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Local hydrological models and quantification of runoff

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1. Local hydrological models and quantification of runoff for sub-basin Auja

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1.1 Introduction

The aim of the workpackage four “Water resources assessment” is the quantitative investigation on the water resources in the Lower Jordan Basin as a basis for Integrated Water Resources Management in the region. The deliverable 405 deals with the application of hydrological models for the calculation of water balance components and especially the quantification of surface runoff in different subcatchments of the study areas. In arid and semi-arid environments the gauging of surface runoff (flash floods) is very difficult due to its high intensity, dynamics, and sediment load. Therefore, in the study area, surface runoff measurements were only performed sporadically. Accordingly, all water resources planning and management considerations still rely on roughly approximated numbers. Furthermore, the hydrological processes of runoff generation shall be investigated in order to enhance the prediction of surface runoff amounts e.g. under a changing climate or land use.

The type of runoff generation is primarily influenced by soil properties (soil hydraulics, effective porosity and initial soil moisture content) and rainfall characteristics (intensity and cumulative amount). Hence, hortonian overland flow (HOF) is expected to take place at sites with bare soil and low infiltration capacity, rock outcrop or sealed surfaces in urban areas and saturation excess overland flow (SOF) at places with thicker soil covered by vegetation and high infiltration rate. For a realistic simulation of runoff processes (especially HOF and SOF) an appropriate short model time step has to be chosen reflecting the high temporal variability of rainfall and runoff. This high-resolution data is often not available making it difficult to apply process based hydrological models on a longer period.

The hydrological model Train-Zin is applied to simulate the temporal and spatial variability of the water balance components in the Wadi Auja study area. Train-Zin is a combination of the soil-vegetation-atmosphere model TRAIN (Menzel 1997) for modelling vertical water flux and the rainfall-runoff model ZIN (Lange 1999) to simulate horizontal water transport and channel routing. Train-Zin has been used for modelling studies in a wide range of Mediterranean, semi-arid and arid environments.

1.2 Study area

The study area of Wadi Auja is located at the eastern slopes of the western escarpment of the Jordan Valley draining to the Dead Sea. A steep relief gradient (1000 m.a.s.l to 200 m.b.s.l.) with a parallel high rainfall gradient (700 mm/a in the western highlands to 150 mm/a in the eastern valley floor) is characteristic for the area. The surface catchment of Wadi Auja consists

of two tributaries, with the confluence located close to the Auja village. The hydrological model is applied to the surface water catchment of the northern branch of Wadi Auja (55 km²), where a gauging station permits quantification of total wadi flow (located at the origin of the irrigation canal).

Beside small built-up areas, land use consists mainly of sparsely vegetated hillslopes with annual plants and dwarf-shrubland, agriculturally used valley planes (mainly rainfed agriculture) and olive plantations on terraced land in the upper part, shrub-vegetation and annual plants during the rainy season in the centre and very sparse vegetation in the lower part (Figure 1.1).

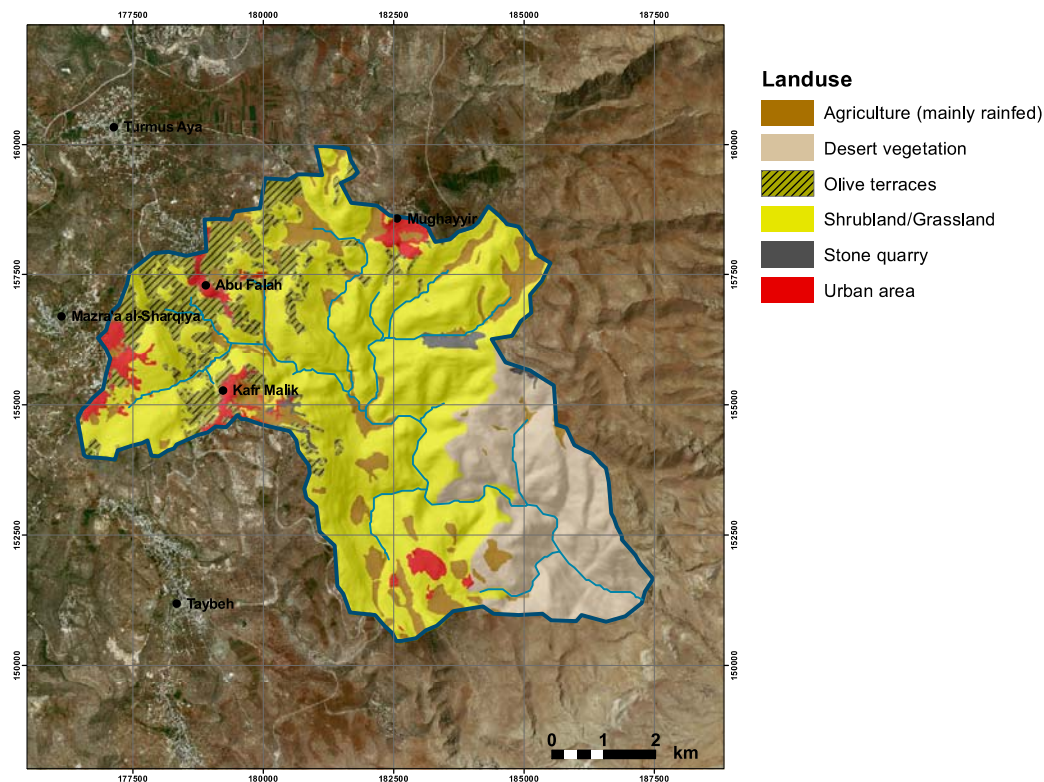


Figure 1.1: Landuse of Wadi Auja drainage area. Proportion of single land use classes: Urban areas 4.3 %. Agriculture 9.8 %. Olive terraces 9.8 %. Stone quarry 0.9 %. Shrubland/ Grassland 54.3 %. Desert vegetation 20.3 %

Soil development depends mainly on climatic conditions, topography, lithology as well as present and past land use. The dominating soil in the Wadi Auja area is Terra Rossa with a characteristic high clay content developing above compact limestone under Mediterranean climate (Dudeen 2001). On softer limestone, marl and chalk Rendzina can be found and are generally shallower than Terra Rossa (Shapiro, 2005). The irregular alternation between rock outcrop and soil pockets is a typical relief form of the hillslopes in the upper parts of the mountain range. At the foot of hillslopes and in valley bottoms fine textured thick alluvial soils (in literature sometimes referred as Grumusols) can be found. In the low-lying areas receiving only little rainfall, shallow Brown Litho-sols and loessial Arid Brown Soils substitute Rendzinas (Shapiro 2005). In the study area detailed information about the soil types, their spatial distribution, thickness and physical properties are missing.

The Geology of the study area consists mainly of Cenomanian and Turonian limestone forming

the upper aquifer of the Eastern Mountain Aquifer. West of the Wadi Auja surface catchment Albian formations are cropping out (lower Aquifer). A detailed description of the geological settings in the area can be found in the report of Deliverable 402 (Schmidt 2013).

1.3 Monitoring network and available data

During the first phase of the SMART project since 2007 a hydro-meteorological network consisting of rain gauges and meteorological stations was constructed. In 2010 and 2011 this network has been significantly expanded and runoff gauges in Wadi Auja and four subcatchments have been installed (Figure 1.2). An overview of the available data for water balance modelling is given in Table 1.1.

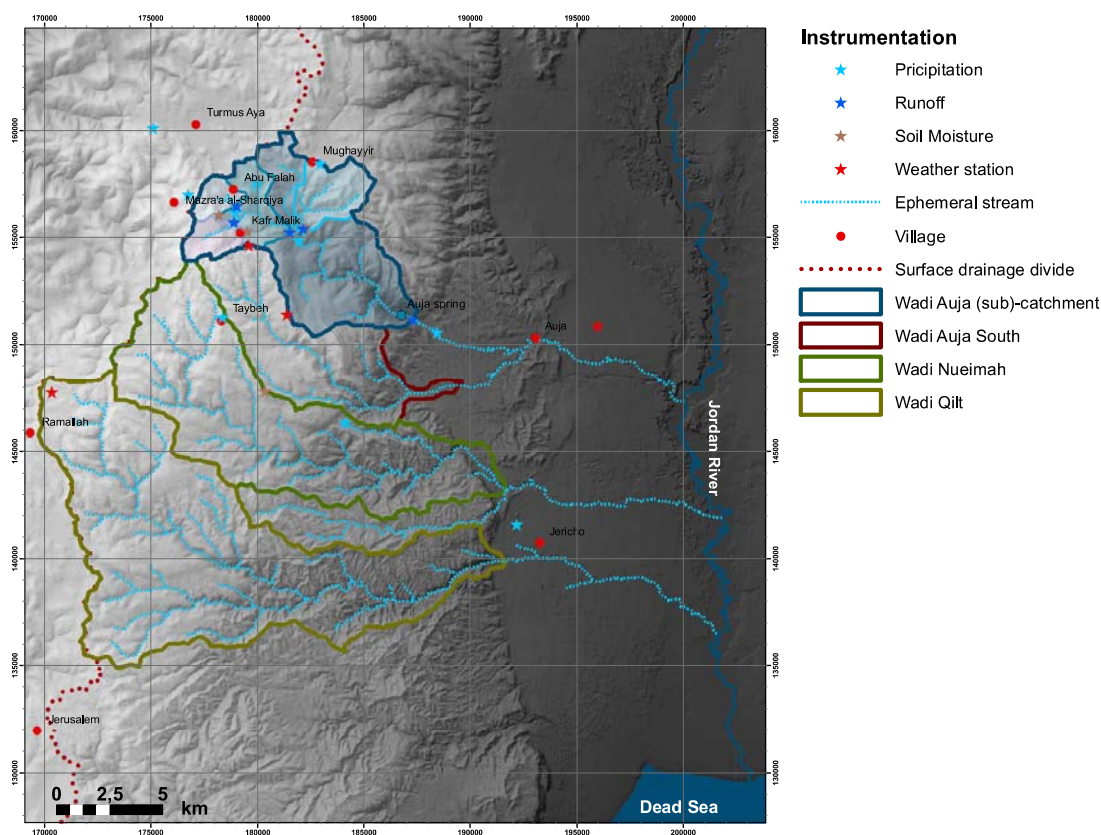


Figure 1.2: Study site and instrumentation of Wadi Auja and surrounding area.

Water level in the streams is measured by automatic pressure transducers in a five-minute interval, corrected for barometric pressure and converted to discharge by usage of discharge flow formulas. Rainfall is recorded by tipping buckets connected to event data loggers and data is converted to a time series with five-minute resolution. Meteorological parameters are recorded at an interval of 10 minutes. The available time series of the stations is listed in Table 1.1. In Wadi Auja catchment and surrounding areas 44 undisturbed soil samples were obtained and were analysed at the Forest Research Institute Baden-Württemberg (FVA). The derived soil physical properties including bulk density, total and effective porosity, water content at field capacity and permanent wilting point are an important basis for the parameterization of the Train-Zin soil module.

During field campaigns 44 undisturbed soil samples from Wadi Auja catchment and surrounding areas have been taken and analysed at the Forest Research Institute Baden-Württemberg (FVA). The derived soil physical properties including bulk density, total and effective porosity. Water content at field capacity and permanent wilting point are an important basis for the parameterization of the Train-Zin soil module.

Table 1.1: Overview of available data for water balance modeling in Wadi Auja area

	07/08	08/09	09/10	10/11	11/12	12/13
Precipitation						
Abu Falah						
Abu Falah Well						
Auja village						
Ein Samia						
Jericho						
Kafr Malik						
Mazra'a al-Sharqiya						
Mughayyir						
Ramallah						
Rimmonim Reservoir						
Sinjil						
Taybeh						
Auja Spring						
Taybeh Junction						
Jerusalem Central ¹						
Meteorological Station						
Auja						
Kafr Malik						
Ramallah						
Rimmonim Reservoir						
Runoff						
Kafr Malik Headwater						
Abu Falah Headwater						
Ein Samia Tributary I						
Ein Samia Tributary II						
Auja Main Wadi						

¹ Station data from <http://data.gov.il/ims>

1.4 Hydrological modelling

1.4.1 Conceptual model

Surface runoff can be produced by a variety of runoff generating processes [e.g. infiltration excess overland flow often referred as hortonian overland flow – (HOF), saturation excess overland flow (SOF), subsurface storm flow – (SSF), groundwater flow]. Each of these runoff processes is linked to a specific building mechanism and occurs under certain conditions. The type of runoff generation is primarily influenced by soil properties (soil hydraulics, effective

porosity and initial soil moisture content) and rainfall characteristics (intensity and cumulative amount).

HOF is expected at places with bare soil and low infiltration capacity (occasionally with biogenic surface crusts or at burned places), rock outcrops or sealed surfaces in urban areas and runoff is produced by peaks of high rainfall intensity. SOF is expected at places with thick soils with higher infiltration rate and vegetation cover where runoff is produced because of high rainfall amounts rather than high rainfall intensity. Lavee et al. (1998) realized investigations on a Mediterranean-arid transect close to the study area of Auja and stated that under semi-arid and arid conditions hortonian flow is the dominant mechanism of runoff generation controlled mainly by abiotic factors while this changes under a more humid climate to a biotic factor controlled saturation excess overland flow. These observations and the dominant occurrence of HOF and SOF under Mediterranean climate are also confirmed by other studies (Martínez-Mena et al., 1998; Gallert et al., 1994). The patchiness of vegetation and surface cover (and the correspondent soil properties) lead to an extreme nonuniform behaviour of infiltration characteristic and runoff generation in space and time (Calvo-Casses et al., 2003). Once runoff is generated it depends on the size of runoff generating areas and its connectivity among themselves and with the next stream segment if stream runoff takes place.

Due to the predominant thick soil cover, the relatively high infiltration rates and the mainly moderate rainfall intensity in the Wadi Auja catchment, SOF is assumed to be the dominant runoff process. This is indicated by the often-observed lack between the start of rainfall events and the initiation of runoff response. On areas with alluvial soil (valley planes) and on olive terraces, which are regularly ploughed, runoff generation is strongly reduced and occur only in very rare occasions. A high percentage of rock outcrops on many hillslopes is expected to decrease the soil water storage and therefore increase runoff generation by SOF. Sealed surfaces in Wadi Auja are restricted to small villages where houses and streets are generally surrounded by gardens and olive orchards, which could considerably reduce the runoff producing characteristics of urban areas. Peak runoff is closely correlated to short rainfall intensity maxima. The triggering of runoff events and runoff volume depends on the amount of model time steps with rainfall intensities above the saturated hydraulic conductivity of the soil after complete saturation of the soil profile.

1.4.2 The hydrological model Train-Zin

Train-Zin is a combination of the soil-vegetation-atmosphere model TRAIN (Menzel 1997) for modelling vertical water flux and the rainfall-runoff model ZIN (Lange 1999) to simulate horizontal water transport and channel routing. The two models have been coupled in order to simulate both fluxes in addition to transmission losses (Gunkel & Lange 2012). Train-Zin has been used for modelling studies in a wide range of Mediterranean, semi-arid and arid environments. A schematic overview of the model concept is given Figure 1.3.

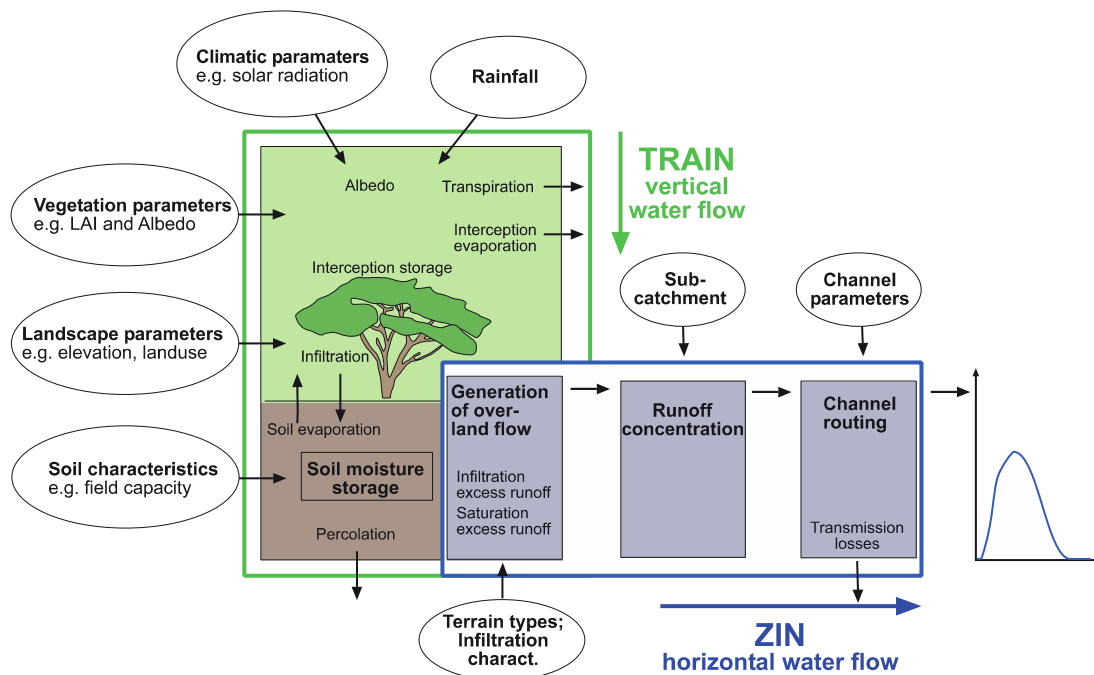


Figure 1.3: Schematic overview of the TRAIN-ZIN model (Gunkel & Lange, 2011)

As a first step in Train-Zin, the spatial distribution of precipitation over the model area is calculated from the precipitation gauging station data based on an inverse distance algorithm with an optional elevation correction factor. After interception (representing vegetation) and initial loss storages (representing depressions) are filled, water can infiltrate and fill up the effective porosity of the soil moisture storage depending on spatially distributed soil physical parameters. If the rainfall intensity is higher than the maximum infiltration rate HOF is generated. Water which infiltrates into the soil storage increase the soil water content and evapotranspiration starts when the permanent wilting point is reached. Evapotranspiration is calculated based on the Shuttleworth-Wallace (Shuttleworth & Wallace, 1985) approach using daily climatic parameters. Percolation towards the phreatic zone takes place once the field capacity is reached and percolation rate into the phreatic zone is calculated with the Mualem-Van Genuchten equation (Van Genuchten, 1980). If the effective porosity is filled and percolation rate is lower than rainfall intensity, SOF is generated. Surface runoff concentration to the next stream segment is modelled using a sub-catchment specific synthetic unit hydrograph. In the stream segment runoff is routed through the channel system according to Muskingum-Cunge (Cunge, 1969). During surface runoff in the channel bed, transmission losses (infiltration into the channel alluvium) are calculated with the Green and Ampt infiltration model (Green & Ampt, 1911). The conceptual model of the soil water module is illustrated in Figure 1.4.

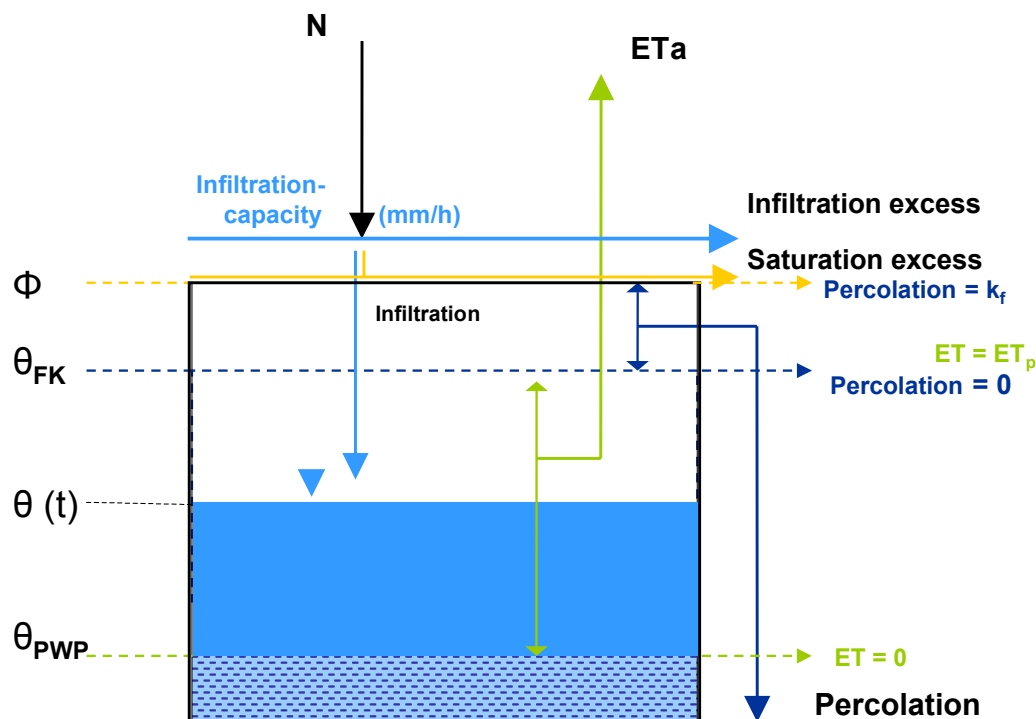


Figure 1.4: Conceptual model of the soil module as used in Train-Zin (Kohn, 2008)

Landuse, runoff generation classes (terrain types), topography, climate and subbasins are provided as ASCII grids. For Wadi Auja a model grid size of 50x50 m has been chosen to reflect small-scale change in landuse and surface cover. The temporal resolution of the model is five minutes.

1.4.3 Model parameterization

As a spatially distributed physically based model, Train-Zin needs the input of spatially distributed data. Climatic data (temperature, relative humidity, wind speed and solar radiation) for the calculation of evapotranspiration is interpolated on the basis of station data on a daily time step under consideration of the pronounced elevation gradient. Rainfall is interpolated using inverse distance weighting and corrected for an elevation effect of the pronounced topography. A mean decrease of annual precipitation with altitude from the crest of the mountain range to the Jordan Valley was found to be around 6 % per 100 m.

Landuse has been identified by GIS analysis of orthophotos and Landsat images and corrected manually where necessary. Especially olive plantations on terraces could not be reliably identified automatically. The resulting landuse map is shown Figure 1.1. Evapotranspiration is calculated based on landuse class parameters (literature values of seasonal varying leaf area index, albedo and vegetation height) and the modelled time dependent soil water content.

