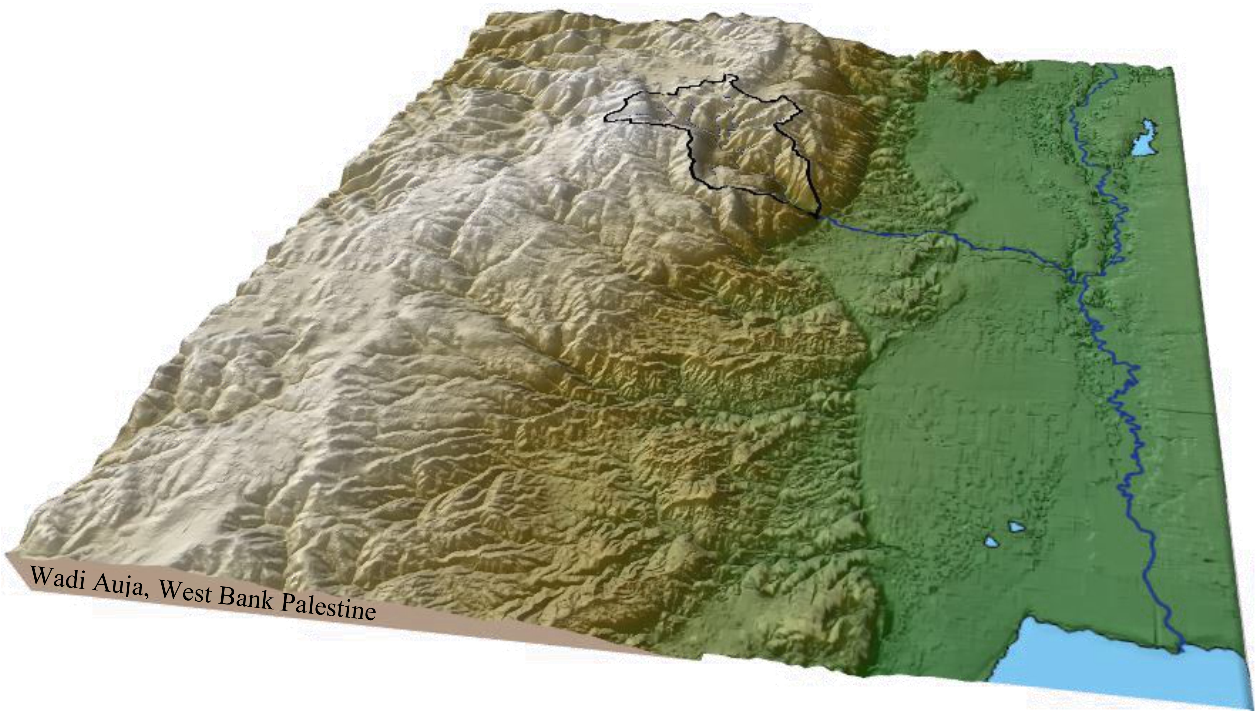
Comparison of two hydrological models, TRAIN-ZIN and SWAT under semi-arid conditions in Wadi Auja, West Bank Palestine



Faculty of Environment and Natural Resources
Albert-Ludwigs-University - Freiburg i. Br., Germany
Chair of Hydrology

Master Thesis

of

Phillip Grimm

Freiburg i. Br., Germany
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"Models are undeniably beautiful, and a man may justly be proud to be seen in their company. But they may have their hidden vices. The question is, after all, not only whether they are good to look at, but whether we can live happily with them."

A. Kaplan, 1964

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Abbreviations	Unit	Name
ALPHA_BF		SWAT: Baseflow alpha factor
ALPHA_BF_D	[days]	SWAT: Baseflow alpha factor for deep aquifer
BMBF		German Federal Ministry of Education and Research
CANMX	[mm]	Maximum canopy storage
ChanNumber		TRAIN-ZIN: Channel number
CH_K(1)	[mm/hr]	Effective hydraulic conductivity in tributary channel alluvium
CH_K(2)	[mm/hr]	Effective hydraulic conductivity in main channel alluvium
CH_W	[m]	Average width of main channel
CN		Curve Number
D*		Budyko climatic classification
Deep AQ	[mm]	Deep aquifer percolation
DEEPST	[mm]	SWAT: Initial depth of water in the deep aquifer
DEM		Digital Elevation Model
endDate		TRAIN-ZIN: End date
EPCO		Plant water uptake
ESCO		Soil evaporation factor
ET	[mm]	Evapotranspiration
evapTrain		TRAIN-ZIN: Transmission losses
fil.cio		SWAT Master Watershed File
GIS		Geographical Information System
GW_DELAY	[days]	SWAT: Groundwater delay
GWQMN	[mm]	SWAT: Threshold depth of water in the shallow aquifer
GW_REVAP		Groundwater "revap" coefficient
HOF		Hortonian Overland Flow
HRU		Hydrological Response Unit
ICALEN		SWAT: Code for writing calendar or julian day to daily outputs
IEVENT		SWAT: Rainfall/runoff/routing option
initMoist		TRAIN-ZIN: Initial soil moisture
IPRINT		SWAT: Print code
IRTE		SWAT: Channel water routing method
K_e	[mm/hr]	effective hydraulic conductivity
K_{sat}	[mm/hr]	saturated hydraulic conductivity

L		Latent heat of evaporation
LAI		Leaf Area Index
LHS		Latin Hypercube Sampling
NSE		Nash Sutcliffe Efficiency
NYSKIP	[years]	SWAT: Number of years to skip
P	[mm]	Precipitation
PCP	[mm]	Precipitation
Q	[m³/s]	Discharge
QConcMethod	[m]	TRAIN-ZIN: Runoff concentration method
QSWAT		Graphical user-interface of SWAT based on QGIS
rainGrad		TRAIN-ZIN: Precipitation gradient
RainMethod		TRAIN-ZIN: Precipitation interpolation
RCHRG_DP		Deep aquifer percolation fraction
RouteStep		TRAIN-ZIN: Routing time-step
SFTMP	[ºC]	SWAT: Snowfall temperature
SHALLST	[mm]	SWAT: Initial depth of water in the shallow aquifer
SMTMP	[ºC]	SWAT: Snow melt base temperature
SMFMX	[mm/ºC day]	SWAT: Melt factor for snow on June 21
SMFMN	[mm/ºC day]	SWAT: Melt factor for snow on December 21
SNOCOVMX	[mm]	SWAT: Minimum snow water content
SNO50COV		SWAT: Fraction of snow volume
SOF		Saturated Overland Flow
SOL_AWC	[mm_{H2O}/mm_{soil}]	Available water capacity of the soil layer
SOL_BD	[g/cm³]	Moist bulk density
SOL_K	[mm/hr]	Saturated hydraulic conductivity
SOL_Z	[mm]	Soil depth
sqmPerCell	[m]	TRAIN-ZIN: Cell size
startDate		TRAIN-ZIN: Start date
SURLAG		Surface runoff lag coefficient
SWAT		Soil Water Assessment Tool
SWAT-CUP		SWAT Calibration and Uncertainty Procedures
Trans_loss		TRAIN-ZIN: Transmission losses option
useBaseflow		TRAIN-ZIN: Baseflow component option
useSediment		TRAIN-ZIN: Sediment generation option
Vegh		TRAIN-ZIN: Vegetation height
WRB		World Reference Base for Soil Resources
xySize		TRAIN-ZIN: Grid size (pixel)
ZinStep	[minutes]	TRAIN-ZIN: ZIN time-step

Acknowledgement

First of all, I would like to thank **Jens Lange** with whom I developed the topic of this master thesis and how gave me the opportunity to perform a hydrological model comparison in Wadi Auja. Thank you for the trust you gave me to work independently and your experience from Israel/Palestine you shared with me.

As a student, who has never been to the study area, or even to Israel/Palestine, it was quite a challenge to set up a high-resolution water balance model without any on-site field experience. During various conversations with **Fabian Ries** from the Chair of Hydrology, Albert-Ludwigs-University Freiburg, I got a deeper insight into specific local catchment characteristics and hydrological processes. Thank you for this support and the field data you have collected and shared with me, which finally enabled me to correctly calibrate my SWAT models.

Above all, my biggest thanks go to **Jens Kiesel** from the Leibniz-Institute of Freshwater Ecology and Inland Fisheries by whom I came the first time in contact with hydrological models and learned a lot from his experience as a professional SWAT modeler. Thank you for your advices and insider tips to specific characteristics of SWAT. Finally, you gave me the motivation to accept the challenge of an ambitious model comparison. Thank you for that.

Preface

In October 2016, I participated at the DAAD Summer School in Tunis Tunisia, where I came in contact with the Soil Water Assessment Tool (SWAT) for the first time. Fascinated by the complexity of the model and its ability to simulate the “reality”, I was convinced of its strengths as a powerful tool for engineers, decision makers and the development cooperation sector. At that time, I had the impression, I could model almost everything within a few minutes with only some open datasets from the Internet. After a while, I realized, that I am modelling and calculating the sediment yield of an environment in Tunisia without prior knowledge of its environment, climate, geology and hydrological processes. The fact, that I achieved useful results with my model, does not automatically mean, that it is representing the reality. As an application-oriented person, I asked myself how likely is the risk for a misapplication/misinterpretation or which errors are committed, if the model is configurated without extensive field investigations, expert knowledge and high-resolution input data. Finally, this led me to the present study and to the comparison of two hydrological models at the Wadi Auja Catchment in the West Bank, Palestine.

Abstract

The emphasis of this present study is an objective hydrological model comparison of TRAIN-ZIN and SWAT under semi-arid conditions. TRAIN-ZIN is a process-oriented rainfall-runoff model specialized on the simulations of highly dynamic discharge processes in semi-arid areas in adequate temporal and spatial resolution. SWAT, in contrast, is a river basin model that was developed to quantify long-term impacts of alternative land management practices on large, complex watersheds. Suitability and applicability of SWAT in semi-arid areas was critically examined.

The study area of Wadi Auja is situated on the eastern slopes of the western margin of Jordan Rift Valley in the West Bank, Palestine. The mountainous area is characterized by typical Mediterranean climate, sparse vegetation on massive limestone and dolomite formations and a pronounced elevation-gradient. Precipitation ranges from east to west (150 to 700 mm/year) and is highly variable in space and time. The entire region suffers from increasing pressure on freshwater and shows a demand on sustainable water resources management for the typical semi-arid karst environment. The watershed is equipped with five runoff gauges covering the subbasins and a highly resoluted meteorological network. Discharge of ephemeral streams is highly dynamic and represents only a small fraction of the water balance.

To conduct an objective and accurate model comparison, which is based on differences in model structure and functions, a SWAT version called SWAT advanced is configurated by equal input data, time-resolution and calibration-guideline as TRAIN-ZIN. This study explains how to configurate SWAT in a sub-hourly time-step and gives insights into a manual expert knowledge calibration. To clarify strengths of specialized models like TRAIN-ZIN and SWAT advanced in comparison to typical SWAT applications, a second version called SWAT light was configurated on a daily time-step using free available data, default model settings and an automatic calibration by SWAT-CUP. However, risks and suitability for applied water management scenarios are discussed.

It could be concluded that SWAT advanced correctly quantifies the annual water balance of semi-arid regions, but has weaknesses representing hydrological small-scale processes, especially saturated overland flow. In this context, SWAT light is unsuitable to determine the water balance and simulate the general discharge-behavior. TRAIN-ZIN, on the contrary, achieved best modelling results and has proven its suitability to exactly depict hydrological small-scale processes and specifying the water balance of semi-arid regions. Therefore, it is ideally suited for scientific investigations on hydrological processes as well as for applied water resource management.

Keywords: TRAIN-ZIN, SWAT, hydrological model comparison, Wadi Auja, West Bank, semi-arid area, sub-hourly time-step, expert knowledge calibration, SWAT-CUP, high discharge-dynamics

Zusammenfassung

Der Schwerpunkt der vorliegenden Studie liegt auf einem objektiven hydrologischen Modellvergleich zwischen TRAIN-ZIN und SWAT unter semiariden Bedingungen. Das prozessorientierte Regen-Abfluss-Modell TRAIN-ZIN ist für die Simulation von hoch dynamischen Abflussprozessen in ausreichender räumlicher und zeitlicher Auflösung in semiariden Gebieten spezialisiert. Im Gegensatz dazu wurde das Wasserhaushaltsmodell SWAT zur Quantifizierung langfristiger Auswirkungen von alternativen Landnutzungsänderungen auf großen, komplexen Wassereinzugsgebieten entwickelt. Eignung und Anwendbarkeit von SWAT in semiariden Gebieten wurde kritisch untersucht.

Das Untersuchungsgebiet Wadi Auja liegt an den Osthängen des westlichen Randes des Jordangrabens in der West Bank, Palästina. Dieses gebirgige Terrain ist gekennzeichnet durch typisch mediterranes Klima, spärlicher Vegetation auf Kalkstein und Dolomit und einem ausgeprägten Höhengradienten. Niederschlag variiert von Ost nach West (150 – 700 mm/Jahr) und ist höchst variabel in Raum und Zeit. Die gesamte Region leidet unter steigenden Druck auf lokale Trinkwasserressourcen und zeigt einen Bedarf an nachhaltigen Wassermanagement Praktiken für typisch semiaride Karstgebiete. Das Einzugsgebiet ist mit Abflusspegeln für jedes der fünf Teileinzugsgebiete, sowie einen dichten Messnetz an Klimastationen in hoher zeitlicher Auflösung ausgestattet. Der Abfluss ephemerer Fließgewässer ist hoch dynamisch und repräsentiert nur einen kleinen Teil der gesamten Wasserbilanz.

Um einen objektiven und fairen Modellvergleich zu gewährleisten, welcher auf Unterschieden in Modellstruktur und Modellfunktionen basiert, wurde eine SWAT Version namens „SWAT advanced“ mit gleichen Input Daten und zeitlicher Auflösung konfiguriert und nach demselben Regelsatz wie TRAIN-ZIN manuell kalibriert. Diese Studie erklärt, wie SWAT in 5-Minuten Auflösung konfiguriert werden kann und gibt Einblicke eine manuelle Kalibrierung nach Expertenwissen. Um die Stärken von spezialisierten Modellen wie TRAIN-ZIN und SWAT advanced gegenüber typischen SWAT Anwendungen zu verdeutlichen, wurde eine weitere SWAT Version namens „SWAT light“ in täglicher Auflösung, mit frei verfügbaren Daten und Standardeinstellungen aufgesetzt, sowie eine automatisierte Kalibrierung mit SWAT-CUP durchgeführt. Risiken und Eignung dieser Modellversion für das integrierte Wasserresourcen-Management werden diskutiert.

Es konnte herausgefunden werden, dass SWAT advanced in der Lage ist die Wasserbilanz eines semiariden Gebietes zu quantifizieren, jedoch Schwächen in der Abbildung von kleinräumigen Abflussprozessen, allen voran Sättigungsoberflächenabfluss zeigt. Zur Bestimmung der Wasserbilanz, sowie für die Simulation von Abflussprozessen stellte sich SWAT light als ungeeignet heraus. Im Gegensatz dazu erreichte TRAIN-ZIN beste Modellierungsergebnisse und stellte seine Eignung unter Beweis, kleinräumige und hoch dynamische Abfluss Prozesse zu simulieren sowie die Wasserbilanz von semiariden Gebieten zu bilanzieren. Damit ist TRAIN-ZIN bestens für wissenschaftliche Untersuchungen hydrologischer Prozesse sowie für das angewandte Wasserresourcen-Management geeignet.

1. Introduction

1.1 General introduction

1.1.1 Project background

In the Mediterranean region, 60 million people are living below the line of absolute water-poverty of 500 m³/year per inhabitant (Estimation of United Nations, EUWI, 2007). The residents of Israel/Palestine are particularly affected by water scarcity, although cities like Ramallah at the central highland of the West Bank have more annual rainfall than London (EWASH, 2013). The suspicion of an insufficient water management comes up. Besides political regulations on the national water supply and climate change, especially the agricultural sector in form of irrigation and livestock increases the pressure on water resources (Figure 1, Karen, 2009). The Mediterranean groundwater report of 2017 (EUWI, 2007) clarified, that most of the groundwater resources at the Palestinian Authority are fully exploited and some aquifers are still over-exploited. According to expectations of Droogers et al. (2012), the local water demand will increase dramatically to meet the needs of economic development and a constantly growing population.

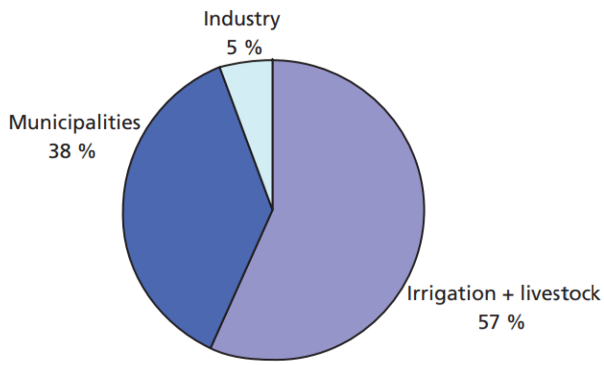


Figure 1: Water withdrawal by sector in the West Bank, Palestine. Total groundwater withdrawal: 0.157 km³ in 2000 (Karen, 2009).

With increasing demand on limited water resources, also the need for improved decision making tools in form of hydrological models is growing (Beven and Young, 2013). Apart from model applications for a more sustainable management of available groundwater resources, hydrological models can be used to determine potentials of surface runoff as an additional water source (rainwater harvesting). The utilization of currently unused surface water like from flash floods, may play a central role in future water resource management in semi-arid areas (Ries, 2016). Therefore, the development of improved hydrological models, which can represent specific surface runoff processes in arid and semi-arid areas are still in great demand.

1.1.2 Previous studies, projects and current state of research

The two proven hydrological models TRAIN (Menzel L., 1996) and ZIN (Lange et al., 1999), were coupled successfully in 2006 (Gunkel, 2006). Thereupon the TRAIN-ZIN model was applied and modified over a wide range of semi-arid and arid conditions at the Lower Jordan River Basin (Gunkel and Lange, 2012, 2017). The result was a specialized hydrological model, which can simulate the high dynamic of hydrological processes in semi-arid regions. Thereafter, the model was successfully utilized to simulate available surface water resources (Shadeed, 2008), to evaluate rainwater harvesting techniques (Shadeed and Lange, 2010) and for water balance estimations in a data-scarce catchment (Wadi Faria) at the northeastern part of the West Bank, Palestine (Gunkel et al., 2015). Moreover, TRAIN-ZIN was applied to a wide range of catchments along the Lower Jordan River Basin within the GLOWA-JR Project (http://www.glowa-jordan-river.de) funded by the Germany Ministry of Education and Research (BMBF) (Siebert et al., 2016; Lange et al., 2012; Alkhoury et al., 2010).

Besides a wide range of TRAIN-ZIN applications, the study area Wadi Auja was subject of intensive investigations within the framework of SMART (Sustainable Management of available Water Resources with Innovative Technologies). SMART was an Integrated Water Resources Management Project of the BMBF at the Lower Jordan Valley, where Prof. Dr. Martin Sauter from the Georg-August-University of Göttingen held the project coordination. In this context, various studies on climate and hydrology took place and a dense measurement network was installed. Most relevant investigations for this thesis are listed below:

- Artificial rainfall experiments (preferential flow at the soil-bedrock interface) - (Sohrt et al., 2014)
- Characterization of karst aquifer (tracer tests - chloride mass balance method - to examine groundwater recharge) - (Schmidt et al., 2014)
- Soil moisture monitoring (analysis of inter-annual soil moisture dynamics and one-dimensional soil hydraulic modelling) - (Ries et al., 2015)
- Rainfall and runoff monitoring (investigation of runoff generation processes and physiographic catchment properties) - (Ries et al., 2017)

To accomplish a critical model evaluation of TRAIN-ZIN, comparison with another hydrological model is still missing (Gunkel, 2016). Therefore, the established model SWAT was selected. “The Soil and Water Assessment Tool (SWAT) has emerged as one of the most widely used water quality watershed- and river basin-scale models worldwide, applied extensively for a broad range of hydrologic and environmental problems” (Gassman et al., 2014, page: 1). More and more frequently SWAT is also applied in semi-arid and arid regions like Tunisia (Ouessar et al., 2009), China (Cheng et al., 2009), Arizona USA (Yuan et al., 2015) and Pakistan (Shimaa, 2015). A published SWAT application in the West Bank Palestine or even in

Israel is still missing. While Shimaa (2015) suggests, that the SWAT model can be used efficiently in semi-arid regions to support water management policies, Yuan et al., 2015 mentioned major challenges during the SWAT modelling, but neither defines an explicit scope of application.

While in 2010 the Soil Water Assessment Tool was upgraded to a sub-hourly time interval with a resolution as high as one minute (Jeong et al., 2010), the usual application range of SWAT is still in annual or monthly time-steps (Gassman et al., 2014). That is because on the one hand, SWAT is still focused and widely used to predict the impact of land use change and water resource management at large catchment scales over long time periods (Arnold et al., 2012b) and on the other hand, because of insufficient time resolution in input data. All in all, just a few studies on sub-daily time resolution were found (Table 1), while none were applied on the Open Source interface QSWAT, based on QGIS (QGIS Development Team, 2017).

Table 1: Overview of SWAT applications in sub-daily time interval.

Paper	Time-interval	Catchment area	Location
Jeong et al., 2010	15-min	1.9 km²	Austin Texas USA
Maharjan et al., 2013	15-min	0.08 km²	norther part of South Korea
Yang et al., 2016	60-min	5803 km²	upper Huai river basin of China
Boithias et al., 2016	sub-hourly	800 km²	river coastal basin southwestern France

Moreover, Gassman et al. (2014) summarized the results of 22 SWAT-related studies and concluded, that the empirical Runoff Curve Number Method (CN) is most commonly used, despite the known disadvantages for spatial and temporal variability of hydrological processes (Ponce and Hawkins, 1996). This stresses the need for further investigations of SWAT applications with alternative methods like the Green-Ampt method (Green and Ampt, 1911), which is an available model option of SWAT, but has only been applied in few watersheds until now.

In conclusion, there is a lack of research on SWAT applications in semi-arid regions. Furthermore, the potential of SWAT to simulate high-magnitude runoff events in dry environments is unclear and so far, little explored. Finally, there are more and more SWAT applications, using the auto-calibration method SWAT-CUP (Arnold and Fohrer, 2005; Villamizar, 2015). It should be examined, whether this kind of calibration can replace intensive field investigations and a manual-expert knowledge calibration. This question should be considered in further research about SWAT-CUP based applications as a secure and meaningful decision-making tool.

1.1.3 Central research issue

The fundamental goal of this thesis is to compare the model performance of TRAIN-ZIN and SWAT under typical semi-arid conditions. In this respect, the central research issue is to determine strengths and weaknesses of both models in their ability to quantify the water balance, simulate highly dynamic hydrological processes and verify the model applicability for semi-arid areas. In this respect, the question arises, whether SWAT can be optimized as far as necessary, to simulate the ephemeral discharge in a sufficient temporal and spatial resolution.

To enable an objective and meaningful model comparison, both models should be based on the same input data, be configurated applying the same calibration-guidelines and preferably use similar physical equations. Therefore, the mandatory prerequisite and challenge of this thesis is to setup SWAT in a sub-hourly output resolution (5-min) like TRAIN-ZIN, utilize as much expert knowledge and input data as possible from previous investigations and process long data series as well as large data volumes.

Furthermore, this thesis analyzes the differences between expert knowledge calibrated and auto-calibrated hydrological models. In this respect, the role of insufficient data preparation, time-resolution and field investigations is discussed carefully. Therefore, a further SWAT model called SWAT light should be calibrated automatically and set up with only free available input data, a usual daily time-interval and default values from the SWAT data base.

1.1.4 Thesis structure

The present thesis is structured into a brief description of main catchment characteristics and hydrological processes, followed by a summary of fundamental model components, functions and the general architecture of TRAIN-ZIN and SWAT. Thereafter, improvements of the internal data base of SWAT advanced by measured field data and expert knowledge out of the TRAIN-ZIN configuration are described (Figure 2). In this context, this study reveals, how to set up SWAT in a sub-hourly time-step of 5 minutes. The TRAIN-ZIN calibration process from Ries (2013) was transferred into a general calibration-guideline and applied for the expert knowledge calibration of SWAT advanced. In contrast to that, setup and handling of the auto-calibration software SWAT-CUP is explained for the application in SWAT light. While SWAT light is calibrated strictly according to the manual of SWAT-CUP, calibration of TRAIN-ZIN is unexceptionally assumed from Ries (2013), SWAT advanced calibration is additionally optimized by an automated R algorithm.

After all model variations were successfully applied, final parameter values, model philosophy as well as different model components and structure were compared and discussed. In that respect, challenges, strengths and weaknesses of the configuration or rather calibration procedure was explained. Finally, simulations of the annual water balance and the single discharge-dynamic was precisely analyzed and compared. Strengths and weaknesses of all model variations are summarized, while concrete suggestions for improvement were made.

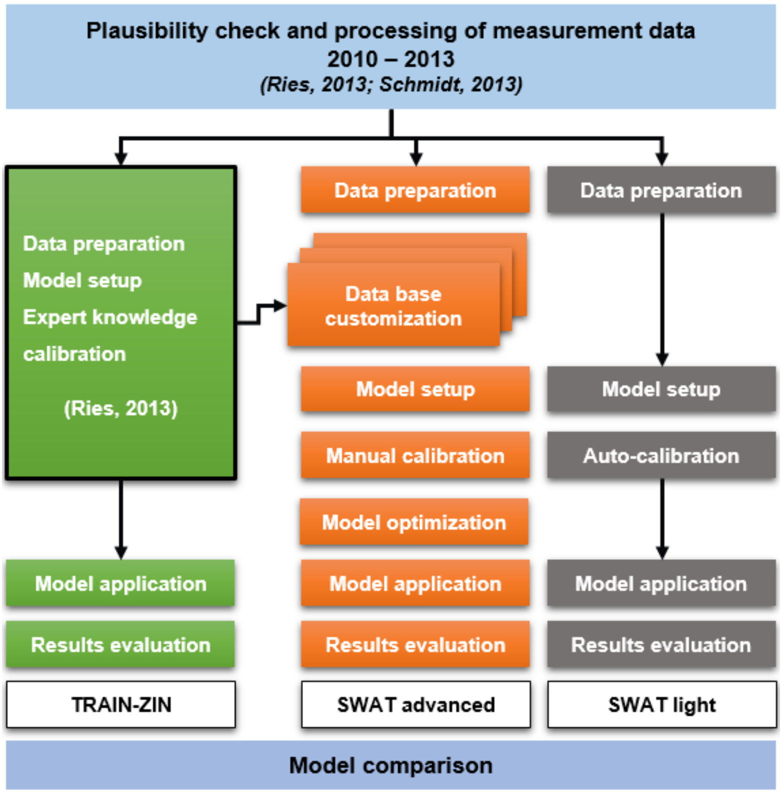


Figure 2: Flow chart of thesis structure and procedure. Green: TAIN-ZIN, orange: SWAT advanced and grey: SWAT light.

1.2 Catchment characterization of Wadi Auja

1.2.1 Study area

The study area is located in a rural and sparsely populated mountain range, in the West Bank of Israel Palestine (Figure 3). The area is characterized by strong gradients due to the topography of the Jordan Rift Valley. Elevations ranges from 1016 m a.s.l. in the mountain range (Tell ‘Asur) to 240 m b.s.l. in the Jordan Valley (Ries, 2016). Closest cities around the study area are Ramallah (ca. 10 km), Jerusalem (ca. 25 km) and Jericho (ca. 15 km). Agricultural activities have influenced the ecosystem and formed the landscape over thousands of years. To prevent the land from erosion and soil degradation, the Romans introduced terracing and agricultural stone walls, which still characterize the landscape of the study area (Yaalon, 1997; Dudeen, 2001). Open shrubland (28 %) and barren land (11 %) are the dominating land use classes in Wadi Auja, followed by olive terraces (6 %) (Ries, 2013).

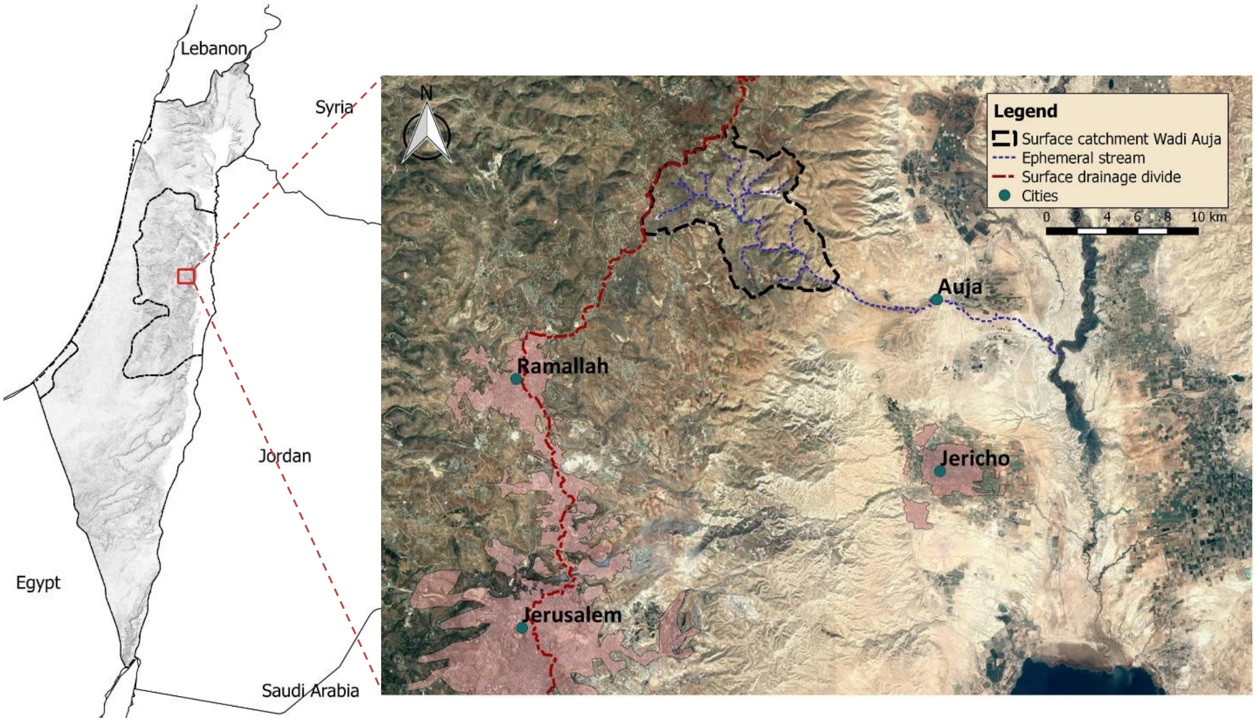


Figure 3: Study area of Wadi Auja in the West Bank Palestine. (Google Satellite, processed by QuickMapServices plugin QGIS).

