Categorizing River Networks into Functional Process Zones using Geographic Information Systems

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ABSTRACT

Understanding the physical properties of river networks is important for understanding their ecology and improving their management. Functional Process Zones (FPZs) are a system for categorizing streams in a watershed into different sections by measuring and grouping different geomorphological variables. In this study, I characterized the Salmon Creek Watershed in Sonoma County, California into FPZs using elevation, geology, and precipitation datasets and measure variables. I collected 9 physical variables that included variables related to climate, elevation, geology, and river valley shape from 87 sites placed every 2 km along the watershed. I then did a cluster analysis in R with a cut off of 80% dissimilarity to identify groupings and visualized the groupings using a Principal Components Analysis. I identified a total of 4 FPZs: Constrained, Open-Valley Upland, Open-Valley Lowland, and Lowland Alluvial. The results of this analysis can help inform management of the Salmon Creek Watershed as climate change and irrigation continue to impact the health of these ecosystems.

KEYWORDS

Agricultural watershed, Salmon Creek, Riverine Ecosystem Synthesis, geomorphology, ArcGIS

INTRODUCTION

The physical structure of a stream can affect the types of aquatic communities that it supports. Physical characters can influence biotic communities, ecosystem metabolism, nutrient processing, and vulnerability to human disturbances (Williams 2013). Knowledge of the physical characteristics of a stream can help inform management practices such as where to conduct restoration or which ecosystem services can be improved (Collins 2015). Physical characteristics of streams also influences the impacts of climate change on hydrology (Ficklin 2009). Concepts such as the River Continuum Concept (RCC, Vannote et al. 1980), proposed that river system dynamics can be understood by looking at physical properties as a gradient that occurs along the drainage channel. These river dynamics regulate processes such as energy input and the movement of organic matter along the watershed. However, this approach has been criticized for looking only and factors that change longitudinally along a stream and not incorporating other variables that may occur in other spatial patterns (Thorp 2006).

Riverine Ecosystem Synthesis (RES, Thorp 2006) instead emphasizes the biocomplexity of rivers as a set of repeating functional process zones (FPZs). FPZs are distinct units that divide streams into categories derived from hydrogeomorphic factors. RES deviates from the RCC by looking at rivers using a patch dynamics model as opposed to a gradually changing continuum. Different physical characteristics occur in patches instead of changing along a gradient. Different FPZs have expressed different physical properties, such as differences is riverbed sediments (Collins 2015), as well as different biological properties, such as different benthic macroinvertebrate communities (Maasri 2019). Thus far, this concept has been applied mostly to watersheds in the central United States within then Mississippi river basin (Thorp 2006; Collins 2015, 2018; Thoms 2018; Scown2017; Maasri2019; Williams 2013) as well as several watersheds in other countries (Pollice 2020, Kobayashi 2011, Schiemmer 2020, Godoy 2016). Most of these examples are very large watersheds in areas that are largely undeveloped. Few studies have characterized watersheds in rural or residential areas.

Agricultural watersheds are increasingly strained by the effects of irrigation, pollution, stream channelization, and climate change. Surface water diversion and groundwater pumping for irrigation decreases the overall waterflow of streams and also changes seasonal flow patterns (Kendy 2006). Runoff from agricultural areas often has higher concentrations of nitrogen and phosphorus, leading to eutrophication in streams. Flow patterns are also affected by different physical properties of the stream. Physical properties such as stream flow and sediment types also affect concentrations of pollutants in streams (McDowell, 2001). Stream straightening, relocation, and dredging in agricultural areas will also impact geomorphological processes in these watersheds (Urban, 2008). Additionally, agricultural watersheds are expected to be especially sensitive climate change, especially the increase in extreme weather events (Ficklin 2009). Because agricultural streams can provide different ecosystems services, farmers are becoming more interested in implementing different conservation practices (Ryan). In all these cases, understanding the physical characteristics of streams can help inform conservation practices in these watersheds.

To better understand the physical properties of agricultural watersheds, I characterized the FPZs in a small, agricultural watershed in California using 9 different variables. I determine the FPZs in this watershed and compared the results with other studies by looking at the distribution of FPZs along the watershed, the number of FPZs, and the importance of different variable in determining FPZs.

METHODS

Study Site

Salmon Creek is a coastal stream in Sonoma County that debauches into the Pacific Ocean at the coastal town of Salmon Creek. The watershed drains about ~90 square kilometers of land and includes 172 kilometers of perennial and intermittent streams segments that range in elevation from sea level to 402 meters. Salmon Creek has 6 major tributaries and links the towns of Occidental, Freestone, Bodega and Salmon Creek (Figure 1). The watershed is dominated by grazing-based agriculture and vineyards. Rural residential housing is the dominant land use in the upper part of the watershed at the towns of Occidental, Freestone, and Bodega (Figure 2, Hammack 2006).

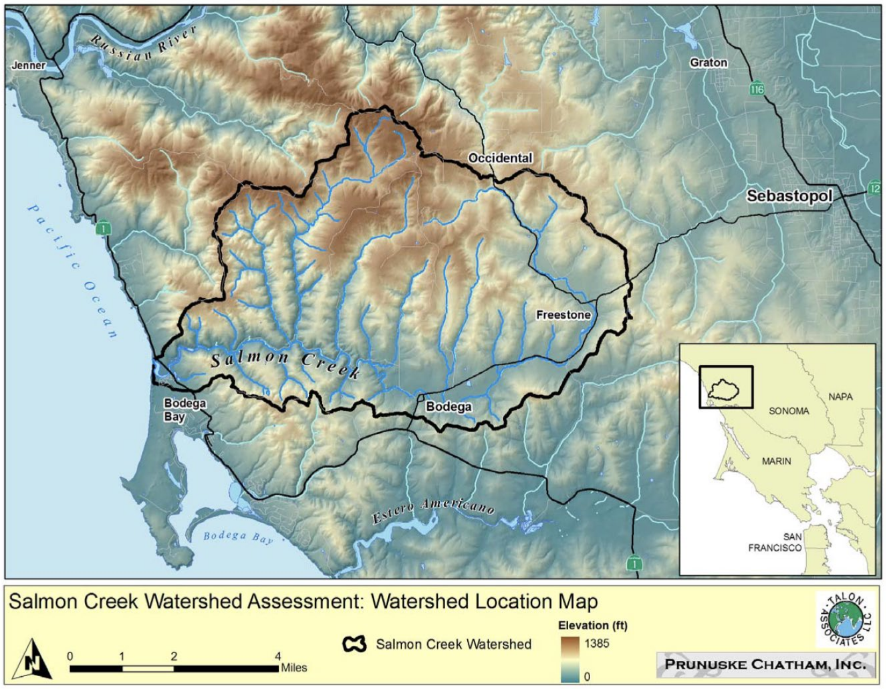


Figure 1. Salmon Creek Watershed. This map of the watershed shows streams, towns, roads, and topography as well as its position in relation to the Bay Area (Hammack 2006).