To reflect the heterogeneous conditions of the unsaturated soil zone, terrain types are defined based on landuse, soil types and topographic aspects (Figure 1.5). Landuse classes are

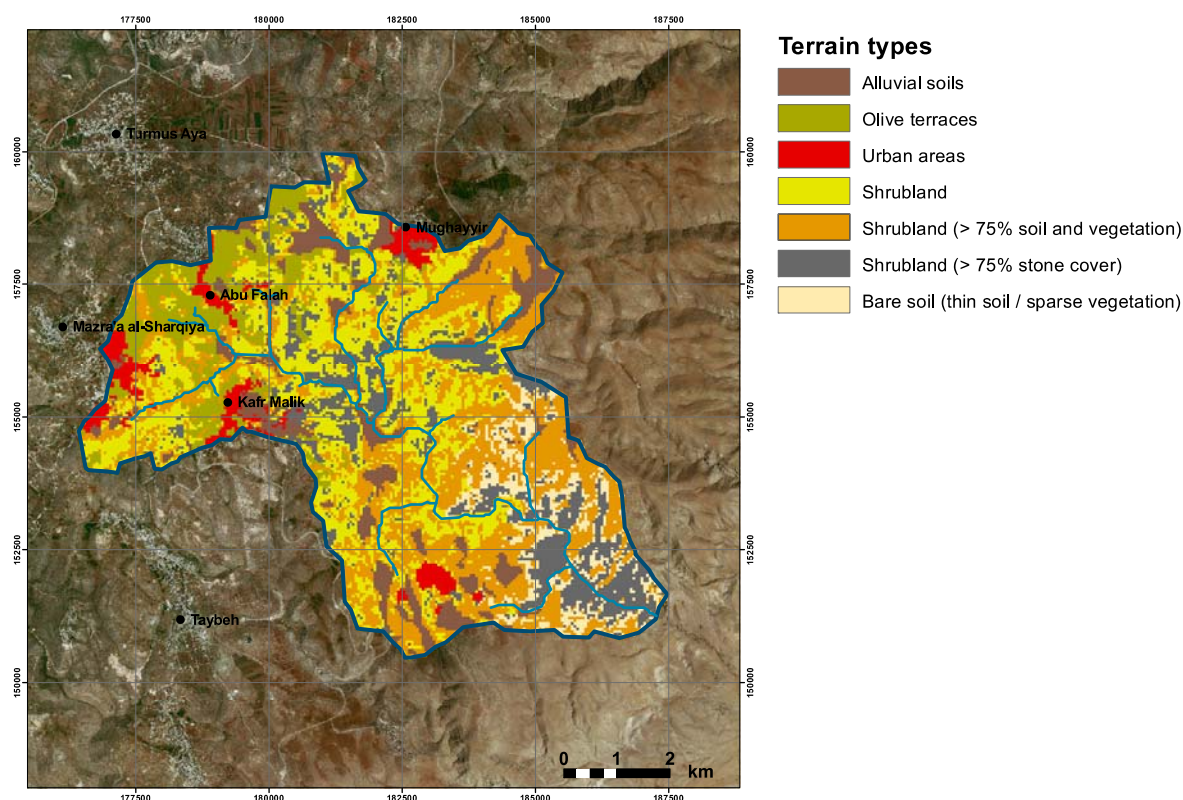


Figure 1.5: Terrain types of Wadi Auja study area.

Table 1.2: Selected terrain type parameter for Train-Zin modeling. The parameters infcap (max. infiltration capacity), soil depth and satcond (sat. hydraulic conductivity) are classical calibration parameter in the limits of field observation.

Terrain class	K_m (mm/h)	I_i (mm)	S_d (m)	ϕ (-)	ϕ_{pwp} (-)	K_s (mm/h)	λ (-)	ϕ_{fc} (-)	ρ (g/cm ²)
Alluvial plane	48	10	1.4	0.52	0.25	0.6	0.5	0.32	1.35
Terraces	25	7	0.7	0.52	0.25	0.6	0.5	0.32	1.3
Urban areas	14	8	0.3	0.52	0.25	0.34	0.5	0.32	1.3
Shrubland	16	4	0.28	0.51	0.22	0.39	0.5	0.28	1.2
Shrubland > 75% soil	22	6	0.32	0.51	0.22	0.39	0.5	0.28	1.3
Shrubland > 50% stone	14	2	0.22	0.51	0.22	0.28	0.5	0.28	1.2
Bare thin soil	12	2	0.24	0.5	0.17	0.25	0.5	0.25	1.2

K_m = Maximum infiltration rate (mm/h)

I_i = Initial storage loss (mm)

S_d = Soil depth (m)

ϕ = Total porosity (-)

ϕ_{pwp} = Porosity at permanent wilting

K_s = Saturated hydraulic conductivity (mm/h)

λ = Van Genuchten parameter (-)

ϕ_{fc} = Porosity at field capacity (-)

ρ = Bulk density (g/cm²)

blended with additional information from landforms and surface cover. Landuse; identified as shrubland and sparse vegetation, has been subdivided into the following classes:

- Shrubland: Typical terrain with dwarf-shrubs and annual plants and medium proportion of outcropping bedrock
- Shrubland (> 75% of soil and vegetation cover): Shrubland with high proportion of soil and vegetation cover and reduced fraction of outcropping bedrock

Shrubland (> 75% of rock outcrops): Shrubland with high proportion of outcropping bedrock

The surface cover has been identified by supervised classification of orthophotos with a pixel size of 50x50 cm following a procedure from Gosh et al. 2013. Due to the clear difference in the RGB colour combination in the orthophotos, bare soil, rock outcrops and vegetation can be reliably distinguished. The model parameter values of the different terrain types were obtained by field samples/analyses and observations, literature data or were calibrated. The final used parameter set is shown in Table 1.2.

To calculate runoff routing and transmission losses, a channel network has been delineated from a 25x25 m digital elevation model. As a channel initialisation threshold a contributing area of 0.1 km² has been assumed. The finally derived channel network is shown in Figure 1.6.

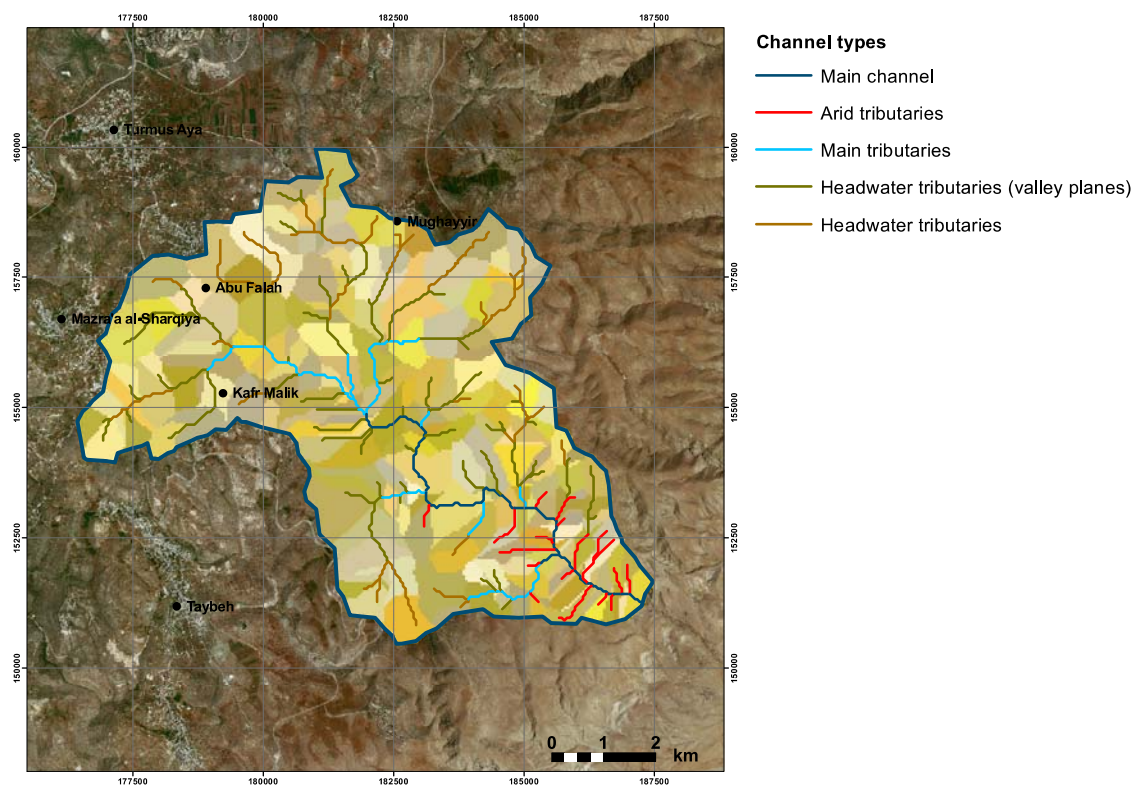


Figure 1.6: Channel network divided in five different channel types for Wadi Auja catchment.

Based on the channel morphology analysed through orthophotos and field observations, the channel network has been divided in five channel types, which are parametrized differently. The parameters have been selected according to field observations, orthophotos analysis and literature values (Table 1.3).

Table 1.3: Selected channel type parameter for Train-Zin modeling

Channel type	D_a (m)	n (-)	c (m)	f_d (-)	ϕ (-)	K_i (mm/h)	K_b (mm/h)	K_f (mm/h)	S (m)	v_k (-)	I (-)	AMI (-)
Main channel	1.6	0.056	0.4	0.9	0.43	60	150	4	0.15	0.02	0.1	0.85
Arid tributaries	0.3	0.036	0.7	0.3	0.38	130	40	10	0.1	0.035	0.1	0.65
Main tributaries	1.2	0.045	0.4	0.9	0.43	60	150	4	0.15	0.02	0.1	0.85
Headwater tributaries I	0.9	0.05	0.7	0.7	0.4	80	100	6	0.1	0.03	0.1	0.85
Headwater tributaries II	0.4	0.04	0.5	0.8	0.4	70	50	5	0.1	0.025	0.1	0.8

D_a = Depth of the active alluvium (m)

n = Manning's n value (-)

c = Cover inner channel (-)

f_d = Depth to bankful stage (m)

ϕ = Effective porosity (-)

K_i = Hydraulic conductivity inner channel

K_b = Hydraulic conductivity of flood plane (mm/h)

K_f = Hydraulic conductivity of the underlying strata (mm/h)

S = Effective suction head (m)

I = Infiltration reduction factor (-)

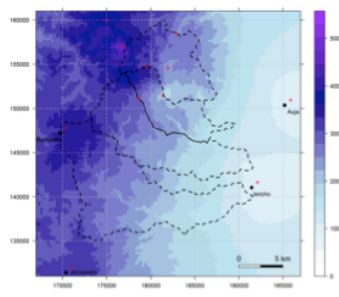
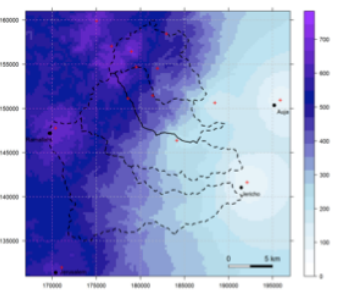
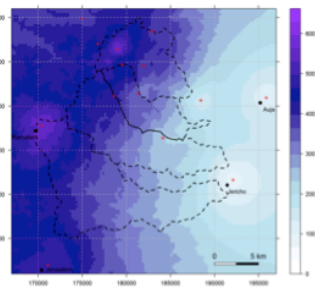
AMI = Antecedent moisture index (-)

1.5 Results

1.5.1 Spatial and temporal distribution of rainfall

Rainfall is known to be highly variable from year to year in the eastern Mediterranean. This is also shown by the SMART rainfall measurements in the Auja-Qilt area. The rainfall amount in 2011/2012 for the Wadi Auja North surface catchment was 483 mm, about double the amount from the winter season 2010/2011. The highest annual precipitation sum was observed in Sinjil (678 mm in 2011/2012), while the lowest amount was registered in Jericho (85 mm in 2011/2012). The spatial and temporal distribution of rainfall in the study area is given in Table 1.4 and Figure 1.7.

Table 1.4: Spatial distribution of interpolated rainfall for the three consecutive hydrological years 2010 – 2013

2010/2011	2011/2012	2012/2013
		
Auja:	241 mm	395 mm
Nueimah:	240 mm	326 mm
Oilt:	250 mm	355 mm

During the measurement period three major runoff events have been observed in the study area. The characteristics of the events are given in the Appendix. All three events resulted in a total runoff volume of 0.82 MCM or respectively 3.8 % of event rainfall. For the complete observation period (winter season 2010/2011 – 2012/2013) runoff accounted for 1.2 % of catchment rainfall, whereby in 2010/2011 no runoff was observed. As already stated by Rofo &

Raffeti (1963), runoff in Wadi Auja needs a certain precipitation threshold to be generated. Only major storms lead to runoff in all ephemeral streams. The observation of a certain minimum rainfall amount is a strong indicator of saturation excess overland flow as the dominant runoff process. Smaller and shorter rainfall events with high intensity have been observed occasionally in Wadi Auja which lead to runoff in subcatchments of Wadi Auja North but did not reach the main catchment outlet. They are assumed to contribute insignificant amounts to the total runoff volume. Figure 1.8 illustrates the daily runoff volume of Wadi Auja North in comparison to Wadi Nueimah and Wadi Qilt for the three consecutive hydrological years 2010–2013.

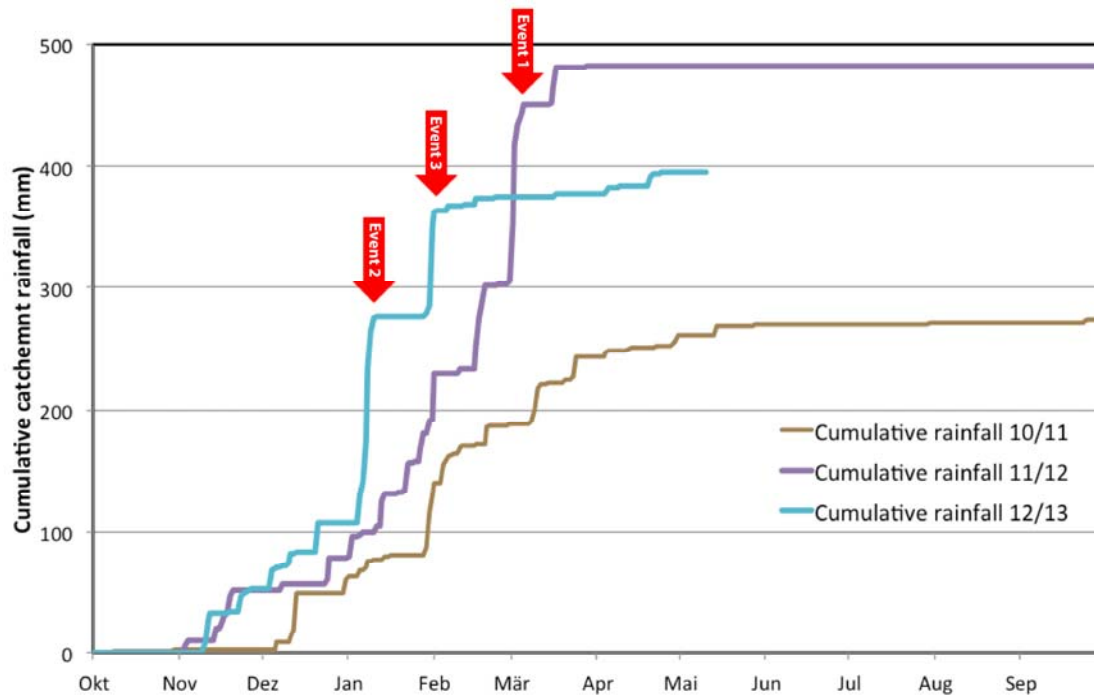


Figure 1.3: Cumulative rainfall for Wadi Auja catchment for the study period. Red arrows indicate major runoff events

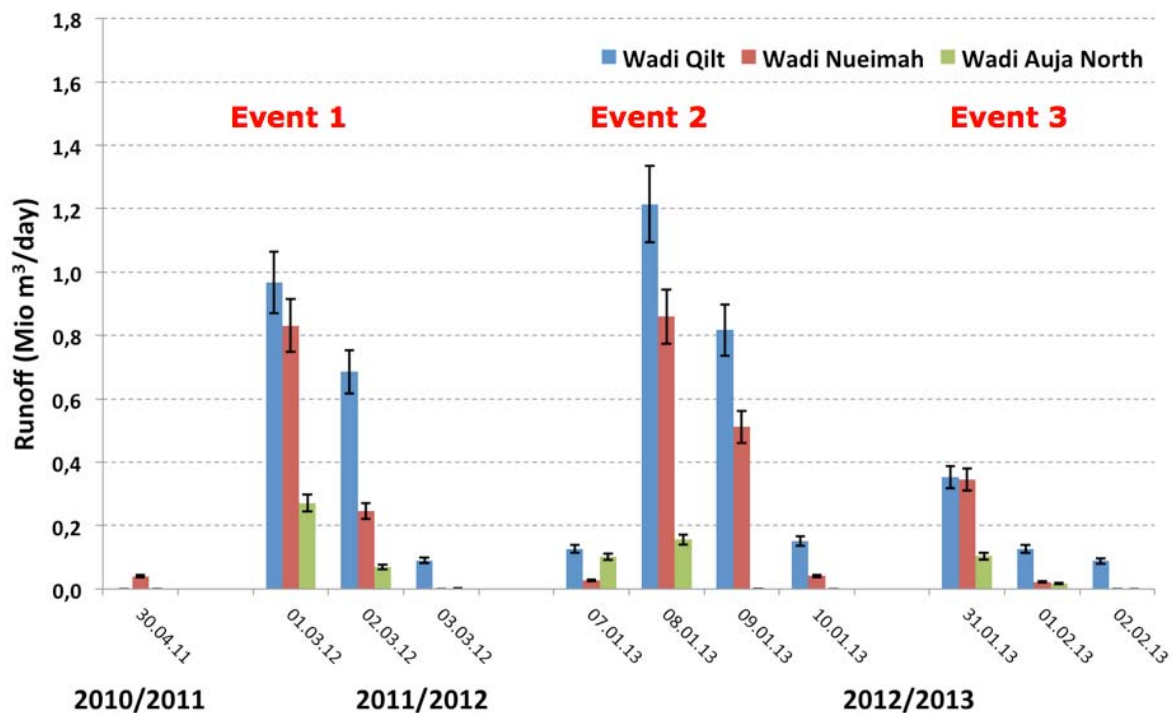


Figure 1.4: Observed runoff events in Wadi Qilt, Wadi Nueimah and Wadi Auja North. Three major runoff events account for nearly hundred percent of the total runoff volume

1.5.2 Results of the hydrological model

The water balance components of Wadi Auja have been simulated for three consecutive hydrological years 2010-2013 with large differences in rainfall quantity and temporal distribution.

Runoff generation processes and mechanisms

The modelled runoff is produced mainly by saturation excess overland flow. Only few time steps of the modelled period show rainfall intensities high enough to exceed the unsaturated hydraulic conductivity of the soils in the catchment. These high intensive rainfalls are more likely to occur at the beginning or the end of the rainy season under dryer catchment conditions which leads to higher transmission losses in the channel stream as on the land surface itself (run-on). During the observation period three major winter storms lead to surface runoff with a relatively high amount of rainfall previous to runoff initialisation. This is an indicator that depending on antecedent moisture conditions a certain rainfall threshold needs to be exceeded to generate runoff. When this threshold is reached and saturated conditions occurred in certain areas, runoff volume and the runoff peak discharge depended on the number of time steps were rainfall intensity surpasses the saturated hydraulic conductivity of the soil layer of certain areas in the catchment. The runoff generation map shows that runoff decreases strongly from west to east due to the rainfall gradient. The highest runoff proportion is generated in urban areas and on sparsely vegetated hillslopes (shrubland) as well as on areas with high outcrop content. No runoff was simulated on agriculturally used valley planes and olive terraces. The thick soil cover on these areas has a high soil water storage volume and is therefore not saturated completely. The distributions of runoff generating areas for the single modelled years are given in Table 1.5.

Quantification of runoff

Observed runoff in Wadi Auja accounted between 0 and 1.7 % of the annual rainfall amount. The runoff coefficient of the three major observed events was between 2.7 % and 4.2 %. The highest peak discharge of around 10 m³/s was measured during the event in March 2012. The mean annual runoff of Wadi Auja North from the three observed years is 0.24 MCM. The model Train-Zin is able to represent the overall runoff behaviour in Wadi Auja. The Nash-Sutcliffe model efficiency for the Wadi Auja weir is between 0.59 and 0.92 and for the subcatchments between -0.33 and 0.97 (see Appendix A for more details). Runoff from single headwater subcatchments for 2012/2013 is partly overestimated which could be an indicator for errors in building terrain classes and their parameterization, which leads to an inadequate representation of the heterogeneity of the hydrological processes in the catchment. For example the reproduction of the slow transition of soil development along the climatic gradient (from west to east) would require a higher number of classes with appropriate parameterization.