During the last decades, a rapidly increasing water demand has led to widespread overexploitation of groundwater resources, which is still the main source of water supply. This put the sustainable management of water resources on the local and even international development agenda (EUWI, 2007). Nevertheless, only 9 % of agricultural areas in the West Bank are irrigated (Dudeen, 2001). The growing population and the expected climate change will further increase the pressure on the naturally low availability of water resources (Gunkel and Lange, 2012).

1.2.2 Climate and precipitation

Israel is situated along the southeastern Mediterranean coast and divided into four longitudinal physiographical strips from west to east according to Goldreich (1998) (Köppen climate classification, Figure 4 left). The Köppen classification is based on climatic conditions relative to natural vegetation and describes the general distribution of climate. According to that, the upper mountain range of Wadi Auja is classified as a typical Mediterranean region (Csa), while the lower areas are characterized by steppe in a semi-desert area (BSh). In the east, the catchment of Wadi Auja ends at the transition to the desert region (BWh) in the Jordan Valley (Goldreich, 1998).

Besides the Köppen classification, Budyko (1956) developed a physical principal based on water and heat balance. He introduced the dimensionless quotient D and the logarithmic value D* between radiation balance R and precipitation P, while L is the latent heat of evaporation (Formula 1 and 2).

$$D = \frac{R}{PL} \tag{1}$$

$$D^* = Log_{10}(D) \tag{2}$$

The quotient D* indicates a water surplus, if it is below and a water shortage if it is above zero. According to Joseph and Ganor (1986) (Figure 4, right), the whole study area is limited by water and suffers a water deficit, with water shortage strongly increasing from west to east (D*: 0.4 to 0.85).

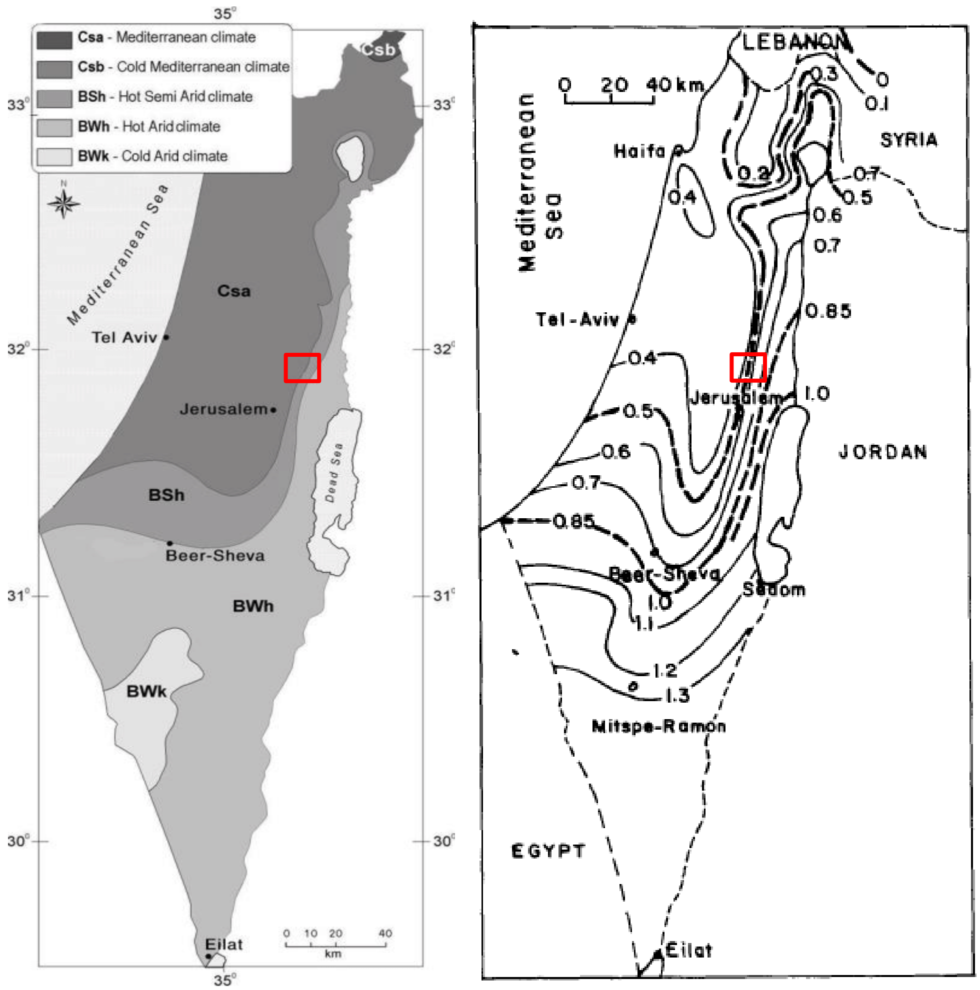


Figure 4: Left: Map of Köppen climatic classification of Israel (Itzhak-Ben-Shalom et al., 2016). Right: Budyko climatic classification (D*) of Israel. Dashed lines have climatic significance (Joseph and Ganor, 1986). The red square indicates the study area.

Large portions of the Wadi Auja are characterized as a typically Mediterranean climate with dry summers and mild, rainy winters (Köppen classification Figure 4). In this area more than 90% of Israel's precipitation can be attributed to the so called Cyprus lows from the Mediterranean Sea (Goldreich, 1998). While these Cyprus lows mainly occur in winter season from October to April (Figure 5) and are characterized by long duration but low intensities. The so called Red Sea Trough is responsible for short and intensive convective rainfall in Autumn and Spring (Goldreich, 1998; Ries, 2016).

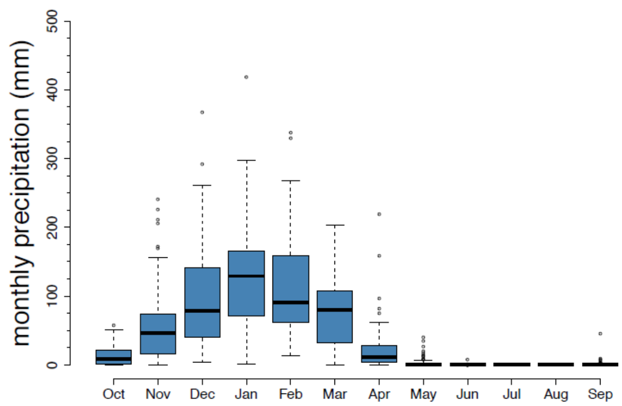


Figure 5: Characteristic monthly rainfall distribution of Jerusalem for the time series period 1950–2015. Graph extracted from Ries, 2016. Data source: Israel Meteorological Service Database (IMS) http://dat.gov.il/ims

Nevertheless, the spatial variability of precipitation is following the steep relief gradient within the catchment area and decreases towards the Jordan Rift Valley. Because of rain-shadowing effects of the mountain range parallel to the coast in the upper catchment, precipitation decreases from 700 mm/year to 150 mm/year. Besides this pronounced spatial variability, the catchment shows a strong inter-annual rainfall variability from year to year (Ries, 2016). Measurement results of Ries (2013) show, that an average annual rainfall of 392 mm/year for the representative hydrological years 2010/11 to 2012/13.

Snowfall at the headwater of Wadi Auja is possible but rare. The Israel Meteorological Service (IMS) reported snowfall only two times between 10/2010 and 10/2013. Snowfall was estimated to be up to 25 mm water equivalent by the difference between uncorrected and corrected precipitation data (actual snow measurements are missing). In December 2013 (outside the observation period) a historic snowfall occurred, but the snow cover only remained for a few days. The weather station at Kafr Malik recorded only two days below zero (-1.2°C, 09 - 10.01.2013). The same two days were determined by the data from IMS. Hence, snowfall occurs very rarely and therefore only has a small influence on the annual water balance.

1.2.3 Geology and geomorphology

The geology of Wadi Auja mainly consists of massive limestone and dolomite formations from the Cenomanian and Turonian age. These formations are widely fractured and karstified and form the upper carbonate aquifer system (Figure 6). Thereby, high permeabilities due to a pronounced conduit system are expected. The underlying main aquifer system is cropping out west of Wadi Auja and consists of thick Albian formations up to 800 m (Figure 6, geological cross-section). Both aquifer systems are draining their groundwater towards the Jordan River and the Dead Sea. Southeast of the study area, the aquifer complex is covered by Coniacian to Maastrichtian sediments, predominantly chalk, which constitute an aquiclude (Schmidt, 2014).

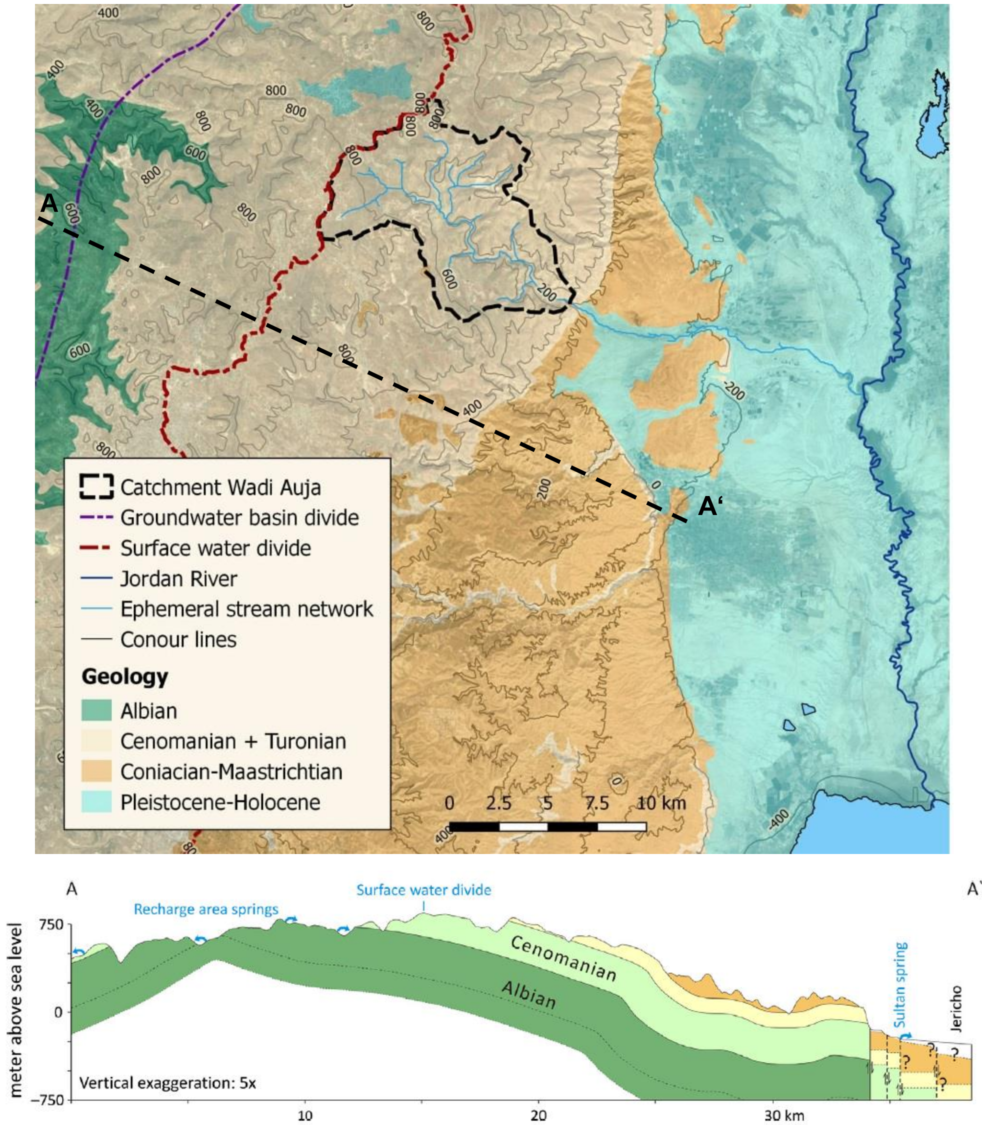


Figure 6: Geological map of catchment Wadi Auja with schematic cross-section above the study area. Contour lines are derived from a digital elevation raster in 25 x 25 m resolution. Geological formations referring to Schmidt et al. (2014). Geological cross-section is directly extracted from Schmidt et al. (2013).

The mountainous topography of Wadi Auja is characterized by massive bedrock exposure, lose rock fragments, canyons and steep slopes (Figure 7). The 3-D model illustrates the deeply incised stream network into the soft limestone and the outlet location on the transition to the Jordan Rift Valley. Due to the degree of carbonate weathering, the surface cover is quite heterogeneous and patchy. Strong features of epi-karst and soil pockets in different dimensions form the geomorphology and influence the hydrogeology (Ries et al., 2017).

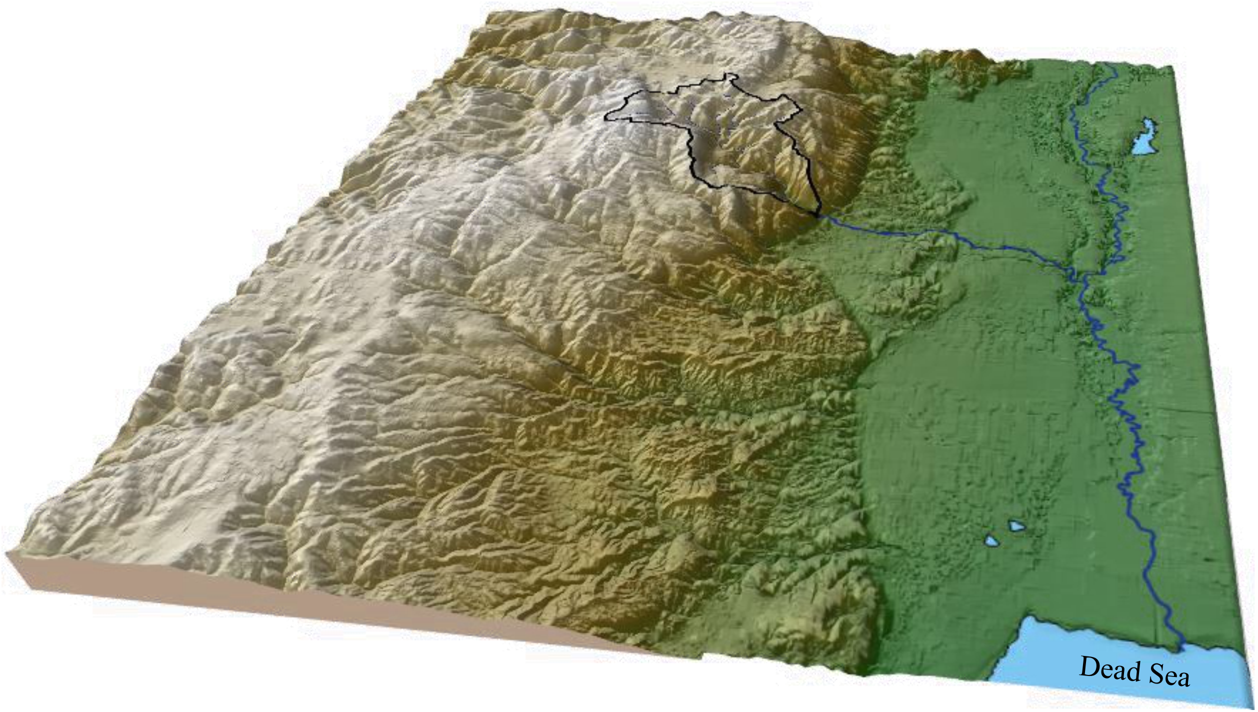


Figure 7: 3-D topography of Wadi Auja at the Jordan Rift Valley. 3-D model was created by the QGIS plugin "Qgis2threejs" on the basis of a digital elevation map (25 x 25m). Vertical exaggeration: 3x.

1.2.4 Surface cover, land use and soils

According to comprehensive field investigations and measurements within the SMART project, the surface cover of the Wadi Auja catchment can be separated into two distinct sections along the rainfall-elevation gradient (Appendix 1) (Ries, 2016). While the mountainous area is characterized by massive bedrock outcrops, shrubs, annual plants and agricultural activity on terraced slopes (mainly olives and fruits), the lower part consists of shallow soils, sparse vegetation and some agriculture on the valley planes (Figure 8

).

Regardless of the soil type, the established plants are highly specialized and well adapted to the strong seasonality and climatic conditions. On north-facing hillslopes, shrub like the *Sarcopoterium spinosum* (Thorny Burnet) is the predominant vegetation type. The south-facing slopes, in contrast, have sparse vegetation with a higher proportion of bare soil and rock outcrops (Kutiel et al., 1998). Extensive grazing by goats and sheep influenced the vegetation composition (Ries, 2013).

Figure 8: Landscape transformation along the strong precipitation gradient from west to east. The images display: a) Olive terraces on rocky terrain close to Kafr Malek in the headwaters area (Auja headwater 3); b) The valley plane of Ein Samia in the center of the Wadi Auja catchment; c) catchment outlet at Auja Spring (Ries et al., 2017) Picture source: Fabian Ries.

Terra Rossa (The Red Mediterranean Soil) was formed under past climatic conditions and is the predominant soil type above compact limestone in the central highland region under typical Mediterranean climate. These typical red soils of loamy texture, are characterized by low fertility due to their poor water holding capacity and high lime content (Dudeen, 2001). Following the climatic gradient towards the more arid zone in the east, a brown Rendzina on softer limestone, marl and chalk is developed. These soils are thinner and still show recent development (Shapiro, 2006). Both soil types are characterized by high clay contents up to 60% in karst fissures and soil pockets. In response to different degrees of carbonate rock weathering and the heterogeneous topography, the soil depth, the clay content and soil organic carbon content are highly variable (Ries et al., 2015). In the more arid valley plane, fine textured and several meter-thick alluvial soils (Vertisols) can be found. These soils are strongly influenced by human activities like deforestation and land cultivation over more than 5000 years (Yaalon, 1997).

Finally, it must be noted, that there is no pronounced dividing line between the two sections, but a smooth transition in a generally high spatial variability. Moreover, the catchment is influenced by urban areas (mainly in the northwest), anthropogenic structures and activities. The distinct characteristics of the upper and lower basin sections are summarized in Table 2.

Table 2: Characterization of predominant surface cover and land use, up- and downstream the Wadi Auja catchment (Ries, 2016).

	Upstream	**Downstream**
Vegetation	mainly shrub and annual plants	sparse vegetation
Surface cover	irregular and patchy terrain, predominant rock outcrops	ratio between rock outcrop and soil cover (50:50)
Dominant soil type	Terra Rossa	brown Rendzina
Soil properties	variable soil depth due to soil pockets (karst)	shallow soils

1.2.5 Hydrology

1.2.5.1 Catchment characterization

The catchment of Wadi Auja is situated on the eastern slopes of the western margin of the Jordan Rift Valley. The surface drainage catchment has a size of around 55 km² and its ephemeral streams are draining towards the Dead Sea (Figure 3) (Ries, 2013). Ephemeral streams are the defining characteristic of many watersheds in dry, arid and semi-arid regions and play an important role in the maintenance of water resources in these regions (Levick et al., 2008). The western catchment boundary of Wadi Auja is formed by the Jordan surface drainage divide, while the outlet is located at the transition to the Jordan Rift Valley (Figure 3). Ries (2016) documented a less dense and developed stream network in the karstic headwater area, than in the southeast desert area. Moreover, streambeds in the mountainous region towards the catchment outlet become wider and are more deeply incised into the landscape. Therefore, Ries (2016) concluded a higher frequency and erosive force of runoff events in this area.

The catchment is divided into five subcatchments, which are defined and represented by five runoff gauges (Figure 9). Wadi Auja provides a dense measurement network, which was mainly installed and maintained within the project framework of SMART (2007). The used rainfall gauges, meteorological stations as well as two soil moisture measurement locations are illustrated in Figure 9.

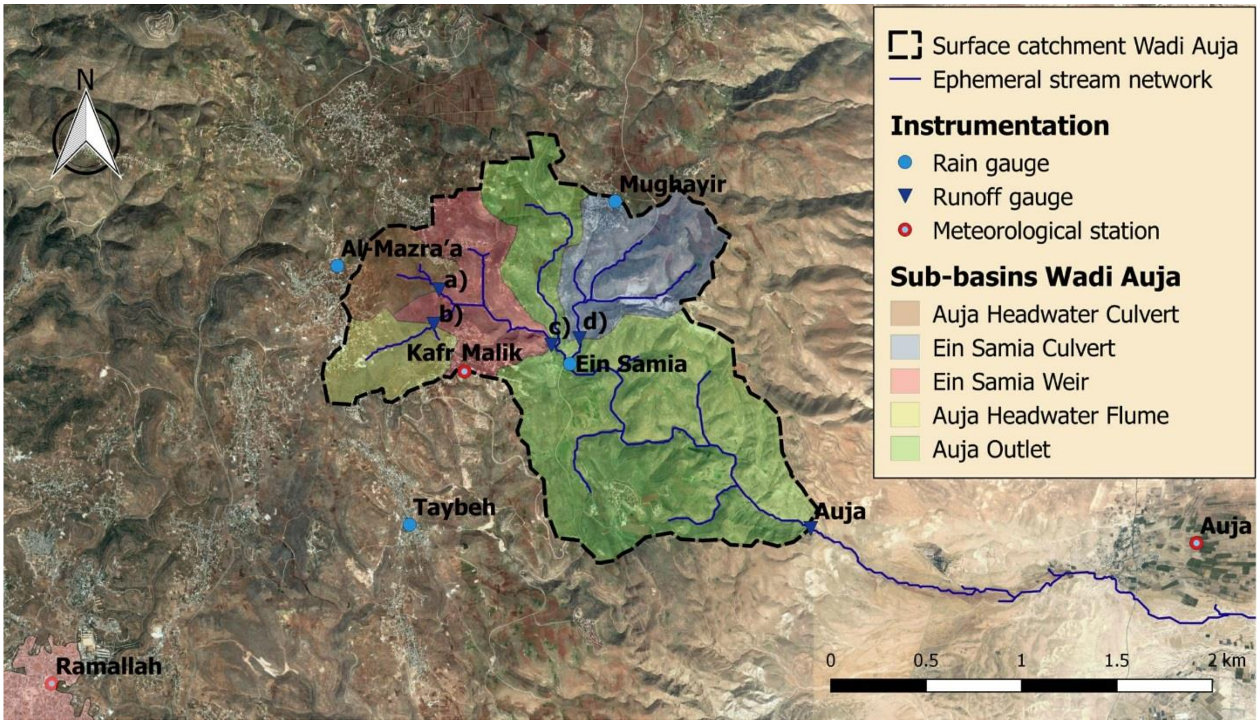


Figure 9: Catchment characterization including rain gauges and meteorological stations of Wadi Auja. The catchment is divided into five subbasins, which are defined and represented by five runoff gauges. a: Auja headwater Culvert, b: Auja headwater Flume, c: Ein Samia Weir, d: Ein Samia Culvert and the Auja outlet.

1.2.5.2 Evapotranspiration

According to a study by Sharakas et al. (2007) almost 60 – 70 % of the total annual rainfall is lost through evapotranspiration. Evapotranspiration is driven by high energy input and wind conditions, but rather limited by water availability within the study area. Actual evaporation makes up the biggest part of the water balance, while transpiration plays a minor role, due to sparse vegetation in the catchment. Furthermore, Ryu et al. (2008) measured the inter-annual variability of evapotranspiration under semi-arid conditions and showed, that actual evapotranspiration (ETa) during winter month is almost equal to potential evaporation (ETp), because of a general energy limitation. On the other hand, during spring and summer months, where evapotranspiration is water limited, ETa is much lower than ETp.

1.2.5.3 Runoff processes

Surface runoff in Wadi Auja is taking place in ephemeral streams, which are the defining characteristic of many watersheds in dry semi-arid regions like the West Bank Palestine (Levick et al., 2008). Due to low rainfall, but high evaporation rates at Wadi Auja, surface water flow in ephemeral streams only occur after long intensive precipitation events with high overall amounts during the mid-winter season. Ries et al. (2017) found an apparent threshold level for runoff formation of 50 mm within one rainfall event. Whenever a runoff effective rainfall event occurs, discharge reactions at the catchment outlet (Figure 10) can be observed within a few minutes producing flashfloods, which are typical for the region. Besides diverse patterns of rainfall events, runoff generation strongly depends on catchment characteristics like geology, surface connections, vegetation cover and preferential flow pathways in the subsurface (Sohrt et al., 2014). Especially in karstified landscapes, the subsurface drainage plays a major role (Ries et al., 2017).

Figure 10: Auja Weir at the catchment outlet (Picture: Sebastian Schmidt).

Using soil moisture observations, Ries et al. (2015) concluded, that despite the presence of carbonate rocks in the headwater, percolation to the epikarst can effectively be limited by a reduced permeability at the soil-bedrock interface. These analyses suggest, that the predominant runoff generation process in the headwater of Wadi Auja is saturation excess overland flow (SOF). In the more arid part of eastern Wadi Auja, surface runoff occurs after only a few millimeters of rainfall, due to thinner soil layers (Ries, 2016). Finally, a strong correlation of rainfall- and single isolated runoff peaks indicates, that Hortonian runoff processes (HOF) are dominant in the arid region. The study clearly confirms the transition of runoff generation processes from SOF to HOF along the transition from semi-arid to arid areas, while the biggest runoff portion is probably generated at the headwater.

1.2.5.4 Transmission losses

Transmission losses are unneglectable in Wadi Auja, but investigations of the ephemeral riverbed demonstrated, that besides some gravel pockets and small water basins, the riverbed is mostly well sealed (Ries, 2013). In general, transmission losses are expected during high discharge peaks and when runoff reaches the flood plains outside the stream channel (Lange, 2005). The quantification of transmission losses – especially in ephemeral streams – is very challenging and subject of current scientific studies. According to a personal quantification and simple comparison of observed discharge at the five subbasin outlets, transmission losses were estimated to 0.8 – 1.7 mm/year, where highest losses were observed downstream.

1.2.5.5 Percolation, groundwater recharge and baseflow

The catchment of Wadi Auja is characterized by a relevant fraction of deep aquifer percolation up to 25 – 50 % of the precipitation, based on a chloride mass balance of Schmidt et al. (2014). Due to shallow alluvium soils, preferential flow paths and a pronounced karst system, it is more likely that the infiltrated water directly percolates into the ~ 800 m thick Cretaceous carbonate aquifer complex, than that it remains in the shallow aquifer. Therefore, (deep aquifer-) percolation is equal to groundwater recharge within this study. Through conduits, high percolation rates and fast groundwater recharge reactions are possible, while it remains unclear, if the percolating water only triggers a reaction on the groundwater table due to pressure transmission (Schmidt et al., 2014). Due to that, Auja spring can react within a few days after a recharge-effective precipitation event is exceeded (mainly in winter season). This threshold is not a fixed value, because it strongly depends on the precipitation pattern like intensity, duration and distribution. Threshold levels around 150 – 240 mm of cumulative rainfall were observed (Schmidt et al., 2014). Therefore, groundwater recharge in Wadi Auja is more an event based phenomena, than a continuous one.

While the recharge reaction could be observed quite precisely, the quantification of aquifer recharge is uncertain due to missing information about the extension and spatial dimension of the groundwater catchment. According to Schmidt (2013), it is difficult to define the subterranean water catchment, because it strongly differs from the surface catchment due to the complex geology. Nevertheless, mean annual percolation fluxes were calculated between 82 and 150 mm (1951-2013) (Ries et al., 2015).

Due to extensive studies within the SMART project, a good understanding of the hydrological system in Wadi Auja is available. A continuous, relevant baseflow from the aquifer into the reach is not assumed. The reasons are diverse, but primary it depends on uncertain and fluctuating hydraulic connections between the reach and the groundwater as well as a pronounced karst system, which can enable fast percolation (Schmidt, 2014; Ries, 2016).

1.3 Brief characterization of TRAIN-ZIN and SWAT

1.3.1 General model description of TRAIN-ZIN and SWAT

1.3.1.1 TRAIN-ZIN

TRAIN-ZIN is a typical process-oriented and physically-based rainfall-runoff model, which is designed to describe most relevant hydrological processes affecting catchment response in arid and semi-arid regions in adequate temporal and spatial resolution (Gunkel et al., 2015). The model combines the vertical oriented long-term model TRAIN (Menzel L., 1996) at the soil-vegetation-atmosphere interface and the horizontal oriented model ZIN (Lange et al., 1999). ZIN is designed to simulate high dynamic hydrological runoff generation processes and transmission losses in dry ephemeral channels, while it was originally developed to simulate single runoff events at the Wadi Zin catchment in Israel. To address long term water balances, both models were coupled to TRAIN-ZIN by Gunkel et al. (2007) (Figure 11). In this respect, the soil moisture routine acts as an interface between these two models (Shadeed and Lange, 2010).

