OREGON STATE UNIVERSITY
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GIS in Water Resources
Final Project Report

Application of Digital Elevation Model (DEM) for Willamette Watershed characterization and morphometric analysis.

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Part 0: Introduction

The Willamette Watershed is an important area for water resource management, habitat conservation, and land-use planning. In order to better understand the physical characteristics of this watershed and inform decision-making about its management and conservation, the use of digital elevation models (DEMs) and morphometric analysis have come into play.

A digital elevation model is a digital representation of the topography of an area, based on elevation data obtained from remote sensing or surveying methods. By analyzing the characteristics of the terrain represented in the DEM, insights into the underlying physical processes that have shaped the landscape can be developed.

Morphometric analysis, which involves quantifying the physical characteristics of landforms, such as drainage density, stream order, slope and aspect. This provides additional insights into the processes that have shaped and influenced the Willamette Watershed over time.

This project aims to review the current state of knowledge about the use of DEM and morphometric analysis in characterizing the Willamette Watershed, including its topography, drainage network, and geomorphological features, and to highlight its potential applications for water resource management.

This report provides the description of the data source and methods used to process the data and generate the watershed characteristics and morphometric parameters. The results of the analysis are presented in the form of maps, graphs, and tables that provide insight into the watershed's topography and drainage patterns. This report concludes with discussion of the problems, limitations of the project, and recommendations for future research.

Part 1: Site Description

The Willamette Watershed is an important area located in the Pacific Northwest region of the United States with a complex and diverse ecosystem of about 29,000 square kilometers land area. The Willamette River Basin from its snowy and forested headwaters in the Oregon Cascades to its green valley floor is water-rich, but with a warming climate. It is home to a variety of flora and fauna and is a critical source of water for the surrounding communities. The land cover of the Willamette Watershed is predominantly forested, with over 50% of the area covered by forestland. Other major land cover types include agricultural land, urban and suburban areas, and wetlands. Figures 1.1 and 1.2 shows the location of the Willamette watershed (study area).

Figure 1.1: Location of Willamette River Basin within Oregon State (ArcGIS Pro).

Figure 1.2: Willamette River (www.google.com)

Part 2: Data Description

A DEM is a digital representation of the topography of an area, based on elevation data obtained from remote sensing or surveying methods. DEM data (raster) is typically stored as a gridded dataset, where each grid cell or pixel represents a small portion of the terrain's surface. The elevation of each pixel is represented as a numerical value, which can be used to create contour lines, 3D visualizations, and other types of maps and models.

Nine DEM tiles for the Willamette Watershed were gotten from the United States Geological Survey (USGS) national map. The DEM tiles are provided in 1 × 1 tiles at 1 arc-second (30meters resolution) and is defined on WGS84 datum (in GeoTIFF format). All unit and elevation values are in meters over the conterminous United States, and are referenced to the North American Vertical Datum of 1988 (NAVD 88).

The raster data (DEM) are then projected to North America Datum 1983 Universal Transverse Mercator Zone 10N (NAD83 UTM Zone 10N). The UTM projection is generally well-suited for areas that are elongated in the north-south direction just like Willamette River basin and this is because the UTM projection divides the earth into a series of narrow, vertical zones that each span 6 degrees of longitude, which helps to minimize distortion in the north-south direction within each zone.

Part 3: Methodology

This part presents the methods performed on the DEM data in ArcGIS pro to analyze Willamette Watershed to derive the watershed characteristics and morphometric parameters such as slope, aspect, and stream order. Figure 3.1 shows the flowchart (using model builder tool) of the major processing steps.

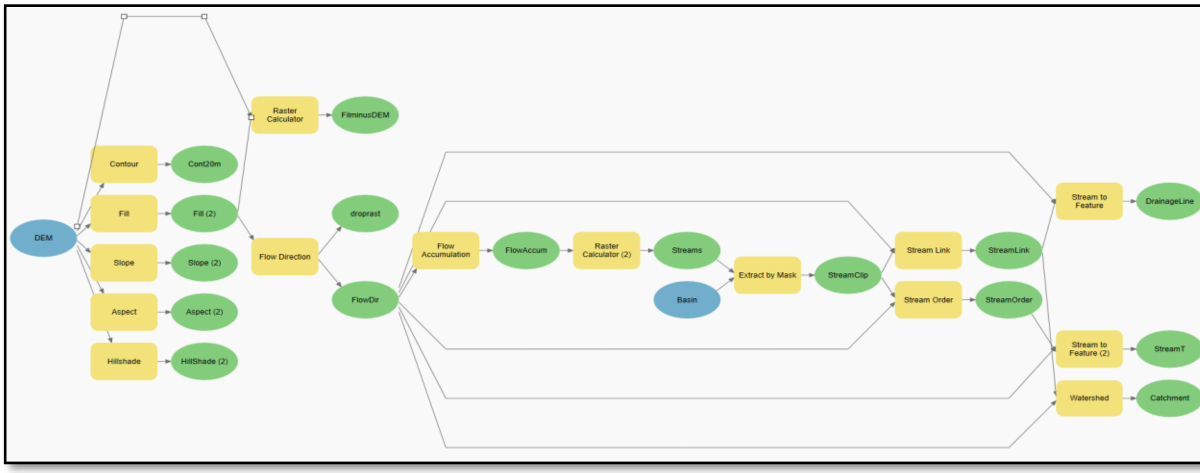


Figure 3.1: Flowchart of processing steps (ArcGIS Pro model builder)

DEM data pre-processing

This involves locating the required area of DEM for the Willamette watershed using the specification in the Data description in Part 2 and merging these DEMs together. The raster data (DEM) are then projected to North America Datum 1983 Universal Transverse Mercator Zone 10N (NAD83 UTM Zone 10N). Subsequent processes are projected to the same coordinate system.

Watershed Delineation

The delineation of Willamette Watershed boundary involves determining the gage point location (latitude and longitude) of Willamette River at Portland, OR from USGS waterdata website and creating a gage point. The watershed in the ready to use Geoprocessing tool was then used to delineate the Willamette watershed.

