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Flood Risk Analysis in Wadi Al-Huski Basin within the Imam Turki bin Abdullah Royal Reserve Using the SCS-CN Model

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Abstract

The problem of this study lies in the limited accuracy of meteorological station data in representing the spatial variability of rainfall in Wadi Al-Huski basin, which affects the estimation of surface runoff and flood risk assessment. The study aims to analyze the hydrological behavior of the basin and estimate surface runoff using the SCS-CN model supported by GIS techniques.The study adopts a quantitative and applied approach using climatic data and satellite imagery, due to their effectiveness in analyzing natural characteristics and simulating surface runoff. The results indicate an increase in future surface runoff despite the slight rise in rainfall, with clear spatial variability and concentration along drainage channels. Most of the basin falls under low to moderate flood risk levels, with limited high-risk areas. The study recommends developing early warning systems, avoiding urban expansion in high-risk areas, and enhancing the use of spatial technologies in flood management.

Keywords: Al-Haski Valley, Flood Hazards, SCS-CN, Surface Runoff, Geographic Information Systems.

Introduction

Water resources are considered among the most important natural resources upon which sustainable development plans depend, particularly in arid and semi-arid regions characterized by water scarcity and irregular rainfall patterns (Al-Shaibani & Al-Amri, 2015). One example of such regions is Saudi Arabia. These regions rely heavily on rainfall and the resulting surface runoff, making the study of the hydrological behavior of drainage basins highly important for understanding water resources and managing them efficiently.

Accordingly, the need for accurate hydrological studies has emerged to contribute to drainage basin analysis and evaluate their hydrological response to rainfall (Abdelkader & El Bastawesy, 2018).

With the advancement of remote sensing technologies and Geographic Information Systems (GIS), it has become possible to extract accurate quantitative information using Digital Elevation Models (DEMs), which contribute to analyzing the morphometric characteristics of drainage basins. This helps explain the hydrological response of basins in terms of surface runoff, discharge rates, and rainfall response time through factors such as drainage network density, basin shape, slope degree, and the nature of stream networks. The integration of these data into hydrological simulation models has also improved the representation of surface runoff, the estimation of water discharge volumes, and the accuracy of flood hazard prediction.

Despite the availability of these technologies, applied studies employing spatial analysis tools and hydrological modeling in local drainage basin studies remain limited, particularly at the level of small and medium-sized basins. Furthermore, the relationship between morphometric characteristics, climatic data, and surface runoff results has not received sufficient attention in some regions, highlighting the need for integrated studies that contribute to filling this scientific gap.

This study focuses on conducting an integrated hydrological analysis of the drainage basin using GIS techniques and Digital Elevation Models to understand its morphometric characteristics and hydrological behavior, as well as to evaluate its response to rainfall. This contributes to supporting water planning, mitigating flood hazards, and enhancing sustainable water resource management.

Within the framework of studying the rainfall and hydrological characteristics of Wadi Al-Huski in the Imam Turki bin Abdullah Royal Reserve, a research problem emerges concerning the varying accuracy of meteorological station data in representing the spatial reality of rainfall distribution, particularly during localized cloud formations (“Al-Marawih”).

Although observational data indicate that the highest rainfall rates were recorded at Zabala Station, with an average of approximately 62 mm, relying solely on these data does not necessarily reflect the actual spatial distribution of rainfall within the wadi. This is due to the heterogeneous nature of localized clouds, which exhibit highly detailed spatial variability in rainfall intensity over very short distances as a result of topographic influences and surface characteristics.

Accordingly, the problem of the study lies in the limited ability of conventional meteorological station data to accurately represent the fine spatial variability of rainfall in Wadi Al-Huski and the resulting challenges in interpreting the hydrological response of the basins and accurately estimating surface runoff. This necessitates integrating these data with other spatial indicators, such as field observations, remote sensing techniques, and rainfall station data from Al-Bidaa, Umm Al-Radhma, Northern Reserve, Zabala, and Qibah stations, in order to achieve a more comprehensive and accurate understanding of runoff dynamics within the Al-Huski watershed.

The study seeks to achieve the following objectives:

1. To study and analyze the natural characteristics of Wadi Al-Huski Basin—including topography, geology, soil types, vegetation cover, and climatic characteristics—in order to

determine their influence on the hydrological behavior of the basin and to understand the mechanisms of surface runoff generation and rainfall response.

2. To apply the SCS-CN hydrological model to simulate the main hydrological processes in Wadi Al-Huski Basin and analyze the dynamics of water runoff within it, thereby contributing to the interpretation of the spatial and temporal variability of runoff, supporting water resource management, and mitigating flood hazards within the basin.

The study also seeks to answer the following questions:

1. What is the nature of the interactive relationships among environmental elements (topography, geology, soil, vegetation cover, and climatic characteristics) in shaping the hydrological behavior of the basin?
2. How do the results of the SCS-CN model contribute to explaining the dynamics of water runoff within the basin?

The importance of the study is highlighted in the following aspects:

1. The study contributes to understanding and analyzing the hydrological characteristics of Wadi Al-Huski Basin in the Imam Turki bin Abdullah Royal Reserve.
2. It clarifies the behavior of surface runoff within the basin through the application of the SCS-CN model.
3. It provides scientific results that can be utilized in water resource management.
4. It offers the possibility of benefiting from the model outputs in future hydrological studies.

Second: Study Boundaries

- **Thematic Boundaries:** This study focuses on the hydrology of Wadi Al-Huski Basin in the Imam Turki bin Abdullah Royal Reserve using the SCS-CN model.
- **Spatial Boundaries:** Wadi Al-Huski Basin within the Imam Turki bin Abdullah Royal Reserve.
- **Temporal Boundaries:** The study covers a thirty-year historical period and includes forecasting for thirty years into the future during the period (2041–2060).

Third: Study Area

Wadi Al-Huski Basin is located north of Wadi Al-Fuwailiq Basin and covers an area of approximately 2,063 km². According to the classification of Schumm (1977), the basin falls under the category of highly elongated basins, with an elongation ratio of approximately 0.4 and a form factor of about 0.19. Based on these characteristics, it is considered one of the large and elongated basins in this part of the Al-Taysiyah Reserve.

The basin contains a broad and extensive runoff channel that receives major tributaries. The length of this channel exceeds 90 km and is characterized by wide and extended floodplains, some reaching dimensions of nearly 800 meters. The headwaters of the wadi originate from the western slopes of the Al-Taysiyah Plateau, particularly from the Tayaran Mountains and the Al-Bidaa Plateaus (Al-Dughairi, 2022).

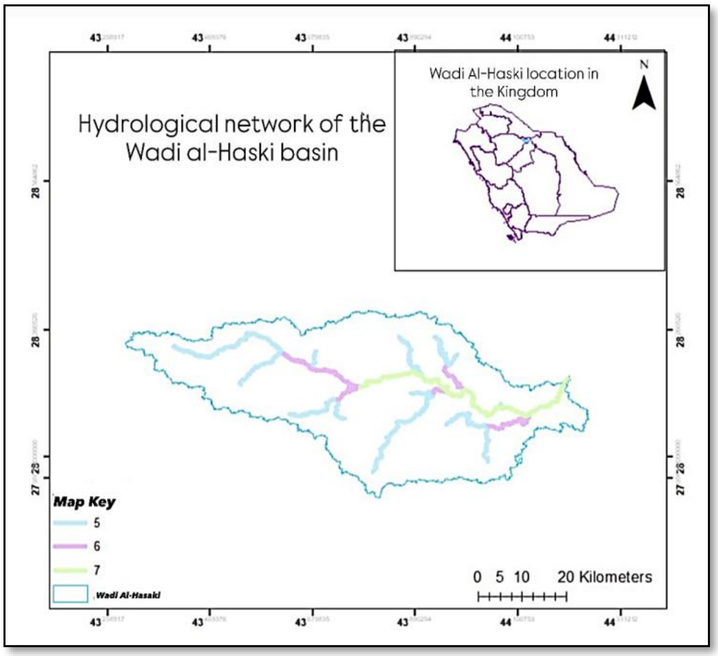


Figure (1): A map illustrating the location of Wadi Al-Huski Basin in relation to the regions of the Saudi Arabia and the hydrological network of the wadi.- Source: Prepared by the researcher based on the Digital Elevation Model (DEM).

The hydrology of the basin is influenced by several natural characteristics. The basin lies within an arid climatic zone where the average annual rainfall ranges between 50–120 mm, while evaporation rates exceed 2,000 mm/year, which limits the sustainability of surface runoff. In addition, the region is dominated by sedimentary and sandy formations with varying permeability, contributing to higher infiltration rates compared to surface runoff, particularly with the prevalence of sandy to silty soils and sparse vegetation cover. Collectively, these factors indicate that the basin is characterized by a rapid and seasonal hydrological response (Ministry of Environment, Water and Agriculture, 2022; General Authority of Meteorology and Environmental Protection, 2019).

The wadi also follows undulating limestone surfaces, either due to the resistant rocky nature of the terrain or because it receives several tributaries, with the number of secondary sub-basins reaching fifteen. One example is Shu‘aib Al-Shawki (Al-Dughairi, 2022).

According to the general soil map of the Saudi Arabia prepared by the Ministry of Agriculture in 1406 AH, the classification of the Kingdom’s soils was based on the United States Soil Taxonomy system adopted since 1975. Wadi Al-Huski Basin includes two soil orders within this classification system: Aridisols and Entisols.

The soils in Wadi Al-Huski Basin are classified as follows:

23- Torriorthents – Rock Outcrops: Silty and gravelly silty soils that are shallow, nearly level to gently sloping, with rocky areas ranging from nearly level to steeply sloping.

