Erasmus+

UNIVERSIDADE DE ÉVORA

BARTIN ÜNİVERSİTESİ
2008

APPLİCATİON OF TOPOGRAPHİC-BASED METRİCS FOR HYDROLOGİCAL CHARACTERİZATİON

Cumhur Eren Bilal

Project report
Receiving organization: Universidade de Évora
Internship supervisor: Associate Professor Nuno de Sousa Neves

1. ABSTRACT

Hydrological analysis in a geographic information system is based in the structure of the terrain, represented as a matricial grid of cell values, representing elevation as a basic infrastructure for modelling. Using this data structure it is possible to apply a set of spatial analysis operations in order to define the flow structure and generate a set of topographic based metrics that can be used as hydrological characterization of hydrographic basins.

The purpose of this project was to perform a detailed hydrological analysis of a given area, namely an hydrographic basin, using Digital Elevation Model (DEM) data to model water flow, accumulation, and terrain characteristics. By utilizing this model, we can accurately predict water movement across the landscape, identify potential areas for river formation, and understand the relationships between terrain slope and water distribution.

The topographic based metrics generated were summarized as zonal statistics to territorial administrative areas/zones (counties), allowing its hydrological characterization. This type of analysis is essential for managing water resources, preventing floods, and planning sustainable land use, especially in areas prone to water-related challenges.

Internship activities program:

- Description and evaluation of the fundamental computational models for the representation and storage of geographic information: Geographic representation: Evaluation of the different representation metaphors and an introduction to a systemic approach to representation metaphors;

- Description of fundamental spatial analysis processes and operations in geographical information systems: Spatial data models: Detailed analysis of vectorial model, raster model and other data models. Unique layer spatial operations: Neighborhood analysis, buffering, masks and filtering. Multiple layer spatial operations: Overlay analysis and geoprocessing operations. Dimensionality of geographic data;

- Evaluation of spatial data models considering their potential for spatial analysis operations: Conceptual design of data models and geographic modeling: Geographic modeling concepts and flowcharts design including map algebra operations.Hydrologic modeling based on spatial analysis operations;

- Evaluation of potential future developments and research directions in relation to spatial data models and spatial analysis: Future perspectives: New spatial data models, new models for spatial relations and new spatial analysis processes.

The teaching methodologies provided the necessary information to understand the theoretical concepts and aspects related to the practical implementation of spatial analysis processes, allowing the design of a small research project dedicated to the study of two river basins in Türkiye, using a set of topographic based metrics.

The topographic based metrics created in the project were integrated as zonal statistics in the administrative divisions of Turkey, allowing a general characterization of hydrological conditions and being able to constitute a decision basis in future analyzes applied to territorial planning and management.

Monitoring

The development of the work plan was closely monitored by the supervisor - Prof. Nuno de Sousa Neves - following the established schedule, lasting 3 months.

2. TABLE OF CONTENTS

3. FIGURE INDEX

4. INTRODUCTION

This repport presents an examination of the computational models and spatial analysis processes foundational to Geographic Information Systems (GIS). ArcMap has been utilized to investigate the topographic and hydrological characteristics within a specific study area. As a student from Bartın University, I am currently conducting my Erasmus internship at the University of Evora in Portugal, supported by a European Union scholarship. During this internship period, from September 9 to October 30, I have been working under the guidance of Professor Nuno de Sousa N**eves**. Our work focuses on GIS-based spatial and hydrological analyses aimed at providing positive contributions to water resource management and land-use planning.

The primary goal of this internship was to analyze fundamental computational models for representing and storing geographic information, evaluate different geographic representation metaphors, and introduce systematic approaches to understanding these metaphors. Within this scope, various spatial data models, such as vector, raster, and hybrid models, which form the foundation of geographic data representation, have been addressed. Each model offers unique capabilities in spatial analysis; for instance, vector data provides accuracy for defined boundaries, while raster data is more suitable for capturing slope changes on continuous surfaces. Practical applications of these models evaluate their strengths, weaknesses, and suitability for different types of geographic phenomena.

The project further focuses on detailed spatial analysis processes conducted through both single-layer and multi-layer operations essential in GIS. In terms of single-layer spatial operations, analyses such as neighborhood evaluation, buffering, masking, and filtering play a critical role in understanding localized geographic characteristics. For example, neighborhood analysis enables the assessment of spatial patterns by examining relationships within a specified radius, while buffering establishes zones around features of interest, supporting land-use planning. Multi-layer operations, including overlay analysis and geoprocessing, expand the analytical scope by integrating multiple datasets, such as overlaying population density with water resources to identify conservation priorities.

Hydrological modeling, which is a central focus of this internship, is conducted using ArcMap's spatial analysis tools such as Fill, Flow Direction, and Flow Accumulation, based on Digital Elevation Model (DEM) data. These tools collectively simulate water flow and accumulation, providing a topographic plan to predict water movement across the landscape(Tarboton et al., 1991). By layering DEM data and applying map algebra operations, we simulate water behavior, identify potential flooding areas, and determine slope impact on water distribution. Hydrological modeling not only enhances understanding of local water dynamics but also underscores GIS's critical role in flood risk management and sustainable resource allocation.

Another focus of this research is the conceptual design of data models and methodologies in geographic modeling. Within this context, flowcharts have been developed to simplify complex geographic processes, and map algebra is applied for spatial computations. By synthesizing spatial data, geographic modeling concepts, and systematic processes, this study emphasizes a structured approach necessary for effectively analyzing real-world geographic issues.

In conclusion, this repport details the analytical procedures undertaken during my internship, presenting a review of ArcMap's capabilities in GIS and hydrological modeling and highlighting its significance in environmental and geographic research contexts. These findings offer insights into current capabilities and shed light on the promising potential of spatial analyses in the future.