Watershed Characterization

Slope: Slope (using the slope spatial analyst tool on the DEM as shown in Figure 3.2) is a measure of the steepness of the land surface and is typically expressed as a percentage or degree of incline. Slope is an important parameter in watershed characterization as it plays a significant role in determining the flow of water within a watershed. High slopes generally result in faster runoff and increased erosion, while low slopes typically result in slower runoff and increased infiltration.

Aspect: Aspect (using the aspect spatial analyst tool on the DEM as shown in Figure 3.3) refers to the direction that a slope faces and is typically expressed in degrees. Aspect is an important parameter in watershed characterization as it affects the amount and distribution of solar radiation received by the land surface, which in turn affects the distribution of vegetation and the rate of evapotranspiration. The slope and aspect map of the Willamette watershed to depict the slope and direction of flow is shown in Figure 3.4.

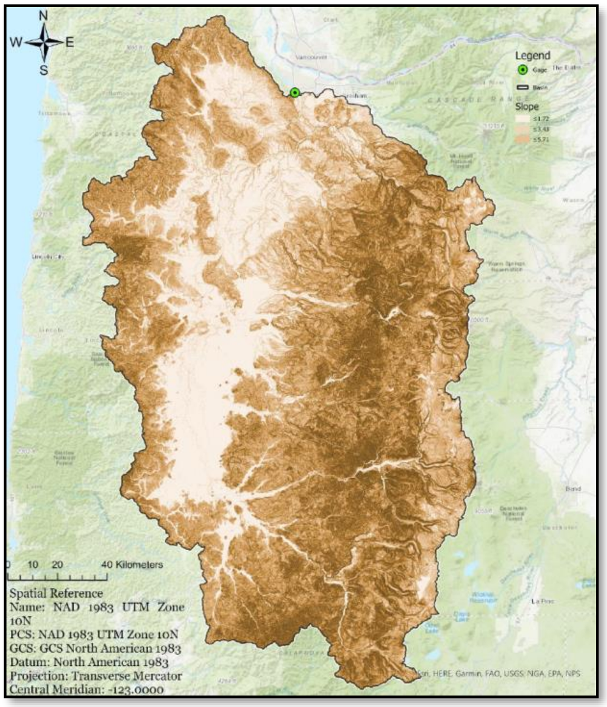


Figure 3.2: Slope in Willamette watershed (ArcGIS Pro)

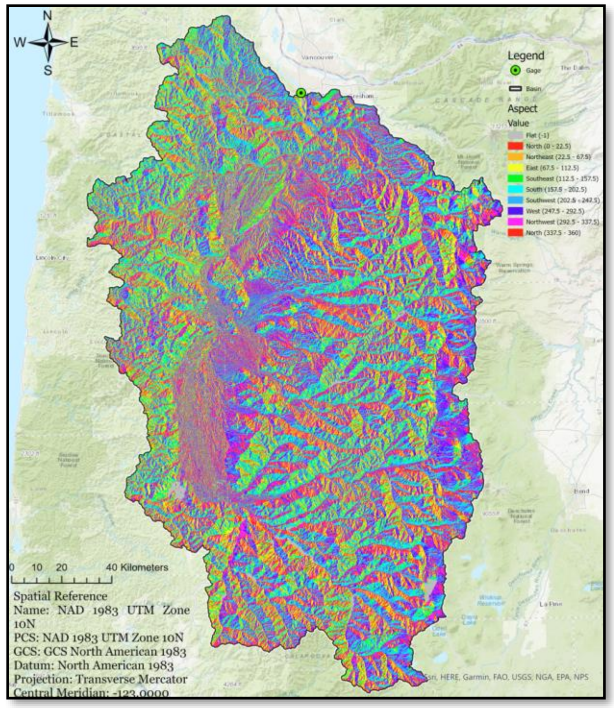


Figure 3.3: Aspect in Willamette watershed (ArcGIS Pro)

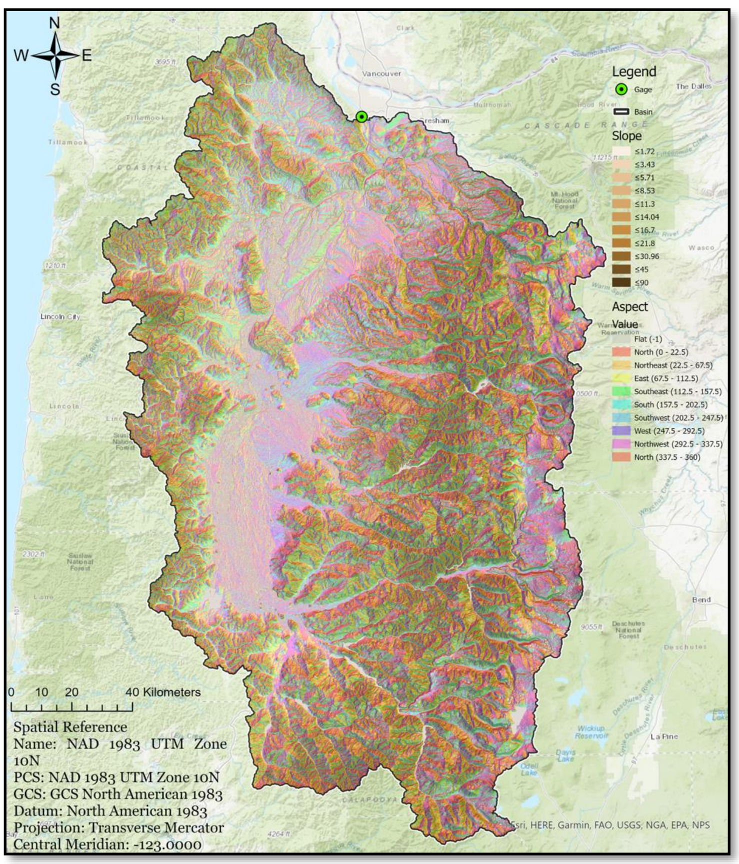


Figure 3.4: Slope and Aspect in Willamette watershed (ArcGIS Pro)

Hillshade: Hillshade (using the hillshade spatial analyst tool on the DEM as shown in Figure 3.5) is a measure of the amount of shading on the land surface and is typically derived from a digital elevation model (DEM). Hillshade is also an important parameter in watershed characterization as it can be used to identify areas of the watershed that are shaded by topographic features such as ridges and hills, which may affect the distribution of vegetation and the rate of evapotranspiration.

