An-Najah University Journal for Research – A
Natural Sciences

Development of channel transmission loss function for WRF_HYDRO modeling of semi-arid regions: The case of wadi Faria, Palestine

Received 25/2/2021, Accepted 24/1/2023, DOI: https://doi.org/10.xxxx
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Abstract: In arid and semi-arid regions, the quantitative understanding of the processes of runoff generation and prediction of the streamflow hydrographs and their transmission to the catchment outlet are among the most basic challenges of hydrology. To address these challenges, hydrological modeling has been used to gain understanding of the hydrological systems and to provide the required inputs needed for sustainable water resources management. Furthermore, coupling hydrological models with climatic models provides even more understanding of the influence of the climatic parameters on hydrological processes and systems, and hence on runoff generation mechanism. In this research, WRF-Hydro (the Weather Research Forecasting model coupled with the Distributed Hydrologic Modeling System) was used for streamflow forecasting in the Faria catchment. Faria (320 km2), located in the northeastern part of the West Bank, Palestine, is a gauged catchment where rainfall and streamflow data are available for more than ten years. This study aims to assess the functionality of the WRF-Hydro to predict reliable streamflow hydrographs at the upper part of the catchment. Additionally, a new channel loss function was incorporated into WRF-Hydro to model the amount of water lost in the ephemeral (loosing) streams of the catchment. Hence, the rainfall and streamflow data for the rainy season; 2017-2018.were utilized. Results indicate that WRF-Hydo model is well functioning, but model calibration and validation is still required to further improve the model performance.

Keywords: WRF-Hydro; Channel Loss; Hydrological Modeling; Faria Catchment; Palestine.

Introduction

Highly variable precipitation events (spatially and temporally) are common in arid and semi-arid regions (Foody, Ghoneim, and Arnell 2004; Givati et al. 2012). This high variability often results in extreme rainfall events that may result in damaging flash floods, or prolonged periods of droughts that threaten the sustainability of water resources (Santos and Fragoso 2013). To be able to mitigate the adverse impacts of these extreme events, a quantitative understanding of the processes generating these events should be achieved, and hence comes the role of hydrological models (Mandal, Barrett, and Smith 2013).

The hydrological models are mathematical simulations of the partitioning of water among the various components of the hydrological cycle and the catchment characteristics to better understand the behavior of catchments and to assess the impacts of various changes (e.g. land use change and climate change) within them (Dooge 1992; Savadamuthu 2004; Shadeed 2008). Nevertheless, these models require reliable data on key hydrological process which are often lacking in arid and semi-arid regions (Foody et al. 2004).

WRF-Hydro is a modeling system in which the Weather Research and Forecasting (WRF) model and the National Center for Atmospheric Research (NCAR) Distributed Hydrologic Modeling System (NDHMS) are coupled (Arnault et al. 2016; Gochis et al. 2013). In this modeling system, as explained in Section four, runoff-infiltration partitioning is calculated by accounting for subsurface lateral flow, overland and streamflow routing, subsurface routing. However, WRF-Hydro does not account for channel loss. This component is important, especially in arid and semi-arid regions, which are characterized by ephemeral Wadis.

The main objective of this research is to model rainfall-runoff in a semi-arid gauged Faria catchment using WRF-Hydro modeling system. The modeling system is updated by integrating a channel loss function into its source code.

Study Area

The Faria catchment (**Figure 1**) is located in the northeastern part of the West Bank, Palestine and extends to the Jordan River. It is characterized as arid to semi-arid region with an area of 320 km^2 (Shadeed 2008; Shadeed and Lange 2010; Shadeed, Shaheen, and Jayyousi 2007). Topographic relief of Faria changes significantly throughout the catchment. In less than 30 km, there is a 1.3 km change in ground surface elevation. The winter rainy season is from October to April and the rainfall distribution within the catchment ranges from 660 mm at the headwater (in Nablus) to 150 mm at the outlet (in the vicinity of the Jordan River) (Shadeed 2008). The mean annual temperature varies between 18^o C at the uper parts of the catchment to 24^o C in the lower parts (Shadeed 2013).Whereas, the potential annual evapotranspiration ranges from 1400 mm in Nablus to about 1540 mm in the lower parts of the catchment (Shadeed 2013). In this research we focus on the upper northwest part (Al-Badan Catchment) since it is the only part with runoff measurements.