5. PROJECT AREA

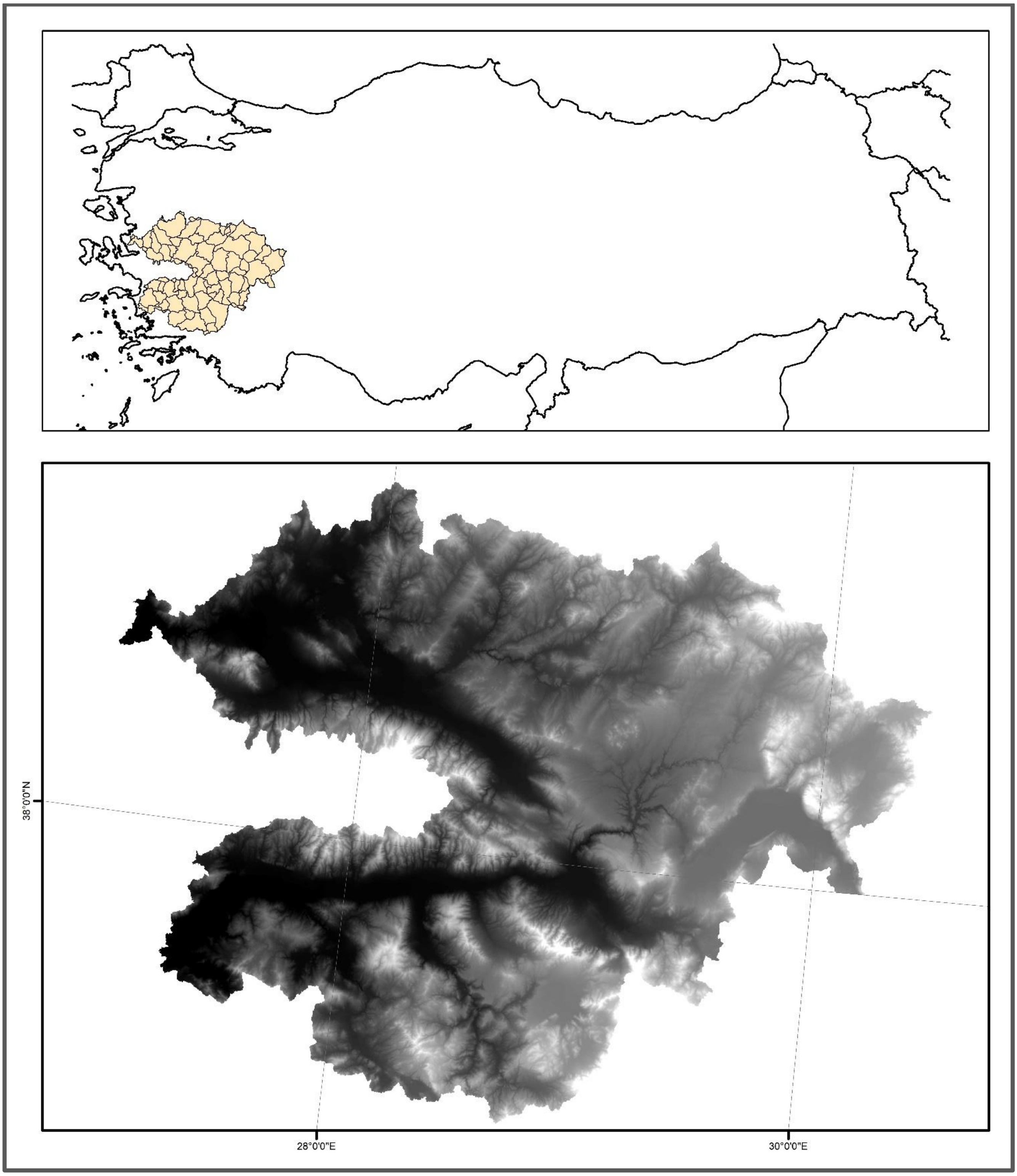

Figure 1 – Study area.

6. METHODS USED

6.1. FILLING DEPRESSIONS - FİLL

6.1.1. General Description

In ArcGIS, the Fill method eliminates areas such as pits or depressions in DEM data. These areas improperly change the natural collection flow of water, causing the results of hydrological analyses to be inaccurate. If a cell or group of cells has a lower value than the cells around it, we can predict that a depression has occurred. The way to eliminate this depression with the Fill method is to equalize the values of the cell group with the low value to the values of the neighboring cells closest to this group. In this way, we will obtain a flatter area with equalized values and the water flow will be allowed to occur correctly(Jenson & Domingue, 1988).

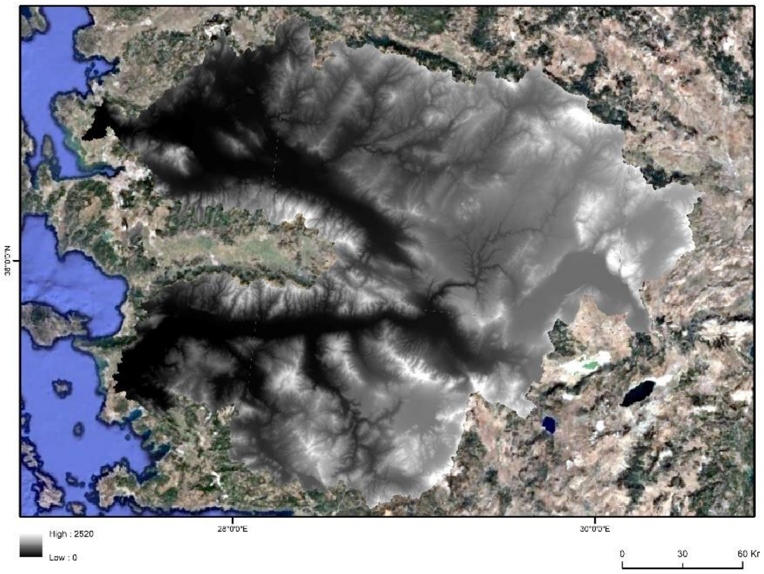

Figure 2 – Filled digital elevation model (DEM) over Google Earth image.

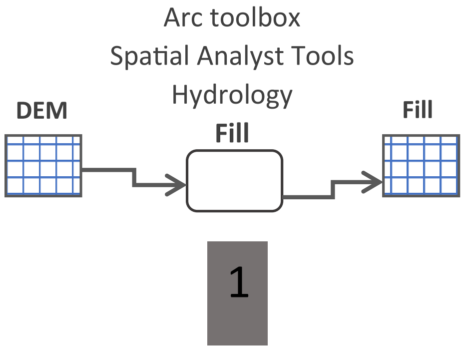

Figure 3 – FILL operation with ArcGIS ArcToolbox tool sequence.

6.1.2. Calculation Method

If we were to explain the application of the Fill model in more detail, the depression areas(areas lower than their surroundings) in our DEM data, which cause disruptions in water flow or lead to inaccurate results in hydrological analyses, are identified. Then, the elevation difference between the cells in the depression and their neighboring cells with higher values is determined. After that, the values of the cells within the depression are gradually adjusted to match the elevation of the neighboring cells. In this way, the depression is transformed into a flat area. This process is applied to every depression area in the DEM data, resulting in a depression-free, error-free DEM dataset(Jenson & Domingue, 1988).

6.1.3. Application

Since the depression areas in our DEM could lead to incorrect calculations in our hydrology analysis, we used the Fill tool as the first step to remove these depressions and ensure that water flows along its natural path(Planchon & Darboux, 2002; Jenson & Domingue, 1988).