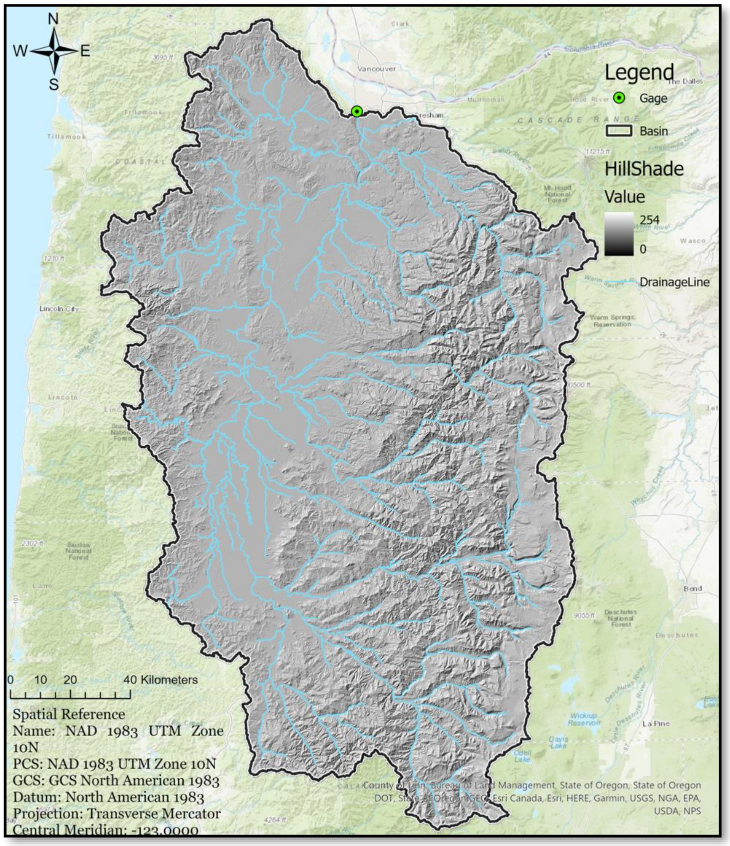


Figure 3.5: Hillshade of Willamette watershed (ArcGIS Pro)

<u>Stream networks in the Watershed</u>

This involves the hydrologic analysis in ArcGIS pro, the steps are: fill pits, flow direction, flow accumulation, and stream definition and links. An outlet point will then be used to define the watershed outlet and then watershed streams using the flow accumulation. The hydrologic functions will be used to define separate stream links and the catchments that drain to them as shown in Figure 3.6.

Fill pits: This function fills the sinks in a grid using the Fill (spatial analyst tool on the DEM). If cells with higher elevation surround a cell, the water is trapped in that cell and cannot flow. The Fill function modifies the elevation value to eliminate these problems. The difference between the DEM and the Fill (using raster calculator) was used to determine the areas where water is being trapped in the Willamette watershed with the deepest sink around Deschutes National Forest as shown in Figure 3.7.

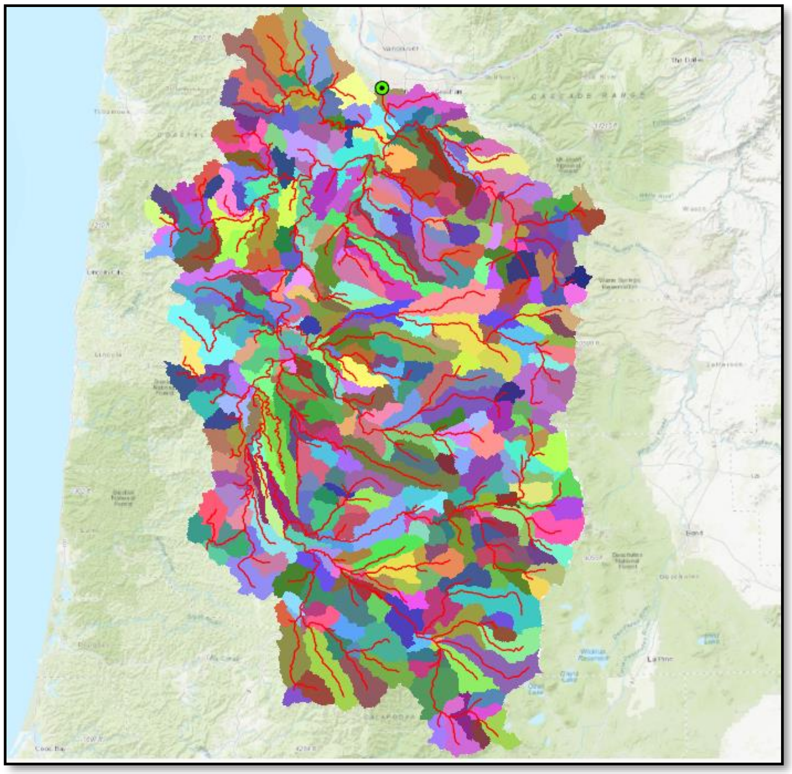


Figure 3.6: Stream links and Catchments in Willamette watershed (ArcGIS Pro)

