LONG TERM GLACIAL RETREAT AND ITS EFFECTS ON STREAM RUNOFF

Purpose

Mount Rainer, Washington (US) holds the largest accumulation of glaciers in the contiguous United States which have decreased in extent throughout the last 150 years (Beason, 2017; Driedger and Kennard, 1986; Sisson, Robinson, and Swinney, 2011, Riedel and Larrabee, 2015, Matthews and Briffa, 2005). By finding the area of the five watersheds in each climate division that drain Mount Rainer, glacial retreat can be shown to indirectly effect stream discharge over time.

2 Methods

2.1 Background Information

The process of quantifying the effects of long term glacial retreat was conducted by first determining the respective watershed to which each glacier drains (Table 1) (Driedger and Kennard, 1986). Once the five watersheds were determined, the most proximal USGS stream discharge gage station to Mount Rainier was determined for each stream (USGS waterwatch, 2017). The USGS gage station site numbers were found as 14226500, 12082500, 12092000, 12094000, and 12097850 for the Cowlitz, Nisqually, Puyallup, Carbon, and White River respectively.

ID (h)	Watersheds	Mt. Rainier Glaciers
1	Cowlitz	Whitman, Cowlitz-Ingraham, Paradise-Stevens, and Ohanapecosh
2	Nisqually	Muir Snowfield, Nisqually, Kautz-Success, Van Trump, Pyramid, South Tahoma, Tahoma (34.56%)
3	Puyallup	North Mowich, Liberty Cap, Flett, Edmunds, South Mowich, Puyalllup, Tahoma (65.44%)
4	Carbon	Carbon, Russell
5	White	Winthrop, Emmons, Inter, Fryingpan, Sarvent

Table 1: Table showing the glaciers on Mt. Rainier that drain into each watershed.

2.2 Numerical Methods

After determining the streams to be used in the study, by Wigley and Jones (1985), the water balance for each watershed can be modeled by:

$$Q = P - ET \tag{1}$$

Where Q represents streamflow discharge, while P and ET are the precipitation and evapotranspiration respectively. For the purpose and scope of this study, discharge, precipitation, and evapotranspiration are reported in annual cumulative volumes. In order to account for glacial meltwater in the watershed water balance, equation (1) can be expanded:

$$Q = P - ET + G_m \tag{2}$$

The additional term G_m denotes the annual volume of discharge resulting from the glaciers that drain to a selected watershed. Continuing by Wigley an Jones (1985), the annual runoff of ratio is show as:

$$w_h(k) = \frac{V_h(k)}{P_h(k)} \tag{3}$$

The runoff ratio, $w_h(k)$, is calculated based on the year, k, and watershed ID, h. Subsequently, the annual volume of discharge for the individual watersheds is $V_h(k)$, while $P_h(k)$ is defined as the annual precipitation volume for each watershed. If the runoff ratio is increasing over time then the annual stream discharge is increasing at a faster annual rate than annual precipitation which indicates glacial melt is increasing over time holding all else steady.

For each USGS gaging station, the stream discharge was measured every 15 minutes (~1987 –present) which allows the cumulative annual volume at the stream to be calculated by:

$$V_{annual} = \int Q \, dt \tag{4}$$

Where V_{annual} is the cumulative annual volume at the stream gage and Q is discharge at all times. Generalizing the approach for each individual year yields:

$$V_h(k) = \sum_{i=1}^{n} Q_n(\Delta t) + \left(\frac{(Q_n - Q_{n-1})}{2}\right)(\Delta t) \qquad (5)$$

In the simplified approach for each year, $V_h(k)$ represents the cumulative annual discharge volume with k denoting the year (e.g. 1995, 1996, etc.), h being the individual watershed's ID (Table 1), and Q_n signifying the stream discharge measured at each time for the calendar year. Time between stream discharge measurements at the gage station, Δt, was 900 seconds or 15 minutes. For example, the cumulative annual discharge for 2002 would have Q_1 as the first discharge measurement of the year and Q_{35040} being the final measurement of the calendar year when Δt is 15 minutes.

After quantifying the cumulative annual discharge volume for each year from the 15 minute discharge data record, the annual precipitation was addressed by first noting the presence of two climate divisions in the area surrounding Mount Rainier. Climate division 5 for the State of Washington is defined as Cascade Mountains West while climate division 4 is the East Olympic Foothills (State of Washington Department of Ecology, 2015). Observing that some or all of the watersheds would have extent in both watersheds through an overview, the annual precipitation volume for each watershed can be written as:

$$P_h(k) = P_4(k)A_{h4} + P_5(k)A_{h5} \qquad (6)$$

In equation 6, $P_h(k)$ denotes the volume of annual precipitation for each year, k, in the corresponding watershed, h. The terms $P_4(k)$ and $P_5(k)$ are the annual total precipitation given for climate divisions 4 and 5, which are a function of the year, k (NOAA 1896-2016). Lastly, A_{h4} and A_{h5} are the areas contained within climate divisions 4 and 5 respectively.

Along with annual precipitation volume, the average annual temperature was required in order to observe the relationship between temperature and glacial extent for each watershed. The average annual temperature for every watershed can be found as a weighted average:

$$T_h(k) = T_{h4}(k)(\frac{\%A_{h4}}{100}) + T_{h5}(k)(\frac{\%A_{h5}}{100}) \quad (7)$$

Through equation (7), the average annual temperature, $T_h(k)$, can be found according to each year, k, and for each watershed, h. Further, $T_{h4}(k)$ and $T_{h5}(k)$ are the average annual temperatures for climate divisions 4 and 5 respectively. The terms $\%A_{h4}$ and $\%A_{h5}$ represent the percentage of area contained within climate divisions 4 and 5 correspondingly.

Although annual precipitation and temperature values were available from 1896-2016, in order to produce a representative annual number, the area was computed for each watershed. By finding the area of all five watersheds separately, an annual precipitation volume could be calculated by equation (6) and an annual average weighted temperature by equation (7) for each watershed. Since average temperature was weighted for each watershed based on area in each climate zone which allowed equation (6) to be solved and the relationship between temperature and glacial extent over time to be observed. Hence, before the effects of long term glacial retreat cannot be quantitated until the areas of every watershed were found along with each watershed's area in climate zones 4 and 5.

It should be noted that for the purpose of this study, the effects of groundwater and long-term storage were assumed to be constant over time.

3 Methods

3.1 Data Collection

- *Mount Rainer Peak*: A shapefile containing a point representing the peak of Mount Rainer. The data was located in the GEO 327G class folder for Lab 10 data taken from the Washington State Department of Natural Resources GIS website whose spatial reference included a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.
- *State of Washington Boundary*: A shapefile containing a polygon for the state of Washington. The data was located in the GEO 327G class folder for Lab 10 data taken from the Washington State Department of Natural Resources GIS website whose spatial reference included a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.
- *State of Washington Rivers:* A shapefile containing 2-D lines representing lines of rivers within the state of Washington. The data was located in the GEO 327G class folder for Lab 10 data taken from the Washington State Department of Natural Resources GIS website whose spatial reference included a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.
- *Area of Interest:* A shapefile containing a rectangular polygon surrounding Mt. Rainier within the state of Washington. The data was located in the GEO 327G class folder for Lab 10 data in a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.
- *Hillshade:* A hillshade contained within the area of interest created from a digital elevation model (DEM) containing rasters for King, Pierce, Yakima, Kittitas, Lewis, and Thurston counties. The data was located in the GEO 327G class folder for Lab 10 data taken from the Washington State Department of Natural Resources GIS website whose spatial reference included a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.

- *State of Washington Counties:* A coverage containing counties within the State of Washington. The data was located in the GEO 327G class folder for Lab 10 data taken from the Washington State Department of Natural Resources GIS website whose spatial reference included a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.
- *ESRI World Topographic Basemap:* Basemap containing a topographic reference map of the world with elevation contours. The data was located as a basemap in ArcGIS online through ESRI.
  http://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f

- *State of Washington Watersheds Levels 2, 6, 8, 10, and 12:* Watershed boundaries for the state of Washington ranging from largest scale at level 12 to the smallest scale at level 2. The data's spatial reference included a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.
  http://www.ecy.wa.gov/services/gis/data/data.htm

- *State of Washington Climate Divisions:* Shapefile containing climate divisions for the state of Washington ranging from 1 – 10. The data's spatial reference included a Lambert Conformal Conic Projection with NAD 83 HARN StatePlane Washington South FIPS 4602 (US Feet) coordinate system.
  https://water.usgs.gov/GIS/metadata/usgswrd/XML/climate_div.xml#stdorder

- *Locations of USGS Gaging Stations:* Points showing the locations of USGS gaging stations 14226500, 12082500, 12092000, 12094000, and 12097850 corresponding to the Cowlitz, Nisqually, Puyallup, Carbon, and White River respectively.