6.2. FLOW DIRECTION

6.2.1. General Description

The Flow Direction method is used in ArcGIS to determine the direction of water flow. It does this by directing each cell in the DEM data to the steepest descent relative to its neighboring cell. For each cell, the algorithm compares the elevation values of 8 neighboring(Jensen s. Dominue 1988) cells and determines which neighboring cell has the steepest downward slope. The direction is then determined by a coding system where each of the eight neighboring cells is represented by a unique direction value (1 north, 2 northwest, 4 south, and so on).

Flow direction is important for many applications, including watershed delineation, surface runoff modeling, and flood risk assessment. It contributes to a better understanding of how water accumulates, the paths it takes, and where it drains.

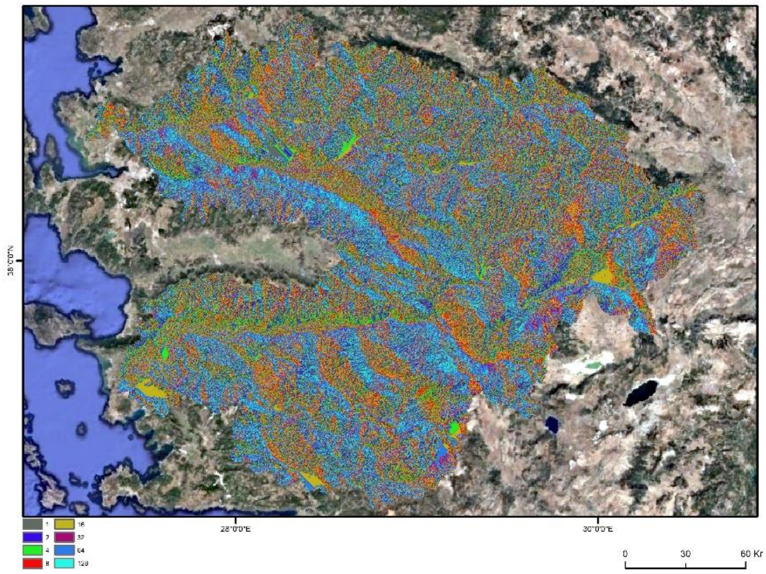

Figure 4 – Flow direction layer over Google Earth image.

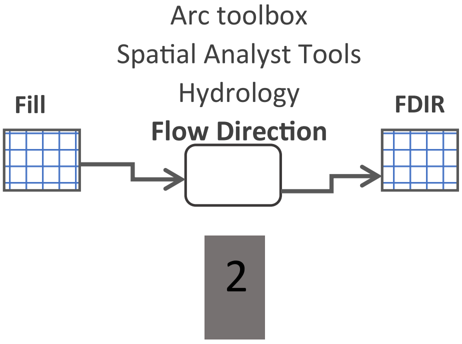

Figure 5 – FLOW DIRECTION operation with ArcGIS ArcToolbox tool sequence.

6.2.2. Calculation Method

First, for each cell, the eight neighboring cells surrounding it are considered. These cells represent the possible flow directions and are defined as north, northeast, east, southeast, south, southwest, and west. Next, the model calculates the slope difference between the main cell (for which the flow is being calculated) and its neighboring cells. The direction with the steepest slope is determined to be where the water will flow(Tarboton, Bras, & Rodriguez–Iturbe, 1991). Finally, the cell is assigned a value based on its flow direction. This value increases according to the eight possible directions: 1 for North, 2 for Northeast, 4 for East, 8 for Southeast, and so on(Jenson & Domingue, 1988). By applying this process to each cell, the flow directions are determined in the DEM data.

6.2.3. Application

With the Flow Direction tool, we can determine the flow direction of each cell, and thus the natural flow of water. By analyzing the flow directions, we can differentiate between rivers, streams, and watersheds. The results obtained can be used in future hydrology analysis tools. Additionally, we can predict where water will accumulate and how it will flow during events like rainfall, allowing us to take necessary precautions accordingly.

6.3. FLOW ACCUMULATION

6.3.1. General Description

In ArcGIS, the flow accumulation method is used to calculate the total amount of water flowing into each cell. The total flow strength is determined by calculating the values of upstream cells that contribute to the flow towards a specific point which allows, hydrological analyses can determine where water accumulates, as well as the strength and direction of the flow(Tarboton, Bras, & Rodriguez–Iturbe, 1991).

This tool is critical for analyzing drainage patterns, designing infrastructure such as drainage systems, and managing water resources in both urban and natural settings. Researchers can improve their understanding of water movement by analyzing flow accumulation, which aids in flood risk assessment, erosion control, and watershed management.

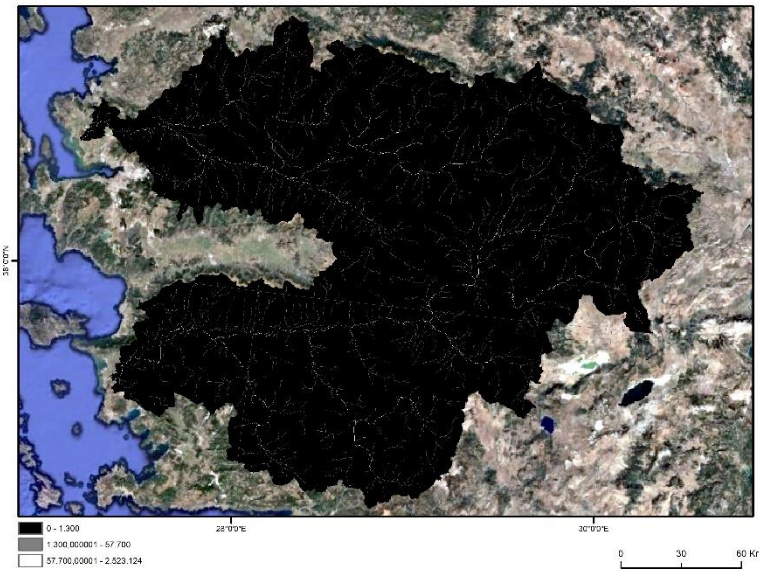

Figure 6 – Flow accumulation layer over Google Earth image.

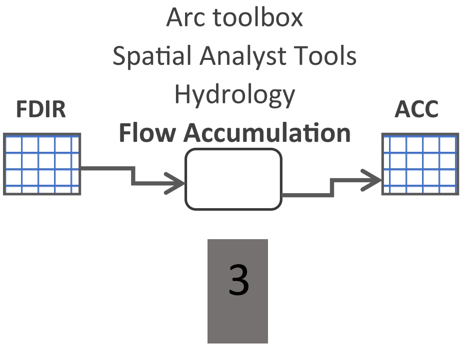

Figure 7 – FLOW ACCUMULATION operation with ArcGIS ArcToolbox tool sequence.

