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Assessing the Effects of Climate Change and Land Use on the Runoff Generation: Case Study Zomar Watershed

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Assessing the Effects of Climate Change and Land Use on the Runoff Generation: Case Study Zomar Watershed

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Thesis Approval

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Dedication

To those who have been my support and strength throughout my academic journey,

To those who planted in me the love of knowledge and raised me on diligence and perseverance
to my beloved father and my dear mother.
To those closest to my heart
My precious sisters and my dear brother.
To those who stood by me in times of exhaustion and shared the joy of my success, my cherished family and friends.
To my esteemed professors, who have always been a source of inspiration and knowledge.
I dedicate this thesis to all of you.

Rawan Ziad Ahmad Khader

Declaration

I certify that this thesis submitted for the degree of Master in Water Resources Engineering is the result of my own research, except where otherwise acknowledged, and that this thesis (or any part of the same) has not be submitted for a higher degree to any other university or institution.

Rawan Ziad Ahmad Khader

Signature:

Date: 27/5/2025

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First, thanks to the great God who helped me accomplish this thesis.

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Abstract

Surface runoff constitutes a critical component of the hydrological cycle, influenced by climate variability, land use changes, and topographical characteristics. In arid and semi-arid regions such as the West Bank, understanding the complex interplay between climate change and land use changes on runoff generation is important for implementing sustainable water resource management strategies and mitigating flood risks. The effects of climate change directly influence surface runoff through variations in temperature, evaporation, and the intensity, frequency, and distribution of precipitation. Additionally, urbanization and changes in land use result in a rise in impervious surfaces, which contributes to an increase in surface runoff and heightens the risk of flash floods. This study aims to assess the effect of climate change and land use transformations on surface runoff generation within the Zomar watershed, especially as it is situated between Nablus and Tulkarm cities, which are considered among the most densely populated cities. Given the urban expansion and the increasing frequency and intensity of extreme rainfall events in the region, this comprehensive analysis quantifies these impacts and proposes evidence-based water management strategies.

The research developed a hydrological model using the Watershed Modeling System (WMS) integrated with the Hydrologic Modeling System (HEC-HMS). The Zomar watershed was divided into three sub-catchments: Nablus, Tulkarm, and Burqa. To build the model, the study used a wide range of data, including daily rainfall records from 2000 to 2023, high-resolution land use maps generated from aerial imagery, and detailed information about soil and topography. The model was calibrated and validated using rainfall-runoff data that were observed during 2005–2006. For simulating infiltration, the Deficit and Constant method was applied, while the Clark Unit Hydrograph method was used to model the runoff process accurately.

The findings demonstrate that the effects of climate change and land use changes have substantially increased runoff generation patterns throughout the Zomar watershed. Quantitative analysis showed that urbanization increased impervious surface coverage by 6.27% in the Nablus subcatchment, 5.03% in the Tulkarm subcatchment, and 1.94% in the Burqa subcatchment between 2000 and 2023, consequently reducing infiltration capacity and amplifying surface runoff volumes. The total surface runoff volume over 23 years is 12.5 MCM, with a surface runoff coefficient of 13.2%. The hydrological modeling established that rainfall intensity distribution patterns have a greater effect on runoff generation than cumulative seasonal precipitation. This was illustrated in the 2013-2014 season, in which rainfall was concentrated on specific days with high intensity, which produced significantly elevated runoff coefficients and peak discharges compared to seasons with comparable or greater total rainfall but more temporally distributed precipitation patterns. Spatial analysis revealed pronounced heterogeneity among the sub-catchments, with the Nablus sub-catchment generating the highest average runoff coefficient (20.6%) due to urban expansion, compared to Tulkarm (14.5%) and Burqa (5.72%).

The study indicates that future urban expansion will increase surface runoff, heightening flood risks. This research conclusively establishes that the cumulative impact of climate change and land use changes significantly increases the risk of surface runoff and flash flooding within the Zomar watershed. The findings emphasize the urgent necessity for implementing integrated watershed management approaches, encompassing sustainable urban development policies, strategic enhancement of green infrastructure networks, and innovative water harvesting

initiatives. These strategies are essential not only for effective flood risk reduction but also for optimizing water resource utilization in alignment with the United Nations Sustainable Development Goals (SDGs), particularly those addressing water security, climate resilience, and sustainable communities in vulnerable regions.

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List of Abbreviations

DEM: Digital Elevation Model

GeoMolg: Geoportal for Geospatial Information in Palestine

HEC-HMS: Hydrologic Modeling System

PMD: Palestinian Meteorological Department

SDGs: Sustainable Development Goals

WMS: Watershed Modeling System

Chapter One

1. Introduction

Surface runoff is a crucial component of the hydrological cycle and is influenced by weather conditions, geology, slopes, topography, land use and land cover, climate change, and human activities. Studying the changes in the surface runoff is crucial to plan and manage water resources (Zhang, H. et al., 2020). Many studies have demonstrated that variation in runoff is a result of a combination of climate change and human activities (Wang et al., 2019; Xue et al., 2021).

Climate change has gained massive interest recently due to its huge impact on water resources, where this impact appears in all water cycle stages (Chen et al., 2022). Hydrological variables influenced by climate change, such as precipitation, temperature, evapotranspiration, radiation intensity, wind speed, and soil moisture content, directly affect the runoff process (Zhang et al., 2020). Rising temperatures lead to an increase in potential evapotranspiration and changes in the intensity and frequency of rainfall, which have a huge influence on regional hydrological processes (Xue et al., 2021; Zheng et al., 2009). Moreover, climate change has a role that cannot be denied in sudden floods and droughts all over the world (Sharafati & Pezeshki, 2020; Xiao et al., 2018). On the other hand, urban expansion and changes in land use affect the intensity and the patterns of rainfall. These changes alter the hydrological response of watersheds, reduce the land's capacity to absorb rainwater, increase peak flow rates, and elevate the risk of flooding (Asmar et al., 2021).

In arid and semi-arid regions like the West Bank, water harvesting is considered one of the most important potential water resources. The spatial and temporal distribution of rainfall quantities in the arid and semi-arid regions is characterized by extreme contrast, where these areas are prone to floods, especially since they usually witness heavy rainfall in a short time, leading to flash floods. These floods often dissipate without benefit, which makes the availability of fresh water in these areas a pressing issue. Additionally, floods can endanger people's lives and property (Rezaei et al., 2019) by sweeping away everything in their path, including plants and streets, resulting in significant damage to civilization and humanity. In the West Bank, there are 33 surface water watersheds, with an estimated total runoff of approximately 165 million cubic meters per year (MCM/yr): 123 MCM/yr flows westward toward the Mediterranean Sea, 22 MCM/yr to the Jordan River, and 20 MCM/yr to the Dead Sea. However, the amount of runoff actually utilized by Palestinians is only around 4 MCM/yr, largely due to the restrictions imposed by the occupation (PCBS & PWA, 2025).

The Zomar watershed is one of the most important watersheds on the West Bank (Asmar et al., 2021).The Zomar watershed's importance came from its location in the northwest of the West Bank between two main cities (Nablus and Tulkarm) and the continuous urban expansion in

these areas. In addition, the hypotheses and the study models confirm the presence of climate change effects across Palestine, particularly in the central and northern regions. This gives importance to studying the impact of the climate and land use on generating the surface runoff and to providing recommendations and solutions to reduce the hazards resulting from the runoff.
The Zomer watershed has been the focus of several studies that examine surface runoff during specific seasons and events, where a comprehensive study was conducted as part of the MERC project (Tal et al., 2007) during the rainy season of 2005-2006. A hydrological model was developed to estimate the amounts of surface runoff in the watershed.
The MERC project (Tal et al., 2007) has shown that surface runoff varies due to the pattern of rainfall and that the distribution of land use plays a major role in determining the amount of surface runoff. For instance, in densely urban areas like the western part of Nablus, it significantly contributes to generating surface runoff, while in areas like Deir Sharif, where tree farming, especially olive trees, is widespread, terraces are used as an effective means to reduce runoff speed and increase water infiltration into the soil.
Another report by the (Tulkarem Municipality, 2013) indicated that the watershed shows significant variation in surface runoff response during heavy rainstorm events, such as the January 2013 storm. This storm underscores the importance of rainfall characteristics such as intensity and frequency, as well as land use, in runoff generation. The effectis particularly pronounced in the Tulkarm sub-catchment, where runoff rates rise due to the spread of plastic greenhouses and urban development, despite nearly half of the area being covered by orchards.
The season 2012–2013 as a case study for extreme climate changes:
The report (Tulkarem Municipality, 2013) highlighted that the season of 2012–2013 experienced exceptional climatic conditions, as the intensity of rainfall increased compared to previous seasons, especially during the rainstorm between January 4–10, 2013, when the average rainfall exceeded 100 mm per day. Hydrological models developed to simulate the impact of this event showed that the amount of surface runoff generated by this storm alone reached approximately 6.7 million cubic meters in the Zomar Watershed. This huge quantity of water in a short period caused severe damage to infrastructure and residential areas.
This study aims to analyze climatic data for the Zomar watersheds and land use changes from 2000 to 2023. Additionally, it aims to develop a hydraulic model using both the Watershed Modeling System (WMS) and the Hydrologic Modeling System (HEC-HMS). This modeling will estimate surface runoff and assess the impacts of climate change (specifically, rainfall patterns) and land use changes (urbanization) on surface runoff generation. Furthermore, the study intends to provide recommendations for enhancing the efficiency of water resource utilization, mitigating flood risks, and improving water infrastructure. These recommendations will align with Sustainable Development Goals (SDGs) 6, 12, and 13 (United Nations, 2015), which focus on sustainable water and sanitation management, responsible consumption, and climate action.

1.2. Problem Statement

Wadi Zomar is one of the main wadis in the West Bank and has witnessed several flooding incidents due to the intense rainfall. These floods have led to the closing of main streets that link cities and, in some cases, loss of life. While many studies discussed the rainfall events in this area, they were limited in focusing on isolated events during specific years and did not cover multiple periods. Therefore, this study is crucial for filling this gap. The study seeks to develop a hydrological model to estimate the amount of generated surface water and assess whether these floods are primarily driven by climate change, urban expansion, or a combination of both.

1.3. Research questions

1- What are the hydrological factors affecting the water flow regime at the Zomar watershed?
2- What are the expected impacts of climate change and land use change (urbanization) on runoff?

1.4. Aims and Objectives

The research aims to develop a hydrological model to estimate the runoff generated at the Zomar watershed as a function of climate change and land use .
Objectives:

1. Analyze and evaluate the climatic conditions, determine the number of extreme events during the years 2000 to 2023, and calculate the generated surface runoff in the Zomar watershed during these years.
2. Analyze the hydrological dynamics of the Zomar watershed and the generated storm water using modeling tools, such as the Watershed Modeling System (WMS) and the Hydrologic Modeling System (HEC-HMS).
3. Evaluate the impact of land use on the generated surface runoff and the hydrological processes.

1.5. Outline of the Thesis

The overall research study was divided into five chapters:
Chapter one: introduction and problem statement, aim, and objective Chapter two presents the literature review related to the study and evaluates the effects of both climate change and land use change on surface runoff generation. In addition, previous studies and research with similar objectives have been reviewed, many of which utilized the HEC-HMS model. Chapter Three outlines the research methodology, including data collection techniques and model setup. Chapter four provides a detailed analysis of results. Finally, chapter five concludes the findings of this study and presents recommendations for future research and practical applications.

Chapter Two

2. Literature Review

2.1. Introduction

This chapter reviews the literature on how climate change and land use changes affect surface runoff. It emphasizes the individual and combined effects of these two factors, specifically focusing on applying the HEC-HMS model.

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2.2. Impact of Climate Change on Surface Runoff

Climate change significantly affects runoff through changes in rainfall patterns, temperature, evaporation rates, and transpiration. Several studies highlight rainfall as the most important factor affecting runoff. Climate change plays an important role in the hydrological cycle, as high temperatures lead to higher evaporation rates, which finally affect runoff generation (Rezaei et al., 2019). There is disagreement regarding whether temperature or rainfall changes have a greater impact. For example, a study argue that changes in rainfall have a huge and important impact on surface runoff, more than temperature changes (Rezaei et al., 2019). Other studies argued that increased rainfall and temperature tend to have opposite effects on surface runoff; greater rainfall tends to increase runoff, whereas higher temperatures reduce it (Hasan et al., 2018). Supporting the importance of rainfall, Kiprotich et al. (2021) mentioned that the primary climate factor that increases runoff is rainfall, emphasizing that extreme rainfall events significantly contribute to runoff fluctuations. Which confirms the important role of rainfall patterns.

Hasan et al. (2018) also mentioned that runoff responses are more pronounced under drought conditions, further highlighting the major effect of precipitation patterns.

2.3. Land Use Changes and Their Effect on Runoff

The changes in land use lead to massive effects on surface runoff, where it is possible to increase or decrease the amount of water that flows to the surface after the rainfall. Urban expansion is recognized as one of the most significant land cover changes influencing surface runoff. The construction of roads and buildings leads to an increase in impervious area, which decreases the ability of water absorption and increases surface runoff (Asmar et al., 2021).

Urbanization usually results in a larger runoff volume, higher peak drainage, faster concentration time, and less infiltration into the soil. Urban density also affects the amount of surface runoff, as shown in Figure 2.1. The higher the density of built-up areas, the greater the amount of surface runoff. Conversely, areas with relatively scattered buildings allow for denser tree canopies, which help retain more water in the soil, consequently producing less surface runoff (Astuti et al., 2019).

In addition to urbanization, agricultural expansion, especially in semi-arid areas and in Mediterranean areas, contributes to soil compaction and reduced infiltration rates. According to a study by Rodrigo-Comino et al. (2018), intensive agricultural practices can increase runoff, especially in areas where agricultural land has replaced natural vegetation. On the other hand, another study explained that the decline in agriculture is one of the reasons for the increase in runoff, which is perhaps because the decline in agriculture leads to a decline in water consumption and evaporation rates. Conversely, increasing cultivation deepens plant roots, which boosts evaporation and helps reduce runoff (Shahid et al., 2020).

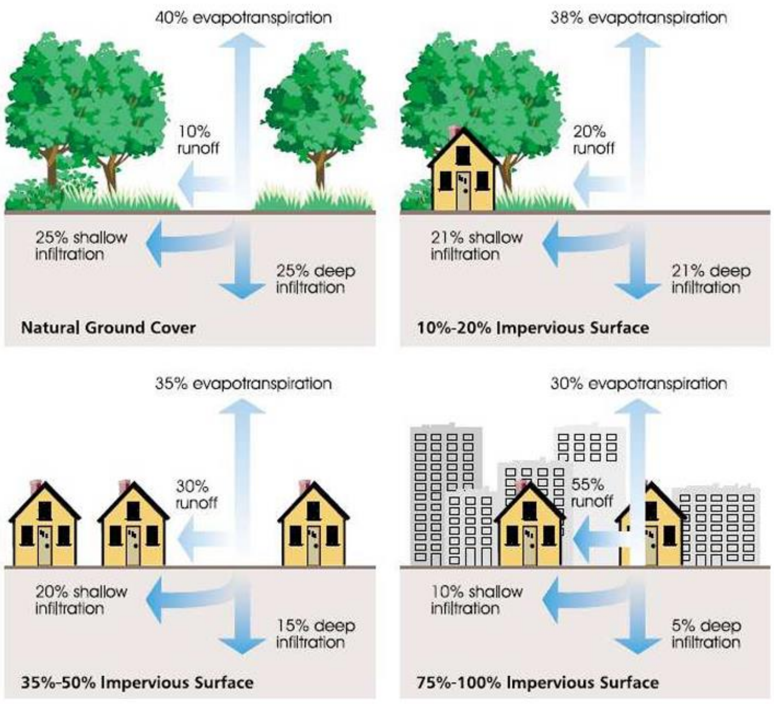


Figure 2.1: Runoff variability with increased impervious surfaces (F.I.S.R.W. Group, 1998)

2.4. Combined Effect of Climate Change and Land Use on Surface Runoff

The combination of land-use changes and climate change exacerbates the impact on surface runoff. In a study, they argued that separating the impact of climate change and land-use change on runoff generation is difficult. The study concluded that while human activities contribute to climate change, climate change also affects land use and land cover. Ultimately, these changes affect the generation of surface runoff.

As Rezaei et al. (2019) discussed in their research, the combination of climate change and land-use changes (such as urbanization and conversion to agricultural land) has significantly intensified the process of surface runoff generation in urban areas.

Analysis of combined and isolated effects of land-use and land-cover changes and climate change on surface runoff demonstrated the hydrological impacts resulting from climate change are more significant compared to the effects of land-use changes on runoff (Mekonnen et al., 2018). Rezaei et al. (2019) agreed that the impact of climate change has a greater impact than other factors, leading to more pronounced surface runoff generation. On the other hand, other studies presented a comprehensive evaluation of the effects of climate change and land use and land cover change variables on runoff and sediment discharge. It showed that land-use change has a more significant effect on surface runoff than climate change (Zeng et al., 2020).

Gulshad et al. (2024) explained in their study that land use/land cover (LULC) changes and climate changes significantly affect runoff, requiring their integration into land use planning and flood risk management. In their study, remote sensing techniques were utilized to analyze both historical and projected changes in Gdańsk City, Poland. In addition, hydrological models such as HEC-HMS were applied to assess the impact of these changes on the local hydrology, focusing particularly on the vital Orunia catchment. The results showed a substantial expansion of urban areas at the expense of vegetation and agricultural lands, leading to a noticeable increase in the runoff coefficient. Furthermore, the studies confirmed that the combined effect of climate change and LULC changes is stronger than the effect of each factor individually.

2.5. Other factors affecting surface runoff

Yang, Long, & Bai (2019) discussed that the primary factor affecting runoff is precipitation, although land use may have a minor impact on reducing annual runoff levels. Furthermore, the study indicates that topography plays a role in runoff generation to some extent.

