GENERATE THE UNIT HYDROGRAPH USING DEM DATA IN AUSABLE RIVER, NEW YORK STATE

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Contents

1. Introduction

1.1 Background & Assumptions

The Unit Hydrograph (UH) technique is commonly applied for catchment runoff estimation, especially for calculating the peak discharges. The Unit Hydrograph technique for flood estimation was developed in 1932 for determining the surface or direct runoff hydrograph from the effective runoff hyetograph.

It is simply one way to convert any rainfall hyetograph into the corresponding runoff hydrograph. There are serval assumptions for the Unit Hydrograph in this project:

- The effective rainfall is distributed uniformly within the unit period the unit hydrograph is form.
- The effective rainfall is distributed uniformly over the entire catchment area.
- The imperviousness is uniform across the whole watershed, since it is a natural catchment, and the size is small.

1.2 Motivation & Method

The DEM data is an important source to conduct the hydrological analysis. Particularly for the Unit Hydrograph technique, since it utilizes the catchment property rather than storm property, which is supposed to be volatile. Compared with the simplest type of unit hydrograph, which neglects the natural terrain of the watershed, it should result in a more sophisticated runoff estimation when the topological data is combined. Hence, in this project, the goal is to use the DEM raster data to predict the time for surface flow to the pouring point and based on the time to obtain the sum of the flow from every single cell and finally generating a unit hydrograph.

2. Data Preparation

2.1 Watershed Introduction

Ausable runs in New York state of the United States, starting from the Adirondack Mountains, passing through Lake Placid and Au stable forks villages, and then empty into Lake Champlain (at 44°33′40″N 73°25′25″W). It has an east and west branch that join at the golden sable fox. The river forms part of the border between Clinton county and Essex County. The Ausable River is famous for its gorge, located a few miles east of Keeseville.

The Eastern Branch originates from the upper and lower lakes of the Ausable Valley, forming the southern side of the great mountain range. The river is then met by the Cascade Brook which flows from the Cascade Lakes, beneath Cascade Mountain, on its way to Au Sable Forks.

The selected watershed is the called Upper East Branch Ausable River and it is shown in the map screen capture below.
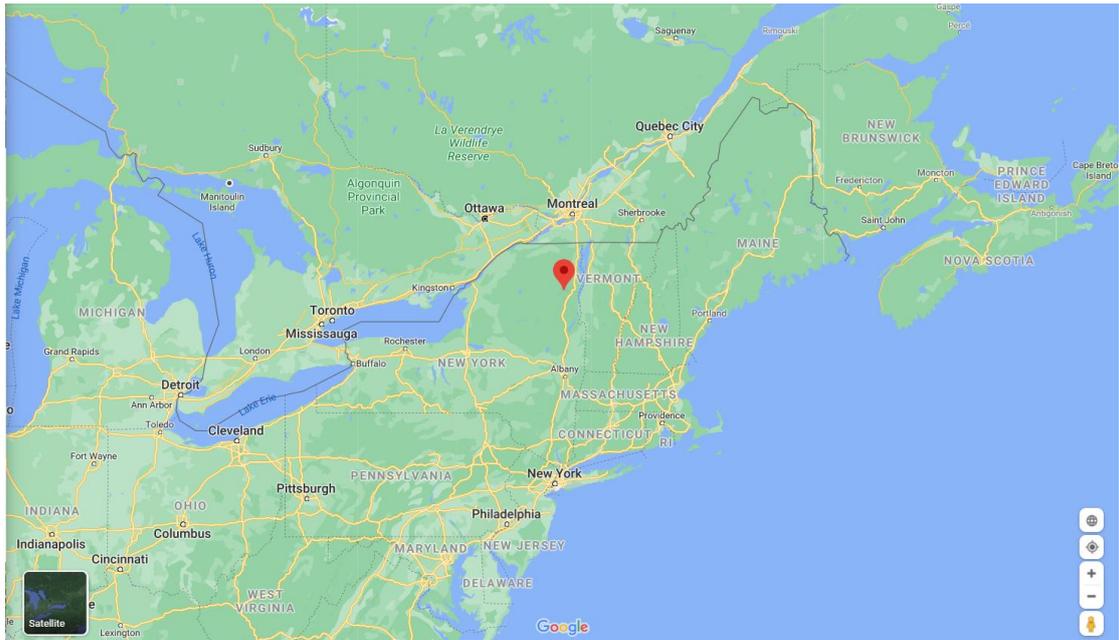
Figure 1 The location of the watershed shown in the Google Map

2.2 Data Collection

The data files are downloaded from The National Map Download (TNM) V2 containing the raster file in the surrounding area and the watershed polygon shapefile.

The data set used in the project is:

- Watershed polygon shapefile: The watershed polygon shapefile is obtained from the USGS Watershed Boundary Dataset (WBD) published 10/30/2020. It is collected by the U.S. Geological Survey (USGS), U.S. Department of Agriculture - Natural Resource Conservation Service (NRCS), U.S. Environmental Protection Agency (EPA), and Other Federal, State, and local, partners. The useful part of this dataset is the 12-digit (6th level) of the hydrologic unit boundaries.
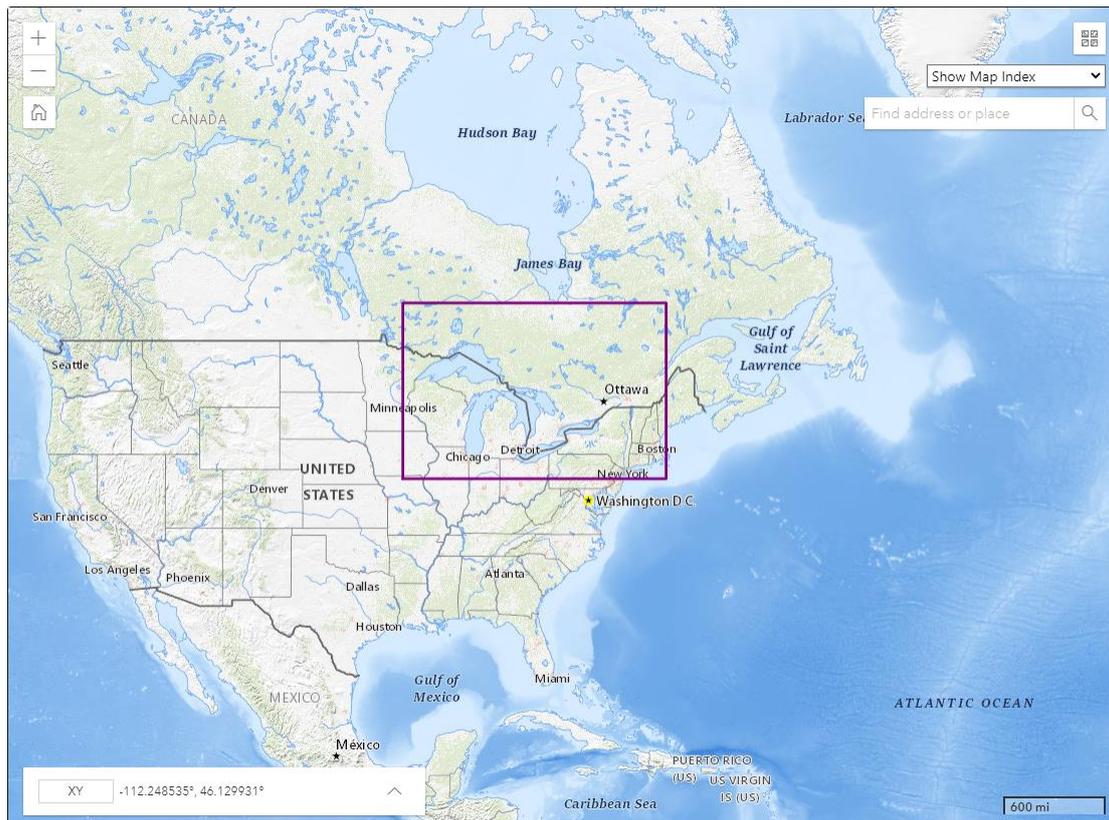
Figure 2 The watershed profile extent used in the project