6.3.2. Calculation Method

In the flow accumulation method, the values of neighboring cells that flow into a given cell, as determined by the flow direction, are summed, and this process continues upstream throughout the network. This procedure is applied to the entire DEM dataset, and each cell is assigned a value based on the total sum of the values from upstream cells flowing into it(Jenson & Domingue, 1988). Additionally, it is assumed that water flows in the direction of the steepest slope and towards lower areas, which is why lower regions receiving flow from a large number of upstream cells show greater water accumulation.

6.3.3. Application

Using the Flow Accumulation tool, we determined where and in what quantities water accumulates on our terrain, helping us predict which areas might form rivers or streams based on the accumulation values (Tarboton, Bras, & Rodriguez–Iturbe, 1991). Additionally, by identifying the amount of water collected in each area, we can anticipate potential hazards such as floods or landslides during periods of heavy rainfall and take preventive measures accordingly(Jenson & Domingue, 1988).

We also performed the Flow Accumulation process using the Slope data as the weight raster. This allows us to observe the slope flow in each cell and shows the accumulated slope values within the cells. By using this data in subsequent processes, we can calculate the average slope (AVG_SLP) per cell.

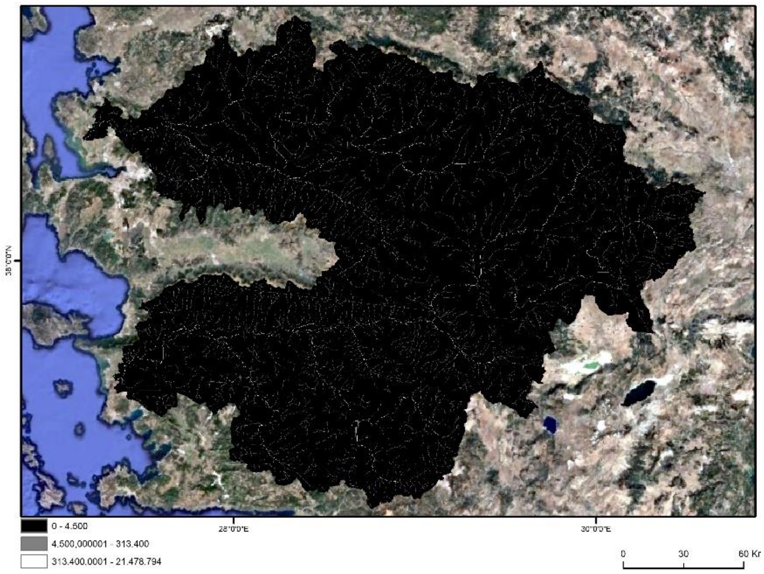

Figure 8 – Flow Accumulation with using Slope as Weight Raster over Google Earth image.

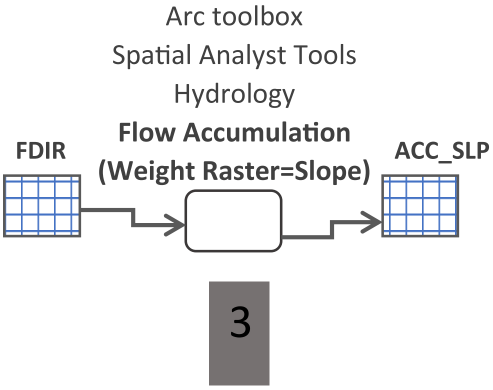

Figure 9 – FLOW ACCUMULATION operation with sloe as weight raster with ArcGIS ArcToolbox tool sequence.

6.4. RECLASSIFY

6.4.1. General Description

The Reclassify process in ArcGIS is used to group data into categories or classes based on their attributes or values, simplifying complex datasets for better analysis and interpretation. By organizing data into classes, such as elevation ranges, land use types, or population densities, the classification process allows patterns and trends to be more easily identified.

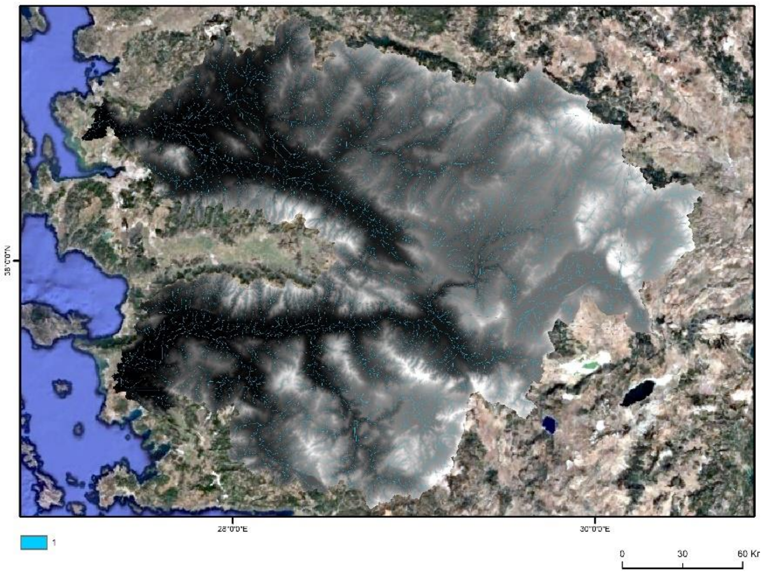

Figure 10 – Reclassify layer over DEM and over Google Earth image.

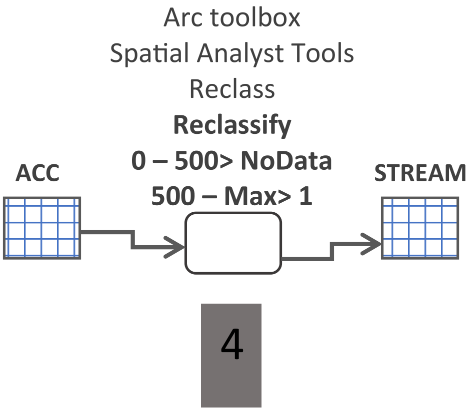

Figure 11 – RECLASSIFY to create stream raster operation with ArcGIS ArcToolbox tool sequence.

6.4.2. Calculation Method

Reclassification is a process that changes the values of cells in a raster dataset into new categories. First, the existing cell values are reviewed, and then you decide how to group them. Once the new categories are set, the cell values are updated according to these rules, making it easier to analyze or simplify the data. For example, let's say you have elevation data ranging from 0 to 2000, all recorded in your dataset. You can reclassify this data by assigning the values between 0 and 200 as NoData, 200 to 1000 as 1, and 1000 to 2000 as 2, effectively removing all values between 0 and 200 and leaving you with two different data classes.