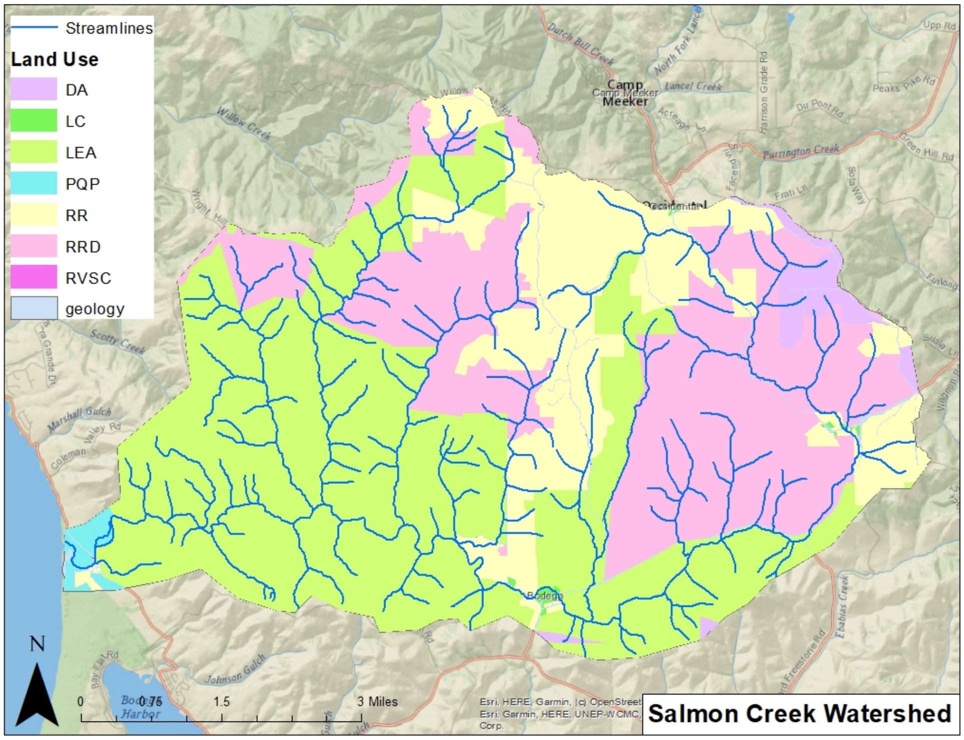
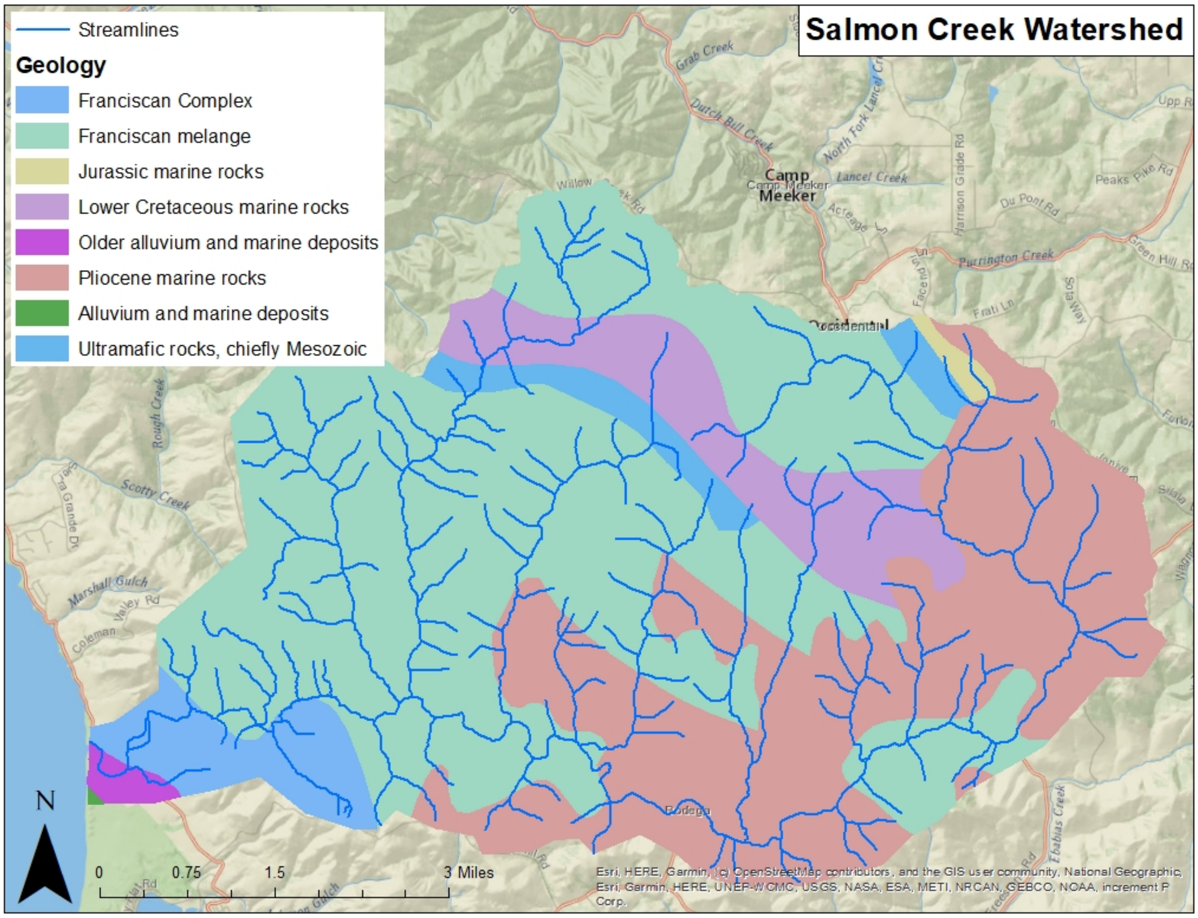


Figure 2. Land Use. This map shows land use designations from the Sonoma County GIS data download website (https://sonomacounty.ca.gov/PRMD/Administration/GIS/Geographical-Information-Systems/). The map shows the designations for the following districts: diverse agriculture (DA), limited commercial (LC), land extensive agriculture (LEA), rural residential (RR), and resources and rural development (RRD).