This mapping unit consists of nearly level to gently sloping lands within plains and plateaus, in addition to areas of rocky outcrops occurring on nearly level plains, small hills, and steep low hills. Some parts of the unit are intersected by intermittent wadi channels, while most parts contain a moderately developed branched drainage network. The individual areas of this unit are irregular in shape and range in size from 5,000 to 500,000 hectares.

Approximately 65% of this unit consists of Calciorthids and Torriorthents soils, 10% consists of rocky outcrop areas, and 25% consists of secondary soil types. Some sections are composed of both Calciorthids and Torriorthents, whereas others consist mainly of either Calciorthids or Torriorthents. The soils are intricately intermingled with rocky outcrop areas.

Calciorthids, Torriorthents, and similar soils occur on convex uplands and along the margins of plains and plateau slopes, with gradients ranging from 0% to 5%. The Calciorthids and Torriorthents soils are shallow, silty to gravelly silty soils, with salinity levels ranging from very low to very high. They are moderately permeable and possess low water-holding capacity. Most parts are covered by desert pavement. Calciorthids soils are calcareous in nature.

Rock outcrops occur within plains, elongated low hills, small uplands, and some discontinuous low escarpments, with slopes ranging from 0% to 15%.

This mapping unit also includes small areas of deep or moderately deep soils located in flat or concave plains. Calciorthids and Torriorthents soils are mixed with soils containing high gypsum content and some sandy soils, such as scattered dunes.

Most of the lands within this mapping unit are unsuitable for large-scale irrigated agriculture, except for approximately 5% of the unit’s lands, which may be suitable for cultivation but require detailed investigation. The limiting factors affecting suitability include shallow soil depth above bedrock, rocky outcrops, aridity, high salinity, and slope conditions. Some areas are also highly gravelly. Except for slope, which may be improved through land leveling, the remaining characteristics are permanent constraints. The presence of rocky outcrops and shallow bedrock depth further restricts land-leveling operations. Although salts can potentially be leached, the shallow bedrock limits this process.

Approximately 20% of the unit’s lands are suitable for small-scale irrigated agriculture, while their suitability for grazing is poor.

Land suitability class: Class VI.

40- Torriorthents – Rock Outcrops: Rocky surfaces and gravelly silty soils, shallow in depth, with slopes ranging from 0% to 15%.

This mapping unit consists of areas of rocky outcrops and soils formed on elevated lands that range from nearly level to steeply sloping terrain. The wadi drainage networks within the unit are branched and well developed, while some channels are deeply incised and intermittent. The individual areas of this mapping unit are irregular in shape and range in size between 10,000 and 80,000 hectares.

Approximately 45% of this unit consists of rocky outcrop areas, 40% consists of Torriorthents and Calciorthids soils, and 15% consists of secondary soil types. Some individual sections are composed of both Torriorthents and Calciorthids. Rocky outcrop areas are intricately intermingled throughout all parts of the unit. These rocky outcrops occur on elevated lands and are often large and continuous, with slopes ranging from 0% to 15%.

Torriorthents, Calciorthids, and similar soil types occur on elevated terrain, with slopes also ranging from 0% to 15%. Both Torriorthents and Calciorthids are gravelly silty soils that range from slightly to highly saline. Most are shallow above the bedrock, while in some places they are extremely shallow. Their permeability is moderate, and their water-holding capacity is low. Most parts are covered by desert pavement, while Calciorthids soils are calcareous.

This unit also includes small areas of moderately deep or deep soils over bedrock. These soils occur within wadi channels and concave locations. Sandy soils are interspersed throughout many parts of the unit, while rocky outcrops appear as steep escarpments. The unit also contains areas of unconsolidated stones with moderate to deep profiles covered by a thin layer of fractured rock.

The lands of this mapping unit are unsuitable for large-scale irrigated agriculture. The main limiting factors are shallow soil depth above bedrock, rocky outcrops, and slope conditions in some locations. All of these are permanent characteristics and cannot be corrected. Approximately 5% of the lands within this unit are suitable for small-scale irrigated agriculture, while their suitability for grazing is poor.

Land suitability class: Class VI.

52- Torripsamments: Sand dunes exceeding 10 meters in height.

This mapping unit consists of steep to very steep soils located on dunes higher than 10 meters. These dunes occur at close intervals and are distributed throughout all parts of the unit. No clearly defined wadi drainage network exists within the area. The individual areas of the unit are irregular in shape and range in size from approximately 2,000 to 4,000,000 hectares.

Approximately 85% of this unit consists of Torripsamments soils on dunes, while 15% consists of secondary soil types and areas of rocky outcrops.

Torripsamments and similar soils occur on the dunes, with slopes ranging from 10% to 60%. The steepest slopes are generally found on the leeward sides of the dunes. Torripsamments are deep sandy soils ranging from non-saline to slightly saline. They have rapid permeability and relatively low water-holding capacity.

This unit also includes small areas of nearly level to gently sloping soils, as well as small areas of silty soils, soils with high gypsum content, moderately to highly saline soils, rocky outcrop areas, and shallow soils over bedrock. These features are all found within the depressions between dunes. The unit also contains soils on dunes with heights of less than 10 meters.

The lands within this unit are unsuitable for large-scale irrigated agriculture. The principal limiting factor is the steepness of the dunes, which is a permanent characteristic that cannot be corrected. Approximately 10% of the lands within the unit is suitable for small-scale irrigated agriculture, while their suitability for grazing is poor.

Land suitability class: Class VI (Ministry of Agriculture and Water, 1986).

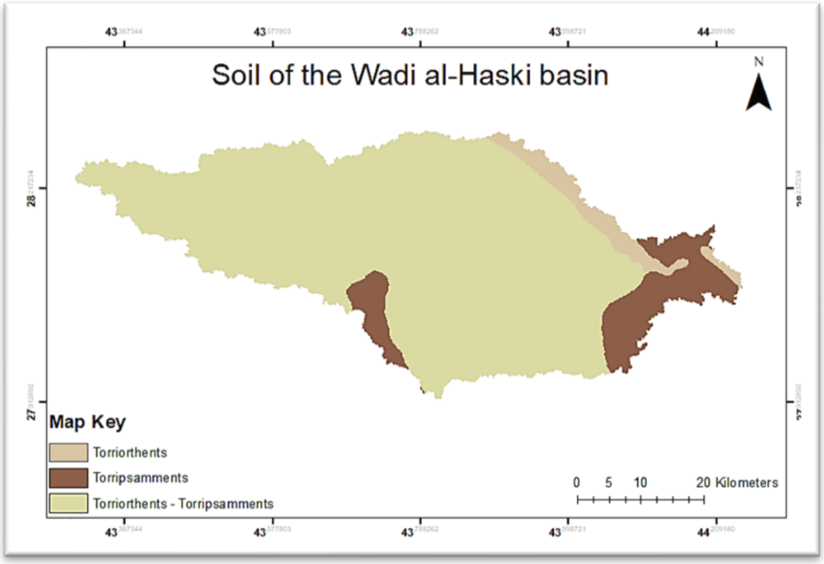


Figure (2): A map showing the soil types in Wadi Al-Huski Basin. - Source: Prepared by the researcher based on the General Soil Map of the Saudi Arabia. Climate of Rafha

The study area lies within the Imam Turki bin Abdullah Royal Reserve, and the nearest meteorological station is the weather station of Rafha. The area is characterized by a semi-arid continental desert climate. Consequently, numerous surrounding sandy surfaces exist, in addition to low rainfall amounts, which make the city hot during summer, while its weather becomes cold and low in humidity during winter.

This study relied on climatic data related to temperature, humidity, wind, and rainfall for Rafha obtained from TuTiempo.net for the period extending from 2015 to 2025, as shown in Table (1).

Table (1): Monthly and annual averages of temperature, rainfall, and wind speed (km/h) obtained from TuTiempo.net. - Source: Prepared by the researcher based on data from TuTiempo.net.

Average Wind Speed (km/h	**Rainfall**	**Average Temperature (°C)**	**Monthly Average Temperature**		**Months**
			Minimum	Maximum	
12,5	7,5	11.5	5,4	17,85	January
13,95	17,12	14,14	7,47	20,93	February
15,96	18,23	19,36	12,18	26,22	March
14.7	7,7	24,63	16,85	31,48	April
13,46	1,8	30,83	22,25	37,75	May
13,43	2,75	34,81	25,85	42,16	June
13,06	2,37	37,18	28,18	44,57	July
11.93	1,18	36,88	28,15	44,4	August
10,92	1,1	34,04	25,9	41,75	September
12.2	3,01	27,85	20,23	35,41	October
12.3	34,45	18,76	13,18	24,2	November
11,3	9,08	13,67	8,3	19,52	December
12,97	8,85	25,30	17,85	32,23	Annual Average

It is evident from Table (1) and Figure (3) that the annual average temperature in the city of Rafha reached (25.30°C), with noticeable variation from one month to another, as shown above. The highest monthly average was recorded in August (36.88°C), where temperatures rise significantly during the summer season (March, April, May, June, July, August, September, and October). In contrast, temperatures decrease during the winter season, with the lowest monthly average recorded in January (11.5°C). Temperatures gradually decline from December to February, as shown above, and then begin to rise again during the spring months (March, April, May), while gradually decreasing during the autumn months (September, October, November). Figure (4) illustrates the monthly temperature averages in Rafha City for the period from 2015 to 2025.