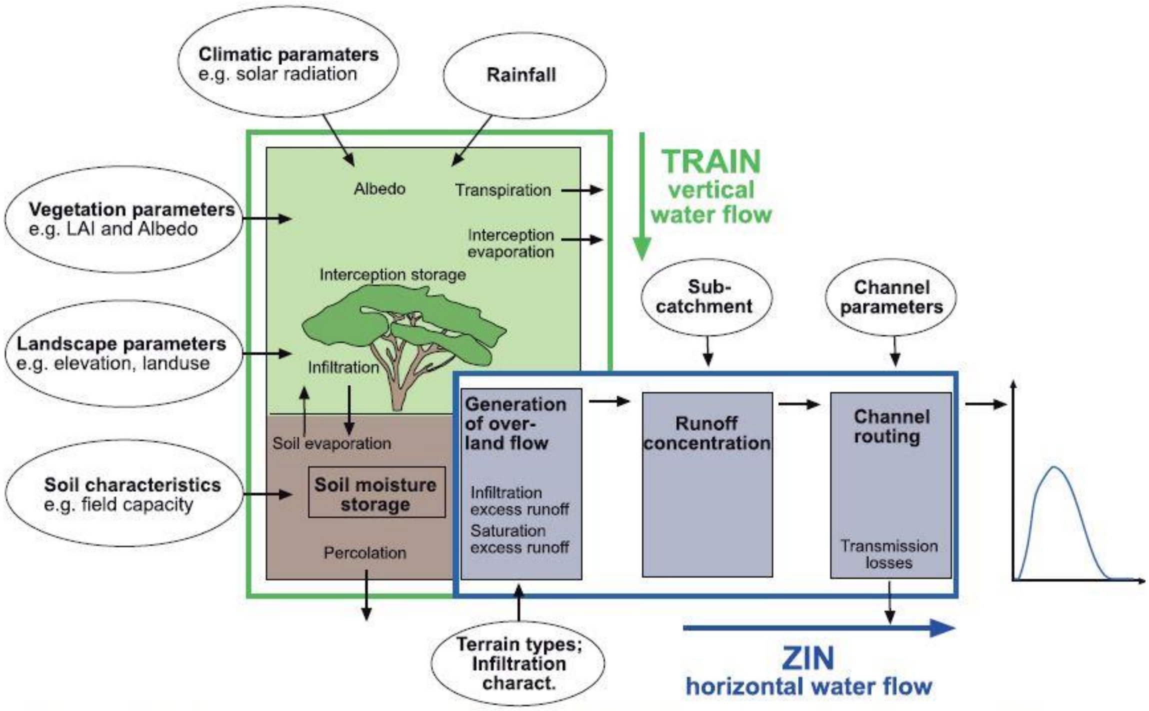


Figure 11: Schematic overview of TRAIN-ZIN (Gunkel and Lange, 2012).

TRAIN-ZIN is written in a combination of C++ and FORTRAN and currently only available for Windows (Gunkel and Lange, 2016). It can be operated without any installation on a non-graphical user-interface. Model setup, data input, parameter selection, component options and output properties are bundled in the control file .ctr (Hagenlocher and Gunkel, 2017). While chapter 1.3.2 gives a basic overview over model components and routines of TRAIN-ZIN, a technical report from Gunkel and Lange (2016) and a current user manual from Hagenlocher and Gunkel (2017) are given and explaining model philosophy, structure and functions in more detail.

1.3.1.2 SWAT

The Soil and Water Assessment Tool (SWAT) is a process-based, semi-distributed river basin model with physical and empirical components and operates on a continuous time step (Arnold et al., 1998). SWAT is a public domain software and was developed by the USDA Agricultural Research Service in Texas USA, mainly to quantify long-term impacts of alternative land management practices in large, complex watersheds. SWAT was developed in the early 1990s to estimate downstream impacts of water management within Indian reservation lands in Arizona and New Mexico (Arnold et al., 2012b). The aim was to simulate stream flow for basins extending over several thousand square kilometers. In this context two existing models, SWRRB (Simulator for Water Resources in Rural Basins) and ROTO were combined and improved to the SWAT model (Neitsch et al., 2009). SWAT combines a land-phase, which controls the amount of water, sediment nutrient and pesticide loadings to the main channel and the routing-phase, which describes the movement through the channel network (Figure 12). In this respect, Neitsch et al. (2009) describes SWAT as a long-term yield model and highlights, that SWAT is not designed to simulate detailed, single-event flood routing.

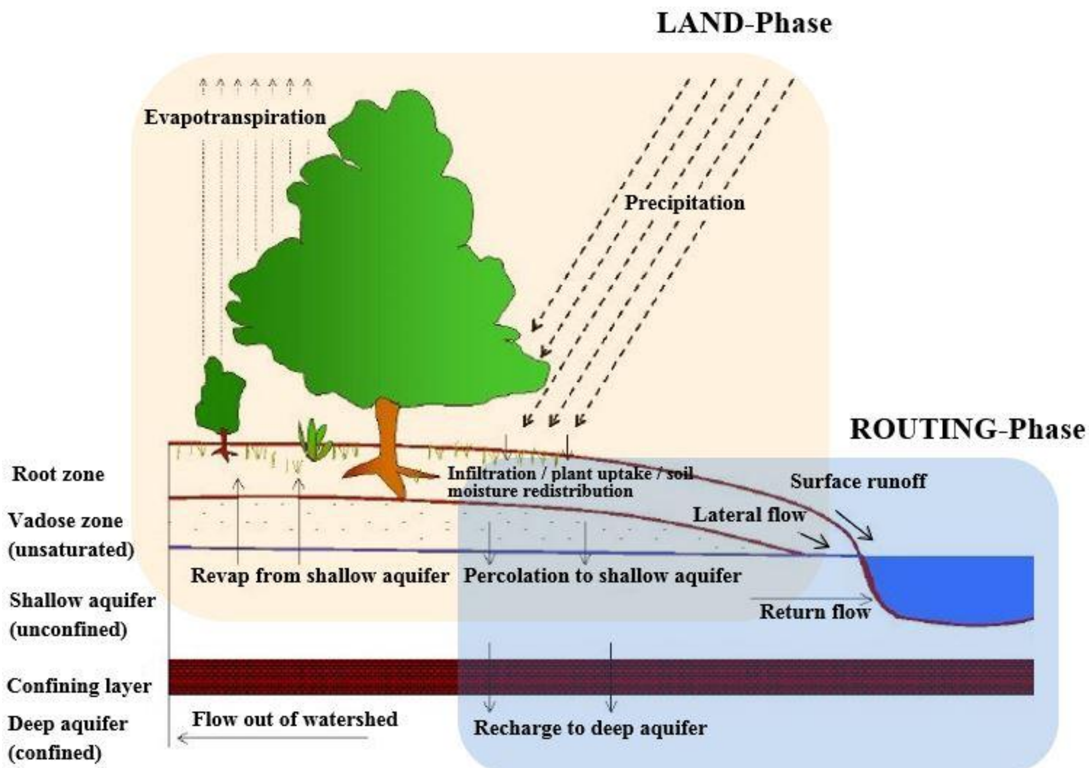


Figure 12: Revised version of schematic overview of SWAT according to Neitsch et al., 2009.

More detailed information about model architecture, function and parameters are given in the input/output documentation of Arnold et al. (2012a) and mathematical equations are described in depth in the theoretical documentation of Neitsch et al. (2009). In addition to that, SWAT input files can be generated using QSWAT, a QGIS user interface and modified using the SWAT Editor. User-friendly manuals including step-by-step model setup instructions are available (Dile et al., 2017).

1.3.2 Model structure and components

1.3.2.1 TRAIN-ZIN

TRAIN-ZIN is a highly specialized hydrological model for arid and semi-arid environments. It contains various routines to represent all relevant hydrological processes in vertical and horizontal water flow directions (Figure 11). These routines are summed up in a modified table according to Gunkel and Lange (2012) (Table 3). While the TRAIN routines are modeled on a daily time-step, the routing processes are typically performed on a 1-minute time-step (Gunkel and Lange, 2016). Thereby, the modules are partly physically and partly conceptually based (Hagenlocher and Gunkel, 2017).

Table 3: TRAIN-ZIN model routines and basic features. Modified from Gunkel and Lange, 2012.

Model routine	**Description**
Rainfall input	> Different options can be chosen: rainfall grids (e.g. radar data) or station data with different interpolation methods (Thiessen polygons, Inverse distance weighting)
Interception	> The amount of water stored in the canopy is assessed, then evaporation loss according to Penman equation is calculated (Menzel et al. 2009) > Seasonal development of the Leaf Area Index (LAI) determines the interception capacity of vegetation types
Evapotranspiration	> The Shuttleworth-Wallace equation (Shuttleworth and Wallace 1985) calculates evapotranspiration from sparsely vegetated areas (soil evaporation and plant transpiration)
Snow routine	> Snow accumulation and melting schemes are simulated by a degree-day equation
Soil moisture storage	> Storage capacity is calculated according to soil characteristics > The storage is filled by infiltrating rainfall and emptied by evapotranspiration and percolation; percolation rates are based on unsaturated conductivity (Van Genuchten1980)
Overland flow generation	> After initial loss by surface detentions is filled, infiltration excess overland flow is calculated comparing rainfall intensity with infiltration rate > When the soil Storage is filled, saturation excess overland flow is simulated
Runoff concentration	> Overland flow calculated for all grid cells is concentrated in subbasins and transferred to corresponding channel segments > Runoff concentration is performed either by measured transfer functions or by a synthetic unit hydrograph considering slope and area of the subbasins
Channel routing	> Routing is achieved by the non-linear, implicit Muskingum-Cunge method (Ponce and Chaganti 1994) > Transmission losses are quantified as instantaneous infiltration using the Green-Ampt approach (Green and Ampt 1911)

Most processes are grid-based (precipitation, snow, interception, evaporation, depression storage and soil moisture processes), while runoff concentration is restricted to subbasins and channel routing to channel segments. Within the catchment boundaries, runoff generation and water budget are calculated for each grid cell and time-step. Because fluxes between grid cells are not considered, the overland flow will be aggregated into user defined subbasins and transferred to the channel. Thereafter, the surface runoff concentration will be transformed into a channel flow for the next stream segment by using a sub-catchment specific synthetic unit hydrograph. Channel flow in the stream segment is then routed by the Muskingum-Cunge method. To consider transmission losses from the channel bed into the channel alluvium, the Green-Ampt infiltration model is applied. As a result of spatial and temporal representation, TRAIN-ZIN delivers output for all elements of the water balance as grids in the required temporal aggregation (daily, monthly and yearly mean) (Gunkel and Lange, 2016; Ries, 2013).

1.3.2.2 SWAT

SWAT is a complex river-basin model, which includes a variety of components (Table 4) and requires a large number of input parameters. Thereby, water balance is the driving force behind all processes in SWAT, because it impacts plant growth, the transport of sediments, nutrients, pesticides and pathogens. The general SWAT input is divided into three different input-levels. Watershed, subbasin and the Hydrological Response Units (HRU's). To describe the spatial variation of the watershed in high resolution, it is divided into multiple subbasins. Each subbasin is associated with one single channel segment (reach) and the closest precipitation gauge in its area (Neitsch et al., 2012).

Table 4: Components and routines of SWAT model in SWAT2009 code (Arnold et al., 2012b; Neitsch et al., 2009).

Components	**Processes**
Hydrology component	Canopy storage, evapotranspiration, surface runoff, lateral subsurface flow, return flow, infiltration, redistribution of water within the soil profile, consumptive use through pumping, tile drainage, recharge to deep aquifer, seepage from surface water bodies and transmission losses
Land cover/plant growth	Potential growth, potential and actual evapotranspiration, nutrient uptake, growth constraints, water use, plant rotations, N-, P- and carbon cycle routine
Routing component	Flood routing, sediment routing, nutrient routing, channel pesticide routing, reservoir outflow
Weather component	Weather generator from observed monthly statistics, snow routine, soil temperature, weather forecast

For geographical configurations like the spatial discretization and delineation of the watershed, SWAT is providing a user-friendly QGIS plugin called QSWAT. Input parameters, modeling options and output specifications are managed by the SWAT Editor interface (Arnold et al., 2012a). SWAT Editor is connected to the data base and used for the calibration process. As alternative, all adjustments could be made manually, directly at the input/output text files. Hereafter the used SWAT model versions are summarized (Table 5).

Table 5: Used software, tool and plugin versions for modeling.

Software/Tool/Plugin	Version
QGIS Desktop	2.6.1-Brighton
QSWAT interface	1.4
SWAT Editor	2012.10_2.19

As an integral part of the hydrology component, SWAT provides two different methods for the infiltration and surface runoff simulation. Here, the Curve Number (CN) and the Green-Ampt method are available for selection. Green and Ampt (1911) developed the Green-Ampt equation (Formula 1) to simulate infiltration processes. The Green-Ampt method is a time-based physical method, where the infiltration parameters are directly related to the catchment properties.

$$f_{inf,t} = K_e \cdot \left(1 + \frac{\Psi_{wf} \cdot \Delta\theta_v}{F_{inf,t}}\right) \quad (1)$$

$f_{inf,t}$ infiltration rate (mm/hr)

K_e effective hydraulic conductivity (mm/hr)

Ψ_{wf} wetting front matric potential (mm)

$\Delta\theta_v$ change in volumetric moisture content across the wetting front (mm/mm)

$F_{inf,t}$ cumulative infiltration (mm H_2O)

The Green-Ampt method assumes a homogenous soil profile and a uniformly distributed antecedent soil moisture. Furthermore, the model assumes a sharp break in moisture content at the wetting front, with the soil above being completely saturated. Figure 13 illustrates the moisture distribution with soil depth in reality and its interpretation in the Green-Ampt equation (Neitsch et al., 2009).

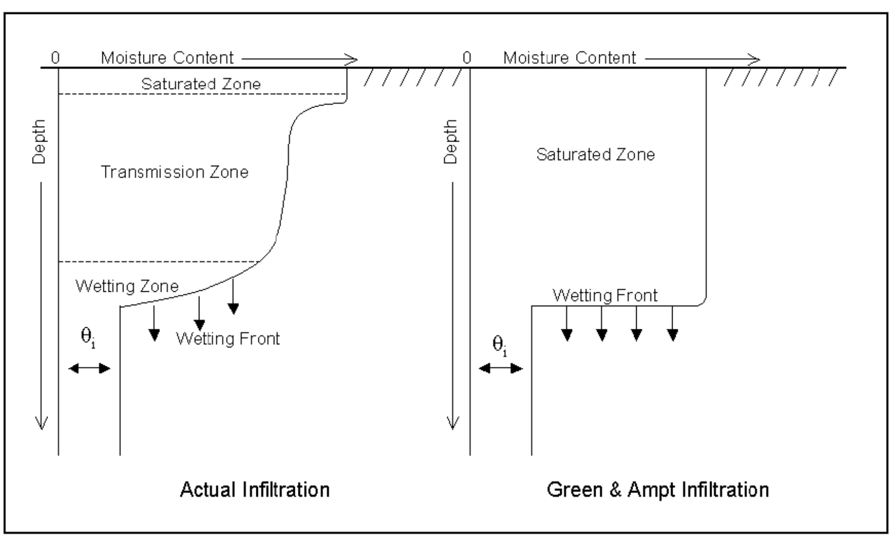


Figure 13: Comparison of moisture content distribution model by Green-Ampt (right) and a typical observed distribution (left) (Neitsch et al., 2009).

According to King et al. (1999) physical models like the Green-Ampt method are more suitable to simulate the impacts of land use on runoff than empirical methods. King (2000) recommends this equation for operational sub-hourly time intervals. Moreover, the Green-Ampt method is selected as a more suitable alternative in this present study to the runoff curve number method (CN), which was initially developed in the 1950s by the Natural Resources Conservation Service USDA (former Soil Conservation Service) to estimate the amount of runoff under cropland. This method is based on empirical relationships between the total rainfall and land use or soil types. The transferability for semi-arid conditions and land uses like in the West Bank of Palestine are unknown though. One of the major limitation of the CN method is, that only the total rainfall volume and neither rainfall intensity nor duration are considered (King et al., 1999). This is highly relevant, because in Wadi Auja runoff generation strongly depends on the rainfall pattern and intensity. Jeong et al. (2010) mentioned, that the CN-method systematically underestimates surface runoff, while in contrast to that, the Green-Ampt method does not show a similar pattern associated with storm events. This implies less bias to model prediction. Within hydrological investigations in Iraq using the CN-method, Hussein (1996) found out, that runoff under low rainfall intensities is overestimated and under high rainfall intensities underestimated. Therefore, within the model setup of SWAT, the Green-Ampt method is selected.

Finally, it should be mentioned, that the Curve Number is still integrated indirectly into the Green-Ampt equation within the SWAT model code (Neitsch et al., 2009). It is used to incorporate land cover impacts into the calculation of the effective hydraulic conductivity K_e, which is part of the Green-Ampt equation (Formula 2) (Neitsch et al., 2009). The influence and sensitivity of CN within the equation of K_e is not fully documented and is analyzed within the calibration process to better understand and interpret the implementation of this process into the model structure.

$$K_e = \frac{56.82 \cdot K_{sat}^{0.286}}{1 + 0.051 \cdot exp(0.062 \cdot CN)} - 2 \qquad (2)$$

K_e effective hydraulic conductivity (mm/hr)

K_{sat} saturated hydraulic conductivity (mm/hr)

CN curve number

2. Methods

2.1 Preparation of input data

2.1.1 TRAIN-ZIN

2.1.1.1 Introduction

Within the framework of the present master thesis, a variety of input data was provided by the Chair of Hydrology at the Albert-Ludwigs University Freiburg. The present model comparison is built on collected data of previous investigations and on latest model results of TRAIN-ZIN at Wadi Auja within the dissertation of Fabian Ries (2016). Therefore, the entire work refers to an already prepared and plausibilized data set, which is described below. For the TRAIN-ZIN modeling, no further data preparation, configuration or calibration is necessary within this study.

2.1.1.2 Digital Elevation Model

A digital elevation model (DEM) forms the basis of each distributed, physically based hydrological model (Figure 14). For TRAIN-ZIN, it is used to delineate the watershed, create the stream network and controls the described hydrological surface runoff processes within the catchment. All preparations were made by Ries (2013). The used DEM in a 25 m pixel size was provided from the Chair of Hydrology at the Albert-Ludwigs University Freiburg.

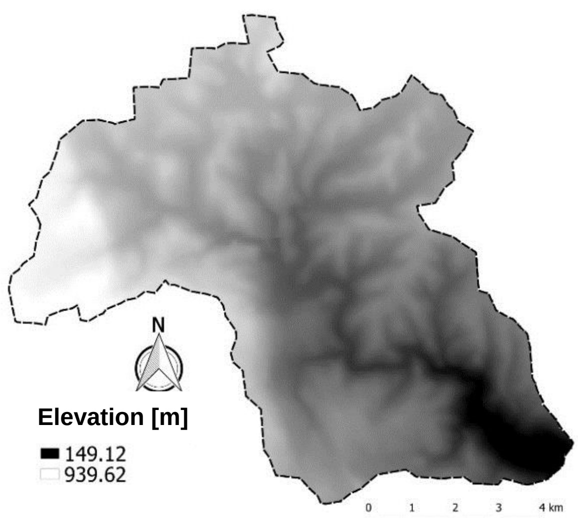


Figure 14: Digital Elevation Model used in TRAIN-ZIN. Spatial resolution 25 x 25 m. (Ries, 2016).

2.1.1.3 Land use

According to previous investigations of Ries (2016), land use and surface cover of Wadi Auja is highly variable and very patchy. To implement this specific spatial information into TRAIN-ZIN, similar land use types were summarized into classes and transformed into a raster-file (ASCII format). Ries et al. (2017) specified five main land use classes in Wadi Auja, by a manual GIS analysis of high resolution orthophotos and Landsat images (Figure 15). Uncertain classifications were verified in on-site field observations.

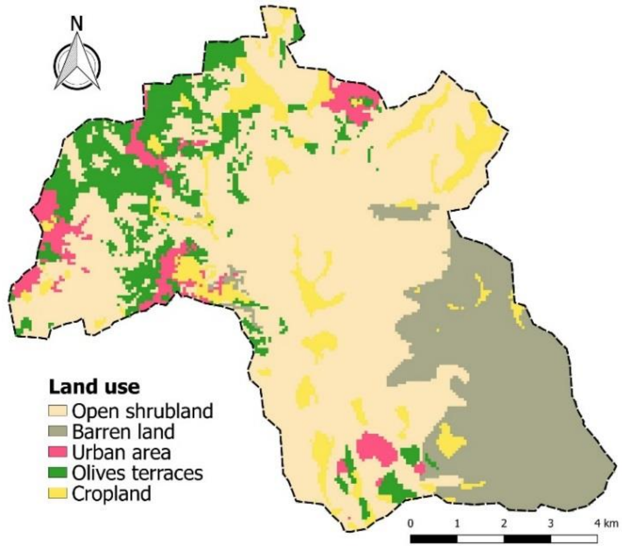


Figure 15: Spatial distribution of land use classes at the catchment Wadi Auja. Land use is determined by manual analysis of orthophotos and through field investigations of Ries et al. (2017). Raster cell size: 50 m.

Each land use raster cell contains a specific land use ID, which enables the connection between the spatial information and the land use database at the TRAIN source code (Table 6). Due to Gunkel and Lange (2016) the database is not designed for user customizations or calibration purpose, but in its latest version, it is already adapted to semi-arid areas in the Eastern Mediterranean, especially to vegetation development in Israel and Palestine. These vegetation parameters are required to calculate interception and evapotranspiration (Hagenlocher and Gunkel, 2017; Gunkel and Lange, 2016).

Table 6: Land use table of TRAIN-ZIN based on the Global Land Cover Characterization (GLCC) (Hagenlocher and Gunkel, 2017). LAI: Leaf area index, Vegh: Maximum vegetation height, ISK: Interception storage capacity.

ID	Land use class	days of phenological development	LAI [-]	Vegh [m]	ISK [mm]	Albedo [-]
33	Open shrubland	305/20/120/220	1/4	0.5	0.69 - 1.61	0.2 - 0.3
66	Barren land	-	0.7	0.2	-	0.3
77	Urban Land	-	1	0.1	-	0.18
116	Olives terraces	332/84/135	0.05/5	0.05/1.5	0.06 - 2.09	0.15 - 0.25
117	Cropland	332/84/135	0.05/6.5	0/0,8	0.06 - 2.43	0.2 - 0.28

2.1.1.4 Terrain Types

A central aspect of TRAIN-ZIN input data is the delineation of so called Terrain Types, in function of hydrological response units (HRU). These units (Figure 16) have similar hydrological characteristics in term of similar soil types, land use and geology. Terrain types play a major role in runoff generation processes and the overall soil-water balance within the TRAIN-ZIN model (Gunkel and Lange, 2016).

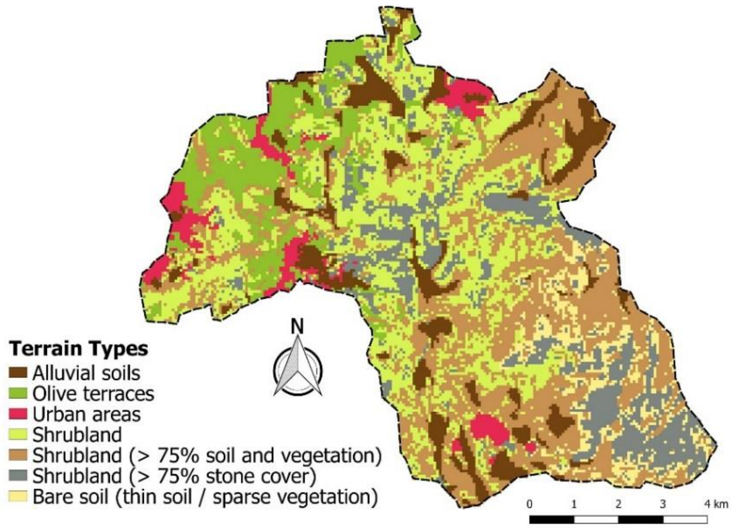


Figure 16: Terrain Type distribution map of catchment Wadi Auja.

Terrain types of Wadi Auja are generally based on the land use distribution (Figure 15), while the two major land use classes, open shrubland and barren land, were subdivided by Ries (2013) into four distinct categories due to additional information on surface cover and landforms:

- Typical Shrubland:	Dwarf-shrubs, annual plants and medium proportion of outcropping bedrock
- Shrubland > 75 % soil:	High proportion of soil and vegetation cover
- Shrubland > 50 % stone:	Shrubland with high proportion of outcropping bedrock
- Bare Soils:	Thin soils and sparse vegetation cover

Olive terraces and urban areas are derived directly from the land use raster map, while alluvial soils represent the distribution of cropland. The more detailed differentiation of Terrain Types was accomplished by Ries et al. (2017), using a supervised classification method of orthophotos. This customization was necessary to reflect the heterogeneous conditions of the unsaturated soil zone and reflect small-scale runoff processes of Wadi Auja. Therefore, the Terrain Type map is also called the runoff generation raster file and is of great importance for the calibration procedure of TRAIN-ZIN. Table 7 shows the latest version of already calibrated physical soil parameters of Wadi Auja (Ries, 2013). These parameters were determined in field campaigns (Ries, 2013, 2016), soil samples (taken and analyzed by the Forest Research Institute Baden-Württemberg, FVA), literature (Shapiro, 2006; Singer, 2007; Yaalon, 1997; Sorman and Abdulrazzak, 1995) and model calibration procedure, which is hereafter described in detail.

Table 7: Final parameter values of Terrain Types within the TRAIN-ZIN calibration process (Ries, 2013).

ID	Terrain Type	K_m [mm/h]	I_l [mm]	S_d [m]	Φ [-]	Φ_{pwp} [-]	K_s [mm/h]	λ [-]	Φ_{fc} [-]	ϱ [g/cm³]
1	Alluvial soils	48	10	1.40	0.52	0.25	0.60	0.5	0.32	1.35
2	Olive terraces	25	7	0.70	0.52	0.25	0.60	0.5	0.32	1.30
3	Urban areas	14	8	0.30	0.52	0.25	0.34	0.5	0.32	1.30
4	Shrubland	16	4	0.28	0.51	0.22	0.39	0.5	0.28	1.20
5	Shrubland > 75% soil	22	6	0.32	0.51	0.22	0.39	0.5	0.28	1.30
6	Shrubland > 50% stone	14	2	0.22	0.51	0.22	0.28	0.5	0.28	1.20
7	Bare soil	12	2	0.24	0.50	0.17	0.25	0.5	0.25	1.20

K_m: Maximum infiltration rate [mm/h]
I_l: Initial storage losses [mm]
S_d: Soil depth [m]
Φ: Total porosity [-]
Φ_{pwp}: Porosity at permanent wilting point [-]
K_s: Saturated hydraulic conductivity (mm/h]
λ: Van Genuchten parameter [-]
Φ_{fc}: Porosity at field capacity [-]
ϱ: Bulk density [g/cm²]

2.1.1.5 Channel network

The channel network represents the ephemeral stream network in Wadi Auja (Figure 17) and was delineated from the DEM with an initialization threshold of 0.1 km² for the contributing area (processed by QGis). 194 channel segments of representative 194 subbasins were created. Based on orthophotos and field observations, the channel morphology (channel_network.txt at ../Input/Zin) like length and width, were analyzed and customized manually by Ries (2013). This optimization is necessary for a correct implementation of transmission losses and runoff generation routing in TRAIN-ZIN. As mentioned before, discharge routing is calculated based on a version of the non-linear Muskingum-Cunge method, which requires the specific channel geometry (Gunkel and Lange, 2016).

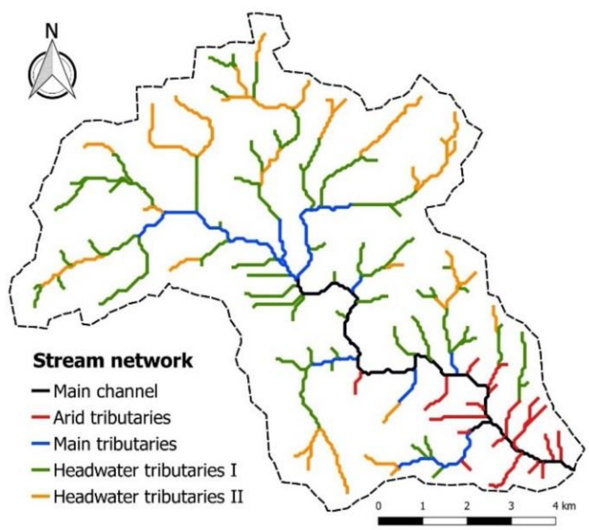


Figure 17: Ephemeral stream network of Wadi Auja (Ries, 2013).

Furthermore, five channel groups were defined to differentiate between regional, climatic and morphologic differences, mainly between the northwest and southeast of Wadi Auja (Figure 17). For each channel type, the user can parameterize individual channel characteristics like hydraulic conductivities and antecedent soil moisture conditions (Gunkel and Lange, 2016). The latest version of calibrated channel type parameters is summarized in Table 8 (Ries, 2013).

Table 8: Channel type parameter for TRAIN-ZIN (Ries, 2013).