Studies have generally proven that the volume and speed of surface runoff increase with the increase of impervious surfaces (Rezaei et al., 2019). Furthermore, the slopes and soft surfaces work to produce flow more quickly and reduce infiltration. Other studies discussed the impact of slope gradient on surface runoff. They conclude that as the slope gradient increases from 5% to 25%, runoff also increases because of reduced infiltration time and higher water flow velocity. However, when the slope exceeds the 25% threshold, the runoff gradually decreases. This is because extremely steep slopes are often rocky, and the soil tends to be irregular, which slows down water or traps it leading to more infiltration in some cases (Jourgholami et al., 2021). Another study showed that slope inclination has an immediate effect on the depth of surface runoff by preventing rainwater from infiltrating from the soil surface into the deeper soil layers (Asmar et al., 2021).

2.6. Runoff Modeling

Many researchers use the HEC-HMS hydrological model to represent flow by simulating rainfall and surface runoff processes. HEC-HMS is a hydrological modeling software developed by the U.S. Army Corps of Engineers at the Hydrologic Engineering Center (HEC), which includes an integrated tool for simulating rainfall-runoff processes. This model consists of several components that simulate precipitation losses and surface runoff. HEC-HMS has been widely used in numerous hydrological studies due to its simplicity (Halwatura & Najim, 2013). In this regard, the study by Hamdan, Almuktar, & Scholz (2021) used the HEC-HMS model to determine runoff by simulating rainfall and runoff processes in the Al-Adhaim Mountains catchments in Iraq. Climatic models were developed using daily rainfall data from 2015 to 2018, which provided the input parameters for the HEC-HMS simulations. The study aimed to assess the increasing water demand in Iraq and to predict potential water storage challenges arising primarily from climate change. Using the HEC-HMS model, it showed that 29.40% of rainfall converts to surface runoff while 70.60% infiltrates into the soil. The model was calibrated for two years and validated for one year, demonstrating a high level of accuracy between observed and simulated flows with an agreement rate of 90%. These results highlight the importance of hydrological simulation, and the results confirm the accuracy of the model in simulating runoff.
A study by Ben Khélifa & Mosbahi (2022) aims to develop a hydrological model using HEC-HMS to simulate the relationship between rainfall and runoff to estimate peak flood discharge and reproduce hydrographs related to major events that occurred in small urban watersheds located in northeastern Tunisia. The study investigated urban flooding using the HEC-HMS hydrological model. The model was applied to simulate rainfall runoff in the Ettorki watershed, a small urban watershed in northeastern Tunisia. Peak discharge and runoff volumes were estimated for two severe rainfall events that occurred in September 2003 and September 2019. The simulation results provided background information about runoff characteristics, including surface runoff velocity, peak discharge time, and magnitude. These results highlight the importance of hydrological modeling in understanding the magnitude of extreme rainfall events and designing appropriate stormwater drainage infrastructure in urban areas.
Daide et al. (2021) also created a hydrological model using HEC-HMS to simulate runoff using six extreme daily time-series events for the Beht watersheds in northwestern Morocco. It was confirmed that input data, such as land use, soil types, and hydrological parameters, play a significant role in the accuracy of the model. The HEC-HMS model performed very well in terms of relative error functions. The results showed that the simulated values were very close to the observed values for all events.
Abdelkebir et al. (2024) study aims to assess the impact of land use changes on the change in runoff volume. The HEC-HMS tool was used to assess the effect of these changes on water resources in the Somnnam Valley watershed in Algeria. Using the HEC-HMS model, the study compares land use and land cover for the years (2005, 2015, 2020, 2030, and 2050) to determine changes over the years. The results indicate a significant increase in urbanization, with a decrease in agricultural areas and forests. The model was simulated and calibrated using available flow data, and then the current and future impacts of Land Use/Land Cover (LULC) changes on peak flows and surface runoff volumes were presented. According to the results, changes in LULC affect surface runoff in the studied area, which leads to an increase in the flow volume and a fluctuation in peak drainage.

2.7. Case Study: Zomar Watershed

The Zomer watershed (Figure 2.3) is located in the northwest part of the West Bank. It is part of the watershed area that represents the largest source of groundwater in the region, known as the Mountain Aquifer. The upper area of the Wadi Zomar watershed includes the city of Nablus and its surrounding villages, while the lower area includes the city of Tulkarm and its surrounding villages. (Yaqob et al., 2015)
Wadi Zomar is a potential water resource for agricultural use, where a huge amount of water is generated from rainfall each year in the winter season, in addition to wastewater flowing from Nablus City and other communities alongside the Wadi. During highly intense rain seasons, the flood in the Wadi caused massive damage, especially to agricultural lands and infrastructure in the nearby communities, which led to heavy economic losses and even fatalities, as notably occurred in 1992 and 2013. Another incident that was even more significant happened in 2013 when the floods caused the blockade of the majority of the main streets that linked cities and closed the whole cities (Figure 2.2). The rainfall of this event, which almost rose more than a meter above the surface, caused a huge flood that led to closing tunnels and ferries for drainage, as well as drowning many houses and secondary and main public roads, and power has been cut off several times due to flooding, and lives lost. (Tulkarem Municipality, 2013).

Zomar, focusing on the nature and quality of its water. However, only a few studies have examined the relationship between surface runoff, climate change, and land use changes. The relationship between land use changes and the possible surface runoff has been analyzed in Nablus Mountains watersheds in 1984, 2000, and 2016, including Zomar Watershed. The land

Figure 2.2: damages and runoff at some events during this exceptional storm 2012-2013

use has been classified into 7 classes: pastures, trees, thick grass, agriculture, bare lands, urban areas, and forests (Asmar et al., 2021). The study showed that there is a massive expansion in the urban areas and an increase in agricultural lands and bare lands versus a decrease in pastures, trees, thick grass, and forests. This transformation came as a result of human activities such as cutting and burning vegetation and building houses, which decreased soil permeability, increased runoff discharge, and led to flash floods at times.

The results have shown that the average depth of the surface runoff has changed between 1984 and 2016 due to the changes in land use, where the Impervious surfaces have increased and the soil permeability has decreased, which led to an increase in the rate of surface runoff in the Zomar watershed (Asmar et al., 2021).

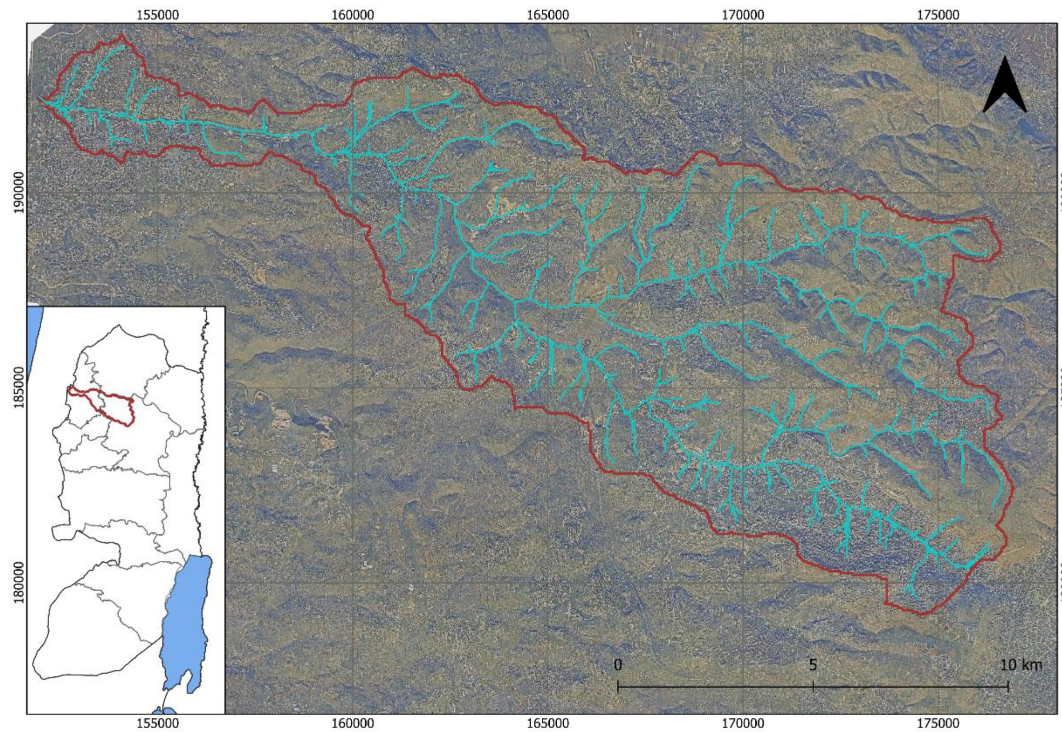


Figure 2.3: Zomar watershed

Chapter Three

3. Methodology

Introduction

This chapter outlines the methodological framework used in the study, consisting of three core components: study area description, data collection, and model development. The study area section introduces the physical context of the Zomar Watershed, describing its key geographic and hydrological features. The second section outlines the data collection process, including spatial data on topography, land use, and soil. These datasets were obtained and processed using GIS tools, remote sensing sources, and elevation models, which were later used to generate the required input maps for modeling. Finally, the modeling section details the hydrological modeling approach using WMS and HEC-HMS, including model calibration and sensitivity analysis to validate performance and assess parameter influence to ensure model robustness and reliability.

3.1. Study area

The Zomar Watershed is a natural drainage system with a total length of 27km within the West Bank. It originates from the western side of Nablus city in the east and flows through Tulkarem city (Figure 3.1). Beyond the West Bank, the watershed continues its course and ultimately discharges into the Mediterranean Sea in the west. The watershed covers a total area of approximately 148 km² of the West Bank, fully or partially including approximately 29 communities, and the population is estimated at 113,362 people in 2023 (Palestinian Central Bureau of Statistics, 2021). The watershed lies within a Mediterranean climate zone and is classified as semi-arid. Average temperatures range from 8–14°C in winter and 21.9–40°C in summer (Attili, 2020). The Zomar area also receives one of the highest levels of rainfall in the West Bank, with an annual average of 550–650 mm.

This stream was naturally ephemeral but became perennial in the 1950s. The change occurred due to raw domestic wastewater discharge from the western neighborhoods of Nablus and Tulkarm and discharge from nearby settlements. Moreover, since 2014, Nablus WWTP has been discharging an average of approximately 5.3 MCM/y of treated wastewater into the watershed (Nablus Municipality, 2023).

The boundaries of the watersheds and the wadis network are defined based on DEM (20-meter resolution) using the Watershed Modeling System software application and GIS software

(Figure 3.1). The watershed was subdivided into sub-catchments based on the topography (Figure 3.2).

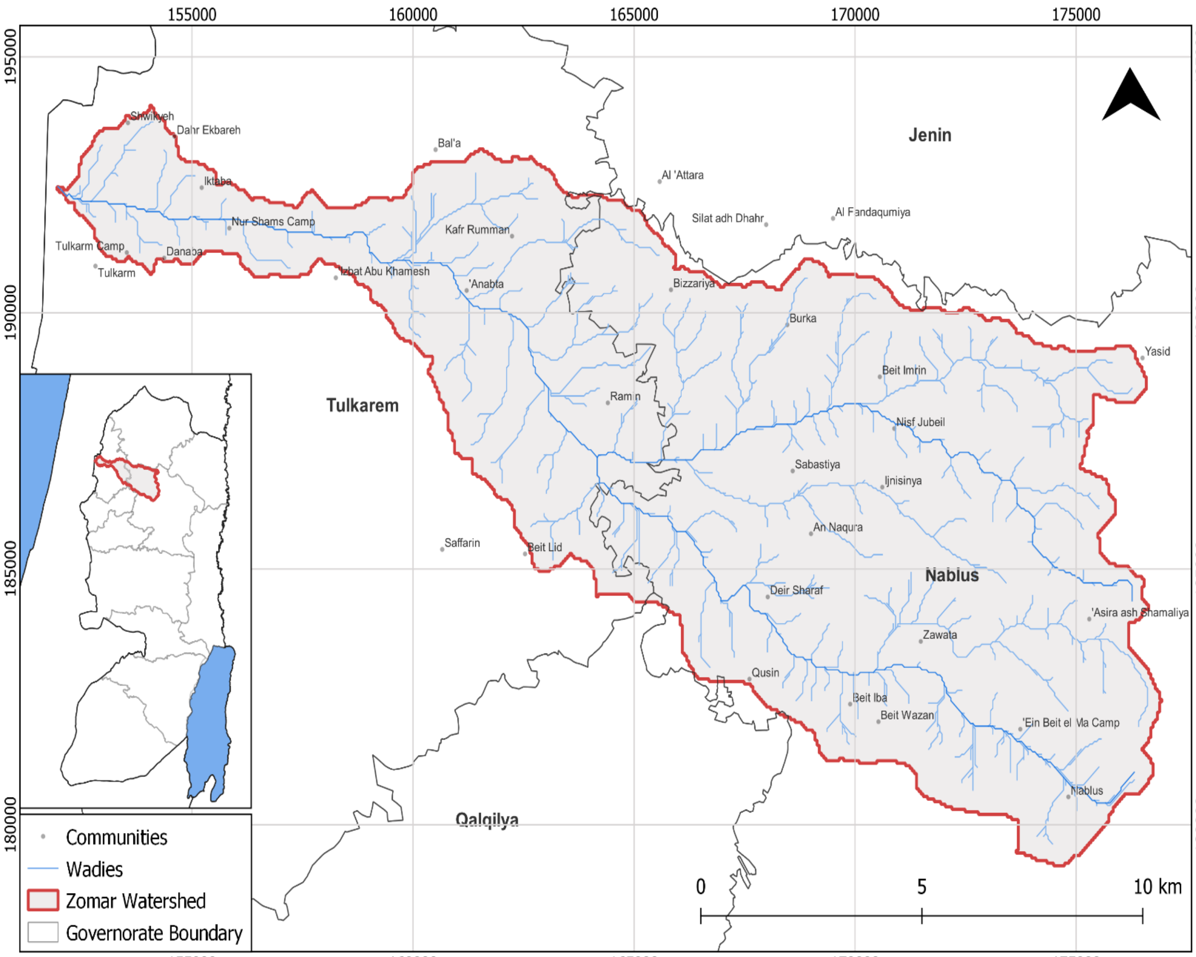


Figure 3.1: Boundaries of the defined watersheds

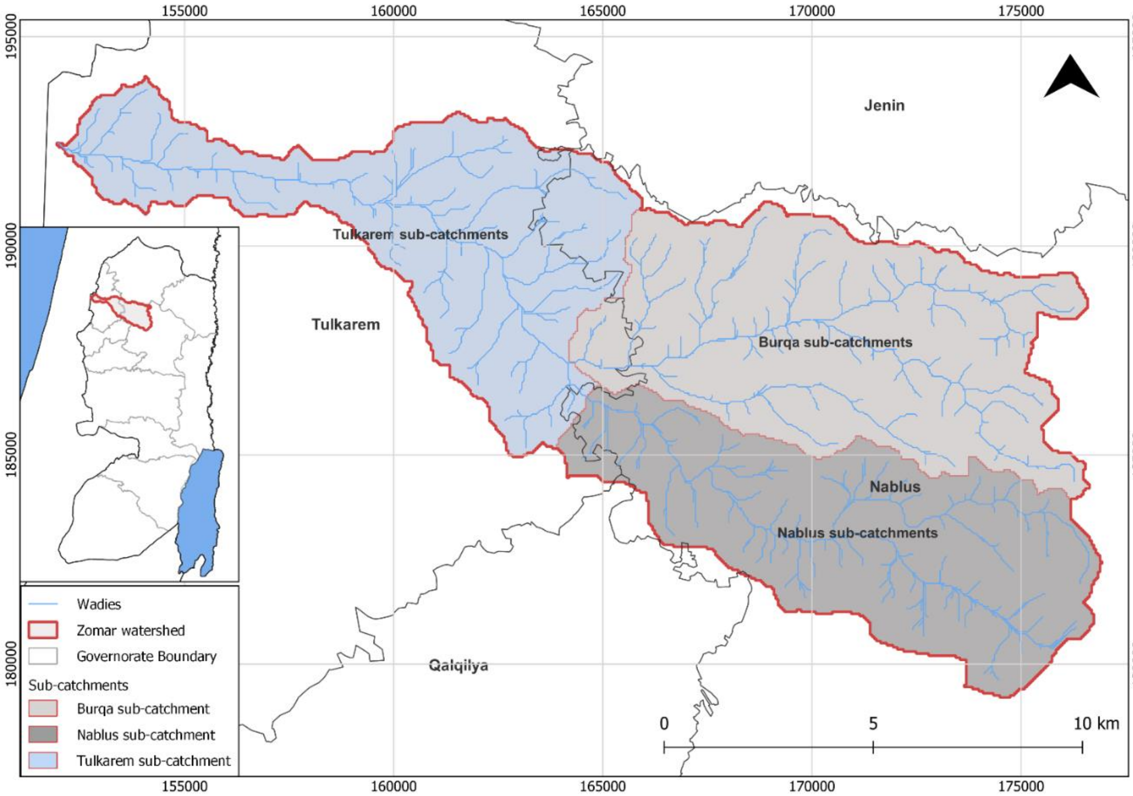


Figure 3.2: Sub-catchments of Zomar Watershed

3.2. Data collection

The data collected for this study includes topography and slope information derived from a Digital Elevation Model (DEM), land use data obtained from Geomolg aerial photographs (2000–2023), soil type, and climatic data provided by the Palestinian Meteorological Department. These datasets were then analyzed and used to generate maps using ArcGIS.