- DEM data: USGS 1/3 arc-second resolution in the zone N45 W074 with 1*1-degree extent. A raster layer that depicts elevation within the study area.

- Pouring point: A point feature layer that depicts the outlet downstream of the river where unit hydrograph is created

2.3 Data Processing

- Watershed polygon

In the project, the Upper East Branch Ausable River shapefile is first extracted by selecting the polygon and exporting the data as new shapefile. Then the filled color is disabled and only keeps the outline.

- DEM data

Since the raster data is 3D Elevation Program (3DEP) with 1/3 arc-second (approximately 10 meters) resolution and the 1 arc second extent, it will be time consuming to process the raw data and the project coordinates of the raster data is not the optimal type.

Hence, firstly, the projected coordinates of the raster data are converted from the GCS_WGS_1984 to NAD_1983_UTM_Zone_18N where the UTM Zone 18N corresponding to the raster location. This operation will change the cell size from the decimal degrees to meters, which will be important to determine the time of the water flowing to the outlet later in the project.

Then clipped the raster according to the watershed boundary. This the final DEM raster data that will be used the following project and it is shown below:
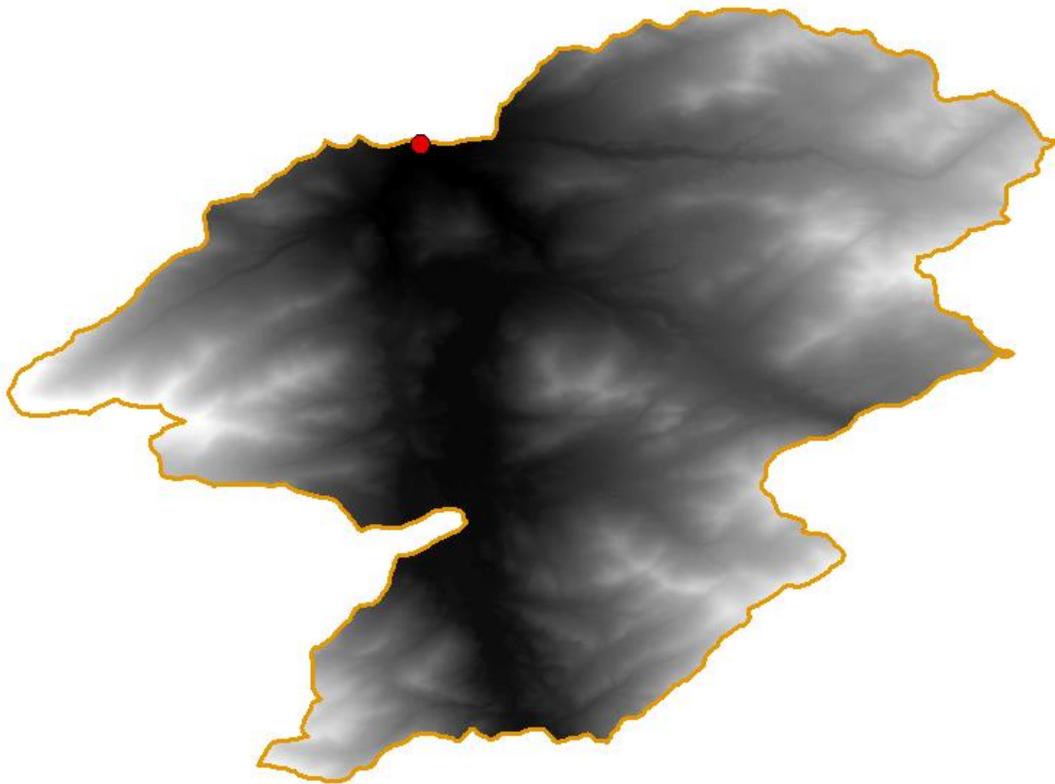
Figure 3 The processed data of the watershed including the pouring point

3. Procedures

3.1 Sinks and fill

A sink is a special unit or group of cells whose flow direction cannot be specified with one of eight valid values in the flow raster. The flow direction of sinks is undefined and will influence the results of the velocity field if they are not fixed. In this step, the sinks (Figure 5) will be identified and replaced by other value to make the raster surface smooth.