The geology of the watershed is mostly Franciscan complex or mélange with overlying Wilson Complex formation in the eastern part of the watershed (Figure 3). Vegetation in the watershed is dense conifer forest in the northeast with an abrupt transition to grassland when it reaches Bodega (Hammack 2006). The watershed used to have abundant Coho salmon and steelhead trout. However, decreased water flows in the stream have made it increasingly difficult for these species to return here to breed. The last Coho salmon was spotted in 1996, and there is now only a small population of steelhead that returns each year to reproduce. The watershed is also home to several endangered species, including freshwater shrimp, tidewater goby, northern spotted owls, red tree voles and southern red-legged frogs (salmoncreekwater.org).



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Figure 3. Geology. This map displays geologic data from the USGS State Geologic Map Compilation (SGMC) geodatabase clipped to the Salmon Creek Watershed boundary.

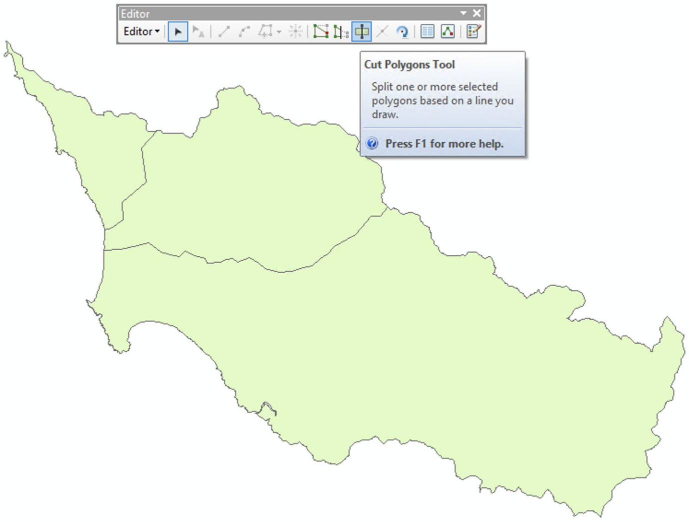
Data Collection

To determine the functional process zones in Salmon Creek, I sampled 87 sites along the creek, collecting 9 different variables: elevation (ELE), precipitation (PRE), geology (GEO), valley width (VW), valley floor width (VFW), right valley slope (RVS), left valley slope (LVS), down valley slope (DVS), and sinuosity (SIN) (Table 1).

Table 1. Variables. This table includes the 9 variables I collected in this study along with its abbreviated name and online source.

Variables:	Name	Source
Elevation	ELE	National Hydrography Dataset (NHD)
Precipitation	PRE	PRISM Research Group
Geology	GEO	US Geological Survery (USGS)
Valley Width	VW	Calculated from NHD DEM
Valley Floor Width	VFW	Calculated from NHD DEM
Right Valley Slope	RVS	Calculated from NHD DEM
Left Valley Slope	LVS	Calculated from NHD DEM
Down Valley Slope	DVS	Calculated from NHD DEM
Sinuosity	SIN	Calculated from NHD DEM

To collect the variables, I obtained watershed and boundary data from the USDA Geospatial Data Gateway (datagateway.nrcs.usda.gov), and streamline data from the National Hydrography Dataset Plus program (www.usgs.gov/core-science-systems/ngp/national-hydrography). Because the watershed boundary data included three different watersheds, I separated the salmon creek watershed on ArcGIS using the cut polygons tool (Figure 4). For all layers, I used NAD 1983 UTM Zone 10N projection.



Cut Polygons Tool

Split one or more selected polygons based on a line you draw.

Press F1 for more help.

Figure 4. Cut Polygons Tool. This figure demonstrates how I separated the Salmon Creek watershed from the larger watershed polygon.

To select study sites, I placed a point every 1km along the stream network. Using the construct points tool on the editor toolbar I set the distance between points at 1 kilometer and generated a point layer. These sample sites were saved as a new point shapefile (Figure 5). There was a total of 173 points, but I sampled every other site for a total of 87 sites.

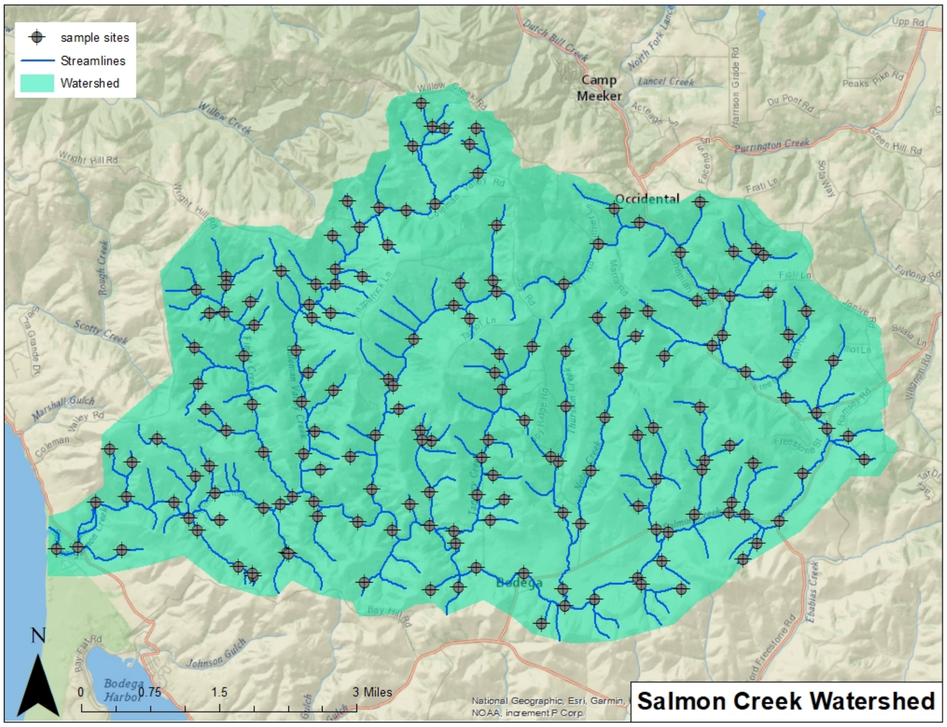


Figure 5. Sample sites. This figure shows the 173 sample sites generated from placing one point every one kilometer along the stream layer.

For the elevation, geology, and precipitation data, I downloaded the data layers from online, reprojected them, and clipped them to the watershed boundary layer. For the ELE and PRE variables, I used the Spatial Analysit Tool: Extract Values to Point to extract pixel value at each from the elevation and precipitation rasters. Geology for each point was obtained using a spatial join.