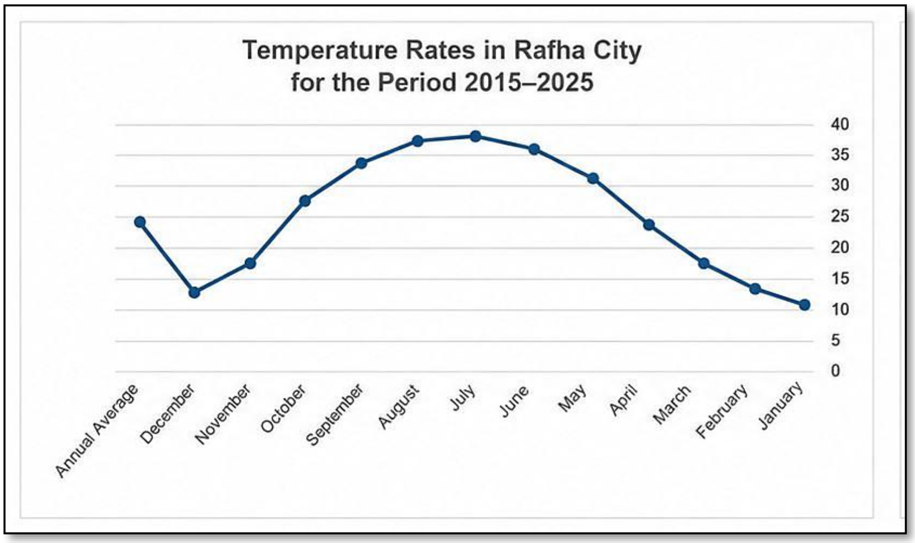


Figure (3): Monthly temperature averages in Rafha for the period 2015–2025. - Source: Prepared by the researcher based on data from TuTiempo.net.

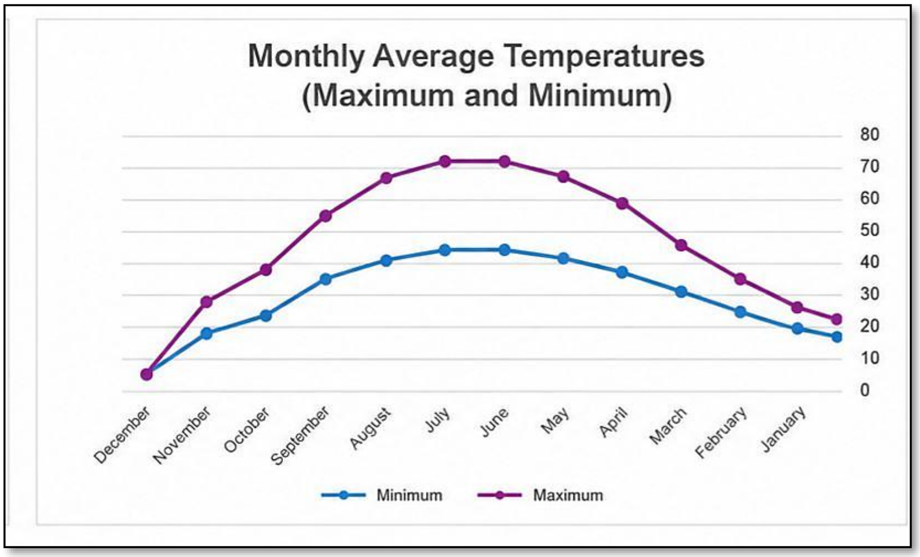


Figure (4): Monthly maximum and minimum temperature averages (°C) for the period 2015–2025 from TuTiempo.net. - Source: Prepared by the researcher based on data from TuTiempo.net.

Due to the generally low precipitation amounts, rainfall events are often sudden and may be accompanied by flash floods. The rainy season typically begins from mid-October to late May. The total rainfall recorded during the winter months amounted to (33.7 mm), while spring rainfall reached approximately (27.73 mm). No rainfall was recorded during the summer season.

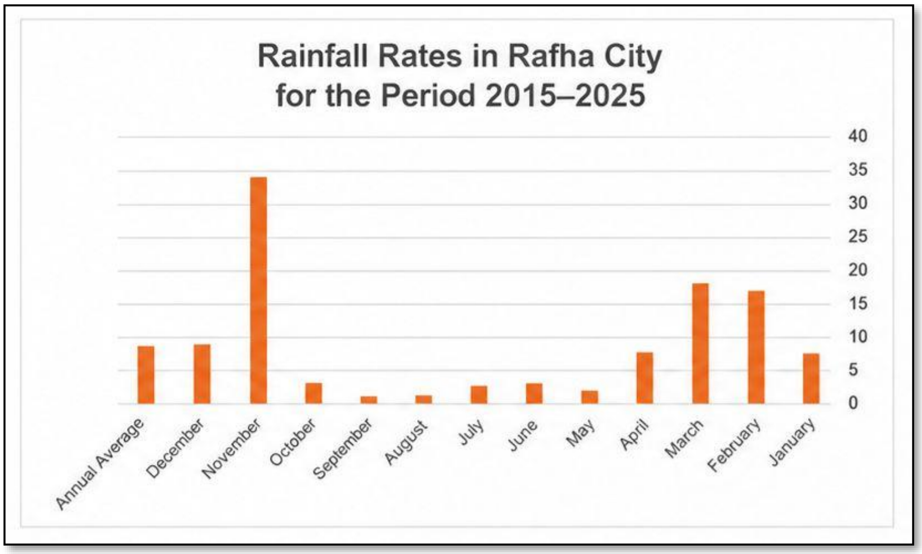


Figure (5): Rainfall averages in Rafha for the period 2015–2025.- Source: Prepared by the researcher based on data from TuTiempo.net.

Fourth: Theoretical Framework

1. Terminology:

• Wadi:

A wadi is a natural basin or depression on the Earth’s surface. Wadis extend between plains, plateaus, and mountains. Rivers and flash floods that flow through wadis gradually move from inland areas toward oceans. Wadi lands are generally fertile, which makes them suitable for agriculture (Abu Al-Ezz, 2001).

• Drainage Basin (Watershed):

A drainage basin is an area that drains its water to a single outlet, such as a river or lake. It is considered the basic unit in hydrological and water geography studies (Abdullah, 2001).

• SCS-CN Model:

The SCS-CN model is an empirical hydrological method developed by the Soil Conservation Service to estimate direct surface runoff resulting from rainfall. It is based on the Curve Number (CN), which reflects the influence of soil properties, land use, and antecedent soil moisture conditions on runoff generation (USDA-SCS, 1985).

2. Previous Studies:

Studies of drainage basins and wadis are of great importance due to their direct impact on settlements and agricultural activities, as follows:

Al-Anzi (2020): Flash Flood Hazards of Wadis Affecting the City of Hail from an Applied Geomorphological Perspective. This study aimed to analyze the hydrological characteristics of the drainage basins influencing the city and determine the levels of flood risk resulting from flash floods. The study relied on spatial analysis using Geographic Information Systems (GIS) to classify basins and residential neighborhoods according to hazard levels. The results revealed a clear variation in flood hazard levels among different wadis, with some basins recording high-risk levels, posing a direct threat to residential areas and infrastructure. The study recommended the use of hydrological analysis results in urban planning and in reducing future flood risks.

Based on this study, the researcher concluded that the wadis affecting the city of Hail vary in flood hazard levels, and some basins pose a clear threat to residential areas and infrastructure. However, the study lacks detailed field data on past flood events and predictive models for future floods. It also suggests the need for more specific practical recommendations to address the most vulnerable neighborhoods.

Additionally, Al-Shuwaish and Al-Dughairi (2020) aimed to conduct a spatial analysis and management of royal reserves in the Kingdom of Saudi Arabia, with a focus on the Al-Taysiyah Reserve as a case study. The researchers used Geographic Information Systems (GIS) techniques, including ArcGIS software, to assess the environmental status and identify sensitive areas within the reserve.

The study succeeded in distinguishing the characteristics of flowing wadi basins within Al-Taysiyah Reserve and extracting the dominant vegetation covers. It also proposed a spatial distribution of wells, management centers, and monitoring stations for the reserve. The researcher believes that spatial data contribute significantly to improving environmental planning and management of the reserve, supporting decision-making processes to achieve sustainability of natural resources. The study further demonstrated that the use of these techniques not only enhances understanding of environmental and spatial characteristics but also provides a practical model for supporting spatial planning and decision-making.

Another study, titled **“Flash Flood Prediction in Southwest Saudi Arabia Using GIS Technique and Surface Water Models” (2024)**, aimed to forecast flash floods and surface runoff in southwestern Saudi Arabia in order to assess flood risk and identify the most vulnerable areas. The study integrated Geographic Information Systems (GIS) with hydrological models such as HEC-HMS to analyze the relationship between rainfall and watershed characteristics and to estimate runoff volume. Researchers used topographic data (DEM), soil properties, and land use data to generate a model simulating runoff behavior during rainfall events.

The results showed that integrating GIS with hydrological models provides high accuracy in predicting hazard zones and discharge volumes. It also demonstrated that rainfall intensity and slope are among the most influential factors in increasing surface runoff, which contributes to improving flood risk management and urban planning in vulnerable areas.

The researcher benefited from previous studies in identifying the research gap. Although there are overlaps between the current study and previous research regarding the Wadi Al-Huski Basin in terms of the importance of hydrological characterization and flood risk assessment, the current study is distinguished by its focus on a specific local environment within the Imam Turki bin Abdullah Royal Reserve. It also employs the SCS-CN hydrological model and integrates it with spatial analysis and field data. This contributes to bridging the gap related to the weak integration between theoretical modeling and field validation, and provides more accurate results that support flood risk management, sustainable environmental planning, and future surface runoff prediction for Wadi Al-Huski Basin.

3. Data Collection and Sources:

To achieve the objectives of the study, a set of spatial and geographic datasets was used to support the hydrological analysis of the study area drainage basin during August 2015 and 2025. The data were obtained from the United States Geological Survey. These datasets included satellite imagery, digital elevation models (DEM), and auxiliary spatial data.