6.4.3. Application

Using the Reclassify tool, we divided the cell range with different values obtained from the Flow Accumulation into the desired categories. This allowed us to remove all flow areas between 0 and 500 from our map and group all flows greater than 500 into a single value, resulting in a more organized map.

6.5. STREAM ORDER

6.5.1. General Description

Stream Order in hydrology analyses helps assess the hierarchy and connectivity of streams, allowing us to identify higher-order streams that carry more water and sediment. This method includes two classification systems. The first, widely used system is the Strahler classification system(Tarboton, Bras, & Rodriguez–Iturbe, 1991). In this system, streams of the same order combine to form a higher-order stream. The other classification system is the Shreve classification system, where the degrees of two streams that join together are summed to determine the degree of the resulting upstream flow.

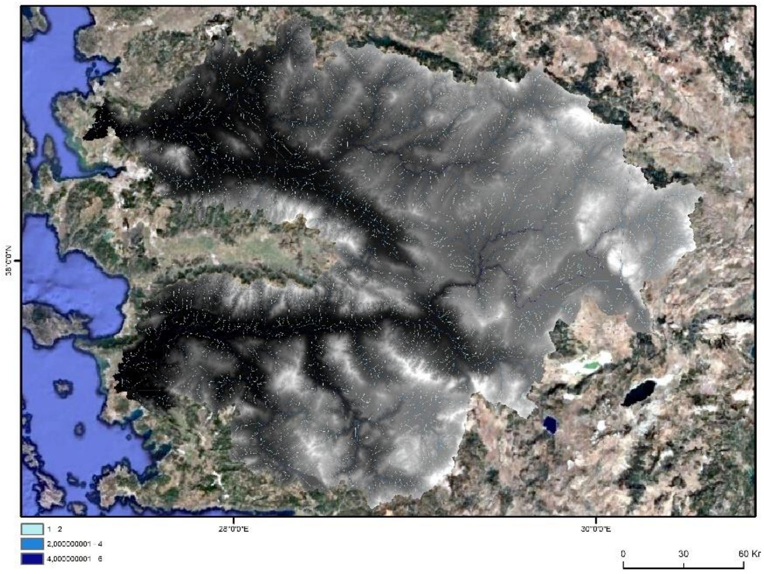

Figure 12 - Strahler Method over DEM and Google Earth image

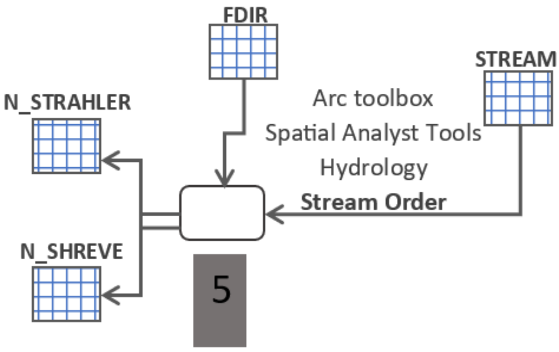

Figure 13 – STREAM ORDER operation (Strahler) with ArcGIS ArcToolbox tool sequence.

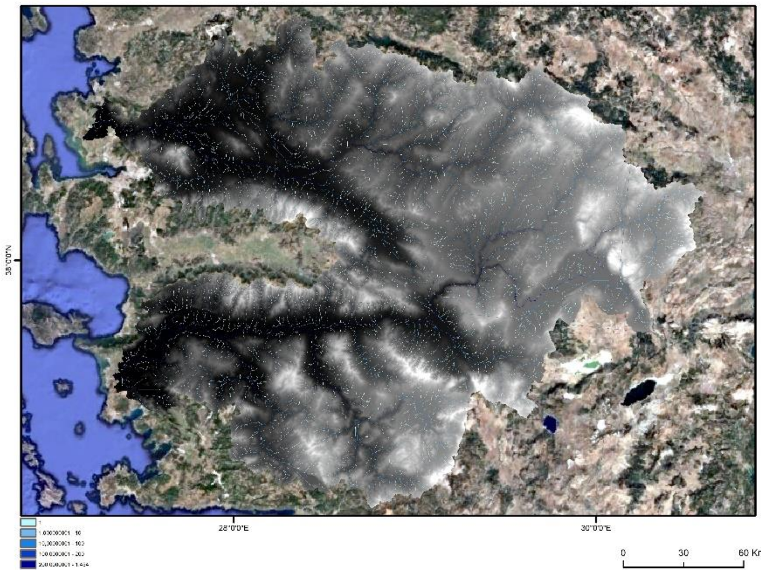

Figure 14 - Shreve Method over DEM and Google Earth image.

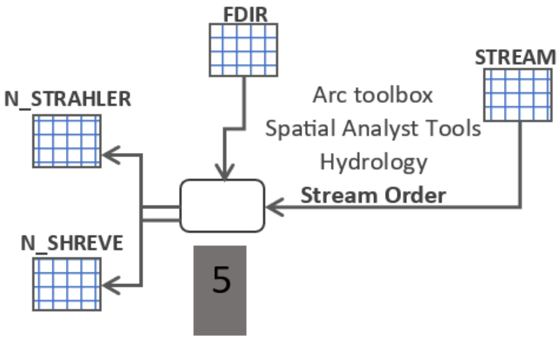

Figure 15 – STREAM ORDER operation (Shreve) with ArcGIS ArcToolbox tool sequence.

6.5.2. Calculation Method

When examining the calculation method of the Stream Order, we analyze it in two separate systems. The first, widely used, is the Strahler method. In this method, the smallest streams, those at the beginning of the branching, are assigned as first-order streams. When two first-order streams merge, they form a second-order stream, and when two second-order streams merge, they create a third-order stream, and this pattern continues. However, if two streams of different orders merge, the stream order does not increase(Tarboton, Bras, & Rodriguez–Iturbe, 1991).

The second method is the Shreve method (Shreve, 1966). In this system, when two first-order streams converge, they form a second-order stream, and when two second-order streams merge, a fourth-order stream is created. Unlike the Strahler system, when a first-order and a second-order stream merge, they form a third-order stream.

6.5.3. Application

Using the Stream Order tool, we classified the streams based on either the Shreve or Strahler method. This allowed us to organize our streams more systematically and eliminate the complexity of the watershed. Additionally, with the Stream Order tool, we can understand the hierarchy of streams and simplify the complexity of the watershed. By analyzing the stream orders, we can predict which streams will carry more debris during floods or heavy rainfall. Identifying higher-order streams helps us take preventive measures against potential floods that may occur during periods of intense rainfall.

6.6. SLOPE

6.6.1. General Description

In ArcGIS, the Slope method is used to calculate the rate of change in elevation or the steepness of the terrain for each cell. It computes how much elevation changes over a certain distance, expressed in degrees or as a percentage. This is done using DEM data by evaluating the elevation of a specific cell and its neighboring cells, determining how much the elevation changes over a given distance.