For the remaining five variables (VW, VFW, RVS, LVS, and DVS), I measured these at each sample site using the 3D-analyst toolbar and the digital elevation model. At each sample site, I used the Interpolate Line tool to draw a line perpendicular to the stream, generating a profile graph for the river valley (Figure 6). I then exported the points on the profile graph to excel and used them to calculate valley width (VW), valley floor width (VFW), right valley slope (RVS), and left valley slope (LVS) (Figure 7). To stay consistent, RVS and LVS were defined as the right and left sides of the valley when facing downstream. To calculate down valley slope (DVS), I used the interpolate line graph to draw another line perpendicular to the stream and generated a profile graph (Figure 8). The points were then exported to excel, and I calculated the average slope 100 meters upstream and downstream from the sample site. To calculate sinuosity (SIN), I took the two points from the profile graph, about 100 meters upstream and downstream from the sample site, and I measured the straight-line distance between them. Then I divided the distance along the stream with the straight-line distance to get the sinuosity value (Figure 9).

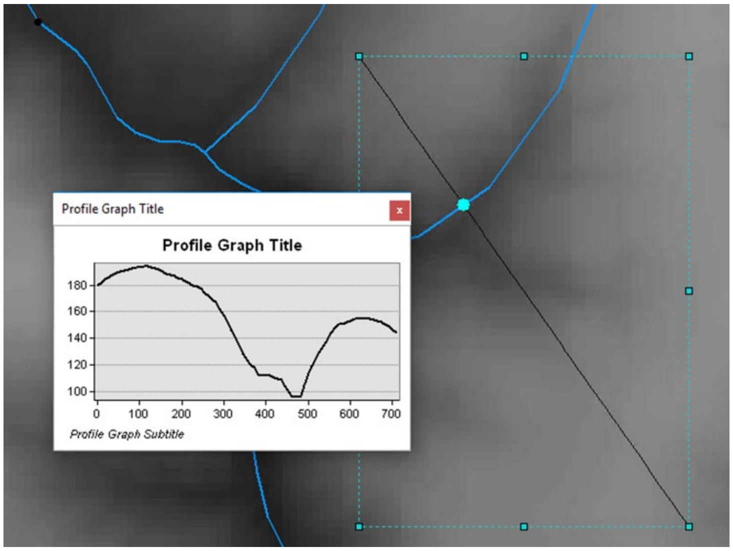


Figure 6. Perpendicular Profile Graph. At each site that I sampled, a profile graph drawn perpendiculat the stream was generated from the DEM layer. This graph was then exported to Microsoft Excel to calculate VW, VFW, RVS, and LVS. The example here is of site 10 out of 173 sites.

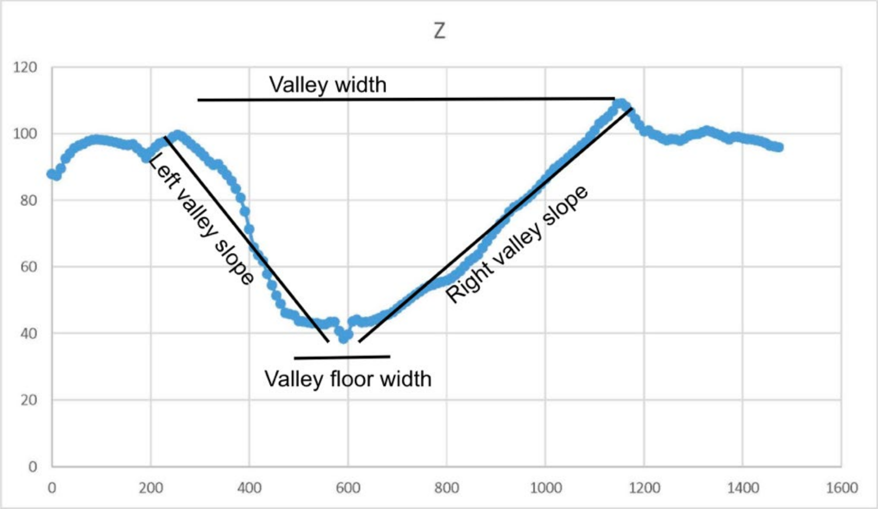


Figure 7. Profile Graph Measurements. Once the profile graph points were exported to excel, I calculate these four variables.

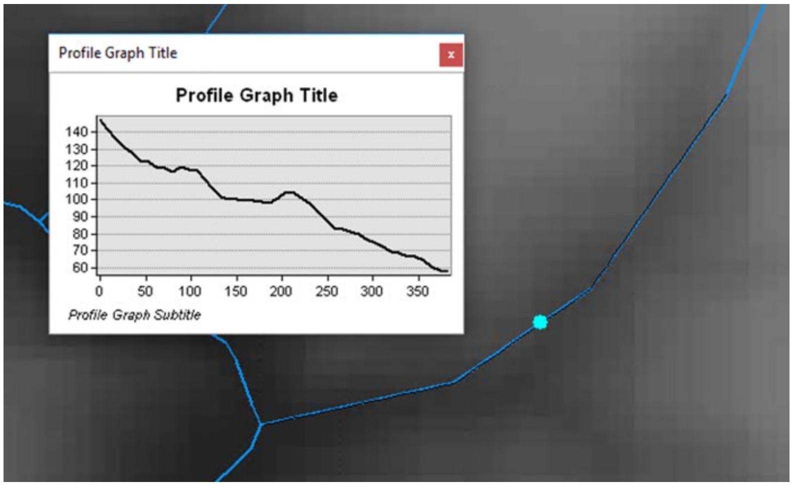


Figure 8. Parallel Profile Graph. A second profile graph was generated following the stream line 100 meters upstream and downstream from the site. This was used to calculate DVS and SIN. This figure depicts the graph for site 10 of 173 sites.

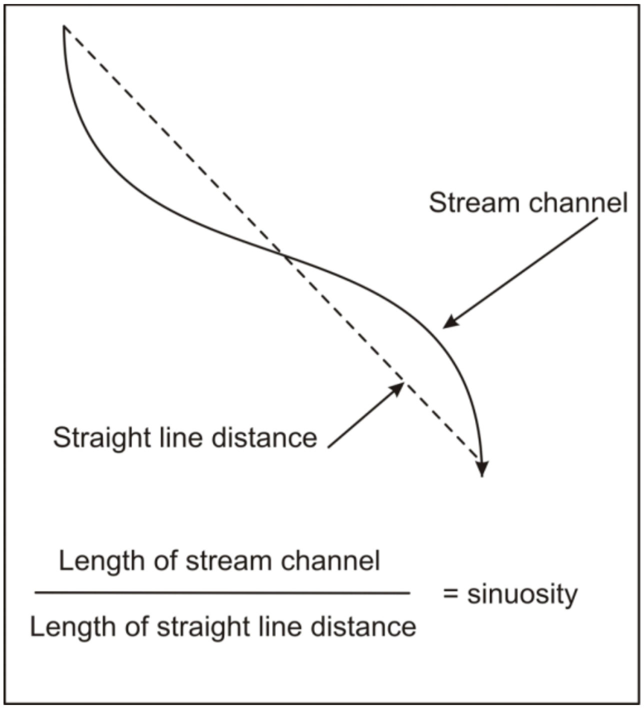


Figure 9. Sinuosity. SIN was calculated by taking the distance measure on the profile graph (length of stream channel) and dividing it by the straight line distanced measured on ArcGIS using the measurement tool.

