the Badia show high carbonate concentrations. The soils are characterized as:

- Gravelly Loam(fine silty clay loam topsoil, silty clay loam subsoil), deep
- Fine silty (silty loam- silty clay loam top soil, silty loam-silty clay loam sublsoil), deep
- Fine silty (stony silty clay loam topsoil, silty clay loam subsoil), shallow

The local climate can be considered as hot and dry, with few erratic rainstorms during the rainy season, making it an arid Mediterranean climate (Palmer, 2013). The watershed receives an average of 150mm precipitation per year (Ali et al., 2006). The rainy season lasts from September till May, with most of the rain falling between December and February. Between June and August there is generally no rain. Averge daily temperatures are 17.5 °C. Maximum and minimum daily means are 24.5 and 10°C respectively (Karrou et al., 2011). Temperatures in the Badia can reach 46°C in summer and -5°C in winter.

Vegetation is only present during the rainy season, as nearly no water is available for uptake in the dry season. The Marab is used for Barley production. The Barley germinates in the middle of the rainy season, in December or January, and reaches around 15cm before being harvested in March or April.

The produced Barley is mainly used as sheep fodder. In the past the Badia supported forage, medicinal plants and other biodiversity as well as enhanced surface water retention and groundwater recharge. Due to overgrazing and droughts the area has degraded (Haddad et al., 2019).

Figure 5 Aerial photograph of the Marab during the dry season (left) and ground picture during the rainy season (right)

Currently there are two water harvesting techniques present in the watershed. Macro scale water harvesting is currently being applied in the Marab (fig 5). Surface runoff from the watershed is concentrated in the Marab for Barley production. Of the total 10km^2 area that encompasses the watershed, 6.3km^2 discharges into the Marab.

Vallerani structures have so far only been implemented in the treated sub-watershed (fig 6). An area is suitable for Vallerani implementation if the slope is less than 25%, it is located at least two metres away from a gully, has a soil depth of more than 40cm and has a stone content of less than 30%. In the treated site this resulted in 12ha of Vallerani structures from the 30ha the treated sub-watershed encompasses.

Other than water harvesting structures, man-made structures are minimal in the watershed. There are a few houses from the Al-Majdiyya community. These are the local farmers and live near the Marab. Further the Jordan traffic institute is situated in the south-western part of the watershed.

Figure 6 Vallerani structures in the treated sub-watershed

3. Methods

3.1 Soil and water assessment tool (Model)

The Soil and Water Assessment Tool (SWAT) is a basin scale continuous time model that operates on a daily time step and is designed to predict the impact of management operations on water, sediment and agricultural chemical yields (Gassman et al., 2007; Arnold et al., 2012). A watershed is subdivided into several homogeneous areas called Hydrologic Response Units (HRU's). These HRU's are homogeneous in land use, management and soil characteristics. Inputs that are required for SWAT are watershed topography, soil, land use and management.

3.1.1 Hydrology

Watershed hydrology is based on the water balance:

$$R_{day} + GW_{in} - Q - E - GW_{out} = \Delta S \qquad (eq. 1)$$

Here R_{day} is the precipitation, GW_{in} is the groundwater inflow, Q is the stream outflow, E is the evapotranspiration GW_{out} is groundwater outflow and ΔS is the change in storage (Dingman, 2015). SWAT uses a slightly rewritten equation, that splits the change in storage to initial and final water content. Further stream outflow is replaced by surface runoff and return flow. The eventual equation used by SWAT is:

$$SW_t = SW_0 + \sum_{i=1}^{t} R_{day} - Q_{surf} - E - w_{seep} - Q_{gw} \qquad (eq. 2)$$

Here SW_0 the initial soil water content (mm), SW_t is the soil water content at time t (mm), w_{seep} the amount of percolation (mm), Q_{surf} surface runoff and bypass flow exiting the soil profile bottom (mm) and Q_{gw} the amount of return flow (mm) (Nietsch et al., 2011).

3.1.2 Surface runoff

SWAT offers several ways of calculating surface runoff volume. For this research the SCS curve number procedure was used. This is an empirical model that was developed to provide a consistent basis for estimating amounts of surface runoff under varying land uses and soil types (Rallison and Miller, 1981). The surface runoff is calculated with the following equation:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad (eq. 3)$$

where Q_{surf} is the amount of surface runoff (mm), R_{day} is the amount of daily rainfall (mm), I_a is the initial abstractions including surface storage, interception and infiltration prior to surface runoff (mm) and S is the retention parameter (mm) (SCS, 1972).

The retention parameter is based on the soil characteristics, land use, management and changes in soil water content. It is thus spatially and temporally variable (Nietsch et al., 2011). The retention parameter is calculated as follows:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (eq. 4)$$

where CN is the curve number. The curve number is dependent on the soil permeability, land use and antecedent soil moisture conditions. CN values are looked up in tables generated by the SCS engineering division (Appendix 2). This table distinguishes four hydraulic soil groups, indicated by letters A through D. These classes are based on the runoff potential. A indicates the lowest runoff potential, while D is assigned to soils with high runoff potential.

Properties regarding water retention change with different moisture conditions of the soil. The Soil Conservation Service (SCS) has distinguished three antecedent moisture conditions: 1-dry (wilting point), 2-Average moisture, 3-wet (field capacity). The curve numbers for average moisture conditions can be found in the tables produced by the SCS. For the other situations correction equations have been developed. Further explenation of these equations can be found in Nietsch et al.(2011).

3.1.3 Evapotranspiration

Evapotranspiration includes all processes at the earth's surface that convert water into water vapor (Nietsch et al., 2011) and is the primary mechanism that removes water from a watershed in arid and semi-arid regions. Potential evapotranspiration (PET) is the amount of water that would evaporate if water was not limited (Dingman, 2015). The system is thus energy limited. For this research the Penman-Monteith method was chosen to calculate potential evapotranspiration. In combination with surface and soil water availability the actual precipitation was calculated. The Penman-Monteith method is the most advanced method SWAT offers. It incorporates energy to sustain evaporation, strength needed to remove water and aerodynamic and surface resistance terms (Nietsche et al., 2011). The equation is:

$$\lambda E = \frac{\Delta * (H_{net} - G) + \rho_{air} * c_p * [e_z^0 - e_z]/r_a}{\Delta + \gamma * (1 + r_c/r_a)} \qquad (eq.5)$$

Where $\lambda E$is the latent heat flux density (MJ/m^2/d), E is the depth rate of evaporation (mm/d), Δ is the slope of saturation vapour pressure temperature curve, de/dT(kPa/°C), H_{net} is the net radiation (MJ/m^2/d), G is the heat flux density on the ground (MJ/m^2/d), ρ_{air} the air density (kg/m^3) and c_p is the specific heat at a constant pressure (MJ/kg/°C). e_z^0 is the saturation vapour pressure of air hat a certain height (kPa), e_z is the water vapour pressure at a certain height (kPa), γ is the psychrometric constant (kPa/°C), r_c is the plant canopy resistance (s/m), while r_a is the diffusion resistance of the air layer (s/m). The equation is updated daily by adjusting parameter values.

3.1.4 Rainwater harvesting modelling

There are several methods to implement water harvesting structures in hydrological models. Used methods include fractional catchment and rainfall runoff relations (Ouessar et al., 2009; Ngigi et al., 2007). Ghimire & Johnston (2013) used two methods to implement water harvesting systems in SWAT. They divided between urban and agricultural water harvesting systems. Urban water harvesting was modelled by changing the curve number, while agricultural structures were represented by ponds. One large pond was implemented to represent multiple smaller ponds in a watershed.

For this research the second method from Ghimire & Johnston (2013) was used. One pond was implemented to represent the total potential Vallerani storage capacity of a sub-watershed. Vallerani structures have a constant spacing of 7 metres and are 5 metres wide. The storage capacity per Vallerani is 223 litres (Strohmeier, 2018). Considering the above mentioned values, a maximum of 223 litres can be stored on every 35 metres of ground suitable for Vallerani implementation.

Regarding the afore mentioned restrictions for Vallerani placement the maximum area viable for Vallerani structures was calculated. The formula to calculate Vallerani pond size per sub-watershed is:

$$V_{pond} = \frac{Pixels_{val}}{Pixels_{total}} * \frac{A_{total}}{35} * Vallerani_{vol} \qquad (eq. 6)$$

Where V_{pond} is the pond volume (m^3), $Pixels_{val}$ are the number of pixels suitable for Vallerani structures in a sub-watershed, $Pixels_{total}$ the total amount of pixels in a sub-watershed, A_{total} the area of the sub-watershed (m^3), 35 the average area(m^2) a Vallerani structures encompasses and $Vallerani_{vol}$ the volume of a Vallerani (=0.223 m^3).

Table 1 Datasets used in SWAT and their respective data sources

Dataset	Source
Short term rainfall (2018/2019 rainy season)	Weather station(field)
Long term climate data (1979-2014)	Queen Alia airport (CFSR)
Digital elevation model (DEM)	ALOS-POLSAR
Land use	Sentinel 2A, field survey
Soil texture	NARC
Soil characteristics	NARC
Discharge treated/untreated sub-watershed	Field measurements
Discharge watershed	Survey

3.2 Input data

The SWAT model needs, as was mentioned in section 3.1, input data watershed topography, soil, land use and management. This chapter describes how the required data was gathered and processed. An overview of all used datasets and their sources can be found in table 1.

3.2.1 Climate data

For climate data daily rainfall, minimum and maximum temperature are required, while solar radiation wind speed and relative humidity are optional (Khelifa et al., 2016). Long term climate data from 1979-2014 was collected through the Climate Forecast System Reanalysis (CFSR), which has a spatial resolution of 30km (Fuka et al., 2014). The data was processed by the WGNmaker 4.1 macro. This excel macro is freely available on the SWAT website.


Figure 7 Weather station located at the Al-Majdiyya village

Measured rainfall data from the watershed was available for the 2018/19 season till 6/3/2019. This data was collected by a weather station in the field (fig 7). The weather station uses a tipping bucket measurement system that tips over when 0.25mm of rain has been collected. The number of tips is measured every 5 minutes. Data from the field is heavily favored, as rainfall in the Badia is very local.

3.2.2 Topography

Remote sensing was applied to determine the watershed topography. The Japanese Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) was used (Rosenqvist et al., 2007). The Alaska Satellite Facility (ASF) processes the images to produce a DEM with a resolution of 12.5m. A high-resolution DEM was needed, because the modelled watershed is relatively small. SWAT uses the ALOS-PALSAR DEM to automatically delineate watersheds and streams, define HRU's and calculate slope steepness (Nietsch et al., 2011). A stream was delineated when the upstream drainage area was larger than 7 ha. For the HRU definition thresholds of 10% were used for land use, soil and slope.

3.2.3 Land use/cover and Soil characteristics

Land use and land cover data was gathered through remote sensing and field observations. Some land use/cover types of the Badia are very distinct in remote sensing images. Hilltops are covered by rocks and thus appear lighter than the yellow/brown hillslopes and were delineated by hand using satellite imagery. Sentinel 2A images were used from March and October of 2016 (fig 8). These are the months with the least and the most amount of vegetation respectively. Thus these two periods show the best contrast between land uses/cover types. Further the urban areas are also easily distinguished. The Marab was measured in the field using a GPS device and streams were determined through the watershed delineation tool in SWAT. Stream dimensions were measured in the field.