This analysis is crucial for a variety of applications, including hydrology, land-use planning, and environmental management, as it helps to identify areas prone to erosion, guide infrastructure development, and model water runoff.

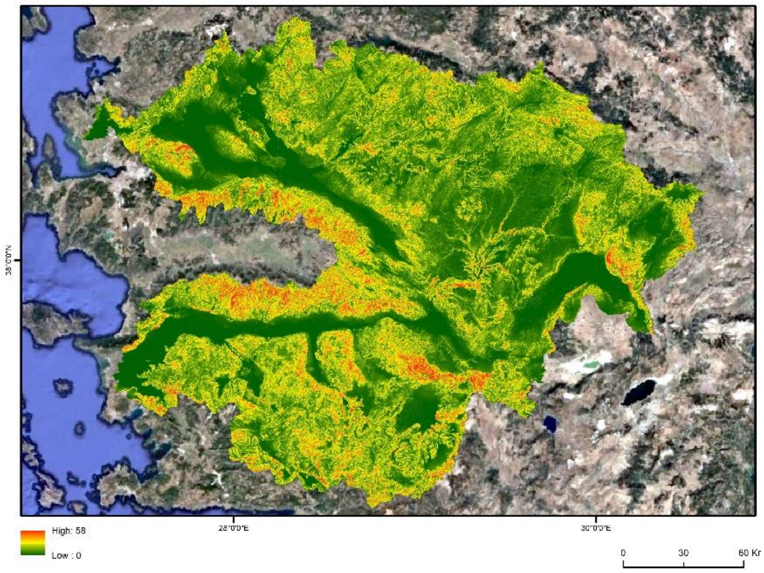

Figure 16 - Slope layer over Google Earth image.

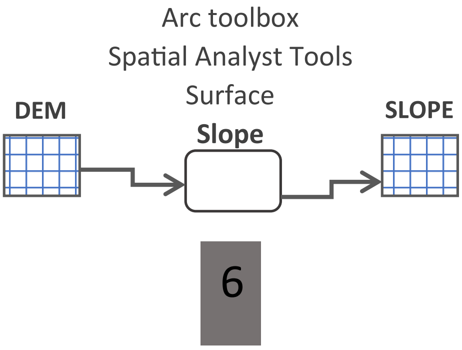

Figure 17 – SLOPE operation with ArcGIS ArcToolbox tool sequence.

5.6.2. Calculation Method

When the Slope tool in ArcGIS is applied, the algorithm first compares the elevation values in a DEM (Digital Elevation Model) for each cell between the central cell and its neighboring cells in both the x (horizontal) and y (vertical) directions to measure the elevation change. The slope is then calculated using a mathematical formula that combines these elevation differences to determine the overall rate of change(Tarboton, Bras, & Rodriguez–Iturbe, 1991). This rate is then calculated either as an angle in degrees or as a percentage. Essentially, the steeper the terrain, the greater the slope, because a sharp change in elevation over a given horizontal distance indicates a higher slope.

5.6.3. Application

Using the Slope tool, we obtained the slope values for the area in our DEM data. With these values, we can determine where the water in the flow moves faster or slower(Tarboton, Bras, & Rodriguez–Iturbe, 1991). With the information on the steepness of the area, we can assess the rate or intensity of erosion and sediment transport. Based on this information, helps us take preventive measures against natural disasters like erosion or floods, as well as prevent sediment transport or the negative effects on fertile soil and water during such events.

6.7. MAP ALGEBRA – RASTER CALCULATOR

6.7.1. General Description

The Raster Calculator method in ArcGIS is a versatile tool used for performing mathematical calculations on rasters. It allows users to combine, process, and analyze one or more raster datasets using algebraic expressions to generate new outputs. These operations can range from simple mathematical tasks (such as addition, subtraction, multiplication, and division) to more complex spatial analyses like slope calculation, land cover reclassification, or modeling environmental factors.

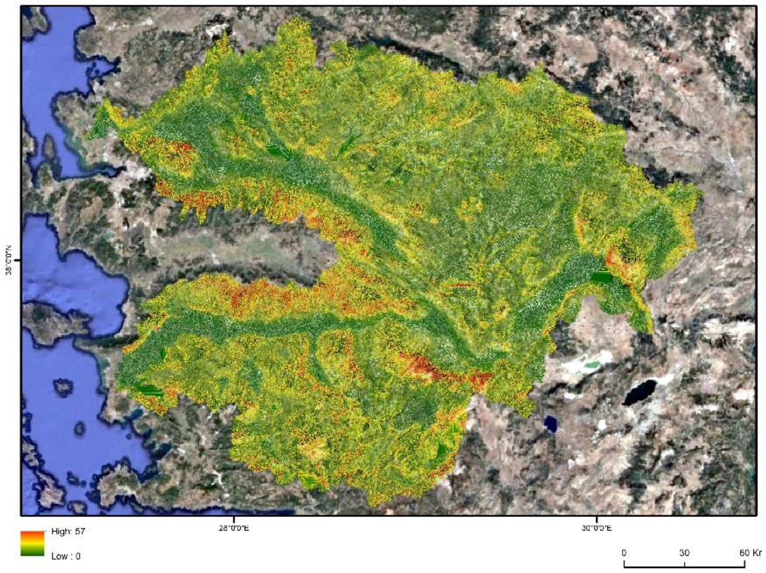

Figure 18 – Map algebra calculation over Google Earth image.

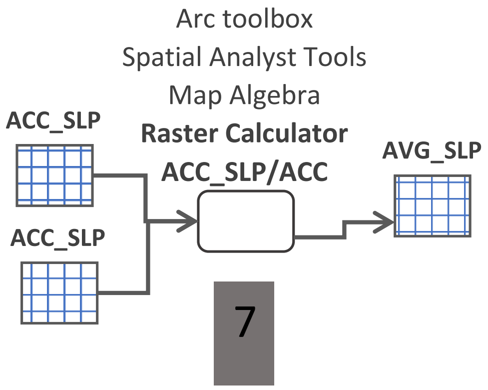

Figure 19 – RASTER CALCULATOR operation with ArcGIS ArcToolbox tool sequence.