For the actual process of sampling points, first I sampled 21 points and did a cluster analysis on those as a pilot study of the method. Next I sampled 66 more points for a total of 87 and did a cluster analysis for all 87 points.

FPZ grouping

To determine FPZ groupings for the watershed, I used a hierarchical cluster analysis of the 87 sampled points using the 9 FPZ variables. I used cutoff of 0.8 dissimilarity for designating clusters. I also conducted a Principal Components Analysis to reduce dimensionality, visualize the points in multidimensional space, and determine the influence of FPZ variables on clusters.

After these clusters were determined, clusters were exported to a tab-deliminated file and joined with the sample sites shapefile on ArcGIS. I then mapped the sample sites and displayed them by cluster. In excel, I calculated the mean, standard deviation, and range for each variable by cluster. Based on differences in the nine variables for each cluster, along with imagery from Google Earth, I categorized the four clusters into functional process zones.

RESULTS

Cluster Analysis results

The FPZ analysis identified 4 different clusters (Figure 10). Most (90%) of the total 87 points belonged to cluster 1, 7% belong to cluster 4, 2% for cluster 2, and 1% for cluster 3. These clusters were also visualized with a. PCA analysis (add graph from PCA), showing the direction of correlation of each of the 9 variables (Figure 11).

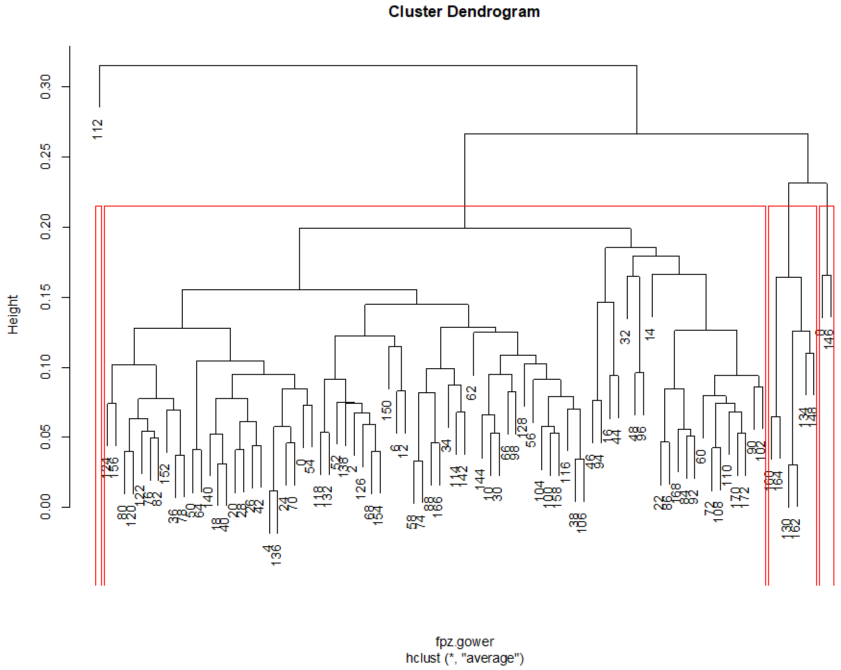


Figure 10. Cluster Dendrogram. the cluster analysis was conducted using the Gower distance. The results are displayed on a dendrogram with clusters outlined in red.

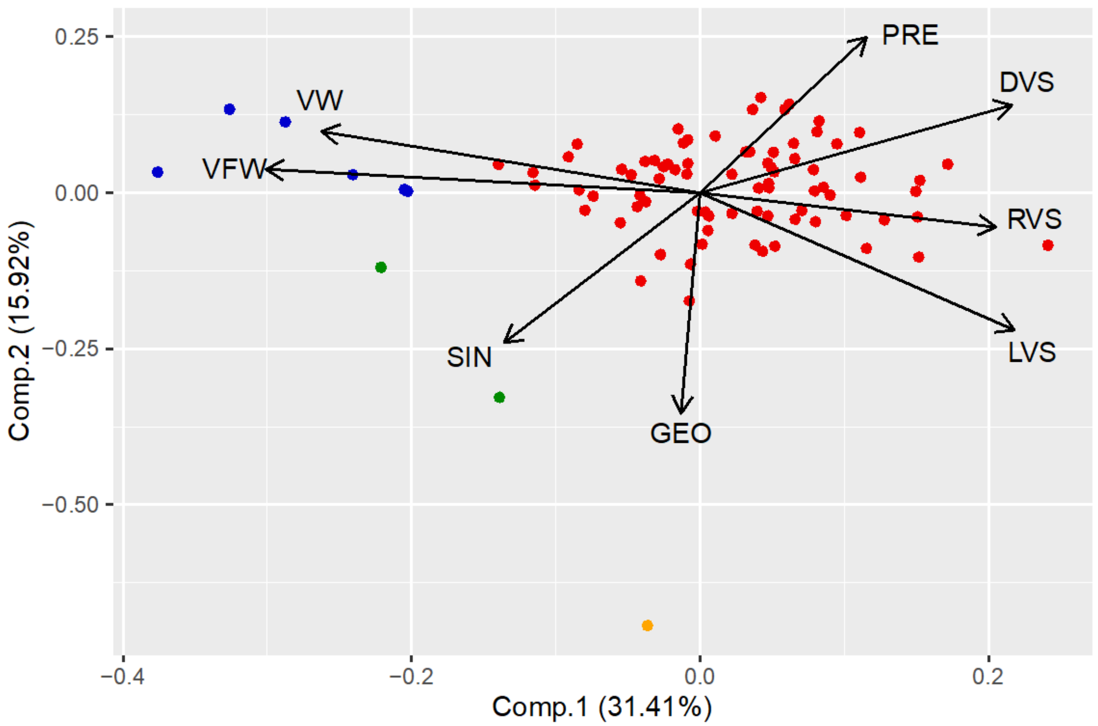


Figure 11. PCA Plot. The first two components of the principle components analysis have been plotted and colored by cluster. The arrows show the 9 different variables included in the analysis. (add color bar to match with clusters)

Cluster Locations and Characteristics

I plotted the results of the cluster analysis on the watershed map (Figure 12). Most streams are in cluster 1. Clusters 2, 3, and 4 all fall along different parts of the main stream branch. Cluster 4 is in upland areas while cluster 3 is right at the mouth and cluster 2 is somewhere in the middle. Cluster 4 streams are all first order streams in the northern part of the watershed.