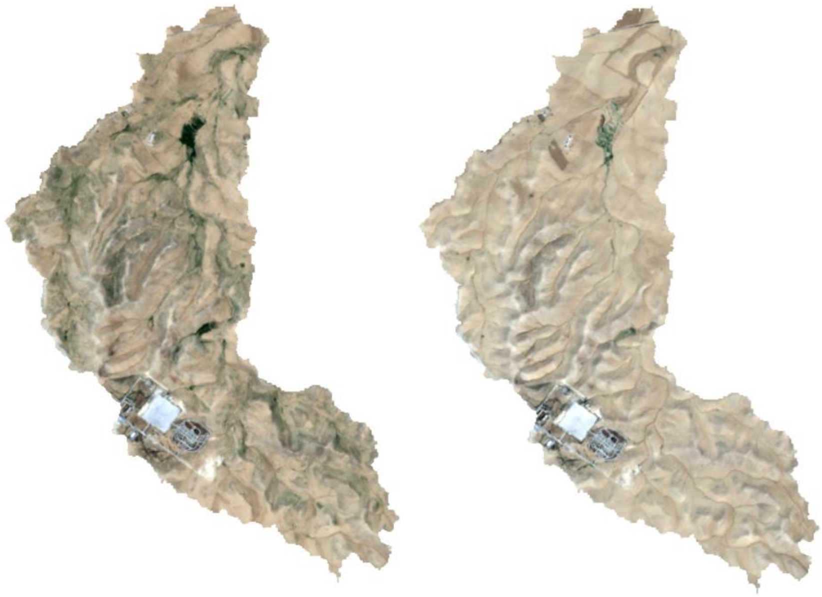


Figure 8 Sentinel 2A images of the watershed from March (left) and October (right) 2016

Soil characteristics were gathered by the National Agricultural Research Center (NARC) in 2017-2018. Ten transects were set out from the Marab to the treated sub-watershed. Because the area where the samples were taken is limited, values were averaged to obtain representative values for the whole watershed. Stone content, soil depth and vegetation coverage of the hilltops was evaluated in the field.

3.3 Calibration and evaluation

Discharge data from the treated and untreated sub-watersheds was gathered during the 2018-2019 rainy season, from 22/12/2018 till 6/3/2019. Cipolletti weirs (USBR, 1997) had been implemented in the streams and were monitored by a Bushnell 20MP trophy cam (fig 9). A picture of the face of the weir was taken every 5 minutes (Appendix 3). The head/water level on the weir was used to calculate discharge as follows:

$$Q = 3.367 * L * H^{1.5} \qquad (eq. 7)$$

Where Q is discharge in cfs, L is length of the weir (feet) and H head of the water (feet) (Dodge, 2001). Discharge events during the 2018-2019 were used to calibrate the SWAT model for the treated and untreated sub-watersheds. During this season six precipitation events happened that produced runoff in the untreated sub-watershed. The same events caused only three runoff events in the treated sub-watershed. The runoff events happened on the 28th of December, 17th of January and the 7th, 9th, 10th and 28th of February (table 2). These events were used as calibration data. The event on January 17 was not usable, because snow was covering the camera.

Figure 9 Discharge measurement setup for the untreated sub-watershed

Automatic calibration is available for SWAT, though the SWAT-CUP module (Abbaspour, 2013). However, manual calibration was applied due to the small amount of the data and large influence of one event. Three parameters were used for calibration: CN for moisture condition II (CN2), water capacity of the soil (SOL_AWC) and the soil evaporation compensation factor (ESCO). These parameters show high sensitivity regarding surface runoff and flow conditions in (semi-)arid watersheds (White and Chaubey, 2005; Yuan et al., 2015; Veith et al., 2010). For Vallerani implementation the fraction of the sub-basin that drains into the ponds (PND_FR) was added to the calibration process. The error in the calibrations was determined using the equation:

$$Err = \sum (Runoff_{modelled} - Runoff_{Measured})^2 \qquad (eq. 8)$$

Due to a lack of discharge values the model could not be validated. Instead the model was evaluated using knowledge from local people on the frequency of discharge events (Appendix 4), which is semi-quantitative data. A discharge events was defined as > 0.5mm discharge, which would fill the Marab to 60% of its maximum capacity. The evaluation period is 30 years. Weather data is available from 1979, but the first five years were used for spin-up and thus not included in the evaluation.

Table 2 Discharge events during the 2018-2019 rainy season

Date	Precipitation (mm)	Runoff Treated (mm)	Runoff Untreated(mm)
28 December 2018	2.75	0	0.5
17 January 2019	5.25	? (snow on camera)	? (snow on camera)
7 February 2019	11.5	0.03	2.5
9 February 2019	5.00	0	1.3
10 February 2019	1.75	0	0.02
28 February 2019	35.75	6.4	12.0

3.4 Scenarios

Several scenarios were modelled for the watershed (fig 10) to determine the hydrological impact, such as downstream discharge, based on the area covered by Vallerani structures throughout the watershed. The modelling period was 30 years, with a daily time step. The scenarios place Vallerani structures in different sub-watersheds. This will have expected effects on the hydrology, as the Vallerani structures decrease runoff and increase infiltration and plant growth. The different sub-watersheds used in the scenarios can be seen in fig 10. The first scenario is a control run, that assumes no Vallerani structures are present.

For the second scenario Vallerani structures were implemented in the three most southern sub-watersheds. The Vallerani volume in three sub-watersheds totals to almost 24% of the maximum Vallerani volume. The third scenario adds three more southern sub-watersheds. Two were excluded, because the Jordan traffic institute is located there. In the fourth scenario another five sub-watersheds were added to the treated area. Scenario three and four include 45% and 66% of the maximum Vallerani volume respectively. For the final scenario all possible Vallerani structures were placed.

The scenarios were evaluated on the number of discharge events (>0.5mm) that occur, total discharge and the discharge efficiency in the Marab. The Marab has a maximum volume of 5400m^3 and is filled when 0.86mm of discharge reaches the Marab. All discharge over 0.86mm leaves the Marab immediately. Here it was assumed that discharge events do not occur in concurrent days and the Marab was completely dry at the start of each discharge event. The efficiency was then calculated as follows:

$$Eff = \frac{\sum Discharge_{used\_Marab}}{\sum Discharge_{total}} * 100\% \qquad (eq. 9)$$

Based on the discharge of each sub-watershed, three additional scenarios were created. In these scenarios, sub-watersheds with the highest discharge were assigned to produce discharge for the Marab. In scenario 6, 7 and 8 Vallerani structures were placed throughout the watershed, except for the 4, 6 and 8 sub-watersheds with the highest discharge, respectively.

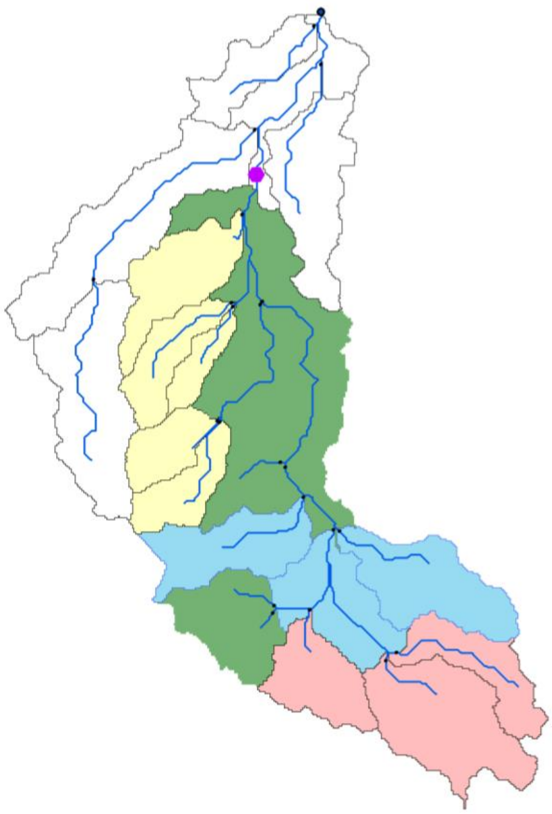


Figure 10 Areas where Vallerani structures are implemented in the different scenarios. The control run has no Vallerani structures implemented. Red indicates the area for the second scenario. Red and blue for the third scenario. Red, blue and yellow for the third scenario. Red, blue, yellow and green are all treated in scenario 5.

4. Results

The results include the input data needed for SWAT to run. Also the results from the manual calibration are presented. Finally, the different scenarios presented in chapter 3.4 are shown in terms of total discharge, number of events (>0.5mm) and discharge efficiency in the Marab.

4.1 Model inputs

As was mentioned in section 3.1, SWAT needs data on watershed topography, soil and land use to run. These are presented in this section as well as climate data over the 30-year modelling period and measured rainfall during the 2018/2019 rainy season.

4.1.1 Climate data

The climate data gathered through the CFSR and processed by WGNmaker4.1 shows a clear distinction between the rainy season and dry season in terms of rainfall (fig 11 and Appendix 5). During the rainy season monthly averages vary from 5.6mm to 31.1mm and do not exceed 1mm during the dry season. Average annual rainfall is 141.2mm. The available weather data shows that the rainy season lasts from October till May. This is almost similar to the findings of Karrou et al. (2011), who stated that the rainy season lasts from September till May.

Average maximum daily temperatures vary from 35.2 °C in August to 13.3°C in January. Average minimum daily temperatures reach 18.3°C in August and go as low as 4.2°C in January. Annual average maximum and minimum temperatures result to 25.4°C and 11.7°C. This is very similar to Karrou et al. (2011), with average annual maximum and minimum daily temperatures of 24.5°C and 10°C respectively. More extensive monthly climate statistics can be found in Appendix 5.

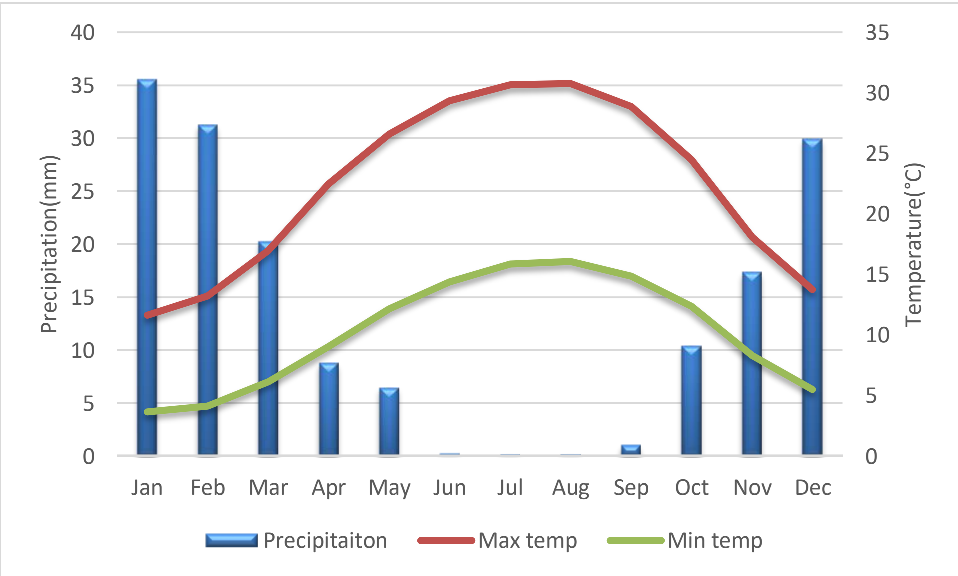


Figure 11 Average monthly precipitation, daily minimum and daily maximum temperature at the Queen Alia International Airport

The 2018/19 rainy season is characterized by a 35.8mm rainfall event on the 28th of February (fig 12). The only other event that exceeded 10mm was on the 7th of February, when there was 11.5mm of precipitation. February was the peak month with a total of 58.5mm. This is over half of the total 102.8mm that was measured till 6/3/2019. In total there were 39 rain days, of which 28 were less than 0.5mm. On four occasions there was 5mm or more precipitation.

