

**THE UNIVERSITY OF WESTERN ONTARIO
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ENVIRONMENTAL ENGINEERING**

Water Resources Research Report

**Instruction for Watershed Delineation in an
ArcGIS Environment for Regionalization Studies**

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Executive Summary

This report describes the procedure for automated watershed delineation and characterization in an ArcGIS environment. The methodology is explained in two steps (i) watershed delineation using digital elevation model (DEM) data and several tools from the *Spatial Analyst* toolbox in ArcGIS; and (ii) the assignment of watershed attributes that influence regional flood response including basin area, channel dimensions, climate statistics, among others. The methodology is then applied to a case study where watersheds are delineated upstream of hydrometric stations in Southern Ontario, Canada, and the spatial distribution of each attribute is mapped over the resultant basins. The outcome can be employed in regional flood frequency analysis studies where watersheds are grouped into homogeneous hydrologic regions based on the similarity of their attributes. Then hydrometric records measured within the same homogeneous regions are combined into regional probability distributions from which hydrologic design values are estimated for specified exceedance probabilities. These values are used in planning and design applications in the water resources management sector.

Table of Contents

1. INTRODUCTION	1
2. LITERATURE REVIEW	3
3. METHDOLOGY	7
3.1 Watershed delineation.....	7
3.2 Assignment of watershed attributes	16
4. CASE STUDY	23
4.1 Data.....	23
4.2 Procedure	27
4.3 Results and Discussion.....	30
5. CONCLUSION.....	35
REFERENCES	36
APPENDIX: PREVIOUS REPORTS IN THE SERIES	38

List of Tables

Table 1: Description of data used and their source.....	24
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List of Figures

Figure 1: Mosaic function of the Data Management toolbox in ArcMap.....	8
Figure 2: Fill function of the Spatial Analyst toolbox in ArcMap.....	9
Figure 3: Flow direction function of the Spatial Analyst toolbox in ArcMap.....	10
Figure 4: Flow direction function of the Spatial Analyst toolbox in ArcMap.....	11
Figure 5: Setting the symbology of the Flow Accumulation layer. The layer is divided into two classes: Flow accumulation and no flow accumulation.....	12
Figure 6: Process for creating a new shape-file in ArcCatalogue.....	13
Figure 7: Setting properties such as the feature type and geographical coordinates of a new shape-file in ArcCatalogue.....	14
Figure 8: Watershed function of the Spatial Analyst toolbox in ArcMap.....	15
Figure 9: Raster to Polygon function of the Conversion toolbox in ArcMap.....	16
Figure 10: Calculate Areas function of the Spatial Statistics toolbox in ArcMap.....	17
Figure 11: Stream link function of the Spatial Analyst toolbox in ArcMap.....	18
Figure 12: Process for joining data to another layer's attribute table.....	19
Figure 13: The Display X-Y Data tool which display's features' locations given their latitude and longitude.....	20
Figure 14: Process for converting a feature layer to a shape-file in ArcMap.....	21
Figure 15: Buffer function of the Analysis toolbox in ArcMap.....	22
Figure 16: Spatial Join function of the Analysis toolbox in ArcMap.....	23
Figure 17: Map of the fluvial regions of Canada (Ashmore and Church, 2001).....	25
Figure 18: Four control points for georeferencing procedure are shown as the red and green crosshairs....	28
Figure 19: Watersheds are shown as blue polygons which are delineated upstream of yellow pour points.	29
Figure 20: Stream links of the channel network are differentiated by colour.....	29
Figure 21: Climate stations (green points) and their 15km area of influence (circle area) are shown here.	30
Figure 22: Distribution of average annual precipitation over watersheds in Southern Ontario.....	31
Figure 23: Distribution of maximum annual precipitation over watersheds in Southern Ontario.....	31
Figure 24: Distribution of average daily maximum temperature over watersheds in Southern Ontario. ...	32
Figure 25: Distribution of main channel slope over watersheds in Southern Ontario.....	33
Figure 26: Attribute table showing the characteristics for each watershed.....	34

Nomenclature

ArcGIS: A software package that is used for manipulating, presenting, analyzing geographically referenced data.

ArcMap: The main component of the ArcGIS software package that is used for mapping and analyzing geographically referenced data.

ArcCatalogue: A component of the ArcGIS software package that is used for managing and organizing geographically referenced data.

Arc Hydro: An extension of ArcGIS that includes specialized tools for water resources applications; for example it includes tools for the delineation and characterization of watersheds.

Raster: A file format where geographically referenced data is stored in cells of a two dimensional grid; each cell is assigned an attribute value.

Vector: A file format where geographically referenced data is represented by points, lines or polygons, and the features' critical points (vertices, end points) are assigned x-y coordinates.

CSV-file: A comma separated values (CSV) file contains numerical or text data that is structured in the form of tables or lists; breaks in the data are indicated by commas.

DEM-file: A digital elevation model (DEM) file contains geographically referenced elevation data in a raster format.

Shape-file: A file that contains geographically referenced data in a vector format; it is composed of several individual files that provide information on feature geometry, position and attributes.

TIFF-file: A Tagged Image File Format (TIFF) file stores image data in a raster format.

Digitize: The process of converting analogue map features to a digital format.

1. INTRODUCTION

Flood frequency analysis is a probabilistic method used to estimate hydrologic design values such as flood levels and flow rates which are used in infrastructure design and water resource management applications. Using this procedure a structure is designed to withstand a hydrologic event corresponding to a selected return period, where a return period is defined as a statistical measurement typically based on historic data denoting the average recurrence interval of the event over an extended period of time. The reciprocal of the return period is called the exceedance probability; if a structure is designed to accommodate a 100 year return period, then it must be able to withstand a hydrologic event corresponding to a 1 in 100 year probability of exceedance every year. Exceedance probabilities and therefore, return periods and hydrologic design values are determined from probability distributions that are developed from observed hydrologic data (Chin, 2006).

In order to obtain reliable estimates of return periods and their associated hydrologic events, an adequately long observed record is needed. It is recommended that the minimum observed record should be five times greater than the return period selected for design (Reed *et al.*, 1994). This is difficult to achieve in many cases; for example by this standard a structure that is designed for a 100 year return period requires 500 years of observed hydrologic data measured at the site of implementation. To address this issue regional flood frequency analysis is employed where data measured at locations with similar hydrologic variables are combined to create a record of sufficient length (Burn, 1990). The general procedure is described in two broad steps: (i) the formation of regions with homogeneous flood responses; (ii) the combination of data measured at flow gauge stations in the same region in order to develop a regionally averaged probability

distribution. From this distribution hydrologic design values are estimated more accurately for a selected return period (Chebana and Ouarda, 2008).

This report explains how to prepare for step (i) which is the formation of homogeneous hydrologic regions using Esri's ArcGIS software package (Esri, 2014). Hydrologic regions are formed by partitioning watersheds and their associated discharge data into groups based on the similarity of their meteorological and physiographic attributes which drive flood generation processes. These attributes include: basin area, channel slope, channel length, land use indices, precipitation and temperature, among others. By using physiographic and meteorological attributes that are independent of observed discharge data to form the regions, the latter can be reserved to validate their hydrologic homogeneity (Srinivas, 2013).

The main objective of this report is to demonstrate how to delineate and characterize watersheds using ArcGIS for regionalization studies. The watersheds are delineated such that hydrometric stations are located at their outlets. This is important in order for the watershed characteristics to be truly representative of the observed discharge data used to estimate hydrologic design values. The watersheds are delineated using elevation data provided by digital elevation models (DEMs) and subsequently, several flood generation characteristics are assigned to each watershed. The outcome of this procedure can be directly applied in regionalization studies where multivariate clustering algorithms are used to group watersheds into hydrologically homogeneous regions based on the similarity of their attributes, and hydrologic variables are estimated from the regions.

The organization of the report is as follows: a literature review is provided in section 2. Section 3 describes the methodology used. Section 4 applies the methodology to a case study in Southern Ontario, Canada. Finally, concluding remarks are found in section 5.

2. LITERATURE REVIEW

Historically, watershed boundaries were delineated by hand with the aid of contour maps. Since the 1980's computer software has been more commonly employed to perform automated watershed delineation; several algorithms are available in geographical information system (GIS) software packages. Lindsay *et al.*, (2008) have identified two main applications of automated watershed delineation as (i) mapping or modeling spatial phenomena; and (ii) developing statistical relationships between basin characteristics and outcome variables related to hydrology or water quality for prediction purposes.

Several studies have been conducted to determine the relationship between basin characteristics and water quality parameters measured at sampling sites located at watershed outlets. Jarvie *et al* (2002) delineated sub-watersheds upstream of 60 sampling stations within the Humber catchment in the United Kingdom using ArcGIS. The objective of the study was to determine linkages between watershed attributes and chemical concentrations measured at the sampling sites in order to observe trends in water quality across the basin. The watershed boundaries were delineated using topographic data provided by the Institute of Hydrology Digital Terrain Models and several functions from the *Spatial Analyst* toolbox in ArcGIS. Then they assigned attributes to the watershed polygons including catchment area, average elevation, average slope, annual rainfall, several geological characteristics and land use properties and explored the relationships

between the attributes and water quality parameters measured at the sampling sites. The relationships were analyzed using a combination of scatter plots and regression analysis.

This methodology is also employed to predict hydrologic variables such as discharge measured at the watershed outlets. Sarhadi *et al* (2012) delineated watersheds in ArcGIS using the Arc Hydro extension for a regional flood frequency analysis application (ArcGIS Resources, 2013). The objective of the study was to form groups of watersheds with homogeneous physiographic and meteorological characteristics in order to obtain reliable estimates of flood quantiles for different return periods. Regression equations were developed for each homogeneous region which used watershed attributes as predictors to estimate flood quantiles. The resultant flood quantiles were used in a flood mapping application in Southeastern Iran.

In these applications it is essential for watershed outlet positions to coincide with water quality sampling or hydrometric stations as well as the stream network derived from digital elevation model (DEM) data; as such, the stations represent outlet points from which watersheds are delineated upstream. A shape-file showing the station locations is imported into a GIS environment. The stations often require repositioning such that they are located on the stream network derived within the DEM, otherwise substantial errors may ensue. The stations may be located upstream or downstream of their true location, on the incorrect reach of the stream network, or off of the stream network entirely. The error associated with stations located upstream or downstream of their true location is fairly insignificant, as long as they are located on the correct stream link; however, the other cases of inaccurate positioning can result in a significant amount of error (Lindsay *et al.*, 2008).

To ensure accurate positioning the stations can be placed manually. When done correctly, manual repositioning provides the most accurate results as it allows the user to integrate their knowledge of the study area; however it is inefficient when there are a large number of stations and it also has a potential for human error (Lindsay *et al.*, 2008). When there are a large number of stations automated repositioning tools are often employed such as the *Snap Pour Point* function of the *Spatial Analyst* toolbox in ArcMap (Esri, 2014). The *Snap Pour Point* function is the most commonly used automated watershed outlet repositioning tool that relocates stations to the raster cell with the highest magnitude of flow accumulation within a certain search radius. It effectively reduces the number of outlets located off of the stream network and it is much more efficient than manual repositioning, however it often moves stations onto the incorrect stream links; for example, it is possible for stations to be initially located on the correct stream link of the flow network, and then repositioned to a different stream link of higher flow accumulation (Lindsay *et al.*, 2008).