3.2 Data Processing

After adding all of the data outlined in section 3.1 to a blank ArcMap document, the data processing could begin. A DEM was not needed for the analysis although a background hillshade raster works well to show terrain and for aesthetic purposes. By using the hillshade (spatial analyst) tool, a background hillshade can be created (figure 1).

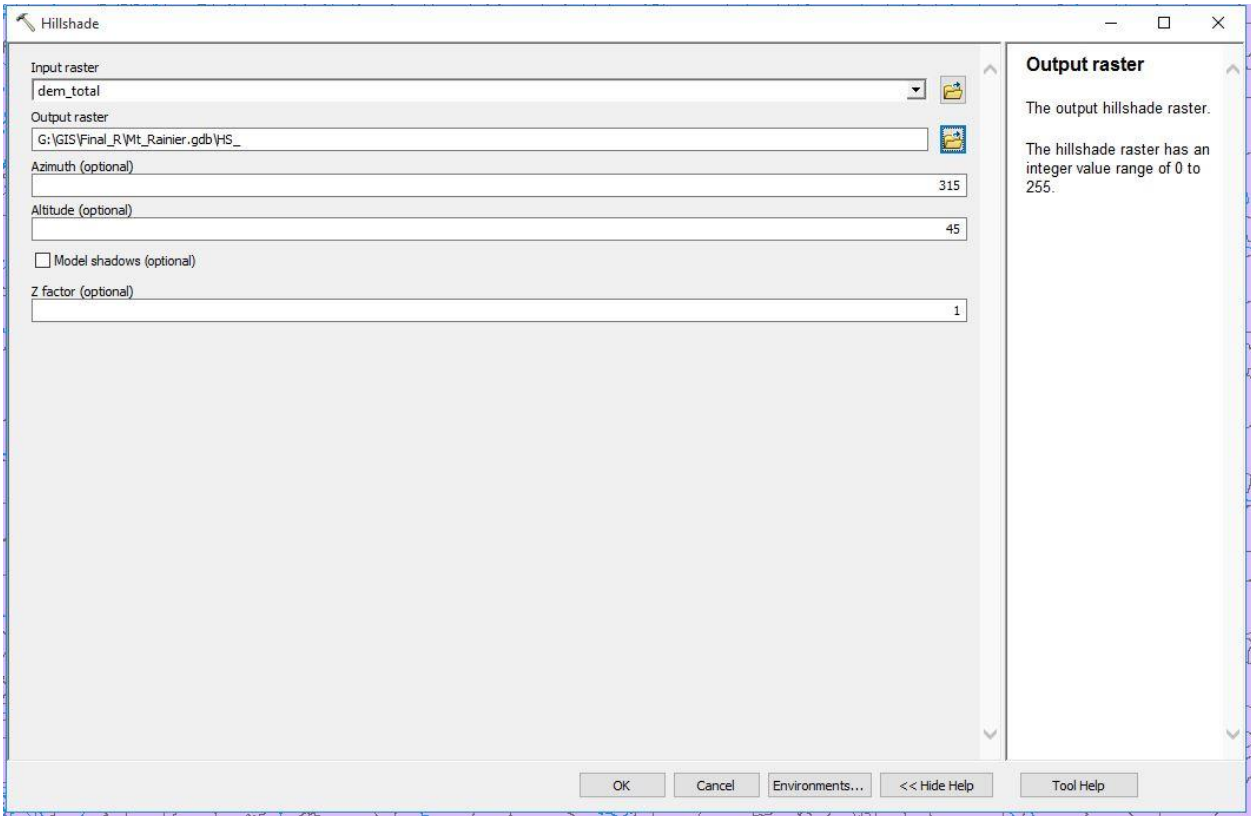


Figure 1: Image showing the input used in the hillshade (spatial analyst) tool used to create a hillshade from the DEM in the area of interest surrounding Mt. Rainier.

After creating the background hillshade raster, the USGS gaging stations needed to be imported as X,Y points based on their geographic location by latitude and longitude (figure 2). The gaging stations act as the lower bounds for each watershed which is crucial for determining the extent of each watershed.

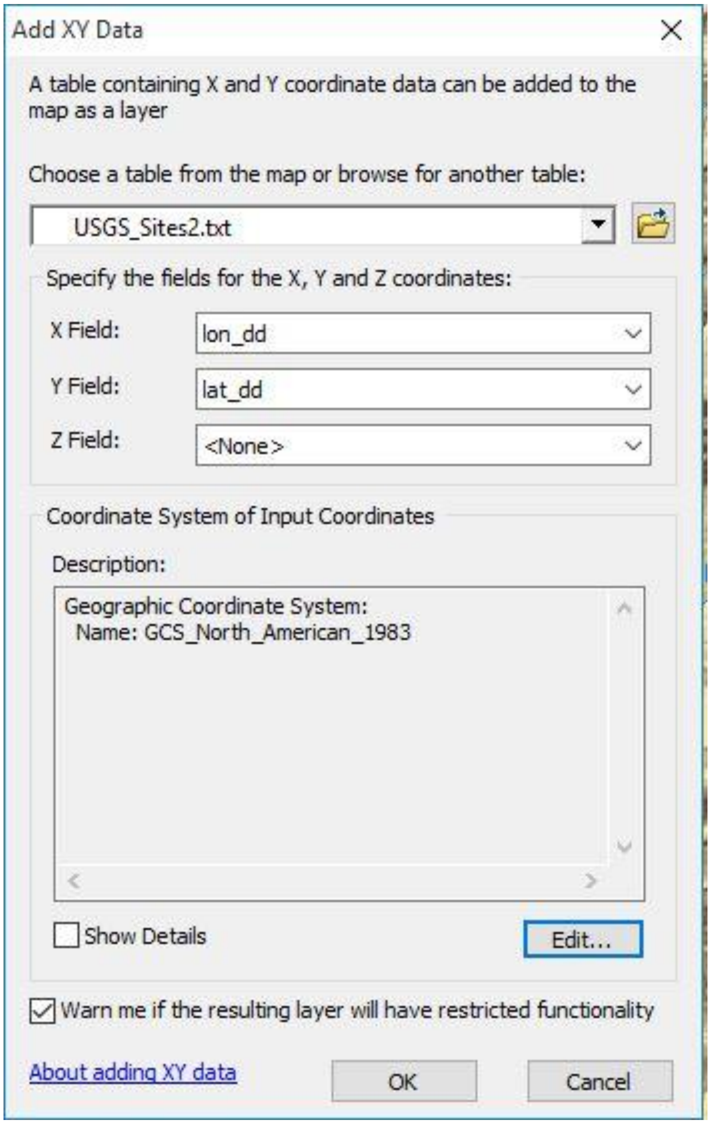


Figure 2: Image showing the add XY data window which was used in taking the latitude and longitude coordinates of each USGS gaging station to representing the points on the map.

3.3 ArcGIS Processing

The process of determining the area of each of the five watersheds began by removing Washington watershed levels 2 – 10 shapefiles while only keeping the level 12 shapefile due to it having the most detailed (i.e. smallest) watershed divisions for the state. Although the USGS gage site locations defined the lower bounds of the watershed for each river, the gage site did not lie directly on a watershed boundary (figure 3).