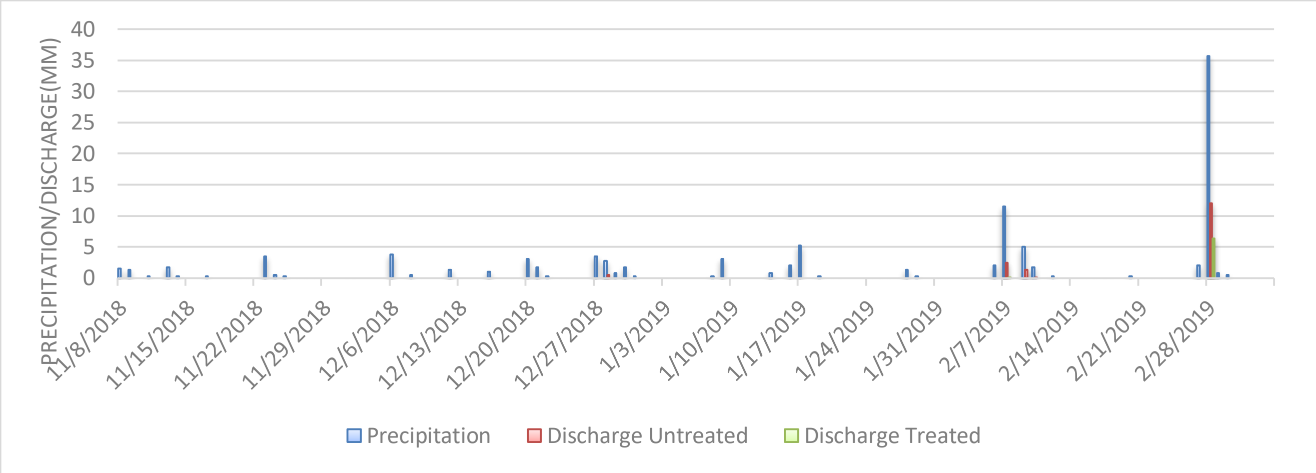


Figure 12 Daily precipitation and discharge in the treated and untreated sub-watersheds during the 2018/2019 rainy season

Rainfall from the 2018-2019 rainy season produced 6 discharge events in the untreated sub-watershed of which 5 were properly captured. The largest event, on the 28^{th} of February, produced 12.0mm of discharge. The same rainfall events produced 2 discharge events in the treated sub-watershed. The event on the 28^{th} of February produced 6.4mm here, almost halve of that in the untreated sub-watershed. Precipitation of less than 5mm did not produce discharge as a singular event, but did if it was preceded by rainy days.

4.1.2 Watershed delineation

The 12.5m DEM from ALOS-POLSAR was used to delineate watersheds. This includes streams, flow paths and sub-watersheds. Streams were delineated when the upstream drainage area is larger than 7 ha. This criterion produced 87 separate sub-watersheds. This was reduced to 23 by manually deleting observation points and combining sub-watersheds. This resulted in the largest sub-watershed being 86.7 ha and the smallest 13.7 ha (Appendix 6). The untreated and treated watersheds were modelled to be 14.0 and 27.9 ha respectively, compared to 14.7 and 30.4 ha when delineated by hand.

4.1.3 Land use

Land use was determined using remote sensing and field research. In total 5 classes were distinguished. These classes are hilltops, streams, urban, Marab and rangeland.

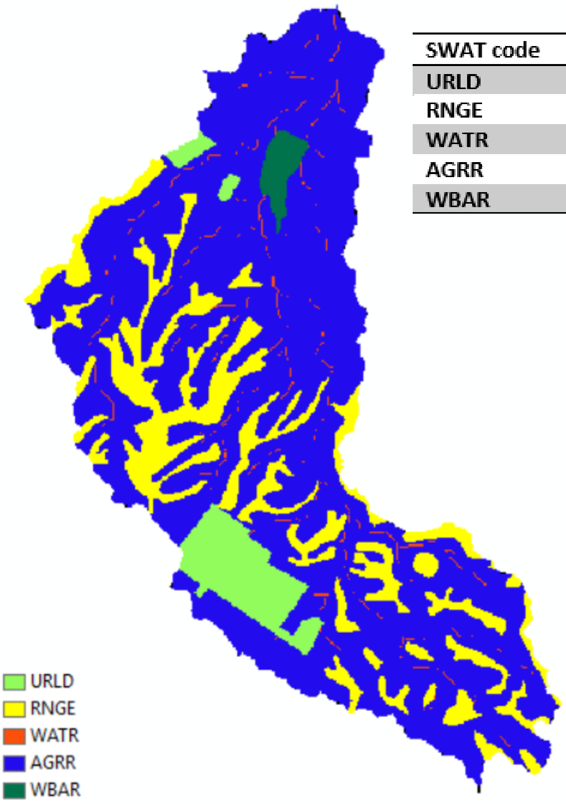
Hilltops were determined using Sentinel 2A images. Most of the hilltops were identified in the southern or upstream part of the watershed (fig 14). Here the hilltops delineate the watersheds. In the downstream areas, with less steep slopes, hilltops occur less frequent. In total over 18% of the $10km^2$ watershed was identified as hilltop.

Streams were produced with the watershed delineation tool from SWAT. For the streams, a buffer area of 5 metres was established around the stream, due to the average stream width of approximately 3 metres and the buffer zone around the gullies that can not be used for Vallerani structures. In some instances this overestimated the stream area, while in other areas the stream area was underestimated. Stream dimensions were measured in the field and found to be on average 2m wide and 1.3m deep for side channels and 3.5m by 1.5m for the main channel. Streams only encompass a small part of the watershed (1.2%).

The Marab was first delineated based on the Sentinel 2A images mentioned in 3.2.3. This provided an area that was smaller than the actual Marab, due to recent expansions (fig 13). The northern part is the actual dammed area. The southern is included as well, because it is affected by the Marab and shares a lot of the characteristics in terms of vegetation as inside the Marab. Due to the increased water height and retention from the dams the upstream area receives substantial amounts of water as well, creating an environment for Barley to flourish.

To finalize the land use map (fig 15), the area not included in the 4 previous land uses was assigned rangeland as land use class. Agricultural area is by far the most common land use, covering 73.8% of the watershed.

Figure 13 Marab in 2016. The current extent is indicated by the blue line



SWAT code	Land use	Area (%)
URLD	Low density urban	5.6
RNGE	Hilltop	18.1
WATR	Streams	1.2
AGRR	Rangeland	73.8
WBAR	Marab	1.3

Figure 14 Land use map of the watershed. The table indicates the respective areas of the land use classes

4.1.4 Soil characteristics

Topsoil characteristics are consistent throughout the watershed, with 35.4% clay, 47.3% silt and 17.3% sand. Further there is 0.62% organic matter and 15.9% stone content, except for the hilltops. Here the stone content is 30.4% (Appendix 7).

Everywhere the soil allows it, the land is used as rangeland. This means that the stone content does not exceed 20% and the soil is at least 40cm deep. These areas were assigned an estimated soil depth of 60cm. Over 25% of the observed hilltop sites showed bedrock (Appendix 7), thus effectively having soil depths of 0cm. Surrounding areas did support soil, but these were shallow. Hilltops were assigned estimated soil depths of 5cm. Soil depths surrounding the gullies can exceed 2m. The Marab, being an accumulation place for sediment in the main channel, was given an estimated soil depth of 2m.

The CN of the rangeland was determined through manual calibration. The Marab was given the same CN value. Urban areas and hilltops have very little water retention capacity and thus produce relatively large amounts of runoff. These areas were assigned an estimated CN value of 90.

4.2 Model results

Manual calibration was used to obtain the SWAT parameters CN2, SOL_AWC, ESCO and PND_FR, as was mentioned in section 3.3. For the first three parameters discharge events from the untreated sub-watershed were used for calibration. Discharge events from the treated sub-watershed were used to calibrate PND_FR. The results from the calibrations alongside the model evaluation are shown in this section.

4.2.1 Calibration parameters

Calibration of the parameter CN2, ESCO and SOL_AWC are based on the discharge events in the untreated sub-watershed (table 2). Manual calibration was applied with a host of different values and combinations of the three calibration parameters (Appendix 8.). It was found that an increase in CN2 mainly increased the discharge for large events (>5mm), while having less effect on small events (<1mm). Further the ESCO and SOL_AWC showed similar influences on both small and large events. Based on the Err value the six best calibrations were chosen (table 3). Important for the discharge events is that surface runoff is the main contributing factor. GW_Q is always 0, while LAT_Q never exceeds 0.05mm.

Table 3 Manual calibration results of the untreated sub-watershed

	CN	ESCO	SOL_AWC (mm/mm)	28 Dec (mm)	7 Feb (mm)	9 Feb (mm)	10 Feb (mm)	28 Feb (mm)	Err
Measured				0.5	2.5	1.3	0.02	12.0	
Calibration1	86	0.90	0.20	~0	0.37	~0	~0	12.39	6.63
Calibration2	84	0.90	0.18	~0	0.55	~0	~0	13.02	6.78
Calibration3	84	0.95	0.19	~0	0.51	~0	~0	12.24	5.96
Calibration4	85	1.00	0.20	~0	0.46	~0	~0	12.08	6.11
Calibration5	84	1.00	0.19	~0	0.56	~0	~0	12.53	5.98
Calibration6	84	1.00	0.18	~0	0.65	~0	~0	13.85	8.79

As can be seen in table 3, the model is not able to reproduce the small discharge event on the 28th of December or those on 9 and 10 February. None of the calibrations show any surface runoff at these dates. This is also true for all of the other calibrations not included in the table (Appendix 8.) All six calibrations show discharge values of less than 0.7mm for the event on 7 February. Further the six calibrations show similar results regarding the event on 28 February. Calibration 4 is closest to the discharge from the Cameras, while the other five are very close and slightly higher. Calibration 6 shows the largest discrepancy on the 28th of February, but does represent the event on 7 February the best.

4.2.2 Model evaluation

Locals from the Al-Maydijja community, who all have been living there for at least 20 years, indicated in a survey that on average 4-6 discharge events to the Marab happen annually (Appendix 4). Over the 30-year modelling period this should result in a total between 120 and 180 events. Some indicated there were fewer events than this, while one indicated more.