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]**	**ν_k [-]**	**I [-]**	**AMI [-]**
Main channel	1.6	0.056	0.4	0.9	0.43	60	150	4	0.15	0.020	0.1	0.85
Arid tributaries	0.3	0.036	0.7	0.3	0.38	130	40	10	0.10	0.035	0.1	0.65
Main tributaries	1.2	0.045	0.4	0.9	0.43	60	150	4	0.15	0.020	0.1	0.85
Headwater tributaries I	0.9	0.050	0.7	0.7	0.40	80	100	6	0.10	0.030	0.1	0.85
Headwater tributaries I	0.4	0.040	0.5	0.8	0.40	70	50	5	0.10	0.025	0.1	0.80

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 (mm/h)
K_b: Hydraulic conductivity of flood plain (mm/h)
Kf: Hydraulic conductivity, of the underlying strata (mm/h)
S: Effective suction head (m)
I: Infiltration reduction factor (-)
AMI: Antecedent moisture index (-)

2.1.1.6 Climate data

TRAIN-ZIN requires climate input information about temperature (°C), relative humidity, wind speed (m/s) and solar radiation (W/m²day) in order to calculate evapotranspiration. The input data can either be delivered as table or as grid file, but it has to be one file per parameter and day. More detailed information on data requirements, are supplied in Gunkel and Lange (2016). Due to the model conception, TRAIN-ZIN requires a gridded input format of precipitation data (ASCII), which is created by an inverse distance weighting method and a correction factor of 6 % per 100 m height for the elevation effect of the pronounced topography (Gunkel and Lange, 2016).

Climate data were collected from the hydro-meteorological network, consisting of rainfall gauges and meteorological stations in Wadi Auja, which was installed during the first phase of the SMART project in 2007 (Figure 9). Thereby, rainfall was recorded by tipping buckets in a 5-minutes resolution, while meteorological parameters (Temperature [°C], relative Humidity [0-1], wind speed [m/s] and global radiation [W/m²day]) are provided on a 10-minutes interval form October 2010 to October 2015 (data gaps included). Within this framework, water levels of five different runoff gauges (at weirs, flume structures and road culverts) were recorded in a 5-minutes resolution by automatic pressure transducers. Using the respective discharge flow formula, water levels were transformed into discharge [l/s] (Ries, 2013). This currently unpublished data set is used in the following for the entire model comparison.

2.1.2 SWAT advanced

2.1.2.1 Digital Elevation Model

The essential element of each SWAT model is a digital elevation model (DEM) in high spatial resolution. Therefore, the provided DEM (25 m grid size) is used. It is important, that for all raster files the same coordinate reference system is chosen (e.g. EPSG:28191 - Palestine 1923 / Palestine Grid). For maps in different projections, raster files were reprojected using the QGIS tool Warp (Reproject). Further preparations of the DEM were not required.

2.1.2.2 Land use

To implement land use information in SWAT, a raster file (.tif) is used. To benefit from the optimized land use data of Ries (2016), and run both models in the same spatial resolution (50×50m), the SWAT model uses the same land use map as TRAIN-ZIN. The Soil Water Assessment Tool was developed initially to predict impacts of extensive land use changes. Therefore, the SWAT Access database contains detailed information about the respective land use. To take into account the specific land use types in semi-arid regions, the SWAT database was customized by the TRAIN-ZIN input data. While the maximal potential leaf area index (BLAI) and the maximum canopy height (CHTMX) could be transfered directly into the SWAT.CROP database, the maximum canopy storage capacity (CANMX) was adjusted for the .HRU database. The land use raster file is linked by its cell values to the "Example1_landuse" Access table. This table is the connection between spatial distribution and the specific property information of each cell. Therefore, it is important to align this table with the raster file.

2.1.2.3 Soil map

In contrast to the DEM and land use map, SWAT does not use the same input data format for physical soil properties like TRAIN-ZIN. SWAT uses a traditional soil map according to the World Reference Bank (WRB) or other classification standards. Due to that, SWAT derives information on soil properties from the spatial distribution of soil types. This means that the Terrain Type map from TRAIN-ZIN (combination of land use, soil types and topographic aspects) and the soil map from SWAT have slightly different spatial distributions and cannot be directly interchanged. Therefore, to take advantage of detailed soil property data and the high resolution (50×50m) of the TRAIN-ZIN Terrain Type raster (Ries, 2013), an artificial soil raster for SWAT was created. This raster is based on the Terrain Type resolution and distribution, while additional required information like soil texture was transferred to it.

The soil texture data, which is not included in TRAIN-ZIN was derived from Singer (2007) (Figure 18). Because the Terrain Type map does not represent the spatial distribution of the soil map of Singer (2007), for each pixel of the seven Terrain Types, the respective soil texture was calculated and transferred from the Singer soil map. The transformation was accomplished by the QGIS tool Zonal Statistics.

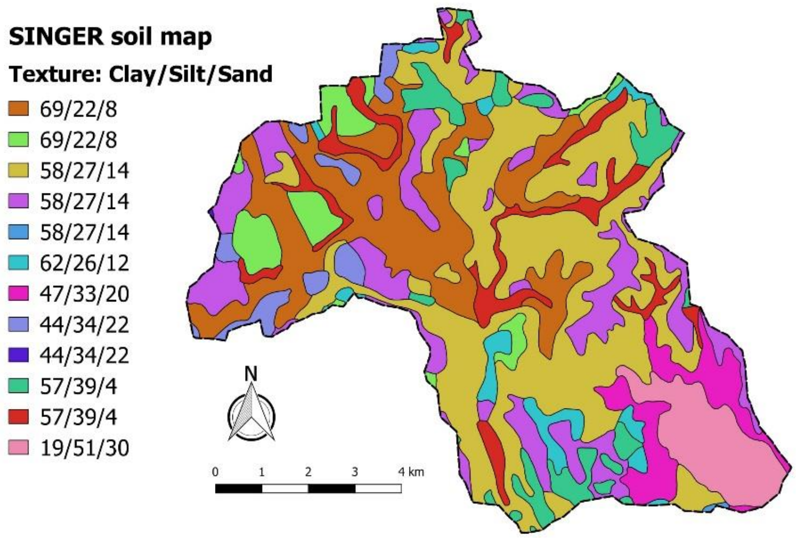


Figure 18: Calculated Soil texture distribution according to Singer (2007). Spatial distribution of 12 different soil types in catchment Wadi Auja. Respective texture from legend was extracted from Singer (2007).

Table 9 shows the final SWAT soil table. Corresponding to the description and investigation of Ries (2016), the seven Terrain Types were classified into four hydrological groups (HYDGRP) based on infiltration characteristics of the soils. The maximum rooting depth (SOL_ZMX) of the soil profile was estimated using values for soil depth (SOL_Z). The available water capacity (SOL_AWC) of the soil layer was calculated using values for field capacity (FC) and permanent wilting point (PWP) from the Terrain Types (AWC = FC – PWP) (Table 7). Bulk density (SOL_BD) and saturated hydraulic conductivity (SOL_K) were obtained directly from the Terrain Type table. Thus, all relevant parameters for hydrological processes were customized as good as possible, while the remaining were kept unchanged on default values (see highlighted parameters of Table 9).

Table 9: Customized and finally used SWAT advanced soil properties at the "Example1_usersoil" data base (Wadi_Auja.mdb). Processed soil properties are highlighted. SNAM: Soil name, NLAYERS: Number of soil layers, HYDGRP: Soil hydrologic group, SOL_ZMX: Maximum rooting depth of soil profile (mm), SOL_CRK: Maximum crack volume of soil profile, SOL_Z1: Soil depth (mm), SOL_BD: Moist bulk density (g/cm³), SOL_AWC: Available water capacity (mm), SOL_K: Saturated hydraulic conductifity (mm/h), SOL_CBN: Organic carbon content (% soil weight), ROCK: Rock fragment content (% soil weight), SOL_ALB: Moist soil albedo, USLE_K: Soil erodibility factor, SOL_EC: Electrical conductivity (dS/m).

SNAM	Alluvial_ Soils	Olive_ Terraces	Urban_ Areas	Shrubland1	Shrubland2	Shrubland3	Bare_Soil
NLAYERS	1	1	1	1	1	1	1
HYDGRP	A	A	C	B	B	C	C
SOL_ZMX	1400	700	300	280	320	220	240
SOL_CRK	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SOL_Z1	1400	700	300	280	320	220	240
SOL_BD1	1.35	1.3	1.3	1.2	1.3	1.2	1.2
SOL_AWC1	0.07	0.07	0.07	0.06	0.06	0.06	0.08

SOL_K1	0.6	0.6	0.34	0.39	0.39	0.28	0.25
SOL_CBN1	0.87	0.89	0.89	0.92	0.92	0.79	0.75
CLAY1	57	60	57	62	57	49	45
SILT1	34	27	27	26	29	33	34
SAND1	7	12	13	12	13	17	19
ROCK1	16	16	16	35	16	55	16
SOL_ALB1	0.19	0.19	0.19	0.19	0.19	0.2	0.2
USLE_K1	0.15	0.15	0.15	0.15	0.15	0.16	0.16
SOL_EC1	2.8	2.64	3.28	2.22	2	2.47	2.69

2.1.2.4 Channel properties

To use as much detailed field observation data (Ries, 2013) as possible, channel characteristics of TRAIN-ZIN are included in the SWAT data base. While the following chapter 2.2 describes the model setup and the watershed delineation, at that time it will be described how this generated data is adjusted and customized. The created stream network of TRAIN-ZIN and SWAT slightly differ in its course and amount of stream segments, because of different used algorithms in GIS (Figure 19). To transfer the channel properties from TRAIN-ZIN to SWAT, the two stream network shape files are linked together by a spatial join in QGIS (Join Attributes by Location). After the geoprocessing, the respective channel properties could be transferred from the joined attribute table to the SWAT databases .sub and .rte.

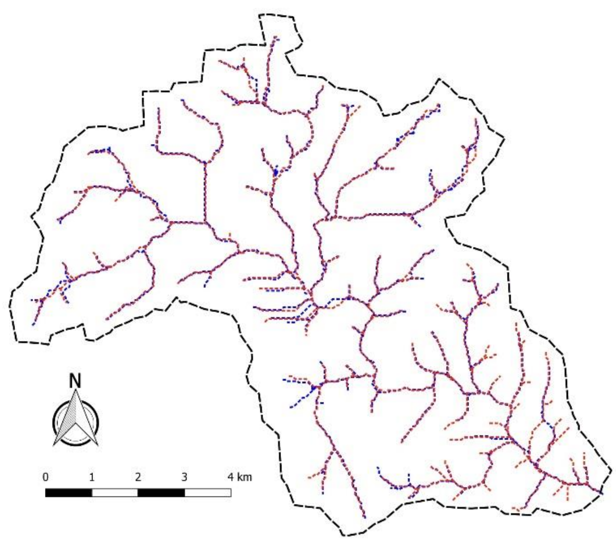


Figure 19: Comparison of the two slightly different stream networks of TRAIN-ZIN in red and SWAT in blue.

In SWAT, physical characteristics of the main channel within each subbasin, like water flow and transport are summarized in the input file (.rte). Further information related to features within the subbasin like properties of tributary channels are contained in the general input file (.sub). According to the channel network (Figure 17) and channel type parameters of TRAIN-ZIN (Table 8), the following values were imported to the respective SWAT data bases (Table 10).

Table 10: Adjusted and customized SWAT channel types. * imported from the TRAIN-ZIN channel type parameters. ** imported from TRAIN-ZIN channel network parameters.

	Data base	Value	Description
CH_K(1)*	.sub	60	Effective hydraulic conductivity in tributary channel alluvium [mm/h]
CH_K(2)*	.rte	60	Effective hydraulic conductivity in main channel alluvium [mm/h]
CH_W(1)**	.sub	1 - 12	Average width of tributary channels [m]
CH_W(2)**	.rte	1 - 12	Average width of main channels [m]
CH_N(1)*	.sub	0.045	Manning's n value for the tributary channel [-]
CH_N(2)*	.rte	0.056	Manning's n value for the tributary channel [-]

2.1.2.5 Climate data

The climate time series must follow a specific syntax and require a uniform data structure to be registered correctly by SWAT. Therefore, the climate time-series were prepared and aggregated in R, according to the SWAT input/output manual (Arnold et al., 2012a). A desired warm-up period of three years is included. For each climate parameter (humidity, precipitation, solar radiation, temperature and wind speed), SWAT requires one unique location file, which provides the geographical and topographical information of each measuring station. Furthermore, SWAT can only manage station data, which covers the complete simulation period and should not contain missing values. The verification of the selected station data revealed, that only the temperature time series contained missing values. After the identification of data gaps and examination of spatial correlation between time-series of Auja and Kafr Malik (correlation strength: 0.92), missing values were extrapolated by a linear regression.

2.1.3 SWAT light

2.1.3.1 DEM, land use, channel network and climate data

SWAT light is based on the same digital elevation model (Figure 14), land use map (Figure 15) and channel network (Figure 19) as SWAT advanced. In contrast to that, the access data base of SWAT light was not customized by specific values from previous field investigations or from TRAIN-ZIN. The main objective of SWAT light is to represent a realistic SWAT application, which is based on public domain data and is not optimized by extraordinary good data quality like provided in Wadi Auja.

Thus, the SWAT light land use raster is described by default values (Arnold et al., 2012a). The same applies for the channel properties, which simply refer to the channel network, which is calculated by QSWAT based on the topographical information from the DEM. Thus, SWAT light indeed uses the same spatial information for DEM, land use and channel network, but only refers to default values of the standard SWAT data base. SWAT light uses the same climate stations and data as SWAT advanced and

TRAIN-ZIN. Only the precipitation time-series was aggregated to daily sums (mm/day), to enable a daily model time-step.

2.1.3.2 Soil map

To only make use of free available, realistic and commonly used data, a separate soil map from isric.org in a 250 m grid size resolution was used (Hengl et al., 2017). This soil map is classified due to the World Reference Base for Soil Resources (WRB) and contains six different soil types for the catchment Wadi Auja (Figure 20). Each soil type is connected to the usersoil data base (Wadi_Auja.mdb), which contains default soil properties for WRB soil types. The data base was not customized and all physical properties, as well as the soil texture were assumed.

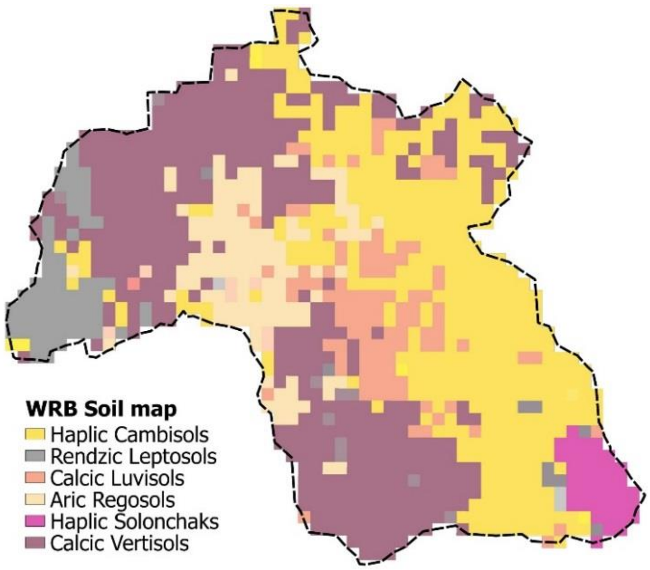


Figure 20: Open source soil map according to the classification of the World Reference Base for Soil Resources (WRB). Grid size: 250 m. (Hengl et al., 2017) Source: SoilGrid, isric.org

2.2 Model setup

2.2.1 TRAIN-ZIN

This subsection briefly summarizes the applied setup properties of TRAIN-ZIN, which were developed and adjusted by Ries (2013). For further model requirements and configuration instructions, the technical report of Gunkel and Lange (2016) and the TRAIN-ZIN user manual of Hagenlocher and Gunkel (2017) is available. All parameter values of TRAIN-ZIN were kept as published in Ries (2013) and Ries et al. (2017).

Model configuration, parameter selection and components options of TRAIN-ZIN are managed and bundled at the control file (.ctr). This file defines the relative paths of input data and output folders, describes spatial information about the raster grid and indicates start and end of modelling as well as the time-step (Hagenlocher and Gunkel, 2017). Table 11 shows a summary of the most relevant setup information from the “auja.ctr” file.

Table 11: Summary of TRAIN-ZIN setup from the control file (.ctr) (Hagenlocher and Gunkel, 2017).

Parameter name	Description	Value	Comment
startDate	Start date	01.10.2010	
endDate	End date	30.09.2013	
ZinStep	ZIN time-step	5-min	
RouteStep	Routing time-step	1-min	
ChanNumber	Channel number	194	
sqmPerCell	Cell size	2500 m²	
xySize	Grid size (pixel)	222 x 192	
useSediment	Sediment generation	0	0 = no
useBaseflow	Baseflow	0	0 = no
Trans_loss	Transmission losses	1	1 = yes
evapTrain	Evapotranspiration method	2	2 = Shuttleworth-Wallace
QConcMethod	Runoff concentration method	1	1 = Fisher-Tippet-distribution
RainMethod	Precipitation interpolation	3	3 = Inverse distance weighting
rainGrad	Precipitation gradient	6	Gradient of Precipitation increase with height in (0-100%/100m)
initMoist	Initial soil moisture	0%	

The applied TRAIN-ZIN model was configurated due to the specific requirements of Wadi Auja and recommendation from the technical report of Gunkel and Lange (2016), to take into account high routing dynamics of semi-arid channel flow. Therefore, TRAIN-ZIN was set up on high spatial and temporal resolution and is running on a 5-minuts time-step. The model period was from 01.10.2010 to 30.09.2013, while Ries (2013) modeled each year separately. Due to the preparation of input data (chapter 2.1), all raster files cover exactly the same area (required) and are projected to the congruent grids of 50 x 50 m. In the present model configuration, the study area is subdivided into 194 subbasins linked by a channel network of respective 194 channel segments (Figure 21).

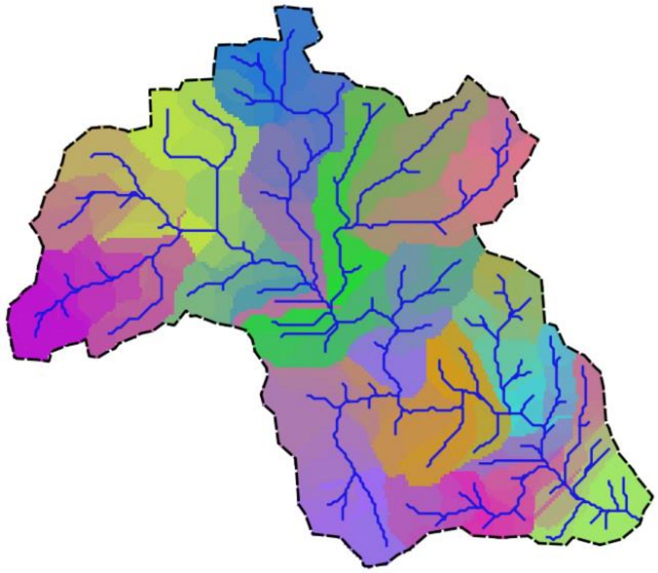


Figure 21: Subbasins and linked stream network of Wadi Auja for the applied TRAIN-ZIN model.

Applied equations and methods for evapotranspiration, runoff generation and rainfall interpolation are specified in Table 11, while for the soil-water-processes (percolation) the Mualem-Van Genuchten equation is used (Ries, 2013). Due to the catchment characterization and description of main hydrological processes of Wadi Auja (see chapter 1.2), the transmission losses routine was switched on while the application of sediment transport and baseflow was switched off (routine inactivated).

2.2.2 SWAT advanced

After the required tabular and spatial data was prepared according to the theoretical documentation (Neitsch et al., 2009) and user manual (Neitsch et al., 2002), the model setup of SWAT advanced could be performed. Based on configuration instruction of Dile et al. (2017) and recommendations of Kiesel et al. (2016), the model setup was realized. In this respect, the provided QGIS interface QSWAT was used (Figure 22). Within this graphical interface, the user will be guided step-by-step through the whole setup process. This process is described hereafter.

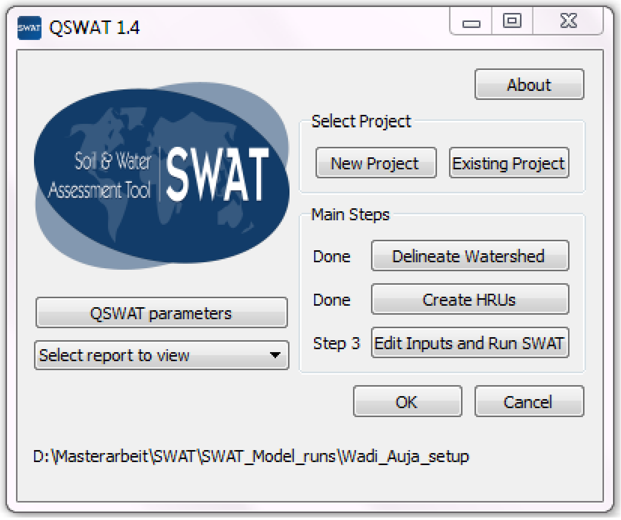


Figure 22: Home screen of the QSWAT interface, which is provided by QGIS plugin.

In step 1 (Delineate Watershed) the watershed is created on basis of the selected DEM, a defined channel initialization threshold of 0.1 km² (the same threshold used in TRAIN-ZIN) and by drawing the outlets, which represent the five gaging stations (Appendix 2). To create streams and generate the watershed, SWAT is using TauDEM (Terrain Analysis Using Digital Elevation Models) developed by Tarboton (2005). Within this calculation, 232 stream segments for respective 232 subbasins were created (Figure 23).

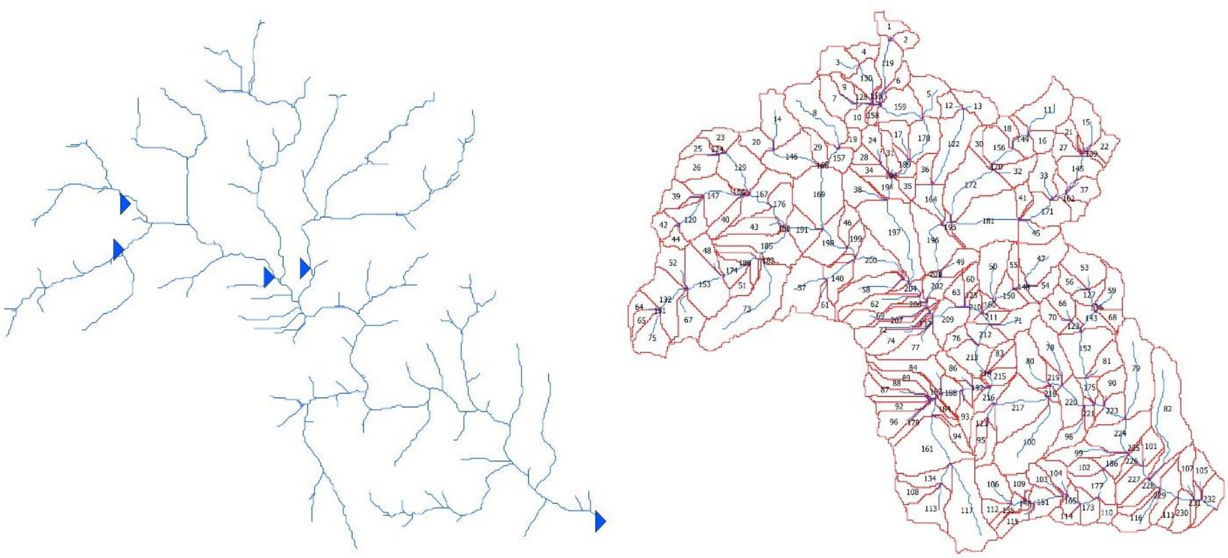


Figure 23: Stream network (left) and watershed with its 232 subbasins (right). The gauges are symbolized by blue triangles. The calculation was run by TauDEM (Tarboton, 2005) on a 25×25m digital elevation model.

In a second step, the hydrological response units are formed by combining information from the land use map, soil map and defining slope bands from 0-10, 10-20 and 20-∞ percent (Appendix 3). In a final step, the SWAT model input data must be edited and written, before the model can be run and calibrated.

Therefore, the SWAT Editor (Figure 24) will be connected to the specific databases. For the selection of Weather Station Data, the relative path of the appropriate location file "loc.txt" must be indicated. For sub-daily precipitation data, the data resolution must be specified (Appendix 4). Moreover, "WGEN_user" in the Weather Generator Data tab must selected, if measured climate data instead of statistically generated data are used. After all Input Tables are written successfully, the model run can be configurated.

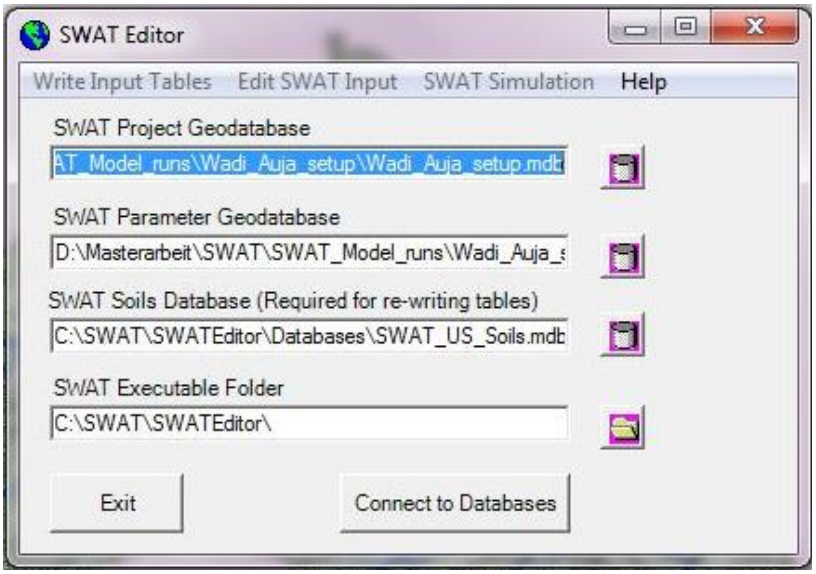


Figure 24: SWAT Editor. The final step of SWAT configuration within the QSWAT interface. SWAT Editor organized the input data, operates the calibration and controls the SWAT model run.

To manage input/output files and configure general model run options, the master watershed file "file.cio" (…\Scenarios\Default\TxtInOut) can be adjusted easily by the "Setup SWAT Run" interface (Figure 25). For a first plausibility check, the output file variables were set to a minimum, in order to save memory and computing time. Moreover, the rainfall sub-daily timestep was chosen to be in 5-min resolution and the warm-up phase NYSKIP (Number of years to skip) was set to 3 years. By pressing "Setup SWAT Run" the settings in file.cio will be overwritten.

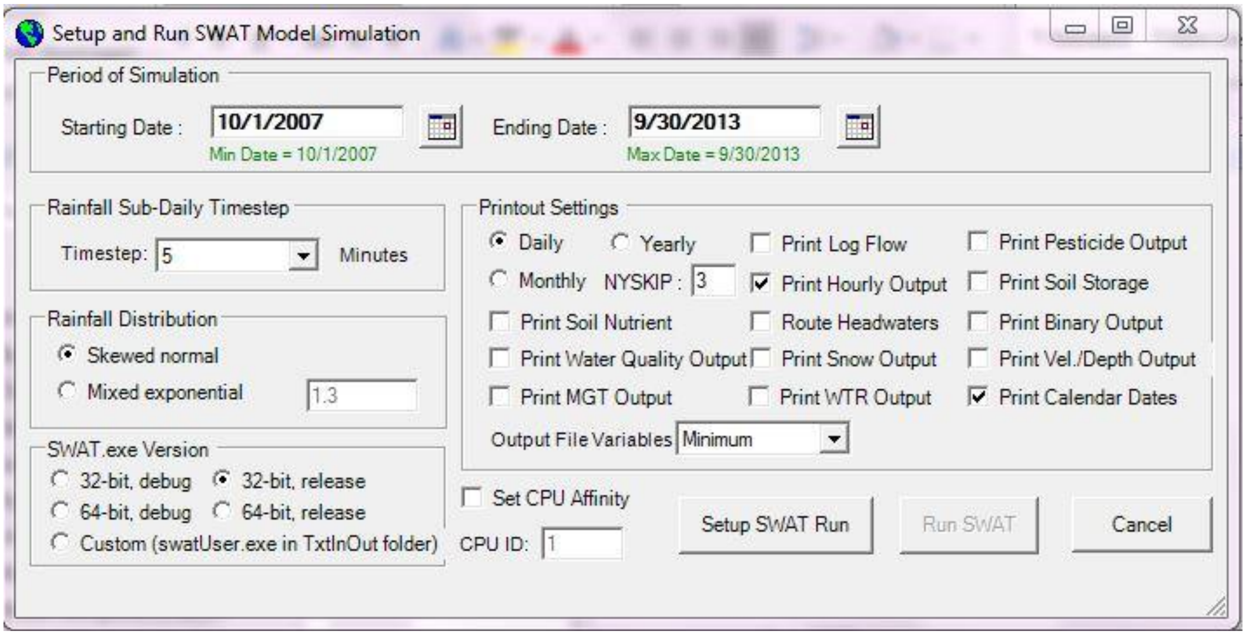


Figure 25: Setup and Run SWAT Model Simulation. User interface of QSWAT within the SWAT Editor to set the model run properties.

To run SWAT in a sub-hourly time resolution, some specific configurations in “file.cio” and “basins.bsn” must be adjusted manually, which are not yet published in the latest input/output documentation (Arnold et al., 2012a). The following settings were discussed and developed in cooperation with Jaehak Jeong, member of the SWAT Developing Team, Texas AgriLife Research. These settings are partly in contrast to the advices in the official SWAT manual, but will be included in the next version of the input/output documentation.