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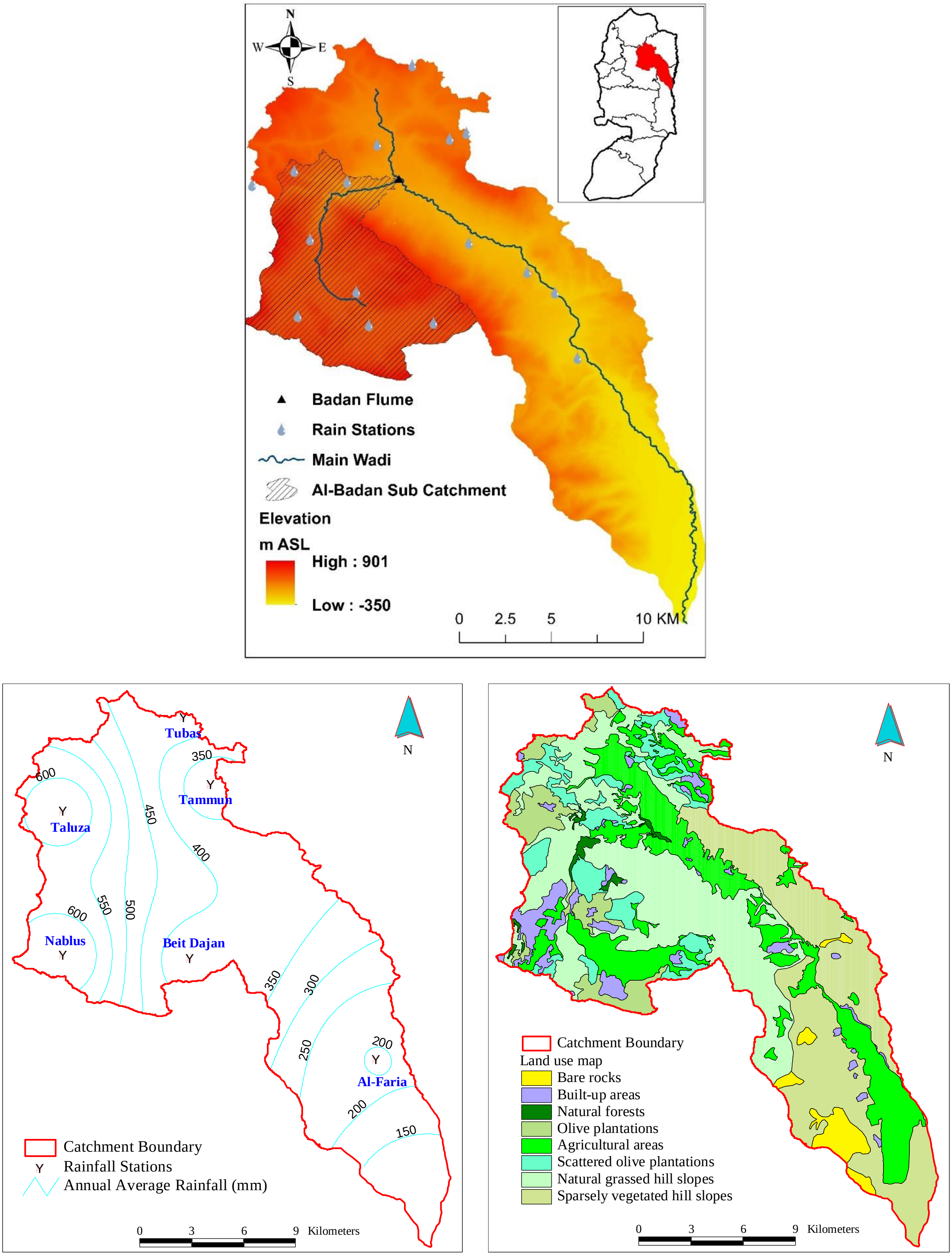

Figure (1): Top: Location and topography of the Faria Catchment, Al-Badan sub catchment, Badan Flume, rain stations, and main wadi. Bottom left: Location of historical rain station and rainfall distribution. Bottom right: Land use map of Faria catchment.