A discharge event was defined as >0.5mm discharge, which would fill about 60% of the Marab's maximum storage capacity. Table 4 shows that calibration 1-6 all underestimate the amount of events in the untreated sub-watershed. Calibration 6 is closest but still underestimates the number of events by at least 28%. Calibration 6 was chosen to be the best calibration. The Err values of the calibrations are very similar and Calibration 6 shows the best results in event frequency.

Table 4 Observed and modelled number of runoff events in the untreated sub-watershed

Model run	Number of events 1984-2014
Observed (locals)	120-180
Calibration 1	79
Calibration 2	83
Calibration 3	83
Calibration 4	80
Calibration 5	83
Calibration 6	86

4.2.3 Vallerani implementation

Representative pond sizes were calculated for the sub-watersheds. Mainly due to different land use distributions throughout watersheds these vary greatly. Area suitable for Vallerani implementation in the sub-watersheds ranges from 86.7% to as low as 11.9%. Most suitable areas are located in the downstream area, as less area is identified as hilltop. The sub-watershed with 11.9% suitable area is located mostly in the southern urban area.

The corresponding pond volumes with the Vallerani areas ranges from 125.7 m^3 to 3803 m^3 (Appendix 6). This means that the sub-watershed with the largest storage capacity is able to store over 30 times as much water as the sub-watershed with the smallest storage capacity.

Calibration of the treated sub-watershed was based on fewer events than the untreated sub-watershed. In the treated sub-watershed there were two events on 7 and 28 February. These events were 0.03mm and 6.4mm respectively (table 2). Using calibration 6 (table 3) it was found that the optimal value for PND_FR was 0.865. This resulted in a discharge of ~0mm on the 7th of February and 6.4mm on the 28th of February (table 5).

Table 5 Manual calibration results of the treated sub-watershed using calibration 6

PND_FR	7 February (mm)	28 February (mm)
Measured	0.03	6.4
0.95	~0	6.1
0.9	~0	6.2
0.87	~0	6.4
0.865	~0	6.4
0.86	~0	6.4

4.3 Scenarios

Implementation of Vallerani structures reduces the amount of discharge by capturing surface runoff in the soil profile. Different implementation rates of the Vallerani structures were represented by five scenarios. Vallerani implementation influenced both the total amount of discharge and the frequency of discharge events (>0.5mm). Here stream evaporation is not taken into account and the assumption is made that all discharge produced in a sub-watershed reaches the Marab.

4.3.1 Event frequency

With no Vallerani structures implemented the calibrated model produced 86 events with >0.5mm discharge over the 30-year modelling period in the untreated sub-watershed (table 4). With the same parameters applied, 75 events were produced for the watershed (fig 15). So the untreated sub-watershed is producing more events than the watershed.

In scenario 2 (fig 10), where 24% of the possible Vallerani structures are implemented, the number of events larger than 0.5mm decreased to 69. Further increasing the area treated with Vallerani structures, decreases the number of events. In scenario 3 the number of events has decreased to 58. In scenario 4 and 5 this was 50 and 41 respectively.

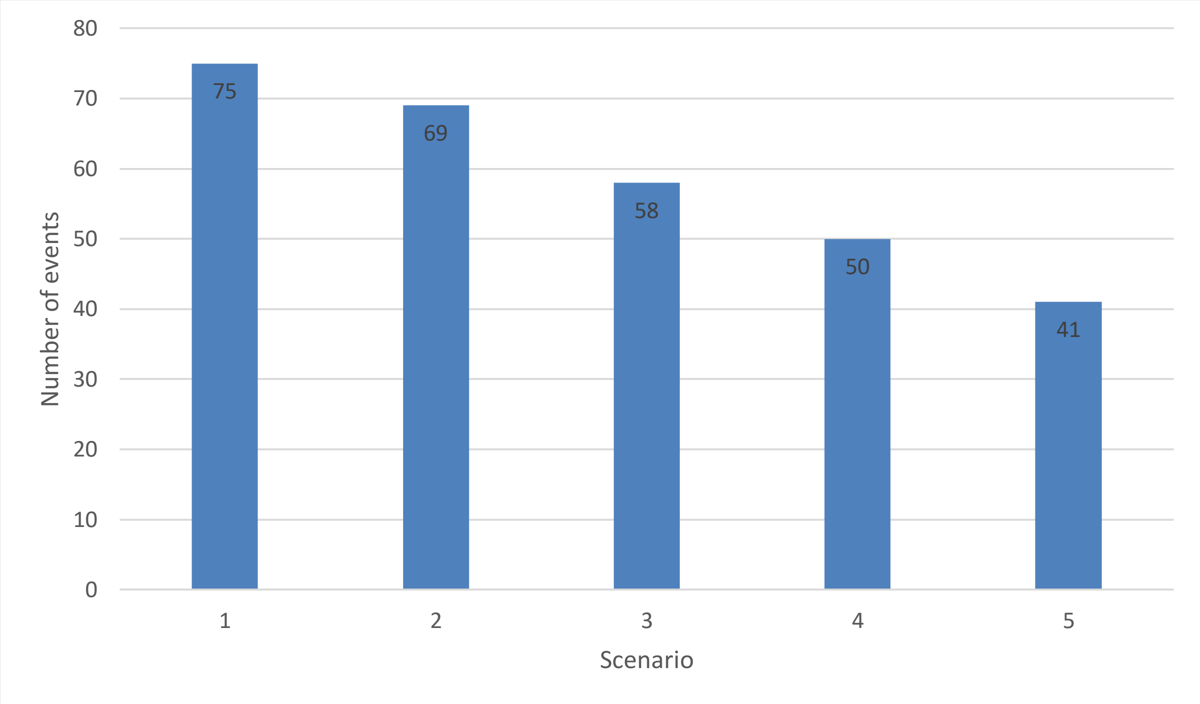


Figure 15 Number of discharge events in the Marab modelled over a 30-year modelling period for 5 scenarios with different numbers of Vallerani structures implemented in the watershed

Comparing the percentages of constructed Vallerani structures with the reduction in discharge events provides a linear relation (R^2=0.984) (fig 16). The reduction of events in scenario 2 is relatively smaller than in the other scenarios. With 100% of the possible Vallerani structures in place there is a reduction in discharge events of 45.3%.

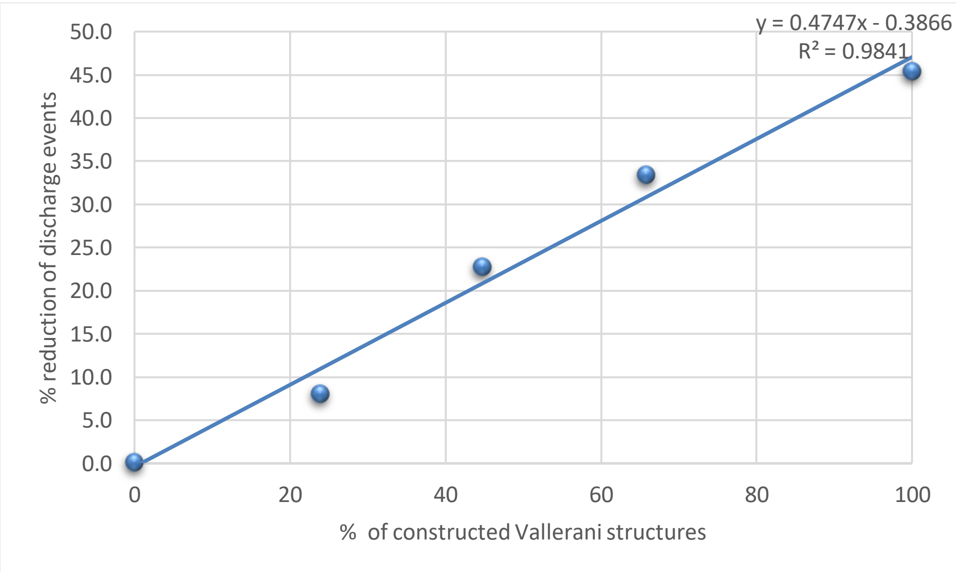


Figure 16 Reduction of discharge events in the Marab due to implementation of Vallerani structures in the watershed

4.3.2 Discharge

Discharge values show a total of 180mm of discharge over the 30-year modelling period for the control run (fig 17). This comes down to 6mm annually and is less than the total of 16.26mm that was measured during the 2018/2019 rainy season. It was assumed that all discharge that is produced in the watershed reaches the Marab. Further all discharge events smaller than 0.01mm were disregarded and assumed to be 0.

The Discharge value for scenario 2 decreased to 166.7mm, which is equal to 5.56mm of average annual discharge reaching the Marab. In scenario 3 total discharge was decreased to 149.6mm or 4.99mm annually. Scenario 4 produced 134.4mm or 4.48 annually. Lastly scenario 5 produced 114.8mm of discharge, equal to 3.83mm of annual discharge.

The efficiency of discharge reaching the Marab for scenario 1 was the lowest at 60.8%. This increased for scenario 2, 3 and 4 to 63.8%, 66.4% and 68.8% respectively. Scenario 5, with all the suitable area treated, shows the highest efficiency at 72.3%.

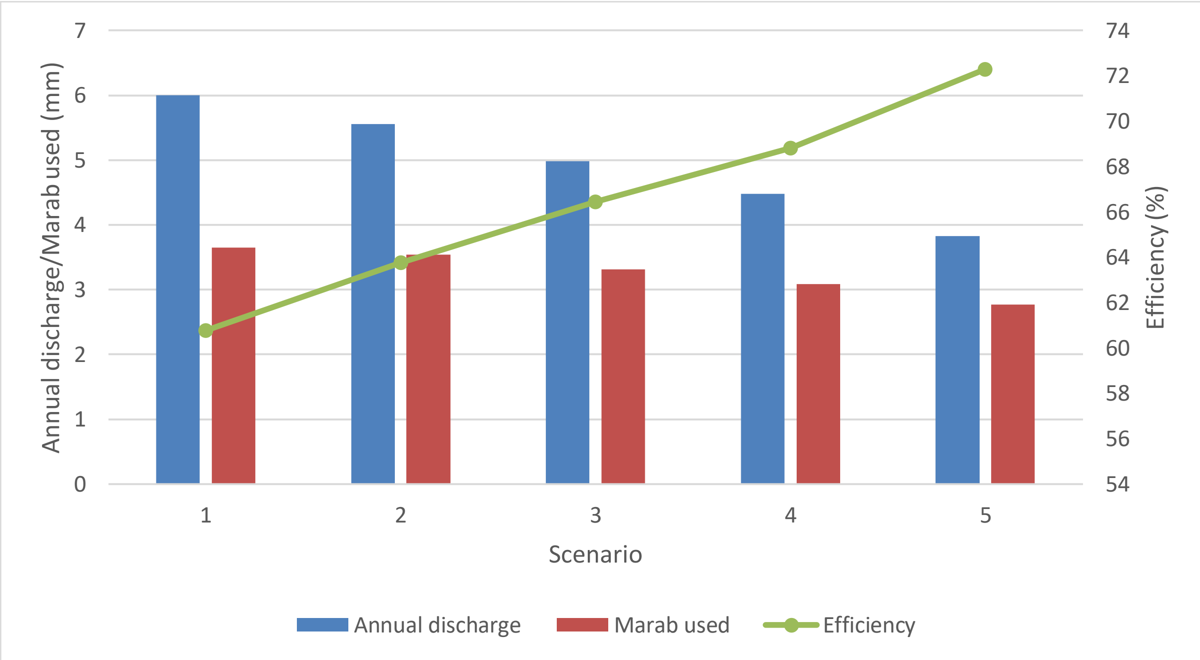


Figure 17 Annual discharge, discharge used in the Marab and efficiency of water reaching the Marab for 5 scenarios with different numbers of Vallerani structures implemented

In the control scenario there were 4 sub-watersheds producing more than 8mm of annual discharge (fig 18), with the highest value being 15.2mm (Appendix 9). There are also 4 sub-watersheds producing between 6 and 8 mm of annual discharge. The most common amount of discharge is 4-6mm. This is true for 8 out of the 18 sub-watersheds. The lowest discharge values were found closest to the Marab. These 2 sub-watersheds produced less than 4mm of discharge, with the lowest being 1.80mm.