Quantification of single water balance components

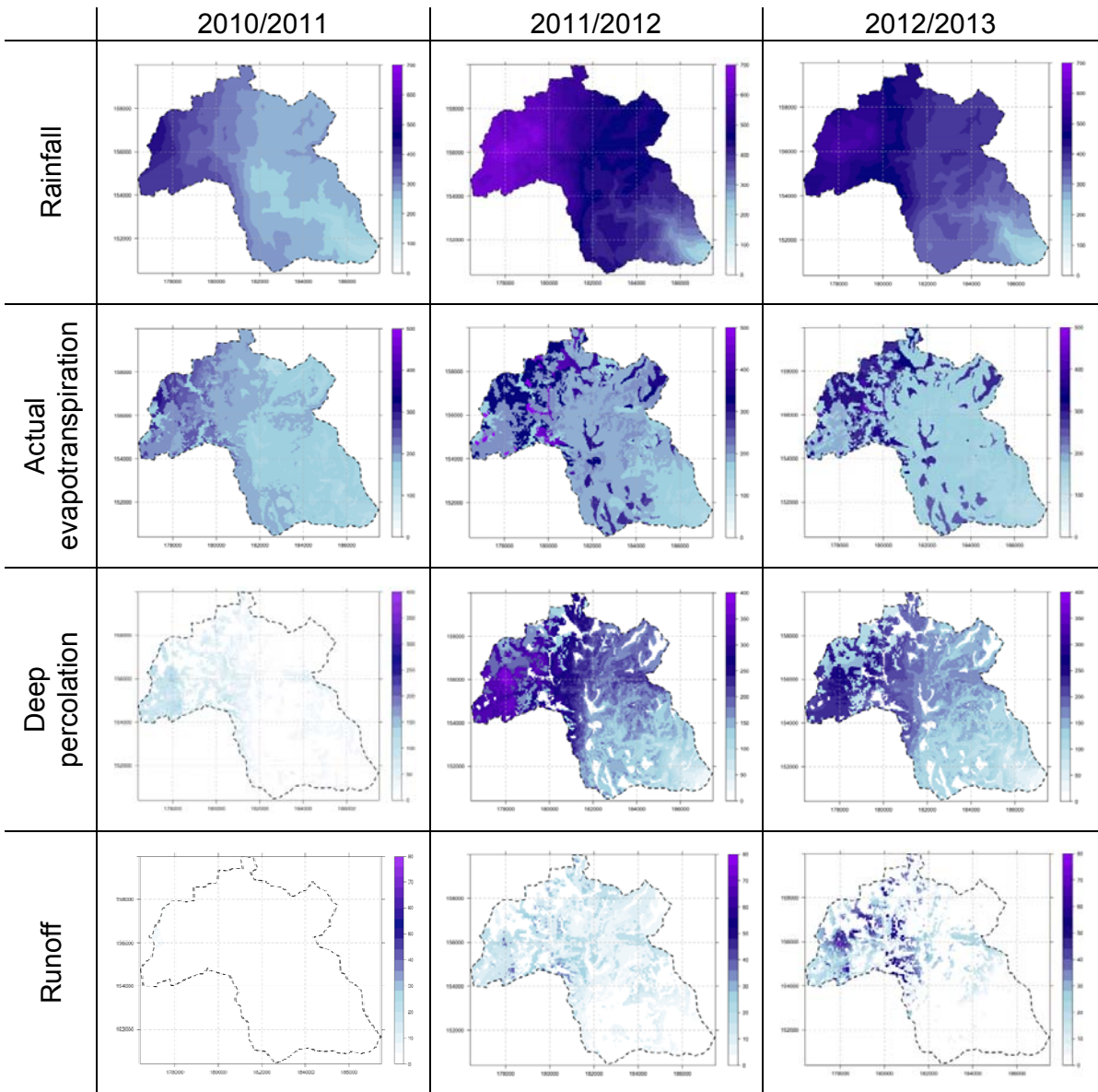
The model results show that all water balance components are highly variable in space and time depending mainly on rainfall amount and spatial distribution, climatic conditions and soil physical properties. The model results of the single water balance components are illustrated in Table 1.5 and Figure 1.9 for the complete model period as well as Figure and Figure in the appendix for runoff of the single hydrological years.

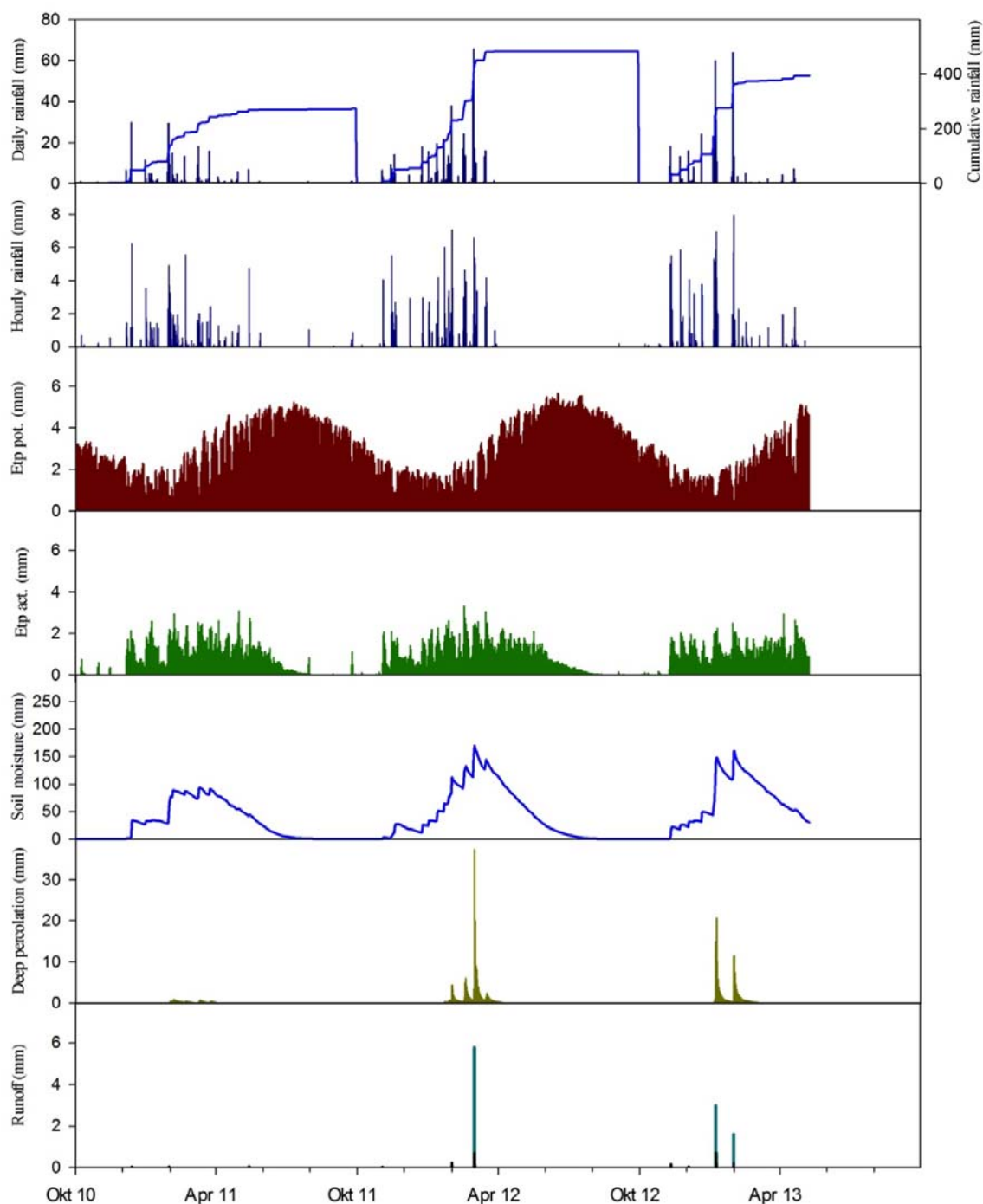
In 2010/2011 precipitation in Jerusalem was about 60% of annual average and no rainfall event was intensive enough to produce runoff in the observed catchments. Soil moisture remained most of the time below field capacity, which explains the low recharge amounts. The model simulates no runoff in that year and about 22 mm (1.2 MCM) of deep percolation (recharge). This is in accordance with Auja spring discharge data (Schmidt, 2013).

In the hydrological year 2011/2012, rainfall was slightly above mean annual average with one major rainfall event in February/March 2012. Runoff was generated in all observed catchments (0.34 MCM over three days in Wadi Auja North). The modelled daily discharge in Wadi Auja has a Nash-Sutcliffe efficiency (NSE) of 0.92. With the exception of one tributary close to Ein Samia (here NSE is -0.18 because of a convective rainfall event mid of March with insufficient spatial rainfall registration) all subcatchments reached similar NSE-values. Soil moisture exceeded several times the field capacity threshold and therefore considerable recharge occurred (170 mm or 9.35 MCM). The modelled recharge areas are mainly in the upper part of the catchment receiving the highest rainfall amounts. Modelled recharge fits well again with measured spring flow in Wadi Auja for the year 2011/2012 (Schmidt, 2013).

During winter 2012/2013, rainfall was close to average with two runoff generating rainfall events in the beginning and end of January 2013 (0.26 and 0.12 MCM). During these events field capacity of the soil was exceeded and high recharge rates were simulated (135 mm or 7.4 MCM). Modelled daily discharge in the headwaters was overestimated and had low NSE values (-0.33 - 0.47) while the NSE for the whole catchment was 0.59.

Table 1.4: Model results for the single water balance components for the period 2010-2013





	2010/2011	2011/2012	2012/2013
Rainfall	290 mm	486 mm	400 mm
Etp act.	268 mm	308 mm	259 mm
Deep perc.	22 mm	170 mm	135 mm
Runoff	0 mm	6 mm	6.9 mm

Figure 1.5: Mean daily values of the catchment water balance components

1.6 Conclusions

Runoff in Wadi Auja shows high temporal and spatial variability within the study area. It is strongly dependent on event precipitation amounts and intensities over short periods. For the generation of runoff, rainfall has to reach certain thresholds depending mainly on the antecedent soil moisture. Data from spring discharge indicates that recharge occurs mainly during heavy rainfall events when field capacity of the soil is reached and water can move deeper into the unsaturated zone and the bedrock. The runoff amounts measured for the catchment area of Wadi Auja were low compared to the neighbouring Wadis Nueima and Qilt, presumably due to the higher percentage of outcropping impermeable rocks in those catchments. A detailed analysis of the different runoff responses of these catchments remain subject of further research.

The hydrological model Train-Zin uses physically based, spatially distributed parameters for the simulation of the water balance components. As runoff and recharge processes occur over short periods, high-resolution rainfall data is required. The model results of the three hydrological years are promising. For better results of modelled discharge the transition of soil physical properties along the strong climatic gradient within the study area should be included in more detail. The application of the model on longer rainfall time series could give more insights on how the water balance components react on rainfall amounts and temporal distribution which are expected to change in the Mediterranean in the coming decades.

2. Local hydrological models and quantification of runoff for sub-basin Qilt- Nueima

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2.1 Introduction

The aim was groundwater modelling of the catchment areas of Wadi al Arab (Jordan) and of Wadi Qilt (Westbank / Israel) (Figure 2.1). An important input parameter of the groundwater model is the information of groundwater (gw) recharge. Therefore hydrological models (J2000g) were developed for both catchments in order to quantify the gw recharge. The HRU-grid of the hydrological models was extended to the area of the subsurface groundwater catchment of the study areas.

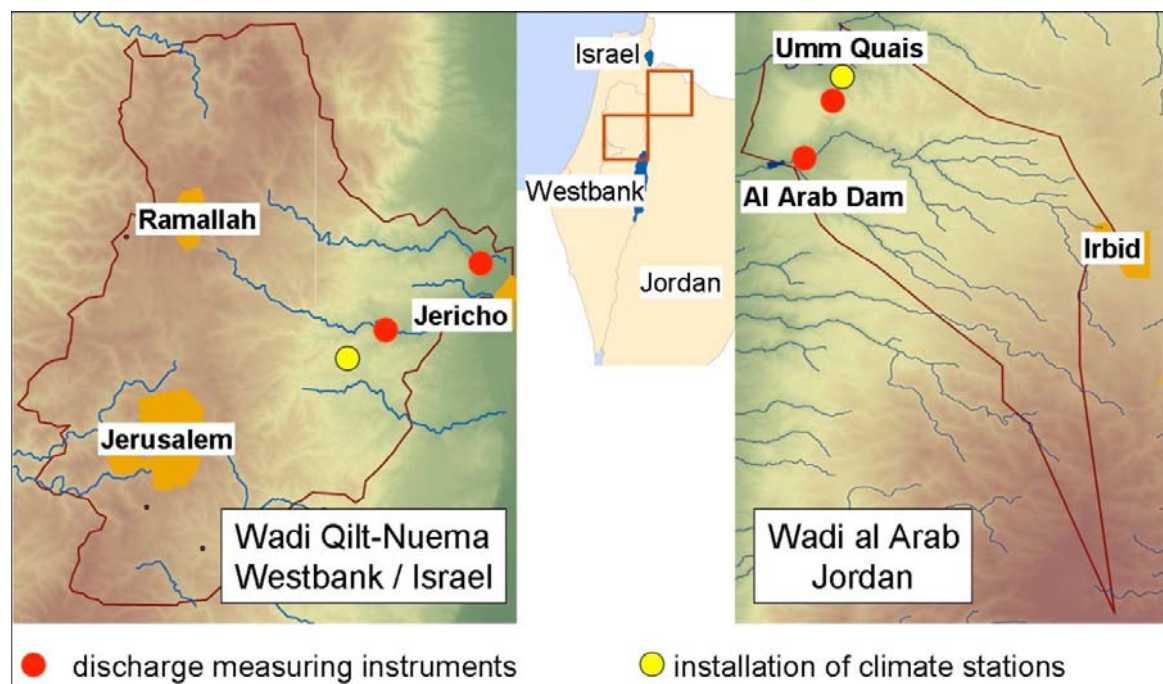


Figure 2.1: Location of discharge measuring instruments and installed climate stations in the study area of Wadi Qilt-Nuema and Wadi al Arab

The hydrological model J2000g

The hydrological model J2000g is a process-oriented distributed rainfall-runoff model to estimate spatially distributed hydrological water balance components (Krause and Hanisch, 2009, Krause et al. 2010). J2000g is implemented within the modular oriented JAVA framework system JAMS (Jena Adaptable Modelling System) (Kralisch and Krause, 2006).

The model expects daily or monthly meteorological input data (rainfall, temperature, sunshine duration, relative humidity, wind speed) and spatially distributed information about the topography, soil types and landcover to describe the physio-geographical conditions of the study area. The values of the soil-parameter are defined by soil-specific physical conditions such as field capacity, thickness, hydraulic conductivity and capacity of capillary rise of water. The catchment is distributed in hydrological homogenous entities named Hydrological Response Units (HRU). HRUs are delineated by GIS overlay analysis of relevant spatially distributed information. Based on GIS derived information each HRU is then described by its elevation, slope, aspect, land-cover type and soil type. These information are provided by ASCII data tables for the modelling system (Figure 2.2).

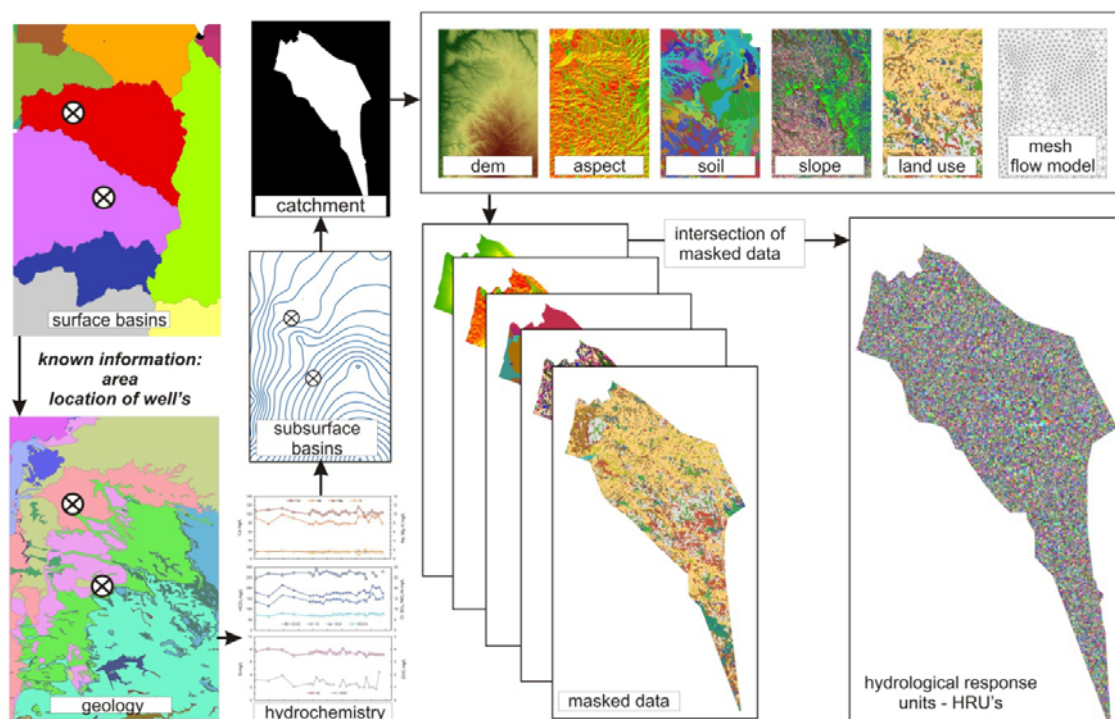


Figure 2.2: Procedure of the hydrological response units approach by JAMS

J2000g calculates for each HRU and each modelling time step the climatological input by spatial interpolation using inverse-distance-weighting and optional elevation correction. The regionalised input data is further used to estimate water balance components, i.e. evapotranspiration, soil water balance and groundwater recharge. Catchment runoff is calculated by spatially weighted summation of the single HRU output fluxes, i.e. direct runoff and baseflow.

Potential evapotranspiration (PET) is calculated with the Penman-Monteith formula as described in Allen et al. (1998). To account for uncertain input data a multiplicative calibration parameter (β) can be used to increase or decrease of the potential evapotranspiration for all HRU by the same relative amount.

The central element of the J2000g water balance is the soil water storage capacity (SWS). The maximum soil water storage capacity (maxSWS) is parameterised using the effective field

capacity FC of the soil horizons within the rooting zone (depth) RD.

With the calibration parameter FCA the maximum soil water storage capacity (maxSWS) can be increased or decreased by the same relative amount for all HRU.

During the simulation the incoming precipitation is added to SWS as long as it is not at the maximum soil water storage capacity (maxSWS). Beyond this point, additional water is first used for evapotranspiration up to the calculated potential evapotranspiration (PET). If there is still an evapotranspiration deficit (ΔET) parts of the soil water storage can be used to decrease this deficit. For this case ΔET is evaluated against the relative storage capacity of the soil and calibrated with the parameter ETR as:

$$\Delta ET = \square ET * actSWS / (ETR * maxSWS) \quad \text{Eq. 2.1}$$

The calibration parameter ETR can be used for the modification of the evapotranspiration deficit ($\square ET$) by the same relative amount for all HRU. Precipitation exceeding the soil water storage capacity and the reduction by evapotranspiration is considered to produce runoff from the HRU. This excess water (EW) is portioned into a direct runoff component (DQ) and groundwater recharge (GR) based on the slope (α) and a calibration parameter (LVD) (Equation 2 and 3). The larger LVD is the more direct runoff is generated whereas smaller values result in a larger amount of groundwater recharge.

$$DQ = \tan \alpha * LVD * EW \quad \text{Eq. 2.2}$$

$$GR = (1 - \tan \alpha) * LVD * EW \quad \text{Eq. 2.3}$$

By assigning a maximum possible percolation rate per time step the GR can be limited to an upper threshold. This maximum percolation rate has to be defined for each hydrogeological unit. These values can be further adapted during model run time with a calibration parameter. The model assumes that direct runoff leaves the catchment within one time step whereas the groundwater component can have a much larger residence time. To provide reliable estimates of the groundwater response two groundwater storages (GWS1,2) are integrated into the model to allow the simulation of an aquifer with a double porosity. The generated groundwater recharge is partitioned between the two storages with the calibration coefficient γ . An overview about the different process units of JAMS is shown in Figure 2.3.

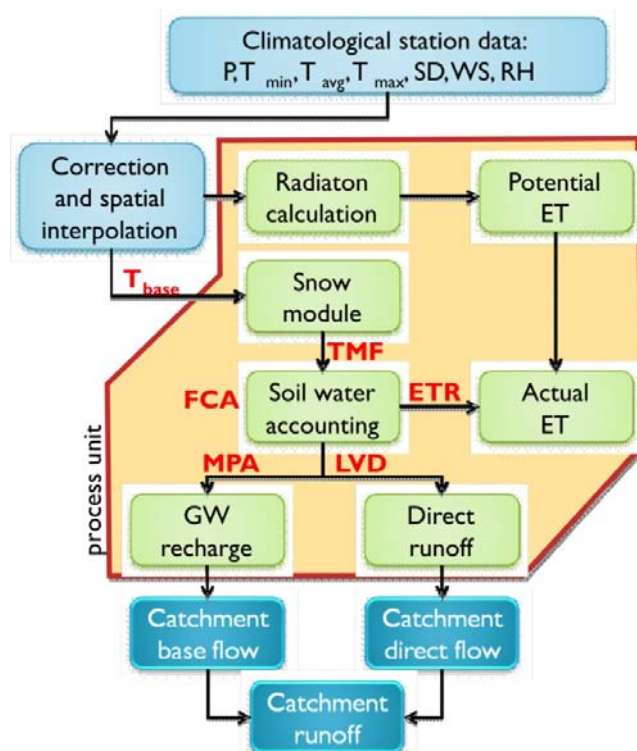


Figure 2.3: The internal program scheme of the soil moisture model JAMS

2.2 Study area – Wadi Nuema Qilt

The catchment of Wadi Qilt-Nueima is located in the central mountainous area of the West Bank, northeast of Jerusalem. The about 200 km² large surface catchment extends from Jerusalem eastward through the Judean Mountains into the plain of Jericho. The subsurface groundwater basin is nearly 760 km² large (Figure 2.4).

The hydrological features of the study area are the aquifers of the Lower (Lower Cenomanian) and the Upper Judea Group (Upper Cenomanian - Turonian). The highest elevated region in the west and the entire western water divide is dominated by a large N-S directed anticline. From there, the strata dip generally towards the east, the reason why the deposits of the Lower JGA crop out in the western part of the catchment area. Towards the Lower Jordan Valley, the layers of the Upper JGA cover the Lower JGA. Close to the Jordan Valley, the base of the Senonian Mount Scopus Group is preserved on the top of the Upper JGA. The drinking water supply is based on both aquifers.

Fractured bedrock and variable karstified rocks represent the Judea Group. The high permeable conditions are controlled by the high tectonics activity of the region and the sedimentary facies and architecture. In the outcrop area both aquifers are characterized as unconfined. Local confined conditions occur where clayey or marly depositions intervene. However, towards the Lower Jordan Valley, the hydrological conditions change from unconfined to confined, forced by the covering low permeable layers. The hydraulic heads fall from above 650 m msl to -50m msl and regional flow directions are eastwards. The groundwater flow patterns show generally no

hydraulic connection to wadis.