3.2.1. Topography

The topography of the study area can be divided into three zones. The first is the mountain area, which is the eastern side of the watershed, with elevations ranging from 700 to 940 m. The slope is high in this area, exceeding 45%, with large areas of impregnable lands. Therefore, it is expected to generate a huge amount of surface runoff. The second zone is the Hillside area, with elevation varying from 100 to 700 m. This area has more moderate slopes compared to the mountain area. The last topographic zone is the Coastal Plain, which starts from the east side of Tulkarm City and extends to reach the Mediterranean Sea in the west. The elevation varies from 0 to 100 m with a very low slope. Figure 3.3. represents the topography for the watershed area. The maximum elevation of the watershed is 940 m, the minimum is 56 m, and the average elevation is 429 m. The maximum slope reaches 47%, while the minimum is 0 %, with an average slope of 12.2 %. Figure 3.4 represents the slopes for the watershed area.

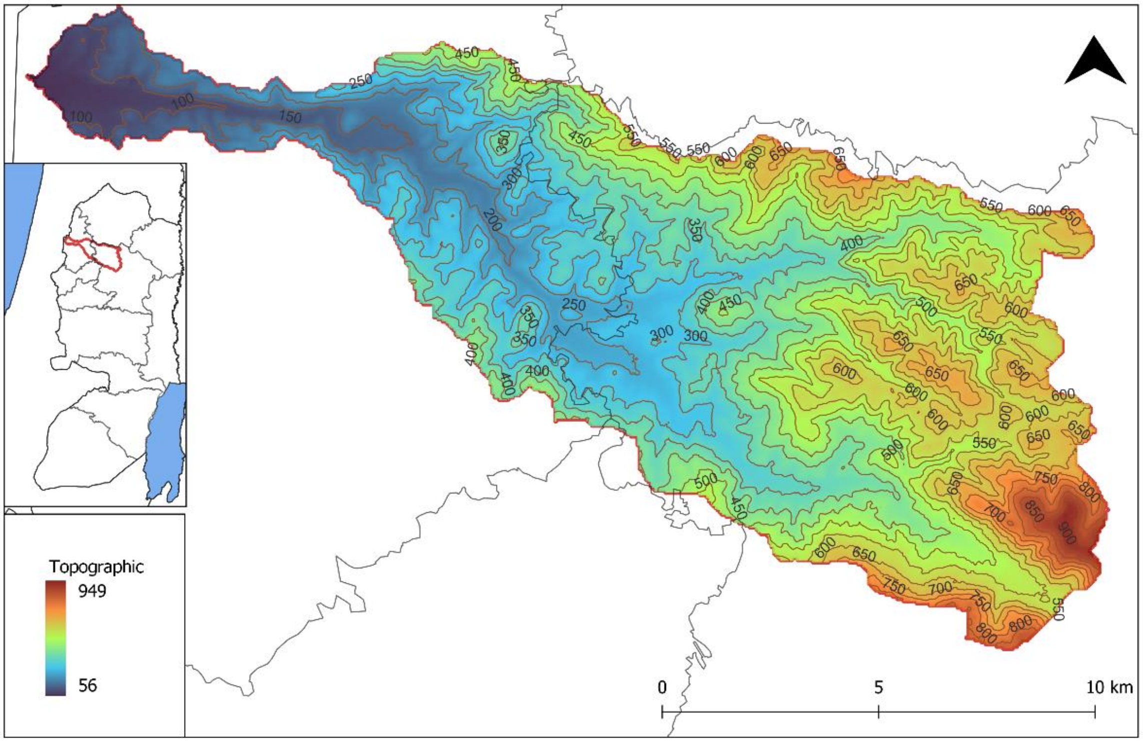


Figure 3.3: Topographic map of Zomar Watershed

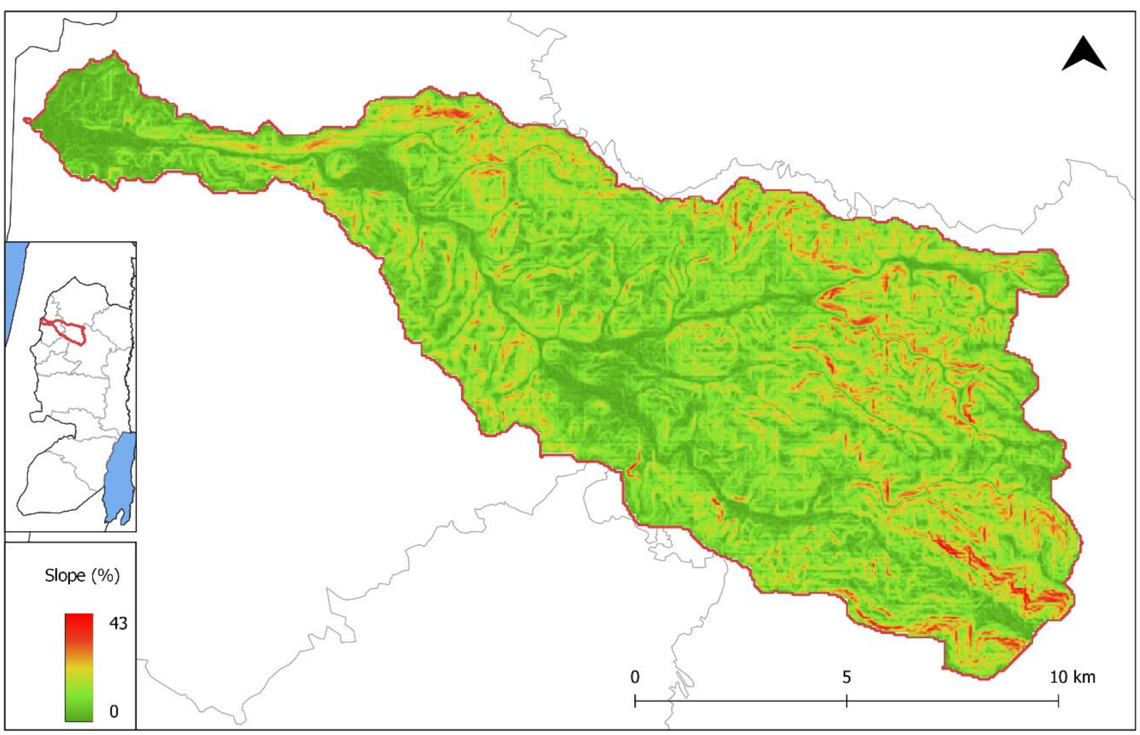


Figure 3.4: Slope map of Zomar Watershed

3.2.2. Soil

The prevailing soil types in the Zomar Watershed belong primarily to Hydrologic Soil Group A (Terra Rossa, Brown Rendzina, and Pale Rendzina soils) and Group B (Brown and Pale Rendzina soils). Additionally, two other soil types are present in smaller areas: Group C soils (Alluvial colloidal soils), present in narrow valleys, and Group D soils (Grumusols), forming inclusions in the Underhand, (Hydro-Engineering Consultancy Database ,2012). Figure 3.5: A detailed description of these four types in Table 3.2. This classification of soils into Groups A, B, C, and D follows the Hydrologic Soil Group system (Figure 3.6), indicating the expected runoff of the soil when fully saturated Table 3.1 (Neilsen & Hjelmfelt, 1998).

Table 3.1: Classification of Hydrologic Soil Groups and Their Impact on Infiltration and Surface Runoff (Neilsen & Hjelmfelt, 1998).

Hydrologic Soil Group	Description	Infiltration Rate	Surface Runoff Potential
Group A	Soils with high infiltration rates, even when thoroughly wetted. Consist mostly of deep, well- to excessively-drained sands or gravels.	High	Very Low
Group B	Soils with moderate infiltration rates. Typically moderately deep to deep with moderately fine to moderately coarse textures.	Moderate	Low
Group C	Soils with slow infiltration rates. Contain a layer that impedes water movement or have moderately fine to fine textures.	Slow	Moderate to High
Group D	Soils with very slow infiltration rates. Include clay soils with high swelling potential, high water table, clay pan, or shallow soils over impervious material.	Very Slow	High to Very High

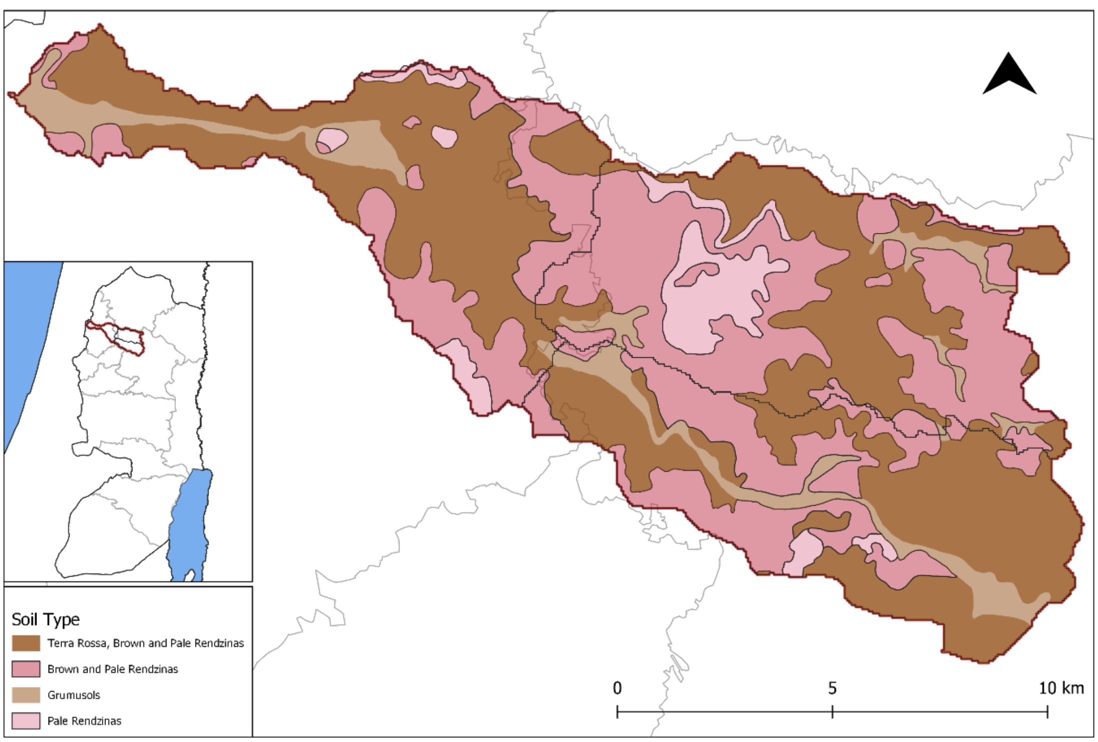


Figure 3.5: Soil map of Zomar Watershed (Hydro-Engineering Consultancy Database, 2014)

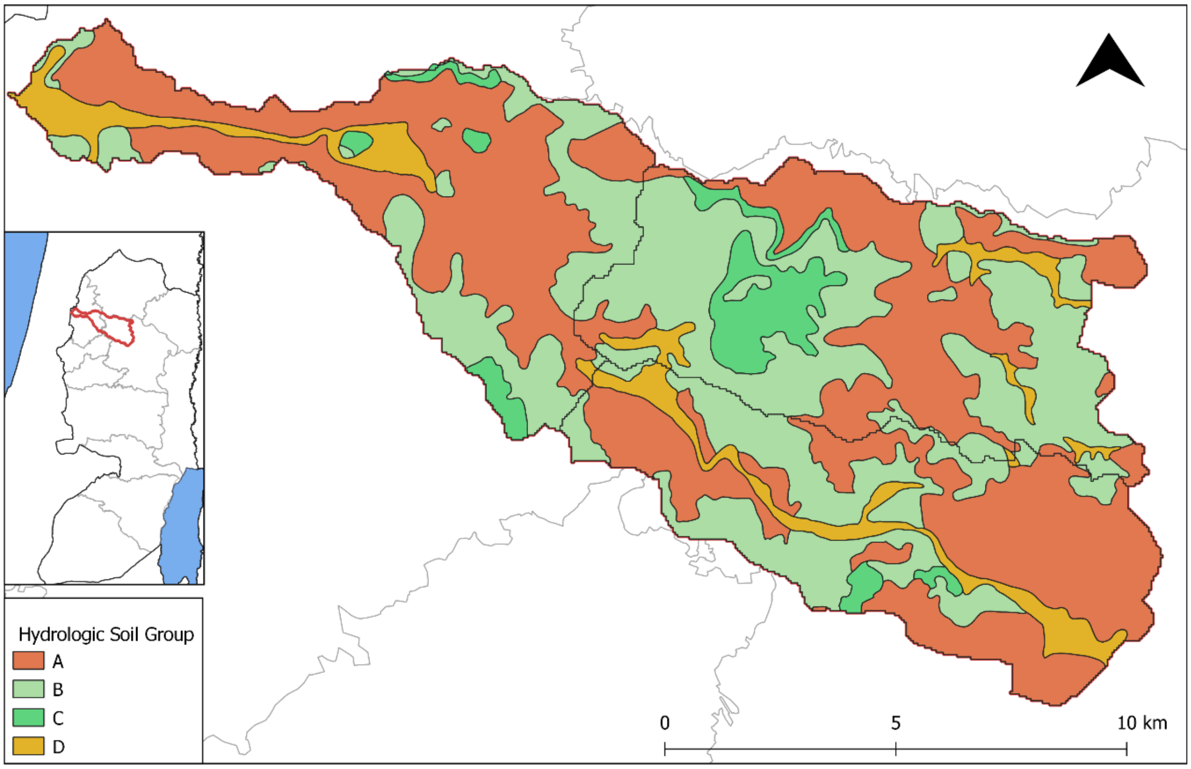


Figure 3.6: Hydrologic soil groups of the Zomar watershed (Hydro-Engineering Consultancy Database, 2014)

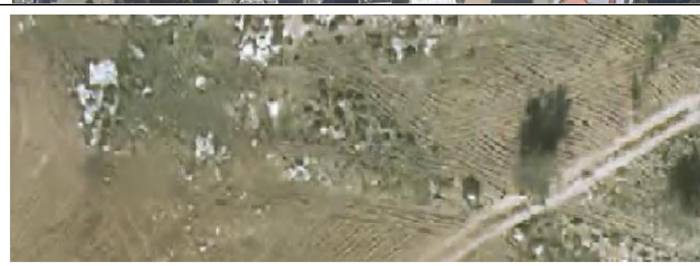
Table 3.2: Soil types and their percentages of soil types within the Zomar watershed

Type		Tulkarem catchment		**Nablus catchment**		**Burqa catchment**	
		Area		**Area**		**Area**	
		km^2	**%**	**km^2**	**%**	**km^2**	**%**
Grumusols	d	4.63	9.91%	4.91	10.43%	2.48	4.62%
Terra Rossa, Brown and Pale Rendzinas	a	27.4	58.66%	25.96	55.15%	18.676	34.78%
Brown and Pale Rendzinas	b	12.753	27.30%	15.29	32.48%	26.8762	50.05%
Pale Rendzinas	c	1.93	4.13%	0.91	1.93%	5.667	10.55%
Total		**46.713**	**100.00%**	**47.07**	**100.00%**	**53.6992**	**100.00%**

3.2.3. Land use

The land use within the boundaries of the Zomar watershed was determined using aerial images from 2000 to 2023. Aerial images from GeoMolg were utilized, where they were digitized to identify land use. The area was classified into six categories as shown in Table 3.3.

Table 3.3: Land use type in Zomar watershed

Land use	
Greenhouses	
Trees, Irrigable areas which mixed irrigated, complementary irrigated or rainfed trees	
Built-up areas include buildings and extensive use of urban areas in addition to streets	
Shrub lands	
Field lands	
Forest	

The 2023 aerial image shows that the largest proportion of land use is attributed to Trees, Shrub lands, and Built-up areas, accounting for 42%, 37.7%, and 17.1%, respectively. A comparison with previous years (2023 to 2022) indicates that built-up areas have increased at the expense of both trees and shrub lands. Table 3.4, Figure 3.7, illustrates land use.

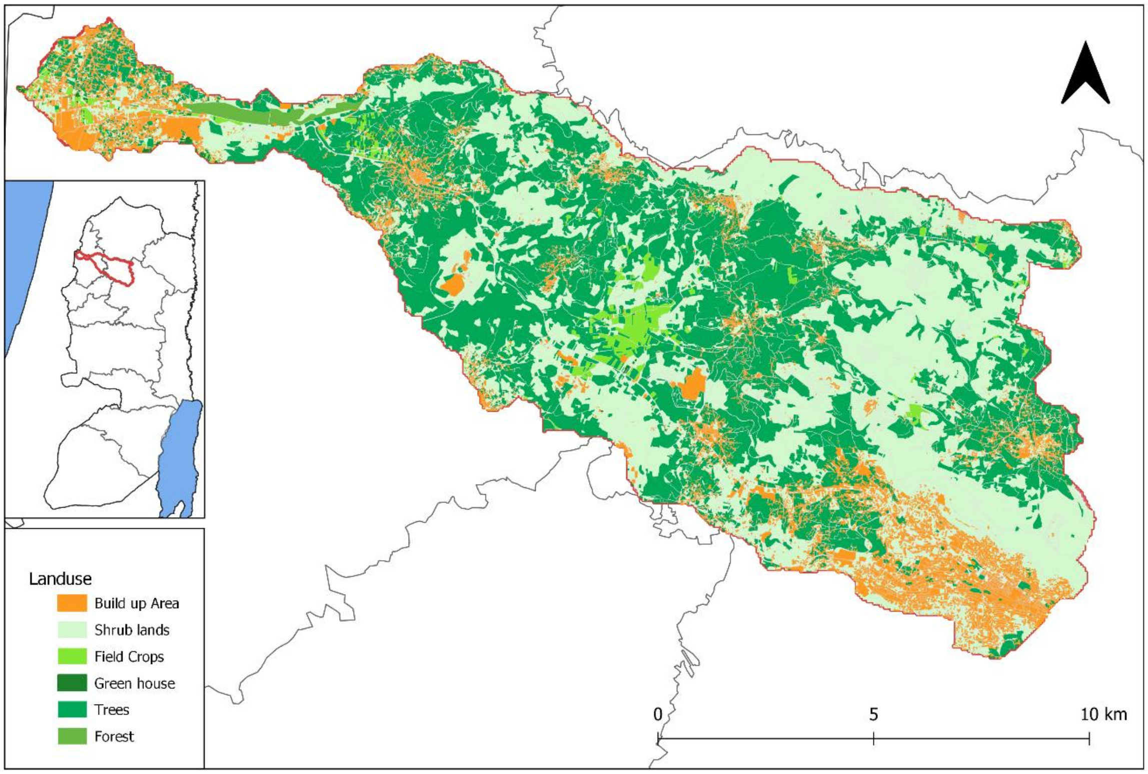


Figure 3.7: Land use of Zomar Watershed

Table 3.4: land use and their percentages of land use within Zomar watershed

Land use	Tulkarem catchment		Nablus catchment		Burqa catchment	
	Area		Area		Area	
	Km^2	%	Km^2	%	Km^2	%
build up area	7.86	16.84	11.91	25.32	4.082	7.61
trees	23.26	49.8	14.48	30.74	25.06	46.66
Shrub lands	13.2	28.3	20.17	42.871	22.86	42.58
Field Crops	1.19	2.53	0.48	1.014	1.69	3.14
greenhouse	0.17	0.35	0.03	0.064	0.007	0.013
Forest	1.02	2.18	-----	------	------	------
Total	46.7	100%	47.07	100%	53.699	100%

3.2.4. Climate:

There are two meteorological stations in the Zomar watershed area: Nablus station and Tulkarem station. The records of these stations are obtained from the Palestinian Meteorological Department (PMD). Then, the data was used to describe the climate in the study area.