• Primary Data:

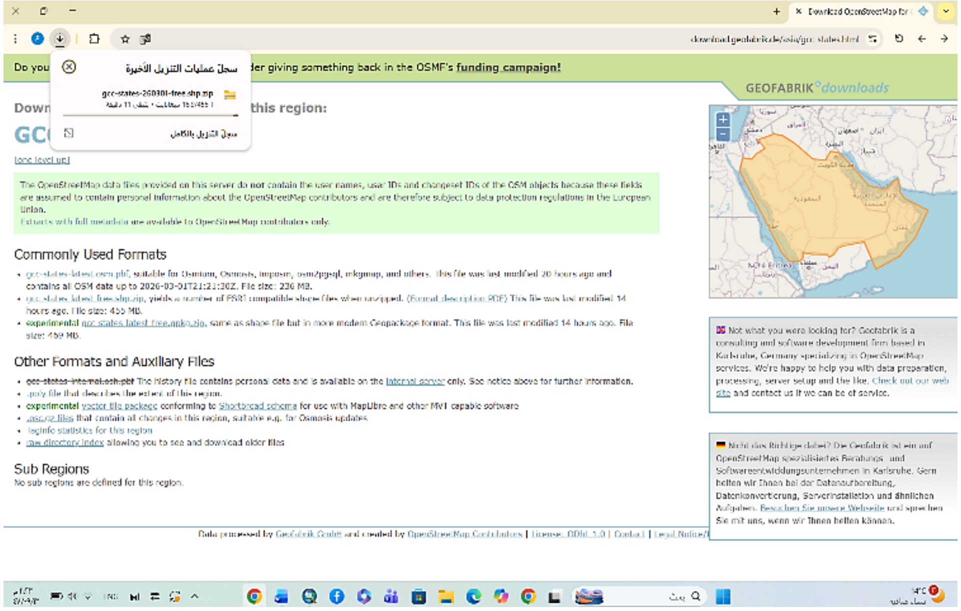
- Satellite Imagery:

Landsat-8 and Landsat-7 (Level-2) satellite images were used. Images captured during the month of August were selected because it represents one of the summer months characterized by clear surface features and minimal vegetation cover. This enhances the visibility of drainage networks and watershed boundaries more clearly. The imagery was downloaded from the official website of the United States Geological Survey.

To verify the spatial accuracy of the used imagery, a visual comparison was conducted between fixed features visible in the satellite images—such as main channels and natural intersections—and the high-resolution reference layer (World Imagery Basemap) within the ArcMap environment. The Measure Tool was also used, and the results showed a high spatial match within pixel-level accuracy (less than 30 meters), which strengthens the reliability of the hydrological analysis of the study.

- Shapefile Data:

Data on the boundaries of the study area and some supporting spatial layers were obtained from the OpenStreetMap (OSM) database via the Geofabrik website, as shown in the following figure:



Do you ... der giving something back in the OSMF's funding campaign!

Down... this region:

GC...

[one level up]

The OpenStreetMap data files provided on this server do not contain the user names, user IDs and changeset IDs of the OSM objects because these fields are assumed to contain personal information about the OpenStreetMap contributors and are therefore subject to data protection regulations in the European Union.
Extracts with full metadata are available to OpenStreetMap contributors only.

Commonly Used Formats

- gcc-states-latest.osm.pbf, suitable for Osmium, Osmosis, imposm, osm2pgsql, mkgmap, and others. This file was last modified 20 hours ago and contains all OSM data up to 2026-03-01T21:21:30Z. File size: 236 MB.
- gcc-states-latest-free.shp.zip, yields a number of ESRI compatible shape files when unzipped. (Format description PDF) This file was last modified 14 hours ago. File size: 455 MB.
- experimental gcc-states-latest-free.gpkg.zip, same as shape file but in more modern Geopackage format. This file was last modified 14 hours ago. File size: 459 MB.

Other Formats and Auxiliary Files

- ~~gcc-states-internal.osh.pbf~~ The history file contains personal data and is available on the internal server only. See notice above for further information.
- .poly file that describes the extent of this region.
- experimental vector tile package conforming to Shortbread schema for use with MapLibre and other MVT capable software
- .osc.gz files that contain all changes in this region, suitable e.g. for Osmosis updates
- taginfo statistics for this region
- raw directory index allowing you to see and download older files

Sub Regions
No sub regions are defined for this region.

Data processed by Geofabrik GmbH and created by OpenStreetMap Contributors | License: ODbL 1.0 | Contact | Legal Notice/

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The image above provides updated geospatial data in formats compatible with Geographic Information Systems (GIS) analysis. These data were used to support spatial analysis procedures and to define the spatial framework of the study. The study area boundary data were processed using ArcMap after downloading the datasets, where only the boundaries of the Saudi Arabia were extracted, excluding neighboring countries.

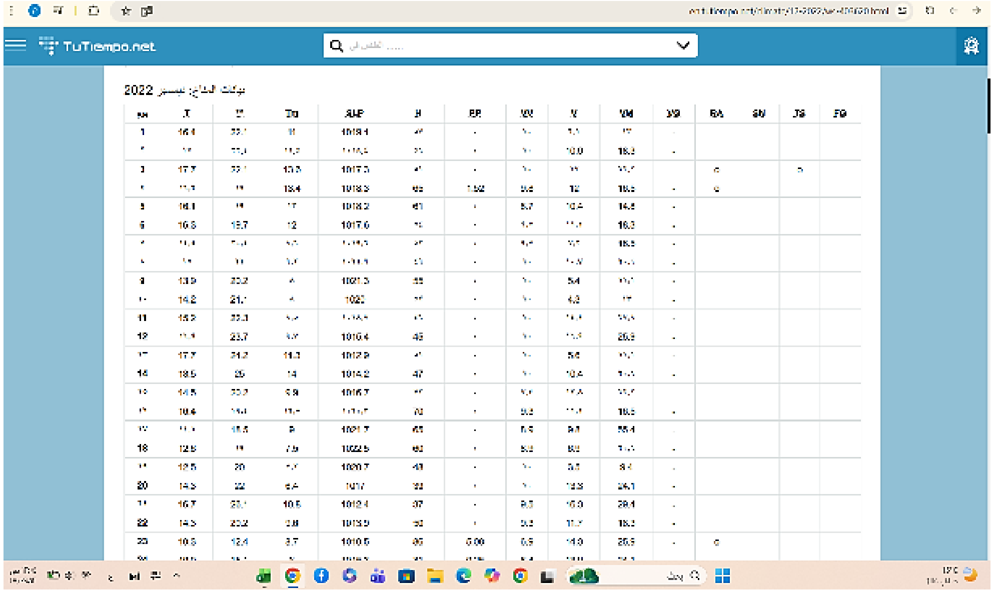
- **Secondary Data:**

Secondary data included relevant maps and reference datasets, such as general geographic information of the area, previous studies, and official data available from relevant authorities. These sources were used to support hydrological analysis and interpret the results.

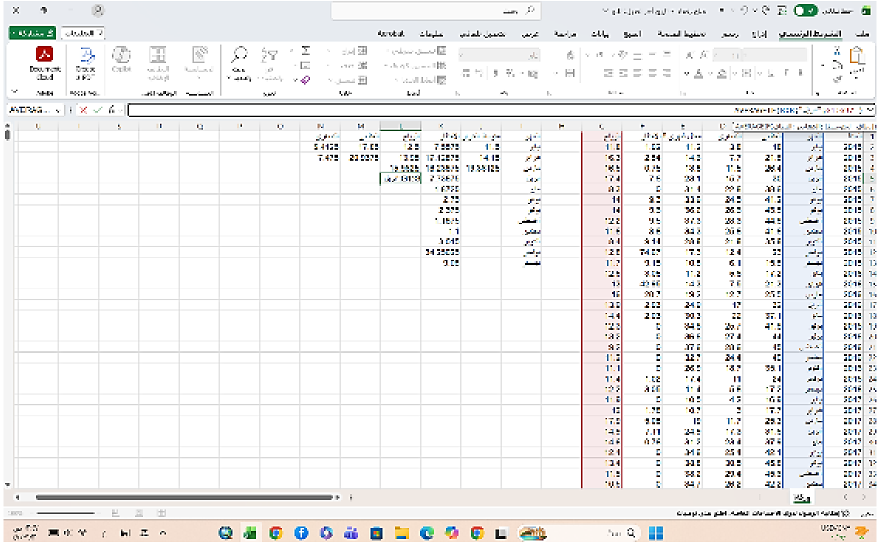
Fifth: Study Methodology

To achieve the objectives of the study, the following approaches were adopted:

The **applied quantitative approach** was used, where digital data were collected from the Digital Elevation Model (DEM) and climatic data from TuTiempo.net for the period 2015–2025, as shown in the figure below:



The data were also processed after being downloaded into Microsoft Excel to derive the results presented in Table (2) in the climate section of the study area. This is illustrated in the figure showing the data processing in Excel.