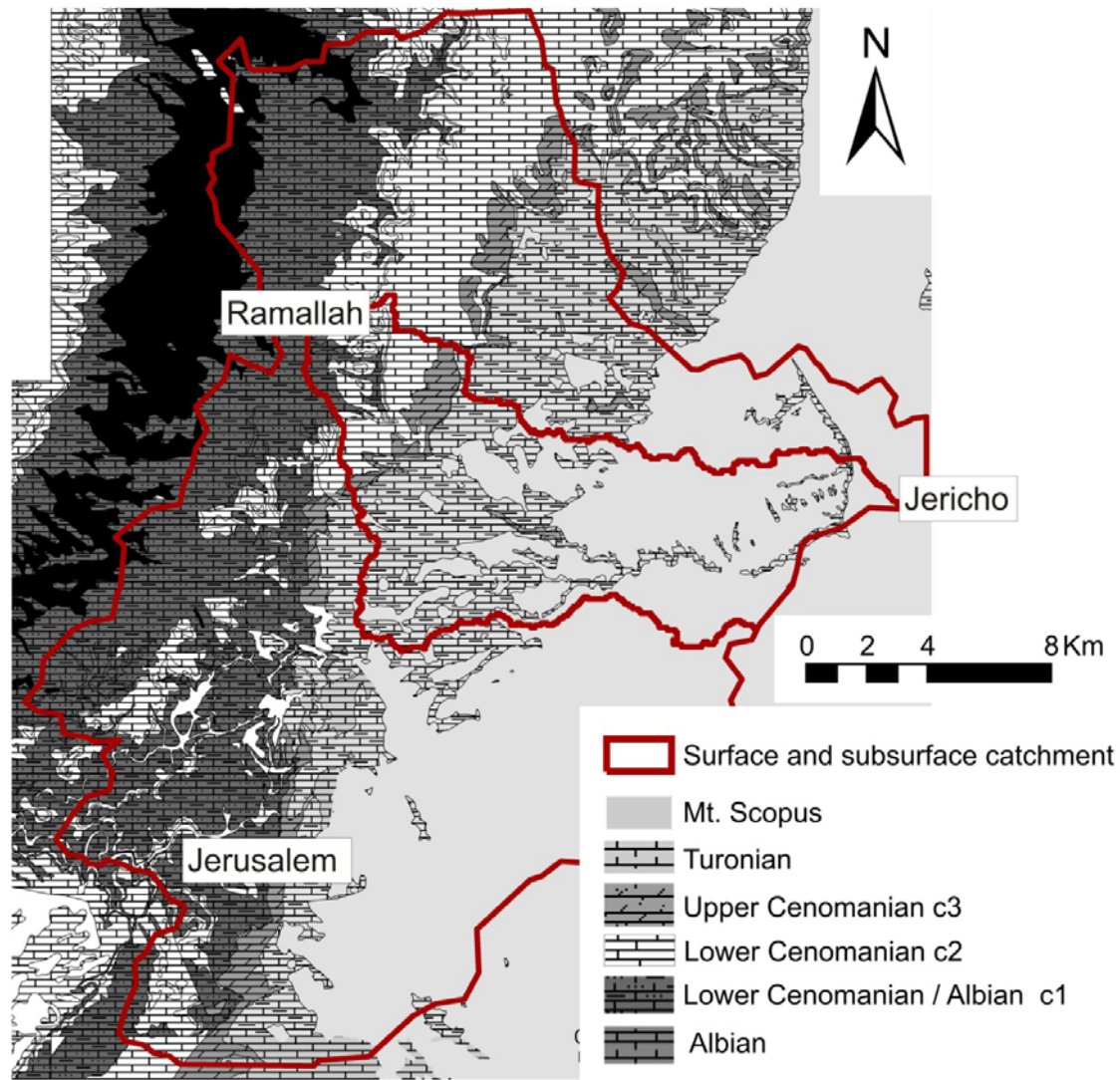


Figure 2.4: Overview about the geology and the extension of the subsurface and surface catchment area of Wadi Qilt

The irregular distribution of annual precipitation ranges from more than 1000 mm on the top of the Judea Mountains to 50 mm and less in the Jordan Valley. Hence, the recharge area is strong delimited to the high-elevated outcrop areas of the aquifers in the western parts of the study area.

2.3 Conceptual model

The conception of the hydrological model was set in the size of the groundwater flow model. Groundwater watersheds surround the subsurface catchment area. Subsurface outlet of the catchment area is the discharge of the Lower and Upper JGA aquifer to the Jordan Valley. The surface runoff of Wadi Qilt occurs only periodical as the result of rare but heavy rainfall events. Continuous baseflow is only existent in the case of the Ein Perrat and Ein Qilt spring system. The generation of surface runoff is subjected to the known process like infiltration excess, saturation excess and infiltration. The main control parameters of these processes are slope,

aspect, land use, soil parameter and percolation rate. Groundwater recharge is only possible about infiltration processes (Figure 2.5).

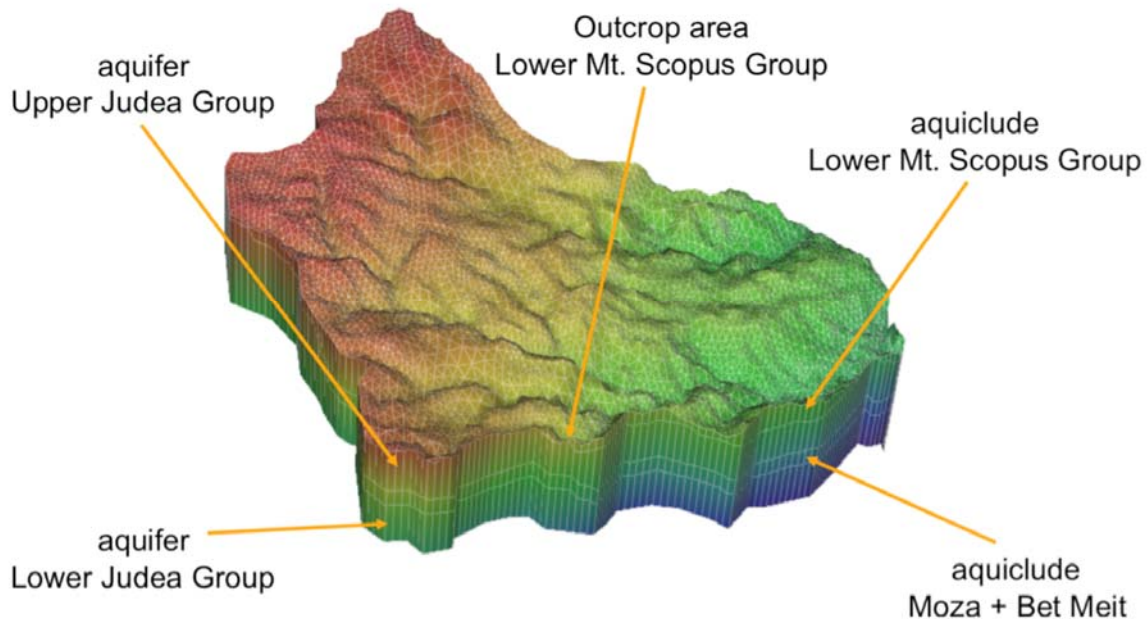


Figure 2.5: Build-up process of conceptual model in progress

2.4 Model setup

For the spatial discretisation of the catchment a HRU mesh of irregular triangular elements with a mesh resolution between less meters and 400x400 m. Based on the HRU mesh spatially distributed parameters describing the HRUs were derived from a GIS along with a priori literature values.

Topographical parameters (slope, aspect and elevation) were obtained from a digital elevation model (DEM 25 x 25 m). Slope was reclassified into four groups (I: 0°-5°, percentage of area (A) = 8.7%; II: 5°-15°, A = 63.3%; III: 15°-30°, A = 27.7%; IV: 30°-90°, A = 0.3%) according to Tilch et al. (2002). Aspect was classified into eight classes by 45° segments (NNE, A = 13.8%; NEE, A = 14.87%; EES, A = 14.5%; ESS, A = 14.2%; SSW, A = 13.3%; SWW, A = 10.7%; WWN, A = 8.4%; WNN A = 9.4%; -1, A = 0.9%).

Land cover information was obtained from different field campaign and from a classification of an ASTER image from May 2000. By the classification 8 major and 15 sub classes were distinguished according to the dominant plant types (Table 2.1). Vegetation specific parameters like leaf area index or stomata resistance were estimated from literature values (Acherar and Rambal, 1992; Baldocchi et al., 2004; Kergoat, 1998; Körner, 1994; Niinemets et al., 2005; Rhizopoulos and Mitrakos, 1990; Schulze et al., 1994; Dorman and Sellers, 1989; Wilson and Henderson-Sellers, 1985) (Table 2.1).

Table 2.1: Land cover parameters of the hydrological simulation

Land cover / subclasses	Area %	Surface resistance of the land cover (s/m) (literature)	Leaf Area Index (m^2/m^2) (literature)
Impervious areas (dense + light)	5.5	10 - 30	-
Agriculture (cultivated + non cultivated)	42.6	67 -1000	0 - 1
Water	0.01	10	-
Rocks	12.2	70	-
Shrubs	4.6	102 - 323	4 - 5
Forest (coniferous + deciduous)	1.2	118 - 667	4 - 7
Rangeland (grass / hill grass (very light) / bare soil)	33.8	70 – 1000	0 – 1.6
Olive orchards	0.1	100 - 1000	3

In combination of the Israeli soil map classified by Dan et al. (1977) and the soil description by Singer (2007) 10 main soil classes and 18 subclasses were digitized. The classes can be distinguished by grain size, porosities, field capacities and depth (Table 2.2). The maximum percolation capacities for the geological units were derived from Berndtsson & Larson (1987). For the HRU grid all input parameters were overlaid and intersected, which resulted in spatially discriminated outputs.

Table 2.2: Soil parameters of the hydrological simulation depend on Israeli soil map by Dan et al. (1977) and Singer (2007)

Soil group / amount of subclasses	Area %	Depth (cm)	Field capacity (mm)
Terra Rossa / 2	53.2	40 - 90	180 – 405
Brown rendzinas and pale rendzina / 2	5.1	50 - 120	223 - 535
Brown Mediterranean Forest Soils / 4	15.5	40 - 140	134 - 630
Rendzina Soils of Mountains / Pale Rendzina / 1	5.1	40 - 90	129 - 290
Alluvial Soil / 3	4.2	90 - 160	290 - 720
Rendzina Soils of Valleys / Calcareous Serozems / 1	1.6	170	704
Coastal Sand Dunes, Regosols / 1	7.1	200	340
Hammada Soils of Mountain / Plateau Reg Soils / 1	0.1	30	43
Hammada Soils of Plains / Valley Reg Soils / 1	0.01	80	80
Loess Raw soils / Silty Loessial Serozems / 1	8.3	170	195

Available climate and rain data are given in Table 2.3. Due to the temporal resolution of the

scarce calibration data, monthly time steps for the period of January 1978 to November 2010 were chosen for precipitation, relative humidity, relative sunshine duration, and temperature and wind velocity.

Table 2.3: Climate and rain stations for the model setup

Location	Station	Time period	Unit
Sdom*	Climate	1978 - 2010	monthly
Sdeboker*	Climate	1978 - 2009	monthly
Gilgal*	Climate	1989 - 2009	monthly
Arad*	Climate	1978 - 1993	monthly
Dragot*	Climate	2006 - 2009	daily
Asify Bar BetGovrin ⁺⁺	Climate	2008 - 2009	daily
Givat Canada Jerusalem ⁺⁺	Climate	2003 - 2010	daily
Beer Sheva ⁺⁺	Climate	1977 - 2010	daily
Jerusalem ⁺⁺	Climate	1977 - 2010	daily
Ramat David ⁺⁺	Climate	1977 - 1991	daily
Mizpe Yeriho [#]	Climate	2007 - 2009	daily
Nablus ^{**}	Rain Gauge	2007 - 2009	monthly
Jenin ^{**}	Rain Gauge	2007 - 2009	Monthly
Hebron ^{**}	Rain Gauge	2007 - 2009	monthly
Tulkarem ^{**}	Rain Gauge	2007 – 2009	monthly
Bethlehem ^{**}	Rain Gauge	1996 - 1997	monthly
Doma ^{**}	Rain Gauge	1999	monthly
Al Arrub ⁺	Rain Gauge	1967 - 1997	monthly
Anata ⁺	Rain Gauge	1967 - 1987	monthly
Beit Jala ⁺	Rain Gauge	1967 - 1987	monthly
Al Hashmiyyah ⁺	Rain Gauge	1967 - 1997	monthly
Deir Dibwan ⁺	Rain Gauge	1967 - 1997	monthly
Hizma ⁺	Rain Gauge	1967 - 1987	monthly
Sinji ⁺	Rain Gauge	1967 - 1995	monthly
Shufat ⁺	Rain Gauge	1972 - 1989	monthly
Al Quds ⁺	Rain Gauge	2004 – 2007	monthly
Qaryut ⁺	Rain Gauge	1968 – 1997	monthly
Jericho ^{+,#}	Rain Gauge	1967 - 2010	monthly

*data source: *Israel Metrological Survey; *Palestine Metrological Survey; ⁺⁺web source (www.wunderground.com; www.tutiempo.net; http://pc105.narc.affrc.go.jp/metbroker/); [#]own data; ⁺data of SMART project partners given in DAISY: www.ufz.de/index.php?de=16882;*

2.4 Modelling result

The model simulation period was set up for a time series from 1978-2010. Because of less runoff data the classical procedure of model calibration and validation was restricted usable. Therefore the calibration based also on the chloride mass balance (CMB) and gauged spring discharge (GSD) methods for the gw recharge on different spring systems in the catchment. The presented model approach of J2000g has the ability to reflect the major hydrological processes of the catchment, including the simulation of a double porosity aquifer system. The simulated groundwater recharge correlates well with the results of gw recharge by CMB and GSD (Roediger et. al. (2009)). The simulation results are summarized in Table 2.4.

Table 2.4: Results of water budget simulated by J2000g in depend on the catchment scale

Catchment (km ²)	Precipitation (P) (mm/yr)	actual Evaporation (E) (mm/yr)	GW recharge (R) (mm/yr)	Direct runoff (RD) (mm/yr)
Qilt surface (163)	403	311	77	15
Qilt subsurface (761)	481	345	112	24
Perrat system (23)	466	340	105	21

Figure 2.6 shows the regionalized annual precipitation, the simulated annual groundwater recharge, the actual evaporation and the direct runoff by the separated response units for the modelling period. Used rain stations for the simulation are shown in the precipitation plot.

The precipitation map shows a good reproduction of the rainfall gradient, with higher values > 600 mm/yr in the western mountain area and lower values 135 mm/yr close to the Jordan Valley. The recharge plot illustrates the consistency connection between precipitation and groundwater recharge in the study area. The groundwater recharge follows in the same gradient like the precipitation. High values of 225 mm/yr groundwater recharge are connected on the hilly parts of the catchment. In the environment of the Lower Jordan Valley the groundwater recharge decrease less than 25 mm/yr. The simulated results of the actual evaporation reflect also the connection to the precipitation. High values are concentrated in the mountain areas, where a high amount of water is available. Deep valley sections are characterized by > 25 mm/yr and represent the surface discharge in the study area.

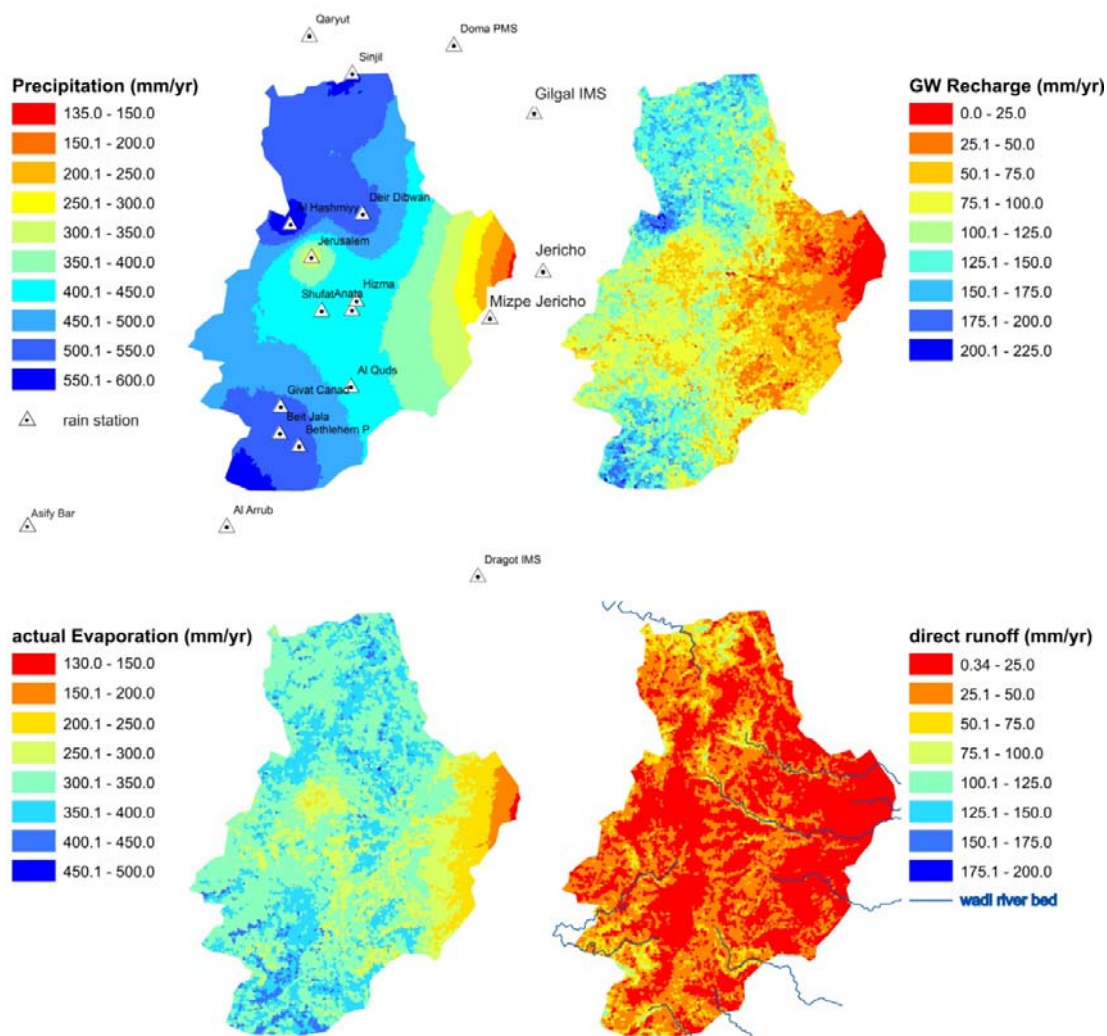


Figure 2.6: Regionalized precipitation, simulated groundwater recharge, actual evaporation and direct runoff by J2000g for the Wadi Qilt catchment.

The final simulated components are shown in Figure 2.7. Both figure illustrated the dynamic of precipitation with rain and dry seasons in the time 1978 - 2010. It is detectable that the years 1998 and 1999 were the driest years and that the years 1983, 1992 and 2003 were the wettest years in the simulated period. Figure A and B demonstrated expectedly that the dynamic of groundwater recharge (black line) and of flash flood events (black line) are strong related to dynamic of rainfall. In figure A is obvious that a rain amount of over 100 mm/month is necessary to produce groundwater recharge. In contrast figure B show that a rain amount of over 115 mm/month is the lower limit for the creation of flash flood events.

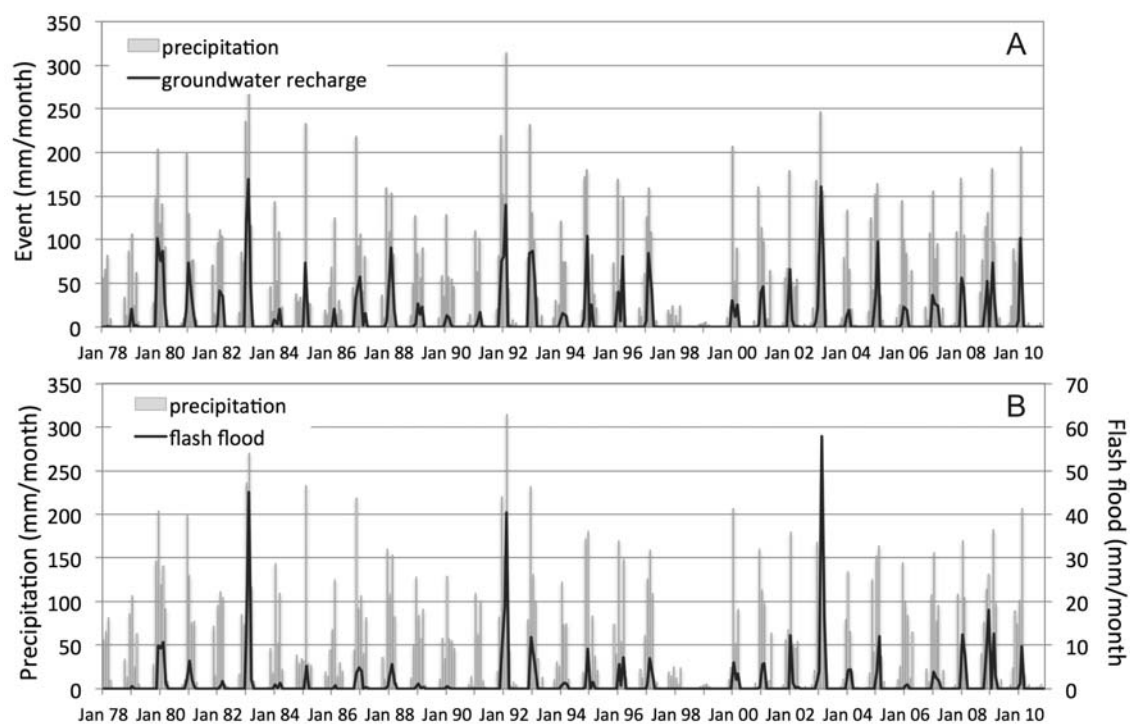


Figure 2.7: Final simulated precipitation (grey column A,B), groundwater recharge (black line A) and flash flood (black line B) by J2000g for the Wadi Qilt catchment (Year 1978 – 2010)

3. Local hydrological models and quantification of runoff for sub-basin Wadi Al Arab

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3.1 Study area- Wadi Al Arab

Wadi al Arab is a semi-arid catchment in NW Jordan (Figure 3.1) and is located between the Yarmouk River valley in the north, the Jordan River Valley in the west, the foothills of the Ajlun Dome in the south and the branch of the Azraq plain in the east. The altitude varies from -20 m a.s.l. in the Jordan River Valley to more than 1100 m a.s.l. in the mountain range of the Ajlun. The surface catchment area covers about 200 km², whereas for the groundwater catchment an area of about 300 km² was estimated (Figure 3.1). Important perennial springs are only existent in the Eastern part of the study area. Wadi al Arab begins west of Irbid, the second largest city of Jordan and runs northwest. Close to the perennial spring region the Wadi changes its direction and leaves the study area to the SW.