3.2.4.1. Precipitation:

The long-term annual average rainfall within the boundary of the Zomar watershed is estimated to be 550-650 mm, where about 70% of the annual rainfall occurs between November and February. In March and April, precipitation usually decreases, while in May and September, rainfall is rare. June, July, and August are almost without rain. The most intensive rainfall storm usually occurs during December and January. Figure 3.8 shows the annual rainfall for the seasons from 2000 to 2023 for both Nablus and Tulkarm stations.

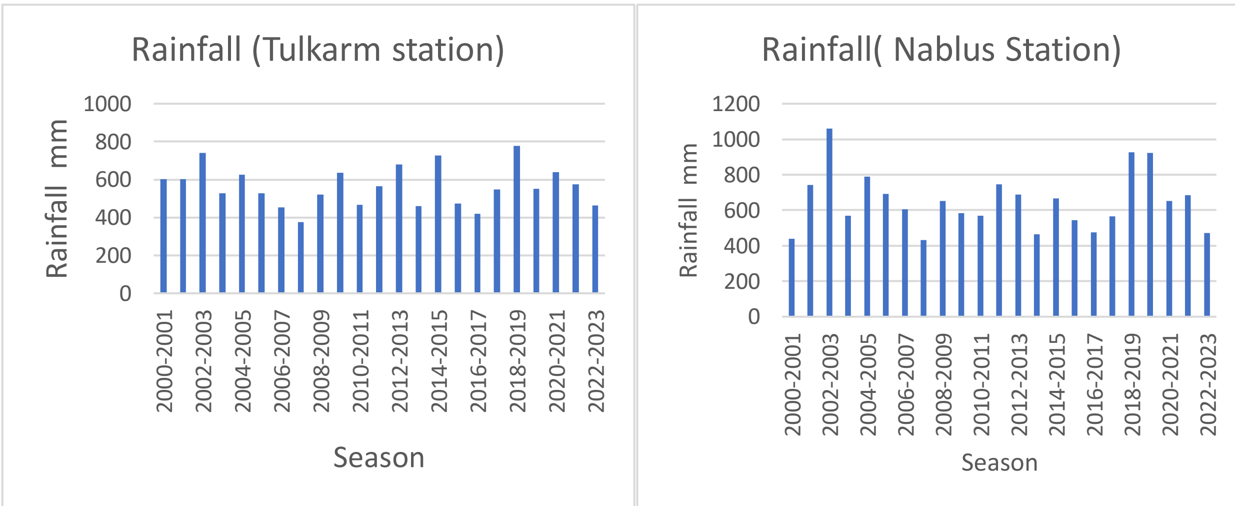


Figure 3.8: Annual rainfall for each season for Nablus and Tulkarm station

3.2.4.2. Temperature

The average monthly temperature within the Zomar Watershed during the summer months (June, July, August, and September) is approximately 24 °C, with mean monthly minimum and maximum temperatures of 20 °C and 28.6 °C, respectively. During the winter months (December, January, February, and March), the mean monthly temperature is 11.6 °C, with minimum and maximum temperatures averaging 8.5 °C and 14.9 °C, respectively (Palestinian Meteorological Department, 2024).

3.2.4.3. Evapotranspiration:

Evapotranspiration rates for the watershed were obtained from previous studies (Tulkarem Municipality, 2013). Climatic data (Table 3.5) show that the evapotranspiration rate in the Zomar watershed varies throughout the year, being low in winter and gradually increasing with the onset of summer. The evaporation rate starts at 36 mm in January, rises to its peak in July at 148 mm, and then gradually decreases to 39 mm in December. This annual variation reflects the direct relationship between evaporation and temperature, as the hotter months record higher evaporation rates.

Table 3.5: Evapotranspiration in Zomar watershed

Month	Rate (mm/month)
January	36
February	41
March	61
April	79
May	111
June	131
July	148
August	137
September	81
October	74
November	49
December	39

3.3. Modeling development

3.3.1. Watershed Models:

Two software applications were used to develop the Watershed Modelling model (WMS) and the Hydrologic Modelling System (HEC-HMS).

3.3.1.1. Watershed Modeling System (WMS)

WMS 11.1 was developed by the Environmental Modeling Research Laboratory at Brigham Young University, in collaboration with the U.S. Army Corps of Engineers Waterways Experiment Station. The software can perform several operations, including automated watershed delineation and the calculation of important watershed parameters such as area, slope, and runoff distances. Details of the model can be found at the Environmental Modeling Research Laboratory (Environmental Modeling Systems, 2004).

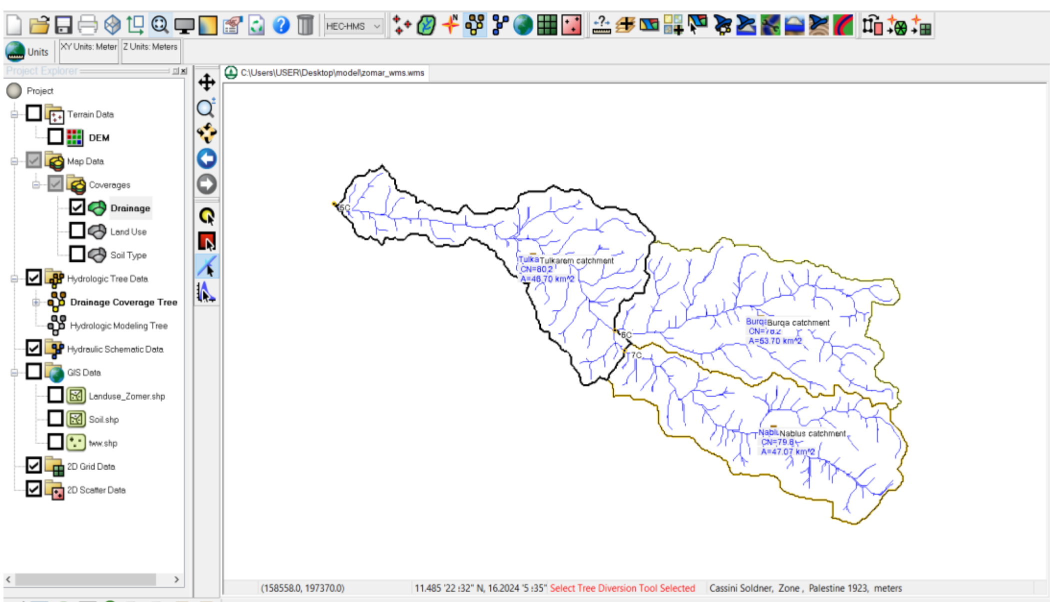


Figure 3.9: Watershed and sub-catchments created by WMS

In this study, WMS was used to define watershed boundaries and calculate hydrological parameters. The Digital Elevation Model (DEM), which has a 25-meter resolution, was used as an input in the WMS to delineate the boundaries of the watershed , determine flow paths and slopes, and calculate channel lengths (Figure 3.9). Moreover, the land use and soil maps were integrated into WMS to estimate additional hydrologic parameters, such as:
Lag Time:
Although direct surface runoff begins with the onset of effective rainfall, the majority of the runoff generally occurs after the rainfall ends, as it takes time for the runoff to travel from any point within the watershed to the outlet. The delay time in the basin is usually defined as the time difference between the center of mass of excess rainfall and the center of mass of the resulting direct surface runoff. (Fang et al., 2005).

Time of concentration (Tc):
The time it takes water to travel from the most remote point in the watershed to the stream outlet (Fang et al., 2005; Boulomytis, 2018).

Storage Coefficient:
The index of the temporary storage of precipitation excess in the watershed as it drains to the outlet point (Hydrologic Modeling System HEC-HMS User's Manual, 2024).
In this model, the Zomar watershed was divided into three subcatchments as shown in (Figure 3.9). Subcatchment Nablus and Burqa contribute their accumulated runoff to sub-catchment Tulkarem, which represents the final outlet of the Zomar watershed. The boundary, area, Lag time, Time of concentration, and storage coefficient were calculated for each subcatchment (Table 3.6).

Table 3.6: Watershed characteristics

catchment Name	Area (km2)	Lag Time(HR)	Time of Concentrat ion(HR)	Storage Coefficient (HR)
Tulkarem catchment	46.713	2.068	2.9	4.729
Nablus catchment	47.07	1.867	2.12	3.462
Burqa catchment	53.699	1.73	2.11	6.607

3.3.1.2. Watershed Model (HEC-HMS):

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) was developed by the U.S. Army Corps of Engineers to simulate rainfall–runoff processes in watershed systems. The model provides flexibility by allowing modelers to select from various infiltration loss methods and unit hydrograph techniques, making it adaptable to a wide range of hydrologic conditions (U.S. Army Corps of Engineers, 2024).
In this study, HEC-HMS version 4.11, linked with WMS, was used to develop the Zomar watershed model. The model components, such as sub-catchments, reaches, and junctions, along with their estimated physical parameters, were initially calculated using a Digital Elevation Model (DEM) within WMS and then transferred into HEC-HMS. These parameters include watershed geometry, slope, time of concentration, and storage coefficients.

HEC-HMS simulates the hydrological response by partitioning incoming rainfall into storage and loss components before computing the runoff. In a model simulation, rainfall first encounters the canopy and surface layers, which intercept part of the rainfall. The remainder infiltrates into the soil or turns into surface runoff. Water in soil may infiltrate or return to the atmosphere via evapotranspiration. In HEC-HMS terminology, interception, surface storage, infiltration, and evapotranspiration are all treated as losses. The runoff volume is defined as the total precipitation minus these losses.

Model Components:

HEC-HMS represents a watershed through three core components: the basin model (a network of hydrologic elements) , the meteorological model and the control specifications.

1. The basin model

This model is built by adding elements like sub-basins, reaches, junctions, and reservoirs, connected in a tree-like (dendritic) network. For each sub-basin, specific methods should be identified, which are canopy, surface loss, and transfer methods. (Hydrologic Modeling System HEC-HMS User's manual, 2024)

Canopy Method

This method accounts for rainfall intercepted by grass, trees, and shrubs that prevents water from reaching the surface layer. (Hydrologic Engineering Center, 2000). In HEC-HMS, rainfall is first applied to canopy storage. The canopy-filling rate is limited by the canopy capacity. Only after the canopy storage is fully saturated does any additional precipitation reach the ground surface.

Surface Method (Depression Storage)

This method accounts for rainfall stored in small depressions, cracks, or roughness on the ground.

Loss Methods

HEC-HMS provides several loss methods to estimate the portion of rainfall that infiltrates into the soil. Three commonly used loss methods are:

a- Initial-Constant Method

The initial and constant methods use the default single soil layer to calculate the changes in moisture content. While this method is immensely simple, it has been used widely for modeling watersheds that lack detailed underground information.

In this method, all rainfall is initially lost to infiltration until a specified initial loss threshold is met. Once this threshold is reached, additional rainfall continues to infiltrate at a constant rate. Any remaining rainfall that does not infiltrate becomes surface runoff. The Initial and Constant Method is typically used for event-based simulations rather than continuous modeling (Hydrologic Modeling System HEC-HMS User's Manual, 2024).

b- SCS curve number Method

The SCS curve number method that the U.S. Soil Conservation Service has established is considered a hydrological tool that is used to estimate rainfall losses by relying on different factors such as the amount of accumulated rainfall, land use pattern, soil cover, and previous moisture level. This method is applied to calculate infiltration during storms. The SCS curve number loss method is used only for event simulation (Hydrologic Modeling System HEC-HMS User's Manual, 2024).

c- Deficit-Constant Method

Deficit-Constant method, like the Initial-Constant method, applies a constant infiltration rate once the soil is saturated. However, it introduces a dynamic soil moisture deficit, representing the effective storage capacity of the soil , which can recover between storms. In this method, when the soil is not saturated (deficit > 0), all rainfall infiltrates. Once the deficit reaches zero (soil saturated), infiltration is limited to a constant rate (the saturated hydraulic conductivity). Any rainfall above that rate becomes surface runoff. This method continuously tracks soil moisture conditions, allowing the deficit to rebuild during dry periods through processes such as evapotranspiration. As a result, it is particularly well-suited for long-term or continuous simulations. By definition, a deficit value of zero indicates saturated soil, whereas a larger deficit indicates drier soil with higher infiltration capacity (Hydrologic Modeling System HEC-HMS User's Manual, 2024).
In this study, the Deficit Constant method was used due to its continuous modeling, whereas the Initial Constant, and SCS curve number methods are used for event-based simulations.
In this method (Deficit-Constant Method), the model has four key parameters:

Initial Deficit
The initial soil moisture deficit at the beginning of the simulation represents the volume (depth) of water required to fill the soil layer at time zero (Hydrologic Engineering Center, 2024). If the basin has experienced a long dry spell, the initial deficit may equal the maximum deficit; if it is saturated, the initial deficit is zero. In this study, the initial deficit values were calculated based on the wilting point of the soil in each sub-catchment, assuming that the simulation starts in the summer, when soil moisture is expected to be close to the wilting point. Soil texture data and the SPAW model were used to determine these values, as shown in Table 3.7. The detailed calculations and assumptions used to derive these values are presented in Appendix 1, where computations are provided for each sub catchment.

Table 3.7*:* The initial deficit for each sub-watershed

catchment Name	Initial Deficit(mm)
Tulkarem catchment	27.1
Nablus catchment	26.9
Burqa catchment	23.8

Maximum Deficit

The total holding capacity of the soil layer, often estimated as the saturation level. This represents the maximum volume of water the soil can store. When the soil is fully saturated, the deficit is zero. The initial deficit must be less than or equal to the maximum deficit (Hydrologic Engineering Center, 2024). Table 3.8 shows the maximum deficit for each sub-watershed. Soil texture data and the SPAW model were used to determine soil saturation. The detailed calculations and assumptions used to derive these values are presented in Appendix 1, where computations are provided for each sub-catchment.

Table 3.8*:* The maximum deficit for each sub-watershed

catchment Name	Maximum Deficit:
Tulkarem catchment	46.44
Nablus catchment	46.5
Burqa catchment	46.6

Constant Rate:

This refers to the infiltration rate once the soil is saturated. In the deficit constant method, the constant rate sets both the rate at which rain infiltrates after the deficit is filled and the rate of percolation out of the soil when it's saturated (Hydrologic Engineering Center, 2024). Physically, it is typically taken as the saturated hydraulic conductivity of the soil. Thus, once the deficit reaches zero, only a fraction of the incoming rain equal to this rate can infiltrate; any excess becomes runoff. The detailed calculations and assumptions used to derive these values before calibration are presented in Appendix 1, where computations are provided for each sub-catchment.

Impervious Area (%)

The portion of the sub-basin where runoff is directly connected to drainage (e.g., building surfaces, sidewalks, roads). Rainfall in this area contributes entirely to excess runoff.

Transform Method

Once excess rainfall is computed, HEC-HMS employs a transform method to convert it into a runoff hydrograph at the sub-basin outlet. Transform methods model the translation and attenuation of flow as it moves through the watershed. Common HEC-HMS transform methods include unit-hydrograph methods, such as Clark and SCS methods.

For this study, the Clark unit hydrograph transform method was used. This method is a synthetic unit-hydrograph method that does not require an observed hydrograph. Instead, it uses the watershed geometry (time–area) and a conceptual linear reservoir to model storage (Hydrologic Modeling System HEC-HMS User's Manual, 2024). By design, Clark is suitable for both event-based and continuous simulations, whereas the SCS method is typically limited to event-based modeling (Odey & Cho, 2025)

In HEC-HMS, the Clark method works as follows: rainfall excess from the basin is first distributed over a set of travel times up to the time of concentration (Tc), forming an initial "translation" hydrograph. Then that hydrograph is routed through a linear reservoir characterized by a storage coefficient (C). The model has two key parameters: time of concentration (Tc) and storage coefficient (C), which were calculated using the WMS software.

2. Meteorological Model

The meteorological model in HEC-HMS defines the atmospheric forcing for the watershed. Its primary function is to provide meteorological boundary conditions, such as precipitation and other related inputs, for each sub-catchment. Within the meteorological model component, specific methods are assigned to each sub-catchment to generate rainfall and evapotranspiration data.