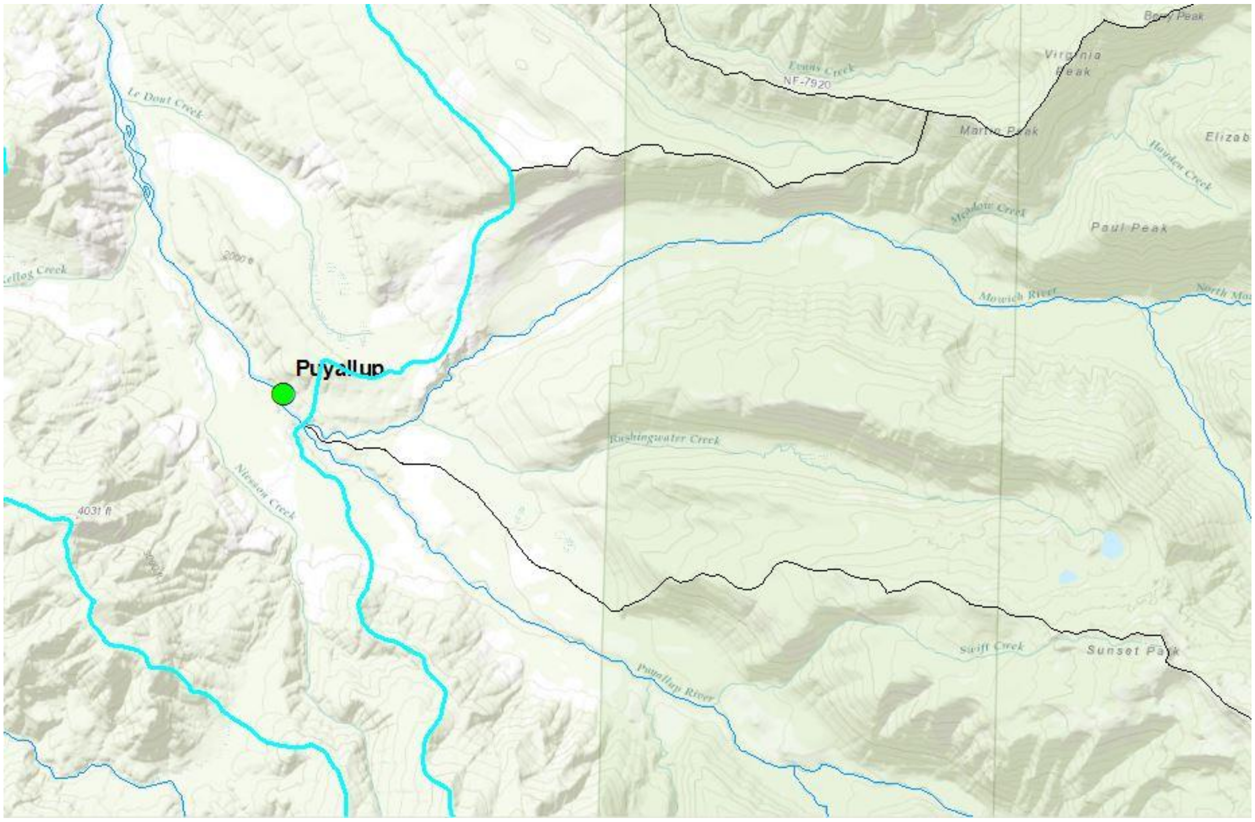


Figure 3: Image showing the location of the Puyallup USGS gage station (site 12092000) measuring stream discharge. The black and highlighted (selected) 2-D lines represent level 12 watershed boundaries for the state of Washington.

In order to account for the runoff area that drains into a river upstream from the gage station but is part of a watershed that also drains into a stream below the gaging station, the polygon highlighted in cyan (figure 3) was necessarily split using the split polygon tool in the editor toolbar (figure 4). The new polygon was created by using elevation contours as guides provided by the world topographic basemap which allowed smaller watersheds than the Washington watersheds level 12 shapefile to be idenified. This same process was done for the gage stations on the Cowlitz, Nisqually, Carbon and White Rivers with site numbers 14226500, 12082500, 12094000, and 12097850 respectively (Figure 5).

Figure 4: Image showing the creation of a new polygon using the split polygon tool and elevation contours in order to account for additional the watershed area. The same process was conducted for the Cowlitz, Nisqually, Carbon, and White Rivers.

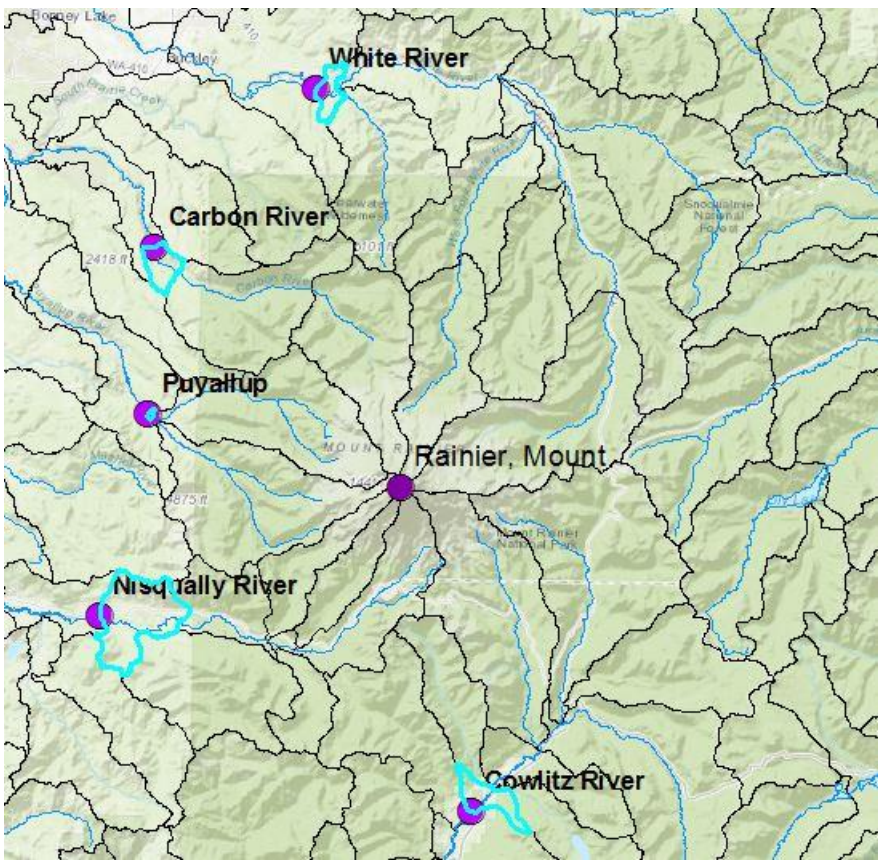


Figure 5: Image showing the polygons created by using the split polygon tool to account for the extra runoff area due to the locations of the USGS stream discharge gaging stations.

Once the additional runoff area was added through editing for all five streams, the level 12 watershed boundary polygons within the five watersheds and the new polygons shown in figure 5 were exported as a new shapefile (figure 6). In order to determine whether a level 12 watershed was contained in one of the five larger watersheds, USGS gaging station which was the lower bound for each watershed and a starting point from which to work upstream through tributaries and the main river itself. Wherever the main river or tributary for each watershed was contained within a level 12 watershed boundary, then that polygon would be selected in order to add to the Watershed_total shapefile (figure 6).

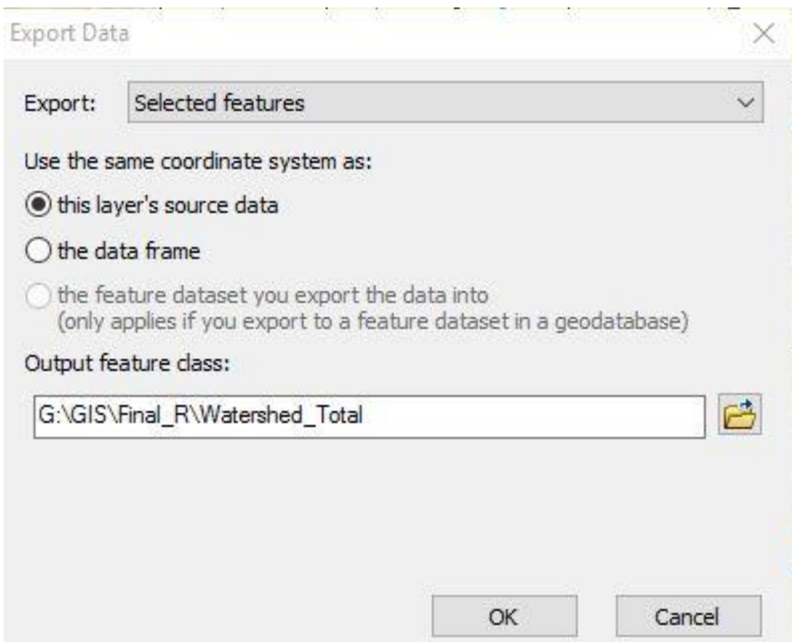


Figure 6: Image showing the export data window in order to create a subset layer from State of Washington level 12 watershed boundaries. The subset represents the total area for the five watershed boundaries in the study.