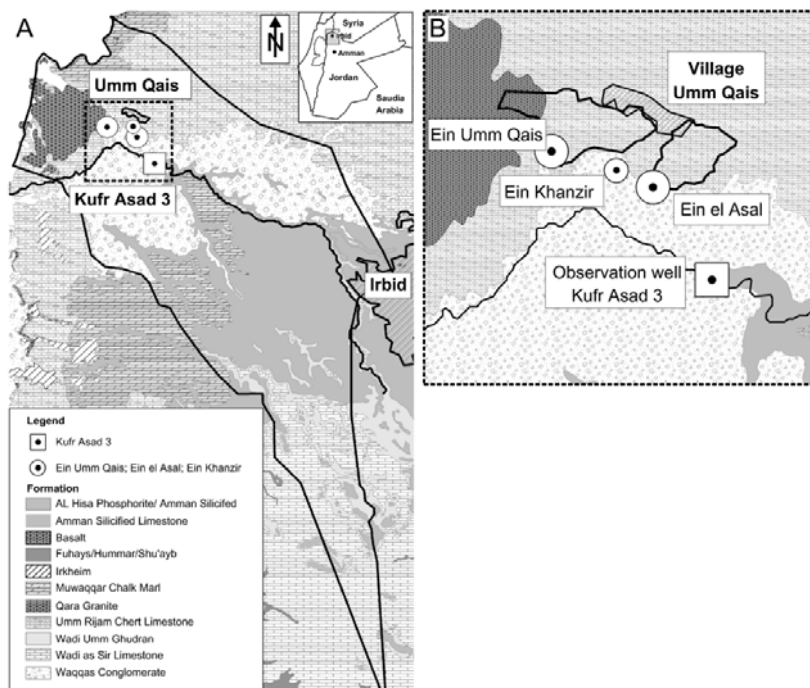


Figure 3.1: A) The extension of the groundwater catchment area (black line), B) the position of the perennial springs (Ein Umm Qais (gw catchment area black line), Ein el Asal (gw catchment area black line) and Ein Khanzir), the observation well Kufr Asad 3 and the built-up area of Umm Qais are shown.

The annual precipitation varies between less than 200 mm and more than 500 mm. The largest

part of the annual rainfall falls during the rainy season from October to April. In this period about 80% of the rainfall is concentrated on the time between December and February. In many years the entire annual precipitation amount falls on one single day resulting in very high rainfall intensities. The average daily temperature is about 12.5 °C during the winter season (from November to April) and around 23.0 °C during the summer season (from May to October).

The geological underground of the catchment is represented by fractured and karstified Upper Cretaceous aquifers. The upper part of the limy Ajlun Group (A7) and the lower units of the Belqa Group (B1+B2) are the main productive aquifers for water supply in the study area. The A7/B2 aquifer is hydraulically separated from the locally productive B4 aquifer by the Muwaqqar aquitard (B3). Because of a north westward dip of all formations, the Muwaqqar formation overlays the main productive aquifers and the hydrological conditions change from unconfined to confined in direction SE to NW. The main outcropping geologic units and their formations in the study area are also shown in Figure 3.1.

3.2 Conceptual model

The conception model was set in depending of the size of the groundwater model of al Arab. Groundwater watersheds surround the subsurface catchment area. Subsurface outlets of the catchment area are the Yarmouk gorge in the NW and the discharge of the A7-B2 aquifer the border to the Jordan Valley. In Wadi al Arab surface runoff occurs only periodical as the result of rare but heavy rainfall events and continuous baseflow is not existent. The generation of surface runoff is subjected to the known process like infiltration excess, saturation excess and infiltration. The main control parameters of these processes are slope, aspect, land use, soil parameter and percolation rate. Groundwater recharge is only possible about infiltration processes.

3.3 Numerical model setup

For the spatial discretisation of the catchment a HRU mesh of irregular triangular elements with a mesh resolution between 50x50 m and 400x400 m. Based on the HRU mesh spatially distributed parameters describing the HRUs were derived from a GIS along with a priori literature values.

Topographical parameters (slope, aspect and elevation) were obtained from a digital elevation model (DEM 25 x 25 m). Slope was reclassified into four groups (I: 0°-5°, percentage of area (A) = 14.1%; II: 5°-15°, A = 51.3%; III: 15°-30°, A = 26.7%; IV: 30°-90°, A = 7.9%) according to Tilch et al. (2002). Aspect was classified into eight classes by 45° segments (NNE, A = 17.0%; NEE, A = 8.7%; EES, A = 4.4%; ESS, A = 6.9%; SSW, A = 13.6%; SWW, A = 14.7%; WWN, A = 14.5%; WNN A = 14.5%; -1, A = 5.8%).

Table 3.1: Land cover parameters of the hydrological simulation

Land cover / subclasses	Area %	Surface resistance of the land cover (s/m) (literature)	Leaf Area Index (m^2/m^2) (literature)
Impervious areas (dense + light)	2.8	10	-
Agriculture (cultivated + non cultivated)	23.8	50 -1000	0 - 1
Water	0.2	10	-
Rocks	4.7	10	-
Shrubs	3.3	102 - 323	4 - 5
Forest (coniferous + deciduous)	1.6	118 - 556	4 - 7
Rangeland (grass / hill grass (very light)	60.0	60 – 1000	0 – 1.6
Olive orchards	3.6	150 - 1250	3

Table 3.2: Soil parameter of the hydrological simulation depend on the National Soil Map of Jordan (Ministry of Agriculture, Jordan, 1994)

Soil Class / amount subclasses	Area %	Depth (cm)	Field capacity (mm)
Vertisols; Entic Chromoxererts / 2	4.87	98 - 110	178.5 – 200.7
Inceptisols; Typic Xerochrepts / 10	63.24	50 - 120	97.2 – 212.2
Inceptisols, Lithic Xerochrepts / 1	7.81	60	101.4
Inceptisols, Vertic Xerochrepts / 1	0.42	100	182.5
Inceptisols, Calcixerollic Xerochrepts / 1	3.47	80	189.9
Entisols, Lithic Xerorthents / 3	17.95	40 - 70	73.0 – 162.0
Ardisols, Ustochreptic Camborthids / 1	0.52	90	164.2
Ardisols, Ustollic Camborthids / 1	1.72	90	175.5

Land cover information was obtained from different field campaign and from a classification of an ASTER image from May 2000. By the classification 8 major and 13 sub classes were distinguished according to the dominant plant types (Table 3.1). Vegetation specific parameters like leaf area index or stomata resistance were estimated from literature values (Acherar and Rambal, 1992; Baldocchi et al., 2004; Kergoat, 1998; Körner, 1994; Niinemets et al., 2005; Rhizopoulos and Mitrakos, 1990; Schulze et al., 1994; Dorman and Sellers, 1989; Wilson and Henderson-Sellers, 1985) (Table 3.2). From the National Soil Map of Jordan (Ministry of Agriculture, Jordan, 1994) 8 main soil classes and 20 subclasses were digitized. The classes can be distinguished by grain size, porosities, field capacities and depth (Table 3.3).

Table 3.3: Climate stations for the model setup

Location	Parameter	Time period	Unit
Irbid (AE 0001)*	Rain	1937 - 2005	mm/d
Irbid (AE 0002)*	Rain	1954 - 2007	mm/d
Kufr Yuba (AE 0003)*	Rain	1937 - 2006	mm/d
Kufr Asad (AE 0004)*	Rain	1962 - 2006	mm/d
Al-Taiyiba (AB 0001)*	Rain	1937 - 2006	mm/d
Deir Abi Said (AB 0002)*	Rain	1937 - 2006	mm/d
Umm Quais (AD 0005)*	Rain	1937 - 2006	mm/d
Kharja (AD 0008)*	Rain	1937 - 1999	mm/d
Husn (AD 0010)*	Rain	1995 - 2006	mm/d
Ibbin (AD 0018)*	Rain	1995 - 2006	mm/d
Baqura (AD 0032)*	Rain	1995 - 2006	mm/d
Rihaba (AF 0002)*	Rain	1995 - 2004	mm/d
Ras Muneef (AH 003)*	Rain	1995 - 2005	mm/d
Umm Quais [#]	Climate	2007 – 2009	mm/d
Irbid ⁺⁺	Climate	1980 – 2009	mm/d
Queen Allia airport ⁺⁺	Climate	1980 – 2009	mm/d
Bet Shean (Metbroker) ⁺⁺	Climate	1961 - 2000	mm/d

*data source: *Ministry of Water and Irrigation, pers. Comm.(given in DAISY: www.ufz.de/index.php?de=16882); ++web source (www.wunderground.com; www.tutiempo.net; <http://pc105.narc.afrc.go.jp/metbroker/>); #own data*

The maximum percolation capacities for the geological units were derived from Berndtsson & Larson (1987). For the HRU grid all input parameters were overlaid and intersected, which resulted in spatially discriminated outputs.

Available climate and rain data are given in Table 3.3. Due to the temporal resolution of the scarce calibration data, monthly time steps for the period of January 1980 to December 2008 were chosen for precipitation, relative humidity, relative sunshine duration, and temperature and wind velocity.

3.4 Modelling results

The model simulation period was set up for a time series from 1980-2008. Because of insufficient runoff data the classical procedure of model calibration and validation was not applicable. Therefore, a multi-response technique was used to reduce the scarce data situation. The multi-response calibration is based upon the chloride mass balance (CMB), water table fluctuation (WTF) and gauged spring discharge (GSD) methods. The presented model approach of J2000g has the ability to reflect the major hydrological processes of the catchment, including the simulation of a double porosity aquifer system. The simulated groundwater recharge correlates well with the results of CMB, WTF and GSD (Roediger et. al. (subm)). The

simulation results obtained with the calibrated model for the study area of Wadi al Arab can be summarized in the water budget equation (Eq. 3.1), where P is precipitation (489 mm/yr), E is actual evaporation (413 mm/yr), RD is direct runoff (flash flood) (15 mm/yr) and RGW is groundwater recharge (61 mm/yr):

$$P = E + R_o + RGW \quad \text{Eq. 3.1}$$

Figure 5 shows the regionalized annual precipitation (A) and the simulated annual groundwater recharge (B) by the separated response units for the modelling period. The precipitation map shows the right reproduction of the rainfall gradient, with higher values > 500 mm/yr in the south eastern mountain area and lower values < 450 mm/yr on the western site of the study area. The recharge plot (B) illustrates the consistency connection between precipitation and groundwater recharge in the study area, because the groundwater recharge follows in the same gradient like the precipitation. High values of > 100 mm/yr groundwater recharge are connect on the hilly parts of the catchment. In the environment of the Lower Jordan Valley the groundwater recharge decrease less than 50 mm/yr. Elongated areas with low groundwater recharge < 50 mm/yr are also remarkable in plot B. These areas are connected to the deep valley section of the Wadi al Arab, where the valley sections are affected by a high slope gradient. In contrast the base of the valley are characterised by higher values of groundwater recharge. The final simulated components are illustrated in Figure 3.2. Both figure illustrated the dynamic of precipitation with rain and dry seasons in the time 1980 - 2008. Figure A and B demonstrated expectedly that the dynamic of groundwater recharge (black line) and of flash flood events (black line) are strong related to dynamic of rainfall. In the shown time frame is visible that thresholds for the producing of groundwater recharge and flash floods events are existent. In figure A is obvious that a rain amount of less 100 mm/month is not enough for the creation of groundwater recharge. In contrast figure B show that a rain amount of over 115 mm/month is the lower limit for the creation of flash flood events.

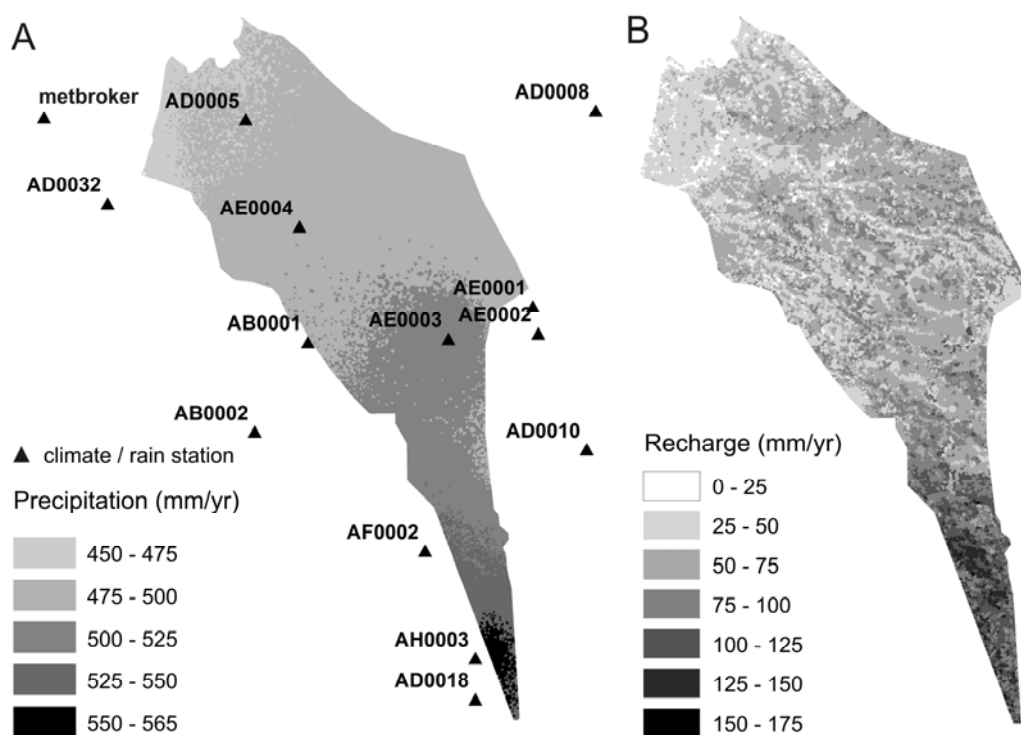


Figure 3.2: Regionalized precipitation (A) and simulated groundwater recharge (B) by J2000g (Roediger et. al. (subm))

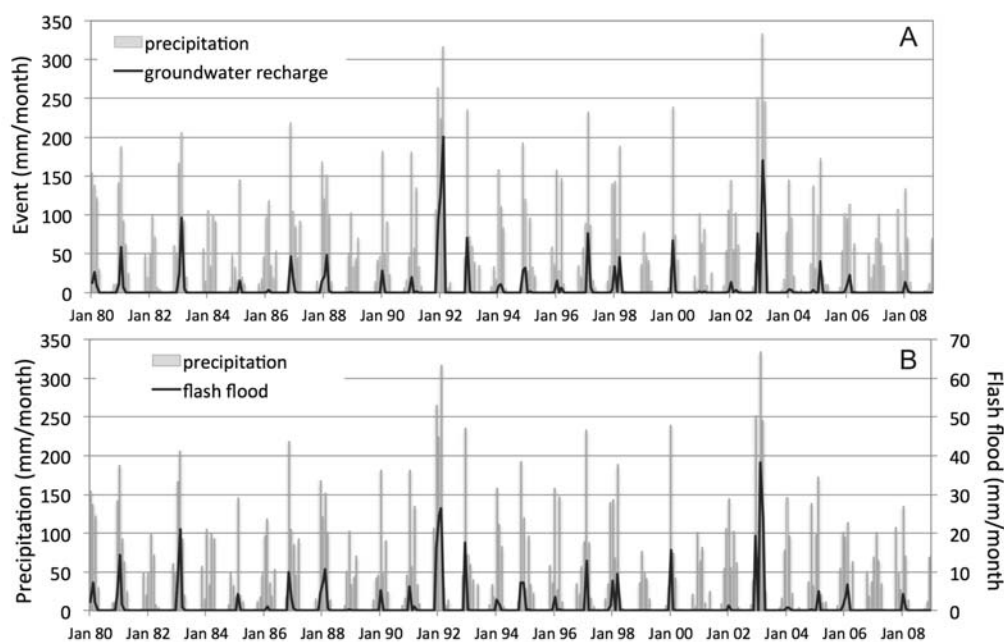


Figure 3.3: Final simulated precipitation (grey column A,B), groundwater recharge (black line A) and flash flood (black line B) by J2000g for the Wadi al Arab catchment (Year 1980 – 2008) (Roediger et. al. (subm))

4. Local hydrological models and quantification of runoff for sub-basin Wadi Kafrein

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4.1 Introduction

The catchment area of Wadi Kafrein is one of several catchments along the Jordan Valley Basin selected for detailed hydrological and hydrogeological investigations within the framework of SMART project. In this work the conceptual and hydrological model of Wadi Kafrein is given. Detailed hydrological investigations took place in the study area aiming to investigate rainfall-runoff relationship. This includes a dense rainfall network and climatic stations, delineation of the drainage network and detailed runoff measurements in different spatial and temporal time steps. The physically based spatially distributed hydrological model of TRAIN-ZIN has been used in this study.

4.2 Study area

The study area of Wadi Kafrein is located 15 km northeast of the northern Dead Sea shore. The catchment area drains to the Kafrein Dam reservoir and runoff goes from the Highlands of the east to the Jordan Valley in the west (Figure 4.1a). The geographical borders are taken to be the same as the surface catchment area of Wadi Kafrein. The rectangular border coordinates are $31^{\circ} 50' 37.7''$ to $32^{\circ} 0' 32.2''$ Northing and $35^{\circ} 40' 1.8''$ to $35^{\circ} 51' 24.7''$ Easting in World Geodetic System (WGS 84).

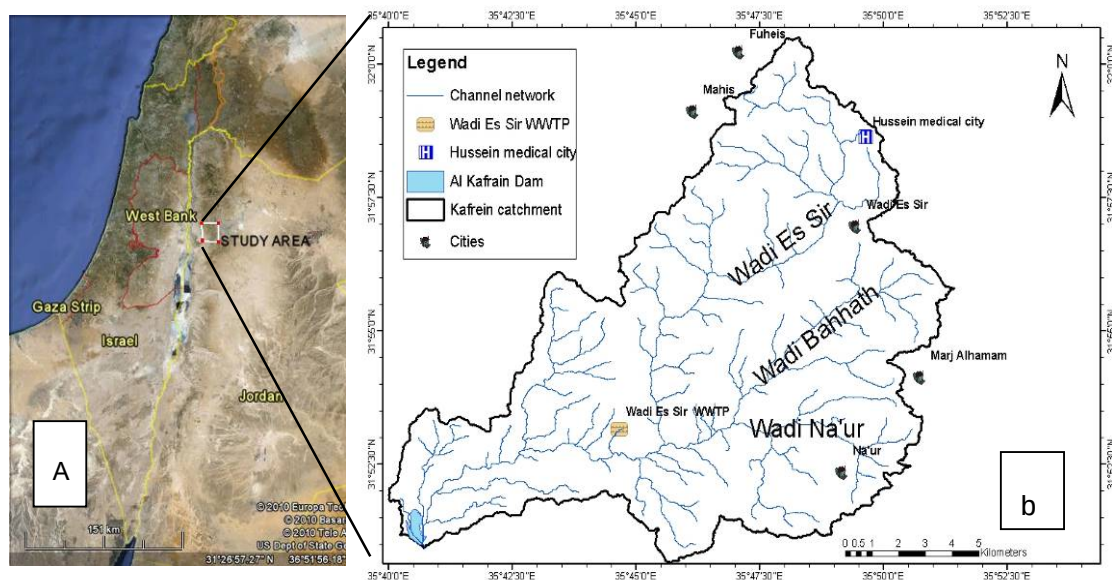


Figure 4.1: Location site of the study area in Jordan (Google earth®). b: Main cities and locations in the study area of Wadi Kafrein (Alkhoury, 2011).

The Wadi has complex topography with relatively large elevation differences over short distances, meaning a steep relief with elevations ranging from 1,079 m asl at the upper east side (east of Fuheis City) down to nearly -139 m asl near the Kafrein Dam. The average elevation is 605 m asl (Alkhoury, 2011).

Wadi Kafrein has three main tributaries with corresponding catchment areas. Wadi As Sir catchment in the North has an area extent of 59.2 km²; Wadi Bahhath catchment is 25.6 km²; and Wadi Na'ur catchment is 22.8 km² (Figure 4.1b). These three main tributaries have springs draining within their respective catchment areas, which are the main sources of base flow. Tributary catchments located in the west and southwest have smaller areas and are sources of large volumes of sediments due to the erosion of the sparsely vegetated landscape, which is characteristic of this region within the Wadi Kafrein catchment area.

4.3 Hydrological model

In this study, the hydrological model of TRAIN-ZIN was used. It consists of two models programmed and developed separately with different focuses and different temporal resolutions. The TRAIN model focuses on the vertical exchanges of water, with evapotranspiration as one of the principle mechanisms. The ZIN model is mainly focused on horizontal water fluxes and interactions, with emphasis on runoff generation mechanisms and the related transmission losses and routing processes.

The rainfall-runoff model of ZIN consists of three main routines and the spatially distributed model parameters are grouped according to spatial sub-unit based similarities. Rainfall is considered to be an input as it varies in space and time and depends on the characteristics of the storm event. A grid map of rainfall intensities is used in the model which can be acquired using radar data or measurements from rain gauge networks. The model and the related parameters are categorized spatially for every sub-unit as follow:

- **Runoff generation:** characterized by terrain types of the spatial sub-units.
- **Runoff concentration:** characterized by sub-tributaries.
- **Channel routing and transmission losses:** characterized by channel types.

The catchment area is sub-classified into several terrain types with different infiltration characteristics, which are defined as model parameters. These terrain types and their parameters determine the spatial sub-units for the runoff generation component. To simulate the runoff concentration, the stream (drainage) network of the catchment area is sub-aggregated into several channel segments. Every segment has an adjacent basin, and these basins and segments together are equal to the spatial sub-units of the entire catchment area. The channel segments used in the runoff concentration routine define the spatial sub-unit parameters for the channel routing and transmission losses routine.

The ZIN model aggregates the spatially homogenous sub-units independently to every sub-routine, which provides high accuracy and requires minimum spatial resolution. Figure 4.2 summarizes the sub-routine of the ZIN model, which includes different types of spatial subdivision.