Jenson (1991) developed an alternative automated watershed outlet repositioning tool in which stations are relocated to the closest raster cell with a flow accumulation magnitude that is greater than or equal to a specified threshold value. The tool has an improved performance in terms of locating stations on the correct stream link when compared to the *Snap Pour Point* function; however the potential for inaccurate repositioning is not entirely eliminated. To address the issue of repositioning stations onto the incorrect stream link, Lindsay (2008) developed the Advanced Outlet Repositioning Approach (AORA) in which stream names are used to identify the reach where the stations are located. The method ensures that stations with the same stream name are

located on the same flow path. It has been successfully employed in regional studies with densely packed stations (Lindsay *et al.*,2008).

This report describes the watershed delineation process for an application similar to the study conducted by Sarhadi *et al* (2012). Various physiographic and meteorological attributes are assigned to the delineated watersheds, which can be clustered into homogeneous regions in future regionalization studies. Regions which exhibit homogeneous physiographic and meteorological attributes also have homogeneous hydrologic parameters measured at the basin outlets and therefore, the flood quantiles are estimated from probability distributions (or alternatively regression equations) developed for these regions. Instruction is provided for watershed delineation using functions of the *Spatial Analyst* toolbox of ArcGIS. Many studies have used the Arc Hydro extension for a simplified watershed delineation procedure and computation of watershed attributes; however the extension is not available for the latest versions of ArcGIS. Instructions are also provided for the manual repositioning of hydrometric stations. Although this method is considered inefficient with a large number of stations, it provides the most accurate results when performed with care. Evidently the *Snap Pour Points* function which is available in ArcGIS requires the user to review and adjust the output, and other watershed outlet repositioning tools are not easily accessible for public use. Finally, similar to other studies described in this section, this report provides instruction on the assignment of common watershed attributes.

3. METHDOLOGY

Here the procedure for watershed delineation and characterization in an Esri ArcGIS environment is described in two parts: (i) Watershed delineation from DEM data; and (ii) the assignment of watershed attributes.

3.1 Watershed delineation

The first step in the procedure is to delineate watershed polygons using DEM tiles and several tools from the *Hydrology* section of the *Spatial Analyst* toolbox. All of the tools or functions used throughout the procedure can be found using the search function located on the ArcMap toolbar (). The first part of the watershed delineation procedure is to define the areas of flow accumulation within the study area as described here:

1. Import several DEM files into ArcMap in order to cover the study area. Employ the *Mosaic* function of the *Raster* section of the *Data Management Tools* toolbox to combine all DEM tiles into one continuous raster layer. Alternatively, use the search function to look up *Mosaic (Data Management)*. Select any one of the DEM tile layers to be the Target Raster that the other tile layers merge with.

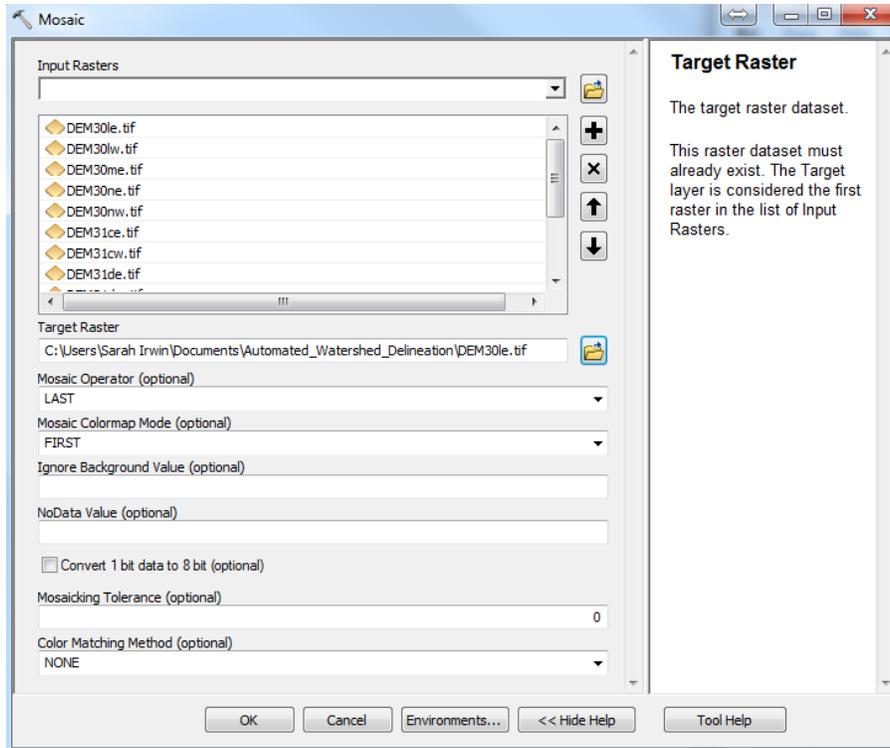


Figure 1: Mosaic function of the Data Management toolbox in ArcMap.

2. Remove all sinks from the DEM layer using the *Fill* function of the *Hydrology* toolbox; search *Fill (Spatial Analyst)*. Use the DEM layer as input to this function. Also indicate the file directory where the resultant layer will be stored. A sink or imperfection is defined as a raster cell which does not indicate the direction of flow from that cell to another (ArcGIS Resources, 2013).

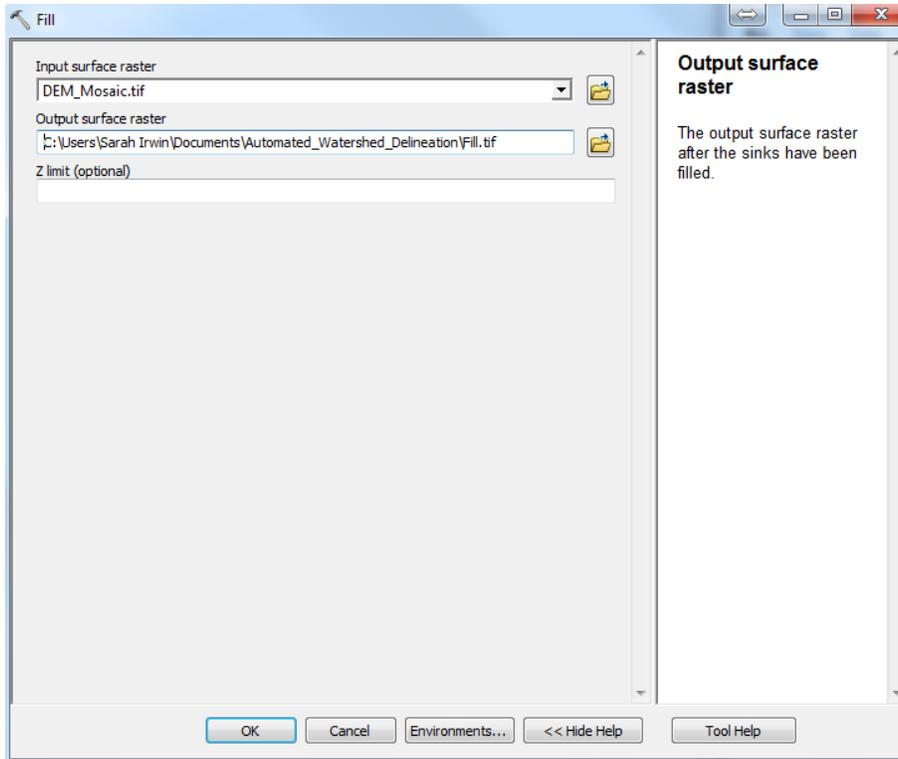


Figure 2: Fill function of the Spatial Analyst toolbox in ArcMap.

3. Employ the *Flow Direction* function of the *Hydrology* toolbox to assign a value to each raster cell indicating the direction of flow leaving that cell; search *Flow Direction (Spatial Analyst)* (ArcGIS Resources, 2013). Use the output layer from the *Fill* function as input.

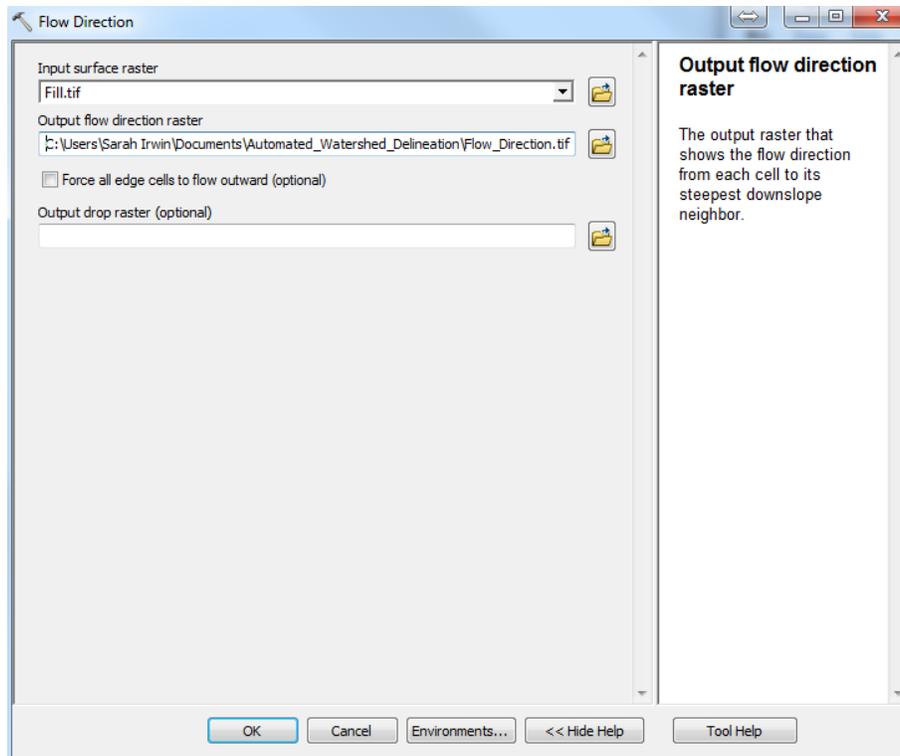


Figure 3: Flow direction function of the Spatial Analyst toolbox in ArcMap.

4. Compute the amount of flow accumulating into each raster cell using the *Flow Accumulation* function of the *Hydrology* toolbox; search *Flow Accumulation (Spatial Analyst)*. Use the output layer from the *Flow Direction* function as input (ArcGIS Resources, 2013).