After exporting the area for all five watersheds as a shapefile named Watershed Total, the level 12 shapefile of the watershed boundaries for the State of Washington was removed (figure 7).

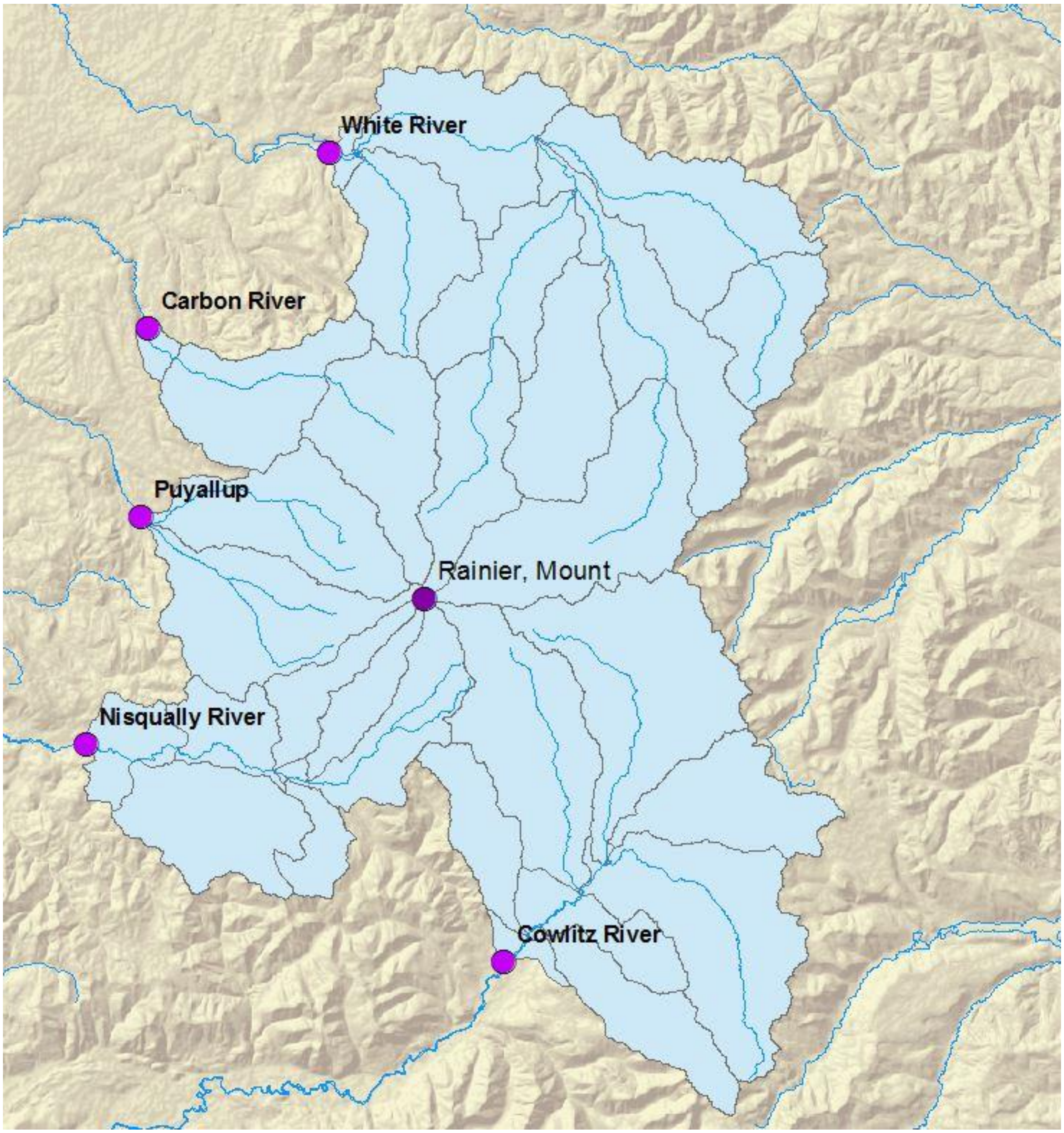


Figure 7: Total area of all five watersheds after being taken as a subset of the Washington level 12 watershed boundaries shapefile.

Next, the new polygons were sorted into their respective watersheds by starting at the lower bound of each watershed at the USGS gaging station and working upstream using the watershed boundaries, elevation contours, hillshade, and State of Washington rivers as a guide. The result from selecting and exporting five new shapefiles was five watershed areas with each representing a watershed (figure 8 and 9).

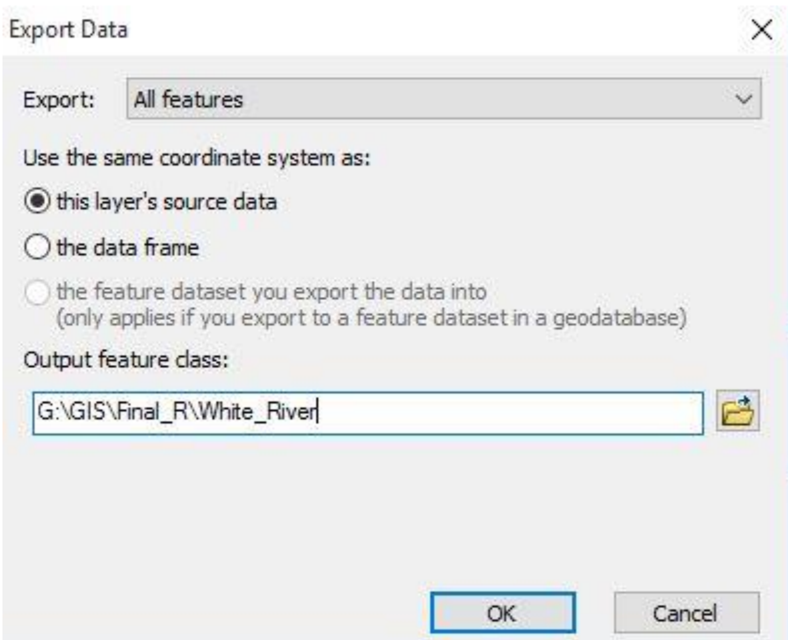


Figure 8: Image showing the export data window where the white river watershed area is being created as a new shapefile from selecting and exporting data as a subset from the Watershed_Total shapefile. This same process was conducted for the Cowlitz, Nisqually, Puyallup, and Carbon Rivers.