The evapotranspiration values used in this study are presented in Table 3.5. Daily rainfall data were obtained from PMD's rainfall stations and are represented as a daily time series within the model.

3. Control Specifications

The Control Specifications define the time frame and time step for a simulation. Starting date/time, ending date/time, and the computation interval (time step) should be entered. These settings determine when the model begins and ends integration and how frequently hydrologic calculations are performed.

3.3.2. Calibrate model

We develop the hydrological model with initial parameters based on the collected data, then calibrate the rainfall-runoff model to optimize the watershed parameters. The calibration period, December 15, 2005, to March 16, 2006, was selected due to the completeness and quality of its available data (Tal et al., 2007). During this phase, the model parameters were systematically adjusted to achieve an optimal alignment between simulated and observed runoff.

The calibration of the model was an iterative process of adjusting the input parameters until the simulated data closely matched the observed data. These parameters included the initial deficit, maximum deficit, constant rate, time of concentration (Tc), and storage coefficient (C).

The calibration results demonstrate a very good agreement between simulated and observed hydrographs. The model performs well in reproducing the timing, magnitude, and shape of flow events within the watershed. The result is clearly depicted in Figure 3.10, which shows a close correspondence between observed and simulated flows during the calibration period.

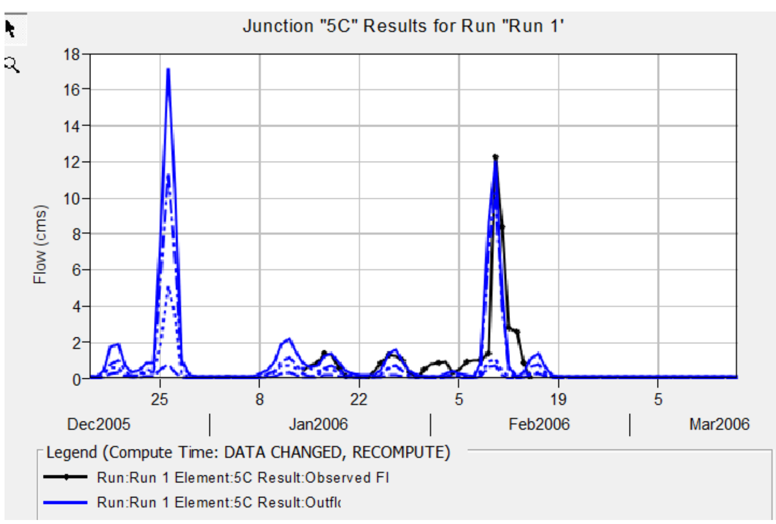


Figure 3.10: Observed and Simulated flow of Zomar watershed

3.3.3. Sensitivity analysis for the parameters

To assess the influence of hydrological parameters on model performance, a sensitivity analysis was conducted as part of the case study. This step is essential in understanding how variations in model inputs affect the simulated output and in identifying the most sensitive parameters that require precise calibration. In this analysis, the values of several critical parameters, the initial deficit, maximum deficit, constant infiltration rate, time of concentration, and storage coefficient were systematically varied across a wide range, from 10% to 250% of their initial estimate.

The model's response to these parameter changes was evaluated at the watershed outlet by analyzing the resulting discharge hydrographs. Among the tested parameters, the constant rate showed the highest sensitivity, with even small changes leading to noticeable variations in simulated runoff volumes and peak flows. In contrast, changes in other parameters ,including initial deficit, maximum deficit, Tc, and storage coefficient, had comparatively minor effects on the discharge simulation. This finding indicated that the model output is highly dependent on the accurate specification of this parameter, and as a result, the calibration process focused primarily on optimizing the constant rate to ensure reliable model performance.

The sensitivity analysis proved to be a crucial step in guiding the calibration strategy by highlighting which parameters exert the greatest control over the model outputs. By prioritizing the calibration of sensitive parameters, the modeling process becomes more efficient, targeted, and scientifically, leading to a model that more accurately reflects real hydrological responses. Table 3,9 presents the constant rate values ranging from 10% to 50% and the surface runoff volume for each sub-watershed.

It was observed that the relationship between discharge and the constant rate exhibits an inverse trend. Specifically, when the constant rate was reduced to less than 10% of its baseline value, the simulated discharge reached its maximum levels.

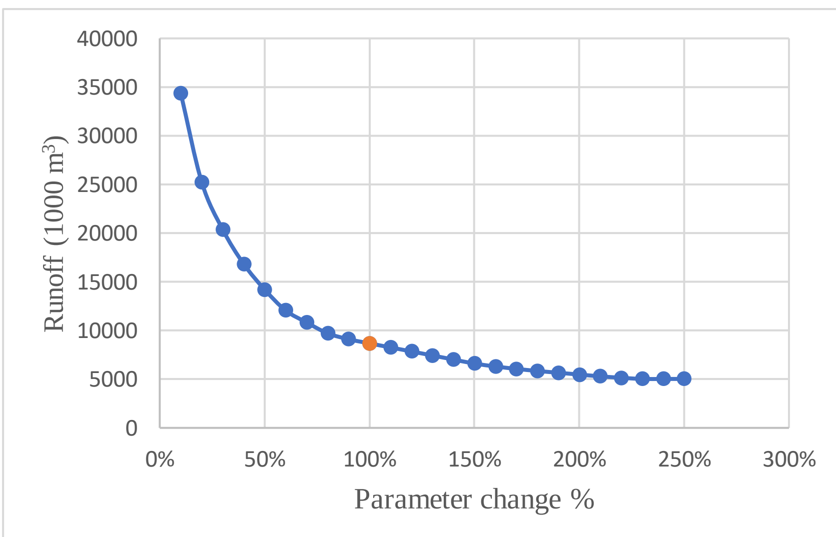


Figure 3.11: Relation between discharge and sensitivity parameter (constant rate)

As the constant rate increased, the discharge progressively decreased, reflecting enhanced infiltration capacity and reduced runoff volumes. This trend continued until the constant rate reached approximately 180% of its original value, beyond which further increases in the constant rate had a negligible effect on discharge (Figure 3.11). At this point, the system approached hydrological equilibrium, and the simulated runoff began to stabilize.

Table 3.9*:* constant rate value in each sub catchment from 10% to 250%

Parameter change	Constant rate in Nablus catchment	Constant rate in Burqa catchment	Constant rate in Tulkarem catchment	Runoff ($1000m^3$)	Peak discharge
10%	0.06	0.17	0.06	34395	61.2
20%	0.12	0.34	0.12	25243.4	50.4
30%	0.18	0.51	0.18	20376.5	43.3
40%	0.24	0.68	0.24	16840.5	36.7
50%	0.3	0.85	0.3	14210.1	31.9
60%	0.36	1.02	0.36	12066.9	28.1
70%	0.42	1.19	0.42	10828.1	24.2
80%	0.48	1.36	0.48	9717.7	20.3
90%	0.54	1.53	0.54	9104.5	18.6
100%	0.6	1.7	0.6	8677.9	17.2
110%	0.66	1.87	0.66	8263.5	15.8
120%	0.72	2.04	0.72	7849.2	14.4
130%	0.78	2.21	0.78	7435	13
140%	0.84	2.38	0.84	7020.9	11.6
150%	0.9	2.55	0.9	6606.8	10.2
160%	0.96	2.72	0.96	6307.9	9.5
170%	1.02	2.89	1.02	6057.3	8.8
180%	1.08	3.06	1.08	5846.2	8.1
190%	1.14	3.23	1.14	5661.8	7.4
200%	1.2	3.4	1.2	5477.5	6.8
210%	1.26	3.57	1.26	5293	6.1
220%	1.32	3.74	1.32	5145.3	5.4
230%	1.38	3.91	1.38	5025.7	4.8
240%	1.44	4.08	1.44	5025.7	4.8
250%	1.5	4.25	1.5	5025.7	4.8

Conclusion

The methodology followed was presented in detail, starting from the description of the study area regarding its geographical, climatic, and physical aspects, and reaching the processes of data collection from multiple sources such as aerial images and digital elevation models. GIS tools were used, and then a simulation model was developed using WMS and HEC-HMS based on these inputs. A calibration process was conducted to adjust the parameters and achieve an accurate representation of surface runoff, followed by a sensitivity analysis to identify the most influential parameters.

Chapter Four

4. Results and Discussion

4.1. Rainfall Preprocessing and Analysis

Rainfall data for each day from 2000 to 2023 were obtained from the Palestinian Meteorological Department (PMD) for both Nablus and Tulkarm stations, representing the amount of rainfall over the Wadi Al-Zomar watershed. Prior to analysis, the dataset was preprocessed to address missing or incomplete records. As detailed in Appendix 2. Following this, the data were analyzed to determine the number of storms, the number of extreme storms, and the number of rainy days above 40 mm, show figure 4.1 (Tables 4.1 and 4.2).

The importance of this analysis lies in identifying the rainfall pattern in the region, as severe storms and days of heavy rain are the primary triggers for surface runoff generation, especially when they exceed the soil's absorption capacity. In cases of frequent, light rain, large amounts of water may be absorbed without significant surface runoff, highlighting the importance of understanding the relationship between duration, intensity, and frequency of rainfall on surface runoff.

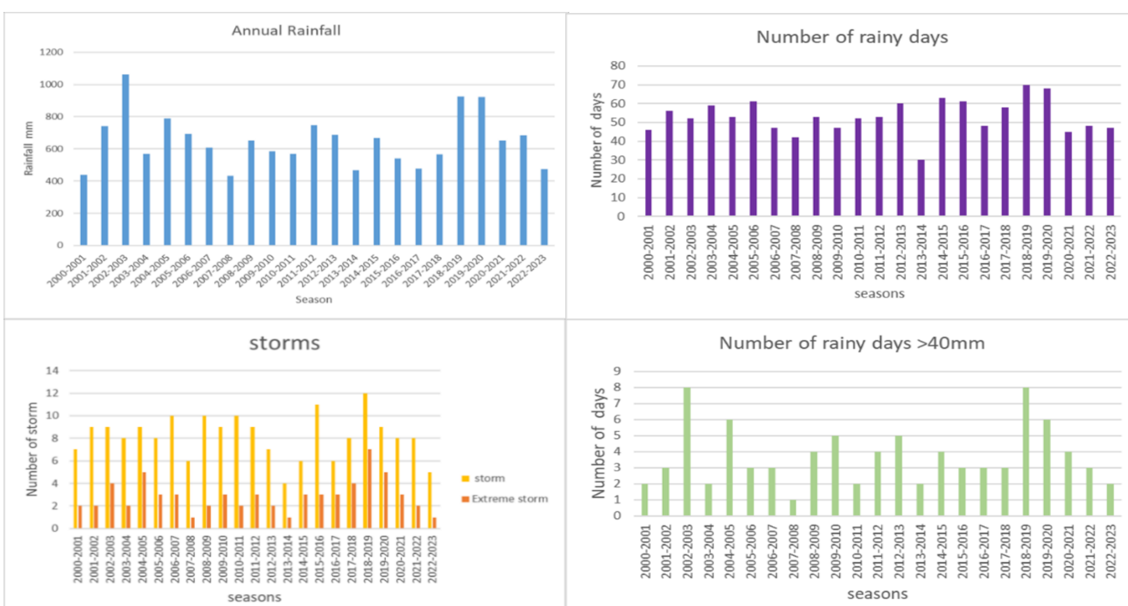


Figure 4.1: Analysis of Rainfall Characteristics over the Wadi Al-Zomar Watershed (2000–2023)

Figure 4.1 illustrates the clear variations between the rainy seasons in the study period in terms of rainfall volume, number of rainy days, and frequency of extreme storms. These variations in rain patterns demonstrate that the resulting runoff quantity will also vary from one season to another.

Table 4.1: Rainfall Analysis in Nablus

Season	Rainfall mm/year	Number of rainy days	No. of storm	no. ex.storm	Rain day >40
2000-2001	438.6	46	7	2	2
2001-2002	741.8	56	9	2	3
2002-2003	1061.5	52	9	4	8
2003-2004	567.8	59	8	2	2
2004-2005	789.9	53	9	5	6
2005-2006	693.5	61	8	3	3
2006-2007	606.3	47	10	3	3
2007-2008	432.2	42	6	1	1
2008-2009	652	53	10	2	4
2009-2010	584.8	47	9	3	5
2010-2011	570	52	10	2	2
2011-2012	746.6	53	9	3	4
2012-2013	686.8	60	7	2	5
2013-2014	465.9	30	4	1	2
2014-2015	667.1	63	6	3	4
2015-2016	542	61	11	3	3
2016-2017	476.1	48	6	3	3
2017-2018	565.5	58	8	4	3
2018-2019	925	70	12	7	8
2019-2020	923.6	68	9	5	6
2020-2021	653.2	45	8	3	4
2021-2022	683	48	8	2	3
2022-2023	473	47	5	1	2

Table 4.2: Rainfall Analysis in Tulkarm

Season	Rainfall mm/year	Number of rainy days	No. of storm	no. ex. storm	Rain day >40
2000-2001	602	52	9	3	3
2001-2002	604.2	55	10	2	2
2002-2003	747.84	52	9	3	7
2003-2004	526.1	57	8	2	2
2004-2005	625.8	53	7	3	4
2005-2006	528.8	51	7	3	3
2006-2007	454.5	38	8	2	3
2007-2008	373.9	31	6	2	3
2008-2009	519.7	44	8	2	4
2009-2010	634.3	40	7	3	4
2010-2011	467.7	43	8	1	1
2011-2012	564.5	44	9	3	3
2012-2013	680	45	7	2	4
2013-2014	460.5	32	4	1	2
2014-2015	726.3	46	6	3	4
2015-2016	472.45	52	11	0	0
2016-2017	418.7	28	5	1	1
2017-2018	547.3	41	9	3	4
2018-2019	778.4	51	11	2	2
2019-2020	552.1	45	8	3	3
2020-2021	638.8	38	8	5	6
2021-2022	573.2	39	10	2	3
2022-2023	462	33	9	3	3

4.2. Impervious Surfaces Digitizing and Analysis

The impervious surfaces in the study area were identified by digitizing aerial images from 2000 to 2023 available in GeoMOLC. This process was used to determine the expansion and development of impervious surfaces over the study period and to extract the percentage of impervious surfaces that prevent water infiltration into the soil and significantly affect surface runoff. These surfaces include urban areas (buildings and roads) as well as greenhouses, as shown in Figure 4.2. Table 4.3 presents the percentage of impervious surfaces for each sub-watershed.

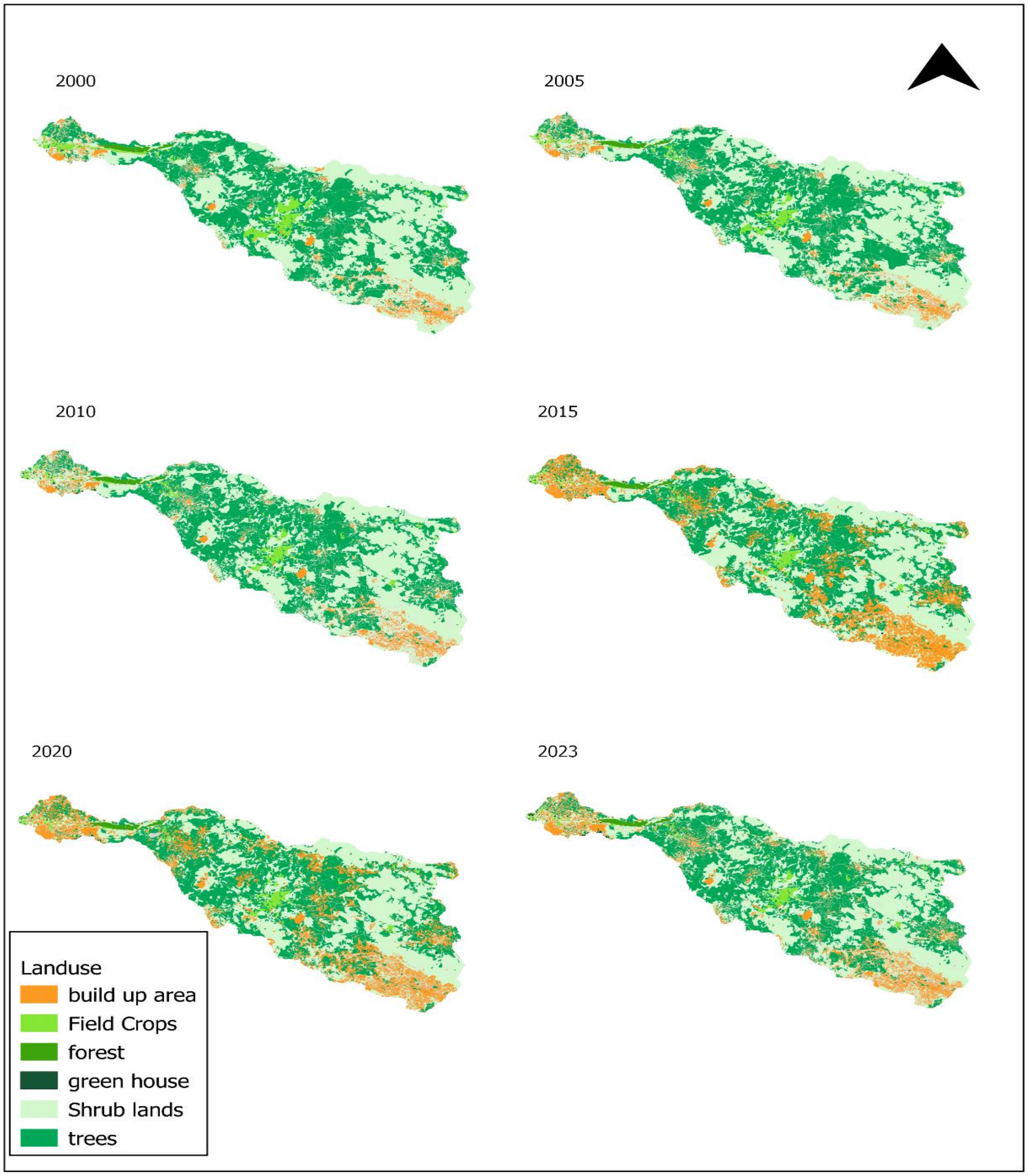


Figure 4.2: Land use of Zomar Watershed from 2000 to 2023

Table 4.3: Impervious surface percentage for three sub-catchments

Year	**Tulkarem sub catchment (impervious%)**	**Nablus sub catchment (impervious%)**	**Burqa sub catchment (impervious%)**
2000	6.50	10.50	2.56
2001	6.57	10.59	2.59
2002	6.65	10.69	2.66
2003	6.72	10.78	2.66
2004	6.8	10.88	2.69
2005	6.87	10.97	2.72
2006	7.14	11.29	2.78
2007	7.41	11.60	2.84
2008	7.68	11.92	2.91
2009	7.95	12.23	2.97
2010	8.22	12.55	3.03
2011	8.48	12.87	3.09
2012	8.75	13.18	3.15
2013	9.02	13.50	3.22
2014	9.29	13.81	3.28
2015	9.56	14.13	3.34
2016	9.87	14.52	3.48
2017	10.18	14.92	3.62
2018	10.48	15.31	3.75
2019	10.79	15.71	3.89
2020	11.10	16.10	4.03
2021	11.24	16.32	4.19
2022	11.39	16.55	4.30
2023	11.53	16.77	4.50

The Tulkarm catchment showed an increase in impervious surfaces from 6.5% in 2000 to 11.53% in 2023, representing a 5.03% increase with an annual growth rate of approximately 0.25%, indicating less urban growth than the Nablus catchment.