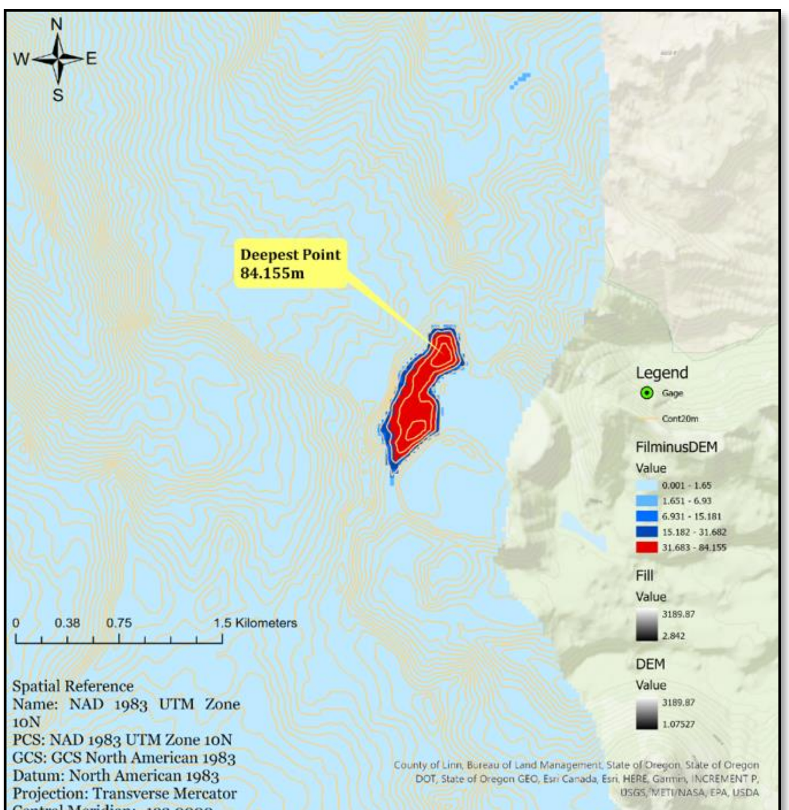
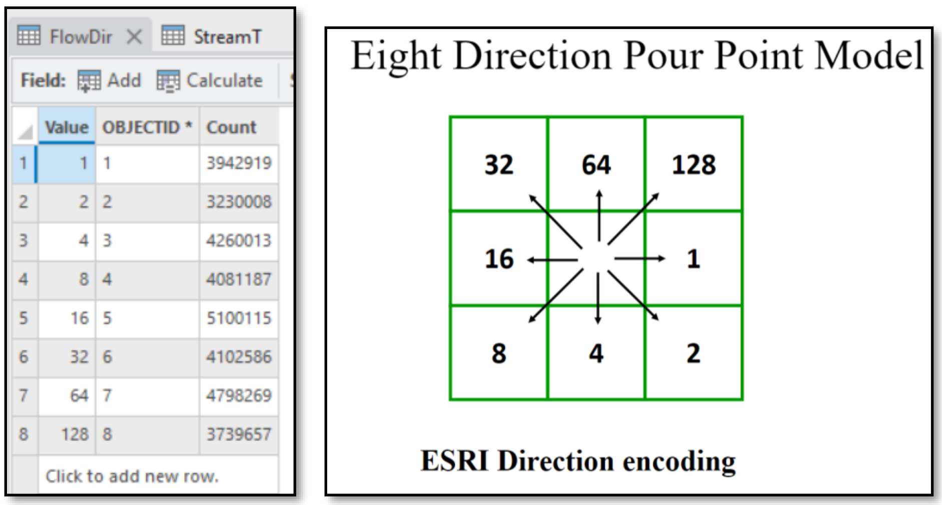


Figure 3.7: Deepest sink in the Willamette watershed (ArcGIS Pro)

Flow Direction: This function computes the flow direction for a given grid using the Flow Direction (spatial analyst tool on the filled DEM as shown in Figure 3.8). The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell. This information can be used for a variety of purposes, such as hydrologic modeling, floodplain mapping, and water quality assessment.
Flow Accumulation: This function computes the flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid using the Flow Accumulation (spatial analyst tool on the flow direction).
Stream definition and links/drainage lines: This is defining streams based on flow accumulation threshold within the Willamette watershed shown in Figure 3.6. That is, flow accumulation greater than forty thousand was used to define the stream links/drainage lines.



	Value	OBJECTID *	Count
1	1	1	3942919
2	2	2	3230008
3	4	3	4260013
4	8	4	4081187
5	16	5	5100115
6	32	6	4102586
7	64	7	4798269
8	128	8	3739657
	Click to add new row.		

Figure 3.8: Flow direction using the 8-direction pour point (ArcGIS Pro)

<u>Stream network characterization</u>

Stream order is important for understanding the hydrology and ecology of rivers and streams. It can be used to predict flood potential, determine the flow characteristics of a river, and assess the health of aquatic ecosystems.
The Strahler stream order is a widely used method for stream ordering, in which streams and rivers are classified into a hierarchy based on their relative size and the number of tributaries they receive. In this method, a first-order stream is a stream with no tributaries, a second-order stream is formed when two first-order streams join, a third-order stream is formed when two second-order streams join, and so on, as shown in Figure 3.9.

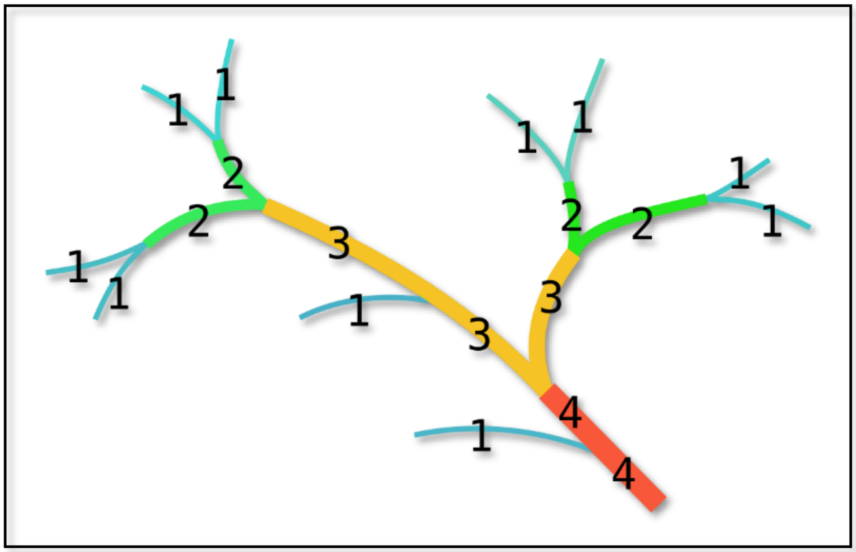


Figure 3.9: Stream order using Strahler approach (www.google.com)

Part 4: Results, Analysis and Conclusion

This part presents the result from Willamette Watershed characterization and morphometric analysis performed on the DEM data in ArcGIS Pro environment.