The flow direction is determined by the 'flow direction' tool in the ArcToolbox. We cannot use the flow direction directly because of the sinks. We use the flow direction file as raster file to obtain locations of all the sinks in the watershed. Then another tool called 'fill' in hydrology is applied to fill the sinks so that the water flow will be able to flow through the sink cells.
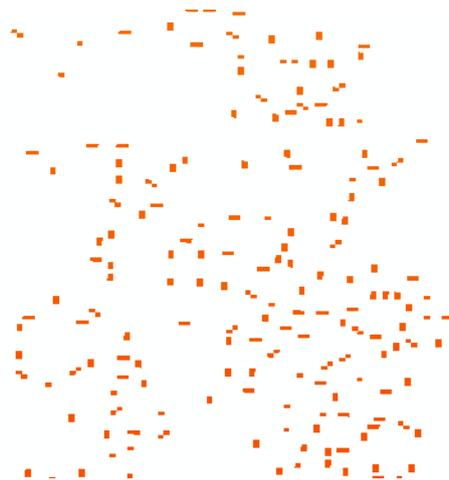
Figure 4 The sinks rendered with 'Yellow to Red' color based on their elevations

3.3 Flow Direction

The method to obtain flow direction is involved in an eight-direction (D8) flow model combined with a technique evented by (Jenson & Domingue). The cell value in a raster cell is represented by one of only eight integers: 1, 2, 4, 8, 16, 32, 64, and 128. These eight integers correspond to the eight possible flow directions. The numbers only show up when the sinks are filled because they are abnormal values outside the range.
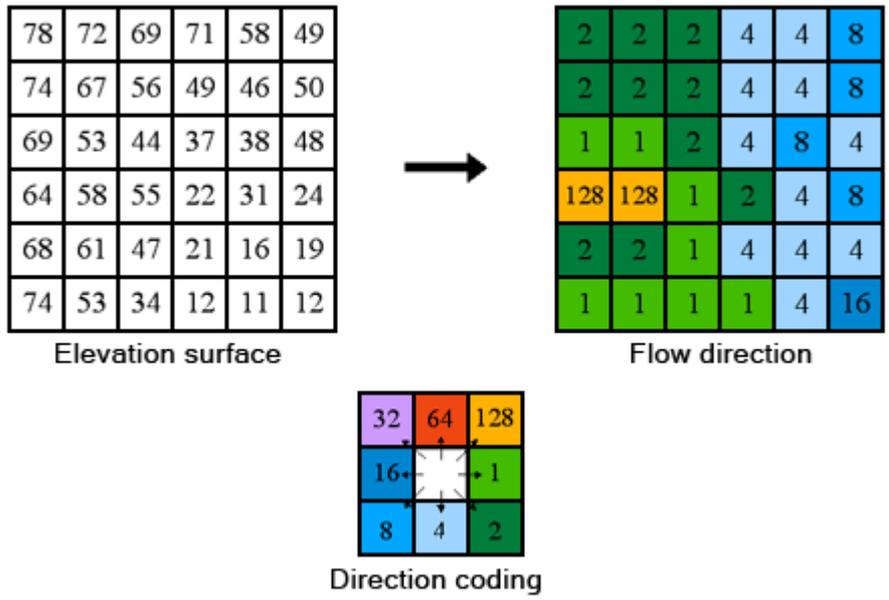
*Figure 5 The flow direction calculation (D8) method*
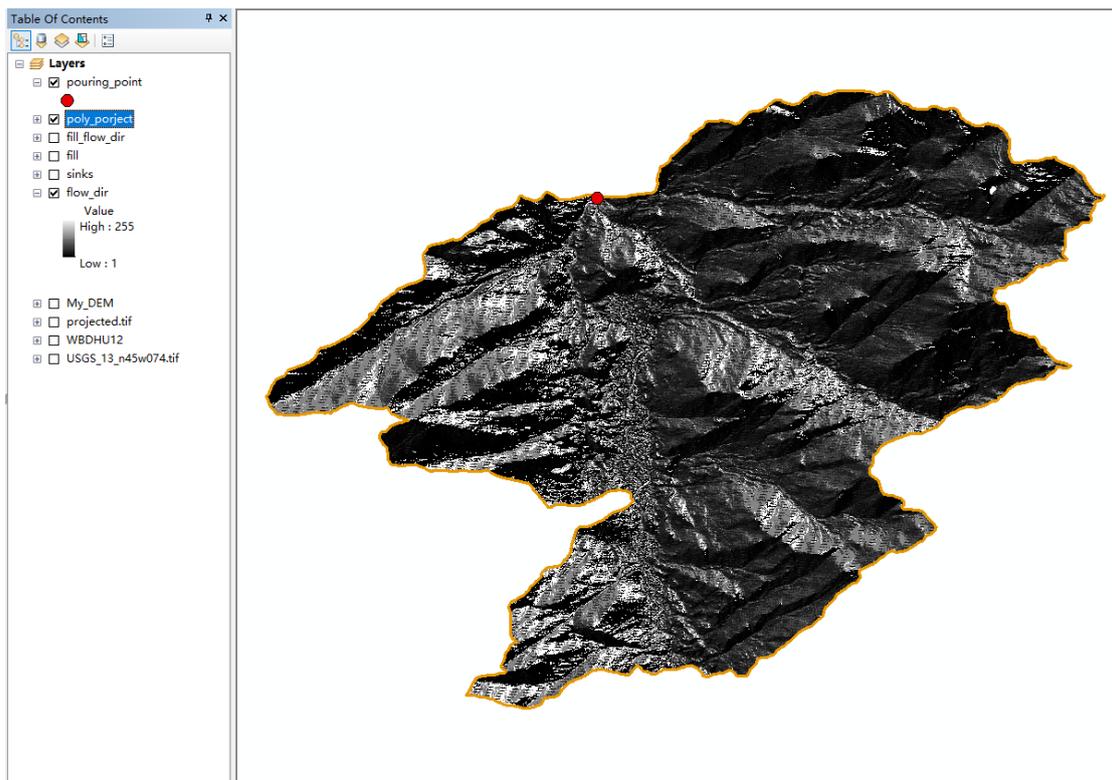
*Figure 6 The unfilled flow direction*
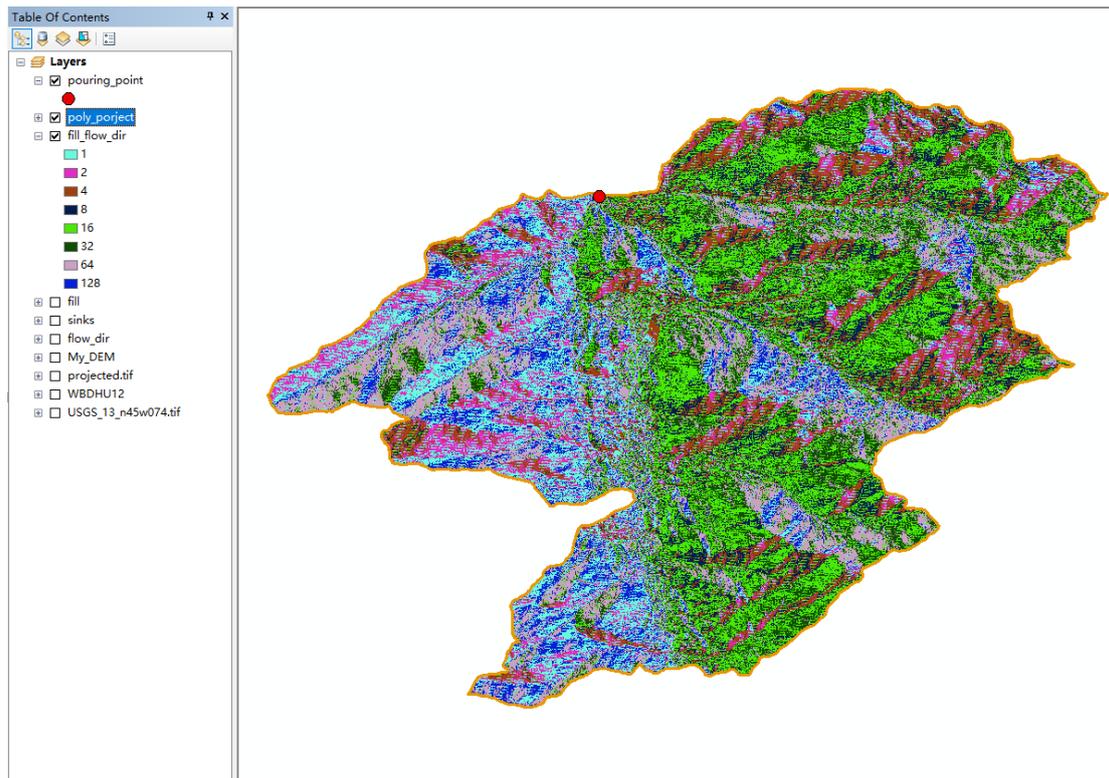
Figure 7 The comparison between unfilled and filled flow direction