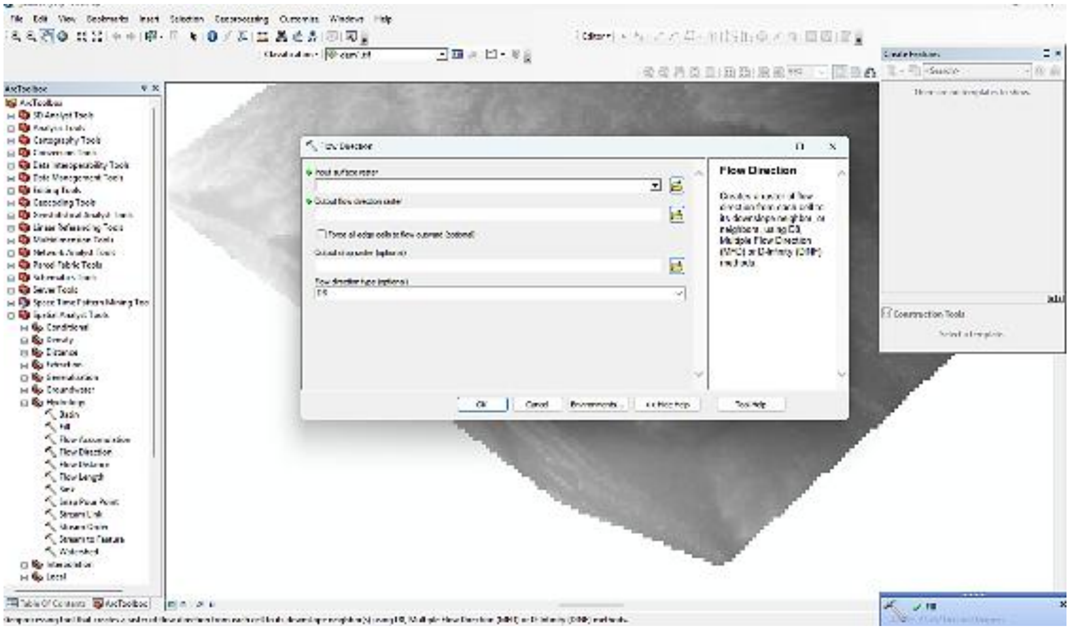


The satellite imagery was then corrected for cloud cover, and the watershed boundaries and drainage networks were delineated using ArcMap. The hydrological characteristics of the land surface were analyzed. The processing procedure began by filling sinks (Fill Sinks) using the ArcToolbox under the Hydrology toolbox. The “Fill” tool was selected, after which a dialog box appeared where the Digital Elevation Model (DEM) was added, resulting in a corrected surface.

Next, Flow Direction was derived using the same workflow by selecting Hydrology → Flow Direction. A dialog box appeared, the output from the Fill step was inserted, and the result was generated. To verify the output, the layer was right-clicked in the Table of Contents and “Open Attribute Table” was selected. The table showed that the Value field contains numerical representations of flow directions, while the Count field represents the total number of cells for each direction.

The fourth step involved deriving Flow Accumulation using a similar procedure, but selecting Hydrology → Flow Accumulation. A dialog box appeared, where the Flow Direction output was added, producing the accumulation layer. A raster attribute table was then created for the Flow Accumulation layer using Data Management Tools → Raster → Build Raster Attribute Table, which generated the attribute table for the layer.

In the fifth step, flow accumulation thresholds were selected to refine the drainage network and extract appropriate stream details. The Con tool was used from ArcToolbox under Hydrology to achieve this process. After that, Stream Link was applied to ensure connectivity within the drainage network by identifying junction points between streams. Finally, Stream Order was calculated using ArcToolbox → Hydrology → Stream Order to classify the hierarchical structure of the drainage network, as shown in the following figure.



Additionally, the SCS-CN hydrological model was prepared, including the creation of Hydrological Response Units (HRUs) and the input of climatic data. After running the model, calibration was conducted to adjust and improve the results. Subsequently, water discharge and related hydrological responses were analyzed, along with the impact of land use on hydrological processes within the basin.

The SCS-CN method for estimating surface runoff depends on variables such as land use, soil type, vegetation cover, and rainfall amounts. The Curve Number (CN) is the key parameter in this method, as it is influenced by soil moisture, land use, and hydrological soil groups.

Soil moisture is classified into three conditions: dry (I), normal (II), and wet/saturated (III), each with corresponding CN tables. Soils are also categorized into four hydrological soil groups (A–D) based on permeability, ranging from high infiltration (A) to very low infiltration (D).

In the study area (Wadi Al-Huski), soils were found to belong to three groups: A, B, and C. The normal condition (II) was adopted, and the corresponding CN tables were used in this application.

Table (2): Curve Number (CN) values for urban areas. - Source: TR-55 (1986), pp. 2–5.)

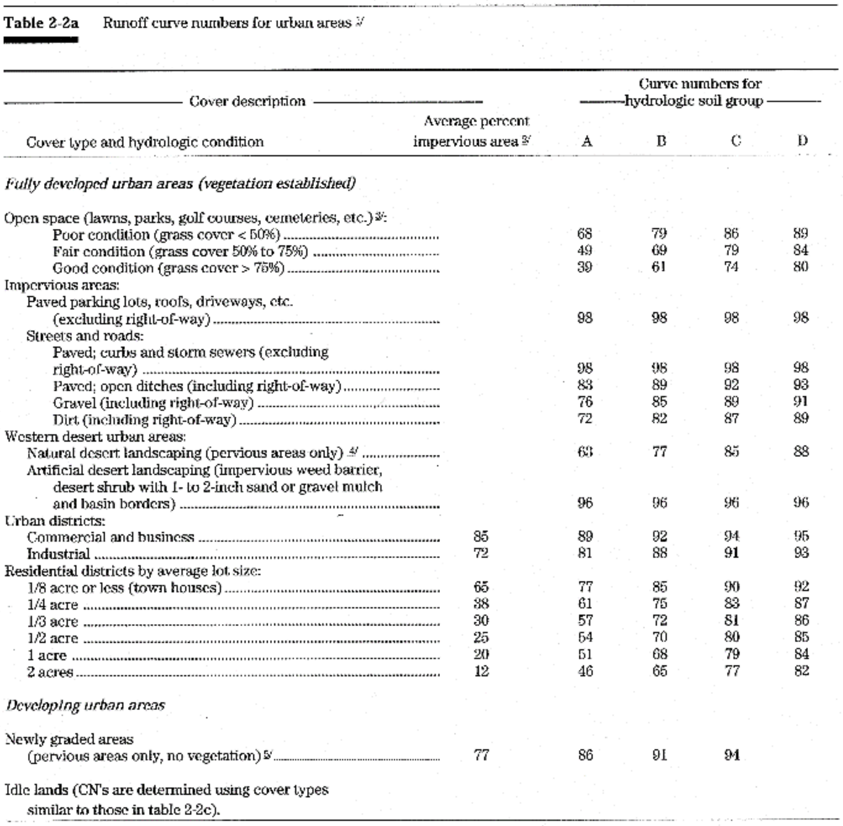


Table 2-2a Runoff curve numbers for urban areas [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]	77	86	91	94	
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

Table (3): Curve Number (CN) values for agricultural areas. - Source: TR-55 (1986), pp. 2–6.

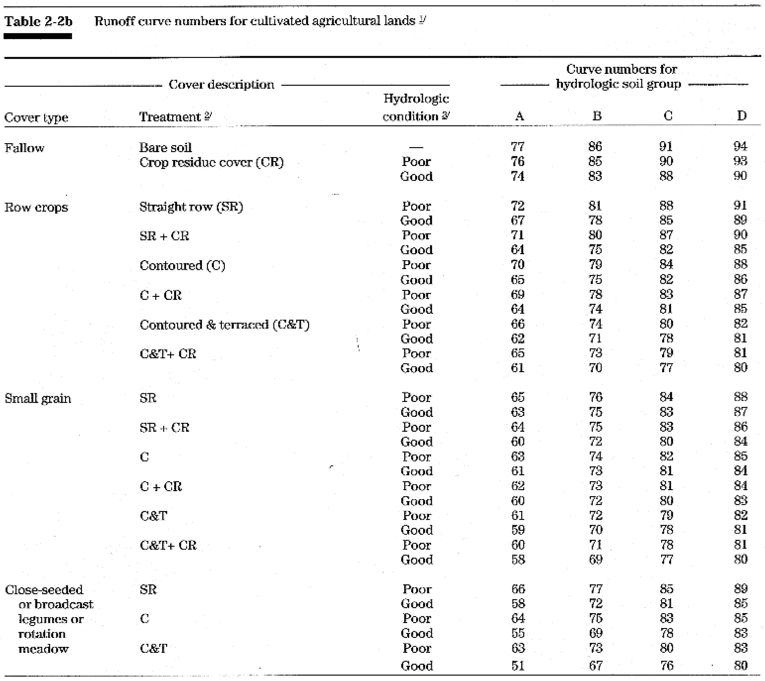


Table 2-2b Runoff curve numbers for cultivated agricultural lands 1/

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment 2/	Hydrologic condition 3/	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

Table (4): Curve Number (CN) values for non-agricultural lands. - Source: TR-55 (1986), pp. 2–7.

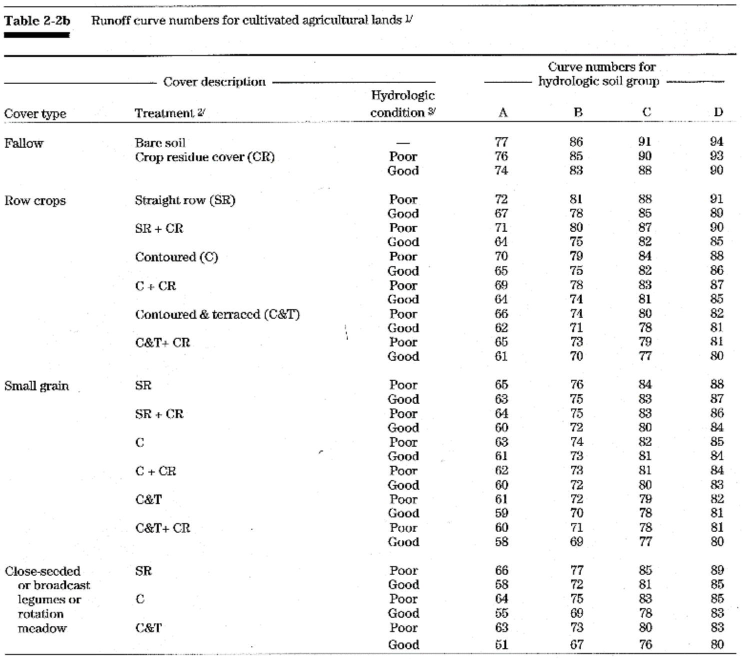


Table 2-2b Runoff curve numbers for cultivated agricultural lands 1/

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment 2/	Hydrologic condition 3/	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