Computation of Morphometric parameters

Computation of basin area, basin perimeter, basin length, Strahler stream order, number of streams, total stream length, bifurcation ratio, drainage density, stream frequency, drainage texture, elongation ratio, circulatory ratio, form factor, compactness coefficient, basin relief, relief ratio, and ruggedness number. These morphometric parameters are all defined in Table 1, 2, 3, and 4 with their results.

Table 1: Basic Morphometric parameters of Willamette Watershed

S/N	Morphometric Parameter	Definition	Result	Unit
1	Basin Area (A)	The area enclosed by the watershed (ArcGIS Pro analysis)	28,879.5564	km^2
2	Basin Perimeter (P)	The perimeter of the watershed (ArcGIS Pro analysis)	1,435.8619	km
3	Basin Length (L_b)	Distance from outlet to the farthest point on basin boundary (ArcGIS Pro analysis)	241.66	km
4	Stream Order (U)	Hierarchical order	11	[-]
5	Number of Streams (S_n)	Total stream number of all orders (ArcGIS Pro analysis)	1,048,575	[-]
6	Total Stream Length (L_t)	Total stream length of all orders	83,177.08195	km

Table 2: Linear Morphometric parameters of Willamette Watershed

S/N	Morphometric Parameter	Definition and Formula	Result	Unit
1	Bifurcation ratios (Br)	$Br = S_n / (S_n + 1)$ where, S_n = Total number of stream segments of order 'U'; $S_n + 1$ = Number of segments of the next higher order.	See Table 5	[-]
2	Mean Bifurcation ratio (Brm)	Brm = Average of bifurcation ratios of all orders	1.5923	[-]
3	Drainage density (Dd)	$Dd = L_t / A$ where, L_t = Total stream length of all orders; A = Basin area (km^2)	2.8801	$km.km^{-2}$
4	Stream frequency (F)	$F = S_n / A$ where, S_n = Total number of streams of all orders; A = Basin area (km^2)	36.3086	km^{-2}
5	Drainage texture (D_t)	$D_t = S_n / P$ where, S_n = Total number of streams of all orders; P = Basin Perimeter (km)	730.2757	km^{-1}

Table 3: Shape Morphometric parameters of Willamette Watershed

S/N	Morphometric Parameter	Definition and Formula	Result	Unit
1	Elongation ratio (Er)	$Er = (2 / L_b) \times (\text{sqrt}(A / \pi))$ where, A = Basin area (km^2); π = 'Pi' value = 3.142; L_b = Basin length	0.7935	[-]
2	Circulatory ratio (Cr)	$Cr = 4 \times \pi \times A / P^2$ where, π = 'Pi' value = 3.142; A = Basin area (km^2); P = Basin Perimeter (km)	0.1760	[-]
3	Form factor (Ff)	$Ff = A / L_b^2$ where, A = Basin area (km^2); L_b= Basin length	0.4945	[-]
4	Compactness coefficient (Cc)	$Cc = P / (2 \text{ sqrt} (\pi A))$ where, P = Basin perimeter (km); A = Basin area (km^2)	2.3835	[-]

Table 4: Relief Morphometric parameters of Willamette Watershed

S/N	Morphometric Parameter	Definition and Formula	Result	Unit
1	Basin relief (R_b)	R_b = Maximum relief − Minimum relief R_b is the height between the highest and lowest points in the basin.	3,187.028	m
2	Relief ratio (Rr)	$Rr = R_b / (1000 * L_b)$ where, R_b = Basin relief; L_b = Basin length	0.013	[-]
3	Ruggedness number (Rn)	$Rn = Dd \times (R_b / 1000)$ where, Dd = Drainage density; R_b = Basin relief	9.1842	[-]

Table 5: Bifurcation ratio of each stream order in the Willamette Watershed

Stream Order	Result	Unit
1	1.2956	[-]
2	1.3993	[-]
3	1.4026	[-]
4	1.6031	[-]
5	1.7478	[-]
6	1.8974	[-]
7	1.5312	[-]
8	2.3037	[-]
9	0.7753	[-]
10	3.5589	[-]
11	0	[-]

Analysis of Morphometric parameters

Morphometric analysis requires a calculation of the linear characteristics, channel network gradient, and contributing drainage basin ground slopes. It is an essential tool for prioritizing subwatersheds (SWs), without even considering the soil map. Horton (1940) and Strahler (1950) conducted initial morphometric research in the field of hydrology. The movement of surface runoffs and sediments to a stream within the drainage basin is a basis for morphometric analysis. This involves the linear, shape, and relief analysis from the computed morphometric parameters.

Subwatershed Analysis

The Willamette watershed resulted in the delineation of 447 catchments (subwatersheds, SWs) using a flow accumulation greater than 40,000 as seen in Figure 3.2. The Willamette River which is the major river in the basin has its source around Dorris Ranch Living History Farm located between SWs 370 and 380, and flows south to north through several other subwatersheds to the basin outlet (Catchment 18) as shown in Figure 3.2.

Basic Morphometric Parameters

The results of the computation of basic morphometric parameters are shown in Table 1. The drainage networks in the Willamette River Basin transport water and sediments of the basin through a single outlet (Willamette River), which is marked as the maximum order of the basin and conventionally the highest order stream (11th order) available in the basin. Based on stream order, Willamette River Basin was graded as 11th order with an area of 28,879.56 km^2 and a perimeter of 1,435.86 km. Figure 4.1 presents a map showing the basin's stream order. The cumulative number of streams in the basin is 1,048,575. The total length of the streams in various orders is 83,177.08 km.