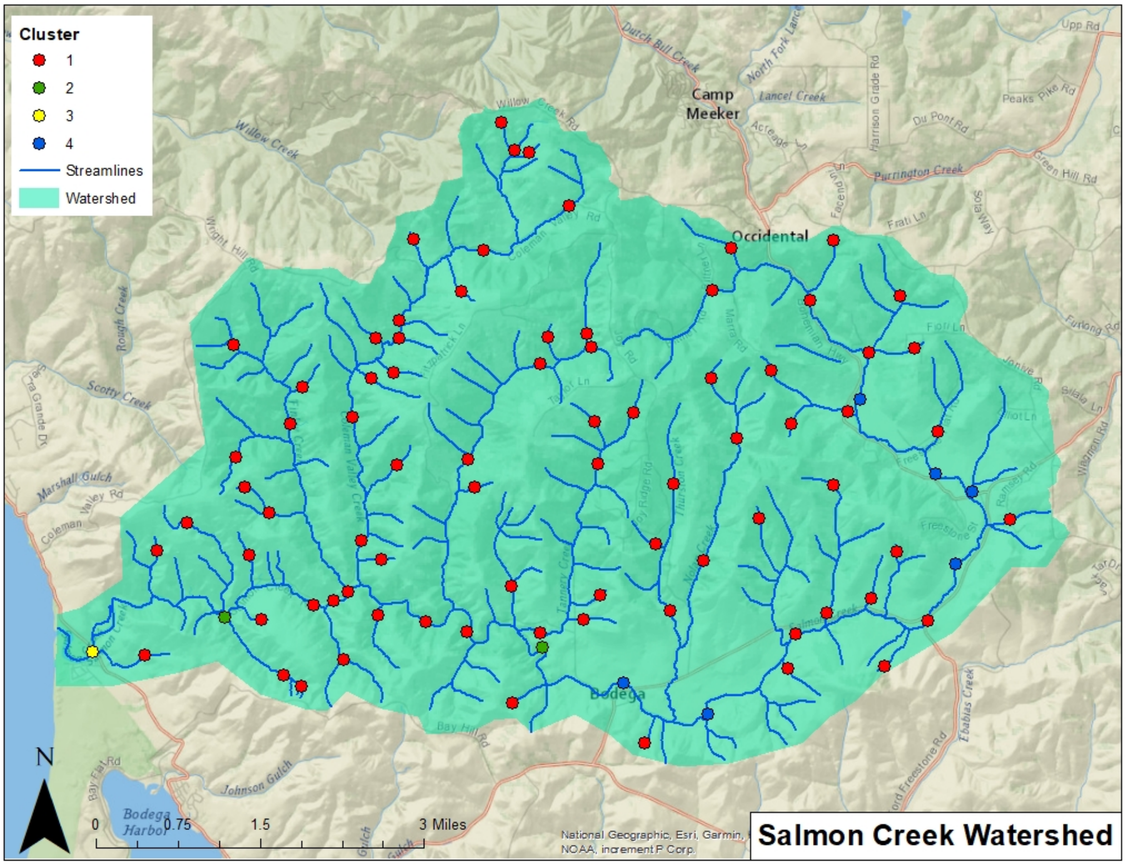


Figure 12. Clusters in the Watershed. The results of the cluster analysis were joined with the point shapefile for sample sites to display the distribution of clusters along the watershed using ArcGIS.

The results of the statistical calculations are informative to defining the geomorphic character of the FPZ (Table 2). Site in FPZ 1 tend to have high ELE, high DVS, and low SIN. This cluster includes the greatest number of sample sites, so it also has large ranges and standard deviations compared to other FPZs. FPZ 2 has much larger VF and VFW values and the lowest average DVS value as well as the highest average SIN. FPZ 3 has the lowest ELE and VW as well as a low DVS. FPZ 4 has low average RVS and LVS values. FPZ 4 also has a very wide range in VW. (reconcile this paragraph with results of PCA graph)

Table 2. Statistical Summary of Clusters. Table 2a shows the means values for each of the nine variables in the four clusters. The number of sites (out of 87 total sites) in each cluster is also displayed. Tables 2b and 2c give the mean,

standard deviation, and range for clusters 1 and 4 respectively. Clusters 2 and 3 did not have enough points to make these calcuations

Table 2a

Mean values for all clusters (no geology)

Cluster (# of sites)	ELE	PRE	VW	RVS	LVS	VFW	DVS	SIN
Cluster 1 (78)	118.07	1223.30	503.39	0.26	0.24	37.57	0.1034	1.04
Cluster 2 (2)	17.87	1033.28	877.54	0.13	0.22	131.67	-0.0088	1.41
Cluster 3 (1)	1.88	967.06	144.90	0.05	0.38	90.56	-0.0012	1.08
Cluster 4 (6)	60.39	1127.06	1341.04	0.08	0.08	273.62	0.0144	1.07

Table 2b

Cluster 1 results

	ELE	PRE	VW	RVS	LVS	VFW	DVS	SIN
Mean	118.07	1223.30	503.39	0.26	0.24	37.57	0.1034	1.04
Standard Deviation	77.56	178.69	334.33	0.18	0.11	40.52	0.0973	0.04
Range	349.35	623.52	1558.79	1.32	0.51	227.38	0.4691	0.19

Table 2c

Cluster 4 results

	ELE	PRE	VW	RVS	LVS	VFW	DVS	SIN
Mean	60.39	1127.06	1341.04	0.08	0.08	273.62	0.0144	1.07
Standard Deviation	23.51	120.86	777.97	0.05	0.03	180.78	0.0161	0.07
Range	58.65	300.39	1881.47	0.13	0.07	465.66	0.0477	0.15

FPZ Names

Based on the cluster analysis, the streams in the watershed were categorized into 4 FPZs based on the 4 clusters (Figure 13). Some patterns can also be found when these results are layered with geology (Figure 14). Cluster 4 occurs in areas with Pliocene marine rocks. FPZ 1 occurs in areas with older alluvium and marine deposits.