Note: In the symbology section, the values of the unfilled flow direction range from 1 to 255, but the values are 1, 2, 4, 8, 16 ,32 ,64 ,128 for the filled raster.

3.4 Flow Accumulation

The accumulated flow is based on the number of cells flowing into each cell in the output raster.

The 'Flow Accumulation' tool will identify the watershed following the rules:

- When the flow accumulation value is high, it is recognized as stream channels
- When the flow accumulation value is low, it is recognized as upslope areas

In this step, the filled flow direction raster is the input file and the 'Flow Accumulation' tool in the Hydrology ArcToolbox is selected. The rest of the box such as the optional input weight raster and the output data type will remain the default setting.

Figure 8 The flow accumulation map with white color representing flow ponding area

3.5 Outlet Snap

Although the watershed pouring point (outlet) has been defined, it might not precisely match the real pouring point. In this step, the real pouring point will be found, and it will then be applied as the point to calculate the time for flow travel outside the watershed.

In the Hydrology tool, the 'Snap Pouring Point' tool can detect the low elevation cell around predefined pouring and generate a single raster cell to represent the outlet point. Then symbology of the point is manually changed to a unique value. The screen capture below shows the calculated pouring point (blue raster) of the DEM data which is different from the original point (red point).
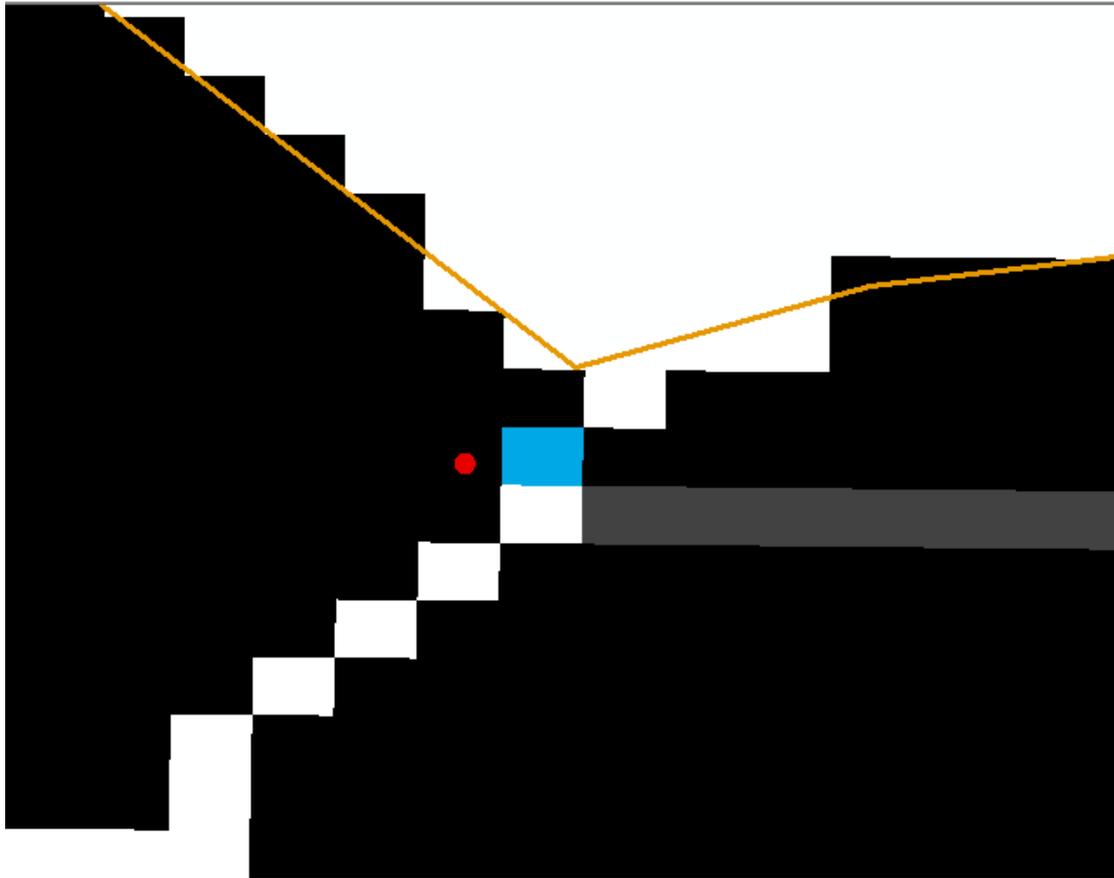
Figure 9The snap pouring point of the catchment (blue cell)

3.6 Slope

So far, with the flow direction and filled DEM data. We are able to know the water movement direction for every single cell. However, the DEM data contains more information that can quantitively measure the difference in the flow with same directions. Since the imperviousness of the watershed has assumed to be uniform, the flow speed is solely determined by the slope.