Table (5): Curve Number (CN) values for rangelands in arid and semi-arid regions. – Source: TR55.1986.2-8

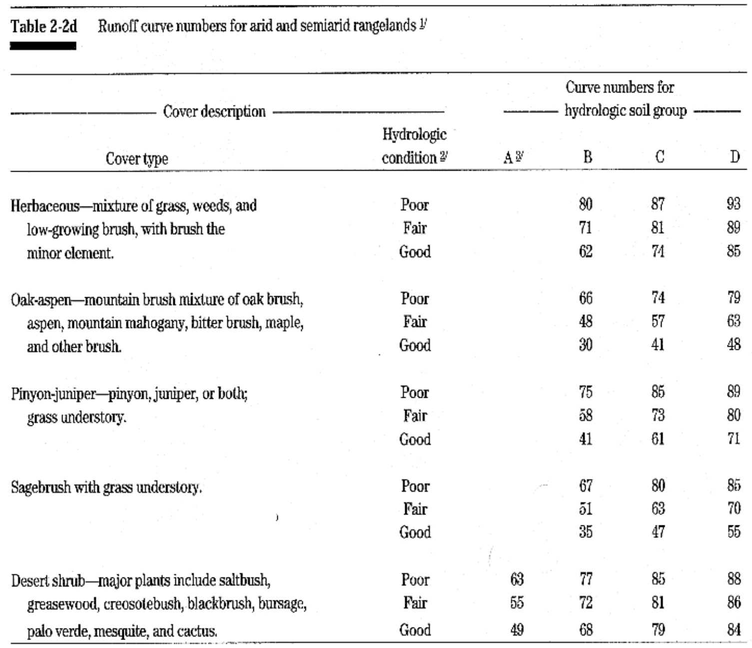


Table 2-2d Runoff curve numbers for arid and semiarid rangelands 1/

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition 2/	A 3/	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

The mathematical formulations for the Runoff Curve Number (SCS-CN) model, according to what was reported in (USDA, 1986), are as follows:

$$Q = \frac{(P - Ia)^{2}}{(P + 0.8S)}$$

---Equation(1)

Where:

-)**Q :(**\Surface runoff depth (inches).
-)**P :(**\Rainfall depth (inches).
-)**I_{a} :(**\Initial abstraction before runoff begins, such as interception by plants and evaporation (inches).
-)**S :(**\Maximum potential retention after runoff begins (inches).

\(I_{a}\) is calculated as follows:

$Ia = 0.2S$

--- Equation (2)

The mathematical formula to calculate \(S\) is:

$$S = \frac{1000}{CN} - 10$$

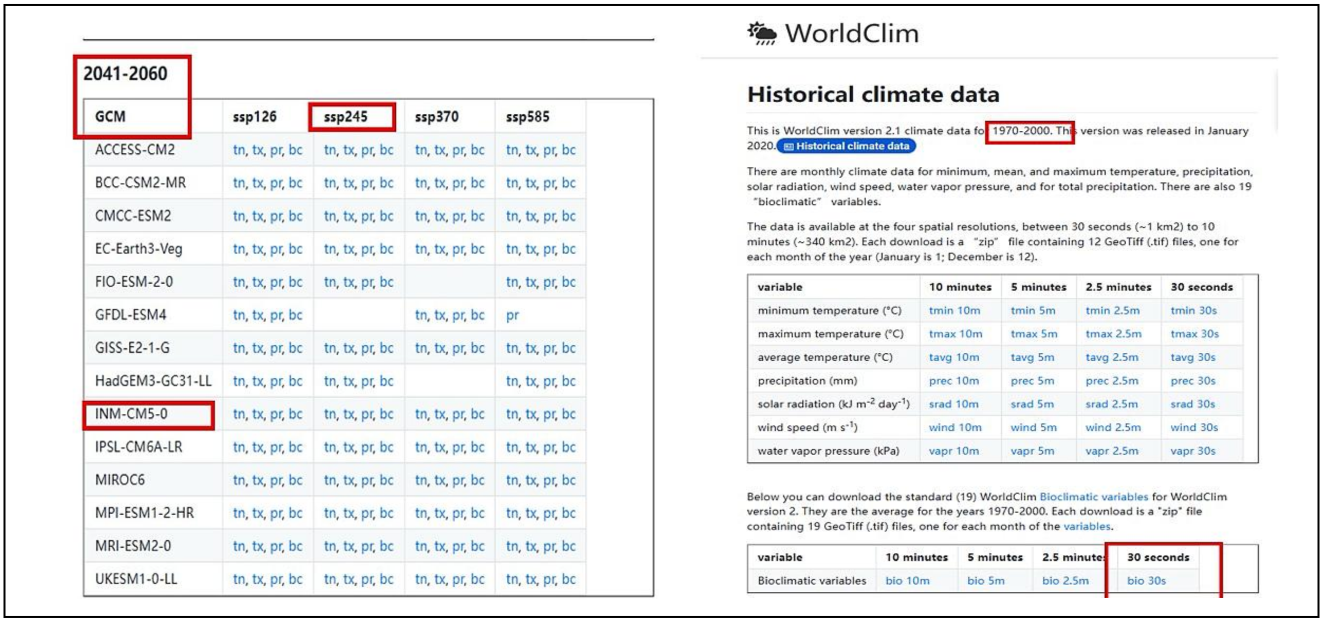
---Equation(3)

Since the inputs of the model are in inches, and our region's rainfall is estimated in millimeters, the equation has been reformulated to fit metric standards. The constant numbers in Equation (3) were multiplied by (25.4) to convert from inches to millimeters, making the equation as follows:

$$S = \frac{25400}{CN} - 254$$

---Equation(4)

Average rainfall data for the historical and future periods were relied upon from the Climate World website, as shown in the following figure, which displays the data extraction interface from the website.



2041-2060

GCM	ssp126	ssp245	ssp370	ssp585
ACCESS-CM2	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
BCC-CSM2-MR	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
CMCC-ESM2	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
EC-Earth3-Veg	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
FIO-ESM-2-0	tn, tx, pr, bc	tn, tx, pr, bc		tn, tx, pr, bc
GFDL-ESM4	tn, tx, pr, bc		tn, tx, pr, bc	pr
GISS-E2-1-G	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
HadGEM3-GC31-LL	tn, tx, pr, bc	tn, tx, pr, bc		tn, tx, pr, bc
INM-CM5-0	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
IPSL-CM6A-LR	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
MIROC6	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
MPI-ESM1-2-HR	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
MRI-ESM2-0	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc
UKESM1-0-LL	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc	tn, tx, pr, bc

Historical climate data

This is WorldClim version 2.1 climate data fo 1970-2000. Thi version was released in January 2020.

There are monthly climate data for minimum, mean, and maximum temperature, precipitation, solar radiation, wind speed, water vapor pressure, and for total precipitation. There are also 19 "bioclimatic" variables.

The data is available at the four spatial resolutions, between 30 seconds (~1 km2) to 10 minutes (~340 km2). Each download is a "zip" file containing 12 GeoTiff (.tif) files, one for each month of the year (January is 1; December is 12).

variable	10 minutes	5 minutes	2.5 minutes	30 seconds
minimum temperature (°C)	tmin 10m	tmin 5m	tmin 2.5m	tmin 30s
maximum temperature (°C)	tmax 10m	tmax 5m	tmax 2.5m	tmax 30s
average temperature (°C)	tavg 10m	tavg 5m	tavg 2.5m	tavg 30s
precipitation (mm)	prec 10m	prec 5m	prec 2.5m	prec 30s
solar radiation (kJ m^{-2} day^{-1})	srad 10m	srad 5m	srad 2.5m	srad 30s
wind speed (m s^{-1})	wind 10m	wind 5m	wind 2.5m	wind 30s
water vapor pressure (kPa)	vapr 10m	vapr 5m	vapr 2.5m	vapr 30s

Below you can download the standard (19) WorldClim Bioclimatic variables for WorldClim version 2. They are the average for the years 1970-2000. Each download is a "zip" file containing 19 GeoTiff (.tif) files, one for each month of the variables.

variable	10 minutes	5 minutes	2.5 minute	30 seconds
Bioclimatic variables	bio 10m	bio 5m	bio 2.5m	bio 30s

Future Data Source (Under SSP2-4.5 Scenario) - Source of Historical Data (Past Data):

Sixth: Discussion and Results

Surface slope is one of the key hydrological factors influencing water runoff. The average slope of Wadi Al-Huski Basin is (0.303), which is considered a gentle slope, as shown in Figure (6). This gentle gradient allows the flow to lose part of its sediment load during movement. The highest elevation along the watershed divide reaches approximately (700 m), while the lowest elevation is about (540 m) at the wadi bed.

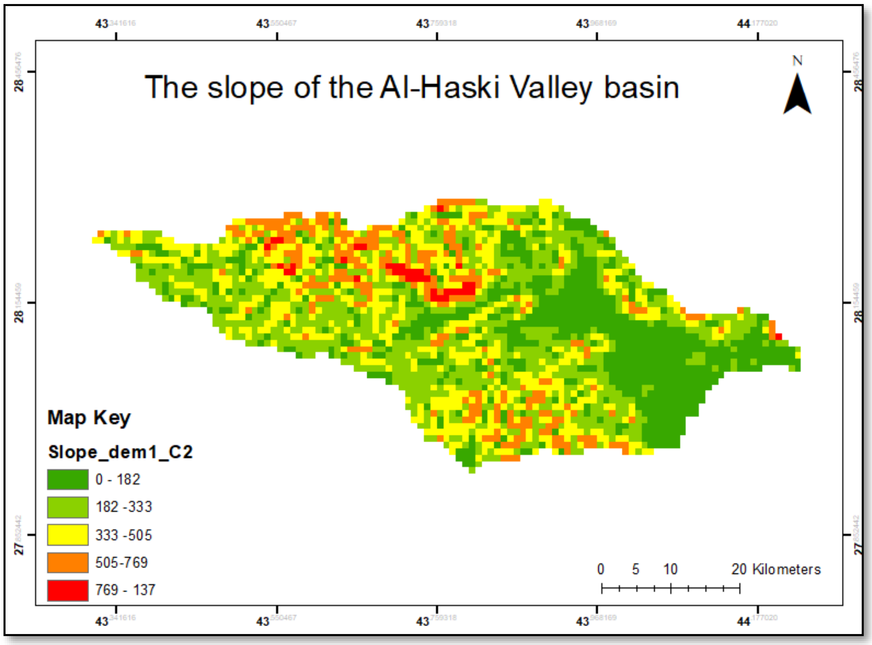


Figure (6): Map showing the slope of Wadi Al-Huski Basin in the Imam Turki bin Abdullah Royal Reserve. - Source: Prepared by the researcher based on the Digital Elevation Model (DEM).