In contrast, the Barqa catchment, which is more rural and less densely populated than the other two catchments, witnessed its percentage increase from 2.56% to 4.5%, an increase of 1.94% over the same period. This represents an annual rate of change of only 0.08%, reflecting relatively stable land use characteristics. However, the catchment showed a slight upward trend, indicating limited or slow urban development.

Comparing the three sub-catchments, it is clear that the Nablus sub-catchment is rapidly urbanizing, potentially increasing runoff volume and the likelihood of flooding during extreme rainfall events. Meanwhile, the impact of changes in Barqa remains relatively limited.

The data analysis highlights the importance of incorporating land use data into hydrological modeling, such as HEC-HMS, as impervious surface ratios are a key input for determining the amount of runoff generated by storms and the amount of loss. Understanding and assessing these changes help decision-makers develop sustainable water management plans, especially in areas experiencing rapid urban growth.

4.3. Modelling result

The HEC-HMS model was used to estimate surface runoff in the Zomar catchment over 23 rainy seasons. Table 4.4 shows the relationship between rainfall and surface runoff, as well as peak discharge, base flow, and runoff coefficient, which represents the percentage of rainfall converted into actual surface runoff.

Table 4.4: Results for Runoff, Peak Discharge, Runoff/Rainfall Coefficients

seasonal	precipitation volume (1000 m3)	Runoff (1000M3)	Peak Discharge m^3/s	Base flow (1000 m3)	Runoff Coefficient (%)
2000-2001	72309.2	6558.3	7.9	2421.6	5.7
2001-2002	102807.4	13236.2	20.9	2516	10.4
2002-2003	141503.9	32379.7	61.2	2610.3	21.0
2003-2004	81738.1	8914.1	16.6	2743.6	7.5
2004-2005	108807.9	21268.7	71.1	2846.2	16.9
2005-2006	94578	13583.1	26.8	2956.3	11.2
2006-2007	82321.2	9619	13.4	3050.6	8.0
2007-2008	61013.2	9027.6	16.8	3185.1	9.6
2008-2009	89769.5	16238.1	38.6	3270.8	14.4
2009-2010	88550.3	16012	26.7	3365.1	14.3
2010-2011	79330	8436.1	9.3	3490.9	6.2
2011-2012	101596.1	15606.6	31.6	3595.1	11.8
2012-2013	100943	27785.5	108.1	3679.6	23.9
2013-2014	68452.9	23044.7	81.1	3805.4	28.1
2014-2015	101139.9	21237.2	23.5	3522.4	17.5
2015-2016	72991.3	7666	4.4	4005.1	5.0
2016-2017	67529	10607.3	11.5	3994.1	9.8
2017-2018	82553.1	13379.3	19	3994.1	11.4
2018-2019	129561.9	25538.5	61.5	4686	16.1
2019-2020	118853.8	25233.6	61	5392.7	16.7
2020-2021	95639.4	19801.2	34	4402.9	16.1
2021-2022	86654.7	14373.2	27.1	4906.1	10.9
2022-2023	69238.5	12466.2	20.2	4654.5	11.3

The results show that the amount of surface runoff varies significantly from one rainy season to another, the values ranging from 44.5 mm in 2000-2001 to 219 mm in 2002-2003. The average surface runoff volume in the Zomar watershed is approximately 12.5 MCM with an average runoff coefficient of approximately 13.2%. This variation reflects the direct effect of the changes in both rainfall amounts and rainfall patterns, including their intensity, frequency, and distribution.

Moreover, results reveal a variation in runoff coefficients. During the 2012-2013 season, the runoff coefficient was 23.9%, along with an exceptional peak discharge reaching 108.1 m^3/s, which was the highest among the rainy seasons, even though the rainfall volume wasn't the highest. This unexpected increase indicates that the rainfall pattern has become more intense, with precipitation occurring over shorter periods and at higher intensities. Such patterns reduce the potential for infiltration into the soil and increase the likelihood of flooding.

The graph in Figure 4.3 illustrates the relationship between rainfall and surface runoff. The relationship between them is generally linear, where the surface runoff increases as rainfall increases. However, it is also clear that there is randomness in the surface runoff amount since some seasons have the same precipitation volume with different surface runoff values, such as the 2011-2012 season and the 2012-2013 season. On the other hand, there are seasons with similar runoff values and different precipitation volumes, such as the 2013-2014 season and the 2019-2020 season.

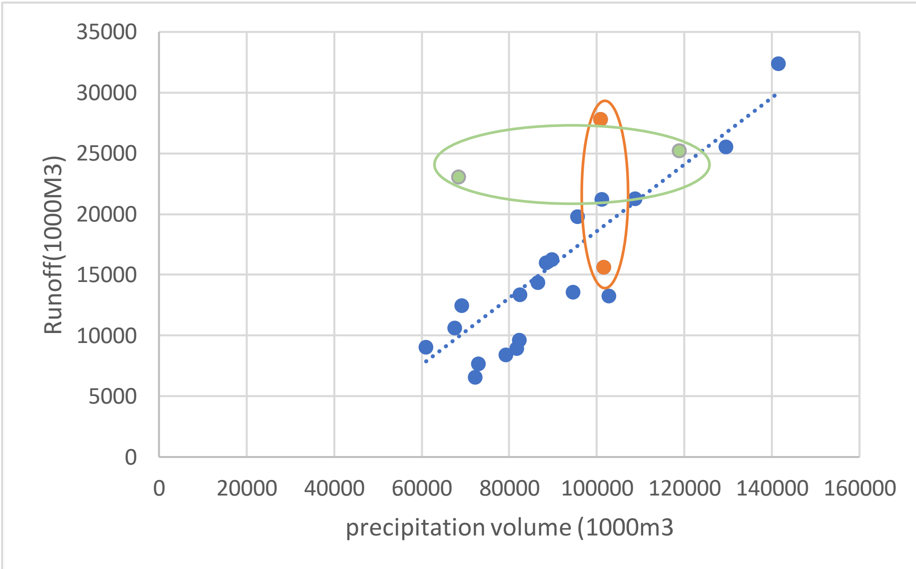


Figure 4.3: Relation between runoff and precipitation

Comparison between Seasons 2011-2012 and 2012-2013 (Similar rainfall with different surface runoff):

Despite the similar total rainfall in both years (approximately 684 mm) the resulting surface runoff volumes varied significantly. In the 2011–2012 season, the surface runoff volume was estimated at around 106 mm, whereas in 2012–2013, it increased by approximately 80%, reaching an estimated 188.4 mm. This increase suggests a higher efficiency in converting rainfall into surface runoff during the 2012–2013 season.

As for the runoff coefficient, we note a clear increase in the surface runoff coefficient from 11.8% to 23.9%, despite the annual rainfall remaining roughly similar (Table 4.5). This increase reflects a shift in rainfall patterns toward heavier, shorter-duration rainfall, leading to increased rapid surface runoff and reduced efficient soil infiltration.

Examining peak discharge, a clearer picture emerges of the differences between the two seasons. In the 2011–2012 season, peak discharge did not exceed 31.6 m^3/s, whereas in 2012–2013, it reached 108.1 m^3/s ,more than three times higher.

Table 4.5: Runoff, Peak Discharge, Runoff Coefficient, and Analysis of the Rain in 2011-2012 and 2012-2013

seasonal	RUNOFF (1000M3)	Peak Discharge	precipitation volume (1000 m3)	Base flow(1000 m3)	Runoff Coefficient(%)	Number of rainy days	No. of storm	No. ex. storm	Rain day >40
2011-2012	15607	31.6	101596	3595	11.8	53	9	3	4
2012-2013	27786	108.1	100943	3679	23.9	60	7	2	5

Although the number of rainy days and extreme storms is similar between the two seasons (Table 4.5), the key difference lies in the intensity of the storms. The 2012–2013 season was characterized by a single, intense storm in January, which recorded 200 mm of rainfall on two consecutive days (Figure 4.4). These massive amounts of water over a very short period of time caused significant damage to human life and infrastructure. This was also emphasized by Tulkarem municipality report about the 2012-2013 season (Tulkarem municipality,2013). On the other hand, in the 2011–2012 season, rainfall was distributed over longer periods, showing several small, distributed peaks (Figure 4.5). This season produced less runoff than the previous season, indicating a distributed response to moderate rainfall.

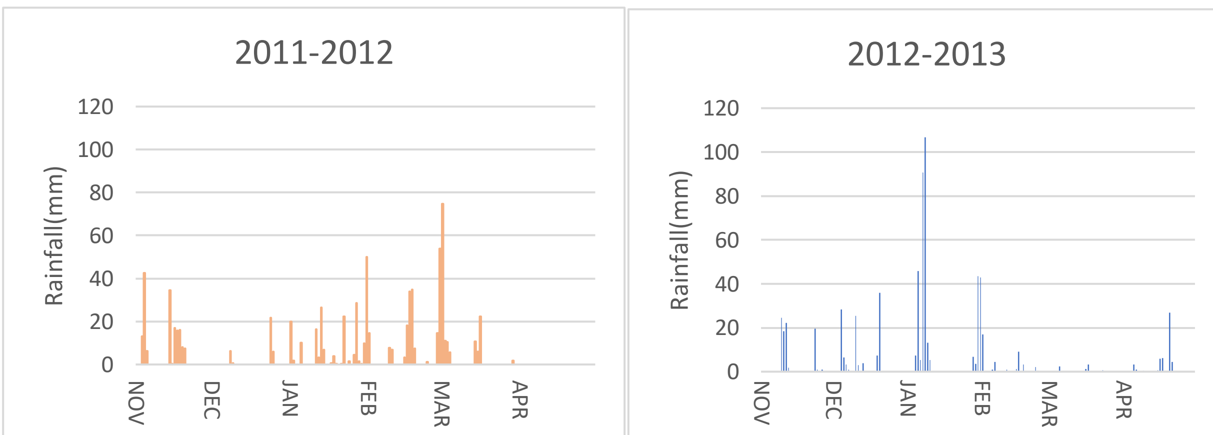


Figure 4.4: Distribution of the precipitation season 2011-2012 and 2012-2013

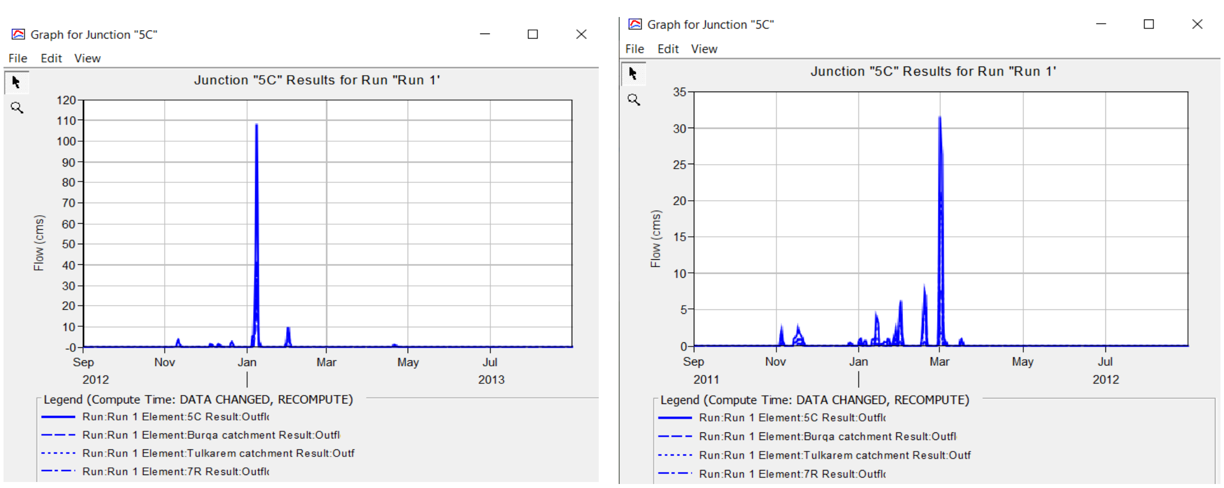


Figure 4.5: Simulated daily discharge at the watershed outlet in 2011-2012 and 2012-2013

Comparison between Seasons 2013-2014 and 2019-2020 (Similar surface runoff with different rainfall):

Analysis of the 2013–2014 and 2019–2020 seasons reveals notable variation in total rainfall, despite the similarity in runoff values shown in Table 4.6. In the 2013–2014 season, rainfall was limited in terms of temporal distribution but very intense. A large amount of rainfall was concentrated in December in a single rain event that exceeded 120 mm in a single day Figure 4.6. This event generated a sharp and rapid peak runoff, as shown in Figure 4.7, which showed a high peak discharge of 81.1 cubic m3/s. This sharp peak reflects the sudden nature of the storm.

On the other hand, in the 2019–2020 season, rainfall was evenly distributed throughout the season Figure 4.6, with a higher number of storm events (Table 4.6). This broader temporal distribution of rainfall contributed to reducing pressure on the watershed, allowing the soil to infiltrate large amounts of water, resulting in a more even distribution of surface runoff over a longer period.

Table 4.6: Runoff ,Peak Discharge, Runoff Coefficient, and Analysis of The Rain in 2013-2014 and 2019-2020

seasonal	RUNOFF (1000M3)	Peak Discharge (m^3/s)	precipitation volume (1000 m3)	Base flow (1000 m3)	Runoff Coefficient (%)	Number of rainy days	No. of storm	No. ex. storm	Rain day >40
2013-2014	23044.7	81.1	68452.9	3805.4	28.1	30	4	1	2
2019-2020	25233.6	61	118853.8	5392.7	16.7	68	9	5	6

Although the rainfall in the 2019-2020 season was significantly higher, the runoff coefficient did not exceed 16.7%, compared to 28.1% in the 2013-2014 season. This significant difference reflects that the majority of the rainfall in 2019-20 was infiltrated into the soil, reducing the proportion that turned into surface runoff. In contrast, the high rainfall intensity in 2013-2014 contributed to a higher runoff coefficient and a greater proportion of water diverted to runoff. Figure 4.6 also supports this conclusion. The 2013-2014 season shows a single, sharp, and concentrated peak, while the 2019-2020 season shows multiple peaks spread over a longer timescale, with a less sharp peak discharge. This clearly reflects how the nature and temporal distribution of storms directly influence runoff volume more than the total rainfall amount.

In light of the above, it can be argued that the 2013–2014 season was characterized by a single extreme rainfall event, while the 2019–2020 season was more balanced in terms of the temporal distribution of rainfall, reducing the risk of flash floods despite the greater rainfall.

This analysis confirms that rainfall volume amount is not sufficient to determine the severity of a season; rather, the intensity of rainfall, the number of storms, and their temporal distribution must always be considered as essential factors in understanding the behavior of the hydrological system. This was also emphasized by previous literature, which indicated that the intensity and frequency of rainfall have a greater impact on runoff than annual rainfall volume averages as (Kiprotich et al., 2021; Rezaei et al., 2019). Moreover, the results are consistent with the literature that indicated a close relationship between storm characteristics and runoff, as increased storm intensity often leads to higher runoff rates (Hasan et al., 2018).