Available Rainfall and Runoff Data

Enhance flood forecasting in the West Bank, Palestine is one of the main IMAP project (Integrated Microwave Link Data for Analysis of Precipitation in Complex Terrain: Theoretical Aspects and Hydrometeorological Applications) objectives. As part of the Project, 48 Tipping Bucket Raingauges (TBRs) were installed in 16 different locations (3 at each location) in the Faria catchment and for two rainy seasons: 2016-2017 and 2017-2018. The distribution of the TBRs in the both seasons is shown in **Figure 1** (rain stations). For the purpose of this research, the model was run using the data for the rainy season 2017-2018, since the streamflow data were available for this season.

Regarding streamflow, the data was available for the rainy season through a streamflow gauges (diver) located at the outlet of Al-Badan sub-catchment, 84 km^2 (**Figure 1**). The location of the diver was selected for logistical reasons such as the availability of a flume and accessibility to the site. **Figure 2** shows the streamflow hydrographs from the diver for the rainy season (2017-2018).

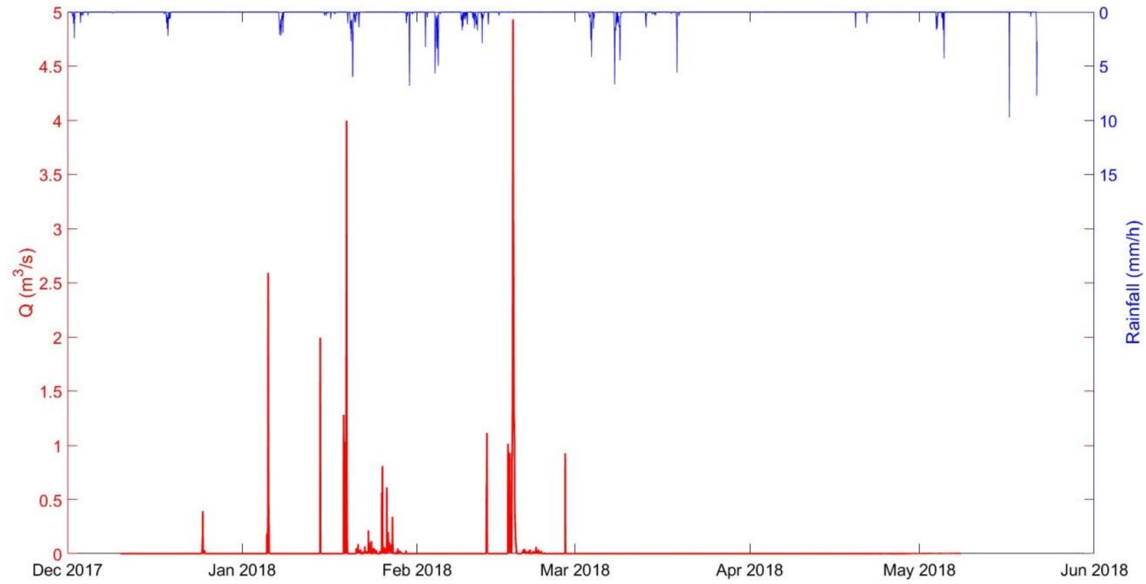

Figure (2): Stream flow hydrograph and IDW-averaged rainfall hyetograph for Al-Badan sub-catchment for the rainy season 2017-2018.

Model Structure and the Added Channel Loss Function

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system(Gochis et al. 2013). The WRF-Hydro is a coupling architecture that is designed to simplify the coupling of terrestrial hydrological models with the WRF model. The main modules include the Land Surface Model (LSM), sub-surface routing routines, overland flow routing routines, channel routing routines, lake/reservoir routing module, and a conceptual catchment model routine. For the LSM, Noah and NoahMP are the only supported LSMs within WRF-Hydro (**Figure 3**).