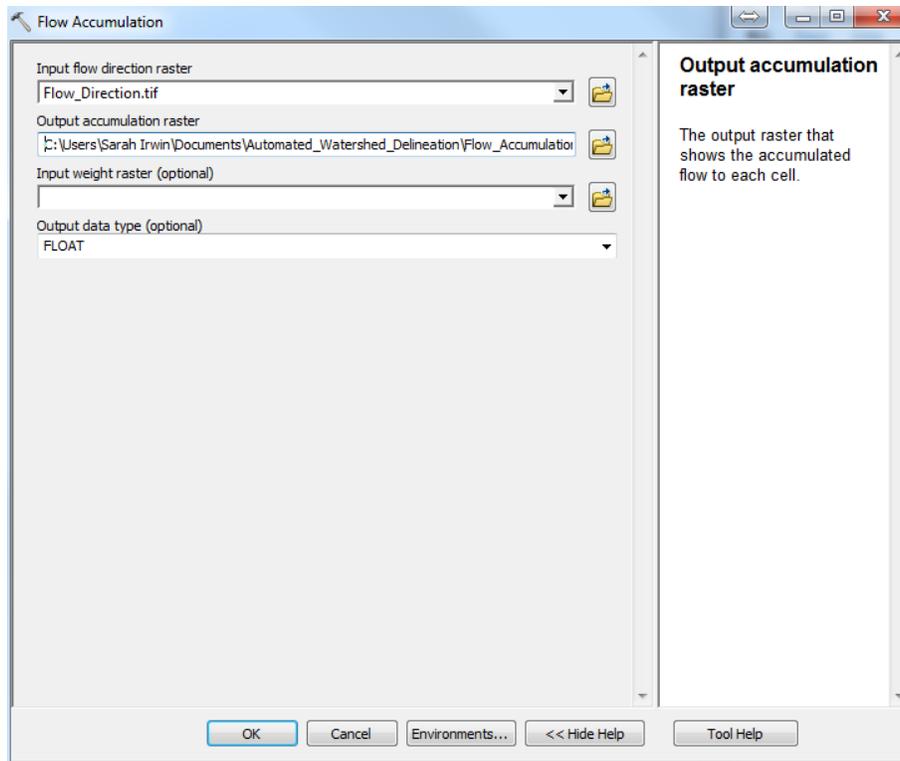


Figure 4: Flow direction function of the Spatial Analyst toolbox in ArcMap.

5. Display the raster cells in which water accumulates. Right click on the *Flow Accumulation* layer in the *Table of Contents* and open the *Layer Properties* dialog box. Under the *Symbology* tab select *Classified* and enter 2 as the number of classes. Adjust the break line until the flow accumulation cells are visible; i.e. the locations of water courses within the study area.

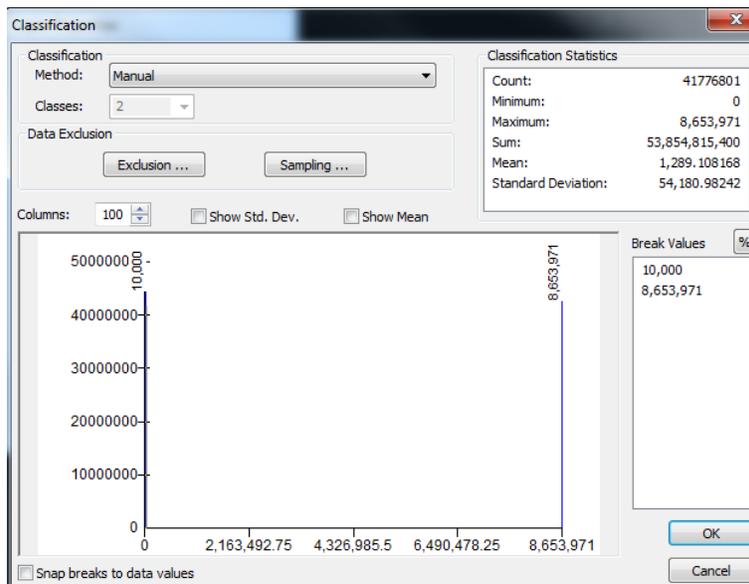
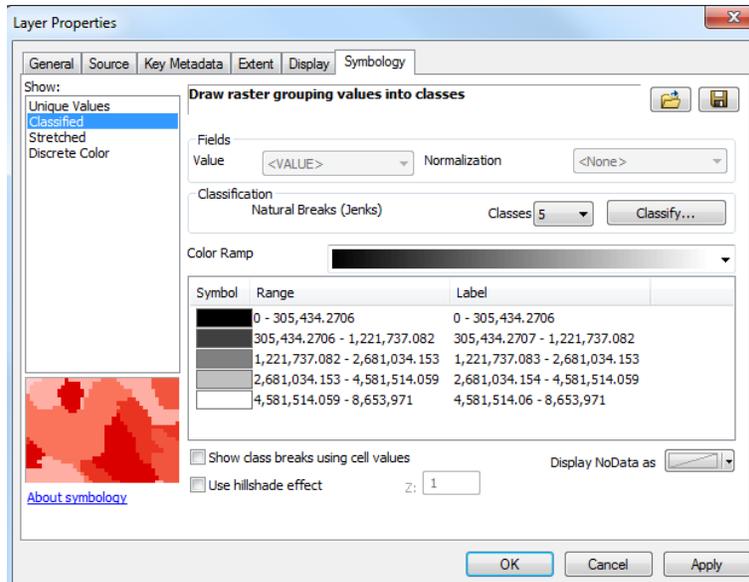


Figure 5: Setting the symbology of the Flow Accumulation layer. The layer is divided into two classes: Flow accumulation and no flow accumulation.

Once the water courses are defined in the DEM layer the watershed outlet points, referred to herein as the pour points, are located. Watersheds are delineated upstream from these points.

6. Create a new Pour Point shape-file layer. Open ArcCatalog, right click on the working folder and select *New* and then *Shape-file*. Enter *point* as the feature type and assign an appropriate geographical coordinate system.

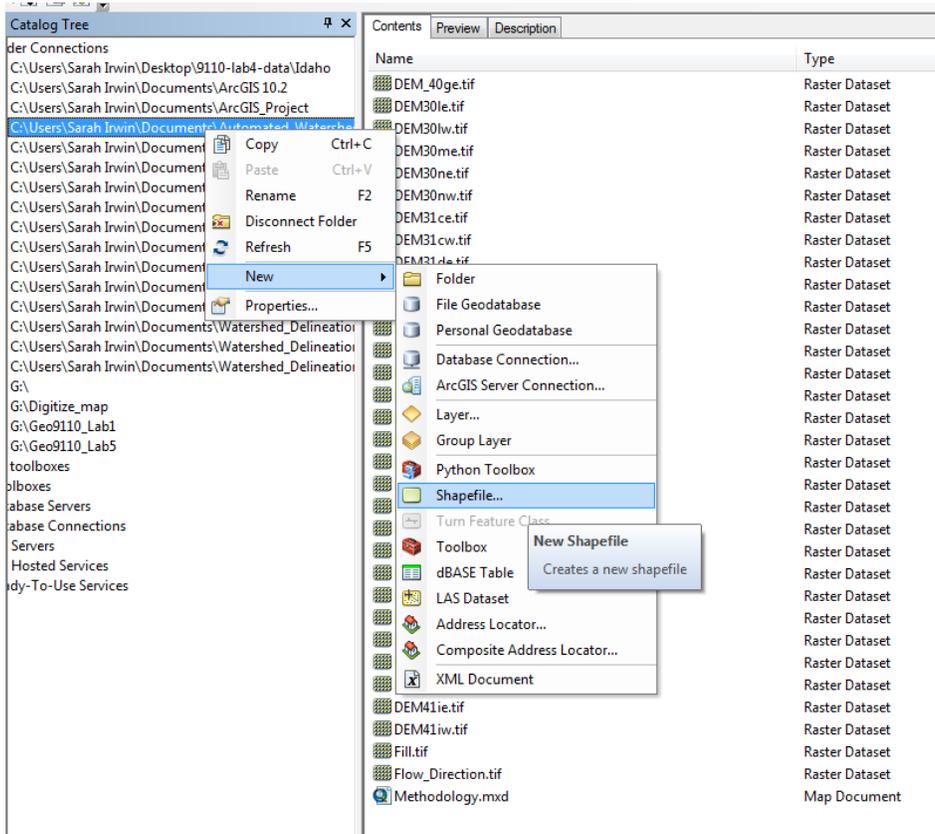


Figure 6: Process for creating a new shape-file in ArcCatalogue.

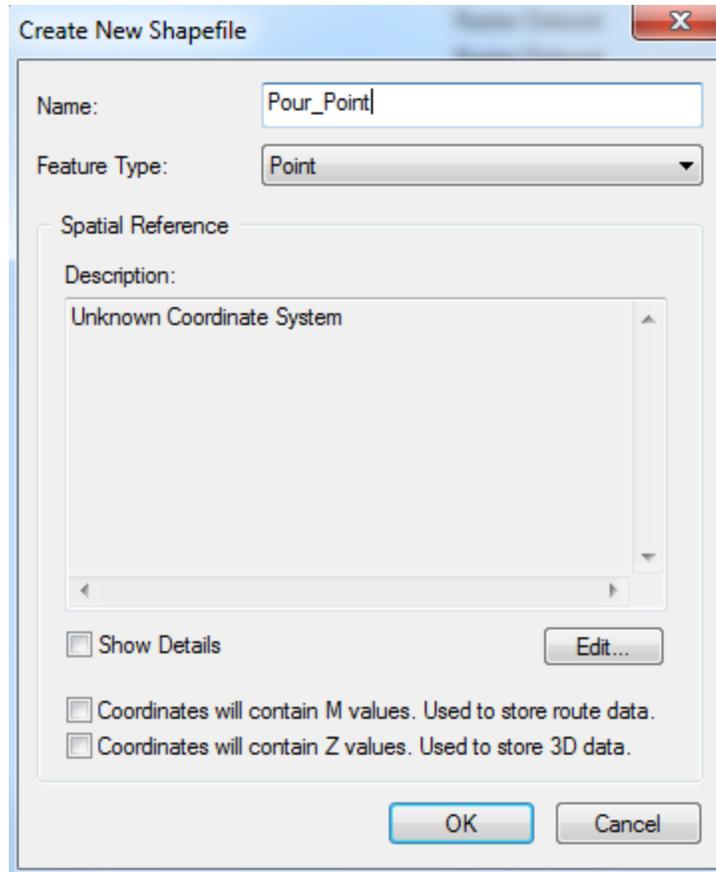


Figure 7: Setting properties such as the feature type and geographical coordinates of a new shape-file in ArcCatalogue.

7. Upload the new Pour Point shape-file layer into ArcMap and overlay this layer with the Flow Accumulation layer by ensuring both layers are selected under the *Table of Contents*.
8. Digitize pour points (watershed outlet points) onto the new layer. Select *Customize, Toolbars, Editor* to turn on the *Editor* toolbar. Select *Start Editing* under the dropdown menu of the *Editor* toolbar and choose the Pour Point layer. Place or digitize points onto the flow accumulation raster cells. The locations of the pour points should coincide with existing flow gauge stations. One way to achieve this is

to upload a shape-file showing the locations of the existing flow gauge stations and to ensure that the digitized pour points and the stations overlap. It is also critical to ensure that the pour points are located on the DEM-derived stream network.