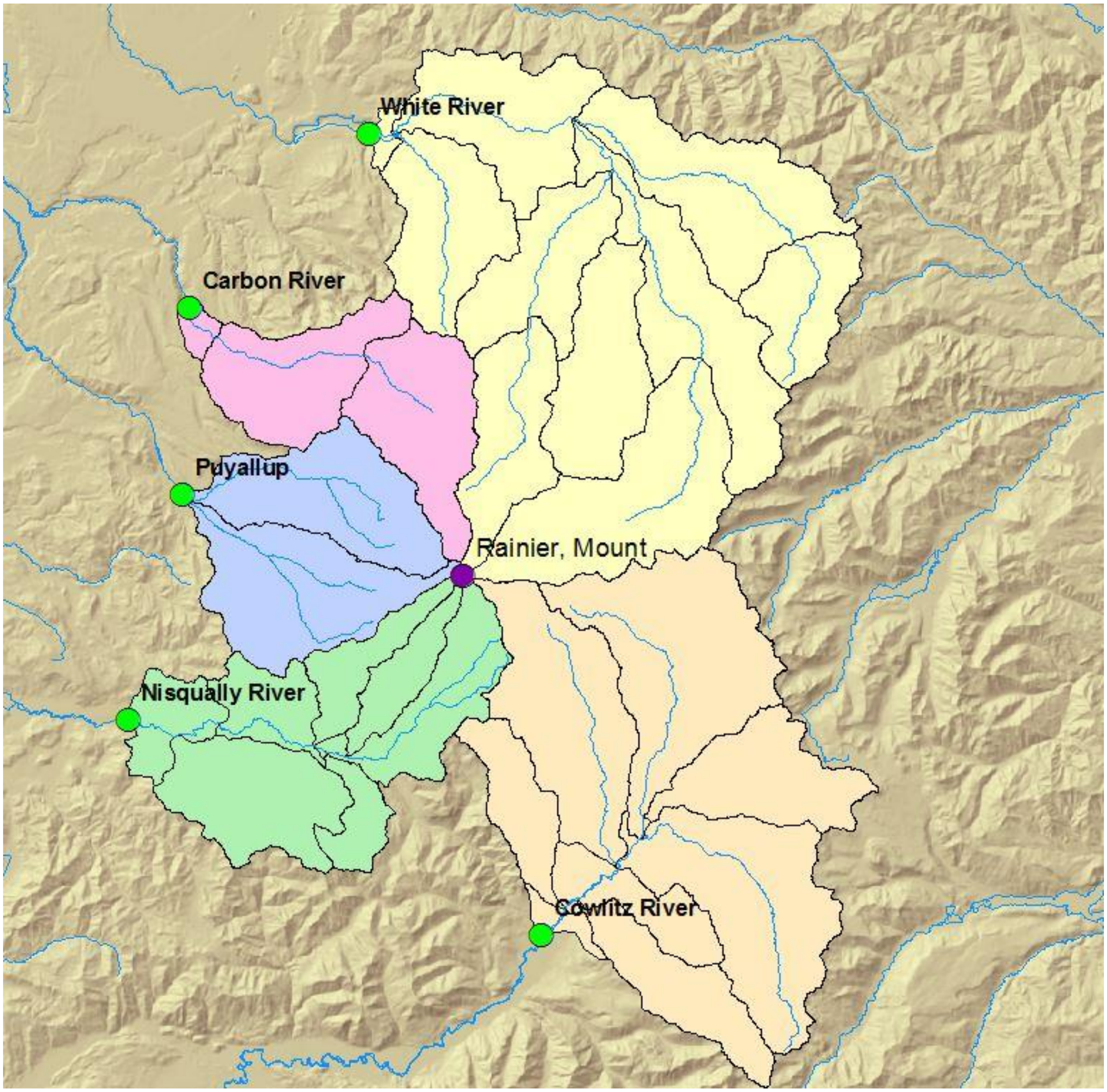


Figure 9: Image showing the result from figure 8 with five watersheds draining the glaciers of Mount Rainier after being separated by selection and export data.

Following the creation of five new shapefiles with one for each watershed, the level 12 boundaries within the individual watersheds need to be combined to result in one polygon for each watershed. This task was completed one watershed at a time by using the editor toolbar by first selecting the smaller level 12 watershed boundaries within one of the five watersheds then merging them into one polygon (figure 10). The result after completing this process for all five watersheds, is a single polygon for each watershed (figure 11).

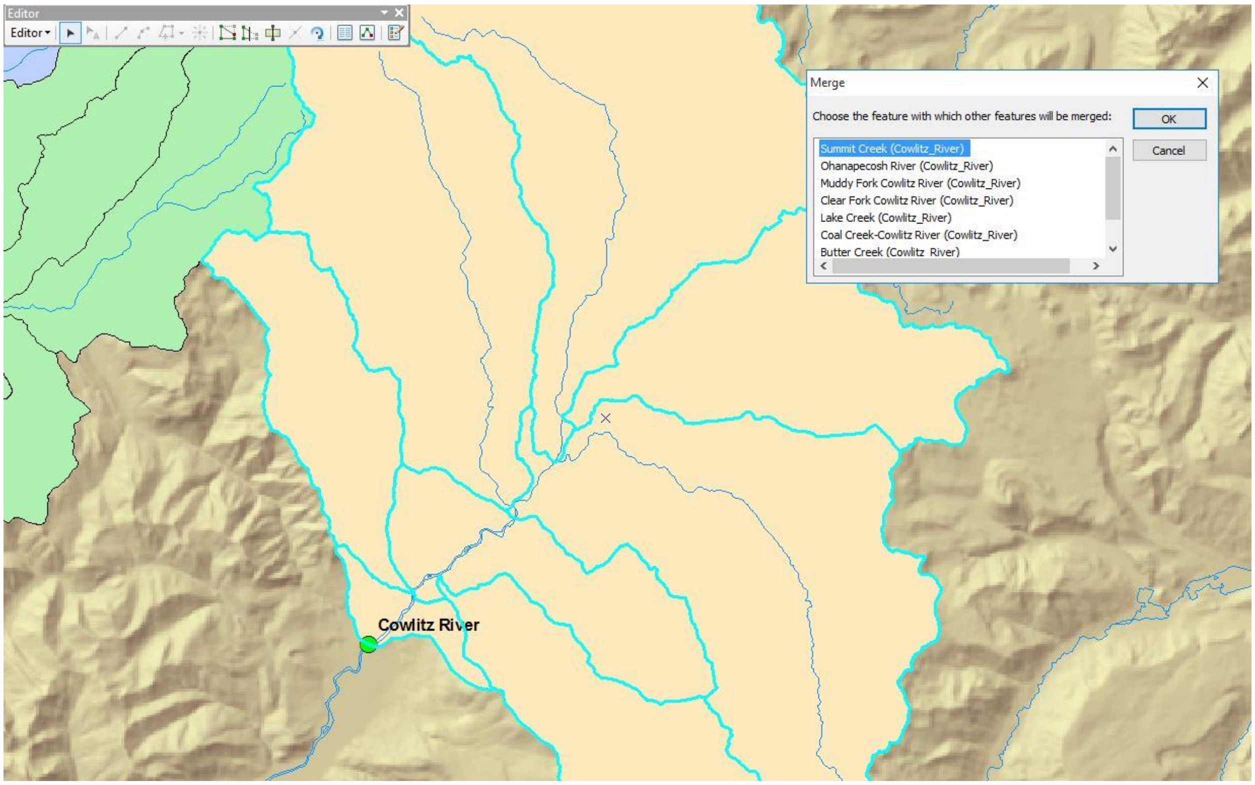


Figure 10: Image showing usage of the merge tool within an editing session where the selected polygons highlighted in cyan will be merged into one single polygon to create the Cowlitz Watershed. The same process was done for the Nisqually, Puyallup, Carbon, and White Rivers.

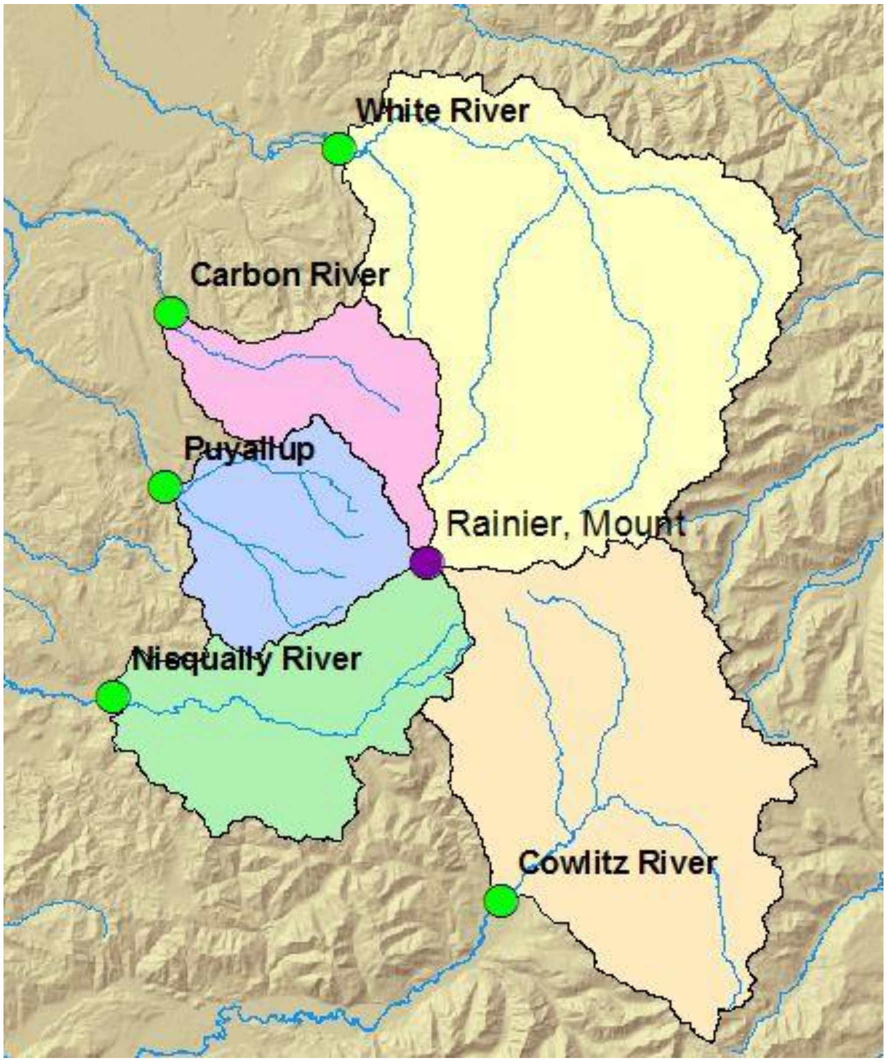


Figure 11: Image showing the result of using the merge tool for the all five watersheds where each watershed now is a single polygon.