In the ArcToolbox 'Slope' tool, the method (Burrough, McDonnell, McDonnell, & Lloyd, 2015) calculates the maximum rate of change in value from that cell to its eight neighbors. It will be represented as a precent in rise (or fall) whose value is a percentage of vertical elevation over horizontal elevation.
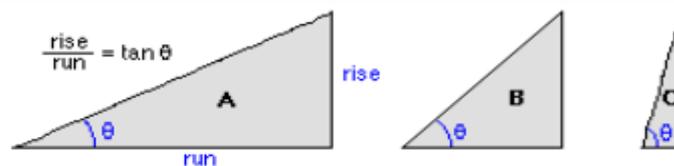
In addition, the method that minimize the slope differences between planar and geodesic selected since it has been proved to be appropriate to small local watersheds. In the graph, the red color indicates a steep slope and green color is the flat area.
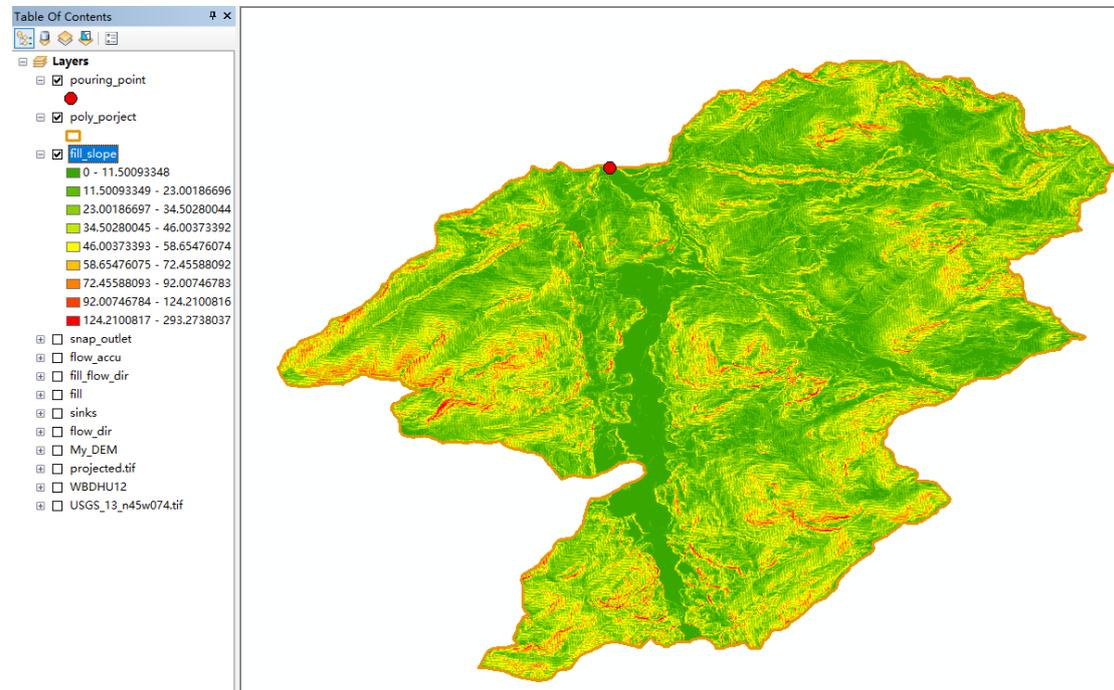

Figure 11 The slope distribution of the watershed.

3.7 Slope Area

According to the method developed by hydrologists (MAIDMENT, OLIVERA, CALVER, EATHERALL, & FRACZEK, 1996), with the increase of water depth, the effective resistance of riverbed and bank to flow decreases, because the hydraulic radius increases. In order to adapt to this factor, we can write the equation to:

$$V = V_m \frac{S^b A^c}{[S^b A^c]_m}$$

- V is the velocity assigned to a cell
- s is the local slope
- A is the upstream drainage area
- The coefficients b and c are can be assumed as 0.5 and it has proved to be reliable in a small natural watershed
- V_m is the average value of the velocity in all cells in the watershed
- $[S^b A^c]_m$ is the corresponding watershed average value of the slope-area term

Therefore, firstly, it is important to calculate the slope area $S^b A^c$ term using the Raster Calculator tool.
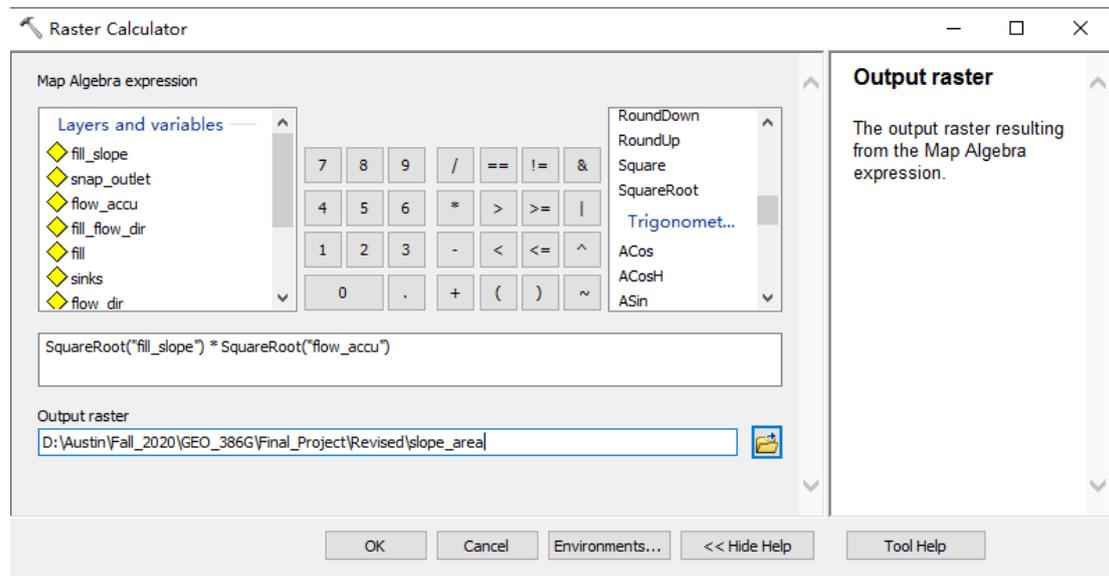
Figure 12 The Raster Calculator expression to get the slope area term

3.8 Velocity Field

As the expression shown in the previous section, the other term that should be determined is the $[S^b A^c]_m$ average velocity which can be viewed under 'Statistics' section in 'Source' tab in the 'Properties' window. In this watershed, it gives a value of 22.14089364485847

The rest unknown parameter in the equation is V_m and according to Maidment's experience in the same article, it is reasonable to assume the mean velocity to be $8 - 9$ m/min or approximately 0.1417 m/s.