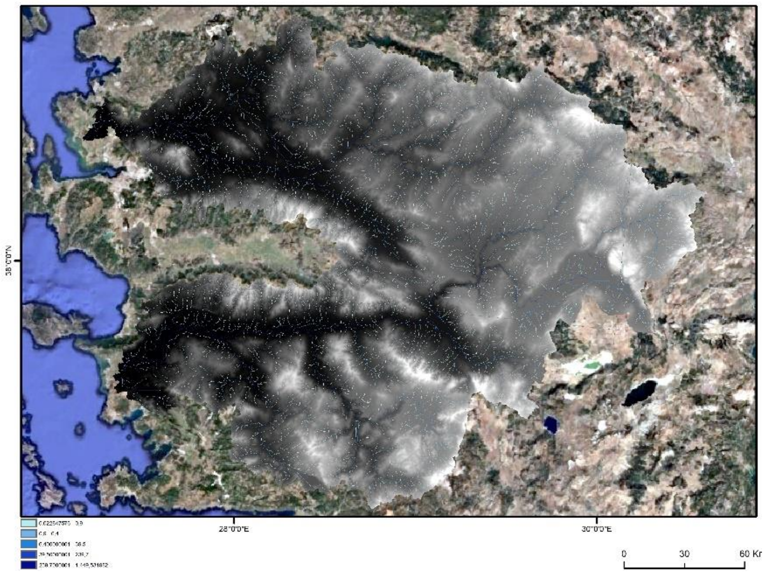

Figure 20 – Map algebra calculation (Shreve divided by the average slope) over Google Earth image.

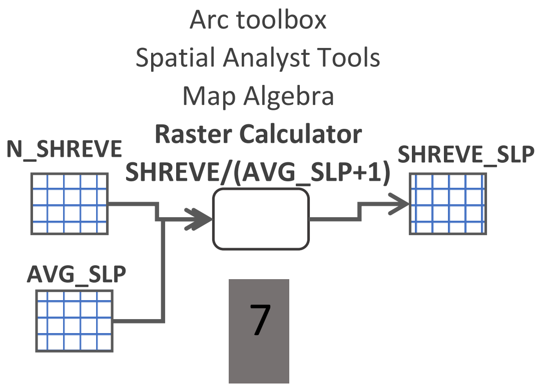

Figure 21 – MAP ALGEBRA operation with ArcGIS ArcToolbox tool sequence.

6.7.2. Calculation Method

In the calculation method of the Raster Calculator tool in ArcGIS, we first need to have a raster map where each cell contains a number (such as elevation, slope, water accumulation capacity, etc.). Using the tool, we can apply formulas or mathematical operations to the raster data. Through these operations, we can add, subtract, or divide values between different maps (for example, combining slope and water accumulation data), or apply new conditions (such as finding areas where water accumulation is greater than 500). In the end, the tool generates a new raster map that shows the result of the calculations. For example, if we add two maps, the result will show the sum of the values in each cell.

6.7.3. Application

Our first operation with the Raster Calculator will be ACC_SLP / ACC. To explain this, let's consider that Flow Accumulation represents the count of cells in a drainage basin, while ACC_SLP data shows the cumulative slope value in each cell. By dividing ACC_SLP by the regular ACC data, we obtain the average cumulative slope over the cumulative distance for each cell. With this data, we can identify areas with a higher risk of erosion, areas with slope structures that may impact natural water flow, and where water storage is more critical, allowing us to make more informed decisions.

In another process, we divide our Shreve data by the value of AVG_SLP + 1. The reason we add 1 to the Avg_Slope is to prevent errors caused by division by zero, as the slope in some areas might be 0. Once this process is complete, we will be able to observe where the slope is high or low and how much water has accumulated in those areas. If the cell value is low, it indicates that the slope in that area is steep, and if the value is high, it indicates a low slope. In summary, this analysis allows us to determine whether an area is flat or steep and whether it is a temporary or permanent water accumulation zone.

6.8. ZONAL STATISTIC AS A TABLE

6.8.1. General Description

The Zonal Statistics as a Table process in ArcGIS summarizes the raster data values within defined zones (typically areas represented by polygons or other categorical features). This tool calculates statistical measures such as mean, median, sum, maximum, minimum, and standard deviation based on the cell values for each zone. The results are presented as a table, where each row corresponds to a specific zone, and each column represents a different statistical metric.

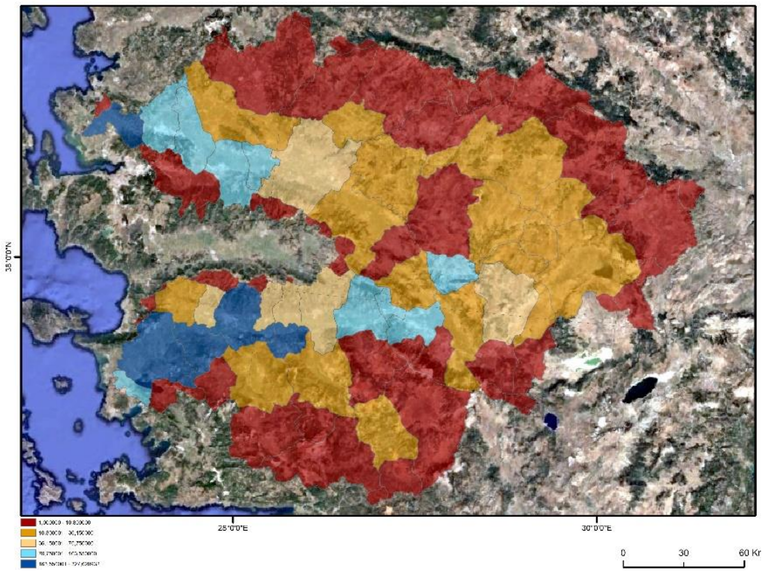

Figure 22 – Zonal statistcs (mean of Shreve by Counties), over Google Earth image.

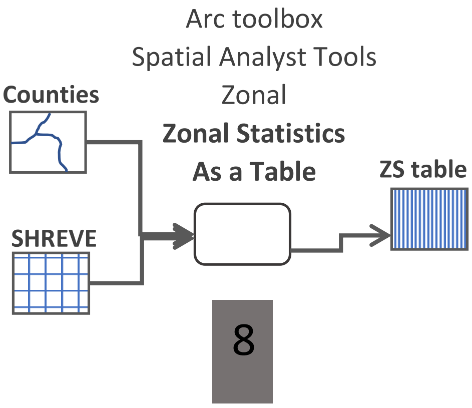

Figure 23 – ZONAL STATISTICS AS TABLE operation with ArcGIS ArcToolbox tool sequence.