The required settings are summed up in Table 12. The Parameter IPRINT (print code) in file.cio governs the frequency that model results are printed to output files and must be changed to 3, while the prescribed range in the manual is 0 to 2. In this context the parameter ICALEN (code for writing calendar or julian day to daily outputs) in file.cio must be 0, otherwise the SWAT code readfile.f resets the IPRINT value to default 1. Furthermore, the IEVENT (rainfall/runoff/routing option) parameter in basins.bsn, which is responsible for the rainfall/runoff/routing option, must be changed to 1. That means a configuration of daily rainfall, Green & Ampt infiltration method for surface runoff processes and a daily routing must be chosen, although configuration 2 and 3 describe sub-hourly precipitation (Nguyen Duy Liem, 2017). Finally, IRTE (channel water routing method) in basins.bsn was set to 1 to choose the Muskingum channel routing method (Neitsch et al., 2009). This method models the storage volume in a channel length as a combination of wedge and prism storage and is also necessary for a sub-daily simulation (Arnold et al., 2012a). Because SWAT Editor overwrites the input files basins.bsn and file.cio, when clicking “Setup SWAT run”, these mentioned changes have to be done directly prior to running SWAT.

Table 12: Summary of required modifications in input files file.cio and basins.bsn for sub-hourly modeling (Arnold et al., 2012a).

Parameter	Adjusted value	Default value	Location	Description due to the input/output documentation
IPRINT	3	0 - 2	file.cio	governs the frequency that model results are printed to output files
ICALEN	0	-	file.cio	code for writing calendar or Julian day to daily outputs of output.rch, output.sub and output.hru files. 0 = print Julian day
IEVENT	1	0	basins.bsn	responsible for the rainfall/runoff/routing option. 1 = daily rainfall/Green & Ampt infiltration/daily routing
IRTE	1	0	basins.bsn	channel water routing method. 1 = Muskingum method

2.2.3 SWAT light

To set up the SWAT light version, the same configuration procedure as SWAT advanced was applied. Major differences in setup properties are due to a different input data base and a coarser space and time-resolution. Therefore, the most relevant settings of SWAT light and differences in comparison to SWAT advanced are summarized in Table 13 and described in the following.

Table 13: Setup configuration of SWAT light.

Parameter	Value	Location	
IDT	0	file.cio	0 = Daily rainfall data time step
IPRINT	1	file.cio	governs the frequency that model results are printed to output files
IEVENT	0	basins.bsn	responsible for the rainfall/runoff/routing option. 0 = daily rainfall Curve Number method
IRTE	0	basins.bsn	channel water routing method. 0 = variable storage routing method

According to previous studies about usual SWAT configurations (see chapter 1.1), SWAT light was setup in a daily time resolution (IDT). Moreover, SWAT light uses the Curve Number method for rainfall-runoff-routing (IEVENT), instead of the Green-Ampt equation. For channel water routing, SWAT light uses the variable storage routing method (IRTE), which is a variation of the kinematic wave model. In that respect, rate and velocity of flow are defined by the Manning's n value (Neitsch et al., 2009). Apart from that, SWAT light uses identical subbasins, stream network, warm-up period and software SWAT advanced.

2.3 Model calibration

2.3.1 TRAIN-ZIN

TRAIN-ZIN is a physically based, time intensive model, with high spatial and temporal resolution. Because of long computing times, the model is unsuitable for automated calibration methods like Monte Carlo, which requires a lot of runs (Gunkel and Lange, 2016). Therefore, the model was calibrated with expert field knowledge by Fabian Ries within his dissertation (Ries, 2016).

Ries (2016) followed a conventionally one-at-the-time calibration procedure, by changing model input parameter values manually. This method could be very labor intensive, but allows the user to involve system knowledge from field experience. Therefore, he started to examine the general model reactions by checking out the parameter limits, within 12 model-structure-runs. By this way, it was possible to get a first understanding of the model architecture, reaction and its sensitive parameters. As part of the calibration process, the spatial distribution of the Terrain Type polygons was adjusted in QGIS by field observations and orthophotos. After that, the channel type parameters (mainly Manning's n value) were used to modify the timing of peak discharge (Table 8). According to Gunkel et al. (2015), soil parameters (mainly represented by terrain classes and channel types) were the most sensitive ones, because they control the separation of rainfall into surface runoff and vertical percolation. In further 45 runoff property runs, the calibration of the Terrain Type parameters was accomplished by a manual model calibration. Land use parameters were kept unchanged (Ries, 2013).

To evaluate model efficiency, the simulated runoff was compared quantitatively with the observed runoff and valued by Nash-Sutcliffe-Efficiency. Because in 2010/11, no runoff was observed, the model was calibrated for the hydrological years 2011/12 and 2012/13. For a further validation of the simulation, the spatial runoff distribution was verified qualitatively with field impressions, e.g. observed runoff in urban areas and in the ephemeral stream itself.

2.3.2 SWAT advanced – expert knowledge calibration

2.3.2.1 Introduction

To accomplish an accurate model comparison, which is based on differences in model structure and functions, instead of differences in model calibration, the calibration procedure of TRAIN-ZIN was adopted and transformed into a calibration-guideline for SWAT. The flow diagram (Figure 26) shows the applied step by step calibration process and the respective calibration objective.

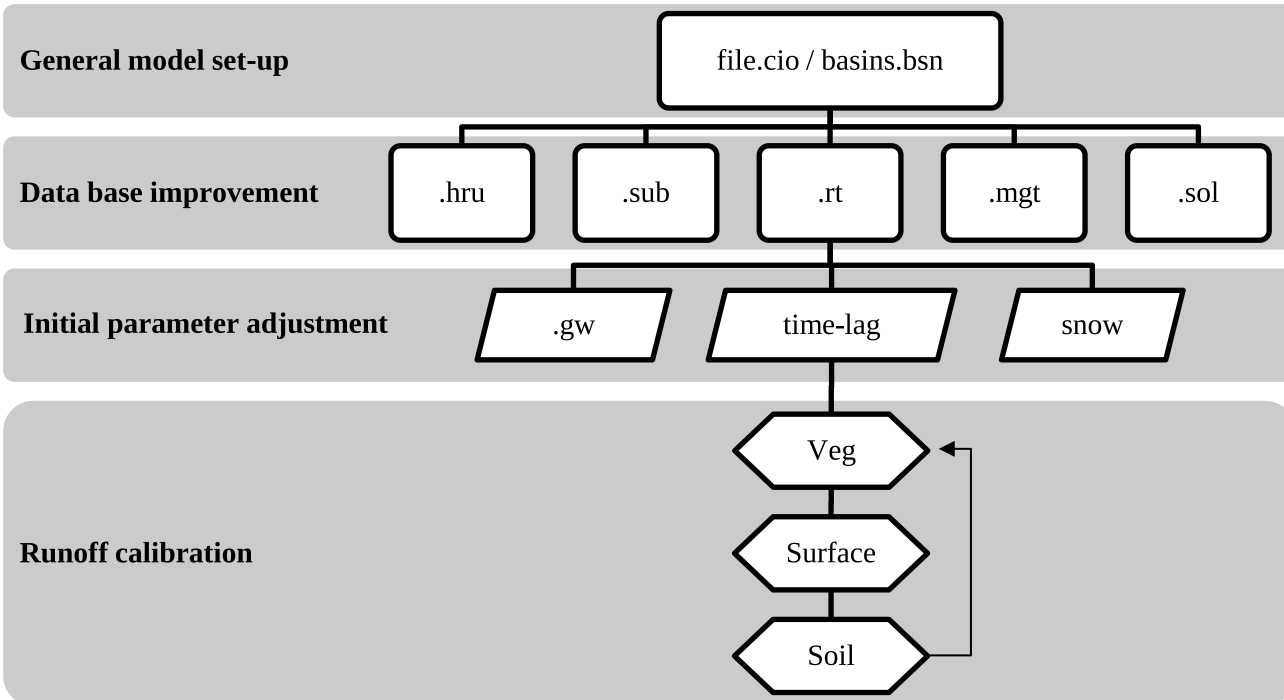


Figure 26: Calibration-guideline of SWAT advanced. Calibration procedure was transformed from TRAIN-ZIN. file.cio: Master watershed file, basin.bsn: Watershed attribut file, .hru: HRU data base, .sub: Subbasin data base, .rt: Routing data base, .mgt: Management data base, .sol: Soil data base, .gw: Groundwater data base, snow: Snow routine, Veg: Parameters refering to vegetation, Surface: Parameters refering to surface properties and Soil: Parameters refering to soil properties.

Once the model is set up on a 5-min time-step and the master watershed file (fil.cio) as well as the general watershed attributes in the basin input file (basins.bsn) are adjusted, model calibration already started during the improvement of the input data (chapter 2.1 Preparation of input data). By customizing input values of the SWAT Access data base, already calibrated parameter values from TRAIN-ZIN were adopted and integrated into SWAT. After the data base is optimized by expert knowledge from previous studies and calibration runs, the manual calibration starts. The initial parameter adjustment prepares the model architecture to enable the representation of main hydrological mechanisms like snow and groundwater routines. Required parameter values for these adjustments were well-known due to literature and investigations of Ries (2013), were changed initially and kept during the whole calibration process. In contrast to that, parameter values of the runoff calibration must be found out gradually by a conventionally one-at-the-time manual calibration procedure.

2.3.2.2 Initial parameter adjustment

In order to get an understanding of general model reactions and principal parameter importance, the calibration was started by 21 initial parameter runs. Within these runs, scientific insights from previous investigations (chapter 1.1.2 Previous studies) were implemented into the model structure. First of all, snow processes were considered as an irrelevant part of the long-time water balance in Wadi Auja and adjusted as a possible, but seldom phenomenon. The snowfall temperature and snow melt base temperature were reduced, because default settings of implemented snow routine, simulated too much snow (5 – 8 mm/year) (Table 14).

Table 14: Used and adjusted (light blue) snow process parameters. Parameters are located in the general watershed attribute file basins.bsn.

Parameter	Value	Description
SFTMP	-0.8	Snowfall temperature [ºC]
SMTMP	0.2	Snow melt base temperature [ºC]
SMFMX	4.5	Melt factor for snow on June 21 [mm H2O/ºC-day]
SMFMN	4.5	Melt factor for snow on December 21 [mm H2O/ºC-day]
TIMP	1	Snow pack temperature lag factor [-]
SNOCOVMX	1	Minimum snow water content that corresponds to 100% snow cover [mm]
SNO50COV	0.5	Fraction of snow volume represented by SNOCOVMX that corresponds to 50% snow cover [-]

After snow processes were adjusted, the groundwater routine was improved by expert knowledge from field investigations of Schmidt (2014), Schmidt et al. (2014) and Schmidt, S. & Ries, F. (2014). Due to their investigations (see chapter 1.2.5 Hydrology), interflow and baseflow are negligible, while percolation could reach high flow rates into the deep aquifer system. Therefore, groundwater routine of the SWAT input file .gw was adjusted to represent these processes.

In this respect, baseflow was reduced to zero, by adjusting the ALPHA_BF factor and RCHRG_DP (Table 15). To simulate a hydrological epikarst system, where the waterflow out of soil and shallow aquifer into the reach is negligible, the fraction of percolation from the root zone, which reaches the deep aquifer (RCHRG_DP) must be set to its maximum value (Arnold et al., 2012a). Otherwise, after a certain time-lag, the model simulates a waterflow from the shallow aquifer into the reach, which would lead to baseflow.

Table 15: Used and adjusted (light blue) groundwater routine parameters. Parameters are located in the input file (.gw).

Parameter	Value	Description
SHALLST	0	Initial depth of water in the shallow aquifer [mm]
DEEPST	0	Initial depth of water in the deep aquifer [mm]
GW_DELAY	500	Groundwater delay [days]
ALPHA_BF	0	Baseflow alpha factor [days]
GWQMN	5000	Threshold depth of water in the shallow aquifer required for return flow to occur [mm]
GW_REVAP	0.02	Groundwater "revap" coefficient
REVAPMN	0	Threshold depth of water in the shallow aquifer for "revap" to occur [mm]

RCHRG_DP	1	Deep aquifer percolation fraction
GWHT	0	Initial groundwater height [m]
GW_SPYLD	0.003	Specific yield of the shallow aquifer [m3/m3]
ALPHA_BF_D	0	Baseflow alpha factor for deep aquifer [days]

As a final step of the initial parameter adjustment, the timing of simulated discharge peaks was examined and adapted. Therefore, the time-lag between simulated and observed runoff was analyzed by an automated R-script. Thereafter, using of the Manning's n value (represented by CH_N1 and CH_N2), the time-delay of runoff reaction was calibrated. CH_N1 and CH_N2 represent the roughness of tributary and main channels and usually control the horizontal shift of discharge (Neitsch et al., 2009). Within 10 iterative model runs of gradual increasing CH_N values (n: 0.045 – 0.061), no relevant time-delay could be achieved. Therefore, the parameters ALPHABF_BNK (baseflow alpha factor for bank storage), SURLAG (Surface runoff lag coefficient; portion of surface runoff that reach the main channel), OV_N (Manning's n value for overland flow), and the Muskingum calibration coefficient parameters MSK_CO1, MSK_CO2 and MSK_X were tested in addition to adjust the time-lag. All parameters were evaluated as ineffective to adjust the runoff timing and therefor were rejected and the time-lag could not be improved.

2.3.2.3 Parameter selection

Due to catchment characterizations and investigations on runoff-recharge processes of Ries (2016), it was documented, that saturation excess overland (SOF) flow is the predominant runoff formation process at Wadi Auja (especially at the Mediterranean headwater section). According to the mechanism of SOF, soil depth (SOL_Z), available water capacity of the soil layer (SOL_AWC) and soil bulk density (SOL_BD) were selected (Table 16). Having in mind, that the Green-Ampt equation was selected for the calculation of infiltration processes (Chapter 2.2 Model setup), its variables were considered in the calibration procedure. The equation contains the Curve Number variable (CN), besides the hydraulic conductivity. In respect of percolation and surface runoff, the saturated hydraulic conductivity (SOL_K) was also included. Considering climatic conditions and surface cover of Wadi Auja, the ESCO parameter (soil evaporation) was also added to the calibration process, in order to represent the impact of soil moisture on runoff formation processes.

Besides the consideration of soil related parameters, CH_K1 and CH_K2 (Effective hydraulic conductivity in tributary/main channel alluvium) were selected to represent hydrological processes in the channel segment. Especially transmission losses are calibrated by these two parameters. To avoid over-parametrization, the parameter selection was limited to the following eight parameters (Table 16).

Table 16: Selection of relevant SWAT parameters according to the characterization of the catchment, investigations of Ries (2016). Parameter description due to the SWAT input/output documentation (Arnold et al., 2012a). Marked parameters (*) are adopted from the TRAIN-ZIN configuration of Ries (2013).

Parameter	Description	Reason of selection
ESCO	Soil evaporation. A low value of ESCO enables the model to extract more of the evaporative demand from lower soil levels.	Impact of soil moisture on runoff formation processes.
CH_K(1)*	Effective hydraulic conductivity in tributary channel alluvium [mm/h].	This parameter controls transmission losses from surface runoff as it flows to the main channel in the subbasin.
CH_K(2)*	Effective hydraulic conductivity in main channel alluvium [mm/h].	Within a recharge area, this parameter controls the losses to the groundwater.
SOL_Z*	Depth from soil surface to bottom of layer. [mm].	Soil depth controls the saturation overland flow (SOF) and was detected as a sensitive parameter during the calibration of TRAIN-ZIN.
SOL_K*	Saturated hydraulic conductivity (mm/h). This parameter relates the water flow rate (flux density) to the hydraulic gradient and is a measure of the water movement through the soil.	Controls the fraction of percolation, surface runoff and interflow.
SOL_AWC*	Available water capacity of the soil layer [mm H2O/mm soil].	AWC controls the timing of soil saturation and thus runoff reaction
SOL_BD*	Moist bulk density [g/cm³]. The soil bulk density presents the ratio of the mass of solid particles to the total volume of the soil	Integral part of the applied Green-Ampt equation, which controls the ratio between infiltration and surface runoff.
CN2	Initial SCS runoff curve number for moisture conditions.	Integral part of the applied Green-Ampt equation, which controls the ratio between infiltration and surface runoff.

2.3.2.4 Runoff calibration

The main objective of the manual runoff calibration, was an accurate simulation of the observed discharge behavior at the outlet of Wadi Auja considering expert knowledge from previous studies. Like the calibration process of TRAIN-ZIN, the runoff calibration of SWAT was oriented to find the best over-all performance, which represents the best runoff characteristic as well as a realistic water balance.

According to the calibration-guidelines shown in Figure 26, a conventionally one-at-the-time calibration procedure was applied. Thereby, the calibration mimics the direction of the water fluxes (top down principle). Initially, the eight relevant variables (Table 16) were analyzed according to their parameter limits, before they were gradually restricted to a narrow parameter range. Based on the evaluation of the previous calibration run, the next parameter set was developed. Multiple parameter combinations were applied, analyzed and documented to evaluate parameter inter-dependencies. Each parameter-set was analyzed by its output statistic and a graphical analysis of water balance and discharge behavior. Due to long computing times of SWAT advanced (25 min for three years, including warm-up period), the manual calibration process was limited to 65 runs. All calibration results are shown in chapter 3.1.

2.3.2.5 Model optimization

To enable an objective model comparison, TRAIN-ZIN and SWAT advanced were calibrated and parameterized as good as possible. Only if this is guaranteed, reliable conclusions about the differences in model structure, process implementation and model goodness-of-fit can be drawn (Kiesel et al., 2017). Otherwise, it cannot be guaranteed, that the results relate on an insufficient calibration or model parameterization (Arnold et al., 2012b). Because the expert knowledge calibration is restricted to few runs due to long computing times of SWAT, it is unlikely that the best parameter values are found manually. Therefore, an automated optimization algorithm is applied within a narrow and specific parameter range to find an optimized parameter set (Pfannerstill et al., 2014). The respective parameter ranges refer to the manual calibration process and are shown in Table 17. In this context, the model optimization is a fine adjustment of the manual model calibration of SWAT advanced.

On the basis of an open source R-algorithms of Pfannerstill et al. (2014) the optimization of SWAT was carried out. In this script, the Latin Hypercube Sampling method (LHS) is used to create 2000 unique input-parameter-combinations within the given range of the eight selected parameters (Table 17). The LHS method is a modern variance reduction technique, based on a stratified sampling scheme, to create parameter distributions under special consideration of variable importance (Iman, 2008). For CPU-intensive models like SWAT on a 5-min basis, the LHS method is a good alternative to random samplings, because it represents the parameter space by less samples and less computing time than the Monte Carlo method (Singhee and Rutenbar, 2010).

Table 17: Applied parameter ranges for SWAT model optimization with R. To keep specific properties of HRU’s, most parameters were changed by a multiplication factor (type of change: multiplied). For those parameters where no differentiated values existed, the parameter was replaced by certain absolute value (type of change: replaced).

Parameter	Database	Min	Max	Type of change
ESCO	.hru	0.01	0.3	replaced
CH_K1	.sub	10	20	replaced
CH_K2	.rte	10	20	replaced
SOL_K	.sol	0.5	0.9	multiplied
SOL_Z	.sol	1	1.6	multiplied
SOL_AWC	.sol	3	7	multiplied
SOL_BD	.sol	0.8	2	multiplied
CN2	.mgt	0.5	1	multiplied

After 2000 different parameter-sets were created, the parameter values at the SWAT input folder (TxtInOut) were gradually overwritten within the program loop of the R-script. To keep differentiated property information of all HRU’s, the existing parameters were changed by a multiplication factor. Only for those parameters where no differentiated values exist, the parameter was simply replaced by a certain absolute value (Table 17). Without this adjustment, every HRU would get the same parameter value. After the input files were changed, SWAT could be performed within the program loop of the R-script. This is an unusual way to call SWAT, but a necessary procedure to automatize 2000 model runs. To run SWAT on R, the *system()* command was utilized.

To enable the model optimization and processing the storage-intensive output data, at the end of each model run the output.rch file (contains discharge values) was automatically clipped to the investigation period and subbasin of interest by a “One-Liner” of the GNU-Utility (Robbins, 2001). These One-Liners are small programs from the Linux environment and can be applied in R. The used One-Liner “Gwak.exe” clipped each output.rch file to 22 MB instead of 5 GB per model run. To call the *gawk.exe* in R, the *shell()* command was used.

To reduce the computing time of 2000 model runs, the R-script was parallelized. A usual SWAT advanced model run in a 5-min resolution over three years plus warm-up period needs up to 30 min on an i7 processor with 2.8 GHz. The parallelization method allows the operator to use as many processor cores as available on different computers simultaneous. In this present case, the 2000 model runs were spread over 10 processor cores on five individual computers. Each processor finally achieved 200 runs and therefore the total computing time was reduced by about 38 days. The improvement of data volume and computing time was required to enable the model optimization in the framework of this present study.

2.3.2.6 Multi-Criteria-Analysis

To complete the model optimization, the best parameter set, in agreement with literature and observed data, must be identified. For this purpose, a multi-criteria-analysis based on observed runoff data at the catchment outlet and findings of Gunkel et al. (2015) about main water balance components in the neighbor-catchment Wadi Faria was performed. Wadi Faria is a typical semi-arid karst catchment situated north of Wadi Auja in the western tributaries of the Lower Jordan River. According to Ries (2013) and Gunkel et al. (2015), same hydrological processes for Wadi Faria as for Wadi Auja were expected. By using hydrological signatures, Gunkel et al. (2015) found out, that the mean annual actual evapotranspiration is about 70 % and recharge about 30 % of mean annual rainfall of Wadi Faria. These findings were confirmed by simulations at Faria Spring of Hartmann et al. (2012), from satellite data for the entire West Bank of Comair et al. (2012) and from long term investigations of Sheffer et al. (2010) for the Western Mountain Aquifer Basin. For that reason, the following values of evapotranspiration and groundwater recharge (Table 18) are used for the multi-criteria-analysis.

Table 18: Criteria values for evapotranspiration and groundwater recharge for the multi-criteria-analysis due to Gunkel et al. (2015). Precipitation is represented by measured values from Wadi Auja, while values for evapotranspiration and groundwater recharge are derived from the respective proportion of mean annual rainfall at Wadi Auja.

Water balance component	Wadi Auja	Proportion of mean annual rainfall
Precipitation	398 mm	-
Evapotranspiration	278 mm	70%
Aquifer recharge	119 mm	30%

A multi-criteria-analysis as part of the calibration procedure is important to obtain the best over-all-performance, which includes the most relevant components of the water balance and not only considers the discharge hydrograph. At Wadi Auja, runoff only represents a small fraction of the whole water balance (~1-2%) and therefore is not representative as the only objective function. Moreover, Gunkel et al. (2015) mentioned, that runoff measurements are often subject of considerable errors. In this respect, Goodrich et al. (1995) stated out, that the exact runoff simulation under high spatial rainfall variability, is strongly affected by errors. For this reason, more realistic results are expected through a multi-criteria-analysis.

Consequently, from each of the 2000 model runs, the simulated runoff was extracted, compared to the observed data and evaluated by the common model efficiency Nash-Sutcliffe-Efficiency (NSE). The NSE was already used to evaluate the goodness of fit of TRAIN-ZIN runoff. From the SWAT summery output file *output.std*, which sums up the long-time annual water balance, values for evapotranspiration (ET) and deep aquifer recharge (DEEP AQ) were extracted. Due to these statistics, the best simulations of evapotranspiration, deep aquifer recharge and surface runoff were selected. To get the best overall performance, only runs with an ET and DEEP AQ deviation of +/- 20% were selected and ordered by the NSE of discharge.

2.3.3 SWAT light – auto-calibration

In contrast to TRAIN-ZIN, SWAT is offering an established tool for automatic calibration, called SWAT-CUP, developed by Karim C. Abbaspour from the Eawag, Switzerland (Abbaspour, 2015). SWAT-CUP is a public domain program which enables sensitivity analysis, calibration, validation and uncertainty analysis. It includes three different optimization schemes, namely: Generalized likelihood uncertainty estimation (GLUE), shuffled complex evolution (SCE) and the parameter estimation program PEST (Parameter ESTimation). These automated techniques are typically based on Monte Carlo or similar sampling schemes to estimate the best parameter values over the course of thousands iterative simulations (Arnold et al., 2012b). SWAT-CUP provides a user-friendly interface and is equipped with multiple options to visualize hydrographs, dotty-plots or confidence intervals. Among other reasons, SWAT-CUP is becoming increasingly popular among SWAT users and can be used for a relative fast model calibration. Therefore, to carry out a common and unbiased calibration of SWAT and mimicking a typical application, the auto-calibration tool is used for SWAT light (Villamizar, 2015).

SWAT-CUP is used as a method to calibrate SWAT light without including previous calibration knowledge from TRAIN-ZIN and SWAT advanced. Thereby, the usage of an automated process is the only way to avoid a subjective calibration. This procedure enables and increases the comparability with other hydrological studies and typically applications of SWAT. The following calibration procedure is based on the official calibration scheme for SWAT-CUP 2012 5.1.6 (Eawag, 2009) from the SWAT-CUP user manual (Abbaspour, 2015) and recommendations of Villamizar (2015).

According to the general catchment characteristics of Wadi Auja and usual SWAT auto-calibration applications, like from Havel et al. (2017), 18 potential parameters were selected (Table 19). Especially CN2, the representative Curve-Number value is considered, because the SWAT standard set is using the CN-method instead of the Green-Ampt-Method. All parameter ranges were chosen as large as possible within a useful and permitted range. Each parameter is replaced by a certain absolute value, while SOL_Z is changed relatively +/- 60% to its default settings form the database.

Table 19: Initial parameter selection (18 parameters) for SWAT-CUP auto-calibration. Except SOL_Z, each parameter is replaced by a certain value within the permitted min/max range. SOL_Z is changed +/- 60% relatively to its default settings. The file extension indicates, to which database the respective parameter belongs to.

Parameter	**File ext.**	**Min**	**Max**	**Method**
CN2	mgt	10.0	80.0	replace
SOL_Z	sol	-0.6	0.6	relative
SOL_K	sol	10.0	120.0	replace
SOL_AWC	sol	0.0	1.0	replace
ALPHA_BF	gw	0.0	1.0	replace
RCHRG_DP	gw	0.0	1.0	replace
ESCO	hru	0.7	1.0	replace
CANMX	hru	0.0	100.0	replace
SOL_BD	sol	0.9	2.5	replace
EPCO	hru	0.0	1.0	replace
CH_K2	rte	10.0	120.0	replace
GW_REVAP	gw	0.0	0.2	replace
CH_K1	sub	10.0	120.0	replace
SURLAG	bsn	1.0	12.0	replace
CH_W2	rte	0.3	4.0	replace
CH_N2	rte	0.0	0.3	replace
OV_N	hru	0.0	0.3	replace
TDRAIN	mgt	0.0	72.0	replace

After the parameter selection, Abbaspour (2015) recommends in the SWAT-CUP user manual, to perform four iterations with respectively 500 automated runs. Therefore, the observed runoff data was prepared as required and the variables for the objective-function (here only discharge at the outlet) were defined. After the first successful iteration of 500 runs, the global parameter sensitivity was analyzed by a useful visualization tool of SWAT-CUP (Figure 27). A low P-value (< 0.05) indicates, that changes of this parameter are likely related to changes in the response variable (null hypothesis, no effect, can be reject). The t-stat is defined as the parameter value divided by its standard error and is a measure of the prediction. Therefore, the larger the absolute value of t-stat (low standard error) and the smaller the p-value, the more sensitive is the respective parameter (Abbaspour, 2015). Because of this, only the most sensitive nine parameters CH_W2, CN2, SOL_AWC, CH_N2, SOL_Z, CH_K2, SOL_BD, ALPHA_BF and SOL_K were selected and used for three further iterations.

Figure 27: Global sensitivity analysis for 18 parameters of the first iteration of SWAT-CUP. The larger the absolute value of t-stat and the smaller the p-value, the more sensitive the respective parameter.

At the end of each iteration (Computing time: 3.5 hours), the SWAT-CUP tool recommends a new parameter-set with adjusted and specified ranges. These proposals were accepted for each of further three iterations. Results are given in chapter 3.

2.4 Concept of model comparison

Within the efforts of data preparation, model configuration and calibration, all requirements for an objective and realistic model comparison between TRAIN-ZIN and SWAT advanced on a 5-min time-resolution are met. To finally compare these results with SWAT light, the runoff output of TRAIN-ZIN and SWAT advanced were aggregated to a daily time-step. The remaining water balance components like evapotranspiration, percolation and soil water content were available on daily resolution for all model set-ups. In that respect, evapotranspiration and percolation can be compared relatively and evaluated according to literature values (Gunkel et al., 2015; Sorman and Abdulrazzak, 1995; Schmidt, 2014). A reference time-series is not provided. In contrast to that, runoff can be evaluated by the observed discharge at the catchment outlet and the soil-water-routine with two measured soil moisture plots from Ries et al. (2015). Soil moisture plot 1 (SM-1) is located at the Auja headwater, while soil moisture plot 2 (SM-2) is situated at the middle section of the catchment. Both soil moisture plots were averaged over the entire soil thickness and converted into mm water content. In contrast to the simulated soil moisture from TRAIN-ZIN and SWAT, which are averaged over the entire catchment area of 55 km², SM-1 and SM-2 are only representing point measurements. This enables an absolute comparison of soil water simulations.

In addition to the water balance comparison over the entire investigation period, the discharge behavior of TRAIN-ZIN, SWAT advanced and SWAT light is compared in detail. To illustrate the event-dynamic, the respective time-intervals of runoff events were analyzed and selected. While TRAIN-ZIN and SWAT advanced are represented in a 5-min time-step, SWAT light is added in its daily time-resolution. This method enables a direct model comparison and a differentiation of runoff reactions at the catchment outlet. To distinguish between runoff formation processes of different sub-catchments, the discharge data from all subbasins were extracted and respectively prepared.