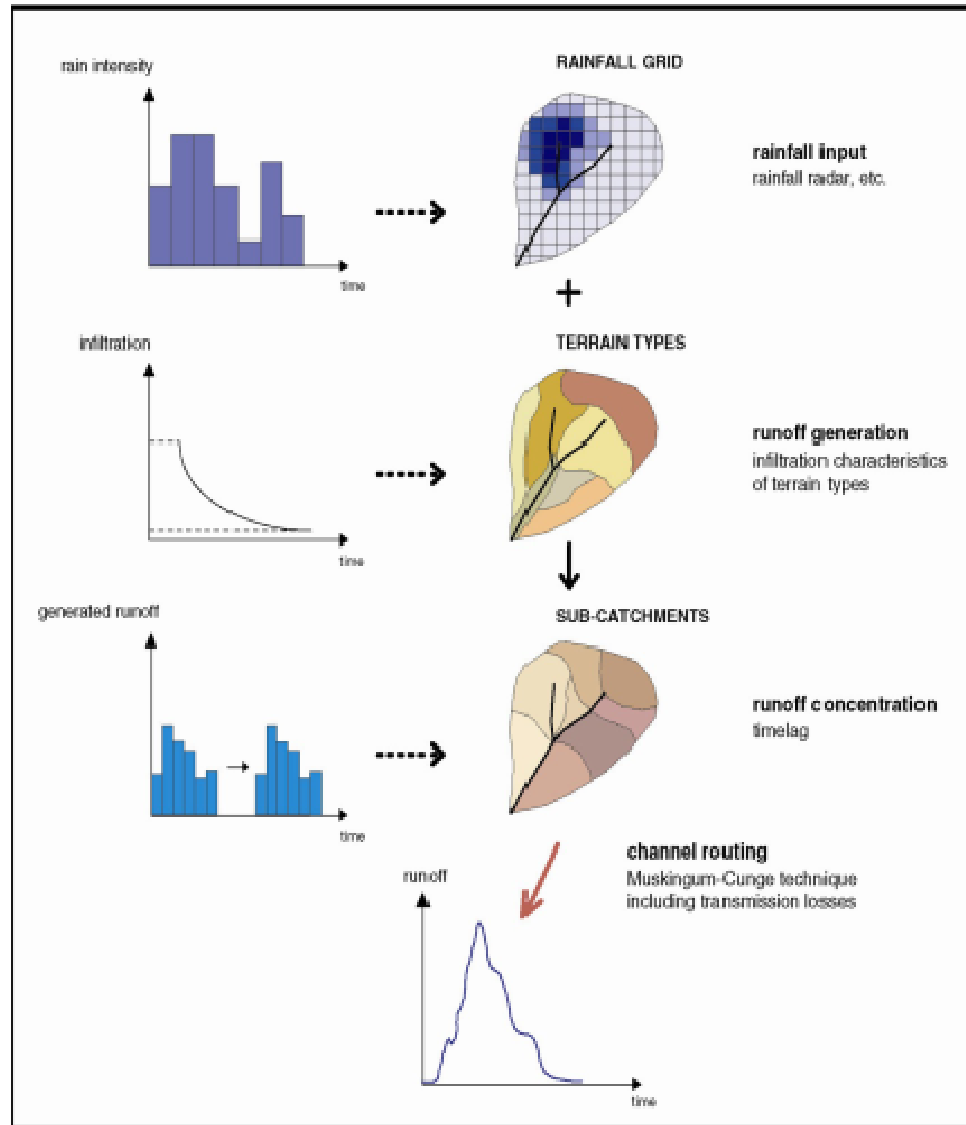


Figure 4.2: Flowchart of the ZIN Model (Thormählen, 2003); modified after (Lange , 1999).

During times of rain, the runoff generation routine of the ZIN model is active, describing the filling of the soil storage and the overland flow generation. Also, the runoff concentration and runoff routing routine are also activated and are conducted using a relatively high time step on the order of minutes. Meanwhile, concerning the activation of the ZIN routines during rain, certain modules of the TRAIN model are deactivated such as the evapotranspiration routine, which is negligible during the rainfall. During the time of no rain, the soil routine of TRAIN is active and the evapotranspiration process is simulated. Considering the soil storage emptying by evaporation and percolation during the no-rain period is very important to simulate the next rainfall event because this constitutes the antecedent soil storage.

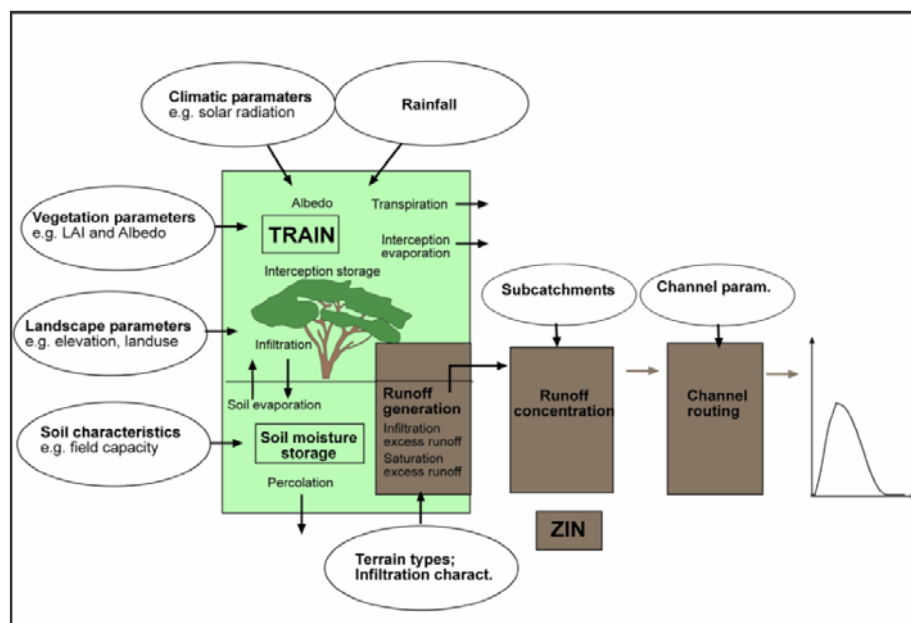


Figure 4.3: The TRAIN-ZIN Coupling (Gunkel, 2006)

4.3.1 Conceptual model

The first step in developing the conceptual model is to define the catchment area boundary. The bounded area should include the surface area from which the modeled area receives recharge or other hydrological input. The boundary of this study has been identified by using the high resolution DEM extracted from the Cartosat-1 stereo image data with the final cell size resolution of 5m X 5m. The DEM was used as basic map in ArcGIS and the catchment boundaries were defined using the “Hydrology Modelling” extension. The watersheds were defined; also, the stream network was identified which plays an important role in runoff flow. It is known that the dominant runoff process in arid and semi-arid regions is overland flow, which is commonly referred as Hortonian flow. Evapotranspiration is expected to be the main component to which most of the rainfall will be transferred; nevertheless, evapotranspiration was never modeled in the study area and due to the unavailability of climatic data, evapotranspiration was estimated using lumped approaches and climatic data outside the catchment area. Groundwater presents the main source of water in Jordan, and Wadi Kafrein catchment area is one of several Wadis along the Jordan Rift, forming together the “Jordan Rift Side Wadis Groundwater Basin.” Recharge from these Wadis is of great importance and quantifying the amount of recharge in Wadi Kafrein, using a physically based model is also of great importance.

4.3.2 Monitoring network and available data

In order to get high resolution rainfall data and overcome the spatial and temporal variability limitations, fully automated rain gauges were installed in addition to the available network within the study area (Figure 4.4). Also, manually built supportive rain gauges were installed along with these rain gauges as secondary sources of data accuracy control (Figure 4.5 a, b). The available precipitation data measured by the MWI is on a daily basis, which is not sufficient for detailed hydrological modelling. Therefore, these additional fully automated rain gauges were installed in the catchment area.

The installed Data Logging Rain Gauges have two main components: the Tipping Bucket Rainfall Collector and a HOBO Event/Temperature Data Logger. The tipping bucket mechanism is designed to measure 0.2 mm of rainfall for every tip.

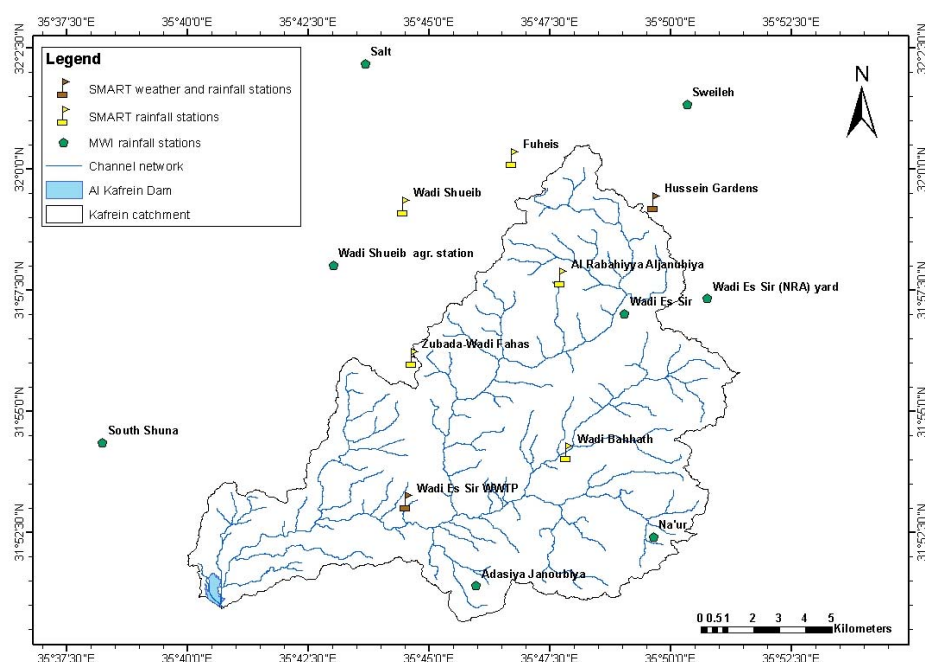


Figure 4.4: Site map of the used rain gauges and weather stations in this study

The maximum rainfall rate which can be measured accurately is up to 127 cm/hour which is much beyond the long term annual precipitation of Wadi Kafrein watershed. Prior to installation, all rain gauges were calibrated in the Laboratory of Water Research of Jordan University, Department of Geology. The calibration has been done following the calibration procedures described in the User manual (Corporation, 2005).

The final installation sites were chosen by taking into consideration the spatial distribution of the rain gauges network, the suitability of the site for installation also to be in close proximity to the monitored subwadis for runoff measurements.



Figure 4.5a: Tipping bucket rain gauge in the measurement site of Wadi Es Sir WWTP.



Figure 4.5b: Manual built supportive rain gauges for data accuracy.

4.3.3 Climatological parameters acquisition

Within Wadi Kafrein catchment area, one climatological station is available, which takes daily measurements. The station is located in the upper part of the study area (Highlands), which has a different climate from the lower-western part (Jordan Valley). The temporal resolution offered by this station is not sufficient for evapotranspiration simulation.

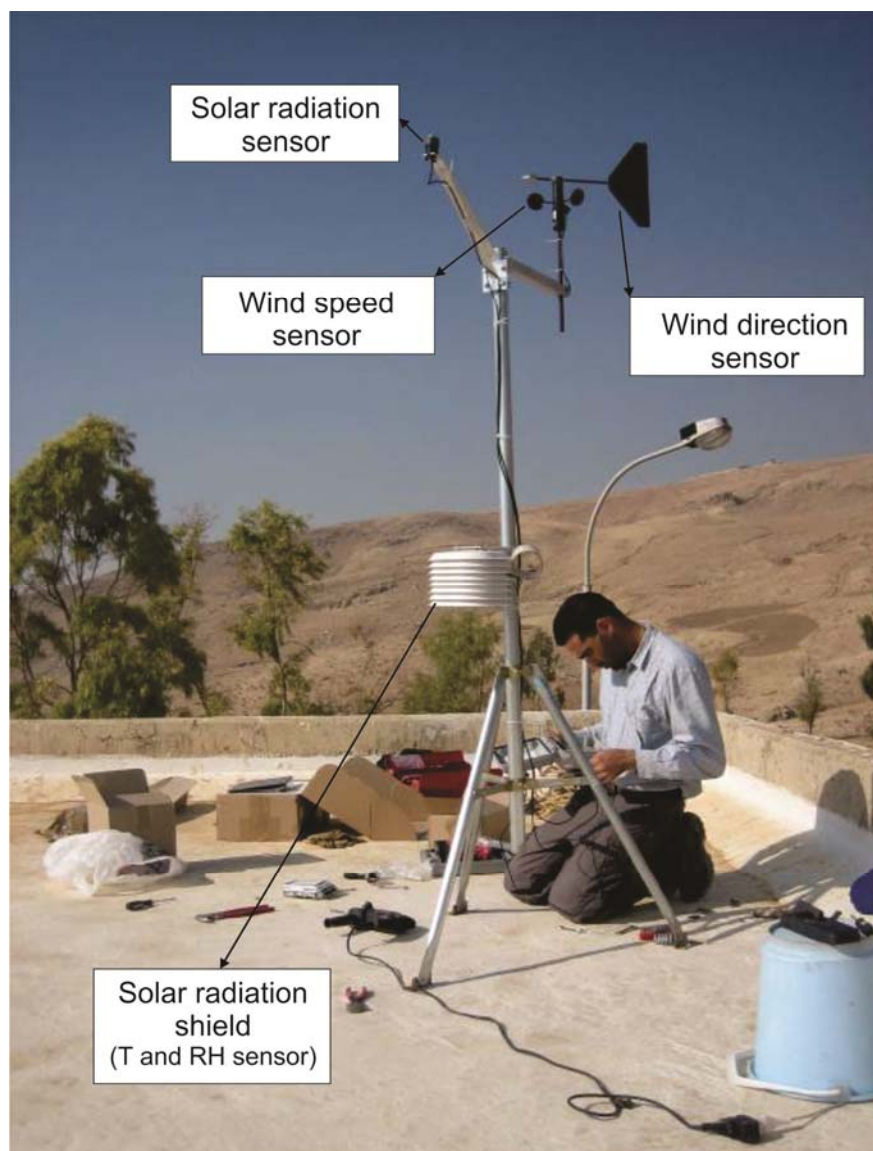


Figure 6: Two meter weather station Configuration. Installation site at Wadi Es Sir WWTP ($31^{\circ} 53' 05''$ N, $35^{\circ} 44' 33''$ E).

To overcome the spatial and temporal variations of the climatological parameters, two automated weather stations were installed in the catchment area to measure the climatological parameters needed for the model.

The first station was installed in the upper northeastern part of the study area in King Hussein Gardens (KHG). The site elevation is 987 m asl with long term annual rainfall average of 500 mm. A Mediterranean climate is present here. The second station was installed in the lower

southwestern part of the study area in Wadi Es Sir WWTP (Figure 4.6).

The elevation of the second station is 232 m asl with long term annual average rainfall of 250 mm, and has a semi-arid climate. More to the west, close to the Kafrein dam, the long term rainfall amount is less than 200 mm where an arid climate prevails. The distance between the two stations is around 14 km, a noticeable difference in the measured climatological values has been measured which indicates the importance of the data quality for hydrological modelling and its influence in such arid and semi-arid regions where variations take place within short distances.

The weather stations measure the main climatological parameters which are needed for the aim of this study. Wind speed is measured in m/s; wind direction in degrees from North; temperature is measured in °C, relative humidity is measured in percent; and solar radiation is in W/m² (Figure 4.6). Close to every weather station is an automatic rain gauge (tipping bucket), and the manual built supportive rain gauge has been installed as well. The HOBO weather stations have a data logger, which is designed to take the measurements through the connected climatic sensors without any need for calibration. A reading of the climatological parameters was taken every 5 minutes.

4.3.4 Initial condition and modelling boundary

To setup the initial condition of the model, the water year was simulated by starting from the first rainfall day and considering no antecedent soil moisture before the rainy season and ending at the beginning of the next water year. In catchment areas like Wadi Kafrein, rainfall is limited to winter months that are from October until April of the following year. During the summer months, high temperatures are observed in Wadi Kafrein. Therefore, the stored water in soil after the rainfall season is removed by evaporation or is percolated, leading to a dry soil layer by the end of the water year and the start of the next water year. The modelling boundary is identified as the surface catchment area of Wadi Kafrein over which flow occurs and which ultimately arrives at the reservoir behind the Kafrein dam.

4.3.5 Defining the model grid

As a spatially distributed model, TRAIN-ZIN requires the specification of an appropriate grid or mesh, which subdivides the model space into a finite number of regions. For a finite-difference model, these regions take usually the form of grid squares or rectangles. The TRAIN-ZIN model requires the following grid maps to simulate the different hydrological processes:

Terrain types grid map (runoff generation routine)

Sub-catchments grid map (runoff concentration routine)

DEM grid map (evapotranspiration routine)

Land use grid map (evapotranspiration routine)

Climatic parameters grid maps (humidity, radiation, temperature, and wind speed)

All grids given in the model input files must have a specific scale. This scale is determined by

the user and it usually depends on the model type and the aim of the modelling process. By defining a very fine scale, the time required to run the model will increase because computing time depends on the total number of grid cells within every grid map. Possibly, one may discretize the fine DEM prepared in this research to 5m x 5m cell grid but this will produce around 6.5 million cells which require tremendous computing power from the computer due to lengthy calculations for each consecutive run as well as requiring much electrical power for the computer. For a macro scale catchment like Wadi Kafrein, suitable is to have a grid cell size of 50m x 50m, which maintains the spatial distribution of the model physical structure, saves a lot of time, and reduces the required power recourses.

4.3.6 Modelling time step

The TRAIN-ZIN model has built-in time step calculations, which limit the size of the time step by taking stability and accuracy criteria into consideration. The TRAIN routines require the climatic data on a daily basis level and for accuracy criteria, radiation data on an hourly basis level is required. On the other hand, ZIN requires a higher temporal resolution. Two time steps are required to be specified in the ZIN model:

ZIN Step: the ZIN-Model time step, in minutes, which was set to 5 minutes.

Route step: the length of the routing time step, in minutes, which was set to one minute.

4.3.7 Time series data

For hydrological modelling, four types of data are required; data can be: structural, time series, physical properties, and observed data. To run the model, two time series data are required:

Rainfall data time series: prepared as a five minutes time step

Radiation data time series: prepared as an hourly time step

Both data time series are prepared in a tabulated format and provided to the model. These time series are necessary to run the model and present a forcing data for the model. Other time series data are required to calibrate and validate the results of the model.

4.3.8 Spatial disaggregation

It has been explained in section 4.3 that TRAIN-ZIN does not run in parallel but in a successive way which means that every model makes its own calculations and through the coupling approach a real time data exchange takes place. Based on this approach, TRAIN requires land cover and soil grid maps to set the evapotranspiration routine parameters in addition to the climatic parameters measured from the two weather stations. No further disaggregation is required by the TRAIN model to simulate the evapotranspiration processes. For ZIN, the model space of the catchment is required to be discretized to sub-units to parameterize the three model routines. The spatial disaggregation for every routine is given in the following paragraphs.

a) Spatial disaggregation for runoff generation:

In this step of the model construction, the entire catchment area of Wadi Kafrein was divided to several sub-units (what is defined for this routine as terrain types) based on soil and land cover characteristics of the catchment. The developed soil map and land cover described in chapter four were used here to define the sub-units of the runoff generation routine. This yielded eight different terrain types as shown in Figure 4.7.

The aim of dividing the catchment area to several terrain types is to prepare a runoff generation map. This map is discretized spatially to grids with similar spatial distribution defined in the model grid. Every grid cell is assigned a special number based on the terrain type which is similar to every sub-unit. The properties of every grid represented by its soil characteristics is given in a tabular way in which the model code is able to read and so runoff generation routine calculations can be performed.

Every terrain type has specific surface characteristics:

Terrains 1 and 2 represent the sub-units which are characterized as having no vegetation and as having clear outcropping of the bare rock of Ajlun group geological formations. They differ from each other by the soil characteristics of the thin soil layer covering them, when present, and by the steepness of the terrain, which plays an important role in the runoff generation process. These two terrains have the potential for generating runoff over their surfaces.

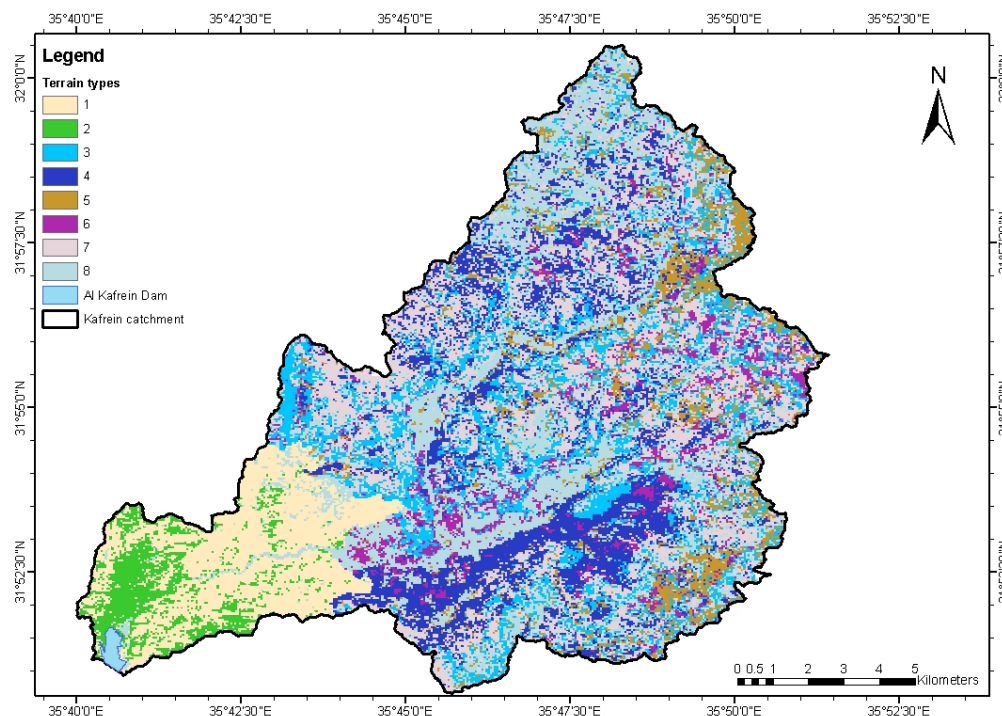


Figure 4.7: Sub-units (terrain types) for runoff generation parameterization

Terrain 3 is characterized by its sharp steepness; it covers a wide part of subwadi S4 and other parts in the middle and south of the study area. Terrain 3 also includes some areas without any

vegetation (mainly subwadi S4). It is covered by grass and olive trees, but the grass cover is limited temporally to a short period during the winter months. This terrain can also be a potential source for generating runoff due to sharp slopes and low vegetation cover.

Terrain 4 is represented by the outcrops of the Kurnub sandstone group and has low slopes. When vegetation is available, terrain 4 may also have either rain fed agriculture or tree crops.

Terrain 5 represents the urbanized area in Wadi Kafrein and is approximately 7 % of the total area. This terrain is mainly impervious surfaces, which are buildings and road network; nevertheless, a part of this terrain can be pervious, e.g., unpaved parking places and the gardens within urban areas. This terrain is considered as a potential surface for runoff generation.

Terrain 6 is represented by areas of high plateaus and terrace remnants and it has low to moderate slopes. Its surface is used mainly for agricultural activities and olive trees plantations. The characteristics of this terrain make this terrain a poor source for runoff generation.

Terrain 7 is represented by a highly fractured and stony colluvium and covers the high convex ridges. The cultivated land cover surface includes mostly agriculture and olive trees, which are on areas where terraces are constructed; therefore this terrain is not a promising terrain for runoff generation.