Once each watershed was represented by a single polygon, the area of each was computed. By the addition of a new field named ‘area’ in all five watershed’s attribute table as a double, the area for every individual watershed can be calculated in km^2 by using the calculate geometry window (figure 12). The area of all five watersheds and their respective ID’s can be seen in table 2 and figure 13.

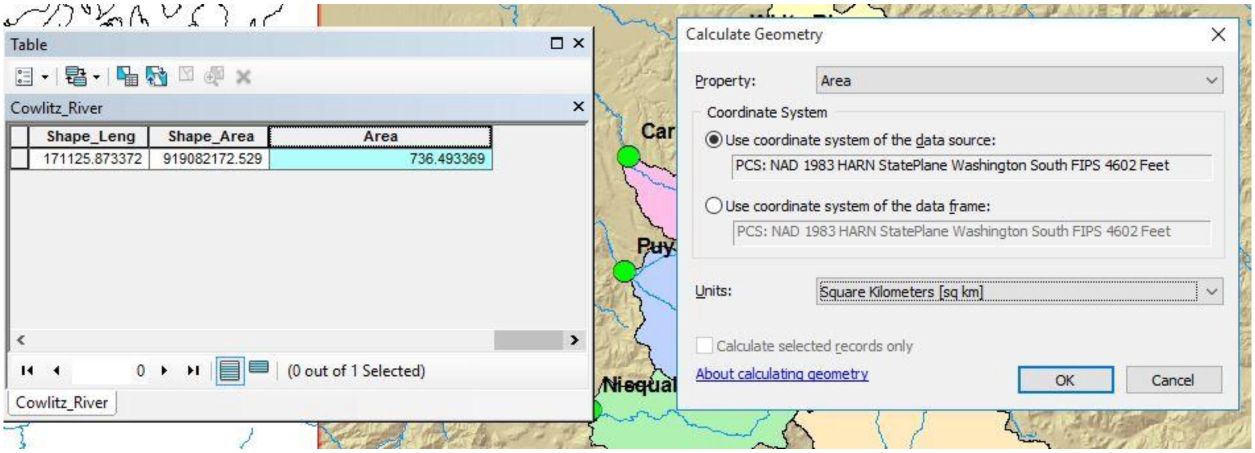


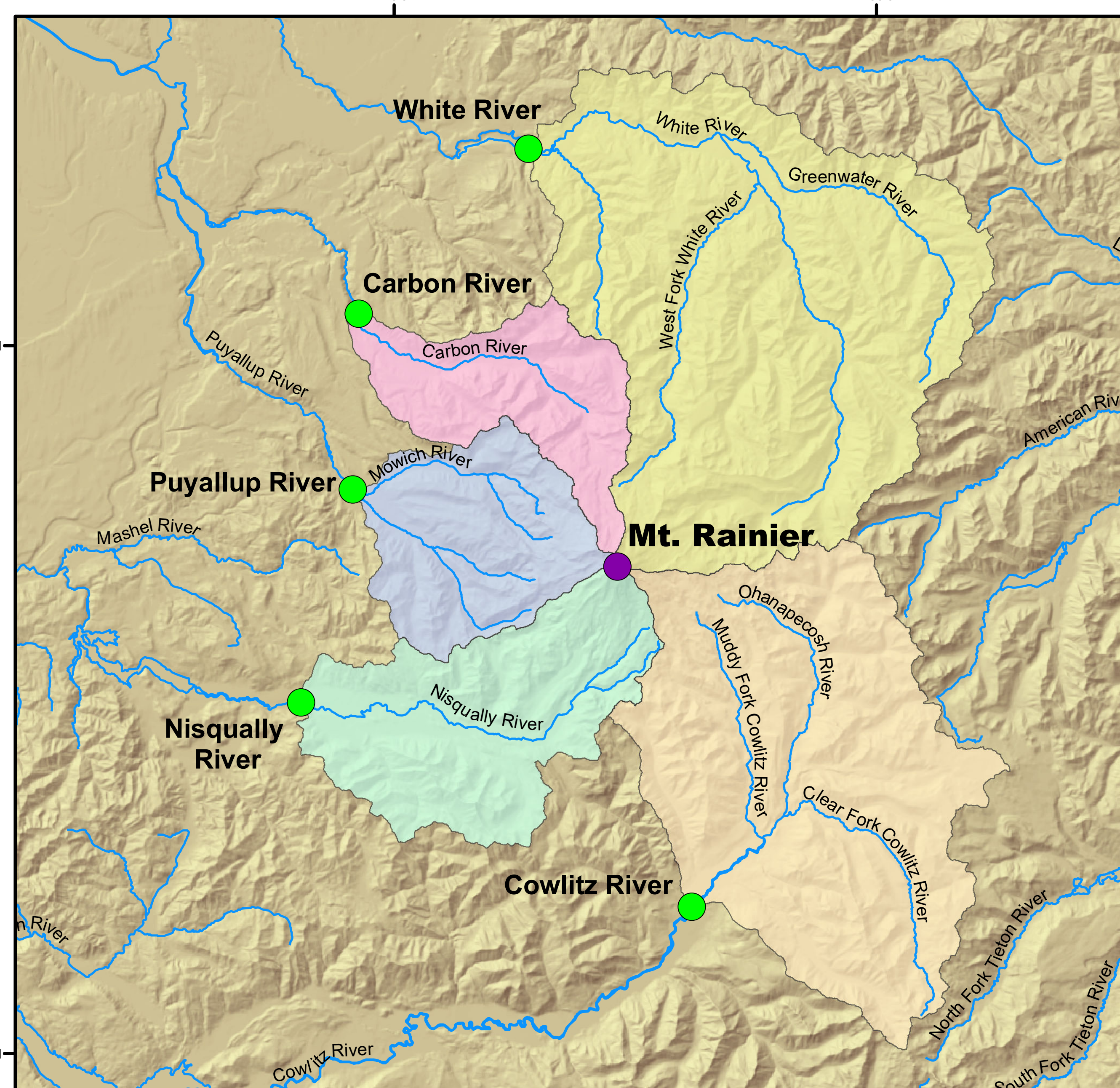
Figure 12: Image showing a new field named ‘area’ created in the Cowlitz Watershed attribute table which is then filled in with the area for watershed by using the calculate geometry window. The same process was conducted for the Nisqually, Puyallup, Carbon, and White Watersheds.

ID (h)	Watershed	Area (km^2)
1	Cowlitz	736.493369
2	Nisqually	352.090141
3	Puyallup	237.320875
4	Carbon	204.830035
5	White	970.283122

Table 2: Table showing each watershed and its corresponding area along with the watershed ID.

Andrew Stearns
December 6, 2017

Watersheds of Mount Rainier, Washington (US)



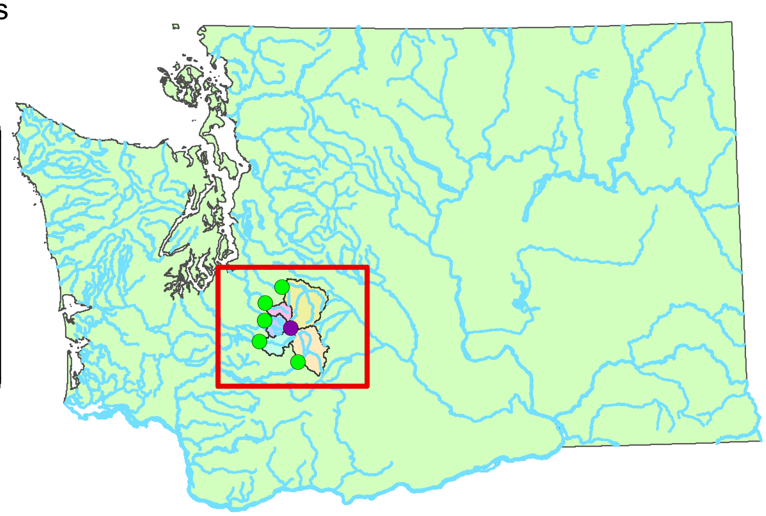
N

0 5 10 20 Kilometers

1:500,000

Explanation

- Cowlitz Watershed
- Nisqually Watershed
- Puyallup Watershed
- Carbon Watershed
- White Watershed
- Area of Interest
- Mt. Rainier
- USGS Gage Stations
- Streams



NAD 83 HARN StatePlane Washington South FIPS 4602 Feet
Lambert Conformal Conic

Figure 13: Map showing all five watersheds draining the glaciers of Mount Rainier along with the USGS stream gage stations used in the study.