Subsurface lateral flow in WRF-Hydro is calculated prior to the routing of overland flow to allow exfiltration from fully saturated grid cells to be added to the infiltration excess calculated from the LSM. WRF-Hydro specifies the water table depth according the depth of the top of the saturated soil layer that is nearest to the surface. It is affected by topography, saturated soil depth, and depth-varying saturated hydraulic conductivity values. In WRF-Hydro, typically, a minimum of four soil layers are used in a 2-meter soil column. WRF-Hydro specifies the water table depth as the depth of top saturated soil layer that is nearest to the surface.

For the overland flow routing in WRF-Hydro, the fully unsteady, spatially explicit, diffusive wave formulation is assumed for the used routing model, which is the CASC2D one developed by Julien, Saghafian and Ogden (1995) and then modified by Ogden (1997). The overland flow in this model is calculated when the depth of water on any grid cell of the model exceeds a specific retention depth. The stream channel flow processes, lakes and reservoirs, and stream baseflow have also been represented through additional modules. The inflow into the stream network and lake and reservoir objects in WRF-Hydro v3.0 is a one-way process only. This means that the overland flow that reaches a grid cell identified as 'channel' grid cell passes a portion of surface water in excess of the local ponded water retention depth to the channel model. The overland flow module in WRF-Hydro can be implemented in either 1-dimensional (steepest descent or 'D8') or 2-dimensional (x and y dimensions) methods. In some complex surfaces, the 2-dimensional method provides more accurate depiction of the water movement than the 1-dimentional method. Although, the 2-dimentional method is more time consuming.

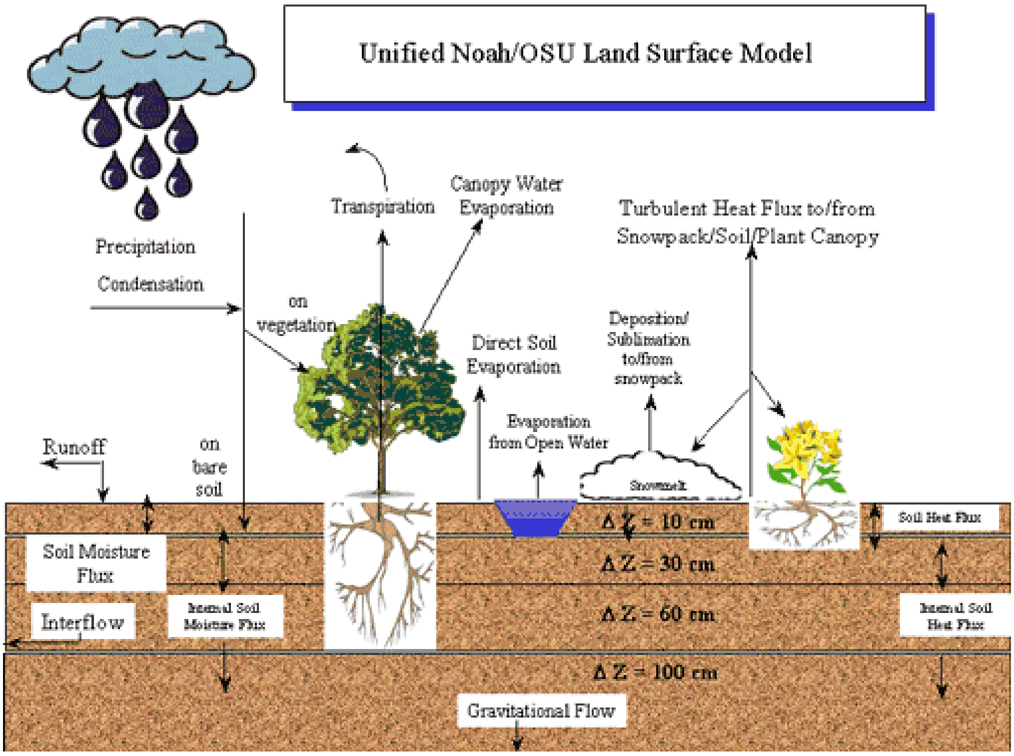

Figure (3): Noah Land Surface Model.