Terrain 8 is found in the valley floor. This terrain has moderate to deep colluvium and is not expected to generate much runoff. Rather, this terrain is of considerable importance concerning transmission losses. The main featured characteristics of the different terrain types are summarized in Table 4.1.

Table 4.1: Terrain types of Wadi Kafrein

Terrain ID	Associated soil units	Slope in degree /steepness	Elevation	Land cover	rainfall amounts
1	80-81	5-90 / medium to very steep	-140 to 300	Bare rocks /alluvium and Wadi sediments	150-250
2	82-83-84	0-20 / low	-140 to 300	Bare rocks /Wadi Es Sir L.S and F-H-S	150-250
3	17	20-75 / steep to very steep	300-950	Grass land and olive trees	250-500
4	7	0-20/ low	350-1030	Rain fed, tree crops and sparse vegetation	300-500
5	1	0-14/ low	750-1000	Urban areas	400-550
6	10-12	0-15 / low	100-950	Irrigated agriculture and olive trees	200-500
7	23-24	5-15 / low	450-1000	Forest, agriculture and olive trees	300-500
8	2	7-18/ low	150-950	Irrigated field crops- shrubs /natural forests	225-500

b) Spatial disaggregation for runoff concentration :

The spatial concentration of runoff is controlled by the morphological characteristics of the catchment area. The highly accurate stream network, which was prepared using the 5m x 5m DEM, was used to disaggregate the catchment area into sub-catchments. The channel network was disaggregated into several segments, taking into consideration the major junctions where the channel nodes were placed. The acquired Google Earth® image and the developed high accuracy DEM were used in the background of the main channel network for placing the channel nodes.

Every segment which was defined by an upper and lower node has an adjacent basin (defined for this routine as sub-catchments). All these sub-catchments present the spatial sub-units of the runoff concentration routine (Figure 4.8). To calculate the distance between the segment nodes, the *Cournant Condition* for explicit numerical solution schemes of the Saint-Venant equations for open channel flow was used (Cournat, R. and Friedrichs, K., 1948):

$$\Delta t \leq \Delta x / v_k \quad \text{Eq. 4.1}$$

Where:

Δt : time step (routing time step)

Δx : distance step (presents the length of the channel segment)

v_k : kinematic wave celerity

If the *Cournat Condition* is not satisfied, this will result in a water accumulation (Chow, 1988). The time step, “ Δt ,” has been defined as one minute. A measured value of maximum flood velocity, “ v_k ,” for Wadi Kafrein is not available; therefore, a value must be given based on measured values of similar catchments from earlier studies.

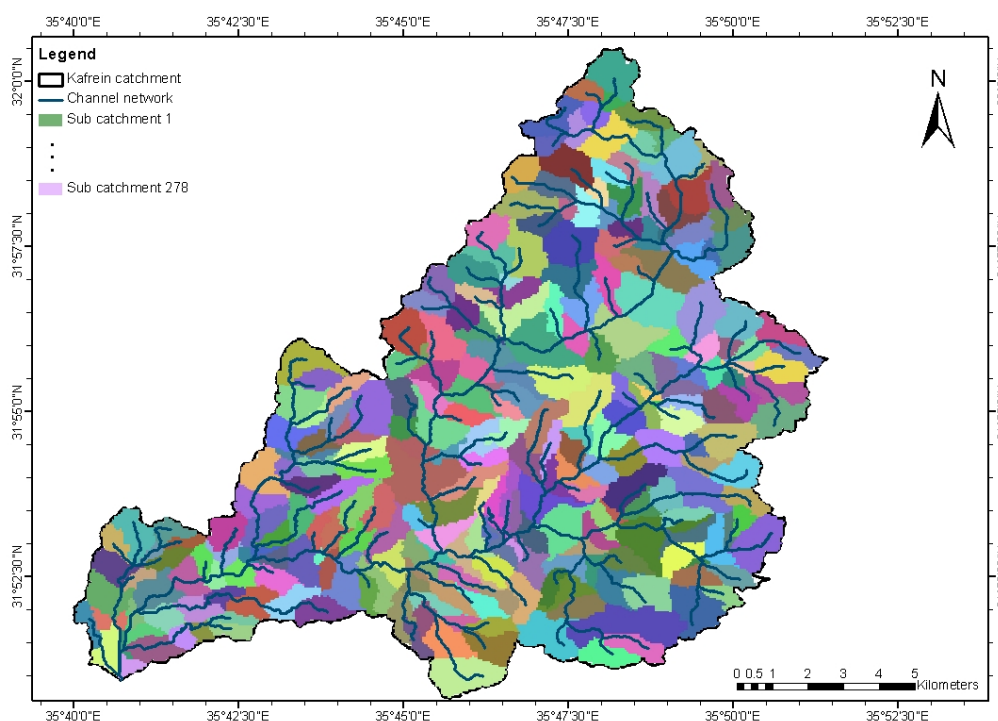


Figure 4.8: Sub units (sub-catchments/tributaries) for runoff concentration parameterization.

It was reported by the (Central Water Authority, 1966) that a surface flow velocity of 5 m/s in Wadi Yutum occurred during the big flood event of November 1966. Similar velocities were observed during the November 1972 flood in Wadi Watir, southeastern Sinai, Egypt (Baker, 1988). The resulting peak flows of November 1966 flood ranged from 325 to 540 m³/s in several catchments ranging in area between 170 and 500 km² (Schick, 1971).

In the absence of a measured value in Wadi Kafrein for the kinematic wave celerity, the value measured by the Central Water Authority of Jordan was used here. Based on equation 4.1, a lower boundary of channel segment length, “ Δx ,” was assigned as being 500 m. An ArcGIS environment (which includes the Google Earth® images and the DEM as explained earlier) was used to delineate the channel network of Wadi Kafrein, considering the Cournat boundary to calculate the distance steps between the single channel nodes. This resulted in 278 channel segments with 839 m as an average length. As explained earlier, every channel segment has a sub-catchment (sub-tributaries) contributing to the channel segment from both sides. The average area of these sub-catchments is 0.58 km².

c) Spatial disaggregation for channel flow and transmission losses :

The generated 278 segments from channel network delineation for runoff concentration are used here as the sub-units (defined for this routine as channel types) for channel flow and transmission losses routine. This routine is controlled by twelve different parameters, which are required to be given for every single segment. Consequently, a total of 3,336 different parameter values are to be determined.

A practical solution to parameterize this routine is to classify the segmented channels to several channel types, which will reduce the required number of parameter values. Nevertheless, there are several classification systems, which are based on macrophytes (Holmes, 1989), invertebrates and fish (Furse, 1984), recreational potential (Zachman, 1984), stability characteristics for engineering works (Simons, 1978), or a combination of disciplines (Otto, 1983). These differently based classification systems may produce entirely different groupings. Furthermore, the geomorphic characteristics of fluvial systems in the study area influence the resultant classification (Kondolf, 2003). Even in the same study area, the channel network undergoes profound changes along the channel length; therefore, the classification system must either limit itself to homogenous sections of the channel (Rosgen, 1994); (Montgomery D. D., 1998) or to a system which addresses the nature of longitudinal change as a basis for classifying different regions (Frissel, 1986); (Montgomery D., 1999).

To simulate the channel flow and transmission losses using the routing routine explained earlier, most convenient is to use a channel classification based on similarities in morphological characteristics. (Montgomery and Buffington, 1997) proposed a hierarchical valley segment and reach level classification of mountain channel networks based on morphologic attributes related to relative sediment supply and the ratio of sediment supply to transport capacity.

In the catchment area of Wadi Kafrein, observations have clearly indicated that a variation in channel morphological characteristics exists with channel length. The classification system used

in this research is based on the following criteria: channel width, gradient, and sub-catchment land cover. The developed DEM, slope map, and the acquired Google Earth® images were all integrated within GIS and the channels were classified accordingly. As some channel segment characteristics are not easy to be determined, effective field observations were highly valued. Following this approach the 278 channel segments were grouped to four channel types. Their spatial distribution is given in Figure 4.9 while channel type characteristics are given in Table 4.2.

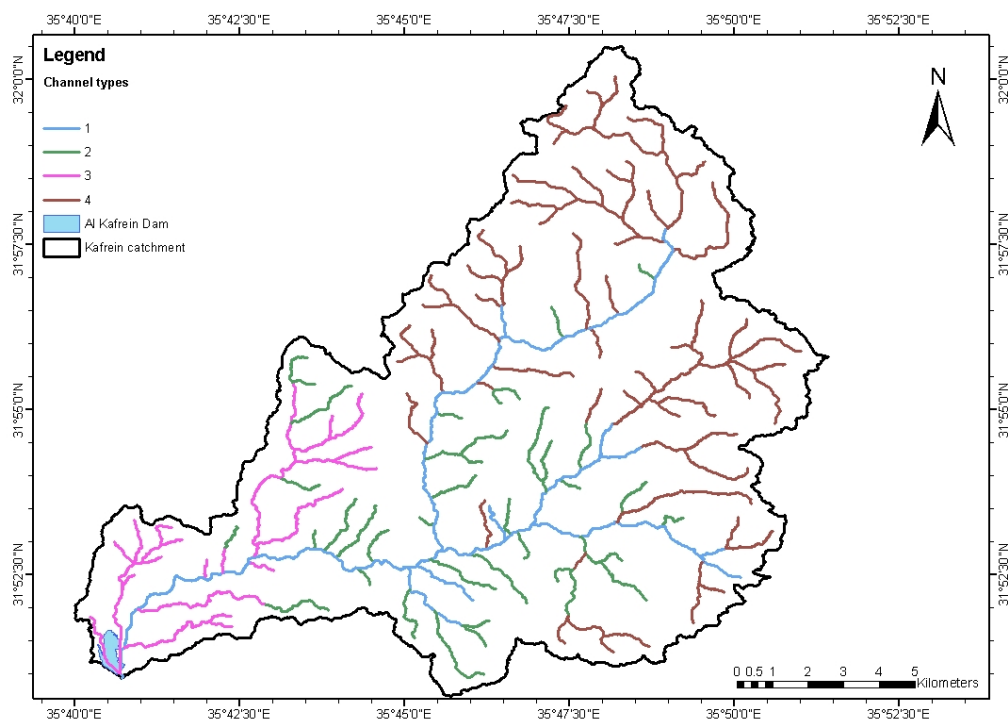


Figure 4.9: Sub-units (channel types) for channel flow and transmission losses parameterization

Segments of channel type 4 are distributed in the upper part of the area and run through agricultural fields, which are considered as a source of fine sediments. Segments of channel type 3 are distributed over areas where no vegetation and a thin soil layer are found; due to its sub-catchment cover, the channels are able to transport coarse and rubble sediments during flood events.

Table 4.2: Channel types characterizes

Channel ID	Width (m)	Gradient (%)	Sub-catchment cover	Occurrence
1	5-43	2-25	Dense vegetation on channel sides, field crops and agriculture in upper part	Represent the main channel network and the spring flow
2	1.5-12	20-46	Mainly through bare rocks and soil slopes, sparse to no vegetation cover	Middle and lower part

3	1.6-12	0.5-16	Limestone and thin layers of soil with low rainfall amounts and no vegetation	Lower western part
4	1.1-14	2-18	Agriculture and urban areas	Northern and eastern part of the catchment

Channel type 1: channels of this type are characterized as being wide with braided channels and having eroding banks; they have an average width of 17.7 m. These channels are optimal for transporting sediment textures ranging from coarse gravel to cobbles. Sediments are bed loaded with side and middle bars. Islands form central bars during flood flows. Channels of this type have a gentle slope ranging from 2-25% with an average of 7%.

Channel type 2: characterized by steep slopes (V notched) and high energy and debris transport. Average slope of these channels was found to be 21%. They have a narrow width ranging from 1.5-12 m and an average of 5 m. They are not braided rather having only one defined main channel.

Channel type 3: these channels have low gradients. The sub-catchments of these channels lack any vegetation cover and have pronounced rocky outcroppings. They have one main channel with low width to depth ratio. Channels of this type are capable of transporting coarse sediments during flood events.

Channel type 4: these channels have narrow to medium width with stable banks and no vegetation within their floodplain; they are optimal for transporting relatively fine suspended sediments coming from their sub-catchments, which are mostly used for agricultural activities.

4.3.9 Model parameterization

After the spatial disaggregation of TRAIN-ZIN model grids, it is required now to give values for the parameters of every routine grid (sub-units in case of ZIN routines). This is explained in more detail in the next four sections. In a distributed model like TRAIN-ZIN, the spatial variations in catchment characteristics and input data are described in a network of grid cells. Every grid cell of the mesh or grid maps is characterized by one or more parameters. This process of defining the spatial pattern of parameter values is known as parameterization. These parameters can be classified to two groups as follows:

Physically based parameters: parameters of this group have physical properties which can be measured in the field. Examples of these parameters are: the soil depth, soil infiltration rate, and channel lengths and widths.

Empirical parameters: parameter values of this group are estimated by the calibration process of the model. Examples of parameters belonging to this group are: parameters of Fisher-Tippet distribution and the Manning coefficient.

i) Parameterization of evapotranspiration

Evapotranspiration is simulated by TRAIN and requires as an input rainfall and climatic data together with soil and land cover maps, which are provided in a grid format. All rainfall data measured during the study period were prepared in five minutes time step; actually, this high

temporal resolution is important and realistic to simulate the infiltration excess runoff in the ZIN model with high accuracy. The rainfall time step determines the ZIN time step, which determines the longest possible routing time step. The point measurements acquired from rain gauge network are required to be presented in a spatial way. Several methods are available for this purpose; among others, the TRAIN-ZIN gives the possibility to generate the spatial distribution of rainfall using one of the following well known methods: the Thiessen Polygons and the Inverse Distance Weighting.

The Thiessen Polygons method is based on the assumption that the station best represents the area which is closest to it. In mountainous areas, orographic effects can create vastly different microclimates over small distances. Significant precipitation can fall on one side of a ridge but little on the other. In such regions the Thiessen method can yield erroneous results and the earlier mentioned assumption is not valid (Linsley, 1979); (Fetter, 2001).

The other method of weighting rain gauge measurements is the inverse distance method, in which the influence of the rainfall at a gauged point on the computation of rainfall at an ungauged point is inversely proportional to the distance between the two points (Wei, 1973). In the TRAIN-ZIN model, the weighted rainfall value for every grid cell can be calculated using the inverse distance weighting method:

$$P(x, y) = a \cdot \sum_i \frac{P_i}{d^2} \quad \text{Eq. 4.2}$$

With:

$$a = \frac{1}{\sum_i \frac{1}{d^2}} \quad \text{Eq. 4.3}$$

Where:

$P(x, y)$: I precipitation value at grid cell (x, y)

P_i : precipitation value at gauge station i

d : distance between grid cell (x, y) and the gauging station i

In this research, the rainfall data has been provided in 5 minutes time interval and was interpolated for every grid cell using the Inverse Distance Weighting (IDW) method. For better interpolation results, an elevation correction factor has been introduced by (Hagenlocher, 2008) and used in the interpolation. The high resolution Digital Elevation Model prepared in this research was used in the interpolation approach. This has been done because stations are on different elevations and there is a precipitation gradient with elevation change. The station on the lowest elevation has been taken as a reference station. The measured precipitation values at PStat (at elevation hStat) of all stations are reduced to precipitation Pref at a reference level h ref:

$$P_{ref} = \frac{P_{stat}}{1 - grad.(h_{stat} - h_{ref})} \quad \text{Eq. 4.4}$$

After the application of the IDW, the same gradient is being used to calculate the precipitation value P_j at the elevation of the DEM at each cell:

$$P_j = P_{ref} \cdot (1 + grad \cdot (h_j - h_{ref})) \quad \text{Eq. 4.5}$$

The density of the rain gauge network, in addition to the geographic location and elevation of the stations, has a direct impact on the interpolated area rainfall amount, which in turn affects the results of a hydrological model. By using all available rain gauges for this research, an area rainfall amount of 167 mm for the hydrological year 2007/2008 was obtained while using two distant stations (Wadi Es Sir WWTP and Hussein Gardens, Figure 4.4); an increase in the interpolated value of 12.3% was obtained. For the next hydrological year 2008/2009 the variations of the interpolated values were up to 16% (Alkhoury et al., 2010a). Such an increase in the interpolated values will cause an overestimation of the precipitated rainfall amount, which consequently will affect the value of ground water recharge and evapotranspiration leading to wrong results.

Regarding the climatic grids, they were prepared by interpolating the measured climatic parameters between the two weather stations; this gives a high accuracy and a physically sound basis for the modelling process, as this takes into consideration the effect of spatial variations over the catchment area. The simulation period of this research extended from November 15th, 2007 until December 23rd, 2009 with a total number of 770 simulated days. For every simulated day, four climatic grid maps were prepared (humidity, radiation, temperature, and wind speed) yielding a total number of 3070 grid maps. In case there is only one weather station or if a user wants to save the time of calculations, TRAIN-ZIN can also simulate the different hydrological processes by having the climatic parameters in a tabular format; i.e., one value of every variable for every day. Nevertheless, considering an interpolated value between the two stations by assigning one value for every grid cell is more accurate than considering one value for the whole catchment area. One last file is required that is the radiation data, they were prepared in hourly basis in a tabular format.

ii) Parameterization of runoff generation

The spatial disaggregation of runoff generation routine resulted in eight different terrain types as explained earlier. For each terrain, the parameter values are the same. Nine parameters are required to be given for each terrain type, resulting in 72 values. The parameters of this routine depends on the soil properties. Prior to this work, Wadi Kafrein catchment lacked any detailed soil class map, while a detailed study on soils had been already conducted in the adjacent catchment, Wadi Shueib. The results of the detailed study prepared by (Kuntz, 2003) on the soils of Wadi Shueib were based on intensive field work and laboratory analysis. Wadi Shueib catchment falls under the same climatic conditions and morphological properties as Wadi Kafrein, making data extrapolation based on scientific processes very realistic and meaningful. The extrapolated soil map of Wadi Kafrein has been prepared based on comprehensive remote sensing approach in which a single pair of Cartosat-1 and multi-temporal ASTER satellite images in addition to DEM, slope map, and Google Earth® images were used. The results were evaluated by ground truthing and were found to be satisfactory; also, the resulting map has good agreement with what was given in the references of the Jordan Soil Map project

(Agriculture, 1994) and the detailed soil map study of Wadi Shueib (Kuntz, 2003).

The prepared soil map of Wadi Kafrein divided the soil types into 12 soil units according to the USDA Soil Taxonomy (USDA, 1975, 1999) and the Keys to Soil Taxonomy of the USDA (1990). Each soil unit is defined by its own moisture properties and soil textures which have been studied in detail on a national scale by Ministry of Agriculture (1994) and catchment scale by Kuntz (2003) and Werz (2006). Based on the measured soil texture of every soil unit of Wadi Kafrein, it is possible to assign all required parameters of this routine.

As a distributed model, TRAIN-ZIN requires the assignment of different parameter values for every single grid cell. This will result in a large number of values for the entire catchment, and if the temporal variations are taken into consideration, the number will become even bigger. This requires an immense number of measurements and efforts. Therefore, it is required to reduce the expenses of parameter estimation. The physical basis of those parameter values allows a degree of hope that this may be possible; in that it should be possible to transfer parameters measured in one location to be representative of similar areas elsewhere. Thus not only may it be possible to define parameters on the basis of vegetation or soil type within the catchment area but it should also be possible to transfer information from studies outside the catchment of interest (Beven, 1982). Table 4.3 summarizes the parameters of runoff generation routine and their calibrated values.

Table 4.3: Parameters for runoff generation routine

ID	I_f	L_i	S_d	ϕ	PWP	K_s	λ	θ_{fc}	ρ
1	2	1	0.10	0.327	0.01	0.085	0.1	0.02	1.32
2	3	1	0.15	0.356	0.046	0.081	0.252	0.138	1.41
3	20	4	0.15	0.35	0.037	0.287	0.234	0.185	1.42
4	30	5	0.45	0.309	0.076	0.228	0.378	0.195	1.44
5	7	6	0.40	0.36	0.124	0.087	0.107	0.18	1.00
6	35	7	0.45	0.432	0.062	0.368	0.234	0.283	1.39
7	25	5	0.20	0.386	0.11	0.258	0.234	0.306	1.38
8	40	9	0.25	0.4	0.131	0.438	0.252	0.282	1.42

Where:

I_f : final infiltration rate, (mm/h)

L_i : initial loss storage, (mm)

S_d : soil depth, (m)

ϕ : effective porosity, (0-1 fraction of sample volume)

PWP: Permanent Welting Point, (0-1 fraction of sample volume)

K_s : saturated hydraulic conductivity, (cm/h)

λ : van Genuchten lamda

θ_{fc} : field capacity, (0-1 fraction of sample volume)

ρ : bulk density, (g/cm³)

All nine parameters can be determined from the soil textures of the 12 soil units. Soil grain size analyses were conducted and the *infiltration rates* of different soil units were measured in several representative sites for every soil unit by Kuntz (2003) and the values ranged from 12 to 252 mm/hr using the double ring infiltrometer, but these values seems to be very high compared to the standard infiltration rates of soil textures given in the literature. (Werz, 2006) related the increased infiltration rates to either the effect of macrospores or the high skeleton content in the soils or to the fact that the required penetration depth of the infiltrometer of 5-10 cm following the DIN 19682-7 (Normung, 1997) was not reached at most locations.

Hillel, (2004) gave values of infiltration rates ranging from less than 1 mm/h for sodic clayey soils up to more than 20 mm/hr for sands soil, while the (FAO, 1988) referred to values from 1-5 mm/hr for clay to less than 30 mm/hr for sand. (Lavee, 1998) studied the variations in infiltration rates from Mediterranean through semi-arid to arid climate and the values ranged from 10-35 mm/hr in the arid and semi-arid regions. Lange J. L., (1999) referred to infiltration rates of different terrain types in arid catchments with ranges from 5 mm/hr to 50 mm/hr. Based on the above argument, the infiltration rates were assigned for every soil unit and later they were calibrated within the accepted range of infiltration rate of every soil texture.

Initial loss is a parameter reflecting the rainfall portion which is lost mainly due to detention losses, which take place before the generation of Hortonian overland flow. This parameter value depends highly on the soil type and is directly affected by the vegetation land cover; therefore, the values were assigned for every soil unit in which low values are given for areas with bare rock surfaces and sealed soil surface while higher values are given for soil units which have higher infiltration rates.