Although the area of each watershed had been found, the annual precipitation volume and annual average temperature weighted by area in each climate division for all five watersheds was required in order to solve equation (6) and (7). Before the areas in each climate division could be found, the areas of climate divisions 4 and 5 were selected and exported as two new shapefiles (figure 14).

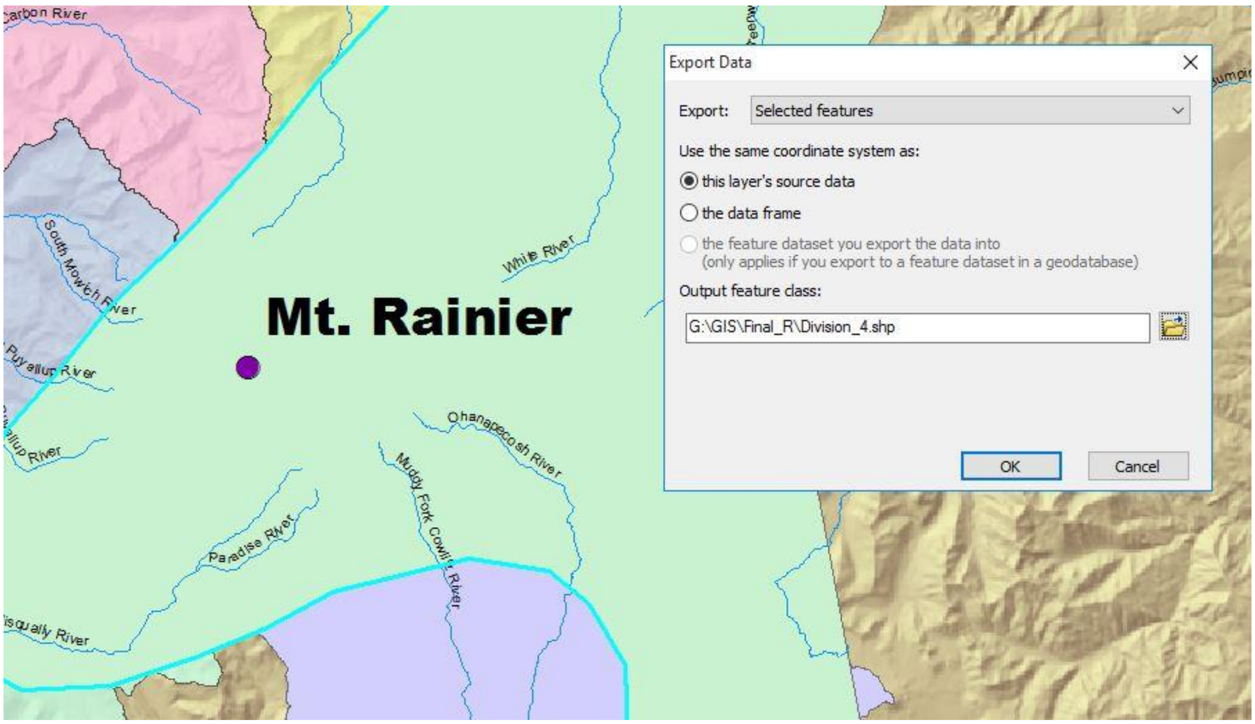


Figure 14: Image showing the creation of a shapefile for climate divisions 4 by interactive selection and exporting the data. The same process was conducted in creating a shapefile for climate division 5.

Next, the intersect tool was used in order to create 10 new shapefiles representing the area of each watershed in climate zones 4 and 5 (figure 15).

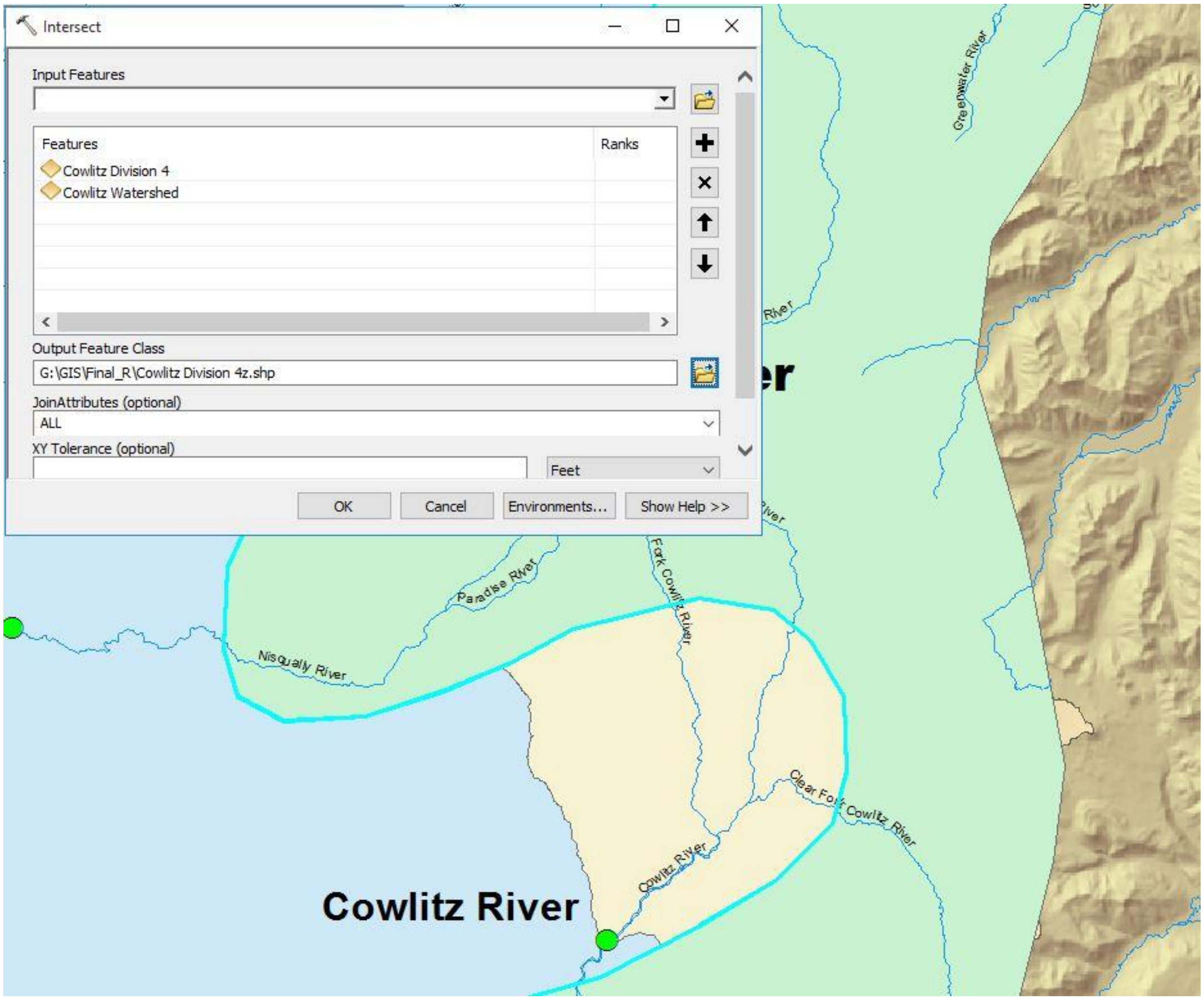


Figure 15: Image showing the use of the intersect tool to create a new shapefile representing the area of the Cowlitz Watershed in climate division 4. The same process was conducted for the Nisqually, Puyallup, Carbon, and White watersheds to find their respective areas in climate divisions 4 and 5. Process also used to calculate the area of the Cowlitz watershed in climate division 5.