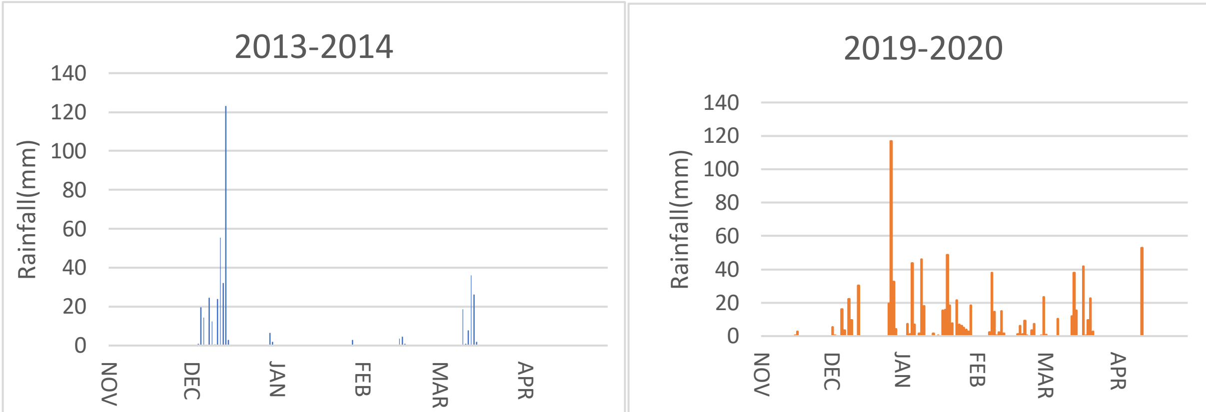


Figure 4.6 : Distribution of the precipitation season 2013-2014 and 2019-2020

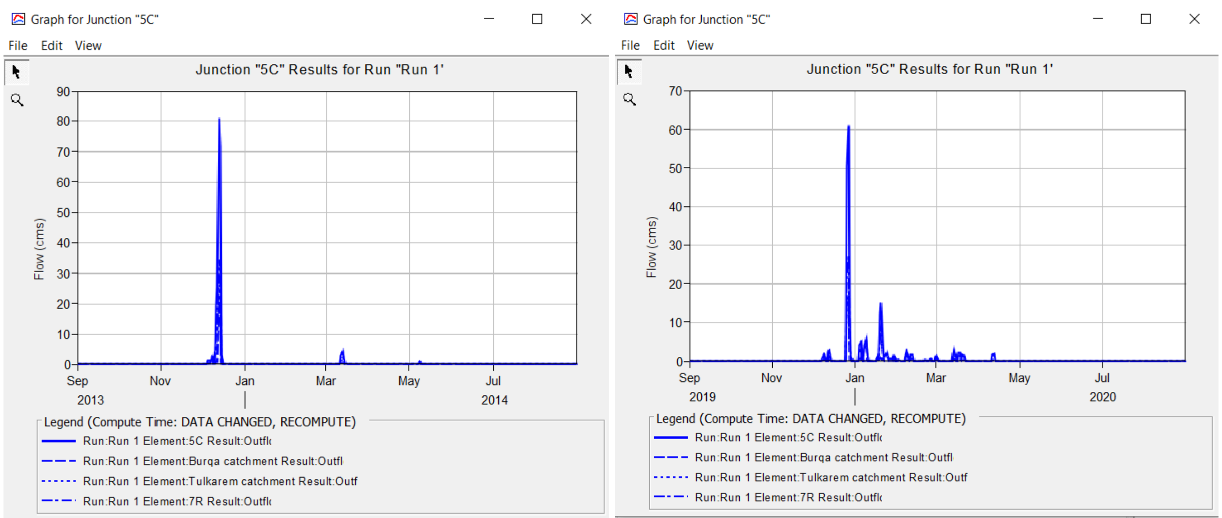


Figure 4.7*:* Simulated daily discharge at the watershed outlet in 2013-2014 and 2019-2020

Analysis of runoff for the sub-catchments:

The rainfall amounts, surface runoff, peak discharge, along with the runoff coefficient for the Nablus, Burqa, and Tulkarm sub-catchments are presented in Table 4.7 for the period 2000-2023. The results showed a clear variation in the surface runoff response between the three sub-catchments. Nablus had the highest values of surface runoff, with an average runoff coefficient of 20.6%. This reflects the increased impervious surfaces in this catchment compared to other catchments. It was followed by the Tulkarm catchment, with an average runoff coefficient of 14.5%. Burqa had the lowest runoff, showing the lowest values of the runoff coefficient, with an average of approximately 5.72%.

Burqa had the lowest runoff rate despite the great similarity in rainfall rates and intensity with the Nablus catchment. This low surface runoff is attributed to the small number of impervious areas in the Burqa area, which are less widespread compared to other catchments. These impervious surfaces are scattered throughout the watershed, while the majority of the area is covered by lands planted with trees and shrubs, which enhances the soil's ability to infiltrate rainwater and reduces the resulting surface runoff.

For example, the 2018-2019 season witnessed significant variation in the response of the three sub-catchments to rainfall, reflecting the influence of topographic factors, soil type, vegetation distribution, and the proportion of impervious surfaces in each area.

The Nablus catchment recorded the highest runoff value, where the rainfall amounted to about 925 mm, resulting in a surface runoff of about 225.5 mm, with a runoff coefficient of 24.4%. This high ratio indicates a high efficiency in converting rainfall into surface runoff, and this is often attributed to the high proportion of impervious surfaces, urbanization, and the intensity of rainstorms. This is clearly shown in Figure 4.8, where severe rainfall events occurred repeatedly, resulting in multiple peaks in discharge, the most prominent of which reached approximately 23.3 m^3/s.

In the Tulkarm sub-catchment, although the rainfall was relatively low compared to the catchments at 778.4 mm, the runoff volume was relatively large at 146.5 mm, with a runoff coefficient of 18.8%. What stands out in this sub-catchment is that it recorded the highest instantaneous discharge value, reaching 27 m3/s. Although the runoff coefficient is not the highest, the hydrograph in Figure 4.8 shows a sharp response during a single rainfall event at the end of December, indicating a rapid discharge associated with a short and intense storm.

As for the Burqa catchment, the rainfall was similar to the Nablus catchment, 925 mm, but the resulting runoff did not exceed 60.29 mm, which represents a runoff coefficient of 15.24% of the total surface rainfall. The maximum discharge did not exceed 6.5 m^3/s. This large difference between rainfall and runoff volume confirms the soil's efficiency of water infiltration, in addition to the widespread vegetation cover, which reduces the speed of runoff and increases infiltration rates. The scarcity of impervious surfaces and their dispersed distribution are also significant compared to the Nablus catchments. Figure 4.8 also shows that there is a single, short-term flow peak in January, followed by near-complete stability for the rest of the season.

By comparison, Nablus and Tulkarm are more prone to high peaks and flash floods, while Burqa exhibits a more conservative, rainfall-absorbing behavior. This disparity is due to differences in land cover and land use patterns.

This analysis demonstrates that one important factor that greatly affects surface runoff is urban expansion, as the more urban expansion increases, the more surface runoff increases. This result is consistent with what many previous studies have indicated, such as (Gulshad et al., 2024), which proved that the increase in urban areas at the expense of agricultural and forest lands leads to a significant increase in the surface runoff coefficient, which enhances the understanding of the relationship between land use patterns and flood risk.

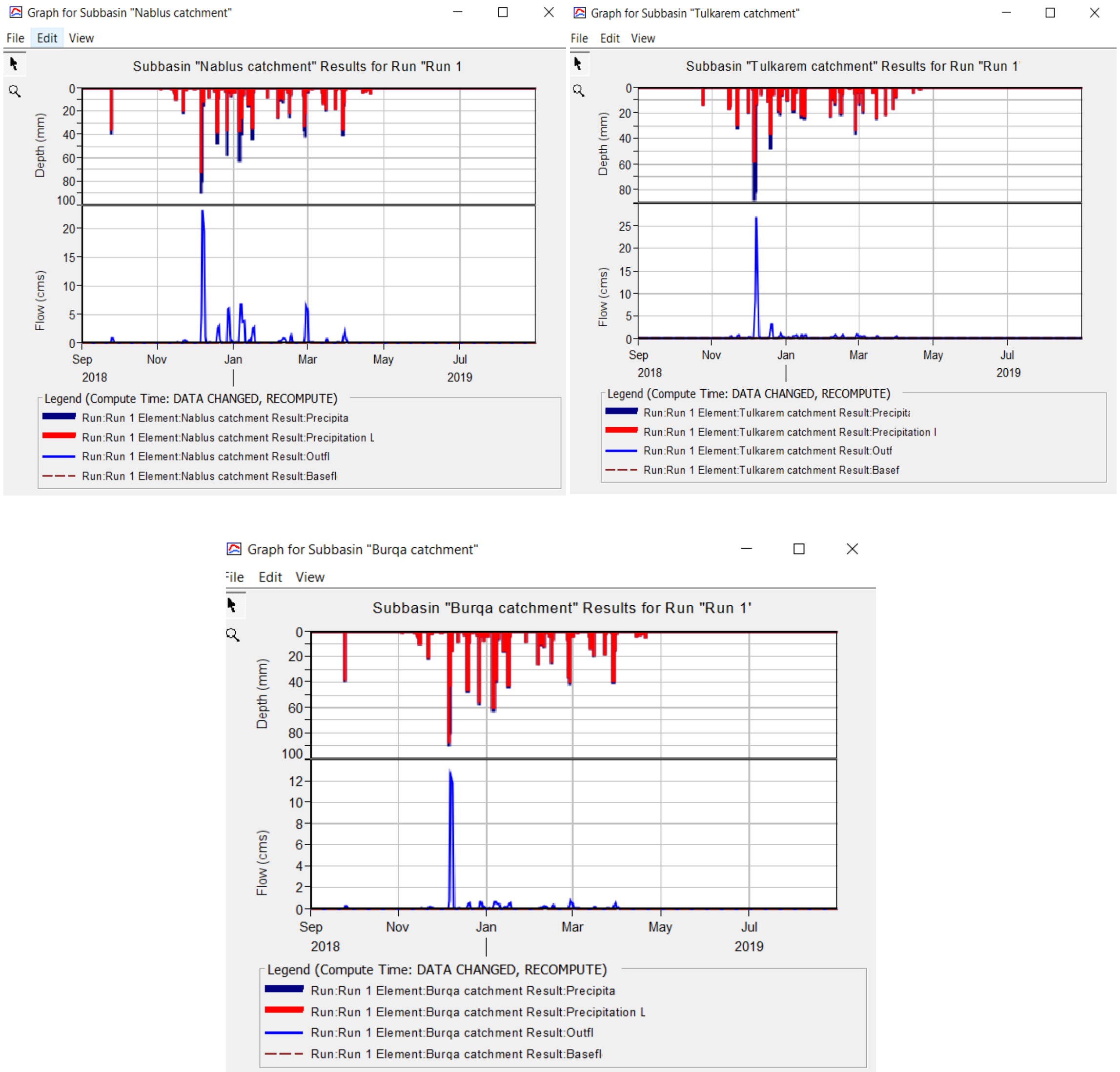


Figure 4.8: Rainfall versus Simulated daily runoff generated in Nablus, Tulkarem, and Burqa sub-catchment in 2018-2019

Table 4.7: The runoff and peak discharge, and runoff coefficient for Nablus, Burqa and Tulkarem from 2000-2023

	Nablus				Burqa				Tulkarm			
	precipitation volume (1000m3)	Runoff (1000M3)	Peak Discharge	Runoff Coefficient (%)	precipitation volume (1000m3)	Runoff (1000M3)	Peak Discharge	Runoff Coefficient (%)	precipitation volume (1000m3)	Runoff (1000M3)	Peak Discharge	Runoff Coefficient (%)
2000-2001	20644.9	1141.7	1.8	5.5	23553.9	385	0.4	1.63	28110.4	2297.5	7.8	8.2
2001-2002	34916.5	6823.3	12.4	19.5	39836.5	882.7	1.7	2.22	28054.4	2935.7	7	10.5
2002-2003	49968.6	16572.4	28.4	33.2	57009.5	6206.1	15.6	10.89	34525.8	6773.8	17.2	19.6
2003-2004	26726.3	3359.8	8.8	12.6	30492.3	659.1	1	2.16	24519.5	2100.4	6.8	8.6
2004-2005	37180.6	9120.7	31.7	24.5	42419.6	3966.5	19.1	9.35	29207.7	5210.6	21.6	17.8
2005-2006	32643	6554.7	14.4	20.1	37242.7	1972.6	7.5	5.30	24692.3	1979.6	5	8.0
2006-2007	28538.5	3484	4.6	12.2	32559.8	591.8	0.7	1.82	21222.9	2448.1	9.7	11.5
2007-2008	20343.7	3477.1	17.7	17.1	23210.2	656.3	2.3	2.83	17459.3	1663.3	7.5	9.5
2008-2009	30595.5	7039.6	20.4	23.0	34906.6	2040	7.1	5.84	24267.4	3783.4	12	15.6
2009-2010	27526.5	5808.9	16.3	21.1	31405.2	1522.4	6.1	4.85	29618.6	5255.8	19.3	17.7
2010-2011	26853.4	3235.2	6.4	12.0	30637.3	563.6	0.9	1.84	21839.3	1091.5	2	5.0
2011-2012	35142.5	7776.4	22.3	22.1	40094.3	2119.4	7.9	5.29	26359.3	2011.1	2.7	7.6
2012-2013	32318.3	10397.6	43.5	32.2	36872.1	5570.3	29.2	15.11	31752.6	8021.4	36.6	25.3
2013-2014	21929.9	8504.9	35.5	38.8	25020	3913.1	20.5	15.64	21503	6726.9	26.3	31.3
2014-2015	31400.4	7769.1	16.1	24.7	35824.9	1671.1	5.9	4.66	33914.6	8169.1	21.7	24.1
2015-2016	25516.6	2220.2	3.5	8.7	29112.1	552.1	0.7	1.90	19959.8	865.4	1	4.3
2016-2017	22410	3717.8	9.7	16.6	25567.8	665	0.9	2.60	19551.2	2185.2	6	11.2
2017-2018	26622.8	4300.7	7.6	16.2	30374.1	750	0.8	2.47	25556.2	4262.4	16.8	16.7
2018-2019	43539.7	10616.7	23.3	24.4	49674.8	3236.5	6.5	15.24	36347.4	6840.5	27	18.8
2019-2020	43473.9	10309.4	27.7	23.7	49599.6	4071.3	16.5	8.21	25780.3	5329.7	17.2	20.7
2020-2021	30746.1	7833.1	20.2	25.5	35078.5	2157	8.2	6.15	29814.8	5318.7	12	17.8
2021-2022	27973.7	5125.2	13.9	18.3	31915.4	831.8	1.3	2.61	26765.6	3426.4	12.7	12.8
2022-2023	22264.1	4598.2	11.3	20.7	25401.3	752.3	1.5	2.96	21573.1	2405.1	8	11.1
Average				20.6				5.72				14.5

4.4. Impact of the urban area

The study analyzes the impact of changes in the percentage of urban area on surface runoff during the period from 2000 to 2023 by comparing two cases. The first case is based on fixing the percentage of urban area at the values of the 2000-2001 season and applying it to selected subsequent seasons: 2005-2006, 2010-2011, 2015-2016, 2018-2019, etc, as shown in Table 4.8. In the second case, the actual percentages of urban area are used as they are for each season. By comparing the surface runoff results between the two cases, the study demonstrates the impact of urban expansion and land use change on surface runoff volume, which helps in understanding the relationship between urban growth and surface runoff.

The results presented in Table 4.8 indicate a clear reduction in runoff volume, peak discharge, and runoff coefficient values when the percentage of urban area was held constant at 2000–2001 levels, compared to the actual values for those seasons. For instance, in the 2018–2019 season, the runoff volume was 202.5 mm when using the actual impervious surface percentage but decreased to 156.33 mm when fixed at 2000–2001 levels, a reduction of approximately 23%. Similarly, the maximum discharge declined from 61.5 m^3/s to 59.3 m^3/s, and the runoff coefficient dropped from 19.4% to 14.2%.

Table 4.8: Runoff and peak discharge, actual land use versus land use 2000-2001

Seasonal	Runoff (1000M3)	Peak Discharge (m3/s)	Runoff Coefficient (%)	Runoff (1000 M3) land use 2000-2001	Peak Discharge (land use 2000-2001) (m3/s)	Runoff Coefficient (%) (land use 2000-2001)
2005-2006	13583.1	26.8	11.2	13392.7	26.7	11.0
2010-2011	8436.1	9.3	6.2	7810.9	8.3	5.4
2015-2016	7666	4.4	5.0	6818	3.7	3.9
2018-2019	29871.7	61.5	19.4	23058.7	59.3	14.2
2019-2020	25233.6	61	16.7	23668.3	60.3	15.4
2020-2021	19801.2	34	16.1	17715.7	32.2	13.9
2021-2022	14373.2	27.1	10.9	12072.1	23.7	8.3
2022-2023	12466.2	20.2	11.3	10786.9	17.4	8.9

This trend was consistent across the remaining seasons, with all hydrological indicators showing noticeable declines when impervious surface percentages were held constant. These results clearly demonstrate the direct impact of increased urbanization and the expansion of impervious surfaces on surface runoff. The analysis reinforces the conclusion that land use changes during the study period significantly contributed to higher runoff volumes and peak flows, highlighting the critical importance of incorporating sustainable urban planning into stormwater and drainage management strategies.

4.5. Analysis of the impact of Land use Change on Projected Runoff (2024 –2033)

In order to assess the impact of land use change on runoff over the next ten years (2024-2033), the rainfall pattern was assumed constant according to what was recorded during the period from 2013 to 2023. This was done to assess the impact of urban expansion as the only variable factor in the analysis. The hydrological model was applied to the Nablus sub-catchment, as it is a densely populated urban area, making it more vulnerable to the effects of the expansion of impervious surfaces.

Projected changes in land use were incorporated into the model, with the annual rate of increase in impervious surfaces calculated using Equation (1). It was found that these areas increase at an annual rate of 2.7%. Based on this, the expected increase in surface runoff during the future period under study was estimated. The estimated percentage of impervious surfaces from 2024 to 2033 is indicated in Appendix 3.

$$\frac{\text{Final Value} - \text{Initial Value}}{\text{Number of Years}} = \text{Average Annual Increase} \qquad \ldots\ldots\ldots\ldots\ldots 1$$

Average Annual Increase = (10.5-16.77)/23 ≈ 0.27

The results presented in Table 4.9 indicate a gradual increase in surface runoff in terms of volume, peak discharge, and runoff coefficient during the period 2024–2033, despite relatively stable rainfall amounts. This trend reflects the direct and cumulative impact of the expansion of impervious surfaces, which reduce infiltration and accelerate the conversion of rainfall into surface runoff.