In scenario 5, where all the Vallerani structures have been implemented, the most common amount of discharge was <4mm. This occurred in 11 of the 18 sub-watersheds. The lowest value was again found closest to the Marab, at 0.62mm. The number of sub-watersheds with 4-6mm of discharge reduced from 11 to 4. Only 1 sub-watershed was found to produce 6-8mm, while 2 produced more than 8mm. The highest value was found in the same sub-watershed as the control run, at 13.3mm.

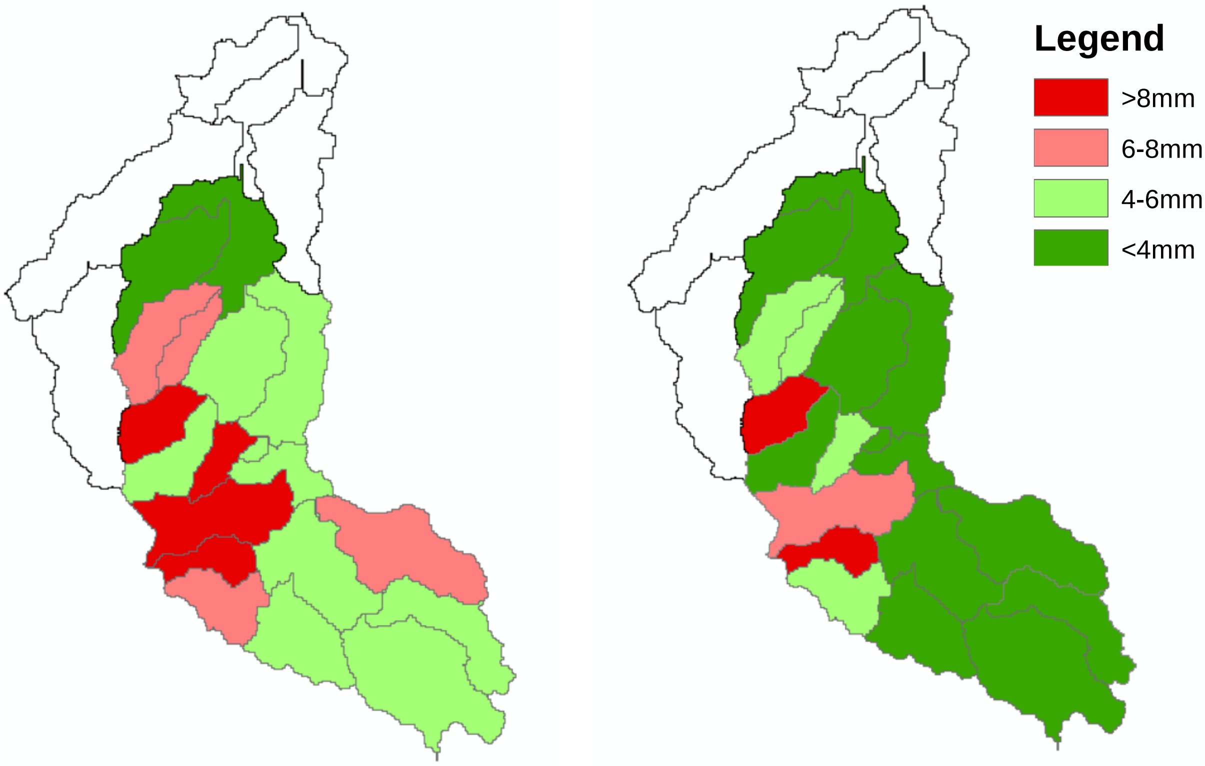


Figure 18 Amount of annual discharge per sub-watershed for scenario 1 (left) and scenario 5 (right)

Figure 19 Shows the change in produced discharge between the control run and scenario 5 per sub-watershed. Only 1 sub-watershed showed a reduction greater than 50%, at 65.4% (Appendix 9). In 8 sub-watersheds discharge reduced between 40% and 50%, while 6 reduced between 30 and 40%. It should be noted that 12 out of these 14 sub-watersheds showed values between 35-45%. 3 sub-watersheds showed that discharge reduced by less than 30%. The lowest value was found in the sub-watershed that produced the most discharge, with a reduction of 12.9%.

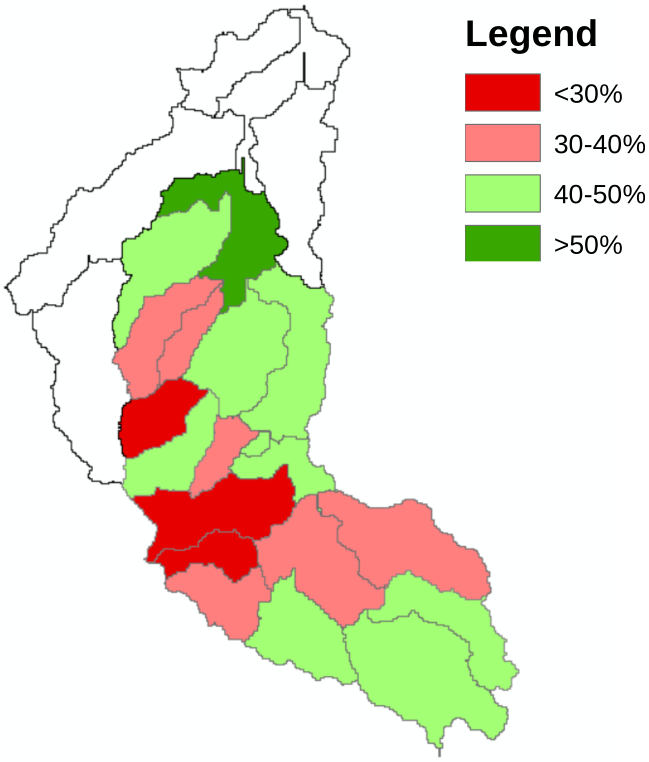


Figure 19 Percentage discharge reduction between scenario 1 and 5 per sub-watershed

The reduction in total discharge compared to the area treated with Vallerani structures can again be described by a linear function (R^2=0.996) (fig 20). The overall trend is also less steep. A similarity with discharge events is again that the impact in scenario 2 is relatively low.

The relative reduction in discharge shows a less steep slope than the number of events. With 100% of the Vallerani structures constructed, a discharge reduction of 36.2% was modelled.

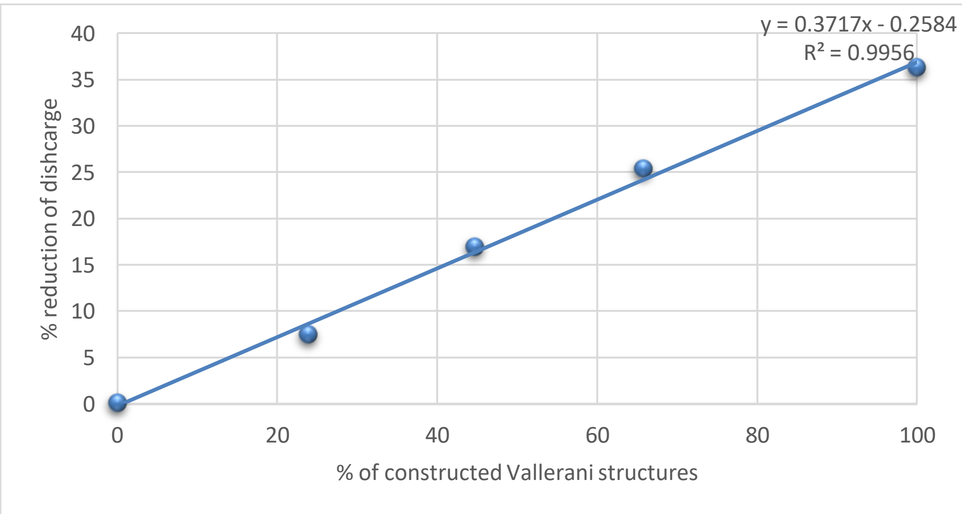


Figure 20 Reduction of discharge reaching the Marab due to the implemented Vallerani structures in the watershed

4.3.3 Vallerani optimization

Based on scenario 1 the 4, 6 and 8 sub-watersheds with the highest discharge values were chosen (fig 19 and Appendix 9). These sub-watersheds were the ones dedicated for discharge production for the Marab and thus not treated for scenarios 6, 7 and 8.

Scenario 6 showed that, with only 4 sub-watersheds untreated, there were 48 events over the 30-year modelling period. For scenarios 7 and 8 this was 51 and 59 respectively. This is in line with the relation found between the implemented Vallerani structures and the number of events (fig 16). The total amount of discharge for the three scenarios is in line with the linear relation as well (fig 21). Scenario 6 produces 127.7mm of discharge, while this was 132.9mm for scenario 7 and 142.1mm for scenario 8.

The efficiency of scenario 6, 7 and 8 is increased compared to scenario 1 through 5. In scenario 6 92mm of discharge was used by the Marab. This is almost the same amount as was used in scenario 4, while the total discharge in scenario 4 is almost 7mm lower. The efficiency of scenario 6 is 72.0%, over 3% higher than scenario 4. In scenario 7 the Marab used 94.7mm of discharge, with an efficiency of 71.3%. For scenario 8 this was 99mm with an efficiency of 69.7%.