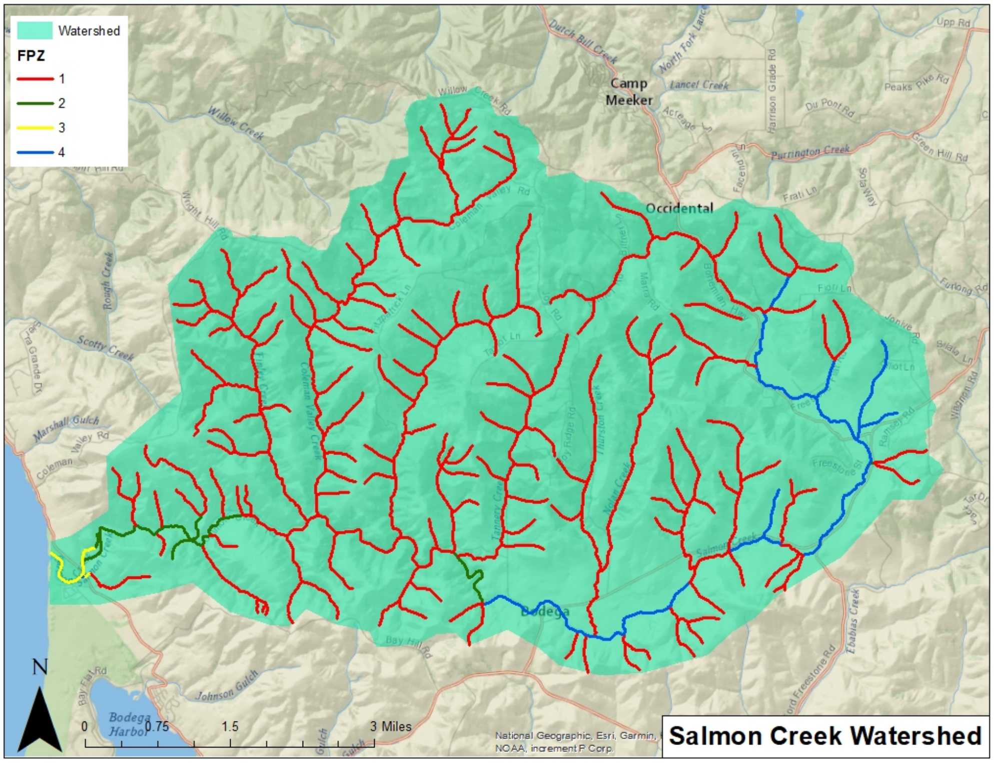


Figure 13. FPZs. This map shows the different FPZs identified in the watershed using the cluster analysis.

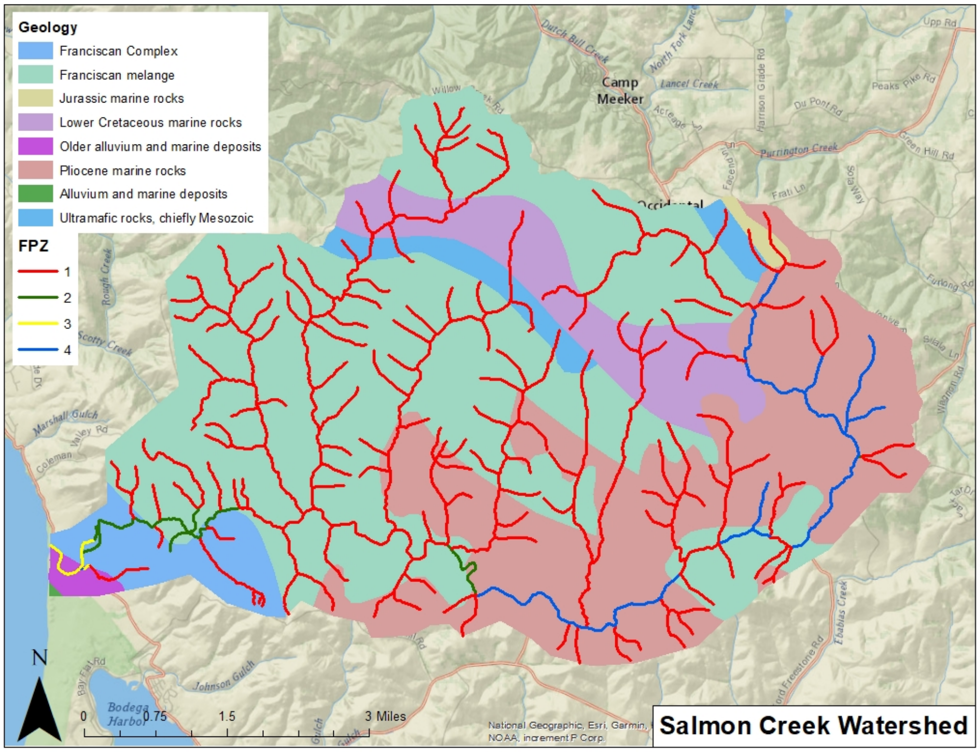


Figure 14. FPZs with Geology. This map shows the FPZs layered with the geology of the watershed.

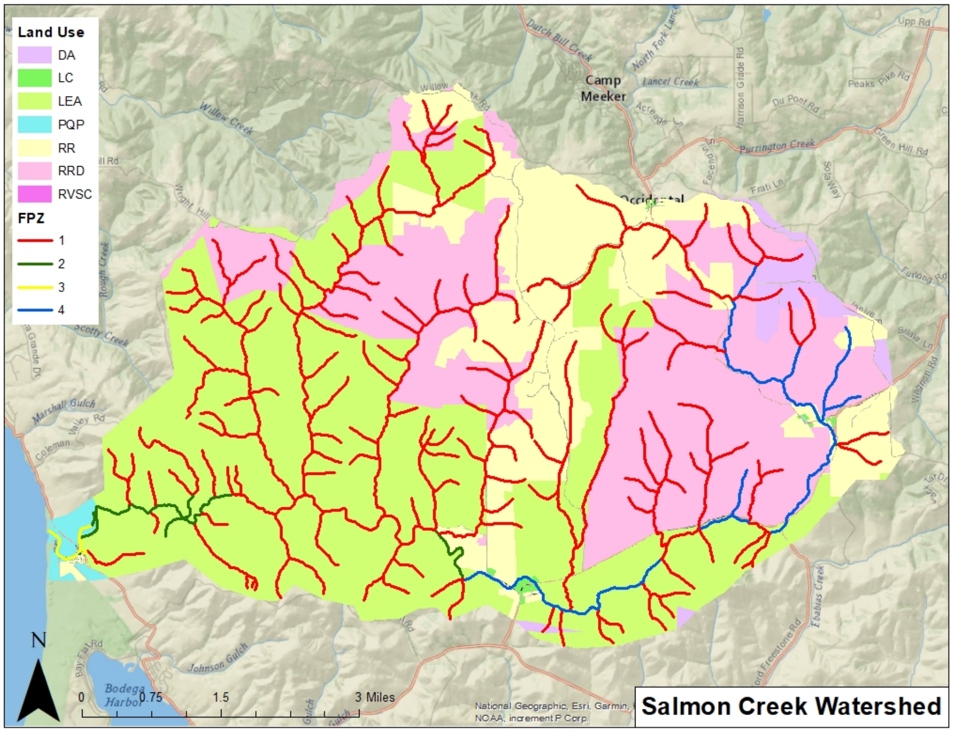
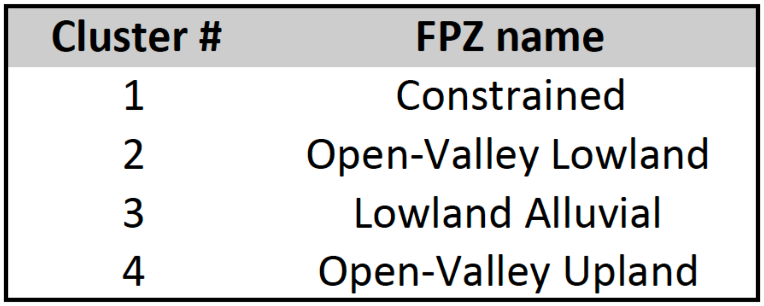