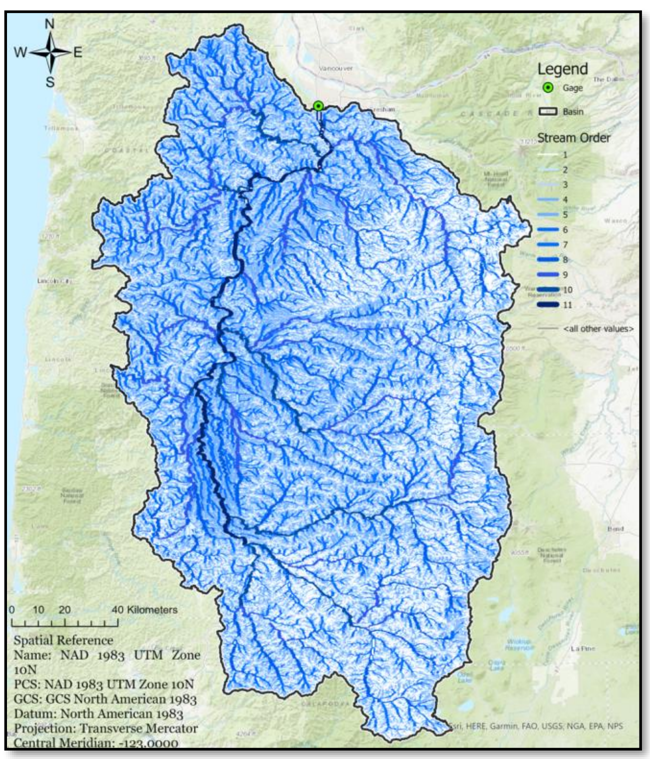


Figure 4.1: Stream Order of the Willamette watershed (ArcGIS Pro)

Some of the morphometric parameters are directly considered as soil erosion metrics and thus are referred to as erosion risk assessment parameters (Biswas et al. 1999). These include the linear, shape and relief morphometric parameters as shown in Table 2, 3, 4, and 5. Linear and relief morphometric parameters have a direct/positive association with erodibility, that is, the higher the values of these parameters, the greater the erodibility in the area and vice versa (Javed et al. 2009). In contrast, shape morphometric parameters have an inverse relation to erodibility, that is, the lower the values of these parameters, the higher the erodibility in the field of analysis and vice versa (Ratnam et al. 2005).

Linear Morphometric Parameters

These parameters include Drainage density (Dd), Stream frequency (F), Mean Bifurcation ratio (Brm), and Drainage texture (Dt) shown in Table 2. A lower Dd in any watershed implies a porous sub-surface soil, strong vegetation cover, low relief and vice-versa. Generally, a drainage density of less than 1 km/km^2 is considered low, while a density of greater than 5 km/km^2 is considered high. In the Willamette watershed, the Dd was computed to be 2.88 km/km^{-2} and would be considered moderate, indicating that the watershed has a fairly well-developed stream network, but is not excessively dissected or eroded (which indicates that this watershed is not highly permeable and is susceptible to erosion.

The Stream frequency has an inverse correlation with porosity and a positive correlation to watershed relief (Montgomery, Dietrich 1992). High F indicates that there is rocky terrain in the watershed and low infiltration ability which correlates to further erosion and vice versa. Willamette watershed has a high stream frequency, F, of 36.31 km^{-2} means that there are relatively high number of streams in a watershed per unit area. This could indicate that the watershed is relatively rocks that are not permeable and highly conducive to the formation of streams.

The bifurcation ratio is a measure of the terrain's structural complexity and porosity and is thus negatively associated with the watershed's porosity. The range of bifurcation ratios that can be considered "low" or "high" can vary depending on the specific characteristics of the watershed in question, as well as the goals and context of the analysis. Generally, a bifurcation ratio of less than 3 is considered low, while a ratio of greater than 5 is considered high. Willamette watershed have a mean bifurcation ratio of 1.59 which is considered a low bifurcation ratio and may indicate a more linear or dendritic stream pattern and a greater potential for erosion and sediment transport. The bifurcation ratio, Br, for each stream order is given in Table 5.

Figure 4.2 and 4.3 shows the graph of the number of stream and bifurcation ratio against the stream order respectively.