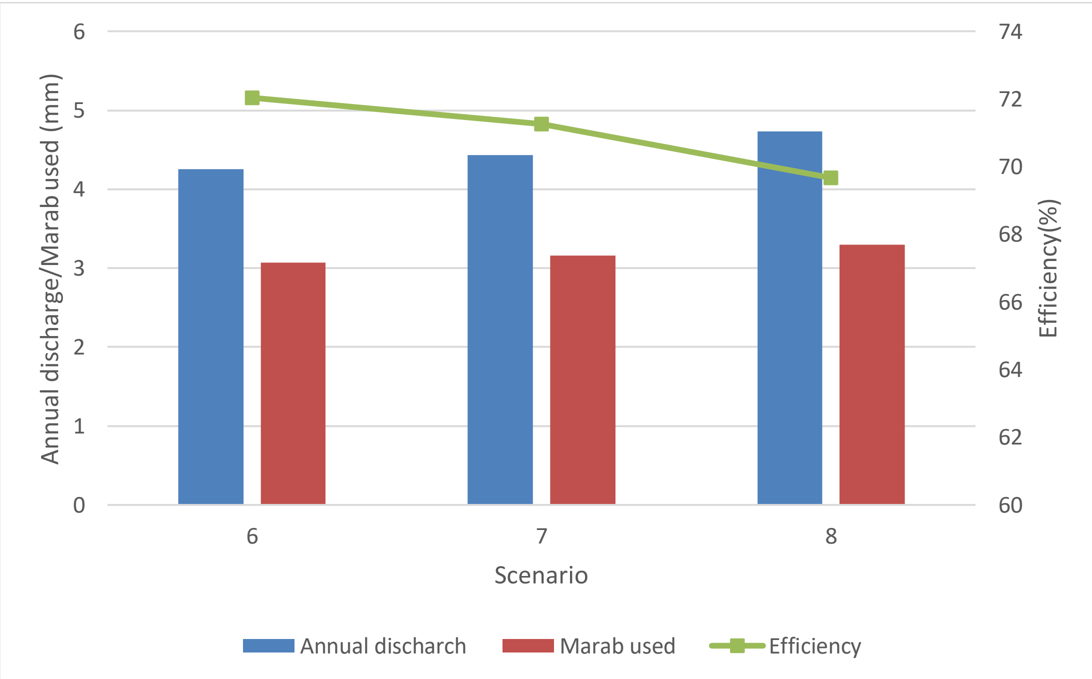


Figure 21 Annual discharge, used by the Marab and effeciency of discharge reaching the Marab with the 4, 6, 8 sub-watersheds with the highest discharge untreated

5. Discussion

SWAT is a capable program for watershed hydrology simulation, due to its extensive customization options it can be used for varying land use and soil conditions (Nietsch et al., 2011). Further different output scales (HRU, basin and reach) provides insight into ongoing processes. This combination gives the ability to adjust surface and sub-surface flow conditions to reflect reality accurately. SWAT has previously been successfully applied in semi-arid and arid environments (Yu et al., 2009; Zettam et al., 2017).

Other studies using SWAT in dry areas have however found that the success of the model is highly dependent on the available input and calibration data (Ouessar et al., 2009; Cheng et al., 2009; Niraula et al., 2012). Using SWAT in arid environments requires longer calibrations periods compared to humid regions. In addition, the predictive capability of the SWAT model is far larger if the model is spatially calibrated on multiple watersheds (Niraula et al., 2012). Ouessar et al. (2009) suggested that calibrating on a single outlet can give misleading results, due to the large spatial heterogeneity in the arid regions. For this research, there was not a large dataset available. Calibration was based on discharge values from a single sub-watershed for the 2018/2019 rainy season using a Cipoletti weir. The data that was available was gathered using a camera. The pictures during dry periods are very clear, but during rain events water can be on the lens (Appendix 3), which reduced the accuracy.

The Cipoletti weir was not used according to the guidelines, which state that the weir should not be used with water levels smaller than 6cm and this level should be measured at a distance of at least four times the water level upstream of the weir (USBR, 1972). For this research the water level was measured at the weir face and rarely exceeded 6cm. The data collected at the weir is, however, the best that is available. The rainy season was characterized by a rainstorm of 35.8mm, the second largest event in the past 40 years (Haddad, 2019). This event might have resulted in a skewed calibration on basis of the Err, where there is too much focus on the large event and smaller events are less well represented.

The results from the calibration showed an accurate representation of the large even on the 28th of February (table 3). All of the calibrations modelled runoff values within 15% of the measured value. These estimates are satisfactory, taking into account the inaccuracies from the Cipoletti weir. The other events were not represented in a satisfactory manner. The SWAT model did not produce any discharge for three of the six discharge events recorded by the cameras. The discharge event on the 7th of February was represented in the model, but only produced 26% of the measured discharge in the best case scenario. The underestimation of the small events was probably a result of limitations in SWAT and the daily time step that was used. SWAT was not able to accurately represent the crusted soils. Further rainstorms in the Badia are short and intense. Because a daily time step was used, the intensity in the model was decreased. Precipitation data from the Queen Alia International Airport was only available as daily amounts.

The qualitative data from the local population of Al-Majdiyya was poorly represented as well by the model. They indicated that on average 4-6 runoff events happened annually, or 120-180 over a 30-year period. The model was only able to produce 86 events. This value is however very arbitrary. A discharge event was characterized as an event with >0.5mm of discharge. If it was found that an event has >0.2mm of discharge, the model would produce 125 events in the untreated sub-watershed. This would be in the range that was suggested by the local population.

Expanding from the untreated sub-watershed to the watershed it can be seen that the number of events (>0.5mm) decreases from 86 to 75. This can be a result of the different composition of land uses. The untreated sub-watershed is covered for 36.8% by hilltop. This is more than double that of the watershed average, which is 18.1%. The hilltops are more prone to runoff than the slopes. So some events that might have been slightly larger than 0.5mm in the untreated sub-watershed could be just beneath this boundary for the whole watershed.

Total discharge values were simulated to be 180mm over the 30-year modelling period, or 6mm annually. Considering the average annual rainfall amount of 141.2mm, this comes to an average runoff ratio of 4.2%. This is similar to the findings of the Jordan Ministry of Water and Irrigation in their surface water budget calculations (WMI, 2015). They found a nationwide runoff ratio off 3% over 2015 and 2% when looking at long term averages. On the other hand, Haddad (2019) estimated runoff rates on the hillslopes of the watershed to be 16.9mm/year.

Implementation of Vallerani structures reduces both the frequency of discharge events and the total modelled discharge on a watershed scale. When 24% of the possible Vallerani structures are implemented the frequency and total discharge decrease by less than 10%. Further implementation decreases these values linearly, with the number of events decreasing faster than the total discharge. With a 100% adoption rate of Vallerani structures, the number of events and total discharge decreased with 45.3% and 36.2% respectively. This difference is present because the total discharge is more dependent on large events with multiple millimeters of discharge. The Vallerani structures can capture a certain amount of runoff before being filled and thus function as a buffer for surface runoff before becoming discharge. If the representative ponds are filled, the rest of the surface runoff becomes discharge. This process was also visible in the field, but the reductions were different. The cameras captured four events >0.5mm in the untreated site, while there was only one in the treated site. This is a reduction of 75%. Total discharge on the other hand was 16.3mm in the untreated watershed and 6.4mm in the treated, a reduction of 61%. Even though reductions observed in the field are larger than the ones modelled and the impact of Vallerani structures are underestimated, the trends are similar. In both cases the number of events decrease more than the total discharge. This means that the Marab will receive discharge less frequently.

When Vallerani structures are constructed, it is recommended to place them in the sub-watersheds producing the least amount of runoff. Not treating the discharge prone sub-watersheds results in higher efficiencies for the discharge reaching the Marab. If, for instance, it is desired that the Marab experiences 50 discharge events over 30 years, scenario 4 and 7 both support 50 events. Scenario 7 would be preferred, as there is more discharge used by the Marab, while less discharge is reaching the Marab. Thus more water is stored in the watershed and can be used for crop growth upstream of the Marab.

The exact effects the implementation of the Vallerani structures throughout the watershed will have on the Marab and its ability to grow barley are still unknown. Morgenson (1980) suggests that one day of water stress results in one day without grain growth, or a 3.8% reduction in yield. In addition, Samarah (2005) states that drought stress is detrimental to grain yield regardless of stress severity. In this research the number of events and total discharge was modelled and not the amount of stress days. Logically the amount of stress days would increase with decreasing discharge and number of events. It is recommended that the amount of stress days is calculated with a groundwater model. For example, Sprong (2019) calculated the amount of stress days for Atriplex Halimus using Hydrus-2D in the Jordan Badia. Another option is using a crop yield model such as CropSyst (Stöckle et al., 2003) to calculate drought stress on crop yields. The discharge values from this SWAT model could be used as input for those models.

Before the data from this research is used in those models it is recommended that the SWAT model is recalibrated using a more extensive dataset. The 2018/2019 rainy season produced little data and effectively only provided two calibration points for the treated sub-watershed. This lack of data becomes even more important considering SWAT models in arid areas require longer calibration periods and perform better if calibrated using multiple gauges (Niraula et al., 2012; Ouessar et al., 2009). More cameras should be added throughout the watershed and a larger database created. The model calibration can be updated after every rainy season and its performance again evaluated. Then the model performance should be reassessed.

6. Conclusion

Vallerani structures can be used to increase water availability for vegetation and decrease land degradation through erosion in the Jordan Badia. The structures are suitable to be placed over a large area using the Vallerani plow. Vallerani structures store surface runoff in the soil profile, where it is used for fodder growth or infiltrates into the ground (Sprong, 2019). This research studied the impacts that the structures have on watershed scale hydrology.

An approximately $10km^2$ Jordanian watershed was used for Vallerani scenario modelling using a discharge measurement system, which was set up in an untreated and treated sub-watershed. The setup consisted of a Cipoletti weir and a camera. Measurements over the 2018/2019 rainy season showed six discharge events in the untreated sub-watershed and three in the treated sub-watershed. This data was used to calibrate the SWAT model. It was found that over a 30-year modelling period the untreated sub-watershed produced more discharge events than the whole watershed due to a difference in land use. The whole watershed produced an average of 2.5 discharge events annually and 6mm of discharge.

Implementing Vallerani structures in the model decreased both the number of discharge events and total discharge. These both decreased linearly with the percentage of constructed Vallerani structures to a maximum of 45.3% and 36.2% respectively. This is lower than the 75% and 61.2% that was observed in the field. Efficiency of the discharge that is used by the Marab increased with the amount of treated area. Further, higher efficiencies were found when the sub-watersheds producing the least amount of discharge were treated. The exact effects of the reduction of water availability on barley growth in the Marab is still unknown, as this is largely based on the amount of water stress days. Other models would be needed to calculate the stress days based on results of this research.

References

Abbaspour, K. C. (2013). SWAT-CUP 2012: SWAT calibration and uncertainty programs–a user manual. *Eawag: Dübendorf, Switzerland*, *103*.

Akhtar, A. (2007). *Evaluating the Effect of Micro-Catchment Water Harvesting on Water and Soil Losses in the Dryland Catchment* (Doctoral dissertation, PhD Thesis. Cßukurova University, Institute of Natural and Applied Sciences, Department of Agricultural Structures and Irrigation, Adana, Turkey, p 255).

Al-Adamat, R. A., Foster, I. D., & Baban, S. M. (2003). Groundwater vulnerability and risk mapping for the Basaltic aquifer of the Azraq basin of Jordan using GIS, Remote sensing and DRASTIC. *Applied Geography*, *23*(4), 303-324.

Al-Hamdan, O. Z., Hernandez, M., Pierson, F. B., Nearing, M. A., Williams, C. J., Stone, J. J., ... & Weltz, M. A. (2015). Rangeland hydrology and erosion model (RHEM) enhancements for applications on disturbed rangelands. *Hydrological Processes*, *29*(3), 445-457.