3. Results

3.1 Calibration results

3.1.1 SWAT advanced – expert knowledge calibration

Figure 28 shows the best manual calibrated hydrograph at the catchment outlet of Wadi Auja, represented by calibration run number 61 (final parameter values are shown in Appendix 5). The graph illustrates a detailed examination of the simulated discharge behavior at the three existing discharge events in 2012 and 2013. A clear uniform time-delay of event one and two can be observed, while discharge event three is extremely underrepresented and also shows its first reaction approximately one day later. It can be seen, that simulated event one and two are highly dynamic and fluctuate more than the observed discharge. Once observed discharge is initiated, the hydrograph is continuous and shows a pronounced recession behavior. In contrast to that, the simulated discharge reacts faster and sharper, while flow stops several times during the observed event. In general, the peak discharge of the first two events overestimates the observed peak flow.

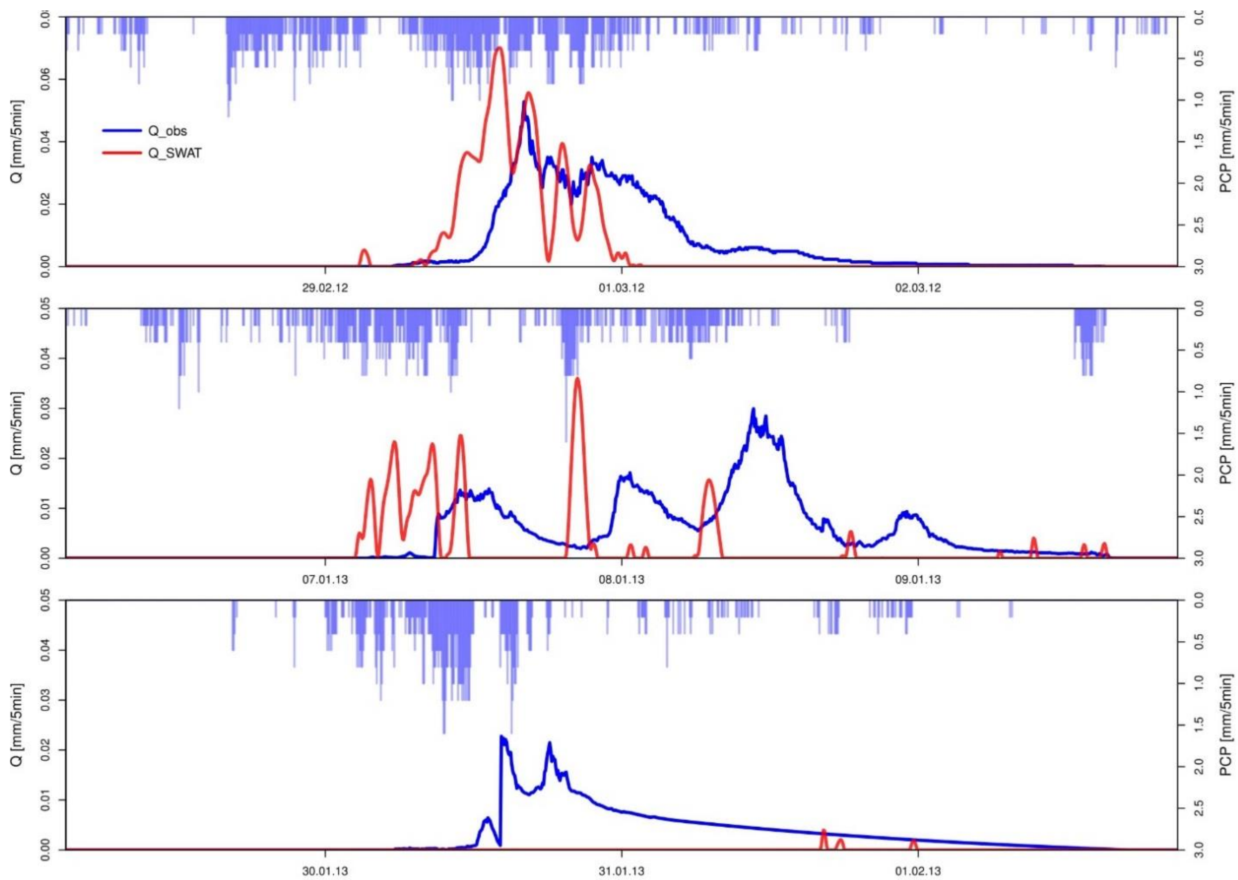


Figure 28: Best manual calibrated hydrograph (run 61) at the catchment outlet of Wadi Auja. Detailed examination of the three existing discharge events from 2012 and 2013 in a 5-min time-step. The figure shows simulated and observed discharge as well as precipitation data.

During the manual calibration process, parameter impact on discharge behavior and water balance, as well as their sensitivity were analyzed. Calibration results and the qualitative determination of parameter sensitivity are summarized in Table 20. The parameters EPCO, CANMX and SURLAG were identified as insensitive, because they showed no relevant impact on the discharge behavior. While SURLAG and CANMX were kept on default values (4 and 0 – 2.43), EPCO was set to its maximum of 1. During the calibration, it was recognized, that SOL_AWC besides its impacts on general runoff generation (Table 20), strongly influenced the second discharge event, while the first event was barely affected. The same reaction was observed for SOL_Z during the adjustment of the soil depth. In this respect, it was also detected, that thick soil layers lead to high evaporation rates at the end of summer, due to higher soil moisture contents. To simulate the third runoff event, a disproportionately low SOL_K would be necessary, which leads to a strong overestimation of event one and two. Because of that, the focus was on the correct simulation of discharge-event one and two.

Table 20: Model reaction, parameter sensitivity and impact on runoff generation within the application of SWAT advanced. Qualitative determination of sensitivity. (+) low sensitivity, (++) medium sensitivity and (+++) high sensitivity.

Parameter	impact	sensitivity
ESCO .hru	Controls soil evaporation. The lower ESCO, the higher evaporation out of soil.	(+)
CH_K1 .sub **CH_K2 .rte**	Controls transmission losses. The higher the conductivity, the higher transmission losses. A lower hydraulic conductivity in the channel segment leads to a more continuous discharge.	(++)
SOL_K .sol	Controls percolation out of soil. The lower conductivity, the more discharge peaks are simulated.	(+++)
SOL_Z .sol	Controls soil moisture content and runoff reaction. The higher SOL_Z (thicker), the higher soil moisture, but slower runoff reaction.	(++)
SOL_AWC .sol	Controls soil moisture content and thus evaporation out of soil. The higher SOL_AWC, the higher soil moisture and ET.	(++)
SOL_BD .sol	Controls the soil saturation process. The higher SOL_BD, the faster soil saturation and runoff formation.	(++)
CN2 .mgt	Controls evaporation and surface runoff (part of Green-Ampt equation). A reduction of CN2 leads to higher ET and less surface Q.	(+)

3.1.2 SWAT advanced – optimization

Statistical results of the multi-criteria-analysis are summarized in Table 21. Depending on the objective function, the four best model runs were selected. Compared to the observed runoff time-series, run 1853 had the highest Nash-Sutcliffe-Efficiency (NSE: 0.3). Run 1913 represents the best ET and run 1902 the best simulation for groundwater recharge. For the best overall performance, run number 1245 was chosen (final parameter values are shown in Appendix 6). Run 1853 and 1913 underestimate the annual long-term observed discharge amount (~ 4.7 mm/year) more than threefold, while runs 1902 and 1245 underestimate the observed runoff by 42 % and 47 % respectively.

Table 21: Multi-Criteria-Analysis results. Depending on the objective function, the Nash-Sutcliffe-Efficiency (NSE), the relative difference of evapotranspiration (ET), deep aquifer recharge (DEEP AQ) and the related model run is displayed.

Objective function	**NSE**	**annual long-term runoff**	**deviation of ET [%]**	**deviation of DEEP AQ [%]**	**Run**
best Nash-Sutcliffe	0.30	1.5 mm	-5.0 **%**	-57 **%**	1853
best ET simulation	0.29	1.5 mm	0.0 **%**	-51 **%**	1913
best DEEP AQ simulation	-0.35	3.3 mm	-42 **%**	0.0 **%**	1902
best overall performance	**-0.08**	**3.2 mm**	**-14 %**	**-20 %**	**1245**

Besides the statistical criteria, hydrographs of the chosen runs were also analyzed visually. Figure 29 shows all four runs in comparison to observed runoff time-series. First, it can be noted, that all runs strongly underestimate the third discharge event in January 2013, while run 1853 is not simulating any discharge at all. In this respect the run with the highest NSE (1853) is the only one that overestimates the first discharge event. In contrast to that, run 1913 constantly underestimates all events, while run 1902 shows a contrary behavior for the first and second discharge event. Run 1245, with the best over-all-performance fits to the first observed discharge peak, but strongly overestimates the second event. All in all, more runoff-events were simulated as where observed. This sensitive reaction to non-discharge effective rainfall events, is demonstrated particularly in the hydrograph of run 1902, where discharge was simulated at six additional times in 2012 and 2011. A similar behavior, but less frequent and pronounced, is also found in the remaining runs 1853, 1913 and 1245.

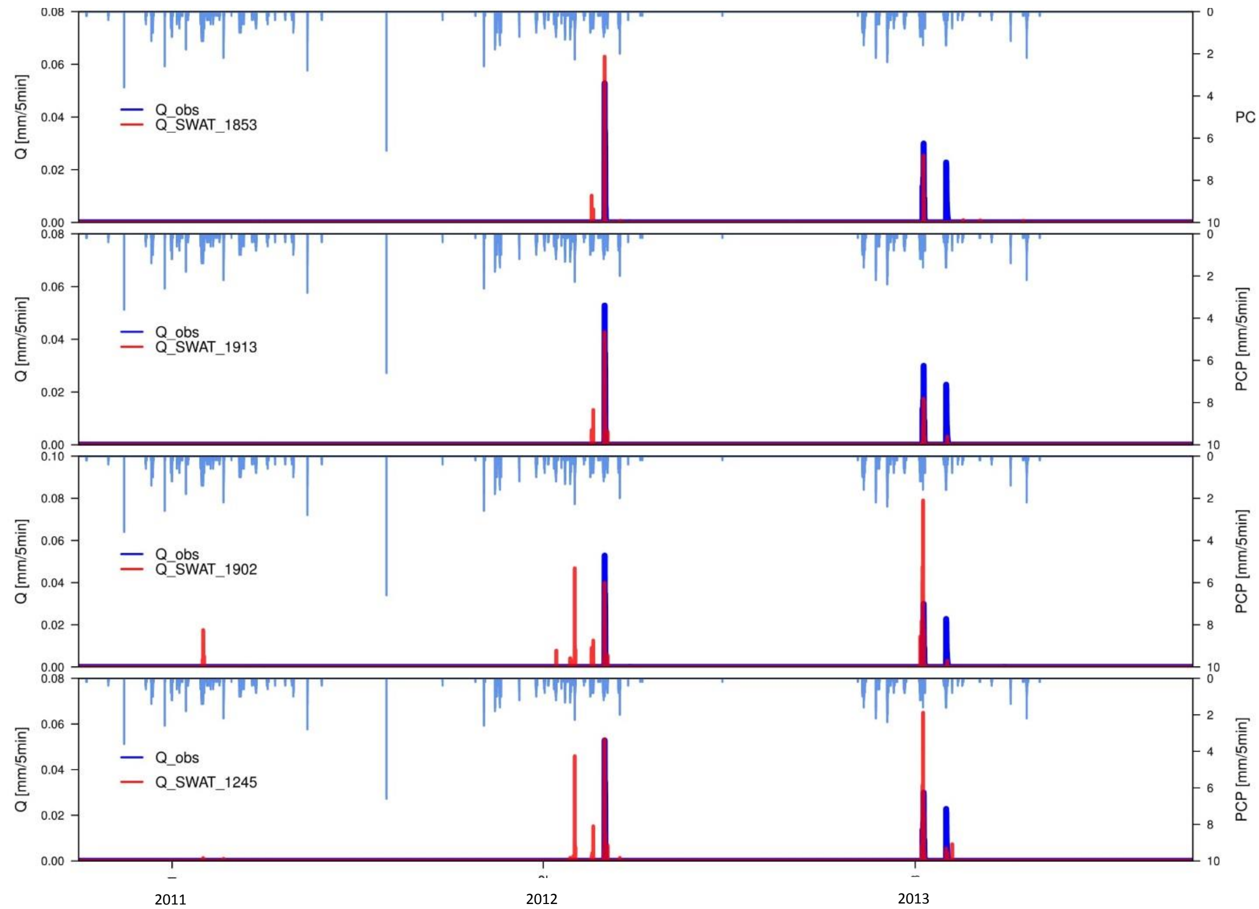


Figure 29: Hydrographs of the multi-criteria-analysis in daily time-step. Four different model runs of SWAT advanced are compared to the observed discharge at the catchment outlet of Wadi Auja.

3.1.3 SWAT light – auto-calibration

The daily time-step results of the iterative auto-calibration, carried out using SWAT-CUP, are shown in Figure 30. Each graph was produced by SWAT-CUP and represents one of four subsequent iterations containing 500 SWAT light model runs. According to that, the 95%-confidence interval (95PPU) refers to 500 model runs. Each graph indicates the NSE oft its best simulation.

The 95PPU shrunk continuously in its extreme values and range, from the first to the fourth iteration. Moreover, it is significant, that the respective best simulation is continuously situated at the lower range of the 95PPU. With the exception of the best simulation of iteration two and three, the peak discharges are underestimated. In general, the simulated discharge is more frequent and dynamic than the observed. Neither in shape, nor in duration or total runoff amount, the simulated hydrograph represents the observed. The Nash-Sutcliffe-Efficiency between simulated and observed daily discharge shows the goodness-of-fit. Here, the second iteration led to the lowest NSE, while it increased gradually for iteration three and four. The first iteration yielded the highest NSE. According to the given calibration procedure, the fourth iteration represents the final model adjustment, independent of the NSE. Its parameter values are summarized in Appendix 7.

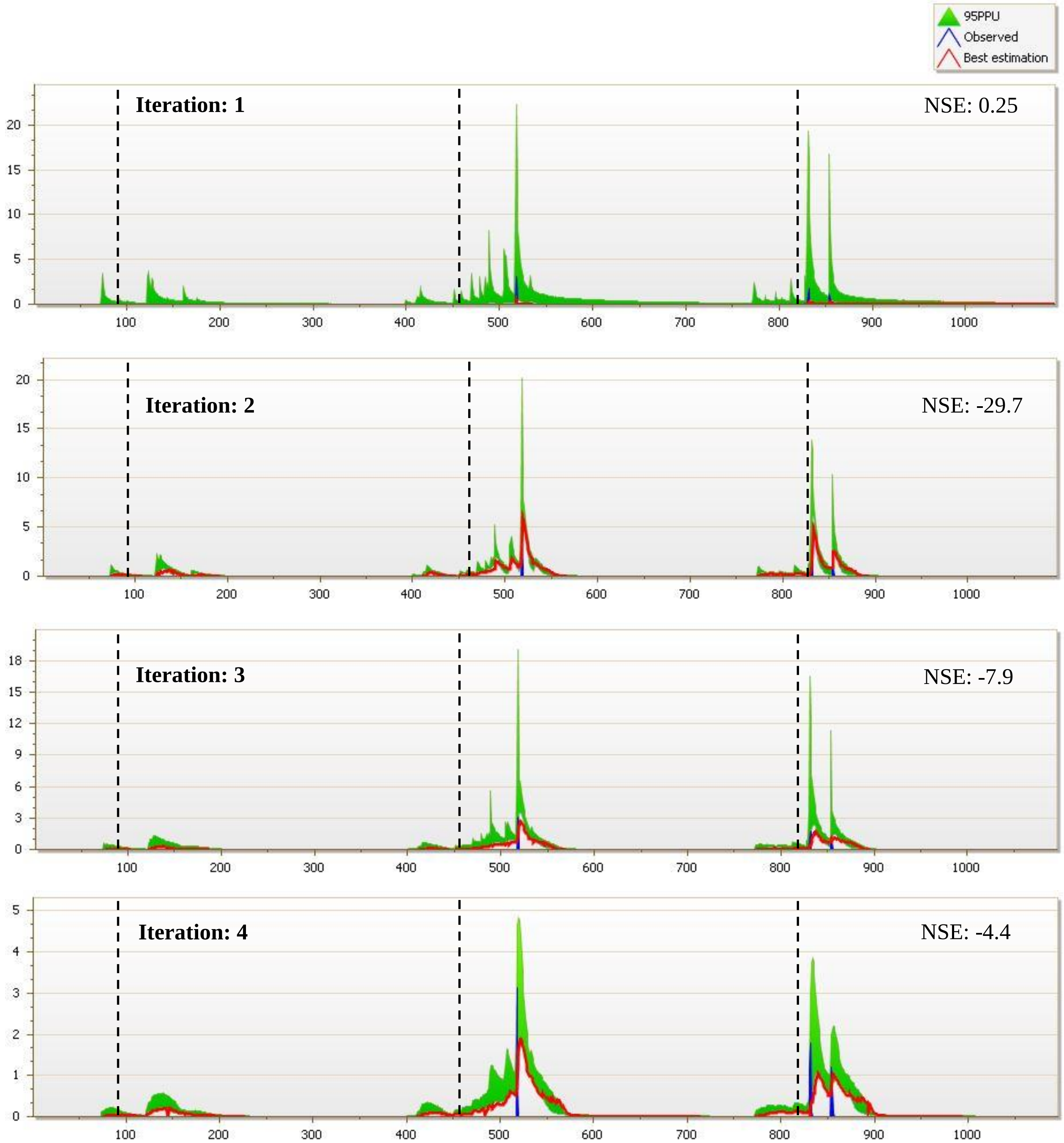


Figure 30: Results of the iterative development of SWAT-CUP auto-calibration for the SWAT light setup. Hydrograph 01 contains 18 initial parameters, while hydrographs 02 – 04 contain 8 selected parameters for the auto-calibration process. Original screenshots are extracted out of SWAT-CUP. x-axis: Investigation period from 01.10.2010 – 30.09.2013 in days. y-axis: Discharge in m³/s and. 95% confidence interval is illustrated in green. Simulated and observed data are in a daily time-step. Dashed lines illustrate the respective years 2010 – 2013.

3.2 Water balance comparison

The following water balance comparison is based on the calibration results of SWAT from this present study and on the published TRAIN-ZIN performance of Ries (2013). Therefore, the best simulation of the final SWAT-CUP iteration (SWAT light), as well as run 1245 with the best over-all-performance from the multi-criteria-analysis are used (SWAT advanced). Measured areal precipitation (averaged rainfall for the entire catchment) and observed flow rates at the catchment outlet are included to illustrate the rainfall-runoff reaction, compare different rainfall interpolation methods and give a reference for the reaction of water balance components. Calculated reference values (observed/literature) for ET and percolation from the multi-criteria-analysis (Table 18Figure 19) are included in this comparison to evaluate the respective components. For a further reference, the observed water balance components of the neighbor-catchment Wadi Faria is added (Gunkel et al., 2015).

Figure 31 illustrates the water balance of Wadi Auja for the investigation period of 01.10.2010 to 30.09.13. The underlying values are summarized in Table 22. It can be seen, that the observed areal precipitation amount is exactly reflected by TRAIN-ZIN, while SWAT advanced and SWAT light overestimate PCP marginally. Actual evapotranspiration of TRAIN-ZIN and SWAT light is higher than the calculated criteria value (observed/literature), but do not exceed the reference values of Wadi Faria (Table 22). In this respect, the simulated ET of SWAT advanced lies below the literature and reference range. Differences for ET between the model variations range from 8 % to 26 %. Regarding the percolation, all models show a similar behavior and underestimate literature and reference values. Hereby, SWAT advanced shows the best simulation and SWAT light the worst. Regarding the simulation of surface runoff (Q), the differences between the models are striking. TRAIN-ZIN and SWAT advanced are simulating similar runoff volumes, which lie slightly over the reference values for Wadi Faria, but below the observed discharge at the catchment outlet. The simulated discharge of SWAT light exceeds the observed annual runoff of 4.7 mm/year about 15 times. This is reflected by a negative soil storage change (ΔS) over the simulation period. In contrast to that, SWAT advanced shows a pronounced surplus in ΔS, while the soil storage in TRAIN-ZIN remains constant.

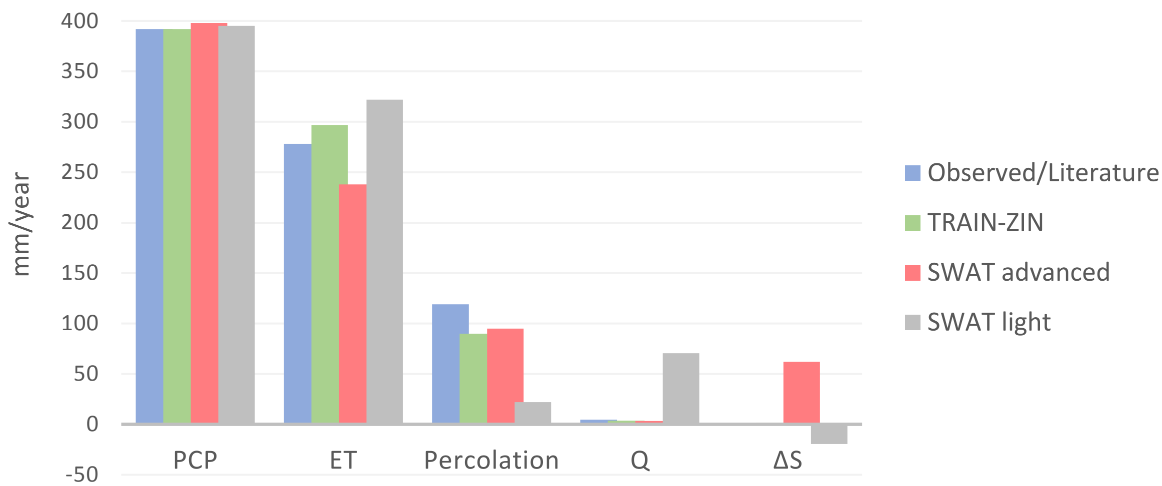


Figure 31: Water balance comparison at the catchment outlet of Wadi Auja. PCP: Precipitation, ET: Evapotranspiration, Q: Surface runoff; ΔS: Change in storage.

Table 22: Water balance comparison at the catchment outlet of Wadi Auja. Long-term average (10/2010 to 10/2013) of yearly 5 min sum from best TRAIN-ZIN and SWAT advanced and daily sum of SWAT light run. For validation, the water balance of the neighbor catchment Wadi Faria (ca. 15 km north of Wadi Auja) is added (Gunkel et al., 2015). PCP: Precipitation, ET: Actual evapotranspiration, Q: Surface runoff, ΔS: Storage change.

	observed/literature [mm/year]	**TRAIN-ZIN [mm/year]**	**SWAT advanced [mm/year]**	**SWAT light [mm/year]**	**Wadi Faria [mm/year]**
PCP	392	392	398	395	497
ET	278	297	238	322	345–373
Percolation	119	90	95	22	123–149
Q	4.7	3.7	3.2	70.5	2–3
ΔS	-	1.3	61.8	-19.5	-

The following section illustrates the dynamics of the water balance components over the total investigation period (Figure 32). The simulated rainfall distribution of all model variations is congruent with the observed distribution. While TRAIN-ZIN exactly simulates the annual rainfall amount, observed rainfall peaks are predominantly higher. The simulations of actual evapotranspiration are directly related to the water availability (rainfall distribution), where TRAIN-ZIN shows the closest relation. In that respect, TRAIN-ZIN simulates higher ET from September to January than SWAT advanced and light. In general, the highest ET can be observed between September and May. In this period, SWAT light models the highest ET values in the hydrological years 2010/11 and 2012/13. While TRAIN-ZIN and SWAT advanced have a quite similar tailing behavior, SWAT light shows a more pronounced and longer tailing up to July/August.

TRAIN-ZIN simulates the highest and sharpest percolation peaks of up to 40 mm/day, although SWAT advanced has higher annual percolation rates (Table 22). This is due to the fact, that SWAT advanced simulates broader percolation events with a more pronounced tailing. Thereby, SWAT light exceeds the maximum percolation of SWAT advanced two times in 2012 and 2013, while in February 2011 no percolation was simulated at all. Apart from that, all model variations show a similar timing, but different shape and peak values of percolation.

Besides the relative comparison of ET and percolation, the soil moisture graph provides observed data of two soil moisture plots from Ries et al. (2015). Soil moisture plot 1 (SM-1) is located in the Auja headwater, while soil moisture plot 2 (SM-2) is situated in the middle section of the catchment. In that respect, it is striking, that the simulated soil moisture of TRAIN-ZIN goes down to zero by June to September, while SM-1, SM-2 and SWAT light remain constantly above 50 mm. In this context, SWAT advanced shows a similar, but less pronounced behavior than TRAIN-ZIN. SWAT light simulates the highest and TRAIN-ZIN the lowest soil moisture content. SWAT advanced lies in between these both simulations and like TRAIN-ZIN is strongly associated with SM-1 during November to May. Over all simulations follow a similar pattern and timing but show a vertical shift.

The bottom graph of Figure 32 shows the observed and simulated hydrographs at the catchment outlet of Wadi Auja. The observed discharge on a three-year timeline looks like a unit-impulse-sequence. The simulated hydrograph of TRAIN-ZIN strongly overlaps with the observed discharge. Especially at the third runoff-event, it is difficult to see the dynamic of TRAIN-ZIN, because it is covered by the observed hydrograph. While TRAIN-ZIN can depict event two and three, the first event is overestimated. In contrast to that, SWAT advanced underestimates the first discharge event, depicts the second well, but neglects the third. In that respect, SWAT advanced simulates two additional runoff events in January 2012. The hydrograph of SWAT light, shows a relatively low, but constant discharge is simulated. Besides a pronounced recession of the hydrograph, the simulated runoff reacts sensitive to little rainfall-events. Therefore, discharge is also simulated in January/February of 2011. Respecting the course and timing of the discharge simulation, it can be seen, that the first and third peak correspond to the respective observed runoff-events. However, the peak flow of the second event cannot be reached and shows a pronounced time-delay. All in all, the results of the hydrograph confirm the unrealistically high annual runoff volumes given in the water balance table (Table 22).

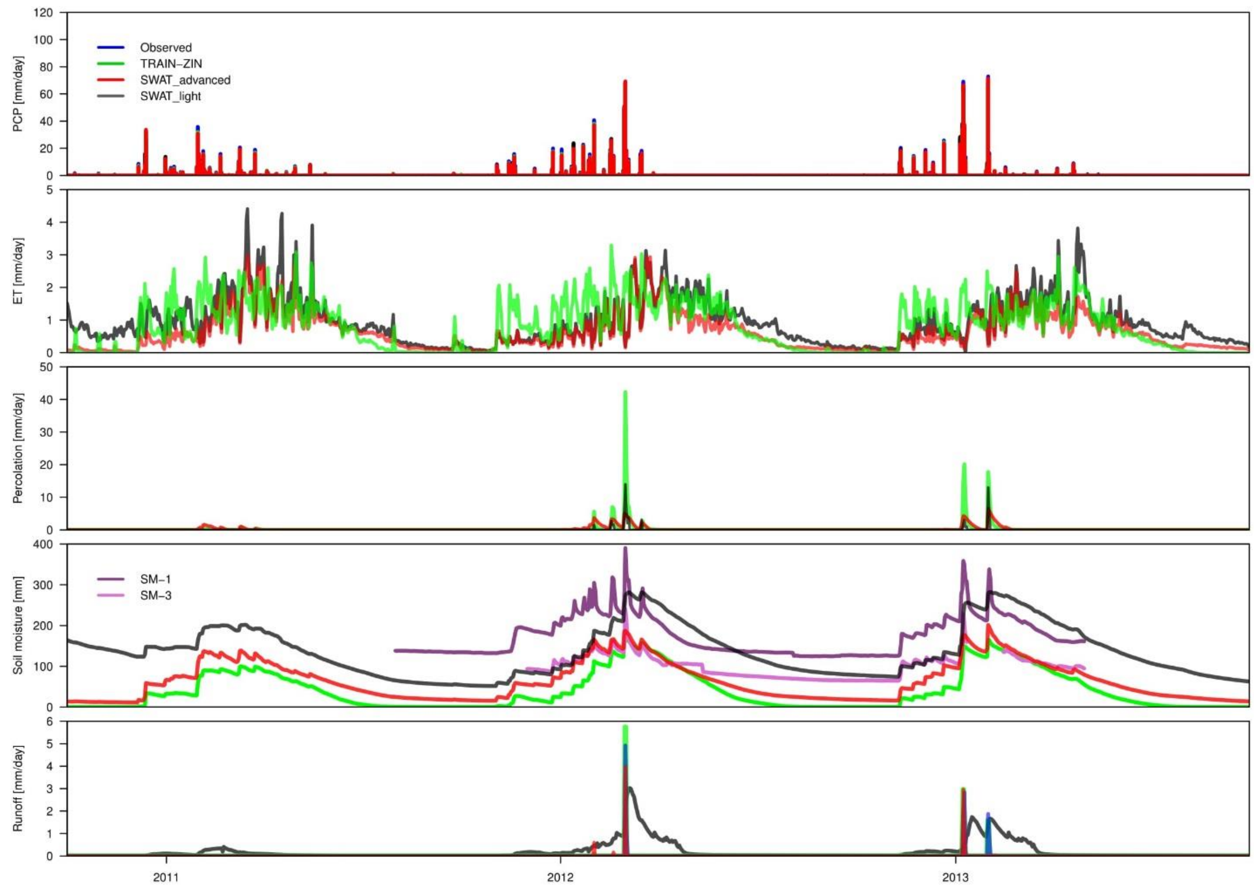


Figure 32: Comparison of the water balance components in daily time-resolution. PCP: Precipitation, ET: Actual evapotranspiration. SM-1: Soil moisture plot in Auja headwater and SM-1 in the middle section.