9. Delineate watersheds using the *Watershed* function of the *Hydrology* toolbox; search *Watershed (Spatial Analyst)*. This function calculates the area contributing water to each outlet point (ArcGIS Resources, 2013). Use the Flow Direction output layer and the Pour Point layer as input. Also indicate the unique feature identification (FID) number as the Pour Point field in order to create multiple watersheds at a time.

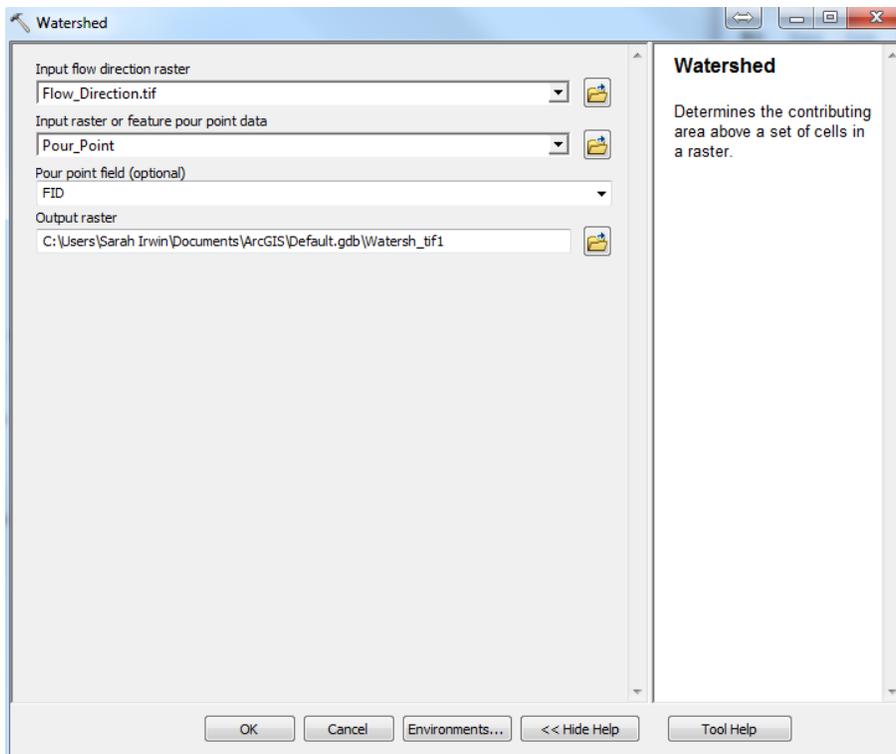


Figure 8: Watershed function of the Spatial Analyst toolbox in ArcMap.

- Convert the Watershed layer from a raster to polygon (vector) format before assigning their attributes in the next section of the methodology; search *Raster to Polygon (Conversion)*. Use the raster type Watershed layer as input to the function.

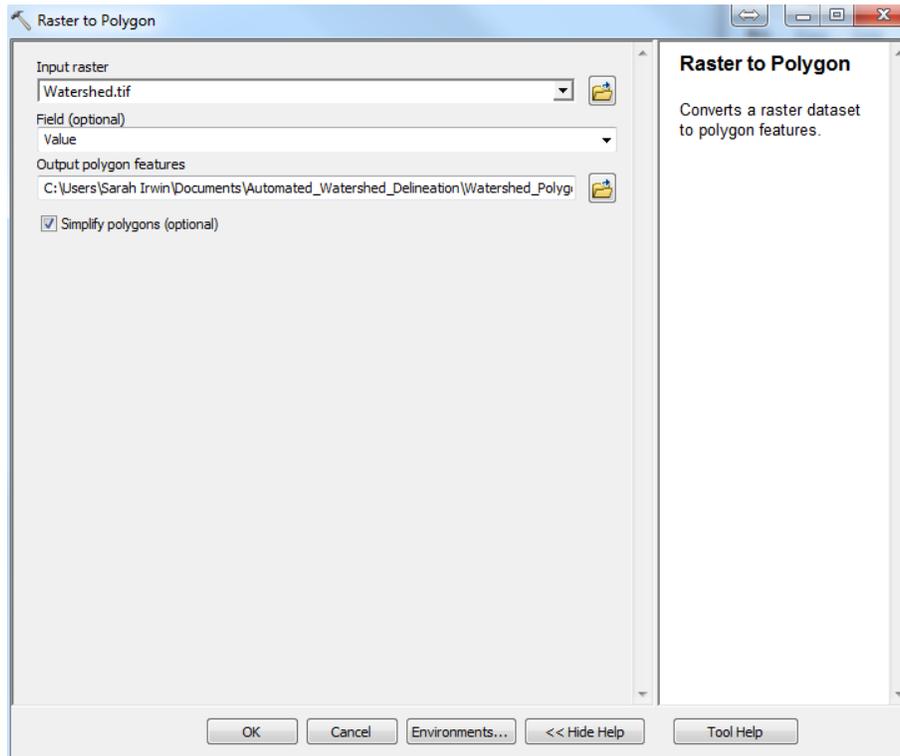


Figure 9: Raster to Polygon function of the Conversion toolbox in ArcMap.

3.2 Assignment of watershed attributes

In this section the procedure for assigning physiographic and meteorological attributes, which influence regional flood response, to each feature in the Watershed Polygon layer is described. These attributes include: basin area, main channel length, main channel slope and climate attributes.

- Calculate basin area using the *Calculate Areas* function in the *Utilities* section of the *Spatial Statistics* toolbox; search *Calculate Areas (Spatial Statistics)*. Use the

Watershed Polygon layer as the input feature class. This function calculates the area of each feature in the Watershed Polygon layer. The values are saved as a column in the attribute table.

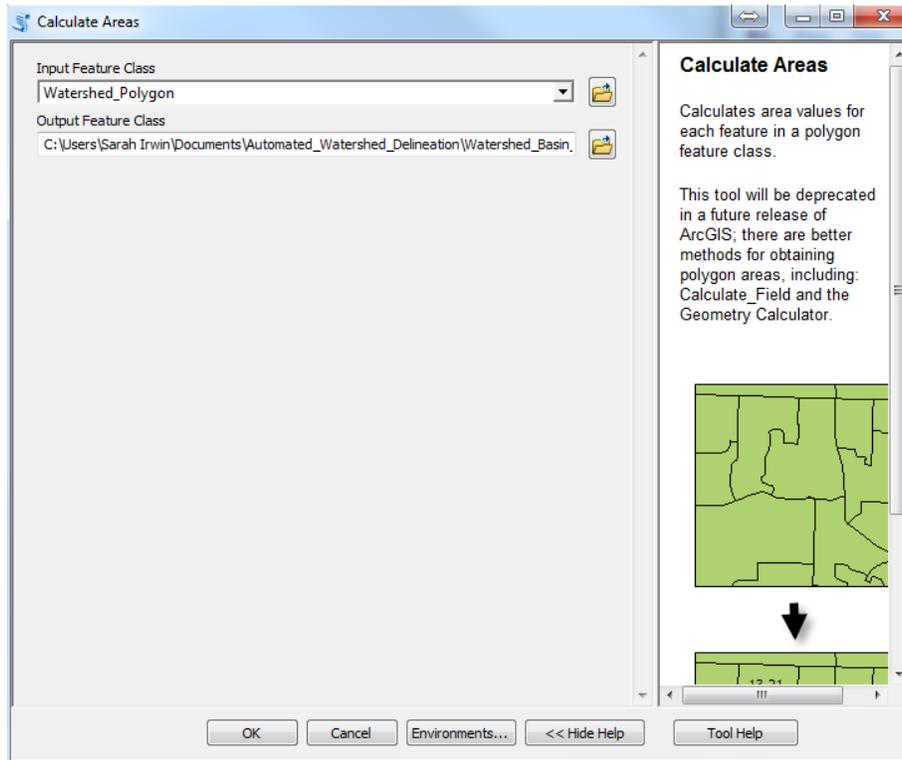


Figure 10: Calculate Areas function of the Spatial Statistics toolbox in ArcMap.

12. To determine the main channel lengths, overlay the Watershed Polygon layer with the Flow Accumulation layer and count the number of raster cells which make up the main channel in each watershed, and then multiply the number of raster cells by the cell length. To reduce the effort required to count the individual cells, use the *Stream Link* function of the *Hydrology* toolbox to define each section or link between intersections in the stream network; search *Stream Link (Spatial Analyst)* (ArcGIS Resources, 2013). Use the Flow Accumulation Layer and Flow Direction layer as inputs to this function. To determine the number of raster cells which make up each

stream link, activate the *Identify* tool and select a link, then the number of raster cells in that link is displayed. The *Identify* tool is located on the main toolbar in ArcMap, (). Add the number of cells in each link together to obtain the total number of cells in the main channel, and multiply the total number of cells by the cell length to obtain the length of the main channel.

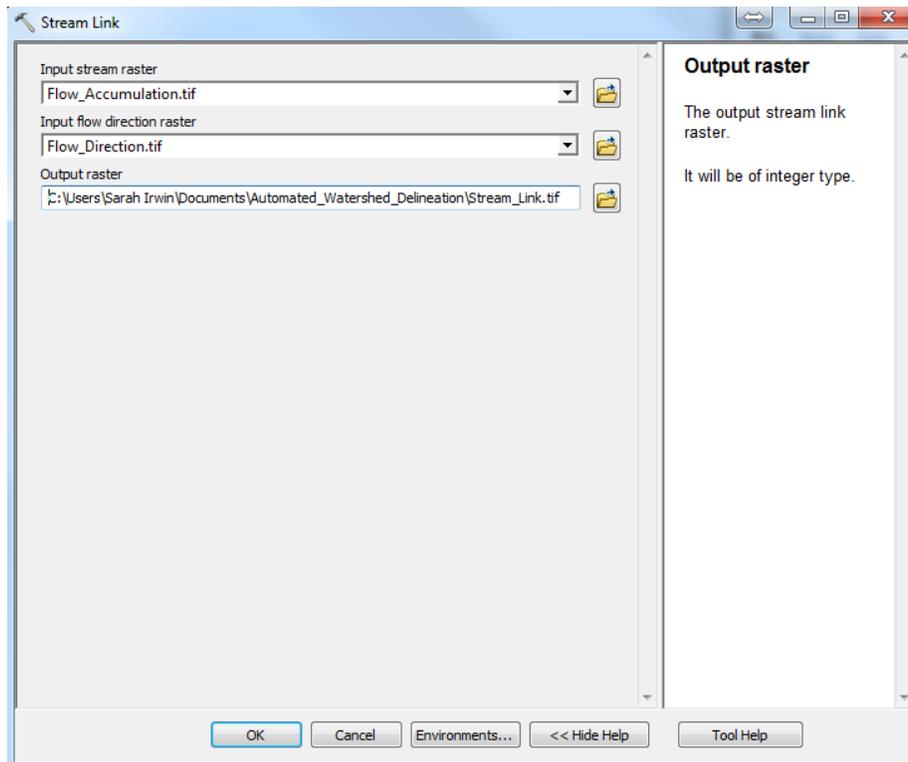


Figure 11: Stream link function of the Spatial Analyst toolbox in ArcMap.