Soil depths were measured at several sites, covering all soil units in the entire catchment area. The *effective porosity* was estimated from soil textures as given by Rawls, (1982). The *Permanent Wilting Point*, *Saturated hydraulic conductivity*, *field capacity* and the *bulk density* were calculated based on the measured grain sizes of every soil unit using the SPAW Hydrologic model (Saxton and Willey, 2006). The *van Genuchten lamda* of every soil unit was assigned based on soil texture as given by Van Genuchten, (1978).

iii) Parameterization of runoff concentration

The runoff concentration is calculated in TRAIN-ZIN using a Unit Hydrograph approach. In the present research, a synthetic unit hydrograph was used for every sub-catchment. The synthetic unit hydrograph uses the *Fischer-Tippett distribution* which has two parameters: parameter “a,” which is used to calibrate the concentration time given in minutes; and parameter “b,” which is used to shape the hydrograph. Parameter “a” is influenced by the average steepness of the

sub-catchment while parameter “**b**’ is influenced by the area of the sub-catchment. Both values were given for every sub-catchment in a tabular format.

iv) **Parameterization of channel flow and transmission losses**

Parameters of this routine are based on the morphological and hydrological characteristics of the channel types mentioned in Table 4.2. For every channel type, a total number of twelve parameters are required to be given. Most of the parameters of this routine are physically based and they are required to be assigned based on field measurements or by analyzing their physical properties using DEM.

For every channel segment, the length and slope is required to be given. This has been done using the high accuracy DEM from which the channel network was prepared and after segmentation the lengths were measured. The slope of every channel segment was calculated by determining the height difference of the two nodes of the segment. The width of the channel segments were calculated by digitizing the area of active channel alluvium between the two nodes of the segment and then this value was divided by the respective channel length as shown in (Figure 4.10). Channel segments length, slope, and widths were determined within GIS. Table 4.4 summarizes the parameters required for this routine and their calibrated values.

Table 4.4: Parameters for channel flow and transmission losses

ID	A_d	n	$c\%$	F_d	ϕ	k_i	k_b	k_f	S	vk	I	AMI
1	1.5	0.033	0.3	1	0.5	0	10	4	0.1	0.01	0.1	0.85
2	0.3	0.04	0.8	0.4	0.35	60	80	5	0.1	0.03	0.1	0.7
3	0.5	0.035	0.6	0.7	0.4	75	93	7	0.1	0.02	0.1	0.8
4	0.6	0.028	0.65	0.75	0.4	80	100	10	0.1	0.025	0.1	0.8

Where:

A_d : depth of the active alluvium, (m)

n : Manning coefficient for different channels

$c\%$: percentage covered by inner channel

F_d : depth to bankfull stage, (m)

ϕ : effective porosity, (0-1 fraction of sample volume)

k_i : hydraulic conductivity of the inner channel, (mm/h)

k_b : initial infiltration rate of bars, banks and the flood plains, (mm/h)

k_f : hydraulic conductivity of the underlying strata, (mm/h)

S : effective suction head, (mm)

vk : critical flow velocity/shear stress

I: infiltration reduction factor

AMI: antecedent moisture index



Figure 4.10: Calculation of the spatially averaged channel width (background image from Google Earth®)

The depth of the active alluvium, percentage covered by inner channel, and the depth to bankfull stage for every channel type was determined based on field measurements and analysis. The Manning coefficient was given based on the roughness of every channel type; the values were estimated from USGS guidelines publications e.g. (Arcement, 1989). The rest of parameters were assigned based on values given in previous studies in arid and semi-arid regions (Leistert, 2005; Shadeed, 2008).

4.4 Runoff generation processes and mechanisms/ Quantification of runoff

Runoff generation mechanisms were quantified in detail for the monitored runoff events. The results show that Infiltration Excess Overland Flow (IEOF) is the dominant runoff mechanism in the study area, which is also known to be the dominant mechanism in other arid and semi-arid regions. On the other hand, and despite that fewer events were generated due to Saturation Excess Overland Flow (SEOF), the results show that, quantitatively, runoff is mainly generated due to SEOF. For similar amounts of rainfall measured in two different storm events, the volume of the generated runoff with SEOF as the dominant runoff generation mechanism was ten times more than an earlier event with a similar measured rainfall amount. This earlier event was characterized by IEOF. This observation may be attributed to the rainfall intensity, the antecedent soil moisture, and the lag time between the storm events. Transmission losses were also quantified on an event basis and on an annual basis. Transmission losses ranged from 18-44% of the generated runoff on an event basis while the average transmission losses were 24%

and 26% of the generated runoff in 2007/2008 and in 2008/2009, respectively. The maximum runoff coefficient was 4% in 2007/2008 and 11% in 2008/2009. Recharge was higher when SEOF was the dominant mechanism and lower when IEOF was the dominant mechanism.

In the present research, the differential split sample test was used to calibrate and validate the hydrological model of Wadi Kafrein. In the water year 2007/2008, the rainfall events have lower intensities and short lag times while in the following year, 2008/2009, the rainfall intensities were higher with much dryer and longer lag times between storm events followed by very wet months with short lag times between rainfall events. This can be recognized by the long dry period prior to February and March, 2009 in which no single runoff event was recorded while 80% of the total rainfall amount of the water year 2008/2009 was recorded in only February and March, 2009.

The differential split sample test is used to test the model's ability to represent changed conditions. Therefore, non-stationary conditions (i.e. changing conditions over time) were used, and the validation period was chosen to be different from the calibration period. The water year 2008/2009 was used for calibration while events from 2007/2008 and 2009/2010 were used for validation purposes. Despite the different conditions of the rain storm characteristics between the periods used for calibration and those used in validation, the overall monitored period is considered as dry, which consequently resulted in few runoff events. Nevertheless, these events were used either for calibration or validation. Figure 4.11 shows the measured and simulated runoff hydrographs for the entire monitored period. Time is given in hours and the vertical solid lines between the hydrographs were used to separate the runoff events from each other (i.e. the periods of no events were skipped).

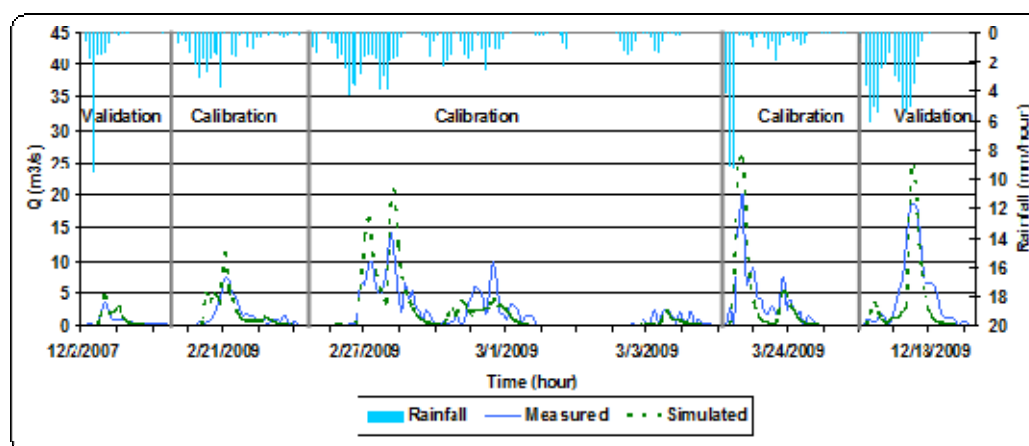


Figure 4.11: Graphical inspection using time series plots for the calibration and validation periods

Runoff coefficients

The runoff coefficient is the percentage of runoff from the precipitated rainfall. The mean daily values of the generated runoff and the precipitated rainfall were used to calculate the runoff coefficients for the entire modelling period of 2007-2009. The water year 2007/2008 had low runoff coefficients, not exceeding 4% (as shown in Figure 4.12) compared to runoff coefficients of more than 10% in the water year 2008/2009 (Figure 4.13).

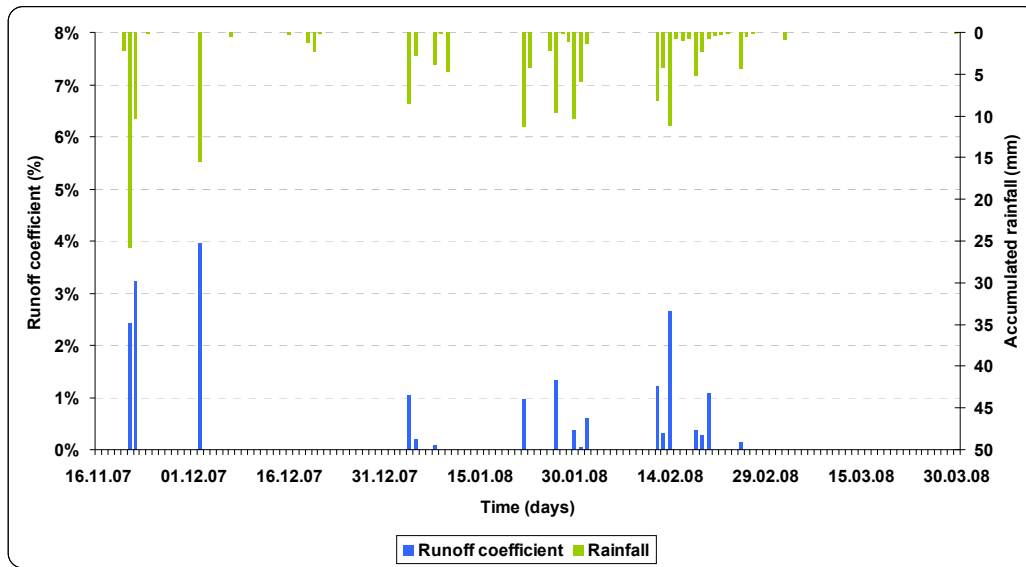


Figure 4.12: Runoff coefficients for all events during the water year 2007/2008.

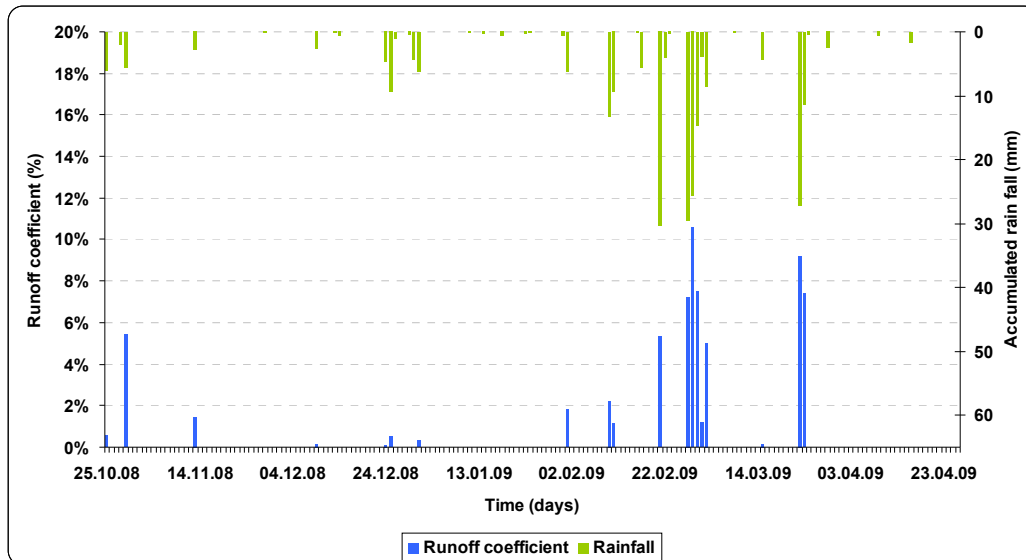


Figure 4.13: Runoff coefficients for all events during the water year 2008/2009

In the calibration year, 2008/2009, the second storm event of 27.02-03.03.09 had the highest runoff coefficients (Feb. 28th) with a value of 10.6%. As stated earlier, the runoff during this day was mainly generated due to saturation conditions of the soil and all the additional rain was transformed to runoff. During the third storm event on Mar. 23rd, a high magnitude of runoff was also generated (9.2%) due to the high intensity of the precipitation and prevailing infiltration excess conditions.

4.5 Conclusion

Among other types of hydrological models, the physically based, especially distributed models,

are the most convenient models to simulate the hydrological processes in study areas similar to Wadi Kafrein, where spatial and temporal variations in rainfall have a large impact on the hydrological processes.

The physically based spatially distributed TRAIN-ZIN model was selected to fulfil the aims of this research as it considers the spatial variations by a spatial disaggregation of the entire catchment to several sub-catchments which increases the efficiency of the model parameterization. The model has been calibrated and validated using stationary and non-stationary data sets and it does not need any further calibration. The model is capable of simulating the hydrological processes in a continuous way while runoff mechanisms and transmission losses can be simulated on an event basis in arid and semi-arid regions.

The results of the present study indicate an average annual recharge of not less than twenty million cubic meters. The long term annual average of the spring discharge in the catchment area was calculated to be around twelve million cubic meters, while the reports of the Ministry of Water and Irrigation of Jordan refers to an average abstraction from wells within the catchment area of Wadi Kafrein of around five million cubic meters. Such numbers reflect the high capabilities of the Kafrein catchment area as a recharge zone which is mainly affected by the highly karstified limestone of the upper aquifer as a result of the highly fractured and faulted zone along the Kafrein catchment.

Runoff components were well simulated using the physically based spatially distributed TRAIN-ZIN hydrological model. This has been done after rigorous calculations of the controlled catchment using reservoir mass balance equation which accounts for all terms controlling Kafrein dam reservoir storage.

The results of this research showed a clear underestimation of the generated runoff in the catchment area of Wadi Kafrein in the available previous studies. The runoff amounts were often estimated to be around one to two million cubic meters as a long term annual average. Such volumes were recorded during dry years within the monitoring period of the present research. The results of this research estimated the long term annual average runoff to be not less than five million cubic meters. This value is supported by the measured water budget of the Kafrein dam reservoir which has been conducted on a daily basis since 2002.

The dominant parameters affecting runoff generation are the soil depth, infiltration rate, and the initial losses. Infiltration rates of different soil types in Wadi Kafrein ranged from 2 mm/h in the compacted soil types represented by Ustic-Aridic transition soil moisture regime in the lower part of the study area, while the highest infiltration rates were 40 mm/h for soil types in the middle and upper part of the study area with Xeric soil moisture regime. Initial losses are highest in agricultural areas and lowest from terrain types with bare rock or thin soil thicknesses. Soil depths range from 10 cm in the Ustic-Aridic transition soil moisture regime zones and 45 cm in the agricultural areas with Xeric soil moisture regime zones.

Transmission losses are mainly affected by channel length, channel width and by the depth of the active alluvium and the infiltration rate of the alluvium which requires intensive field measurements.

It has been recognized that the transmission losses process is one of the most important

components of the water balance of many of the arid and semi-arid regions (Hughes, 2008). The process of recharge into alluvial aquifers has been also documented (Crerar, 1988). In this research, transmission losses were quantified in Wadi Kafrein and the results show that transmission losses present around 18-44% of the generated runoff on an event basis while their average values ranged from 24% to 26% in 2007/2008 and 2008/2009, respectively. These values reflect the importance of this component in arid and semi -arid regions.

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Appendix A

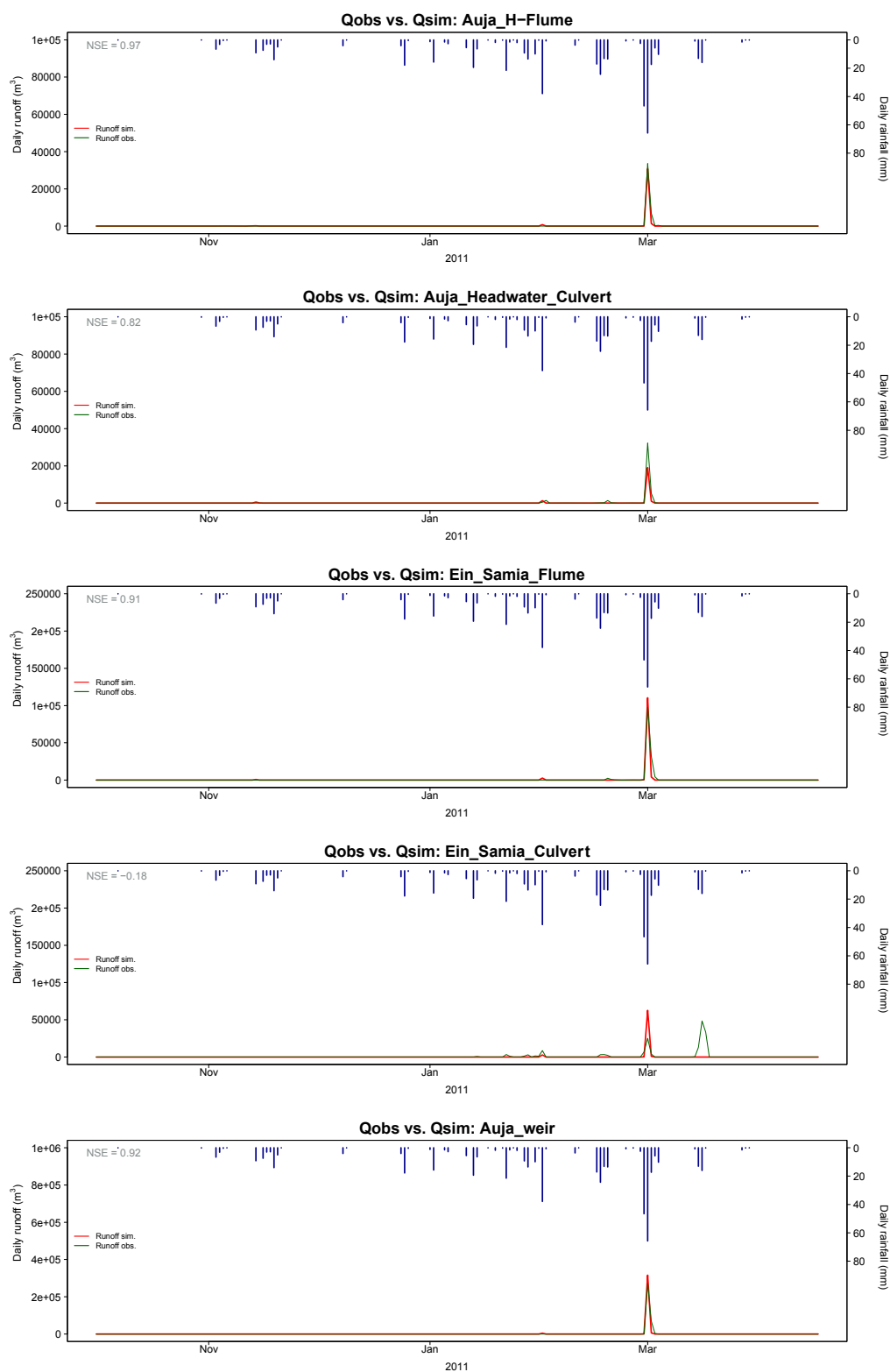


Figure A1: Model results for the hydrological year 2011/2012.

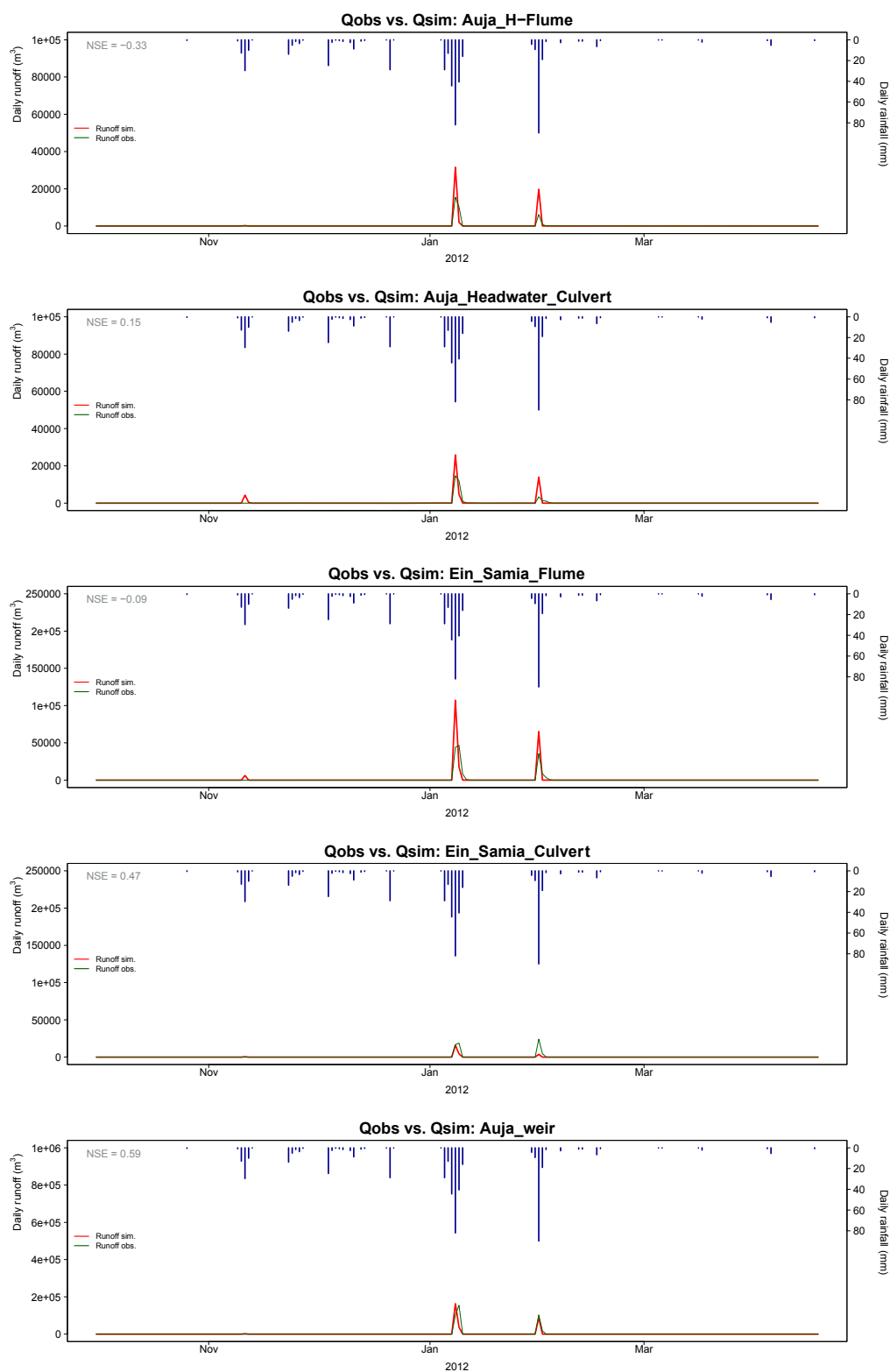


Figure A2: Model results for the hydrological year 2012/2013

Table A1: Event comparison for Wadi Auja North