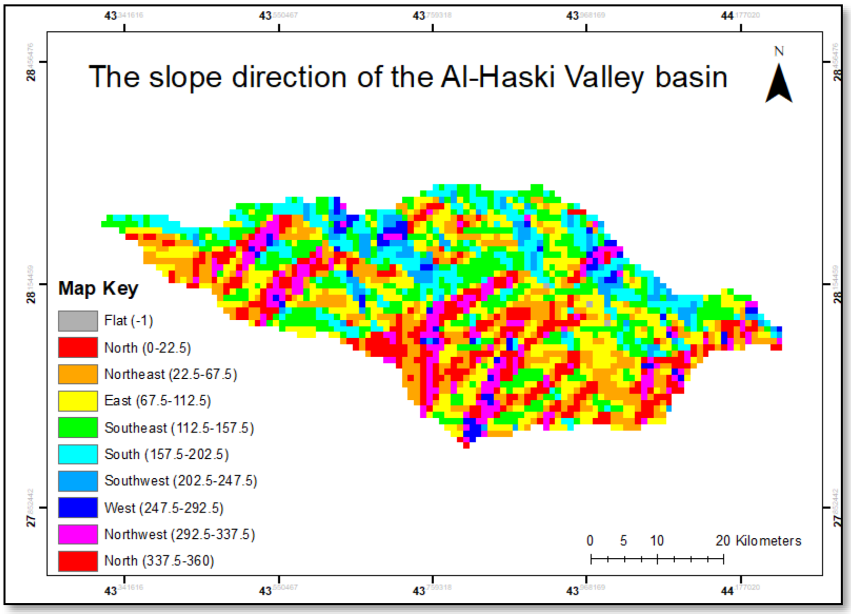


Figure (7): Map showing the slope direction of Wadi Al-Huski Basin in the Imam Turki bin Abdullah Royal Reserve. - Source: Prepared by the researcher based on the Digital Elevation Model (DEM).

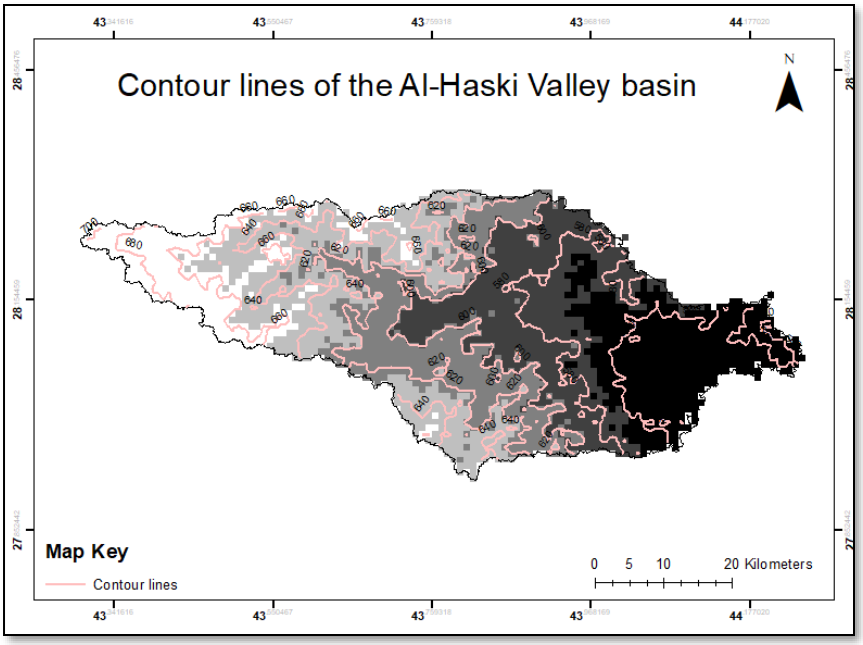


Figure (8): Contour map of Wadi Al-Huski Basin in the Imam Turki bin Abdullah Royal Reserve. - Source: Prepared by the researcher based on the Digital Elevation Model (DEM).

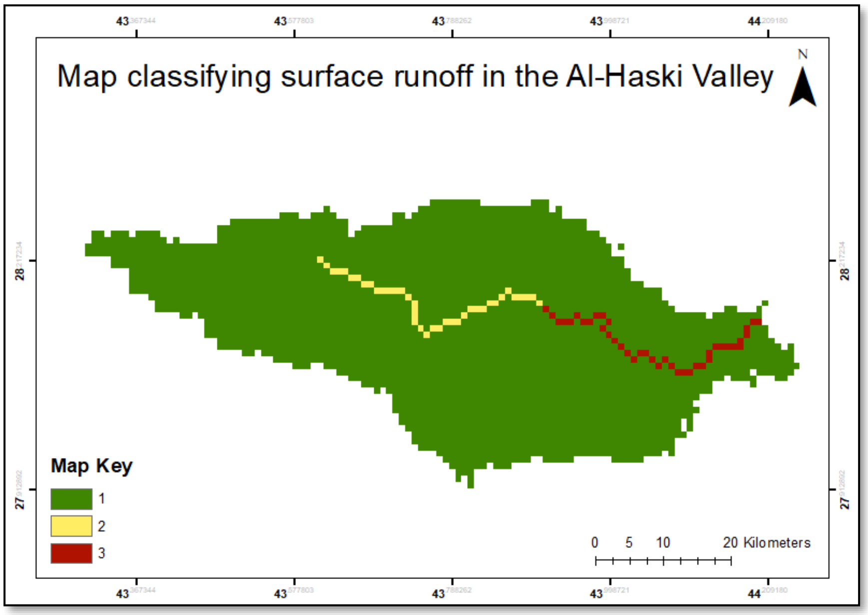


Figure (9): Map showing surface runoff accumulation classification in Wadi Al-Huski Basin. - Source: Prepared by the researcher based on the Digital Elevation Model (DEM).

This map illustrates the classification of surface runoff accumulation within Wadi Al-Huski Basin, reflecting the degree of water concentration generated from rainfall as it moves across the basin surface. The accumulation values are represented using three color gradients: green indicates areas of low runoff accumulation, yellow represents moderate accumulation zones, and red indicates high accumulation areas.

It is observed that most of the basin area is dominated by the green color, indicating low surface runoff accumulation across most regions. In contrast, a linear feature appears in the central part of the basin, extending from yellow to red zones. This feature represents the main wadi channel and runoff concentration zones, where water accumulation gradually increases along this path due to topographic slope and natural drainage direction.

Overall, this map reflects the internal water movement pattern within the basin and highlights the main flow pathways where surface runoff is concentrated and directed toward the basin outlet.

• Morphometric Characteristics of the Wadi Al-Huski Drainage Network:

1. Basin Area:

Basin area is one of the most important morphometric characteristics that directly influence the volume of water discharge. It is defined as the total area enclosed by the watershed divide through which water is collected and drained via the main wadi channel. The importance of basin area lies in its effect on runoff volume. The area of Wadi Al-Huski Basin is approximately (2,063 km²).

2. Basin Length:

The length of Wadi Al-Huski Basin represents the maximum distance from the headwaters to the outlet. It is a key factor in determining the hydrodynamic behavior of surface runoff within the basin. The basin length is approximately (89.96 km), reflecting a medium-to-long basin extension, which allows the gradual accumulation of rainfall and floodwater along the wadi channel.

Basin length plays a major role in controlling runoff velocity and direction, as longer basins tend to exhibit a more gradual hydrological response compared to very short basins.

3. Basin Perimeter:

Basin perimeter refers to the total length of the outer boundary that surrounds the basin from all directions. It is the line that clearly defines the basin's external shape and encloses its entire area. The perimeter of Wadi Al-Huski Basin is approximately (3,660 km).

4. Basin Width:

Basin width plays an important role in determining the amount of rainfall that contributes to runoff generation within the basin. The study of basin width has gained increasing importance in recent years in analyzing drainage basin morphology. The width of Wadi Al-Huski Basin is approximately (31.19 km).

5. Mean Basin Width:

Mean basin width refers to the average transverse distance between the farthest two points along the basin boundary. Several methods can be used to calculate mean basin width; in this study, the following method was adopted:

Mean basin width = Basin area ÷ Basin length

= 2063 ÷ 89.96

= 22.95 km

Table (6): Morphometric characteristics of Wadi Al-Huski Basin. - Source: Prepared by the researcher.

Morphometric Variable	Basin Area (km²)	Basin Length (km)	Basin Perimeter (km)	Basin Width (km)	Mean Basin Width (km)
Value	2063 km²	89.96 km	3660 km	31.19 km	22.95 km

The SCS-CN model equation was applied to calculate surface runoff for two periods: the first is the historical period (past conditions), and the second is the future period. This was carried out by substituting the extracted values from the study data, as follows:

$$Q = \frac{(P - Ia)^2}{(P + 0.8S)}$$

Where:
Q: Runoff depth (inches).
P: Rainfall depth (inches).
Ia: Initial abstraction before runoff begins, such as interception by vegetation and evaporation (inches).
S: Maximum potential retention after runoff begins (inches).