However, it also shows that the unlimited velocity field often fail to represent some steep and flat area flow velocity. In the natural catchment, the velocity normally ranges from 1.65 m/s to 220 m/min or 0.0275 m/s to 3.6667 m/s. Hence, the velocity field should be limited so that the there is no extreme velocity in both steep and flat area. The expression formulas are shown below:

Velocity lower limit is:

$$con(\text{"v\_unlimited "} \leq 0.0275, 0.0275, \text{v\_unlimited})$$

Limited Velocity is:

$$con(\text{"velocity lower limit"} \geq 3.6667, 3.6667, Velocity\ lower\ limit)$$

The quarried raster that represents the modified velocity filed is:
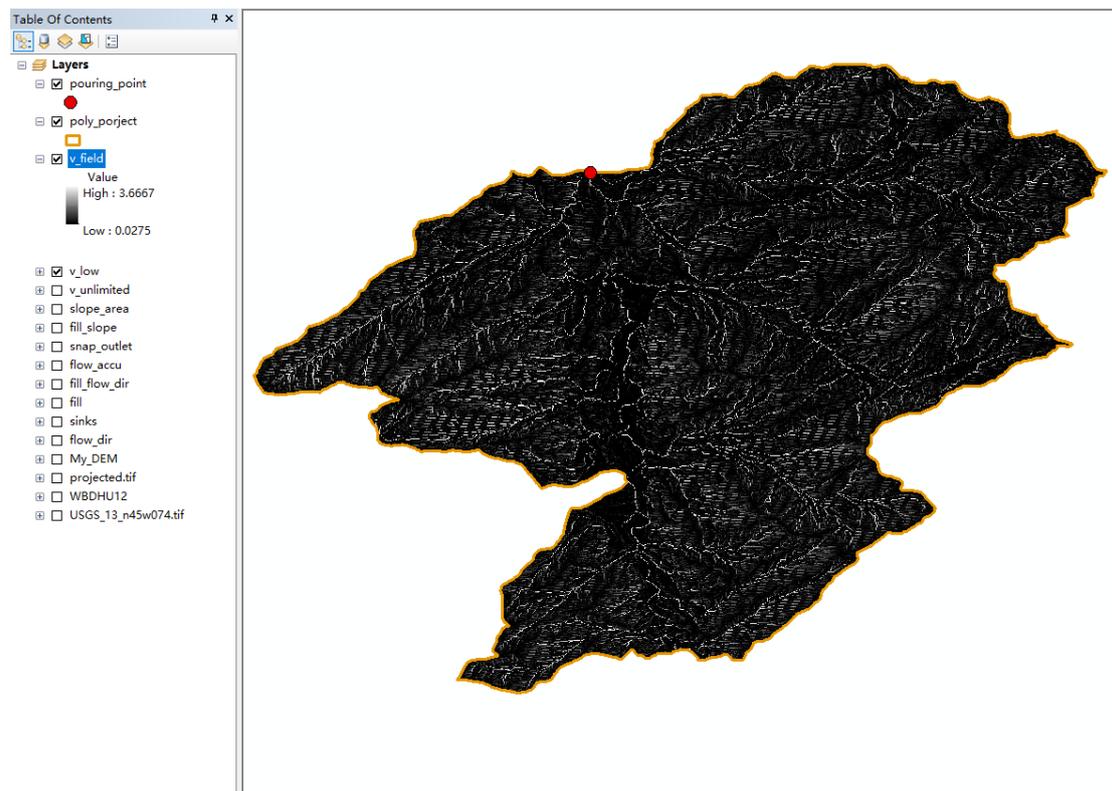
Figure 14 Velocity field with the minimum and maximum velocity are 0.0275m/s and 3.6667m/s respectively

3.9 Weight & Time to Outlet
The flow time is determined by a simple function:

$$time = \frac{length}{velocity} \qquad (1)$$

To determine the length of a flow, there are two variables should be figure out: flow direction (known) and weight (unknow). In terms of flow, weight represents impedance. Although it seems difficult to calculate the weight without detailed topological data, the formula for calculating the weight to obtain the flow time according to the following formulas:

$$time = length * weight \qquad (2)$$

Combining equation (1) & (2), we have:

$$weight = 1/velocity$$

It can be also achieved by the 'Raster Calculator', which generates the map:
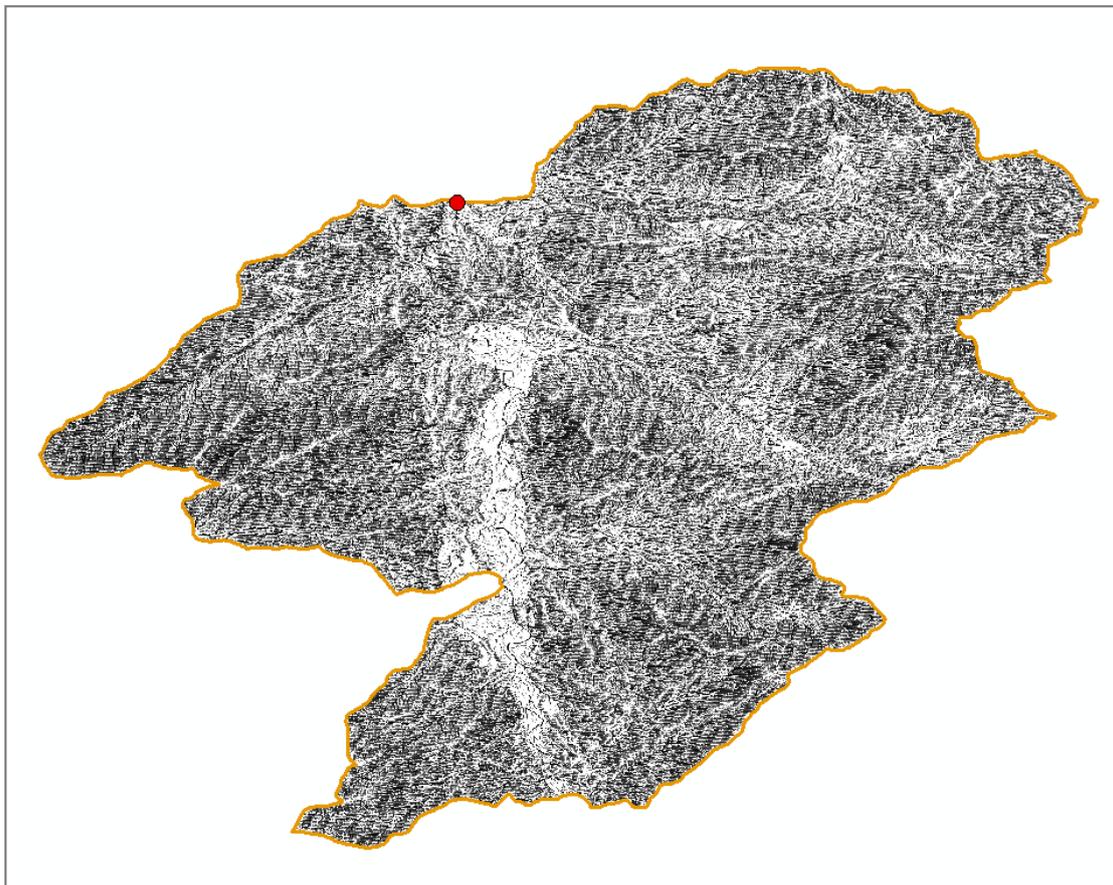
Figure 15 The weight field of the watershed

With all the datasets, it is now possible to calculate the water running time (Figure 16) to the pouring point and plot the distribution. Then to simplify the problem, it is necessary to define some isochrone zone so that all the flow time within the zone will result in same direction. Otherwise, it is time consuming to calculate the flow time and sum the total flow for each cell separately. In this project, the time interval is 15 min

using the 'Reclassification' in the 'Spatial Analysis' section, although finer time interval will return a more precise output.
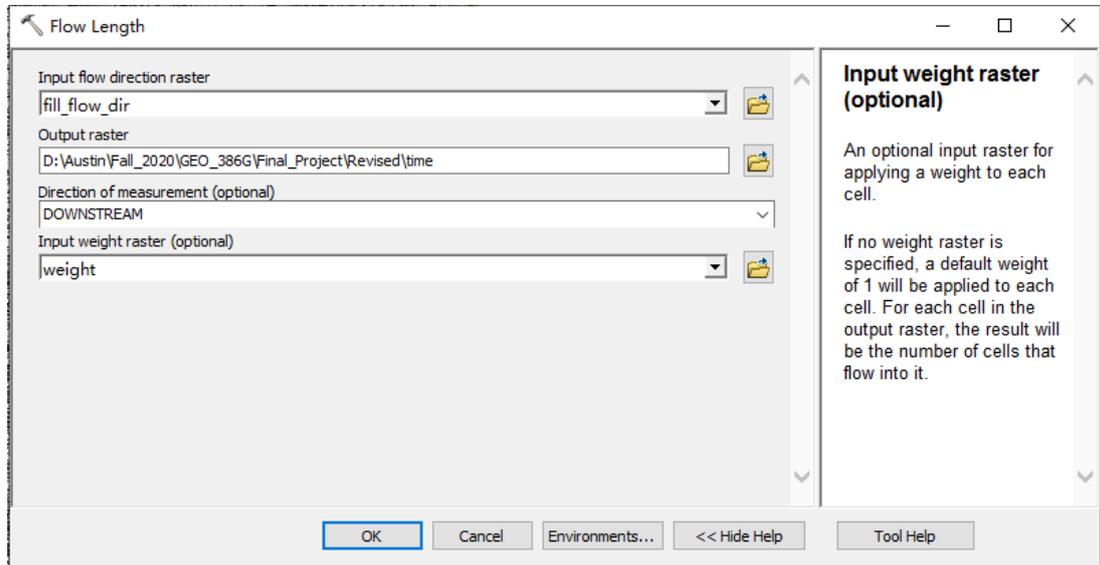
Figure 16 The flow length calculation tool window
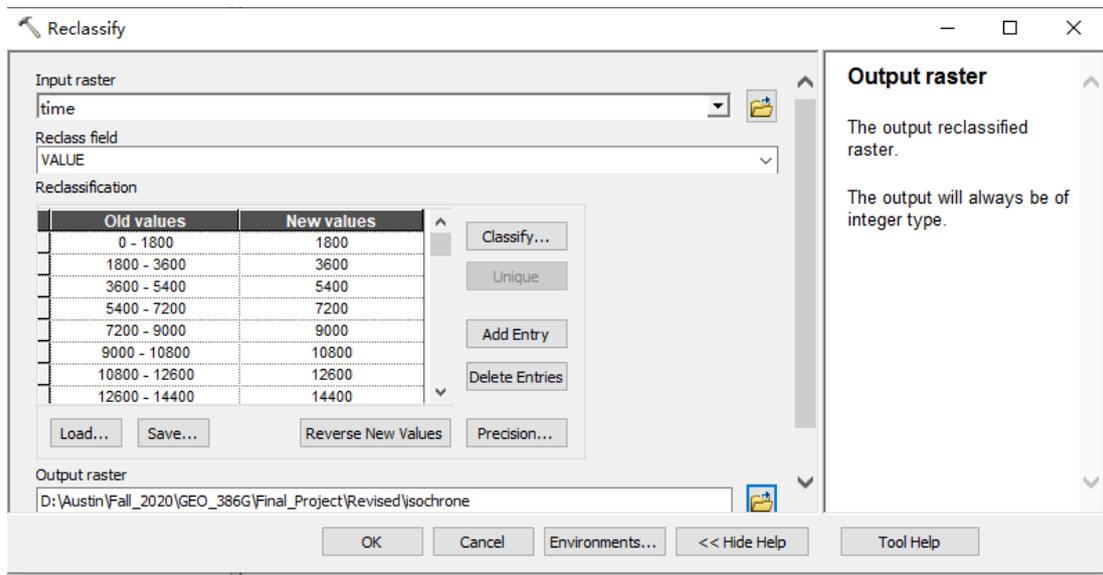
Figure 17 Reclassify the flow time with different isochrone zones in the watershed