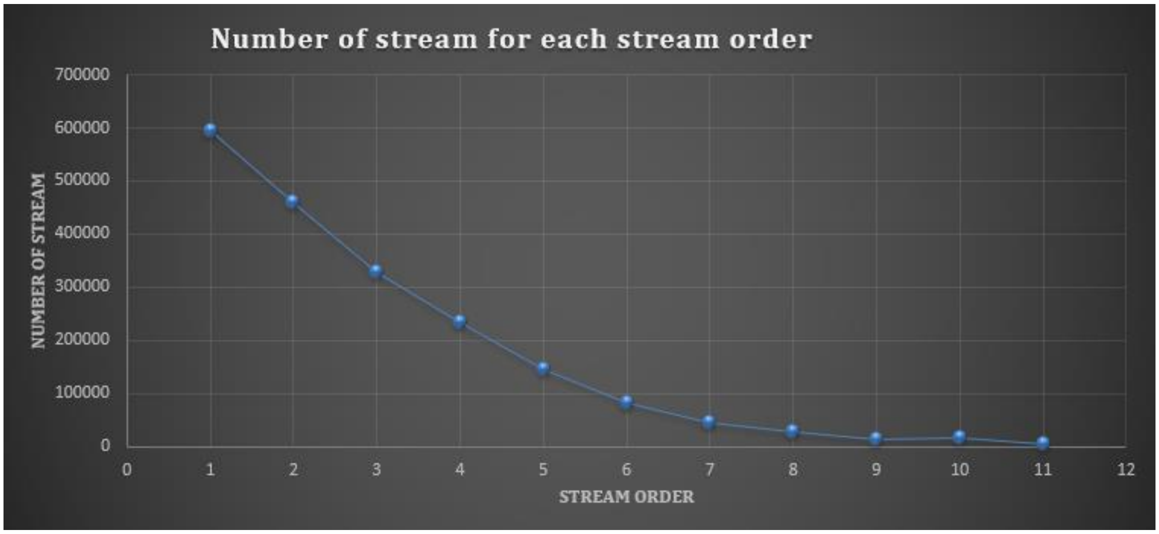


Figure 4.2: Number of streams against the stream order

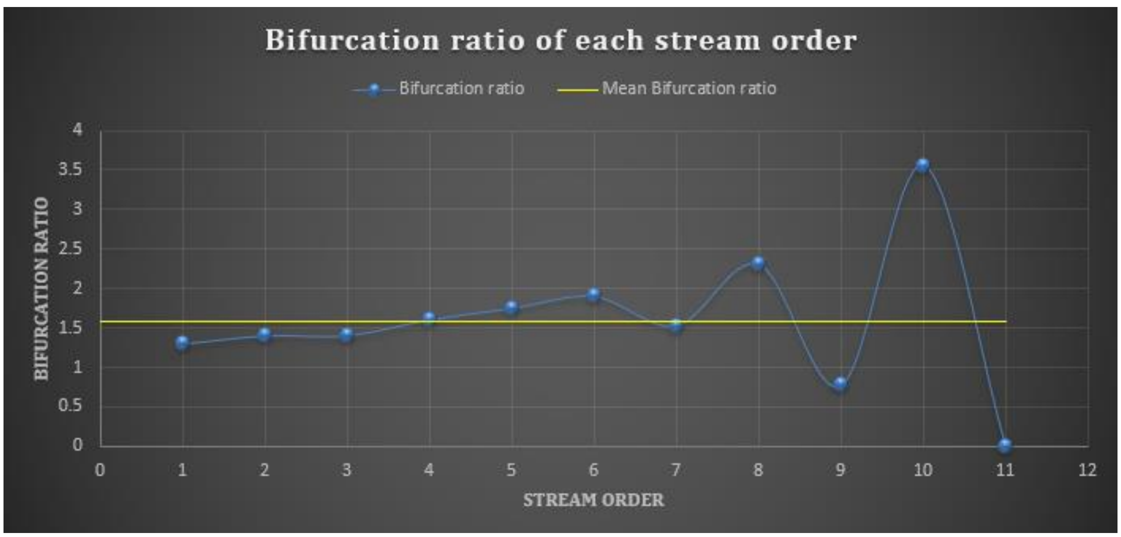


Figure 4.3: Bifurcation ratio against the stream order

The final linear morphometric parameter is the Drainage texture (Dt) that is strongly affected by the infiltration ability. Low infiltration regions will produce higher Dt and thus result in more erosion. High value of Dt indicates that the watershed is susceptible to erosion due to a low infiltration rate and low value of Dt indicates that the watershed is less vulnerable to erosion based on the study of the drainage texture. Willamette watershed has a Dt value of 730.28 km^{-1} which indicate that the watershed is susceptible to erosion due to a low infiltration rate.

Shape Morphometric Parameters

The basin shape mainly regulates the rate at which the water is delivered to the secondary stream. These parameters include Elongation ratio (Er), Circulatory ratio (Cr), Form factor (Ff) and Compactness coefficient (Cc) shown in Table 3.

The Er ranges from 0.6 to 1.0 and is correlated with climate and geology. Er values close to 1.0 are transmitted to very low relief areas, while those values of 0.6–0.8 are correlated with high relief and steep slopes on the ground. Willamette watershed has an Er of 0.79 (high relief and steep slope) which indicates susceptibility to erosion.

The Cr is influenced primarily by characteristics such as stream length and frequency, geological structures, climate, relief, and gradient of the basin. Cr values range from 0 (in line) to 1 (in one circle). A low Cr (that is, 0.18 in Willamette watershed) indicates rapid discharge from the watershed and consequently, a higher susceptibility to erosion. Higher values reflect more basin-shaped circularity and vice-versa.

The Ff has an inverse correlation to erosion. The Ff values are within the range of 0.1–0.8. High-shaped basins have high peak flows of shorter length whereas elongated drainage basins with low shaped influences have lower peak flows of longer duration. The result of the Ff derived from the Willamette watershed is 0.5 which is averagely susceptible to erosion. A watershed's Cc is directly related to the potential for watershed penetration (ranges from 0.025 to 0.8). Therefore, the rating adopted was identical to that adopted by Ff. The lowest Cc was recorded to be 2.38 for Willamette watershed, which means that it thus has high erosion sensitivity and low capacity for infiltration.

Relief Morphometric Parameters

These parameters include Total Basin relief (Rb), Relief ratio (Rr), and (Rn) shown in Table 4.

The total Basin relief (Rb) is the difference in altitude of the highest and lowest point of a basin valley floor. A strong correlation exists between the hydrological characteristics and a drainage basin's Rb. The Rb is an indicator of a drainage basin's total slope, as well as the ferocity of the erosion processes functioning on the basin slopes. In this case, the ranking system implemented was equivalent to the one implemented in the case of D, F, and Brm, since they all infuse the same erosive traits in any landscape. The Willamette watershed has its minimum and maximum relief to be 2.84 located at the gage point and 3189.87 meter located around the South sister hill respectively as shown in Figure 4.4. Rb is 3,187.03 meter which generally have high steepness and therefore high sensitivity to erosion.