As discussed earlier, WRF-Hydro does not account for channel transmission loss. These losses can be significant in arid and semi-arid regions, where the majority of the streams are ephemeral streams. Transmission loss can be defined as abstractions of water volume along the flow path in the channel bed (Leistert 2005; Shadeed 2008). This "lost" is usually absorbed in the dry alluvial fills of the channel beds (Sorman and Abdulrazzak 1993). It either percolates through the unsaturated zone and recharges the underlying aquifer, or evaporates back into the atmosphere (Shadeed 2008).

Among the factors that transmission loss depends on are the flooded area and the section geometry. Gunkel and Lange (2016) suggested that the potentially flooded area is divided into three sections (**Figure 4**): i) the inner channel; ii) the bars and banks with a steep incline; and iii) the floodplains.

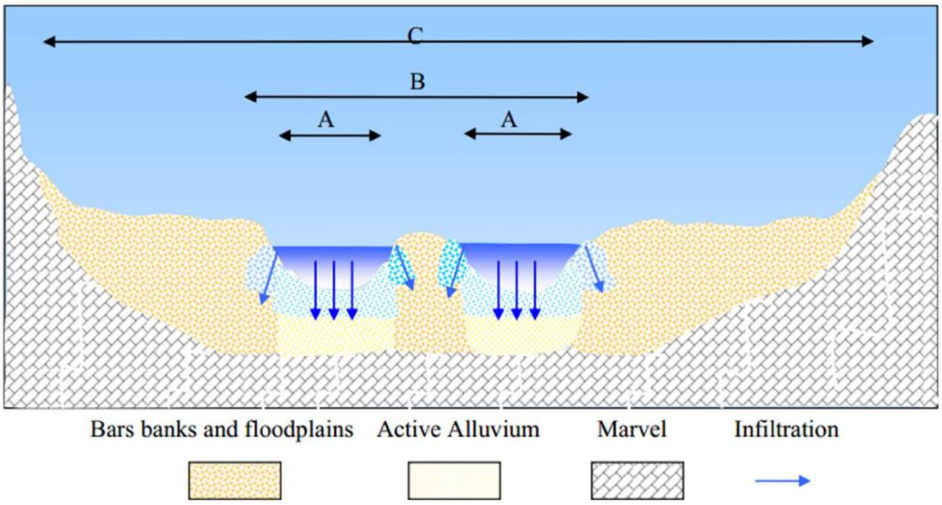

Figure (4): A cross sectional channel geometry in a perennial stream in a semi-arid region; A: inner channel area; B: banks and bars, and C: floodplain areas (Gunkel and Lange 2016).

In this research, we propose the following equation to account for the channel transmission loss:

$$T_L = b_v \times L \times \left(K_b - K_f\right) \times e^{-\sqrt{\frac{\theta}{\theta_m}}} \quad (1)$$

where,

L: channel length

K_b: infiltration constant (bars, banks and floodplains) in (mm/hr)

K_f: final infiltration rate (hydraulic conductivity of the underlying strata) in (mm/hr)

θ: soil moisture

θ_m: maximum (saturated) soil moisture

b_v: variable channel width. It has three cases:

If the water depth in the channel is greater than the full depth of the channel bottom (section C in **Figure 4**), then:

$$b_v = b_w \quad (2)$$

where,

b_w: the physical channel width

If the water depth in the channel is inside the inner channel (the, section A in **Figure 4**), then:

$$b_v = b_w \times v + b_w \times v \times H^x \tag{3}$$

where,

v: the percentage of the inner channel width from the total channel width

H: the water depth in the channel

x: tuning parameter for inclination of bars and banks

If the water depth in the channel is less than the full depth of the channel and outside the inner channel bottom (section B in **Figure 4**), then:

$$b_v = \left(\frac{H-f_b}{f_a}\right)^{\frac{1}{f_d}} \tag{4}$$

$$f_a = \frac{b_w - 0.1^{\frac{1}{x}}}{{b_w}^{f_d} \times (1 - 1.1 \times v^{f_d})}$$

$$f_b = b_w - f_a \times {b_w}^{f_d}$$

where,

f_d: tuning parameter for inclination of flood plains

Model Build up and Preliminary Results

The offline (standalone) WRF has been built for the Faria catchment. After the domain of the model had been selected for the study area, the other input data for the domain including the land surface model grid, the terrain routing grid, and the meteorological forcing data were prepared and entered to the model.