The final flow time defined by different isochrone time zone is shown in Figure 18:
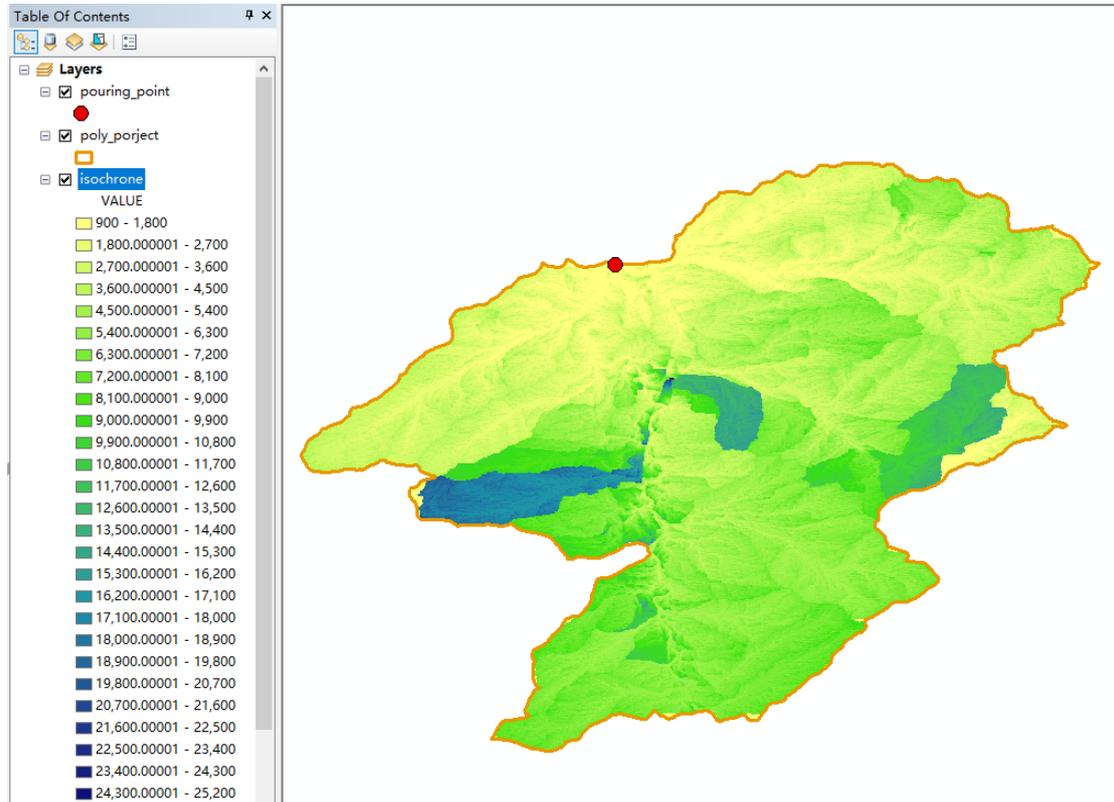
Figure 18 The flow time distribution with 27 isochrone zones

4. Result

Completing all the steps and results in part 3, finally, by counting the number of cells in different isochrone zones, I can compute the flow reaches the pouring in different time. From the attribute table, two extra fields can be added to attribute table to represent the area and UH ordinates of the unit hydrograph. The unit hydrograph can now be plotted in excel.
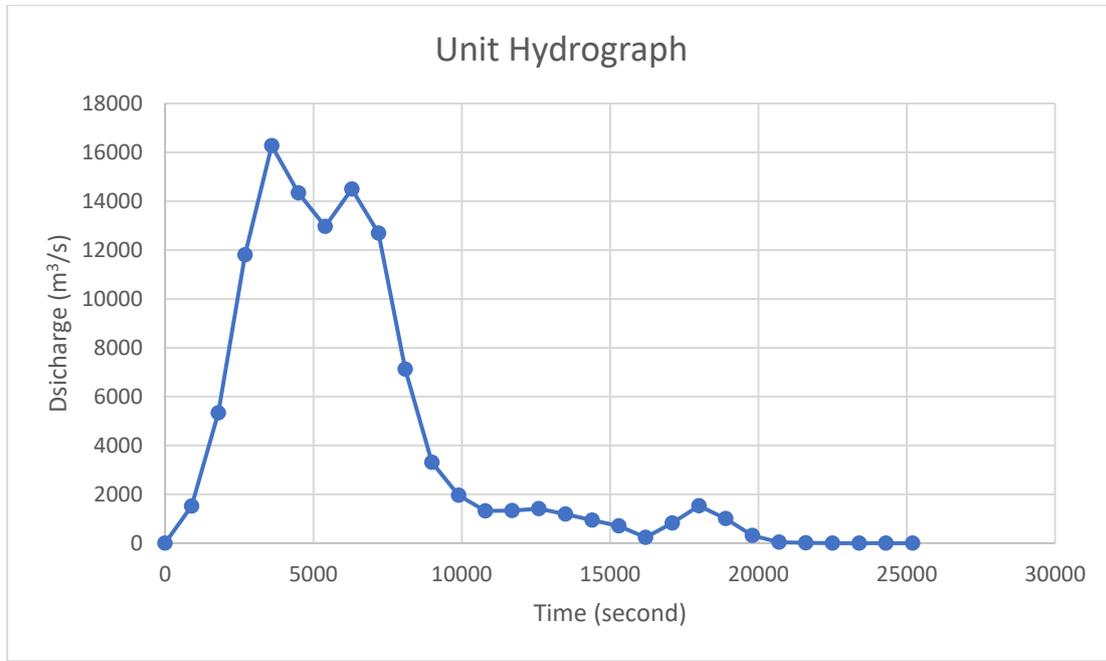

Figure 19 The final unit hydrograph for the watershed

References

Burrough, P. A., McDonnell, R., McDonnell, R. A., & Lloyd, C. D. (2015). *Principles of geographical information systems*: Oxford university press.

Jenson, S. K., & Domingue, J. O. Extracting topographic structure from digital elevation data for geographic information system analysis.

MAIDMENT, D. R., OLIVERA, F., CALVER, A., EATHERALL, A., & FRACZEK, W. (1996). UNIT HYDROGRAPH DERIVED FROM A SPATIALLY DISTRIBUTED VELOCITY FIELD. *Hydrological Processes, 10*(6), 831-844. doi:https://doi.org/10.1002/(SICI)1099-1085(199606)10:6<831::AID-HYP374>3.0.CO;2-N