We begin by calculating the value of **S**:

Given that: **CN = 83**

$$S = \frac{25400}{83} - 254$$

We calculate **Ia** as it equals **0.2S**:

Ia = 0.2 × 52.02 = 10.40 mm

After substituting into the main equation, surface runoff is calculated for the first period (1970–2000) in order to estimate the hydrological response resulting from rainfall during that period within the study area.

Where:
P = 163.2 mm

We begin substituting into the equation:

$$Q = \frac{(163.2 - 10.40)^2}{163.2 + 0.8 \times 52.02}$$

$$Q = \frac{(152.8)^2}{163.2 + 41.62} = \frac{23346}{204.82}$$

$$Q \approx 113.98\,\mathrm{mm}$$

Then, surface runoff is calculated for the second (future) period, followed by a comparison of the results and highlighting the magnitude of change between the two periods.

Where:
P = 166.6 mm

$$Q = \frac{(166.6 - 10.40)^2}{166.6 + 0.8 \times 52.02}$$

$$Q = \frac{(156.2)^2}{166.6 + 41.62} = \frac{24400}{208.22}$$

$$Q \approx 117.17\,\mathrm{mm}$$

Substituting into the equation:

The hydrological analysis results indicate that surface runoff response in the study area does not follow a simple linear pattern with changes in rainfall amounts. Instead, it exhibits clear sensitivity, reflecting the complexity of the physical processes governing runoff generation.

Based on rainfall data derived from the WorldClim database, the Curve Number (CN) model was applied to estimate surface runoff over two different time periods. The results show an increase in surface runoff from approximately **113.98 mm** during the historical period (1970–2000) to **117.17 mm** in the future period (2042–2060).

Although the increase in average rainfall was relatively small (from 163.2 mm to 166.6 mm), surface runoff showed a relatively larger increase. This can be explained by the non-linear nature of the CN model, where exceeding the initial abstraction (Ia) leads to a faster conversion of rainfall into surface runoff. In addition, the relatively high Curve Number value (CN = 83) in the study area indicates a low infiltration capacity of the soil, which increases runoff generation efficiency.

In this context, this study was conducted to analyze and assess flash flood hazards in Wadi Al-Huski Basin using hydrological models and Geographic Information Systems (GIS), aiming to identify potential risk zones and support planning and water resource management in the region.

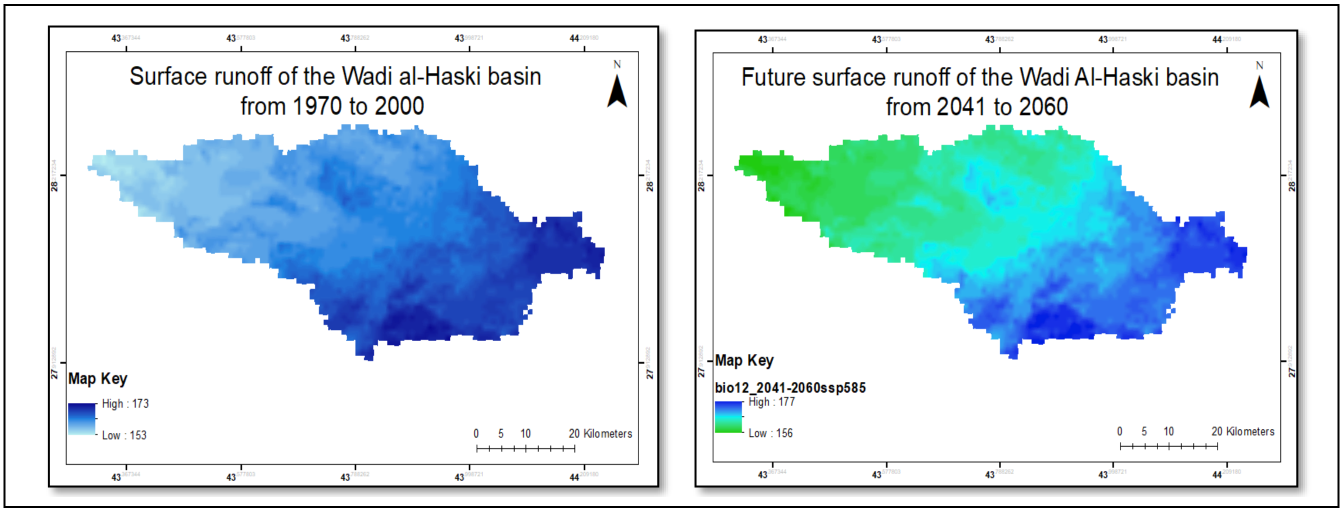


Figure (10): Surface Runoff Map of Wadi Al-Huski. - Source: Prepared by the researcher based on the BIO12 layer (mean annual precipitation)

The maps illustrate the spatial distribution of surface runoff in Wadi Al-Huski Basin over two different time periods. The first map represents the historical period (1970–2000), while the second shows future projections for the period (2041–2060). Both maps display clear spatial variability in runoff values using a color gradient, ranging from lighter colors indicating low runoff to darker colors indicating high runoff.

During the historical period, runoff values ranged between a minimum of 153 and a maximum of 173, while in the future period values increased to range between 166 and 177. The highest values remain concentrated in the eastern part of the basin, whereas the western parts record the lowest values.

The main difference between the two maps lies in the noticeable increase in surface runoff values in the future period compared to the past period, both in minimum and maximum values. This suggests a potential change in climatic conditions, such as increased rainfall intensity or changes in surface characteristics. The spatial pattern, however, remains largely unchanged, with runoff still increasing toward the east. Nevertheless, the intensity of runoff becomes higher, indicating a possible increase in flash flood risk and higher hazard levels in the basin in the future.

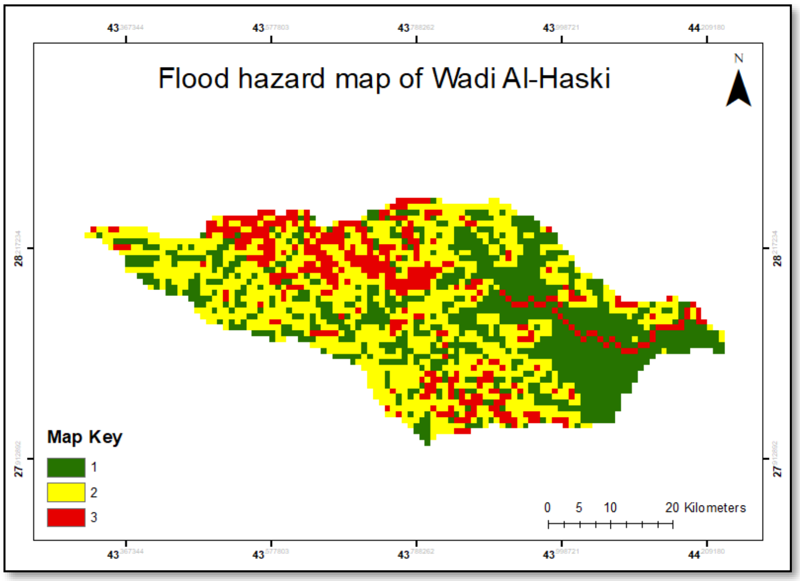


Figure (11): Flood Hazard Map of Wadi Al-Huski. - Source: Prepared by the researcher based on the Digital Elevation Model (DEM).

This map illustrates the classification of flood hazard levels in Wadi Al-Huski Basin, where flood risk is divided into three main categories represented by green, yellow, and red colors. Number (1) refers to the green color, representing low-risk areas. Number (2) refers to the yellow color, representing moderate-risk areas. Number (3) refers to the red color, representing high-risk areas.

It is observed that the yellow category covers the largest portion of the basin, indicating that most areas fall within a moderate hazard level. This is followed by the green areas, which represent low-risk zones distributed across different parts of the basin. In contrast, red zones are limited in extent and are mainly concentrated along the main wadi channel and low-lying areas.

Overall, the results indicate that Wadi Al-Huski Basin is predominantly characterized by low to moderate flood risk, with limited high-risk hotspots that require careful attention in planning and flood risk management.

These findings also suggest that the Wadi Al-Huski area may become more vulnerable to increasing flood hazards in the future, even under slight changes in rainfall amounts. This highlights the importance of integrating future climate data with hydrological models when assessing water-related risks and planning for sustainable water resource management.

Seventh: Results

1. The study shows that Wadi Al-Huski Basin is characterized by a rapid hydrological response due to low soil permeability and a relatively high Curve Number (CN = 83).
2. There is a non-linear relationship between rainfall and surface runoff, where a small increase in rainfall leads to a greater increase in runoff.
3. Surface runoff increased from approximately 113.98 mm in the historical period to 117.17 mm in the future period.
4. The maps reveal clear spatial variability in runoff distribution, with higher values concentrated in the eastern part of the basin.
5. The hazard map indicates that most of the basin falls within a moderate risk level, with limited high-risk areas mainly along wadi channels.
6. The results show that future climate changes may increase the likelihood of flash flood occurrence in the region.

Eighth: Recommendations

1. The establishment of an early warning system for flash floods in Wadi Al-Huski Basin is necessary to reduce future risks.
2. The study results should be utilized in urban planning, with avoidance of expansion in high-risk areas.
3. The use of Geographic Information Systems (GIS) and remote sensing techniques in future hydrological studies should be enhanced.
4. Detailed field studies should be conducted to validate the model results and improve their accuracy.
5. A more dense network of meteorological stations should be developed to accurately represent the spatial variability of rainfall.
6. Sustainable water resource management should be implemented to effectively utilize floodwater.

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