13. The channel slopes are computed as the difference in elevation between the source and mouth of the main channel, divided by the main channel length. Use the *Identify* tool to determine the elevation of the source and mouth of the main channel from the DEM layer.

14. Record each watershed's feature identification (FID) number, channel length and channel slope in a Microsoft Excel spreadsheet. Upload the spreadsheet into ArcMap and join the data to the Watershed Polygon layer's attribute table. To add the data to the attribute table right click on the Watershed Polygon layer and select *Join and Relate* and *Join*, and join the data to the Watershed Polygon's attribute table based on their FID numbers.

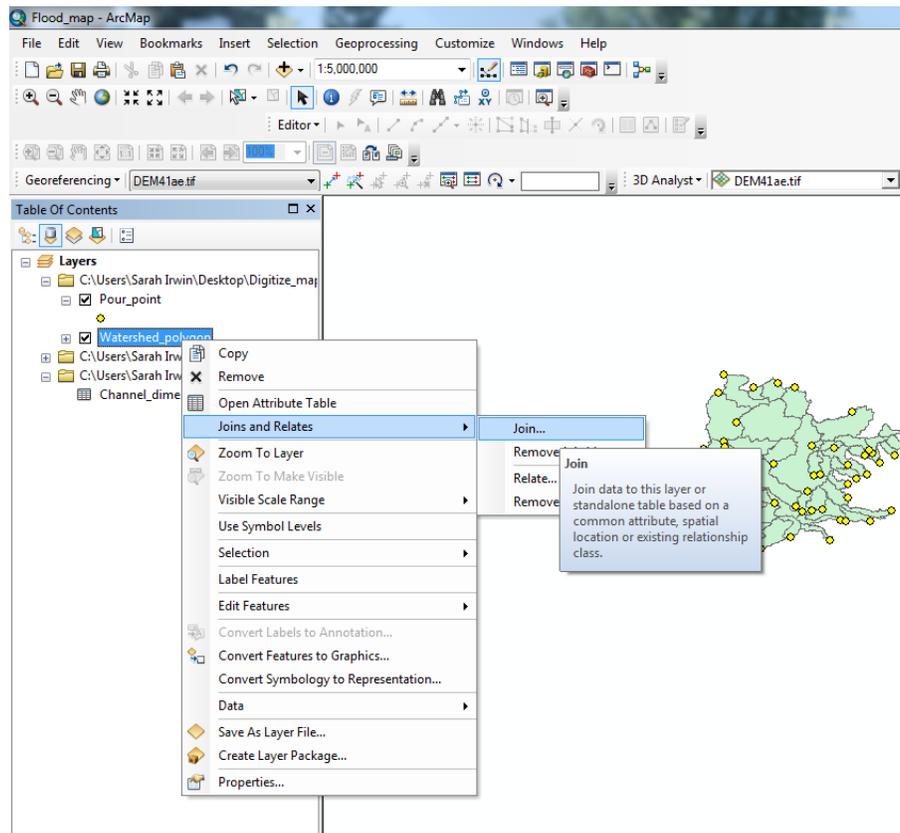


Figure 12: Process for joining data to another layer's attribute table.

15. Import a Microsoft Excel spreadsheet containing a list of the climate stations, their geographical coordinates and meteorological attributes into ArcMap. Right click on the new table in the *Table of Contents* and select *Display X-Y Coordinates* in order to display the climate stations as points. Right click on the new Climate Stations layer

and select *Data, Export Data* and save the layer as a shape-file in the working directory. In ArcCatalog, right click on the new shape-file and assign an appropriate geographical coordinate system; name the layer Climate Stations. Import the Climate Stations shape-file into ArcMap; all climate attributes are stored in the new layer's attribute table.

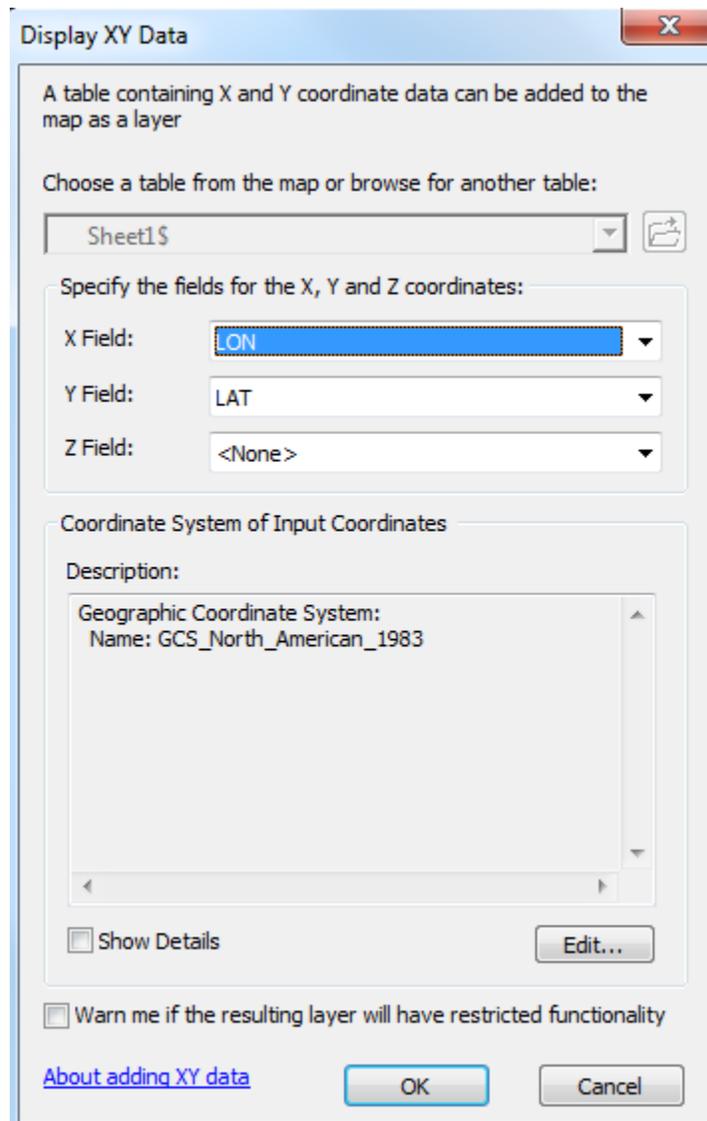


Figure 13: The Display X-Y Data tool which display's features' locations given their latitude and longitude.

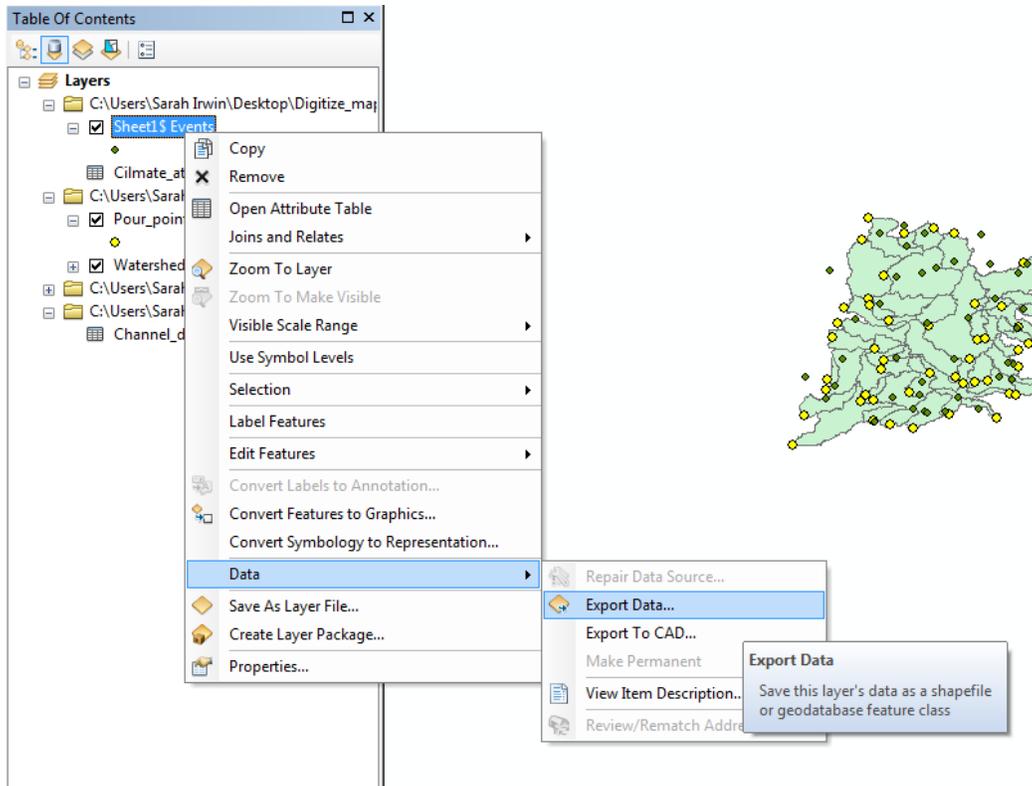


Figure 14: Process for converting a feature layer to a shape-file in ArcMap.

16. Employ the *Buffer* function of the *Proximity* section of the *Analysis* toolbox to create a buffer around the points of the Climate Station layer in order to represent their influence areas; search *Buffer (Analysis)*. Use the Climate Station shape-file as input to this function and specify an appropriate area of influence.