Ali, A., Oweis, T., Aal, A. A., Mudabbar, M., Zubaidi, K., & Bruggeman, A. (2006). The Vallerani Water Harvesting System. *ICARDA Caravan*, (23), 13.

Ali, A., Yazar, A., Aal, A. A., Oweis, T., & Hayek, P. (2010). Micro-catchment water harvesting potential of an arid environment. *Agricultural water management*, *98*(1), 96-104.

Antinori, P., & Valleriani, V. (1994). Experiments with water harvesting technology with new special ploughs. *Water Reports (FAO)*.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., ... & Kannan, N. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1491-1508.

Cheng, L., Xu, Z. X., Luo, R., & Mi, Y. J. (2009). SWAT application in arid and semi-arid region: A case study in the Kuye River Basin. *Geographical Research*, *28*(1), 65-73.

Cronshey, R. (1986). *Urban hydrology for small watersheds*. US Dept. of Agriculture, Soil Conservation Service, Engineering Division.

Dingman, S. L. (2015). *Physical hydrology*. Waveland press.

Dodge, R. (2001). *Water measurement manual: A guide to effective water measurement practices for better water management*. Government Printing Office.

Freiwan, M., & Kadioğlu, M. (2008). Climate variability in Jordan. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *28*(1), 69-89.

Fuka, D. R., Walter, M. T., MacAlister, C., Degaetano, A. T., Steenhuis, T. S., & Easton, Z. M. (2014). Using the Climate Forecast System Reanalysis as weather input data for watershed models. *Hydrological Processes*, *28*(22), 5613-5623.

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE*, *50*(4), 1211-1250.

Ghimire, S. R., & Johnston, J. M. (2013). Impacts of domestic and agricultural rainwater harvesting systems on watershed hydrology: A case study in the Albemarle-Pamlico river basins (USA). *Ecohydrology & Hydrobiology*, *13*(2), 159-171.

Haddad, M. (2019). Exploring Jordan's rangeland transition: Merging restoration experiment with modeling – A case study from Al Majdiyya village (Msc). The University of Jordan, Faculty of Graduate studies, Amman.

Karrou, M., Oweis, T., Ziadat, F., & Awawdeh, F. (2011). Rehabilitation and integrated management of dry rangelands environments with water harvesting. *Community-based optimization of the management of scarce water resources in agriculture in Central and West Asia and North Africa. Aleppo, Syria: ICARDA*.

Khelifa, W. B., Hermassi, T., Strohmeier, S., Zucca, C., Ziadat, F., Boufaroua, M., & Habaieb, H. (2017). Parameterization of the Effect of Bench Terraces on Runoff and Sediment Yield by Swat Modeling in a Small Semi-arid Watershed in Northern Tunisia. *Land Degradation & Development*, *28*(5), 1568-1578.

Millington, A., al-Hussein, S., & Dutton, R. (1999). Population dynamics, socioeconomic change and land colonization in northern Jordan, with special reference to the Badia Research and Development Project area. *Applied geography*, *19*(4), 363-384.

Ministry of Water and Irrigation(MWI) (2015). Jordan Water Sector Facts & Figures.

Mogensen, V. O. (1980). Drought Sensitivity at Various Growth Stages of Barley in Relation to Relative Evapotranspiration and Water Stress 1. *Agronomy Journal*, *72*(6), 1033-1038.

Ngigi, S. N., Savenije, H. H., & Gichuki, F. N. (2007). Land use changes and hydrological impacts related to up-scaling of rainwater harvesting and management in upper Ewaso Ng'iro river basin, Kenya. *Land Use Policy*, *24*(1), 129-140.

Nietsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and water assessment tool theoretical documentation version 2009*. Texas Water Resources Institute.

Ouessar, M., Bruggeman, A., Abdelli, F., Mohtar, R. H., Gabriels, D., & Cornelis, W. M. (2009). Modelling water-harvesting systems in the arid south of Tunisia using SWAT. *Hydrology and Earth System Sciences*, *13*(10), 2003-2021.

Oweis, T., Prinz, D., & Hachum, A. (2001). *Water harvesting: indigenous knowledge for the future of the drier environments*. ICARDA.

Oweis, T. (2016). Effective Mechanized Rainwater Harvesting: Coping with climate change implications in the Jordanian Badia.

Palmer, C. (2013). Biogeography. *Atlas of Jordan: history, ter-ritories and society. Contemporain Publications, Beirut*, 77-87.

Rallison, R. E., & Miller, N. (1981). Past, present, and future SCS runoff procedure. In *Rainfall-runoff relationship/proceedings, International Symposium on Rainfall-Runoff Modeling held May 18-21, 1981 at Mississippi State University, Mississippi State, Mississippi, USA/edited by VP Singh*. Littleton, Colo.: Water Resources Publications, c1982.

Reynolds, J. F., Kemp, P. R., & Tenhunen, J. D. (2000). Effects of long-term rainfall variability on evapotranspiration and soil water distribution in the Chihuahuan Desert: a modeling analysis. *Plant Ecology*, *150*(1-2), 145-159.

Rosenqvist, A., Shimada, M., Ito, N., & Watanabe, M. (2007). ALOS PALSAR: A pathfinder mission for global-scale monitoring of the environment. *IEEE Transactions on Geoscience and Remote Sensing*, *45*(11), 3307-3316.

Samarah, N. H. (2005). Effects of drought stress on growth and yield of barley.

Soil Conservation Service. 1972. Section 4: Hydrology In National Engineering Handbook. SCS.

Sprong, C.H.C. (2019). Soil water dynamics affected by micro rainwater harvesting structures in Jordanian Badia restoration context (Msc thesis). University of Utrecht, Faculty of Physical Geography, Utrecht.

Strohmeier, S. (2018, April). Restoring Degraded Rangelands in Jordan: Optimizing Mechanized Micro Water Harvesting using Rangeland Hydrology and Erosion Model (RHEM). 1st World Conference on Soil and Water Conservation under Global Change-CONSOWAAt: Lleida, Spain.

Stöckle, C. O., Donatelli, M., & Nelson, R. (2003). CropSyst, a cropping systems simulation model. *European journal of agronomy*, *18*(3-4), 289-307.

United States. Bureau of Reclamation, & United States. Natural Resources Conservation Service. (1997). *Water measurement manual*. The Bureau.

Veith, T. L., Van Liew, M. W., Bosch, D. D., & Arnold, J. G. (2010). Parameter sensitivity and uncertainty in SWAT: A comparison across five USDA-ARS watersheds. *Transactions of the ASABE*, *53*(5), 1477-1486.

White, K. L., & Chaubey, I. (2005). Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model 1. *JAWRA Journal of the American Water Resources Association*, *41*(5), 1077-1089.

Yuan, Y., Nie, W., & Sanders, E. (2015, April). Problems and Prospects of SWAT Model Application on an Arid/Semiarid Watershed in Arizona. In *Proceedings of the 2015 SEDHYD Conference, Reno, NV, USA* (pp. 19-23).

Ziadat, F. M., Mazahreh, S. S., Oweis, T. Y., & Bruggeman, A. (2006, May). A GIS based approach for assessing water harvesting suitability in a Badia benchmark watershed in Jordan. In *Fourteenth International Soil Conservation Organization Conference: Water Management and Soil Conservation in Semi-Arid Environments, Marrakech, Morocco*(Vol. 1419).

Appendices

Appendix 1 Treated and Untreated sub-watersheds

Treated sub-watershed:

Untreated sub-watershed:

Appendix 2 Curve number table

Runoff curve numbers for cultivated fields (Cronshey, 1986)

Cover			Hydrologic Soil Group			
Land Use	Treatment or practice	Hydrologic condition	A	B	C	D
Fallow	Bare soil	----	77	86	91	94
	Crop residue cover*	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row w/ residue	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured w/ residue	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured & terraced w/ residue	Poor	65	73	79	81
		Good	61	70	77	80
Small grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row w/ residue	Poor	64	75	83	86

Appendix 3 Camera pictures of treated and untreated sub-watershed during discharge event and dry conditions

Treated: Dry

Treated: Discharge 28th of February

Untreated:

Dry:

Treated: Discharge event 28th of February

Appendix 4 Marab survey

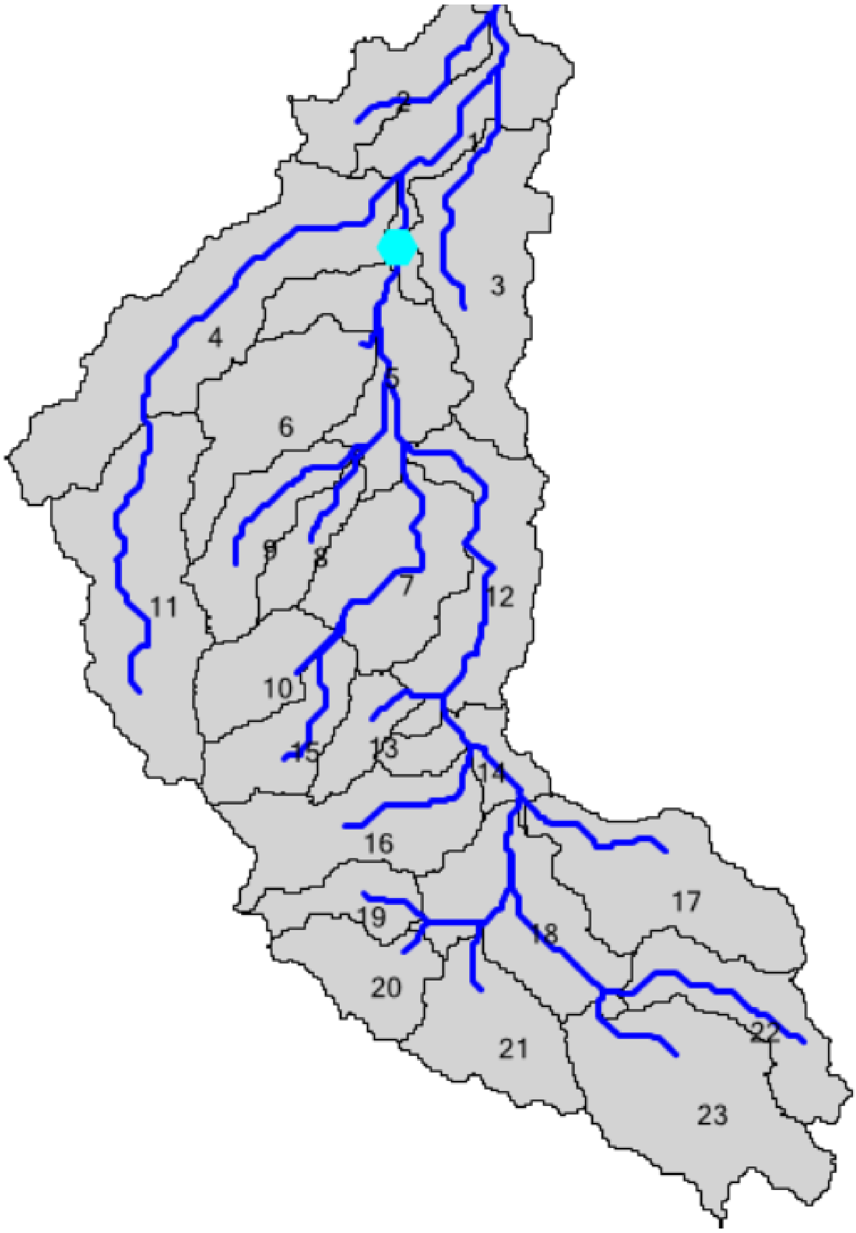
Name	Ibrahim Masardeh	Fatmeh Al Taamneh	Menwer Masardeh	Aqeleh Abdulalh	Ghabain Mohammad	Issa Ayed	Khalf Al dgheem
Age	56	54	28	85	53	29	55
Years in Majdiyya	25	23	20	45	33	20	40
How often is the Marab flooded per year?	4-6	7-10	4-6	4-6	1-3	1-3	4-6
How many days does it take before the Marab is dry again?	5-7	8-10	8-10	8-10	5-7	8-10	1-4