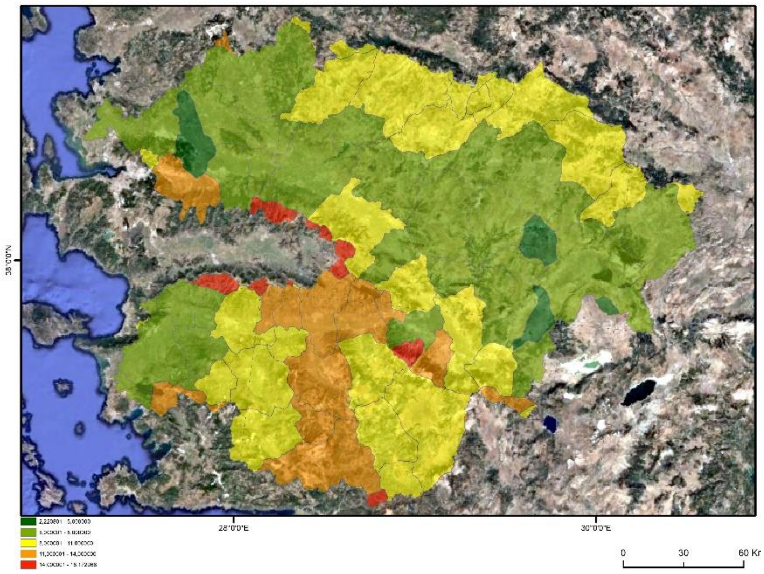

Figure 24 – Zonal statistcs (mean of Slope by Counties), over Google Earth image.

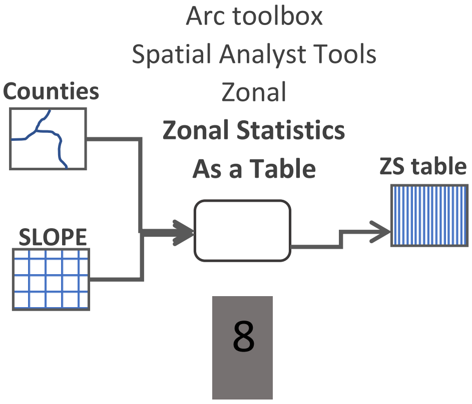

Figure 25 – ZONAL STATISTICS AS TABLE operation with ArcGIS ArcToolbox tool sequence.

6.8.2. Calculation Method

The application of the Zonal Statistics as a Table tool in ArcGIS requires two datasets: the "value data," which contains the values you want to calculate, and the "zone data," which defines the regions where the calculations will take place. The tool then uses mathematical calculations to generate statistics (mean, maximum, minimum, sum, etc.) for the values within each zone. For example, we can calculate the average water accumulation capacity for each region. Finally, the tool creates a table that shows these statistics for each zone, allowing us to see the highest or lowest value, the total, or the average for each region.

6.8.3. Application

Using the Zonal Statistics as a Table tool, we defined the areas in which we processed the statistical values of our stream data. This allows us to determine which areas in our region are wet or dry, the average rainfall, how much water is accumulated in each area, and the maximum or minimum water accumulation values we also do this for the slope. With this information, we can identify areas with higher flood risks during heavy rainfall, where water flow is stronger, and which areas require more attention for water control. Similarly, the same processes are repeated with the Slope data. This way, we can determine values such as our area's average slope, maximum and minimum slope, or total slope. These insights assist us in managing flood and erosion control, irrigation, and reservoir management in our region.

7 – FINAL REMARKS

The study that was developed started from the prior consideration of hydrological analysis in a geographic information system naturally based on the structure of the terrain, duly represented by a data structure aimed at the application of several well-known spatial analysis algorithms of wide application.

The first challenge was the creation of a matrix base of elevation values suitable for the exploratory study that was intended to be carried out. Having considered the size of the study area against the inherent data volume, two river basins were analytically defined in western Turkey as the study area and basic infrastructure for modeling.

The matrix data structure created allowed the application of a set of classic spatial analysis operations from hydrological modeling, resulting from the D8 structure (Jenson & Domingue, 1988), to define the flow structure and generate a set of topographic-based metrics, namely the calculation of order numbers of watercourses, which can be used as hydrological characterization of river basins.

The exploratory research project focused on carrying out a set of hydrological analysis processes aimed at obtaining characterization metrics such as the Strahler (Strahler, A. N., 1952) and Shreve (Shreve, R. L. 1966) indices, and, based on these indexes, carry out a detailed hydrological analysis of a given area, namely the two river basins considered as the study area.

The model developed, namely the generation of Strahler and Shreve indices, in their original versions and in the composite formulations used in this study, allows for a better characterization of hydrological characteristics, helping to understand the relationships between the terrain structure and the distribution and water drainage.

The use of topographic-based metrics generated as zonal statistics for the territorial administrative areas/zones (counties) considered allowed a better hydrological characterization, in an administrative dimension, particularly adapted to carrying out territorial planning and management processes.

Finally, we consider what type of analysis is essential for water resources management, flood prevention and sustainable land use planning, especially in areas prone to water-related challenges.

8.BIBLIOGRAPHY AND REFERENCES

Planchon, O., & Darboux, F. (2002). A fast, simple and versatile algorithm to fill the depressions of digital elevation models. CATENA, 46(2-3), 159–176. https://doi.org/10.1016/s0341-8162(01)00164-3

Tarboton, D. G., Bras, R. L., & Rodriguez-Iturbe, I. (1991). On the extraction of channel networks from digital elevation data. Hydrological Processes, 5(1), 81–100. https://doi.org/10.1002/hyp.3360050107

Jenson, S. K., and Domingue, J. O. 1988. Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing* 54 (11): 1593–1600.

Qin, C., Zhu, A. -X., Pei, T., Li, B., Zhou, C., & Yang, L. (2007). An adaptive approach to selecting a flow-partition exponent for a multiple-flow-direction algorithm. International Journal of Geographical Information Science, 21(4), 443–458. https://doi.org/10.1080/13658810601073240

Ligas, M., & Banasik, P. (2011). Conversion between Cartesian and geodetic coordinates on a rotational ellipsoid by solving a system of nonlinear equations. Geodesy and Cartography, 60(2), 145–159. https://doi.org/10.2478/v10277-012-0013-x

B. Hofmann-Wellenhof, H. Lichtenegger and J. Collins, 2001. *GPS - theory and practice*. Section 10.2.1. p. 282.

David Eberly 1999. *Least Squares Fitting of Data* (Geometric Tools, LLC), pp. 3.

Rob J. Hyndman and Yanan Fan (1996) "Sample Quantiles in Statistical Packages" *The American Statistician*, Vol. 50, No. 4 (Nov., 1996), pp. 361-365.

Shreve, R. L. 1966. 'Statistical law of stream numbers", Journal of Geology, 74, 17-37.

Strahler, A. N., 1952, "Hypsometric (area-altitude) analysis of erosional topology", Geological Society of America Bulletin, 63 (11): 1117–1142, doi:10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2

https://data.humdata.org/dataset/turkey-rivers

https://data.humdata.org/dataset/cod-ab-tur

https://dataspace.copernicus.eu/explore-data