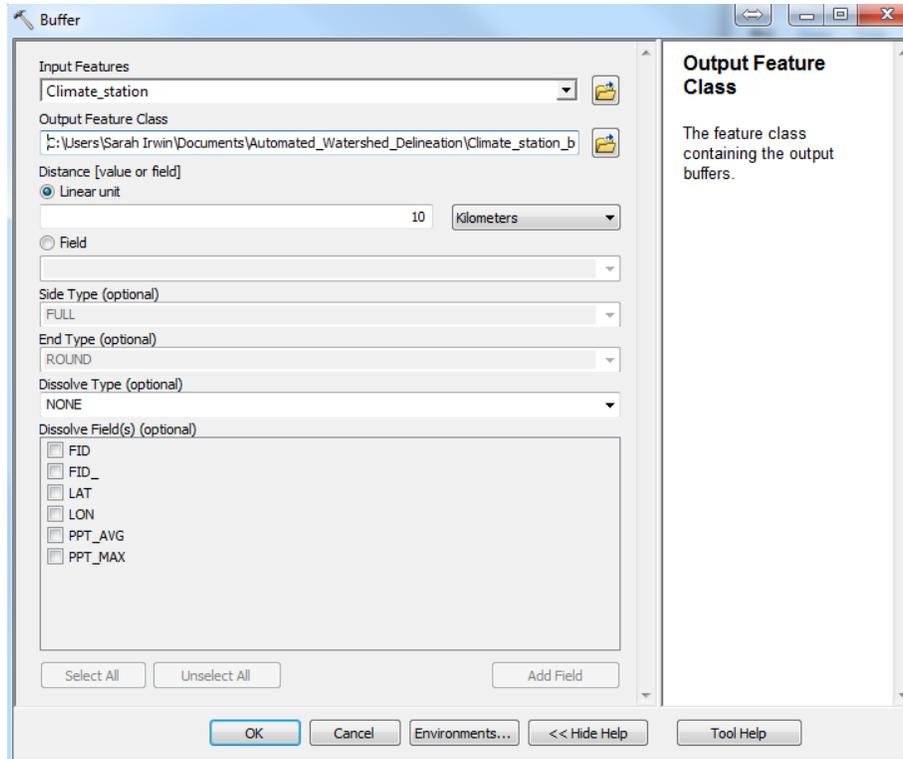


Figure 15: Buffer function of the Analysis toolbox in ArcMap.

17. Assign meteorological attributes to the Watershed Polygon layer using the *Spatial Join* function of the *Overlay* section of the *Analysis* toolbox; search *Spatial Join (Analysis)*. This function assigns the attributes of one feature layer to another based on their spatial relationship. Select the Watershed Polygon layer as the Target Feature layer and the Climate Station layer as the Join Feature layer. Select the meteorological attributes of the Climate Station layer to be assigned to the Watershed Polygon layer in the Field Map of Join Features dialog box. Right click on each of the attributes listed in this field and select *mean* in order to assign the average values of all climate stations intersecting each polygon (ArcGIS Resource, 2013).

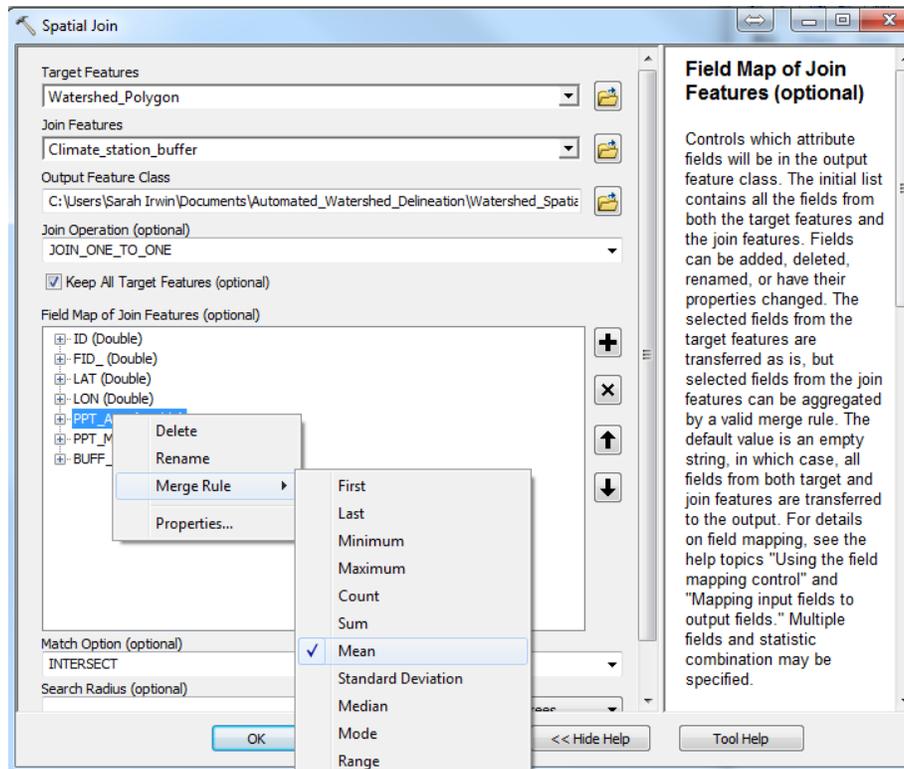


Figure 16: Spatial Join function of the Analysis toolbox in ArcMap.

4. CASE STUDY

For demonstration, the methodology presented in Section 3 is applied to a case study in Southern Ontario, Canada. Watersheds are delineated and characterized with the following attributes: basin area, channel length, channel slope, average annual precipitation, maximum annual precipitation and average daily maximum temperature. This section includes a description of the data used, a brief explanation of the procedure, a discussion of the results and a conclusion.

4.1 Data

This section provides information on the data used in the case study. **Table 1** summarizes the features, coordinate systems and sources of the data.

Table 1: Description of data used and their source.

DATA	FILE TYPE	FORMAT	SPATIAL REFERENCE	SOURCE
Fluvial Regions of Canada	Raster band	TIFF-file	N/A	Natural Resources Canada https://www.nrcan.gc.ca/home
Canadian Digital Elevation Data	Raster	USGSDEM-file	GCS North America 1983	GeoBase http://www.geobase.ca/geobase/en/
HYDAT Database Canada	Vector	Shape-file	GCS North America 1983	Environment Canada http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1
Canadian Daily Climate Data	N/A	CSV-file	N/A	Environment Canada http://climate.weather.gc.ca/index_e.html

The Fluvial Regions of Canada map was created by Ashmore and Church (2001); see **Figure 17**. It divides Canada into several fluvial regions based on their climate, topography, geology and surficial materials. Each region has similar flood generation processes; although they are too large to be considered hydrologically homogeneous. They do, however, provide practical study area boundaries for the regionalization procedure and as such, the Great Lakes fluvial region which covers Southern Ontario is used to define the study area in this investigation. The map is available online from the Natural Resources Canada website as a PDF-file (see Table 1). It is converted to a TIFF-file in order to be uploaded into ArcMap. The electronic version of the map is not geographically referenced.

particularly affects watershed characterization including the basin area, channel length and channel slope of the resultant watersheds. Alacron (2006) found that high resolution DEMs outperformed low resolution DEMs for watershed delineation in flat regions, where low resolution DEMs tended to overestimate the channel length and slope. In addition, he found that watersheds were more segregated when delineated from low resolution DEMs resulting in smaller basin areas. All DEM files are downloaded from the GeoBase website. Geobase provides free, high quality geospatial data for Canada. GeoBase was adopted by the Canadian Council of Geomatics in October 2001 and its data is provided by several stakeholders (GeoBase, 2013).

A map of Canadian flow gauge stations and their associated discharge data is available from the HYDAT (hydrometric data) database distributed by Environment Canada, (Environment Canada, 2013). The database contains daily and monthly mean flow data, water levels and sediment concentrations measured at each flow gauge station. A shape-file containing the locations of the flow gauge stations as point features is used in this study.

Daily precipitation and temperature data are available as CSV-files from the Canadian Daily Climate Data (CDCD) archive of Environment Canada for climate stations across the country. The data is imported into MATLAB where a script is employed to retain all climate stations which have complete precipitation and temperature records for the 1981-2000 time period. The station's name, geographical coordinates, average annual precipitation, maximum annual precipitation and average daily maximum temperature data are written to a Microsoft Excel spreadsheet.

4.2 Procedure

Prior to delineating and characterizing watersheds the study area is defined. In order to do this the Fluvial Regions of Canada TIFF-file is imported into ArcMap where it is geographically referenced using several tools on the *Georeferencing* toolbar. First the TIFF file is assigned a geographical coordinate system to match the DEM files, which is the North America 1983 system. The map is then imported into ArcMap and the geographical coordinates of several known control points are assigned to the unreferenced map using the *Add Control Points* function of the *Georeferencing* toolbar. The locations of the five control points are obtained by hovering the cursor over a referenced map of Ontario in ArcMap such that their latitude and longitude are displayed in the bottom right hand corner of the program. The control points are shown as cross-hairs in **Figure 18**. The *Link Table* function of the *Georeferencing* toolbar is opened and the *Auto Adjust* option is selected in order to update the geographical transformation. Once the transformation is updated according to the coordinates of the control points, the root mean square (RMS) error is checked to ensure it is reasonable. It should be noted that the Fluvial Regions of Canada map is georeferenced in order to define a study area for the watersheds to be delineated within. As such, the accuracy of the georeferencing procedure as indicated by the RMS error results does not have a significant impact on the final results of this work. The RMS error for the transformation is 0.0212 decimal degrees which is fairly insignificant given the map covers such a large area.



Figure 18: Four control points for georeferencing procedure are shown as the red and green crosshairs.

After the study area is defined the watersheds are delineated following the methodology outlined in section 3.1. The areas of flow accumulation within the study area are defined following steps 1 through 5 of the methodology. When importing the GeoBase DEM files into ArcMap, the raster calculator is employed to multiply each layer by 1 in order to standardize the range of elevations. The Pour Points layer is created using step 6. The HYDAT shape-file showing the locations of the hydrometric stations in Canada is imported into ArcMap, and the pour points are digitized such that they coincide with the flow gauge stations in step 8. The pour points and hydrometric stations are located directly on the raster cells of flow accumulation; this is essential to the watershed delineation procedure. The watersheds are delineated upstream of the pour points using step 9 of the methodology and the results are shown in **Figure 19**. The watersheds are characterized following steps 11 through 17 of the methodology. The stream links are used to determine the main channel lengths as shown in **Figure 20**, and a distribution of the climate stations and their influence areas are shown in **Figure 21**. A 15km radius is selected to represent the climate station's area of influence; this value is chosen in order to cover the entire study area and ensure that each watershed polygon is assigned climate attributes.

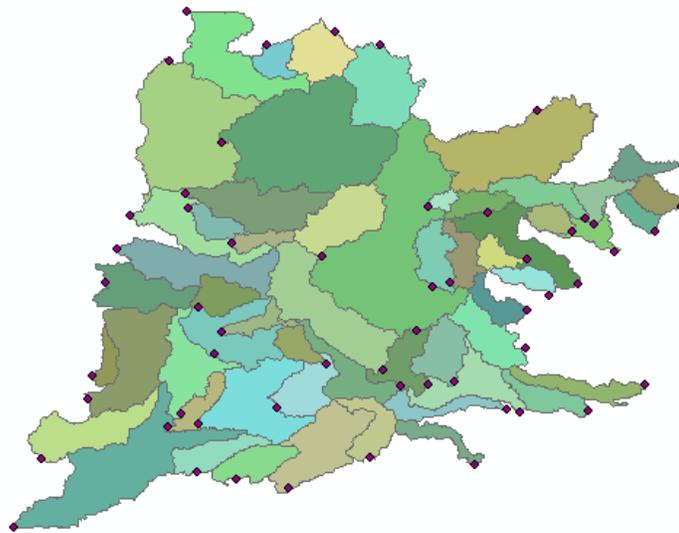


Figure 19: Watersheds are shown as blue polygons which are delineated upstream of yellow pour points.