Appendix 5 Climate data

	Daily max temp(°C)	Daily min temp(°C)	Precipitation(mm)	Precipitation days	Daily solar radiation	Relative humidity	Daily wind speed(m/s)
Jan	13.32	4.18	31.07	15.97	11.48	0.68	3.66
Feb	15.12	4.73	27.34	15.17	15.11	0.64	3.88
Mar	19.37	7.01	17.73	15.86	20.01	0.57	3.92
Apr	25.66	10.31	7.66	10.81	25.13	0.44	3.99
May	30.39	13.92	5.61	7.17	28.22	0.39	4.09
Jun	33.53	16.43	0.19	4.14	30.33	0.41	4.54
Jul	35.06	18.14	0.17	5.17	29.75	0.45	4.70
Aug	35.16	18.34	0.16	5.20	27.55	0.47	4.33
Sep	33.00	16.99	0.89	8.20	23.98	0.48	3.73
Oct	27.94	14.15	9.09	9.40	18.24	0.49	3.09
Nov	20.68	9.48	15.14	10.03	13.36	0.54	3.22
Dec	15.71	6.31	26.17	13.17	10.65	0.64	3.37
Average/sum	25.41	11.67	141.23	10.02	21.15	0.52	3.88

Appendix 6 Watershed delineation & sub-watershed characteristics

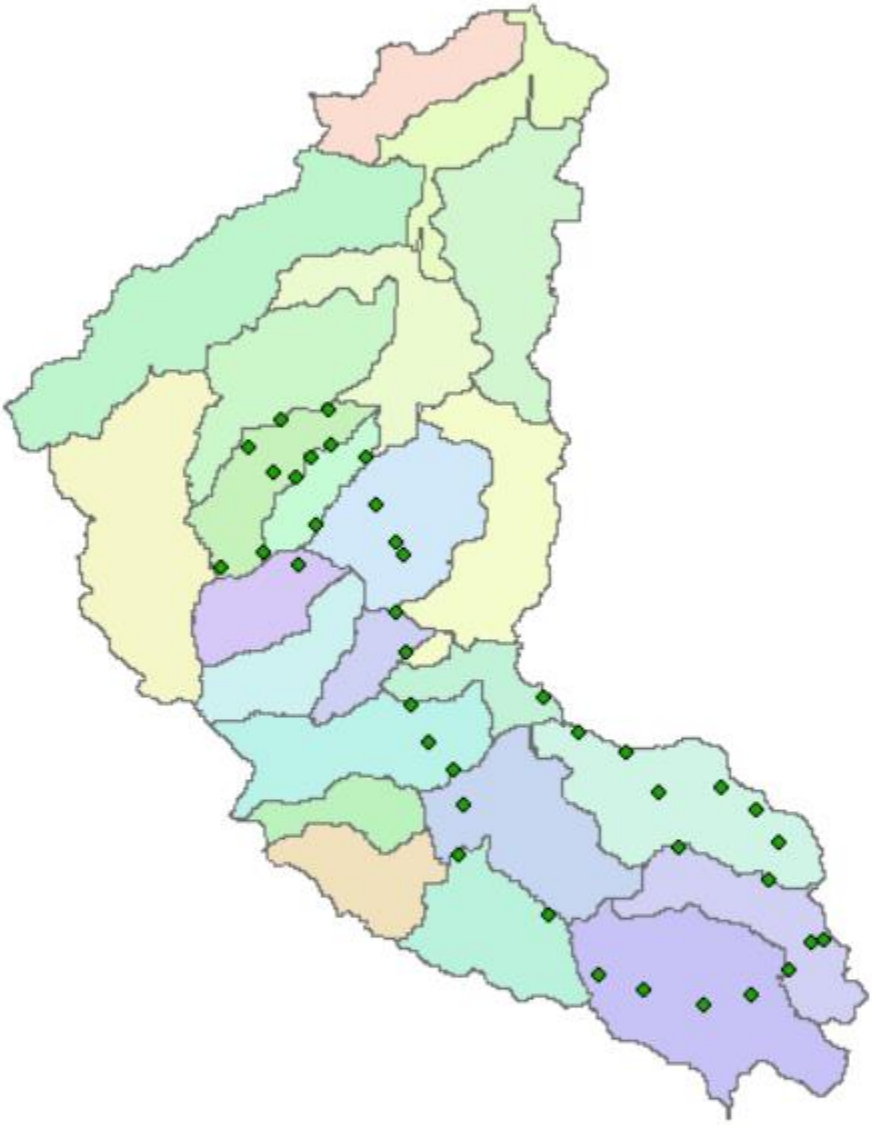
Final watershed delineation, after DEM manipulation. The light blue dot indicates the Marab.



Sub-watershed characteristics and relative pond size

Sub-watershed	Shape_Area	Vall_perct	Vallerani_Area(m2)	Vallerani_amount	Pond_size(m3)	pond_area(ha)
1	372343.75	76.25	283929.61	8112.27	1809.04	1.83
2	290156.25	86.67	251479.85	7185.14	1602.29	1.62
3	570781.25	83.84	478520.50	13672.01	3048.86	3.08
4	867031.25	68.85	596910.16	17054.58	3803.17	3.84
5	413750.00	76.08	314782.75	8993.79	2005.62	2.02
6	434687.50	79.40	345127.75	9860.79	2198.96	2.22
7	449531.25	72.01	323712.00	9248.91	2062.51	2.08
8	140156.25	61.40	86060.75	2458.88	548.33	0.55
9	279218.75	64.43	179890.50	5139.73	1146.16	1.16
10	224062.50	37.61	84269.50	2407.70	536.92	0.54
11	734843.75	66.68	489989.00	13999.69	3121.93	3.15
12	501718.75	78.27	392698.19	11219.95	2502.05	2.52
13	136562.50	56.37	76982.25	2199.49	490.49	0.49
14	178750.00	71.89	128498.75	3671.39	818.72	0.83
15	255781.25	69.54	177858.05	5081.66	1133.21	1.14
16	444375.00	43.47	193152.12	5518.63	1230.65	1.24
17	540156.25	65.78	355336.17	10152.46	2264.00	2.28
18	461875.00	67.58	312154.50	8918.70	1988.87	2.01
19	165468.75	11.92	19729.65	563.70	125.71	0.13
20	253125.00	63.90	161751.91	4621.48	1030.59	1.04
21	357500.00	67.43	241077.60	6887.93	1536.01	1.55
22	348125.00	71.67	249503.21	7128.66	1589.69	1.60
23	695156.25	71.82	499279.71	14265.13	3181.12	3.21

Appendix 7 Hilltop data



Observation point	Stone content(%)	Shrub content(%)	D50(cm)	Special
835	35	2	3	
836	30	2	2	Bedrock showing
837	30	8	1	
838	25	5	3	
839	35	5	5	
840	25	2	4	Bedrock showing
841	30	2	4	
842	35	2	7	
843	30	2	3	

844	20	2	1	Bedrock showing
845	30	2	2	
846	30	8	1	Bedrock showing
847	30	2	4	Bedrock showing
848	20	2	1	
849	30	1	4	
850	35	1	4	
851	40	2	4	
852	35	0	4	
853	25	2	2	
854	30	2	4	
855	25	4	4	
856	40	5	8	Bedrock showing
857	25	4	3	Bedrock showing
858	40	0	8	Bedrock showing
859	20	5	1	Bedrock showing
860	35	5	4	
861	20	3	3	
862	25	2	2	Bedrock showing
863	25	2	2	
864	35	2	4	
865				
866	30	2	2	
867	30	4	2	
868	30	4	4	
869	35	4	3	
870	25	2	4	
871	35	2	4	
872	25	2	3	
873	40	2	4	
874	45	0	8	
Average	30.38	2.77		

Appendix 8 Manual calibration results

	CN	ESCO	SOL_AWC	28Dec(mm)	7Feb(mm)	9Feb(mm)	10Feb(mm)	28Feb(mm)	Err	Number of events
Measured				0.5	2.5	1.3	0.02	12.0		
Calibration1	86	0.90	0.2	0	0.37	0	0	9.67	11.91	
Calibration2	82	0.90	0.2	0	0.37	0	0	12.39	6.63	79
Calibration3	82	0.90	0.12	0	1.15	0	0	20.34	73.32	
Calibration4	82	0.90	0.16	0	0.71	0	0	14.3	10.43	
Calibration5	82	0.95	0.16	0	0.72	0	0	14.31	10.44	
Calibration6	82	0.70	0.12	0	0.94	0	0	19.0	53.37	
Calibration7	82	0.70	0.15	0	0.62	0	0	14.5	11.72	
Calibration8	82	0.60	0.15	0	0.55	0	0	14.03	9.86	
Calibration9	84	0.90	0.15	0	0.72	0	0	16.1	21.92	
Calibration10	84	0.90	0.22	0	0.20	0	0	8.75	17.79	
Calibration11	84	0.90	0.18	0	0.55	0	0	13.02	6.78	83
Calibration12	84	0.95	0.19	0	0.51	0	0	12.24	5.96	83
Calibration13	85	1	0.2	0	0.46	0	0	12.08	6.11	80
Calibration14	84	1	0.19	0	0.56	0	0	12.53	5.98	83
Calibration15	84	1	0.18	0	0.65	0	0	13.85	8.79	86

Appendix 9 Annual discharge values per sub-watershed for scenario 1 and scenario 5

Sub-watershed	mm discharge scenario 1	mm discharge scenario 5	% reduction
5	1.796036	0.622149	65.35988
6	3.816993	2.062878	45.95543
7	5.438973	3.174551	41.63326
8	7.711451	4.993923	35.24017
9	6.886588	4.27585	37.91047
10	11.96753	8.68724	27.40992
12	4.030888	2.189206	45.68924
13	8.415033	5.460188	35.11389
14	4.862452	2.914873	40.05342
15	5.527068	3.217127	41.79325
16	10.35692	7.580024	26.81198
17	6.412642	3.940917	38.54456
18	5.711312	3.552213	37.8039
19	15.22555	13.25476	12.94392
20	6.390296	4.043239	36.72846
21	4.16737	2.4451	41.3275
22	5.163552	3.050967	40.91341
23	5.202336	3.120491	40.01749