For the simulations, observed streamflows are available at only one location in the upper part of the catchment at Al-Badan sub-catchment outlet (see **Figure 1**). Model functionality has been tested on two different rainstorm events during the rainy season 2017-2018. The results from simulations during these events are illustrated in **Figure 5**. As shown in the figure, and by eyes inspection, good matching between the observed and simulated runoff were noticed for both events. Moreover, the obtained result of continuous simulation for the entire rainy season (see **Figure 6**) was poor. This intensified the dire need to calibrate the model input parameters. Once the model calibrated, it will be validated for a different rainy season.

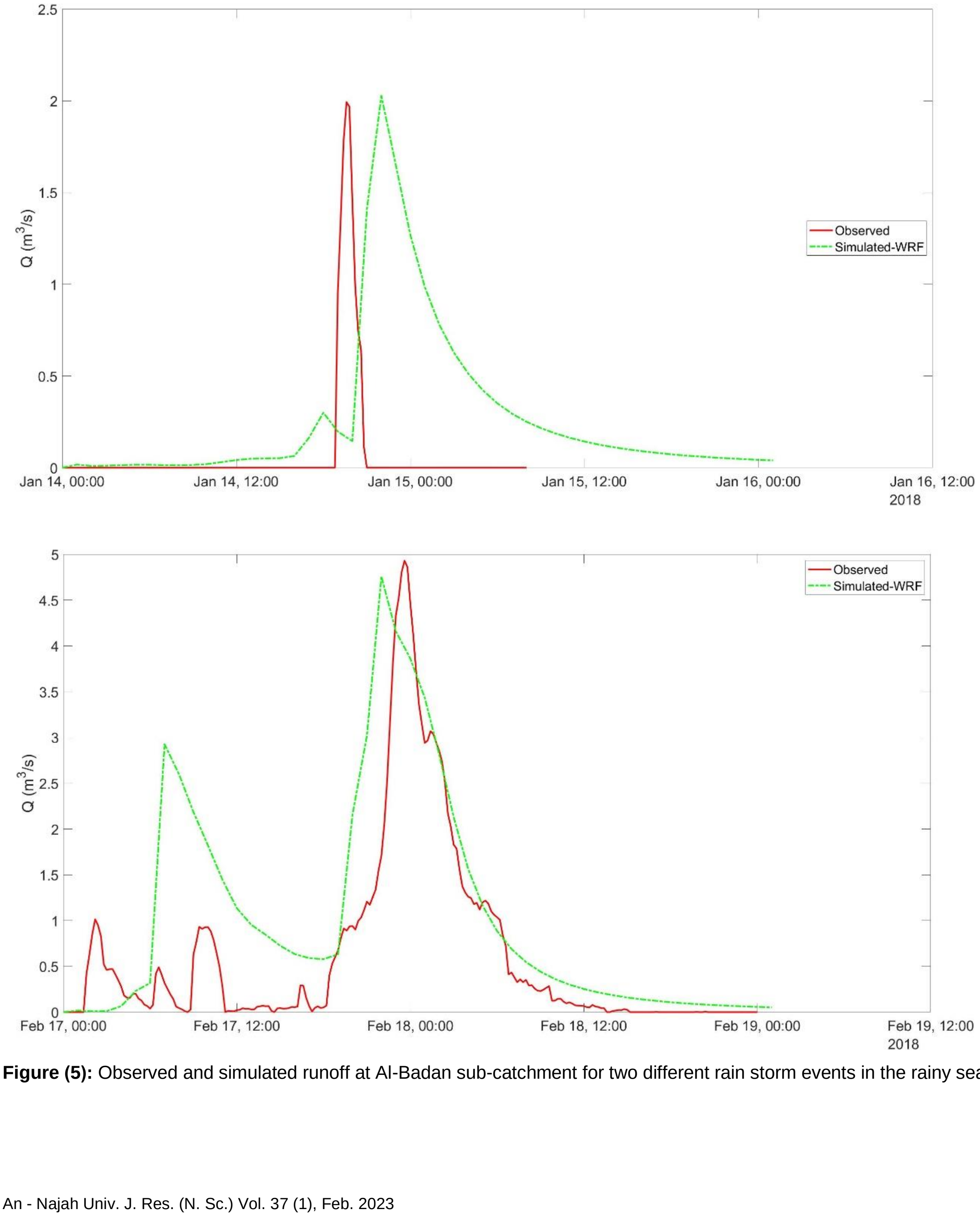

Figure (5): Observed and simulated runoff at Al-Badan sub-catchment for two different rain storm events in the rainy season 2017-2018.

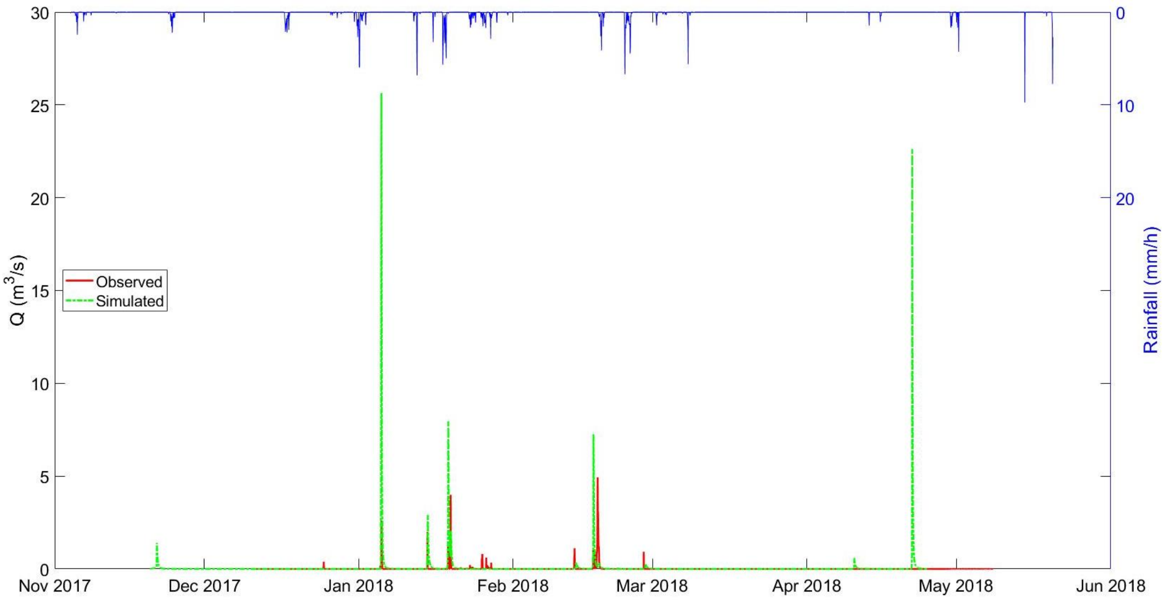

Figure (6): Observed and simulated runoff at Al-Badan sub-catchment for the rainy season 2017-2018.

Conclusions

Due to the high variability of rainfall events in the Faria catchment (semi-arid), hydrological modeling is necessary to quantitatively understand and manage the runoff resulted from these events. To achieve this, WRF-Hydro modeling system was used to model rainfall-runoff in this catchment. Usually, the streams in a semi-arid catchment like Faria are ephemeral (loosing). Moreover, since WRF-Hydro does not account for the water lost while transmitting in these streams, a channel loss function was added to the source code of the system. The results of the model simulations show good matching between the observed and the simulated streamflow data. However, more work is needed to calibrate and validate the model.

Acknowledgements

The authors are thankful to the German Research Foundation (DFG) for providing the fund for this research as part of the IMAP project. The IMAP project is a research project funded by the DFG (German Research Foundation) and implemented in the Faria catchment jointly by An-Najah National University (Palestine) and Karlsruhe Institute of Technology (Germany). We are also grateful to Thomas Rummler from Karlsruhe Institute of Technology and Moamar Ishtayyeh from An-Najah National University for providing technical help on WRFHydro.

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