Table 4.9: The runoff and peak discharge and runoff coefficient, for the season from 2013-2014 to 2022-2023 versus the next ten years of land use in Nablus sub-catchment

seasonal	Runoff (1000M3)	Peak Discharge	precipitation volume (1000m3)	Runoff Coefficient(%)	seasonal	Runoff (1000M3)	Peak Discharge	Runoff Coefficient(%)
2013-2014	8504.9	35.5	21930	38.78221	2023-2024	8835.4	35.7	40.28929
2014-2015	7769.1	16.1	31400	24.74204	2024-2025	8312.8	16.5	26.47355
2015-2016	2220.2	3.5	25517	8.701002	2025-2026	2633.9	3.9	10.3223
2016-2017	3717.8	9.7	22410	16.58992	2026-2027	4184.2	10.2	18.67113
2017-2018	4300.7	7.6	26623	16.1542	2027-2028	4778.1	8	17.9474
2018-2019	10616.7	23.3	43540	24.38395	2028-2029	11388.4	23.9	26.15636
2019-2020	10309.4	27.7	43474	23.714	2029-2030	11084.6	28.2	25.49714
2020-2021	7833.1	20.2	30746	25.47673	2030-2031	8253.9	20.6	26.84536
2021-2022	5125.2	13.9	27974	18.32149	2031-2032	5508	14.4	19.68992
2022-2023	4598.2	11.3	22264	20.65298	2032-2033	4939.2	11.9	22.18459

For example, surface runoff volume in 2028-2029 reached approximately 241.91 mm, compared to 226.5 mm in the reference year 2018–2019, despite stable rainfall in both years. The runoff coefficient also increased from 24.4% to 26.2%, reflecting the increased surface capacity to generate rapid runoff. In the same context, peak discharge increased from 23.3 to 23.9 m^3/s, indicating increased flow intensity during periods of maximum rainfall, which represents increasing pressure on drainage networks in urban areas. This remarkable difference is a clear example of the cumulative impact of urbanization on the hydrological system. Several years of urban expansion can significantly alter runoff volume, even with consistent rainfall. These results confirm that maintaining an urban planning approach without incorporating surface water considerations will increase cities' vulnerability to flooding and weaken their ability to effectively manage stormwater in the future.

Chapter Five

5. Conclusions and Recommendations

5.1. Conclusions

This comprehensive study aimed to investigate the influence of climate change and land use change on surface runoff in the Zomar Watershed during the study period, 2000 -2003. It followed a structured methodology to analyze and evaluate the climatic conditions, determine the number of extreme events during the years 2000 to 2023, and calculate the generated surface runoff in the Zomar watershed during these years. The study utilized the WMS and HEC-HMS hydrological models to analyze the hydrological dynamics of the Zomar watershed and the generated storm water. Then, the results of the model were used to evaluate the impact of the climatic factors and land use on the generated surface runoff and the hydrological processes.

The results of the study revealed a notable increase in runoff, primarily due to the increased frequency of severe storms. Frequent rainfall with high volumes, especially when consecutive, significantly contributed to this increase. These results highlight a strong relationship between storm characteristics, such as rainfall intensity and frequency, and surface water runoff rates. The runoff coefficient analysis shows that it rises significantly in seasons with short, intense rainstorms, even if the total rainfall is low. Climatic factors were among the most influential, showing a clear correlation with increased runoff volumes across the watershed.

In addition to climatic factors, changes in land use, specifically urban expansion, were found to play a major role in exacerbating surface runoff. The growth of impervious areas due to urban development led to substantial increases in runoff volumes, demonstrating the impact of human activities on flood risk.

The results also showed that the surface runoff coefficient in the Zomar watershed ranged between 5% and 28.1%, with an average of approximately 13.2%. At the sub-catchment level, the highest average was recorded in Nablus (20.6%), followed by Tulkarm (14.5%), while the lowest average was recorded in Barqa (5.7%). Moreover, the estimated average runoff volume in the Zomor watershed, approximately 12.5 million cubic meters (MCM), represents a significant and underutilized water resource. Without effective intervention, these quantities contribute to increased flood risks rather than supporting sustainable water supply solutions. The model also forecasted the future projections (2024–2033), which held rainfall constant and only changed the percentage of impervious surfaces, showed a gradual increase in runoff as a result of urban expansion.

According to the findings of the study, there is an urgent need to develop a comprehensive action plan that addresses both climate and land use challenges. Such a plan should aim to enhance water resource utilization, reduce flood hazards, and support the achievement of Sustainable Development Goals (SDGs) 6, 12, and 13, which promote clean water access, responsible land use, and climate resilience.

5.2. Recommendations

1- Recommendations to Decision-Makers (Palestinian Water Authority, Ministry of Agriculture, and Municipalities) for the construction of water harvesting structures such as ponds or dams to enhance water harvesting. These efforts aim to make better use of surface runoff for supporting agricultural activities and contributing to sustainable development.
2- It is recommended that municipalities regularly develop, expand, and maintain the wadi channel to mitigate flood risks.
3- It is recommended that cooperation between municipalities and the Palestinian Meteorological Department should be strengthened to monitor weather conditions and take upcoming storm events into account, with the aim of implementing proactive measures to reduce flood risks.
4- It is recommended to establish early warning systems in urban areas near the wadi channel to provide timely flood alerts to residents and enable them to take necessary preventive actions.

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Appendices

Appendix 1: HECHMS Model

Figure from the HECHMS program for the Zomar watershed, and calculate some parameters such as the initial deficit, the Maximum Deficit , and constant rate.

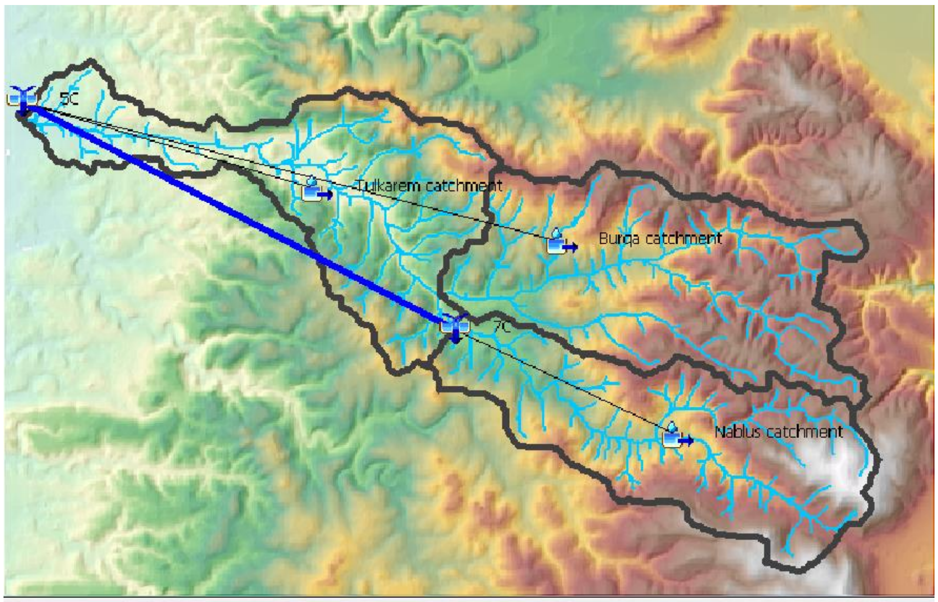


Figure: The hydrological model for the Zomar watershed in HEC-HMS

Initial deficit

TYPE			**Tulkarem catchment**	**Nablus catchment**	**Burqa catchment**
		Wilting Point	AREA% *Wilting Point	AREA% *Wilting Point	AREA% *Wilting Point
Grumusols	D	35.2	3.5	3.7	1.6
Terra Rossa, Brown and Pale Rendzinas	A	29.7	17.4	16.4	10.3
Brown and Pale Rendzinas	B	20.2	5.5	6.6	10.1
Pale Rendzinas	C	16.4	0.7	0.3	1.7
SUM (Initial deficit)			27.1	26.9	23.8

Maximum Deficit

TYPE			Tulkarem catchment	Nablus catchment	Burqa catchment
		saturation	AREA% *saturation	AREA% *saturation	AREA% *saturation
Grumusols	D	50.9	5.04	5.3	2.4
Terra Rossa, Brown and Pale Rendzinas	A	45.7	26.81	25.2	15.9
Brown and Pale Rendzinas	B	46.6	12.72	15.1	23.3
Pale Rendzinas	C	45.9	1.90	0.9	4.8
SUM(Maximum Deficit)			46.47	46.5	46.4

Constant Rate

TYPE			Tulkarem catchment	Nablus catchment	Burqa catchment
		saturated hydraulic conductivity	AREA% *saturated hydraulic conductivity	AREA% *saturated hydraulic conductivity	AREA% *saturated hydraulic conductivity
Grumusols	D	0.25	0.02	0.03	0.01
Terra Rossa, Brown and Pale Rendzinas	A	1	0.59	0.6	0.3
Brown and Pale Rendzinas	B	6	1.64	1.9	3.0
Pale Rendzinas	C	20	0.83	0.4	2.1
Constant Rate			3.08	2.9	5.5

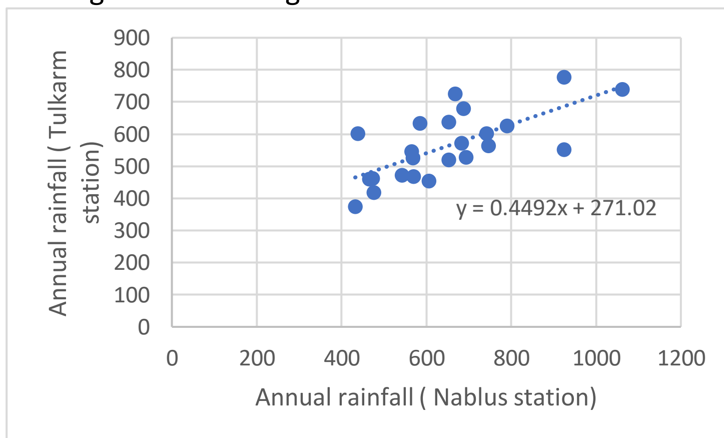
Appendix 2: Estimation Methods for Missing and Aggregated Rainfall Data

Some data at the Tulkarm station was missing and was estimated using the linear regression method. Additionally, on certain days, rainfall was reported as a cumulative total over multiple days rather than as individual daily values.

Table:Annual rainfall in Nablus and Tulkarm stations

season	Nablus station	Tulkarem station
2000-2001	438.6	602
2001-2002	741.8	601.507
2002-2003	1061.5	739.2981
2003-2004	567.8	526.3388
2004-2005	789.9	625.2523
2005-2006	693.5	528.8
2006-2007	606.3	454.5
2007-2008	432.2	373.9
2008-2009	652	519.7
2009-2010	584.8	634.3
2010-2011	570	467.7
2011-2012	746.6	564.5
2012-2013	686.8	680
2013-2014	465.9	460.5
2014-2015	667.1	726.3
2015-2016	542	472.45
2016-2017	476.1	418.7
2017-2018	565.5	547.3
2018-2019	925	778.4
2019-2020	923.6	552.1
2020-2021	653.2	638.8
2021-2022	683	573.2
2022-2023	473	462

Figure : Linear regression for Annual rainfall



(Nablus station, Tulkarm station)

The following equations were used to estimate daily rainfall values in cases where data was missing or when cumulative rainfall was reported over multiple days

$$\frac{P_{dN}}{P_{AN}} = I$$

$P_{AT} * I = P_{dT}$

Where :

P_{AN}: Annual precipitation in Nablus

P_{dN}: Daily precipitation in Nablus

I: index

P_{AT}: Annual precipitation in Tulkarem

P_{dT}: Daily precipitation in Tulkarem

Appendix 3: Impervious Surface

Impervious surface percentage from 2024-2033

Year	**Tulkarem catchment (impervious%)**	**Nablus catchment (impervious%)**	**Burqa catchment (impervious%)**
2024	11.82	16.98	4.55
2025	12.12	17.28	4.61
2026	12.31	17.58	4.67
2027	12.56	17.88	4.73
2028	12.8	18.18	4.79
2029	13.05	18.74	4.85
2030	13.29	18.77	4.91
2031	13.54	19.07	4.97
2032	13.78	19.37	5.03
2033	14.03	19.67	5.09

تقييم آثار تغير المناخ واستخدام الأراضي على توليد الجريان السطحي :دراسة حالة مستجمعات المياه في زومر

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الملخص:

يشكل الجريان السطحي مكونا حاسما في الدورة الهيدرولوجية، ويتأثر بتقلبات المناخ والتغيرات في استخدام الأراضي والخصائص الطبوغرافية. وفي المناطق القاحلة وشبه القاحلة مثل الضفة الغربية، يعد فهم التفاعل المعقد بين تغير المناخ، والتغير في استخدامات الاراضي المتعلقة بتوليد الجريان السطحي أمرا مهما لتنفيذ استراتيجيات الإدارة المستدامة للموارد المائية والتخفيف من مخاطر الفيضانات. حيث تؤثر التغيرات المناخية مباشرة على الجريان السطحي من خلال التغيرات في درجات الحرارة، والتبخر، وشدة هطول الأمطار، وتكرارها، وتوزيعها. بينما يؤدي التحضر وتغيرات استخدام الأراضي إلى زيادة الأسطح غير المنفذة، مما يزيد من كمية جريان المياه السطحية ويزيد من خطر الفيضانات. تهدف هذه الدراسة إلى تقييم تأثير تغير المناخ وتحولات استخدام الأراضي على توليد الجريان السطحي داخل مستجمعات المياه في زومر، خاصة وأنها تقع بين مدينتي نابلس وطولكرم، اللتين تعتبران من أكثر المدن كثافة سكانية. بالنظر إلى التوسع الحضري وزيادة تواتر وشدة أحداث هطول الأمطار الشديدة في المنطقة، فإن هذا التحليل الشامل يحدد هذه الآثار ويقترح استراتيجيات إدارة المياه القائمة على الأدلة.

في الدراسه تم تطوير نموذجا هيدرولوجيا باستخدام نظام نمذجة مستجمعات المياه (WMS) المتكامل مع نظام النمذجة الهيدرولوجية (HEC-HMS) لمستجمعات زمور. تم تقسيم مستجمعات المياه في زومر إلى ثلاثة مستجمعات فرعية: نابلس وطولكرم وبرقه. لبناء النموذج، استخدمت الدراسة مجموعة واسعة من البيانات، بما في ذلك سجلات هطول الأمطار اليومية من عام 2000 إلى عام 2023، وخرائط استخدام الأراضي عالية الدقة التي تم إنشاؤها من الصور الجوية، والمعلومات التفصيلية حول التربة والتضاريس التي تم تحليلها. تمت معايرة النموذج والتحقق من صحته باستخدام بيانات هطول الأمطار والجريان السطحي

الذي تم رصده خلال الفترة 2005–2006. لمحاكاة التسلل، تم تطبيق طريقة العجز والثابت، بينما تم استخدام طريقة وحدة كلارك الهيدروغرافية لنمذجة عملية الجريان السطحي بدقة.

تظهر النتائج أن آثار تغير المناخ وتغيرات استخدام الأراضي قد ادت الى زيادة في توليد الجريان السطحي في جميع أنحاء مستجمعات المياه في زومر. التحليل الكمي أن التحضر زاد من التغطية السطحية للأسطح الغير منفذه في المستجمعات الفرعية بنسبة 6.27٪ في نابلس و5.03٪ في طولكرم و1.94٪ في البرقة بين عامي 2000 و2023، مما أدى إلى تقليل قدرة التسلل وتضخيم أحجام الجريان السطحي. وقد بلغ معدل الجريان السطحي في وادي زومر خلال 23 سنه 12.5 مليون متر مكعب بمعدل معامل الجريان 13.2 %. أثبتت النمذجة الهيدرولوجية أن أنماط توزيع شدة هطول الأمطار لها تأثير أكبر على توليد الجريان السطحي من تأثير هطول الأمطار الموسمية التراكمية. و قد تجلى ذلك في موسم 2013–2014، حيث تركز هطول الأمطار في أيام محددة ذات كثافة عالية، مما أدى إلى ارتفاع كبير في معاملات الجريان السطحي وتصريف الذروة مقارنة بالمواسم ذات الأمطار الإجمالية المماثلة أو الأكبر ولكن أنماط هطول الأمطار موزعة زمنيا وكشف التحليل المكاني عن عدم تجانس واضح بين مستجمعات المياه الفرعية، حيث حقق مستجمعات نابلس الفرعية أعلى متوسط معامل جريان سطحي (20.6٪) بسبب التوسع الحضري، مقارنة بمستجمعات طولكرم (14.5٪) وبرقع (5.72٪).كما اوضحت الدراسة ان التطور العمراني في المستقبل يزيد من الجريان السطحي مما قد يأدي الى خطر الفيضانات.

تثبت هذه الدراسة بشكل قاطع أن التأثير التراكمي لتغير المناخ وتغيرات استخدام الأراضي يزيد بشكل كبير من خطر الجريان السطحي والفيضانات المفاجئة داخل مستجمعات المياه في زومر. وتؤكد النتائج على الضرورة الملحة لتنفيذ مناهج الإدارة المتكاملة لمستجمعات المياه، بما في ذلك سياسات التنمية الحضرية المستدامة، والتعزيز الاستراتيجي لشبكات البنية التحتية الخضراء، ومبادرات مبتكرة لحصاد المياه. هذه الاستراتيجيات ضرورية ليس فقط للحد الفعال من مخاطر الفيضانات ولكن أيضا لتحسين استخدام الموارد المائية بما يتماشى مع أهداف الأمم المتحدة للتنمية المستدامة (SDGs)، لا سيما تلك التي تتناول الأمن المائي والقدرة على الصمود في وجه تغير المناخ.