3.3 Comparison of event-dynamics

As a result of the water balance comparison, it can be concluded, that the high discharge dynamic of ephemeral streams in Wadi Auja cannot be sufficiently depicted on a hydrograph over the entire investigation period (Figure 32). Therefore, Figure 33: Event-dynamic comparison of TRAIN-ZIN, SWAT advanced and SWAT light in daily time-resolution. The graphs show the three discharge-events over the entire investigation period from 01.10.2010 to 30.09.2013. illustrates a detailed consideration of discharge-events in a resolution of one day. This graph clarifies, that TRAIN-ZIN represents the best discharge timing and simulates runoff peaks in a comparable magnitude to the observed. SWAT advanced shows a similar discharge behavior for the first and second event, but fails to simulate the third event. In contrast to TRAIN-ZIN and SWAT advanced, SWAT light is not able to represent the observed discharge behavior. SWAT light neither shows a discharge reaction on the observed runoff initiation, nor a similar runoff duration. Because SWAT light shows a rather constant discharge behavior, no significant daily fluctuations and only provides daily runoff volumes, it is not considered in further sub-daily examinations.

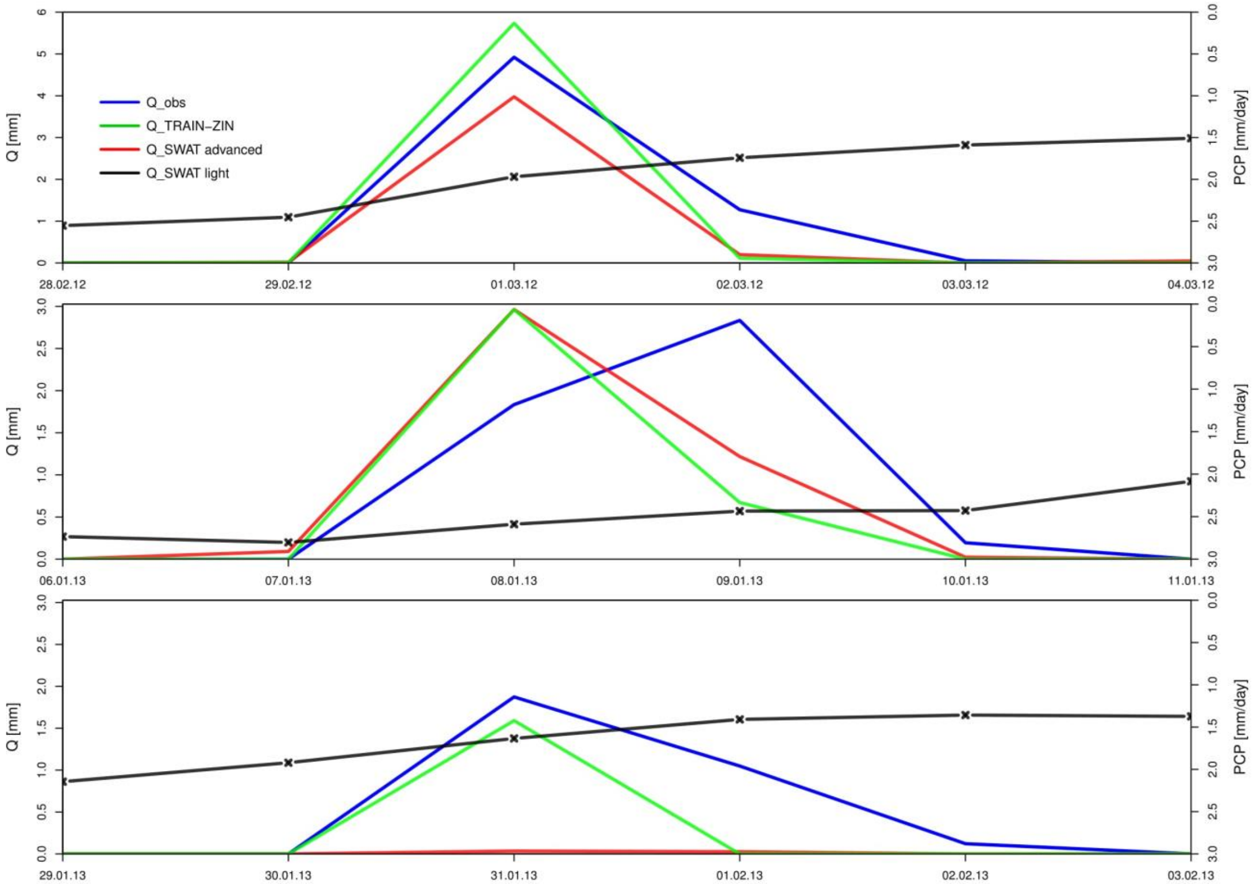


Figure 33: Event-dynamic comparison of TRAIN-ZIN, SWAT advanced and SWAT light in daily time-resolution. The graphs show the three discharge-events over the entire investigation period from 01.10.2010 to 30.09.2013.

Figure 34 illustrates the detailed event-dynamics of TRAIN-ZIN and SWAT advanced for the three discharge events in a 5-min time-resolution. The first observed discharge event at 29th of February 2012 shows the highest peak flow during the entire investigation period (Figure 34). As already described in chapter 3.1, SWAT advanced shows a pronounced time-lag and reacts ahead of time. Apart from this, the peak discharge of 0.053 mm/5min (respectively 9.7 m³/s) is reached almost exactly. The same applies to the simulation of TRAIN-ZIN, which exactly fits the amount of the observed runoff peak, but in addition to that, also shows a good timing. While the observed runoff-increase of TRAIN-ZIN is simulated well, the recession is too fast. Over all, the discharge behavior is less dynamic as the observed, but the general runoff course can be depicted. In this respect, SWAT advanced reacts very sensitive to rainfall and strongly fluctuates within the observed event duration.

The second observed discharge event in January 2013 occurred two days without interruption. In contrast to that, neither the simulation of TRAIN-ZIN nor SWAT advanced were able to represent the continuity of this runoff event. In that respect, the timing of peak discharge one and two was fitted by TRAIN-ZIN, while the third peak was simulated to early and the last peak neglected. Besides the discharge reaction being too slow, TRAIN-ZIN overestimates the first and second peak, while underestimating the third and fourth. Considering the simulation of SWAT advanced, four major discharge peaks can be seen, the timing does not fit. The runoff peaks are generally overestimated, and the pattern is very fluctuating. Especially the highest simulated runoff peak at 07.01.2013 between 10pm and 11pm is striking, because it occurs shortly after a pronounced rainfall event. A similar rainfall-event on 09.01.2013 did not lead to any runoff simulation of TRAIN-ZIN or SWAT advanced.

The last discharge event at the end of January 2013 represents the smallest event and is characterized by its sharp runoff reaction and a long and pronounced recession. It can be seen, that TRAIN-ZIN correctly starts the runoff depiction when a specific rainfall amount is exceeded, but is not flexible enough to depict the high observed dynamic. Therefore, peak one and two are interpreted as one single runoff peak. While the second peak is overestimated, the simulation cannot represent the long-observed tailing. SWAT advanced can neither simulate the discharge peaks, nor the pronounced recession. Five runoff reactions can be seen, all of them strongly underestimate the observed hydrograph.

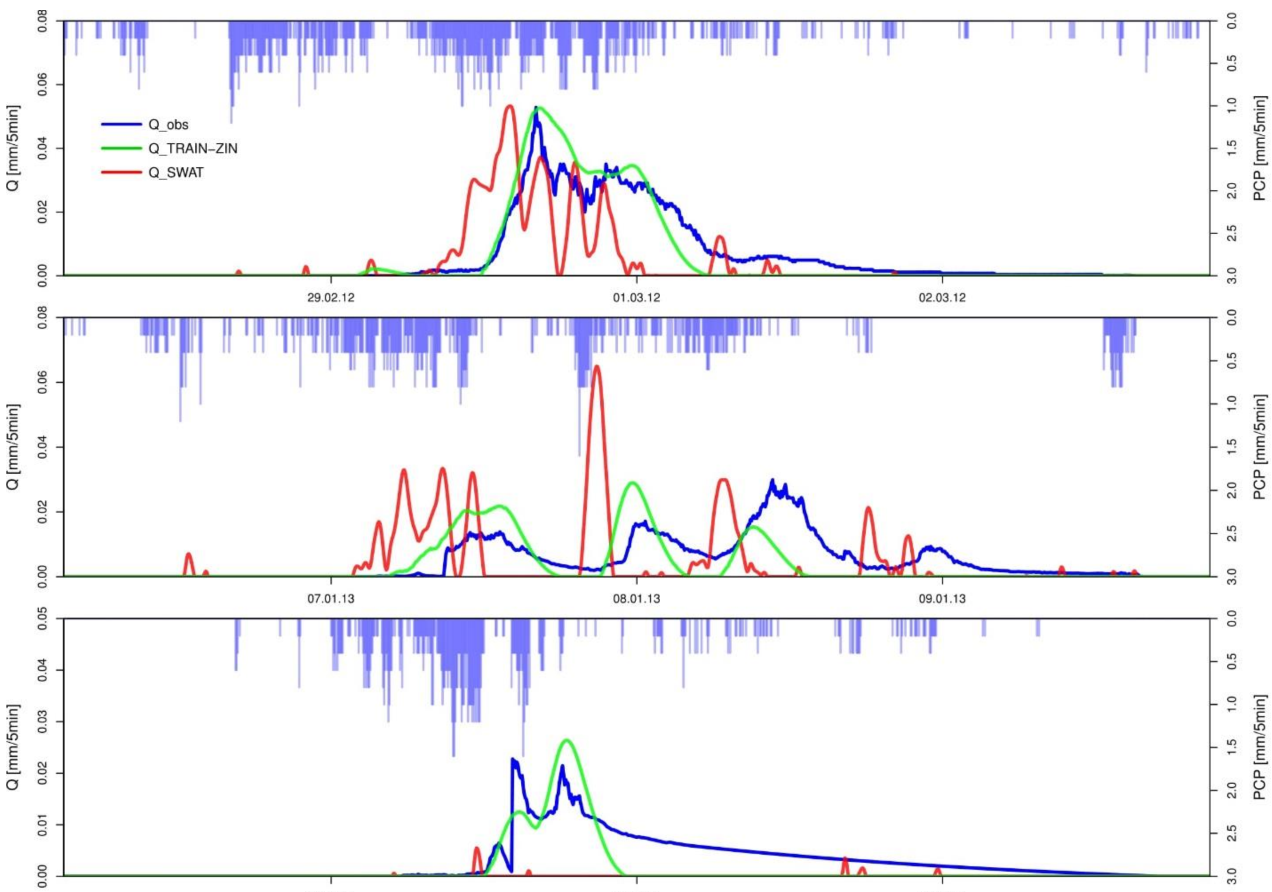


Figure 34: Event-dynamic comparison of TRAIN-ZIN and SWAT advanced. The graphs show the three discharge-events over the entire investigation period from 01.10.2010 to 30.09.2013 in a sub-daily time-step of 5-min for TRAIN-ZIN and SWAT advanced and a daily time-resolution for SWAT light. In addition to that, the observed discharge as well as the observed areal rainfall is illustrated.

3.4 Comparison of spatial discharge variation

The last two chapters considered the water balance and event-dynamics at the catchment outlet of Wadi Auja. To examine spatial differences in runoff generation, Figure 35 shows an overview of the reaction in the five given sub-catchments of Wadi Auja (designation of runoff gauges in Figure 9). All subbasins show at least three discharge events, which were also recorded at the catchment outlet. While all subbasins finally drain to the catchment outlet, subbasin A and B initially flow into subbasin C. In that respect, in subbasin C, the most and highest discharge events were observed.

TRAIN-ZIN is able to simulate almost every observed discharge peak, except the highest peak of subbasin C, which is completely neglected. It can be seen, that runoff at sub-catchment B and D is generally underestimated, while sub-catchment A and C, with exception of the highest peak, are well fitted. In contrast to that, SWAT advanced in general simulates too many discharge events, that overestimate the discharge amount in all subbasins, especially in subbasin B. For subbasin D, SWAT advanced does not simulate two of four discharge events are not simulated. Furthermore, the highest discharge events in subbasin C and D cannot be simulated by SWAT advanced. In addition to that, SWAT advanced simulated a runoff event in 2011, which is detected at the catchment outlet and was obviously generated in sub-catchment B.

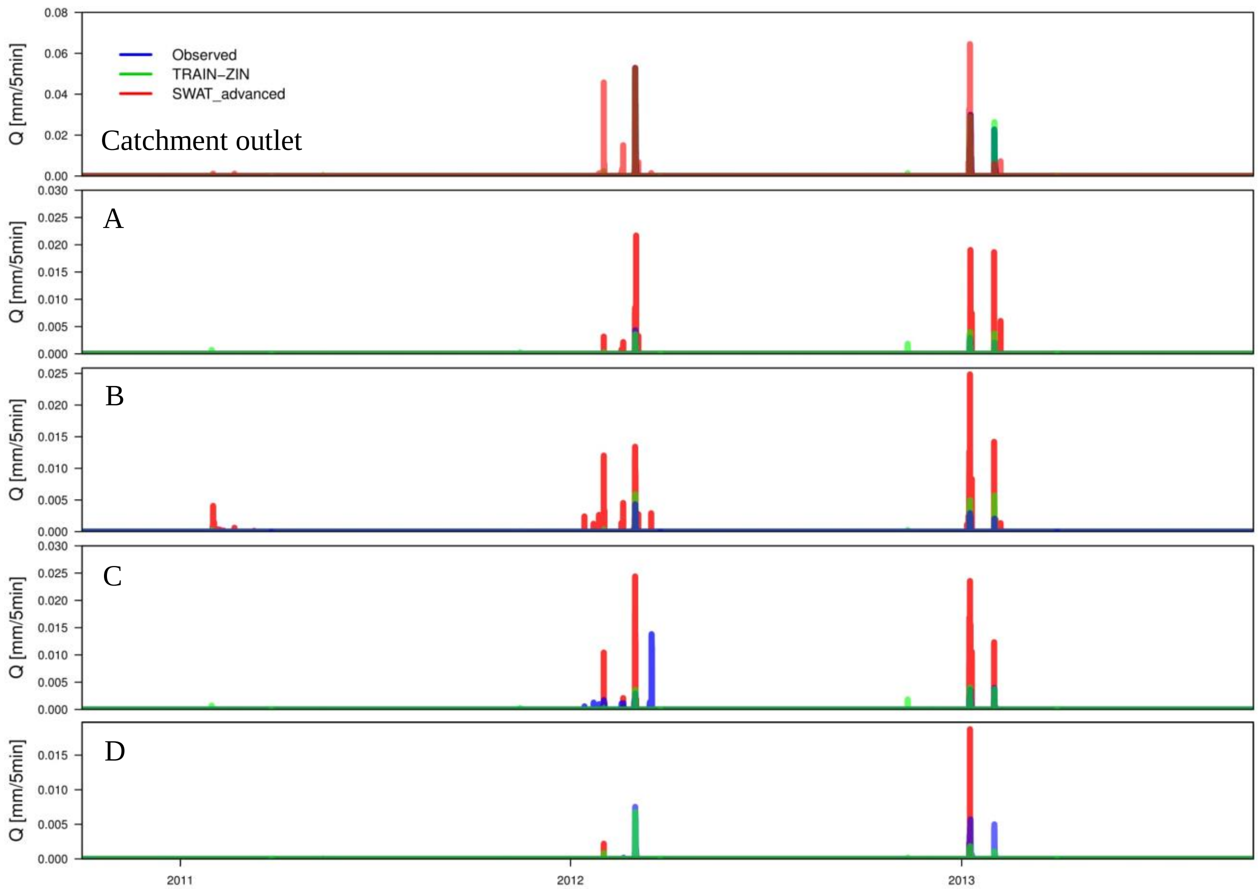


Figure 35: Hydrographs of all subbasins within the entire investigation period in a daily time-step. Designation of runoff gauges refer to Figure 9.

Figure 36 to Figure 38 illustrate the detailed comparison of the three major discharge events on the subbasin level. While TRAIN-ZIN can depict the first discharge event (Figure 36) at subbasins A, B and C, it is not able to represent the discharge behavior of the north-eastern subbasin D for which it strongly overestimates the runoff. In contrast to that, SWAT advanced simulates no discharge at all for subbasin D and overestimates the runoff of all other subbasins. In generally SWAT is too fluctuating and not continuous enough to simulate the observed runoff. In addition to that, SWAT advanced simulates an extreme peak discharge in subbasin A after the observed runoff event ended.

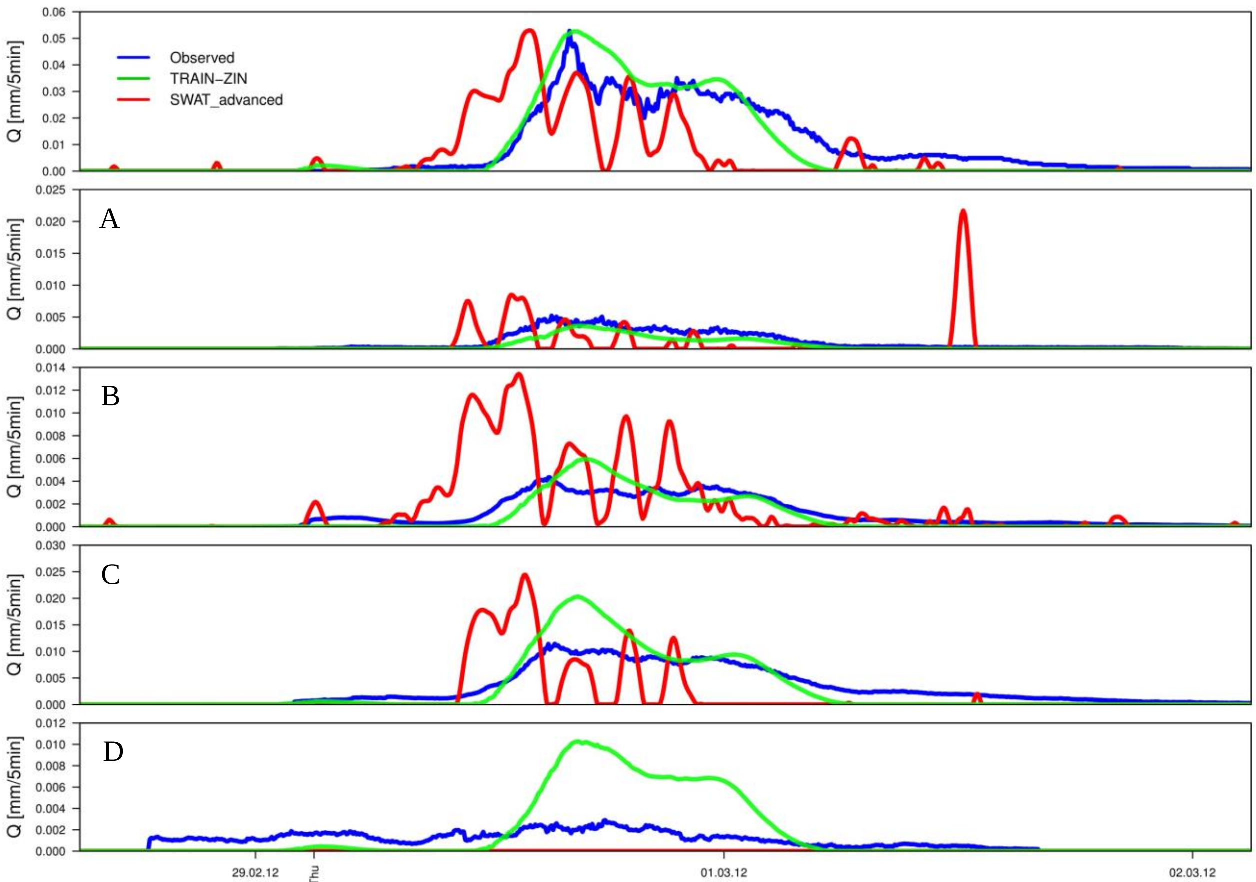


Figure 36: Detailed comparison of the first discharge event in February/March 2012, differentiated by subbasins

For TRAIN-ZIN a similar deviation from observed time-series was found for the second discharge event (Figure 37). Here, the first two runoff peaks of subbasin C are overestimated, while the rest of all other sub-catchment simulations show a good fit. Especially the timing in all subbasins seems to be good, while the third runoff peak at the catchment shows a divergent reaction. Like at the first discharge event, SWAT advanced cannot represent the discharge behavior of subbasin D. Similar difficulties exist for subbasin A, where one extreme value is dominating the discharge behavior. In addition to that, a runoff peak in subbasin A, B and C is simulated after a time-delay of almost one day. However, these peaks are not reaching the catchment outlet.

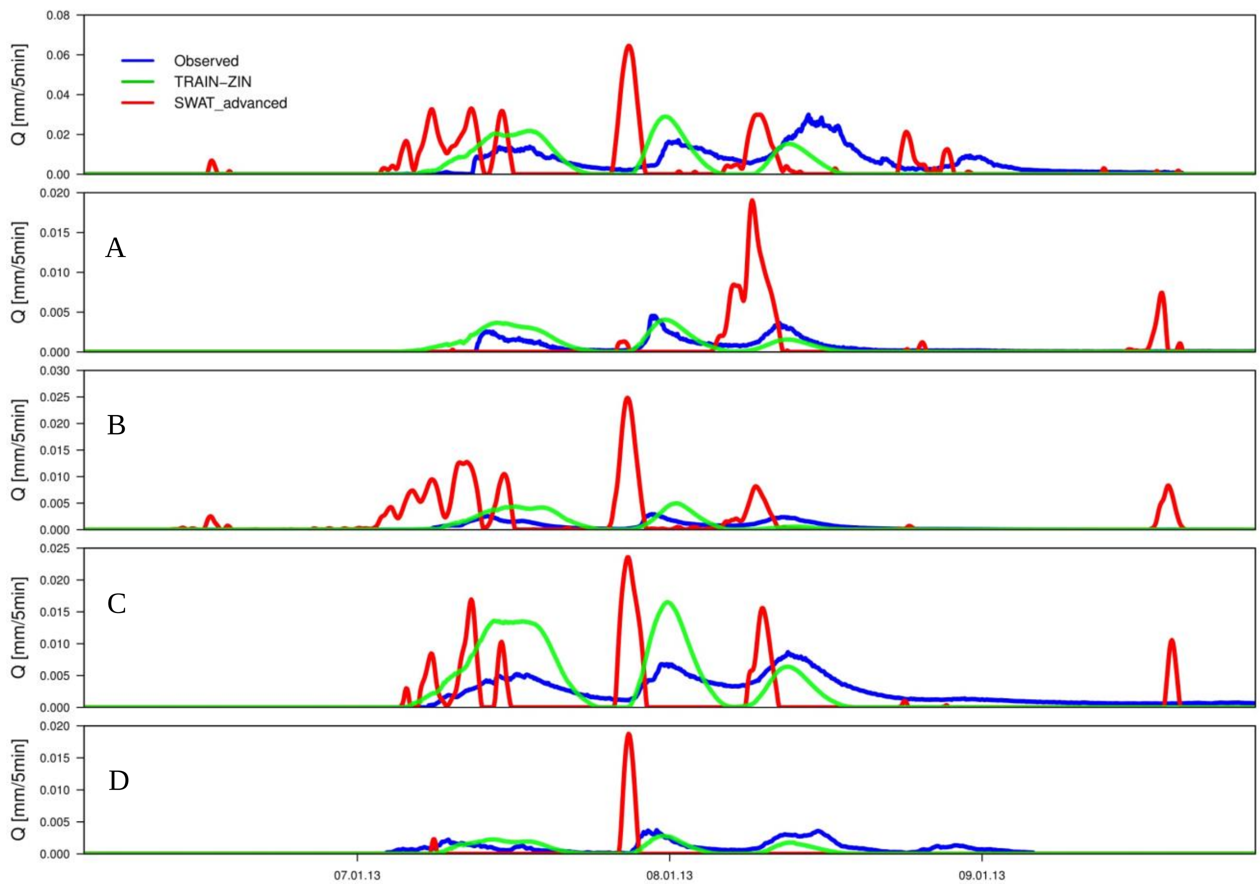


Figure 37: Detailed comparison of the second discharge event in January 2013, differentiated by subbasins.

The third discharge event (Figure 38) is characterized by a pronounced overestimated runoff peak of SWAT advanced at the beginning of the observed events in subbasin A, B and C. Like at the second discharge-event before, these pronounced runoff peaks are not transmitted to the catchment outlet. In addition to that, SWAT once again overestimates the discharge of subbasin A, B and C, while for sub-catchment D no runoff is simulated. In comparison to the simulation of SWAT, TRAIN-ZIN shows a similar behavior for all discharge-events before. For subbasin A, B and C the runoff is overestimated and only for subbasin D the simulation falls below the observed hydrograph.

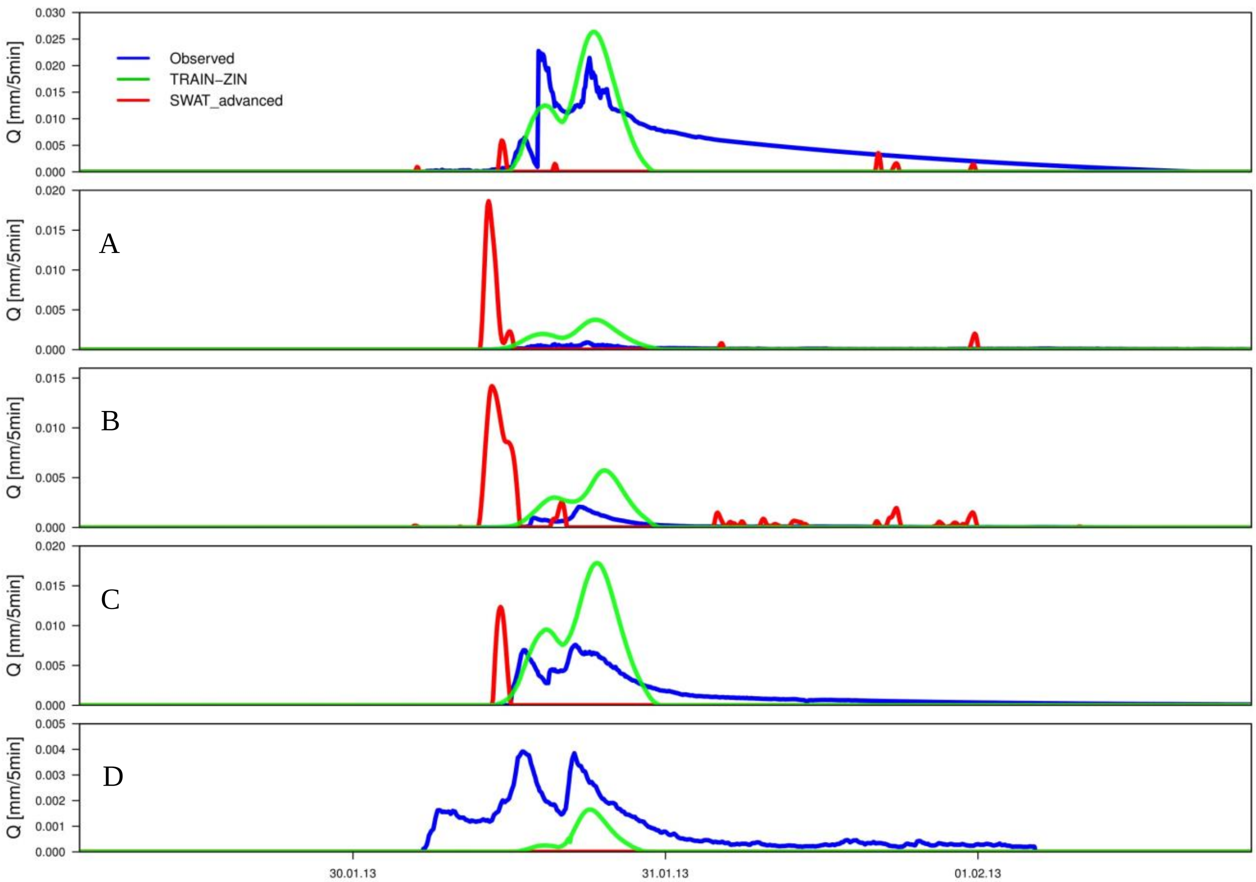


Figure 38: Detailed comparison of the third discharge event in January 2013, differentiated by subbasins.

4. Discussion

4.1 Model structure and philosophy

The configuration of SWAT advanced has revealed, that the Soil Water Assessment Tool is technically prepared to be set up in high temporal and spatial resolution like the event-based model TRAIN-ZIN. Even though, SWAT was initially developed for large catchment simulations over a long period of time (Arnold et al., 2012b). Having in mind, that Neitsch et al. (2009) described SWAT as a long-term yield model, which is not designed to simulate detailed, single-event flood routing, like taking place in Wadi Auja, the model comparison is based on two fundamentally different models. SWAT advanced is able to simulate the water balance and general discharge behavior of Wadi Auja, while it is not clear, if this is only the result of high temporal and spatial input resolution, the result of an improved SWAT data base or a combination of both.

Certainly, the available data material plays a major role for the success of model calibration and simulation. Especially in semi-arid areas of the eastern Mediterranean region, where usually low data quality and quantity hinders an accurate water resource management (Gunkel et al., 2015). In this context, it should be mentioned, that Wadi Auja provides an extraordinary dense measurement network in high time-resolution and of good data quality. Even though, Ries (2013) noted, that more detailed information about soil types, their spatial distribution and thickness are missing for a better calibration of the TRAIN-ZIN terrain types. The same applies for SWAT advanced, which allows the implementation of additional catchment specific information, especially regarding soil properties, land use and vegetation characteristics. In that respect, SWAT offers opportunities to describe the vegetation period, harvesting time, land management options like tillage, irrigation type or further soil information such as rock fragment and organic carbon content. It would be expected, that the model performance could be improved, if more measured field values of these additional catchment information were provided and implemented into SWAT. However, there remains a risk of over-parametrization and equifinality.