4 Results

Finally, after the extent of the five watersheds was been found in each climate division, a new field named ‘area’ was created in the attribute table for every watershed as a double, and by using the calculate geometry window the areas of all five watersheds in climate divisions 4 and 5 was computed (figure 16). The result is the areas of each watershed in climate divisions 4 and 5 (Table 2, 3, and figure 17)

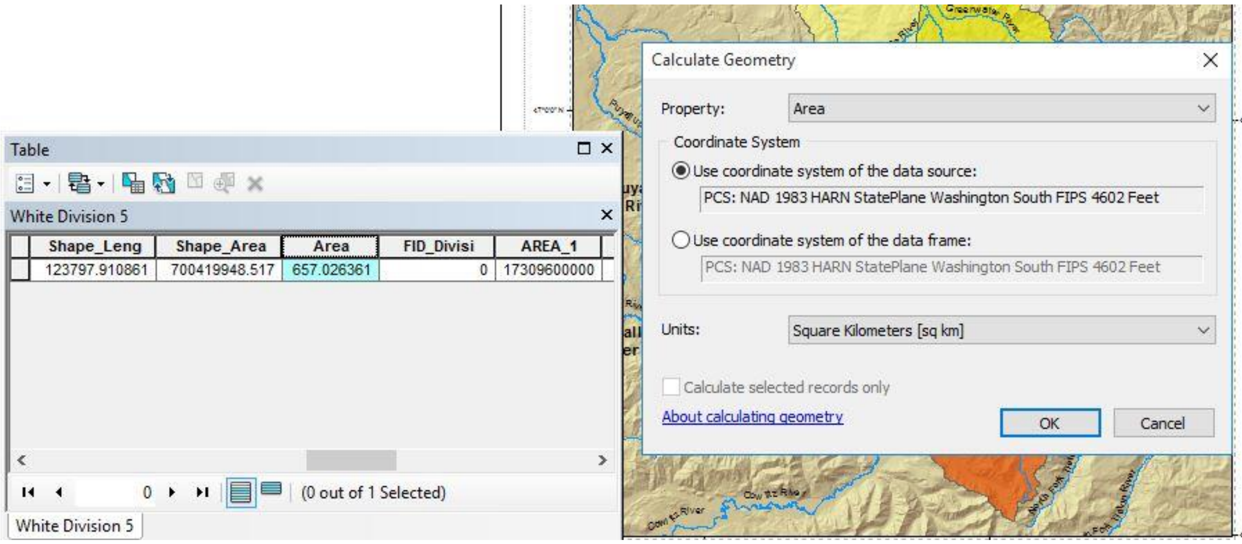


Figure 16: Image showing the creation of a new field called 'area' as a double in the attribute table for White Watershed Climate Division 5. The calculate geometry window was then used to compute the area in km^2. This process was conducted for the Cowlitz, Nisqually, Puyallup, and Carbon watersheds to find their respective areas in climate divisions 4 and 5. Process also used to calculate the area of the White watershed in climate division 4.

ID (h)	Watershed	Area Climate Divison 5 (km^2)	% Area Climate Division 5	Total AreaArea (km^2)
1	Cowlitz	513.25	69.68833958	736.493369
2	Nisqually	173.05	49.14934554	352.090141
3	Puyallup	61.8426	26.05864318	237.320875
4	Carbon	19.7543	9.644239918	204.830035
5	White	657.026361	67.71491187	970.283122

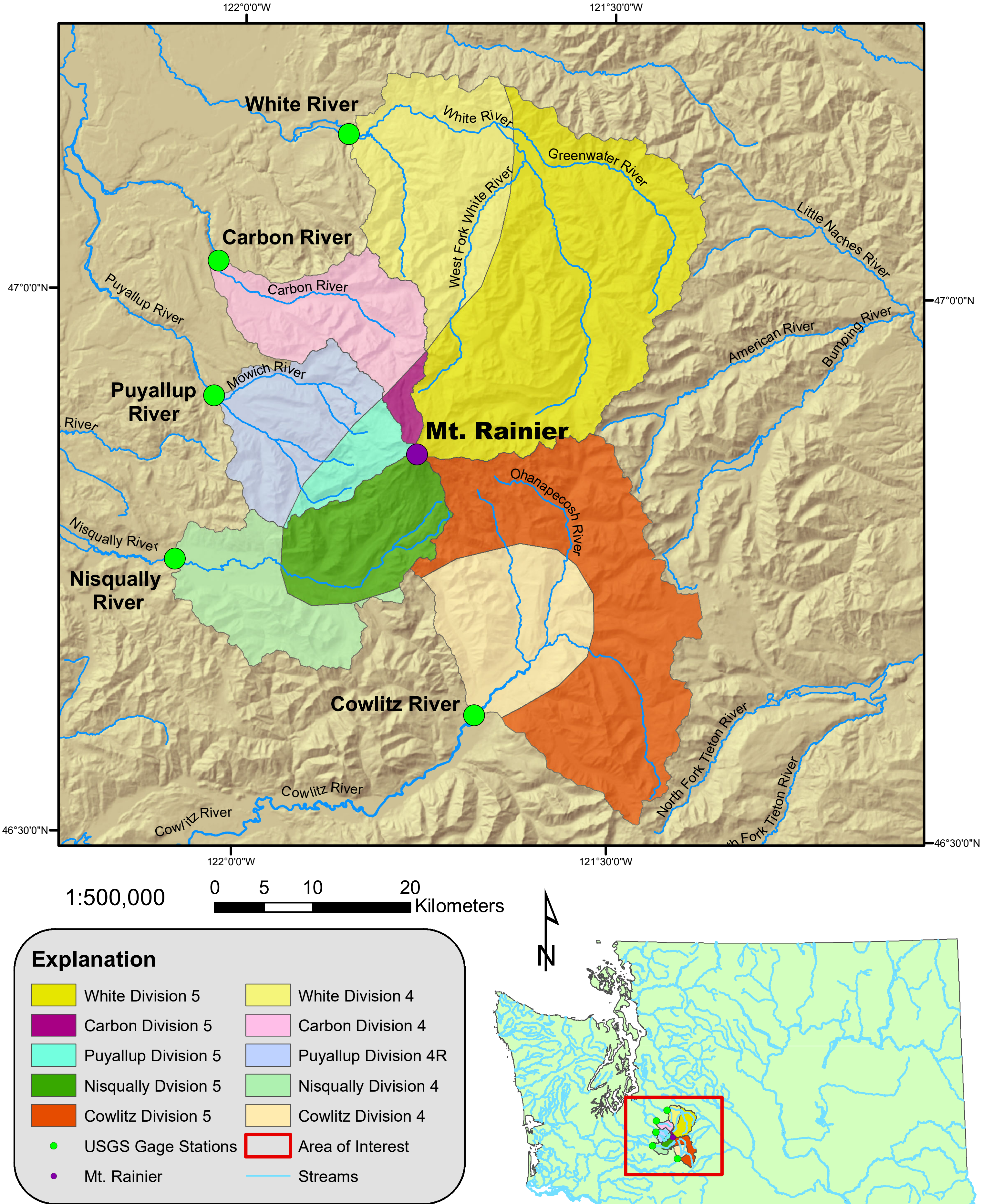
Table 2: Table showing area and percentage of area of each watershed contained within climate division 5.

ID (h)	Watershed	Area Climate Divison 4 (km^2)	% Area Climate Division 4	Total AreaArea (km^2)
1	Cowlitz	220.412	29.92722125	736.493369
2	Nisqually	179.06823	50.85863225	352.090141
3	Puyallup	175.513	73.95598891	237.320875
4	Carbon	185.101	90.3680947	204.830035
5	White	313.286	32.28810158	970.283122

Table 3: Table showing area and percentage of area of each watershed contained within climate division 4.

Climate Divisions of Mount Rainier Watersheds

Andrew Stearns
December 6, 2017



NAD 83 HARN StatePlane Washington South FIPS 4602 Feet
Lambert Conformal Conic

Figure 17: Map of watersheds of Mount Rainer according to the area of each watershed in climate divisions 4 and 5.

5 Discussion and Future Research

Finding the area of each watershed in climate divisions 4 and 5 (Table 2 and 3) allows equations (6) and (7) can be solved. With the annual volume of precipitation for each watershed, the runoff ratio in equation (3) can be calculated and shown as a function of the year. The annual runoff ratio will allow the relationship discharge and precipitation over time to be quantified for all five watersheds to determine is discharge is increasing at a faster rate than precipitation and hence an increase in glacial melting. Furthermore, with the annual average temperature weighted by area of each watershed in climate divisions 4 and 5 allows the relationship between glacial extent and temperature to be examined over time. The subsequent results found by the annual precipitation volume and temperature would not have been accurate without finding the areas of the watersheds within each climate division.

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