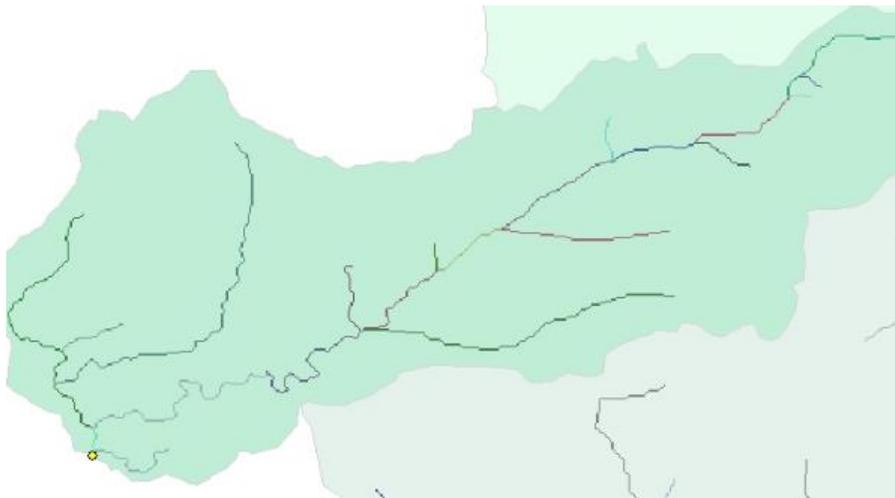


Figure 20: Stream links of the channel network are differentiated by colour.

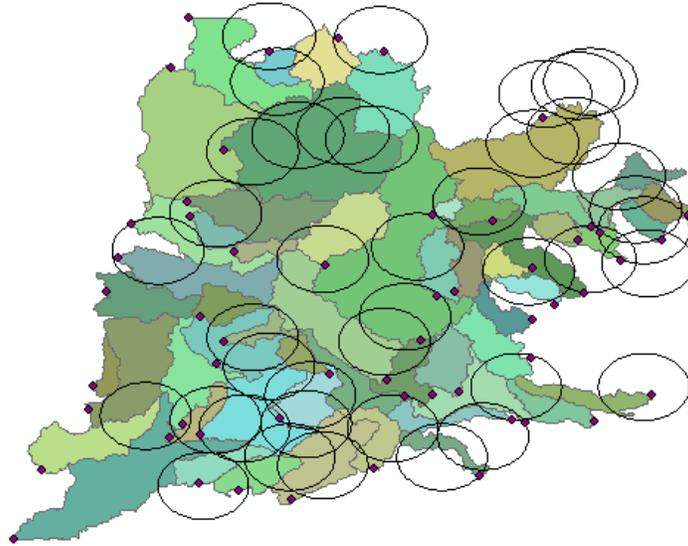


Figure 21: Climate stations (green points) and their 15km area of influence (circle area) are shown here.

4.3 Results and Discussion

The magnitude of each attribute field is plotted in **Figure 22** through **Figure 25** in order to observe their spatial patterns. In **Figure 22** and **Figure 23** the distribution of average and maximum annual precipitation are shown, respectively. Watersheds which experience higher volumes of precipitation are shown in red, while watersheds which experience lower volumes of precipitation are shown in green and precipitation is measured in millimeters. Evidently, watersheds located in the Northwestern part of Southern Ontario receive higher volumes of precipitation and watersheds located in the Eastern part of Southern Ontario receive lower volumes of precipitation for both average and maximum values.

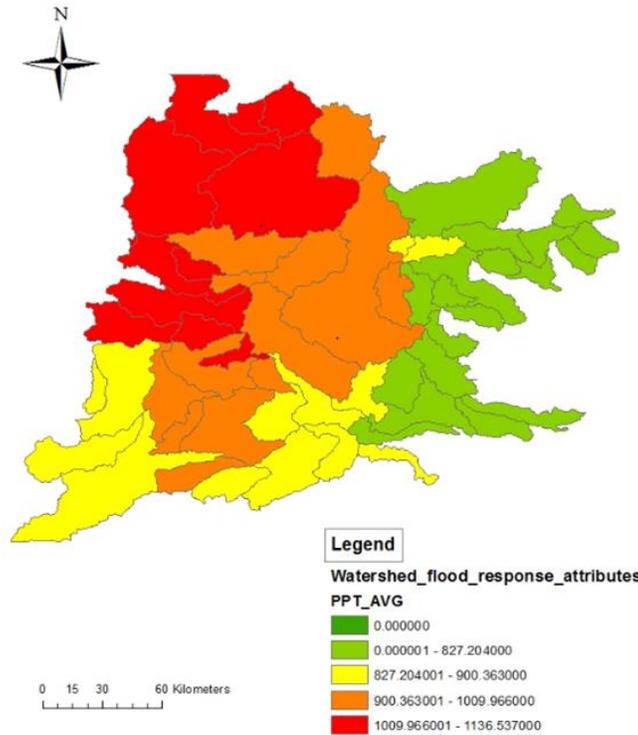


Figure 22: Distribution of average annual precipitation over watersheds in Southern Ontario.

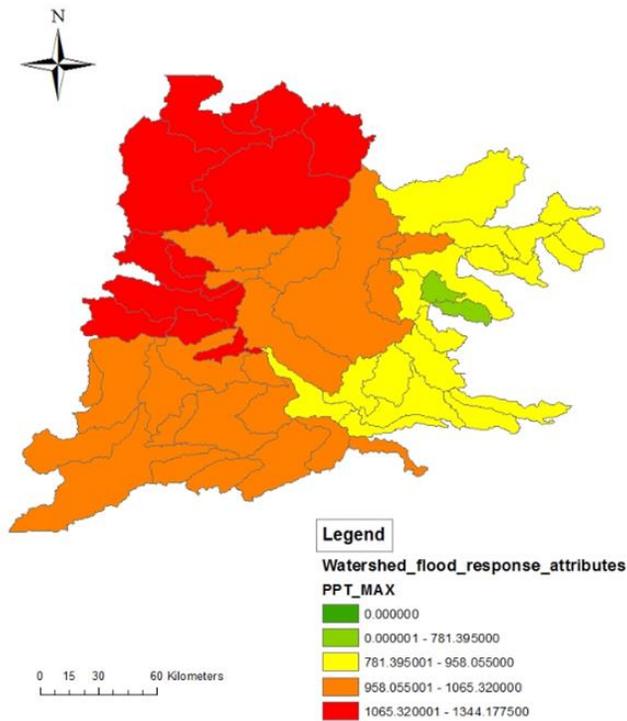


Figure 23: Distribution of maximum annual precipitation over watersheds in Southern Ontario.

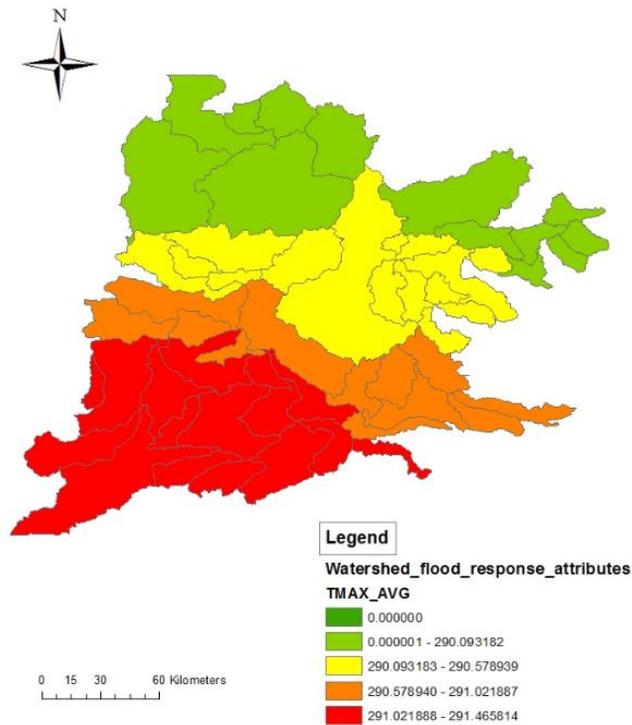


Figure 24: Distribution of average daily maximum temperature over watersheds in Southern Ontario.

The distribution of average daily maximum temperature values are shown in **Figure 24**. Here the results make sense as Southern watersheds that are located closer to the Earth's equator experience higher values of average daily maximum temperature and Northern watersheds experience lower values of average daily maximum temperature, and the distribution is fairly linear. Temperature is measured in degrees Kelvin.

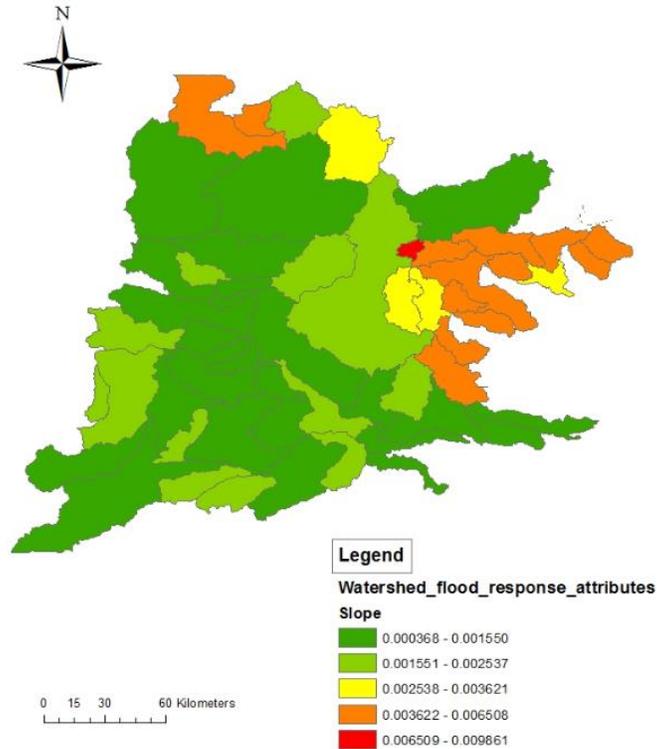


Figure 25: Distribution of main channel slope over watersheds in Southern Ontario.

In **Figure 25** the distribution of the channel slope is presented. Evidently, most of the watersheds delineated in Southern Ontario have a relatively mild channel slope of less than 0.3% as indicated by the substantial number of green watersheds. The watersheds containing channels with steeper slopes are located in the Eastern part of Southern Ontario which makes sense because the Niagara Escarpment is located here. The basin area and channel length attributes have also been omitted from this discussion since their distribution can be determined by the shape and size of the watershed boundaries.