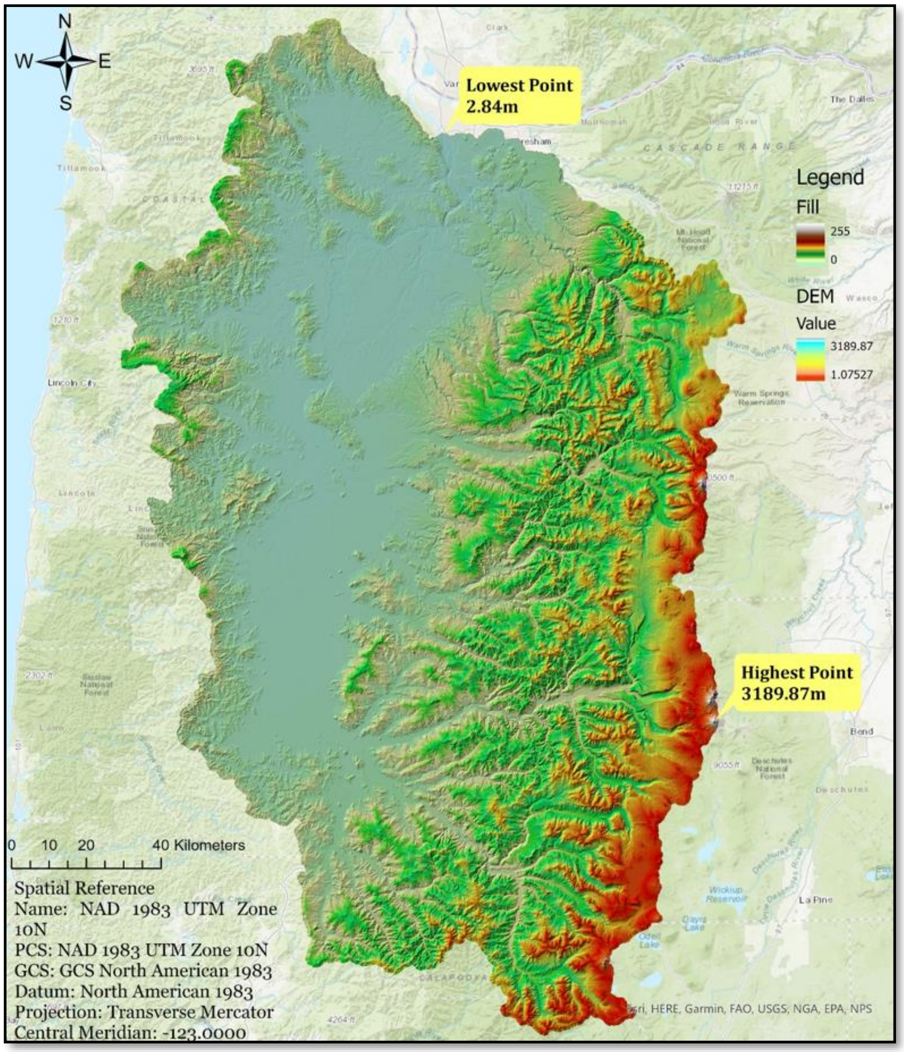


Figure 4.4: Willamette watershed relief (ArcGIS Pro)

The next parameter is the Rr that is specifically linked to the slope of the streams and the surface of the earth; which influences the hydrological processes and the watershed's erosion. The Rr basin has a direct correlation with the watershed's erodibility. In the Willamette River Basin, the Rr is 0.013 which is vulnerable to erosion.

The final parameter, Rn, is used to compute stream flood potential. It symbolizes the geometrical characteristics of the Willamette watershed. Rn has a direct relationship with erodibility so that the erodibility also increases with increasing values of that parameter. Generally, a Rn between 0.5 and 2.0 is considered acceptable for most applications. A Rn lower than 0.5 indicates that the experimental design may be too robust and insensitive to changes in experimental conditions, while a Rn higher than 2.0 suggests that the experimental design is too sensitive to variations in experimental conditions and may not be reliable, just like the Willamette watershed with Rn of 9.18. This also indicate a need for further investigation and optimization of the experimental design.

Part 5: Problems, Limitations, and Recommendations

The application of DEM (digital elevation model) for Willamette watershed characterization and morphometric analysis can provide valuable insights into the topography and hydrology of the watershed. However, this approach also has some potential problems, recommendations, and limitations to consider:

Problems

Data quality: The accuracy and resolution of the DEM data can significantly affect the accuracy and reliability of the watershed characterization and morphometric analysis. The quality of the DEM data depends on the source of data, processing methods, and the spatial resolution of the data.

Scale issues: The watershed characterization and morphometric analysis may not be accurate if the scale of the analysis is not appropriate for the size of the watershed. The scale issues may arise due to the resolution of the DEM data or the size of the study area (Willamette watershed).

Data processing: The DEM data requires significant processing to derive the morphometric parameters, and the accuracy of these parameters is dependent on the processing methods used.

Limitations

Assumptions: The watershed characterization and morphometric analysis are based on assumptions regarding the nature of the terrain and the hydrological processes, which may not be accurate for all areas of the watershed.

Data availability: The availability and quality of the data required for the analysis may be limited, which can affect the accuracy and reliability of the results.

Uncertainty: There is inherent uncertainty associated with the DEM data, processing methods, and assumptions used in the analysis, which can affect the accuracy and reliability of the results.

Recommendations

Data validation: The accuracy of the DEM data should be validated against field measurements or other reliable data sources.

Scale considerations: The scale of the analysis should be carefully selected to ensure that the resolution of the DEM data is appropriate for the size of the watershed.

Quality control: Careful quality control of the processing methods and parameters used to derive the morphometric data is crucial to ensure accuracy and reliability.

In summary, the application of DEM for Willamette watershed characterization and morphometric analysis has potential problems, recommendations, and limitations that need to be carefully considered to ensure accuracy and reliability of the results. Careful selection of the appropriate scale, data validation, quality control, and careful consideration of the assumptions and limitations of the analysis can help to mitigate these issues.

Appendix

References

Biswas S., Sudhakar S., Desai V.R., (1999). Prioritization of subwatersheds based on morphometric analysis of drainage basin, district Midnapore, West Bengal. Journal of the Indian Society of Remote Sensing 27(3): 155–166. DOI 10.1007/bf02991569.

Horton R.E., (1940). An approach toward a physical interpretation of infiltration capacity. Proc. Soil Sci. Soc. Amer. 5: 399–417.

Javed A., Khanday M.Y., Ahmed R., (2009). Prioritization of subwatersheds based on morphometric and land use analysis using remote sensing and GIS techniques. Journal of the Indian society of Remote Sensing 37(2): 261. DOI 10.1007/s12524-009-0016-8.

Montgomery D.R., Dietrich W.E., (1992). Channel initiation and the problem of landscape scale. Science 255: 826–830. DOI 10.1126/science.255.5046.826.

Ratnam K.N., Srivastava Y., Rao V.V., Amminedu E., Mur-thy K., 2005. Check dam positioning by prioritization of microwatersheds using SYI model and morphometric analysis - remote sensing and GIS perspective. Journal of the Indian Society of Remote Sensing 33(1): 25. DOI 10.1007/BF02989988.

Strahler A.N., (1950). Equilibrium theory of erosional slopes approached by frequency distribution analysis; Part II. American Journal of Science, 248(11): 800–814. DOI 10.2475/ajs.248.11.800.