Even though the performance of SWAT advanced shows substantial enhancement in comparison to SWAT light, there are several possible improvements to realize. Although SWAT advanced uses the Green-Ampt method for infiltration and surface runoff processes in order to prevent the application of the Curve Number method, the curve number parameter CN2 is still an integral part of the Green-Ampt equation (Formula 2). Within the manual calibration process of SWAT advanced, a low influence of the CN2 parameter on the runoff simulation was observed. The SWAT model restricts the Curve Number parameter from 35 to 98 (Arnold et al., 2012a). For most HRU's in Wadi Auja, the lowest possible CN2 value of 35 was chosen for the SWAT advanced setup, while some HRU's would require even lower CN parameters, indicating low runoff potential (Appendix 6). This could imply, that SWAT has difficulties to simulate low runoff potentials of semi-arid areas like in Wadi Auja. The Curve Number method is appropriate for moist soil conditions and hill slopes of 5 % (Arnold et al., 2012a). According to the characterization of the catchment, soils are frequently dry and hill slopes can easily exceed 5 %. Shadeed and Almasri (2010) applied a GIS based CN method in the West Bank Palestine and determined a Curve Number of about 50 for the entire West Bank assuming dry conditions. This also indicates, that SWAT experiences difficulties in configurating a model for low runoff potentials, because the CN2 parameter is set to its bottom limit and is therefore also much lower than the cited value of 50.

In comparison to that, the routines of ZIN (model part of TRAIN-ZIN for horizontal fluxes, Figure 11) are specialized for arid regions and simulates saturated overland flow after the soil storage is filled. A further structural advantage of TRAIN-ZIN is the opportunity to select the Shuttleworth-Wallace method as an alternative to the Penman-Monteith equation for the calculation of evapotranspiration. Moreover TRAIN-ZIN provides a better and more detailed adjustment opportunity for channel segments. In contrast to SWAT, TRAIN-ZIN is able to differentiate between hydraulic conductivity of inner channel, floodplain and the underlying strata (Gunkel and Lange, 2016). This especially could improve the representation of transmission losses.

According to the model handling, SWAT has advantages due to its user-friendly interface of SWAT Editor and QSWAT. In comparison to that, TRAIN-ZIN is controlled by a usual text editor and the Microsoft DOS interface, which requires a certain experience. By contrast, the TRAIN-ZIN .exe do not require an installation, which facilitates the application. Apart from the model handling, TRAIN-ZIN provides a grid based output for all water balance components. In contrast to that, the SWAT output is restricted to HRU's and subbasins. Finally, it could be mentioned, that SWAT has a large and active user-community, which ensures a constant development of the model and provides a variety of support opportunities, manuals, papers and use cases.

4.2 Discussion of calibration procedure

The following subchapter discusses the findings and experiences made during the manual calibration process of SWAT advanced. Because TRAIN-ZIN was calibrated by Ries (2013) and SWAT light by an auto-calibration procedure, the focus lies on the SWAT advanced setup. During the manual calibration of SWAT advanced (Table 16), initial signs of equifinality were observed. The frequency of surface discharge events could be modeled by a thinner soil layer (SOL_Z) or a lower saturated hydraulic conductivity (SOL_K). Both adjustments led to similar discharge reactions. Keeping realistic soil depths from photos and soil samples in mind (Ries et al., 2015), the adjustment of SOL_Z was limited to + 60 %. To represent all runoff events (especially the third event), a disproportionately low SOL_K would have be necessary to adjusted. This would have led to a strong overestimation of the two first discharge peaks as well as to additional peaks over the entire investigation period. In order to find the best over-all-performance, which represents a realistic discharge behavior of ephemeral streams, focus was laid on a correct timing and number of runoff generation peaks. In this respect, the underrepresentation of the third runoff peak was accepted. Without measured reference values for SOL_K, this parameter was mainly used to adjust the discharge frequency of SWAT advanced. In comparison to SWAT light (Appendix 7), SOL_K of SWAT advanced (Appendix 6) and K_s of TRAIN-ZIN (Appendix 8) are lower by two orders of magnitude. In contrast to that, Ries et al. (2015) calculated the saturated hydraulic conductivity in Wadi Auja to 21 – 417 mm/hour. In that respect, all model set-ups had to adjust a disproportionate low saturated hydraulic conductivity to represent the observed discharge behavior, while having in mind, that model results were not equal in their goodness-of-fit. Further soil property values like bulk density, available water capacity and soil depth are in the same order of magnitude for all model variations. Because the calibration of SWAT advanced is based on the final calibration results of TRAIN-ZIN (Ries, 2013), it is however not unlikely to achieve similar parameter values.

Apart from the soil property characteristic, TRAIN-ZIN and SWAT advanced show major differences in physical channel properties like the hydraulic conductivity of the inner channel. TRAIN-ZIN is calibrated to a range of 60 – 130 mm/hour, while SWAT advanced only shows 16 – 20 mm/hour. Although infiltration rates of TRAIN-ZIN are 4 – 6 orders of magnitude higher, simulated transmission losses (1.05 mm/year) are 20 orders of magnitude lower than simulated by SWAT advanced (20.9 mm/year). In that respect, it should be remembered, that transmission losses were estimated to 0.8 – 1.7 mm/year, based on observed discharge values of five subbasins. This means that infiltration processes of TRAIN-ZIN and SWAT are differently implemented and interpreted by the respective model structure. Transmission losses are accurately represented by TRAIN-ZIN, while SWAT advanced shows weaknesses to simulate low infiltration rates. It is not expected, that a different infiltration area is the reason for differences in transmission losses, because the channel geometry of SWAT advanced was assumed from TRAIN-ZIN. However, the simulation of transmission losses has not been the focus of the manual calibration procedure of SWAT advanced. The question, which parameter range is more realistic cannot be answered conclusively, because measured reference values are missing. In comparison to the calibrated saturated hydraulic conductivity of soils (TRAIN-ZIN: 0.25 – 0.60 mm/hour and SWAT advanced: 0.20 – 0.48 mm/hour), the hydraulic conductivity of the inner channel of TRAIN-ZIN appears slightly too high. For a final evaluation of the channel routine and transmission losses respectively, further investigations of the channel network are required.

Furthermore, the manual calibration revealed, that SWAT advanced obviously differentiates between different runoff formation processes. This can be shown with the adjustment of soil depth (SOL_Z) and available soil water capacity (SOL_AWC), which both were much more sensitive for the second discharge-event, than for the first one. In addition to that, the third event was not simulated at all. This could suggest, that SWAT advanced has complications to represent specific hydrological processes in Wadi Auja, which are mainly dominated and controlled by saturated overland flow (SOF). Capillary rise, soil moisture, infiltration and percolation processes are expected to be differently implemented into the model structure of TRAIN-ZIN and SWAT.

In contrast to that, the auto-calibration of SWAT-CUP, was not able to reveal such insights into different hydrological processes and catchment reactions, because it is only based on statistical criteria instead of field knowledge. Especially for complex models like SWAT, with many possible parameter adjustments, it would be advisable to involve expert knowledge. Otherwise, SWAT-CUP can easily be overparameterized and run into equifinality. For unexperienced users the risk exists, to use a disproportionately high number of parameters in order to exactly calibrate the discharge behavior. In addition to that, SWAT light showed an unusual calibration development, because the NSE decreased from the first to the second iteration, before it increased again (Figure 30). A possible reason for this could be equifinality, because of the reduction from 18 rather to 8 input parameters after the first iteration. According to these results, it seemed to be easier for SWAT-CUP to fit the objective function with 18 than with 8 parameters. Apart from the fact, that the parameter selection of this present SWAT-CUP application is only based on statistical criteria (NSE) of runoff, insider knowledge about catchment characteristics and runoff generation processes are not implemented. SWAT light could be possibly improved, if the objective function of auto-calibration would be extended to evapotranspiration or soil moisture. SWAT-CUP is prepared for that. Further improvements could be realized, if the recommended parameter values of SWAT-CUP after each iteration would be multiplied by a specific factor (relative change) and not only replaced by a certain value (Table 19). Otherwise, the spatial distribution of specific catchment characteristic gets lost, because one unique value is assigned to every HRU.

Considering the hydrographs from the multi-criteria-analysis of SWAT advanced (Figure 29), it is hardly possible to identify the best model run only based on a graphical analysis. Therefore, the model with the best over-all-performance was selected considering the evapotranspiration, percolation and Nash-Sutcliffe-Efficiency of runoff. Having in mind, that SWAT advanced had a pronounced unadjustable runoff time-lag, the informative value of the NSE is questionable. This may be due to the lack of an implemented transfer function in SWAT since the generated surface runoff from each time step is directly entering the reach. To overcome this problem and get a more significant NSE, an attempt was made to manually eliminate the time-lag by a relative shift of simulated to observed time-series, but the analysis of the output file showed an inconsistent time-delay. In that respect, an alternative measure of quality, which considers the whole discharge pattern, would be better suited to evaluate and select the best model run. In this context, it cannot be ruled out, that one of the 2000 model runs of the SWAT advanced model optimization is slightly better than the selected run 1245. A further opportunity to improve the runoff concentration performance and time-lag of SWAT advanced and sub-daily SWAT simulations in general, could be the implementation of a measured transfer function or a synthetic unit hydrograph as used in TRAIN-ZIN (Gunkel and Lange, 2016). The direct comparison of runoff timing between TRAIN-ZIN and SWAT advanced revealed significant advantages of TRAIN-ZIN.

Considering the event-dynamic results of manual calibration (Figure 28) in comparison to the results of automated model optimization (Figure 34) of SWAT advanced, it must be stated, that the differences are not significant. While an automated model optimization is very time-consuming and data intensive, noticeable improvements through this process could not be achieved. This could suggest, that the expert knowledge calibration was well realized and fully developed, or that an inaccurate objective function and target parameter (here streamflow) was used.

4.3 Discussion of simulation results

The water balance comparison of Table 22 shows, that simulated annual evapotranspiration of all model variations are in equal dimensions and correspond to calculations and literature values of Gunkel et al. (2015), Hartmann et al. (2012), Comair et al. (2012) and Sheffer et al. (2010) (see criteria values of multi-criteria-analysis Table 18). In comparison to the calculated ET according to Gunkel et al. (2015) (70 % of annual precipitation), TRAIN-ZIN represents the best simulation. For an adequate evaluation of the simulated temporal dynamics of actual evapotranspiration, a reference time-series is missing (Figure 32). According to investigations in the Kingdom of Saudi Arabia, Sorman and Abdulrazzak (1995) determined a maximum actual evaporation for typical arid climates of up to 3.0 mm/day immediately after precipitation events. Lowest rates of bare soil evaporation of 0.1 - 0.2 mm/day were found during the dry season. Considering these findings, ET peak values of SWAT light (max. 4.5 mm/day) are estimated too high, especially considering arid conditions of Saudi Arabia, in contrast to a semi-arid climate in Wadi Auja. Considering the findings of Ryu et al. (2008), evapotranspiration of SWAT light is not only too high during rainy season (peak values), but also during dry season, where evapotranspiration is water limited. The reason for that, is a strong soil water retention and high soil moisture conditions of SWAT light, which governs evapotranspiration during dry periods. This can be shown in the water balance comparison (Figure 32). Soil parameters like available water capacity (SOL_AWC), bulk density (SOL_BD) and even soil thickness (SOL_Z) are in equal dimension as SWAT advanced, which clarifies, that the differences are probably based on the input data (soil map) and used model equations (Curve Number) (Appendix 6 and Appendix 7). In contrast to that, simulations of TRAIN-ZIN and SWAT advanced do not exceed the maximum value of 3.0 mm/day (Sorman and Abdulrazzak, 1995) and show a plausible annual distribution. To sum up the relative comparison of simulated evapotranspiration, all model variations showed differences in seasonality, tailing and maximum values, which are most probably the result of different calculation methods. According to the final parameter values of SWAT advanced, the influence of different available water capacities is low but not excluded (Table 17). TRAIN-ZIN uses the Shuttleworth-Wallace method, while the Penman-Montheith equation is implemented in SWAT. The Penman-Montheith equation is developed for transpiration processes of closed uniform vegetation covers, while the Shuttleworth-Wallace method is focused on sparsely vegetated areas and soil evaporation (Hagenlocher and Gunkel, 2017). Due to the specific surface cover characterization of Wadi Auja (see chapter 1.2), the Shuttleworth-Wallace method represents the catchment conditions better. In addition to that, Gunkel and Lange (2016) mentioned, that the Shuttleworth-Wallace method is generally favorable in drier climates. Therefore, it is assumed that simulations based on the Shuttleworth-Wallace method are more suitable for the catchment Wadi Auja. While SWAT has not implemented the Shuttleworth-Wallace method, it provides the opportunity to import calculated daily potential evapotranspiration values. Thus, SWAT users are able to use any recommended calculation method for the specific needs of the respective watershed (Neitsch et al., 2009).

According to Gunkel et al. (2015), annual percolation rates in Wadi Auja are estimated to be 119 mm/year (30 % of annual precipitation). All model variations underestimate this annual percolation amount, while keeping in mind, that water balance components in Wadi Auja are quite variable from year to year (Ries, 2016). This consistent underestimation of percolation is stressed by the results of a chloride mass balance investigation by Schmidt et al. (2013), where the long-term mean recharge fraction in Wadi Auja was estimated between 25 % and 50 % of annual precipitation. According to these estimations, SWAT light represents the worst and SWAT advanced the best simulation of annual percolation amounts. In contrast to annual percolation rates, no reference values for timing, initial thresholds or maximum percolation rates are available. Therefore, the percolation dynamic cannot be finally evaluated and compared. Moreover, it should be remembered, that the dimension of the recharge area is uncertain and percolation processes are still focus of current research (Ries et al., 2015; Schmidt, 2014). In that respect, there is a need for further investigations of recharge processes to enhance parameterization of both TRAIN-ZIN and SWAT.

The consideration of soil moisture simulations explained, that the soil water routine is the main controlling factor of surface runoff for all model variations (Figure 32). Because SWAT light is missing specific information about deep aquifer percolation (RCHRG_DP), too much water is remaining in soil, which finally led to a fast soil saturation and high potentials of saturated overland flow. This illustrates the high simulated runoff potential of SWAT light. Furthermore, missing information on baseflow fraction (ALPHA_BF) and interflow, increases the inflow into the reach and led to a continuous discharge behavior. In contrast to that, TRAIN-ZIN and SWAT advanced can represent single discharge-events and show similar soil moisture thresholds (~180 mm) for runoff initialization. Although SWAT advanced simulates the highest soil moisture content at the third observed discharge-event, no runoff is generated. In contrast to that, SWAT advanced simulates two extra runoff-events at a lower soil moisture content. This indicates problems to represent the dominant runoff processes of saturated overland flow.

Besides the acquired knowledge from the soil moisture simulation, the consideration of the event-dynamic showed, that the simulated runoff of SWAT advanced reacts fast and sharp, while the simulated flow stops several times during a single observed discharge-event (Figure 34). This is an unexpected discharge behavior, because the soil moisture simulation represents realistic values in comparison to SM-1 and SM-2 and would enable saturated overland flow (Figure 32). This confirms the recognitions of the water balance comparison, that SWAT has visible disadvantages to represent saturated overland flow.

Apart from the discharge behavior at the catchment outlet, SWAT advanced had visible difficulties to represent the discharge in subbasin D (northeastern corner). Similar problems of TRAIN-ZIN could not be noted. This could be explained by the fact, that for TRAIN-ZIN and SWAT advanced, different catchment characteristics are relevant for runoff generation. Further investigations in sub-catchment D and implementation in SWAT could improve the model performance. Finally, all models are only as good as their input data. Therefore, measurement uncertainties especially of discharge in ephemeral streams should be consider within the entire model comparison.

5. Conclusion

According to the central research issue of this present thesis, it can be concluded, that the Soil Water Assessment Tool (SWAT) can be configurated in a sub-hourly time-resolution of 5-min and is suitable to quantify the water balance of Wadi Auja under semi-arid conditions. Therefore, SWAT advanced could be used for the management of available water resources in the West Bank Palestine. In that respect, the manual customization of the internal SWAT data base by real measurement field data, the usage of the Green-Ampt method as well as the extension of the model structure to a sub-hourly runoff resolution improved the simulation significantly and was determined as a fundamental requirement. This confirmed the comparison with a typical SWAT application on default settings (SWAT light).

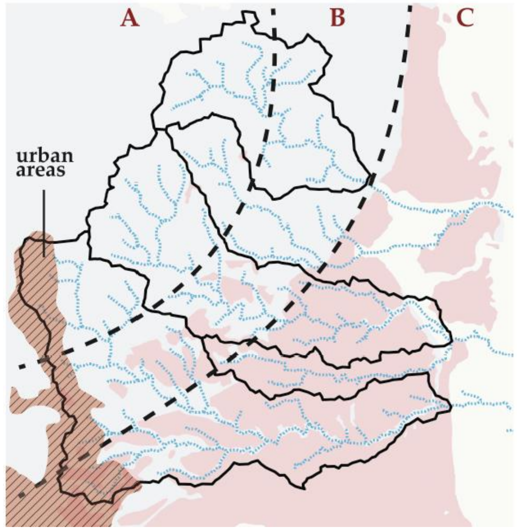
In contrast to that, SWAT advanced showed deficiencies to simulate hydrological small-scale processes in a sufficient temporal and spatial resolution. This showed the analysis of single discharge-dynamics. This thesis revealed weaknesses of SWAT to simulate saturated overland flow processes (SOF). In general, the discharge simulation of SWAT advanced cannot represent all observed discharge-events, is highly fluctuating and shows a pronounced time-lag. Therefore, SWAT on its current state of development is not the first choice for scientific investigations of specific hydrological runoff generation processes. Even the highest parametrization effort of SWAT advanced cannot finally compensate the missing structural requirements of a long-term yield model, which is not developed and specialized for semi-arid regions.

However, it can be concluded, that a profound expert knowledge calibration based on real field measurement data from the study area (SWAT advanced), cannot be replaced by an automated calibration process based on default settings (SWAT light). This was illustrated by the comparison of SWAT light with SWAT advanced. SWAT light strongly overestimates the annual discharge rate and is neither able to simulate a correct discharge timing, nor a realistic duration. In this respect, SWAT light is unsuitable for the simulation of ephemeral streams in semi-arid regions. Thus, it is not advisable to use a comparable SWAT light setting for the applied water resource management in regions like Wadi Auja. To improve SWAT light and investigate strengths and weaknesses of the SWAT-CUP auto calibration, the model could be configurated by the same advanced input data as SWAT advanced and compared only due to their different calibration methods.

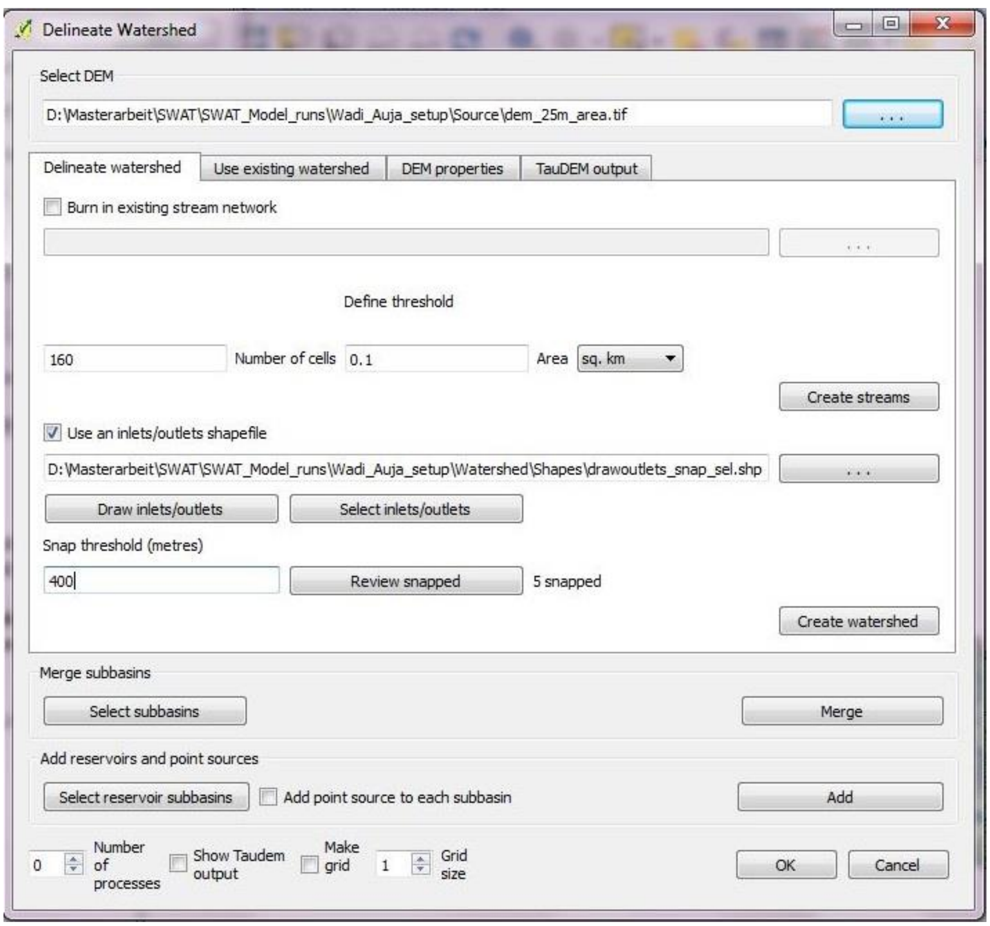
Finally, TRAIN-ZIN has demonstrated its strength to simulate the high dynamic of ephemeral streams and precisely represent the water balance under semi-arid conditions. Regarding the simulation of single short-term discharge-events, TRAIN-ZIN showed clear benefits in runoff timing, behavior and magnitude in contrast to SWAT. TRAIN-ZIN has proven its strengths to exactly depict hydrological small-scale processes in semi-arid regions and therefore is ideally suited for scientific investigations on hydrological processes as well as for the applied water resource management. This model comparison has finally revealed, that specialized hydrological models like TRAIN-ZIN are necessary to satisfy specific hydrological requirements in semi-arid regions.

Appendices

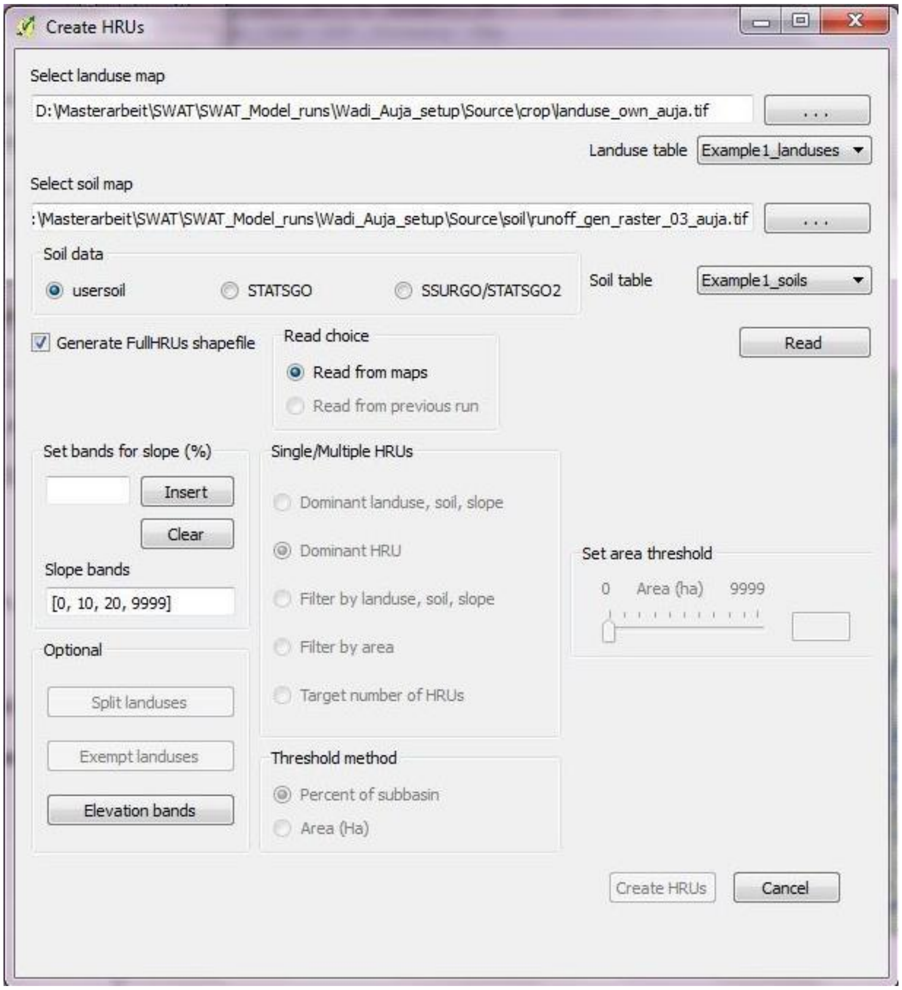
Appendix 1: Schematic illustration of sections with similar catchment characteristics due to Ries (2016). The top catchment represents Wadi Auja, which consists of section A and B respectively upstream and downstream.



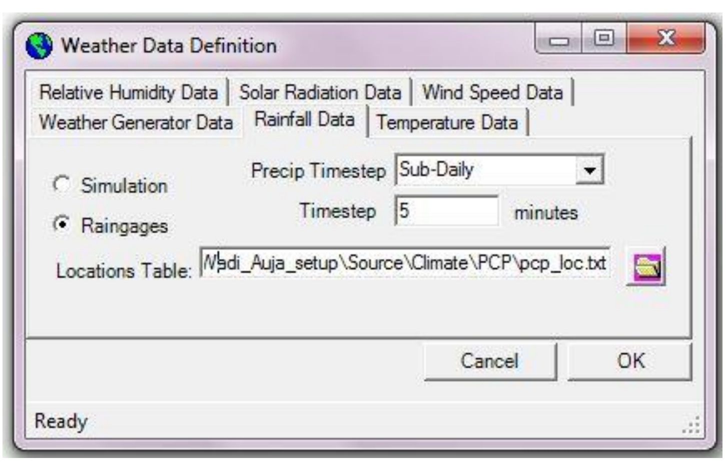
Appendix 2: Delineate Watershed. The first step of SWAT configuration within the QSWAT interface.



Appendix 3: Create HRUs. The second step of SWAT configuration within the QSWAT interface



Appendix 4: Weather Data Definition of Precipitation. The selected table is the location table “loc.txt” in the SOURCE/CLIMATE/PCP Folder.



Appendix 5: Final parameter set of manual expert knowledge calibration.

Parameter	unit	value
ESCO	-	0.01
CH_K1	mm/h	15
CH_K2	mm/h	15
SOL_K	mm/h	0.21 – 0.51
SOL_Z	mm	330 - 2100
SOL_AWC	mm H_20/mm soil	0.3 – 0.4
SOL_BD	g/cm³	1.20 – 1.35
CN2	-	35

Appendix 6: Best parameter set of SWAT advanced run 1245, analyzed by a multi-criteria-analysis.

Parameter	unit	value
ESCO	-	0.16
CH_K1	mm/h	19.7
CH_K2	mm/h	16.3
SOL_K	mm/h	0.20 – 0.48
SOL_Z	mm	335 - 2136
SOL_AWC	mm H_20/mm soil	0.22 – 0.30
SOL_BD	g/cm³	0.97 – 1.10
CN2	-	35 - 40

Appendix 7: Best parameter set after fourth SWAT-CUP iterations. The fitted value is representing the best parameter value, whining the parameter range of min and max value.

Parameter	unit	value
CN2	-	42.7
SOL_Z	mm	820 - 1025
SOL_K	mm/h	28.3
SOL_AWC	mm H_20/mm soil	0.70
ALPHA_BF	1/day	0.49
SOL_BD	g/cm³	0.32
CH_K2	mm/h	190.5
CH_W2	m	2.58
CH_N2	-	0.27

Appendix 8: Final parameter values of Terrain Types within the TRAIN-ZIN calibration process (Ries, 2013).

ID	Terrain Type	K_m [mm/h]	I_l [mm]	S_d [m]	Φ [-]	Φ_{pwp} [-]	K_s [mm/h]	λ [-]	Φ_{fc} [-]	ϱ [g/cm³]
1	Alluvial soils	48	10	1.40	0.52	0.25	0.60	0.5	0.32	1.35
2	Olive terraces	25	7	0.70	0.52	0.25	0.60	0.5	0.32	1.30
3	Urban areas	14	8	0.30	0.52	0.25	0.34	0.5	0.32	1.30
4	Shrubland	16	4	0.28	0.51	0.22	0.39	0.5	0.28	1.20
5	Shrubland > 75% soil	22	6	0.32	0.51	0.22	0.39	0.5	0.28	1.30
6	Shrubland > 50% stone	14	2	0.22	0.51	0.22	0.28	0.5	0.28	1.20
7	Bare soil	12	2	0.24	0.50	0.17	0.25	0.5	0.25	1.20

K_m: Maximum infiltration rate [mm/h]

I_l: Initial storage losses [mm]

S_d: Soil depth [m]

Φ: Total porosity [-]

K_s: Saturated hydraulic conductivity (mm/h]

λ: Van Genuchten parameter [-]

Φ_{fc}: Porosity at field capacity [-]

ϱ: Bulk density [g/cm²]

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Eidesstattliche Erklärung

Hiermit versichere Ich (Phillip Grimm, Matr.-Nr: 4147926), die vorliegende Masterarbeit ohne Hilfe Dritter nur mit den angegebenen Quellen und Hilfsmitteln selbstständig angefertigt zu haben. Alle Stellen, die aus den Quellen entnommen wurden, sind als solche kenntlich gemacht worden. Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

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Declaration

Herewith I (Phillip Grimm, Matr.-Nr: 4147926) declare that this thesis is my own work and is done without the help of any third person and only supported by sources and materials that are duly acknowledged and indicated. This thesis has never been submitted in an equal or similar version to any other examination board.

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