Watershed_flood_response_attributes								
	FID	PPT_AVG	PPT_MAX	TMAX_AVG	TMAX_MAX	Basin_Area	Channel Length	Slope
▶	0	978.534	1117.05	289.564044	290.543982	4209.901524	20160	0.003621
	1	1136.537	1344.1775	289.568263	290.538847	171816392.632	41670	0.004776
	2	1059.998667	1264.11	289.579551	290.553975	396227554.173	11070	0.002168
	3	1136.537	1344.1775	289.568263	290.538847	792593618.64	44100	0.006508
	4	969.966	1153.22	289.777969	290.771315	680875733.102	29160	0.003326
	5	813.012	928.98	289.932638	290.897342	177351288.26	<Null>	<Null>
	6	0	0	0	0	4240.759373	<Null>	<Null>
	7	802.73475	894.95625	289.735065	290.718941	1269587831.24	56880	0.001336
	8	1087.067714	1235.098571	289.992244	290.978628	1997946979.65	92520	0.001221
	9	1103.5084	1274.154	289.962919	290.930883	1595180181.19	59040	0.00105
	10	858.616	1011.195	290.270786	291.248764	62501803.2531	7200	0.009861
	11	807.7315	902.205	289.981064	290.944716	184212124.022	21150	0.004539
	12	852.586	980.383333	290.226744	291.202197	185779447.121	15480	0.005685
	13	816.9104	945.474	290.093182	291.061227	314478736.152	53640	0.004903
	14	804.329333	903.981667	290.045262	291.009868	203516220.063	35370	0.004354
	15	771.6852	865.764	290.020015	290.982264	136062718.802	15750	0.005016
	16	953.786	1054.05	290.537961	291.520776	696148368.141	53820	0.001505
	17	797.525	907.535	290.173657	291.140172	157049583.211	16830	0.005704
	18	1079.089	1215.505	290.578939	291.558652	177755357.322	38250	0.001699
	19	779.068	877.698571	290.063912	291.02738	149335873.249	23670	0.003042
	20	953.786	1054.05	290.537961	291.520776	128623360.69	26370	0.001441
	21	947.85	1032.315	290.503317	291.483378	579952509.439	42570	0.002537
	22	1079.089	1215.505	290.578939	291.558652	513639083.445	69120	0.001085
	23	574.448	729.88	290.349343	291.31499	145410261.366	15120	0.00496
	24	771.459	900.041667	290.28758	291.255966	524927780.291	61380	0.00448
	25	763.893333	917.423333	290.296972	291.270839	239341284.27	33930	0.003065
	26	935.27	1031.64	290.409039	291.386346	310876821.76	34470	0.003568

Figure 26: Attribute table showing the characteristics for each watershed.

The objective of this study is to delineate watersheds in Southern Ontario such that there is a flow gauge station located at their outlets and subsequently, to assign their meteorological and physiographic attributes which influence regional flood response. As such, the most important result of this work is the attribute table associated with the Watershed Polygon layer; a sample of the attribute table is shown in **Figure 26**. The table summarizes the physiographic and meteorological attributes assigned to each watershed which can be directly employed in the regionalization procedure to form regions of homogeneous flood response as discussed in the introduction of this paper.

5. CONCLUSION

This report demonstrates how to delineate and characterize watersheds using ArcGIS software for the purpose of regional flood frequency analysis. A step-by-step methodology is provided, which is then applied to a case study in Southern Ontario. The results of this methodology can be directly applied in regionalization studies where watersheds are grouped into homogeneous hydrologic regions based on the similarity of their attributes.

The effect of the DEM resolution on the watershed characterization results has been identified. In the case study low resolution DEM data has been employed in order to reduce computational time and storage requirements. In future studies, however, it is recommended to employ high resolution DEM data as it tends to provide more accurate results in terms of channel length and channel slope, particularly in flat regions. Application of high resolution DEM files is especially beneficial in Southern Ontario since much of the region is characterized by mild channel slopes and low relief. This report provides a basis for watershed delineation and characterization to prepare for regional flood frequency analysis; however it can be extended to assign additional attributes to the watershed polygons including soil type and land use indices which have strong influences on regional flood response, in order to obtain enhanced results.

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APPENDIX: PREVIOUS REPORTS IN THE SERIES

In addition to the following publications, there are 65 reports (no. 01 – no. 065) prior to 2010.

(1) Leanna King, Tarana Solaiman, and Slobodan P. Simonovic (2010). Assessment of Climatic Vulnerability in the Upper Thames River Basin: Part 2. Water Resources Research Report no. 066, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 72pages. ISBN: (print) 978-0-7714-2834-0; (online) 978-0-7714-2835-7.

(2) Christopher J. Popovich, Slobodan P. Simonovic and Gordon A. McBean (2010). Use of an Integrated System Dynamics Model for Analyzing Behaviour of the Social-Economic-Climatic System in Policy Development. Water Resources Research Report no. 067, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 37 pages. ISBN: (print) 978-0-7714-2838-8; (online) 978-0-7714-2839-5.

(3) Hyung-II Eum and Slobodan P. Simonovic (2009). City of London: Vulnerability of Infrastructure to Climate Change; Background Report 1 – Climate and Hydrologic Modeling. Water Resources Research Report no. 068, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 102pages. ISBN: (print) 978-0-7714-2844-9; (online) 978-0-7714-2845-6.

(4) Dragan Sredojevic and Slobodan P. Simonovic (2009). City of London: Vulnerability of Infrastructure to Climate Change; Background Report 2 – Hydraulic Modeling and Floodplain Mapping. Water Resources Research Report no. 069, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 147 pages. ISBN: (print) 978-0-7714-2846-3; (online) 978-0-7714-2847-0.

(5) Tarana A. Solaiman and Slobodan P. Simonovic (2011). Quantifying Uncertainties in the Modelled Estimates of Extreme Precipitation Events at the Upper Thames River Basin. Water Resources Research Report no. 070, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 167 pages. ISBN: (print) 978-0-7714-2878-4; (online) 978-0-7714-2880-7.

(6) Tarana A. Solaiman and Slobodan P. Simonovic (2011). Assessment of Global and Regional Reanalyses Data for Hydro-Climatic Impact Studies in the Upper Thames River Basin. Water Resources Research Report no. 071, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 74 pages. ISBN: (print) 978-0-7714-2892-0; (online) 978-0-7714-2899-9.

(7) Tarana A. Solaiman and Slobodan P. Simonovic (2011). Development of Probability Based Intensity-Duration-Frequency Curves under Climate Change. Water Resources Research Report no. 072, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 89 pages. ISBN: (print) 978-0-7714-2893-7; (online) 978-0-7714-2900-2.

- (8) Dejan Vucetic and Slobodan P. Simonovic (2011). Water Resources Decision Making Under Uncertainty. Water Resources Research Report no. 073, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 143 pages. ISBN: (print) 978-0-7714-2894-4; (online) 978-0-7714-2901-9.
- (9) Angela Peck, Elisabeth Bowering and Slobodan P. Simonovic (2010). City of London: Vulnerability of Infrastructure to Climate Change, Final Report - Risk Assessment. Water Resources Research Report no.074, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 66 pages. ISBN: (print) 978-0-7714-2895-1; (online) 978-0-7714-2902-6.
- (10) Akhtar, M. K., S. P. Simonovic, J. Wibe, J. MacGee, and J. Davies, (2011). An integrated system dynamics model for analyzing behaviour of the social-energy-economic-climatic system: model description. Water Resources Research Report no. 075, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 211 pages. ISBN: (print) 978-0-7714-2896-8; (online) 978-0-7714-2903-3.
- (11) Akhtar, M. K., S. P. Simonovic, J. Wibe, J. MacGee, and J. Davies, (2011). An integrated system dynamics model for analyzing behaviour of the social-energy-economic-climatic system: user's manual. Water Resources Research Report no. 076, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 161 pages. ISBN: (print) 978-0-7714-2897-5; (online) 978-0-7714-2904-0.
- (12) Millington, N., S. Das and S. P. Simonovic (2011). The Comparison of GEV, Log-Pearson Type 3 and Gumbel Distributions in the Upper Thames River Watershed under Global Climate Models. Water Resources Research Report no. 077, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 53 pages. ISBN: (print) 978-0-7714-2898-2; (online) 978-0-7714-2905-7.
- (13) Andre Schardong and Slobodan P. Simonovic (2012). Multi-objective Evolutionary Algorithms for Water Resources Management. Water Resources Research Report no. 078, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 167 pages. ISBN: (print) 978-0-7714-2907-1; (online) 978-0-7714-2908-8.
- (14) Samiran Das and Slobodan P. Simonovic (2012). Assessment of Uncertainty in Flood Flows under Climate Change: the Upper Thames River basin (Ontario, Canada). Water Resources Research Report no.079, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 67 pages. ISBN: (print) 978-0-7714-2960-6; (online) 978-0-7714-2961-3.
- (15) Rubaiya Sarwar, Sarah E. Irwin, Leanna M. King and Slobodan P. Simonovic (2012). Assessment of Climatic Vulnerability in the Upper Thames River basin: Downscaling with SDSM. Water Resources Research Report no. 080, Facility for Intelligent Decision Support,

Department of Civil and Environmental Engineering, London, Ontario, Canada, 65 pages. ISBN: (print) 978-0-7714-2962-0; (online) 978-0-7714-2963-7.

(16) Sarah E. Irwin, Rubaiya Sarwar, Leanna King and Slobodan P. Simonovic (2012). Assessment of Climatic Vulnerability in the Upper Thames River basin: Downscaling with LARS-WG. Water Resources Research Report no. 081, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 80 pages. ISBN: (print) 978-0-7714-2964-4; (online) 978-0-7714-2965-1.

(17) Samiran Das and Slobodan P. Simonovic (2012). Guidelines for Flood Frequency Estimation under Climate Change. Water Resources Research Report no. 082, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 44 pages. ISBN: (print) 978-0-7714-2973-6; (online) 978-0-7714-2974-3.

(18) Angela Peck and Slobodan P. Simonovic (2013). Coastal Cities at Risk (CCaR): Generic System Dynamics Simulation Models for Use with City Resilience Simulator. Water Resources Research Report no.083, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 55 pages. ISBN: (print) 978-0-7714-3024-4; (online) 978-0-7714-3025-1.

(19) Abhishek Gaur and Slobodan P. Simonovic (2013). Climate Change Impact on Flood Hazard in the Grand River Basin, London, Ontario, Canada. Water Resources Research Report no. 084, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 92 pages. ISBN: (print) 978-0-7714-3063-3; (online) 978-0-7714-3064-0.

(20) Roshan Srivastav and Slobodan P. Simonovic (2014). Generic Framework for Computation of Spatial Dynamic Resilience. Water Resources Research Report no. 085, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 81 pages. ISBN: (print) 978-0-7714-3067-1; (online) 978-0-7714-3068-8.

(21) Angela Peck and Slobodan P. Simonovic (2014). Spatial System Dynamics: Coupling System Dynamics with Geographic Information Systems DRAFT REPORT. Water Resources Research Report no. 086, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 60 pages. ISBN: (print) 978-0-7714-3069-5; (online) 978-0-7714-3070-1.