Figure 15. FPZs with Land Use. This map shows FPZs layered over land use data obtained from the Sonoma county GIS database ((https://sonomacounty.ca.gov/PRMD/Administration/GIS/Geographical-Information-Systems/). Different designations stand for the following districts: diverse agriculture (DA), limited commercial (LC), land extensive agriculture (LEA), rural residential (RR), and resources and rural development (RRD).

Based on the characteristics of each FPZ, I categorized them into partially constricted, unconstructed upland, unconstricted lowland, alluvial lowland, and constricted upland (Table 3).

Table 3. FPZ Names. The four FPZs were named based of categories given in Thorp's (2006) Riverine Ecosystem Synthesis book.



Cluster #	FPZ name
1	Constrained
2	Open-Valley Lowland
3	Lowland Alluvial
4	Open-Valley Upland

DISCUSSION

The overall goal of my project was to create an FPZ model for the Salmon Creek Watershed, and to see if this watershed would show unique physical properties because it is an agricultural watershed. I collected 9 variables from 87 sample sites along the watershed and did a cluster analysis on them with a cut off at 80% dissimilarity. This resulted in 4 clusters which I used to create and name the four FPZs in the watershed. I compared my model with those of two other studies, focusing on differences in the distribution of FPZs, the number of FPZs, and the importance of different variables in defining FPZs. Compared to other models, my model has more homogeneity in low order streams and fewer FPZs. The most important variables for defining FPZs in my model were similar to those in other models.

Distribution of FPZs

For the Salmon River in Northern California, the majority of sites fell into one FPZ. There was the most uniformity in 1st to 3rd order streams, which are all in the constrained FPZ. The other FPZs all occurred in higher order streams. I wanted to see if this pattern held true in other watersheds as well. Comparing my results with a study done on the Kanawha river basin (Figure 15), where RES was first studied, this basin appears to have more variety in low order streams. This difference could be due to the difference in size between these two watersheds. The Salmon creek watershed is about 90 square kilometers while the Kanawha river basin over 30,000 square kilometers. Because the Salmon Creek watershed is much smaller, there may just be less variation.

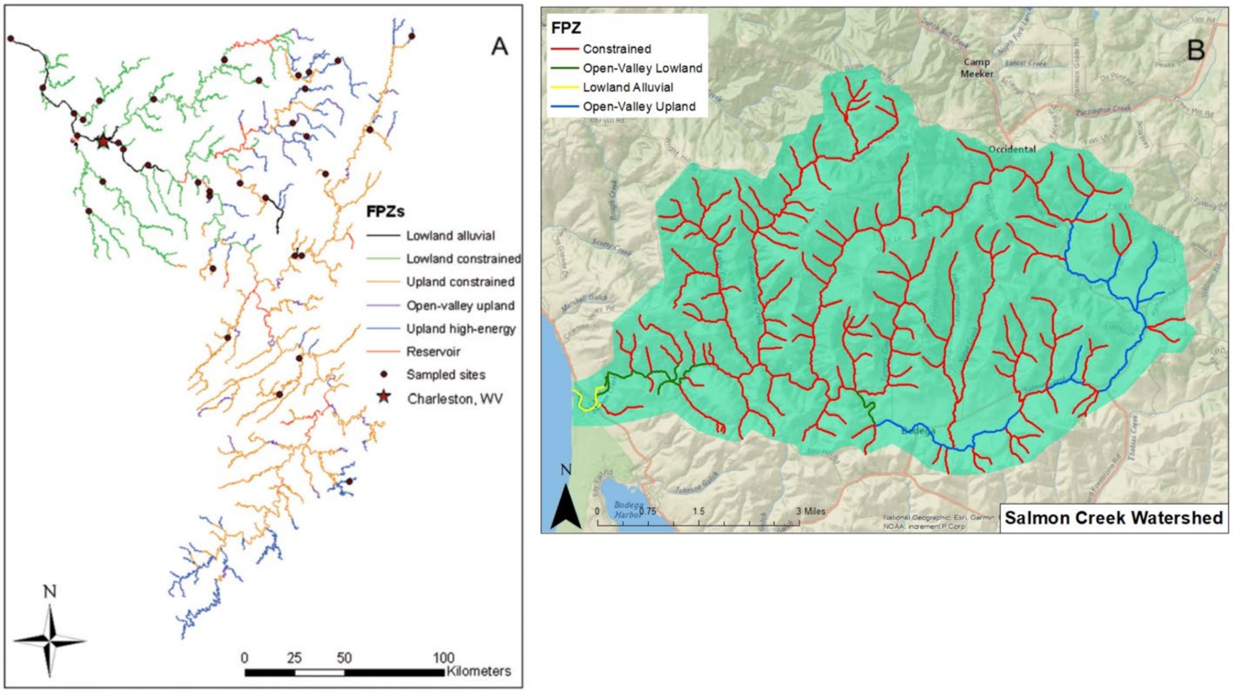


Figure 16. Comparison of FPZs in Kanawha River Basin and Salmon Creek Watershed. Figure 16a shows the FPZ model for the Kanawha River Basin (Williams et al. 2013). Figure 16b shows the Salmon Creek FPZ model for comparison,

Looking at another study conducted on the Little Miami River Catchment (Thoms 2018), this watershed also shows heterogeneity in low order streams (Figure 17a) this watershed is about 4,000 square kilometers, so smaller that the Kanawha river Basin, but still much larger than the Salmon Creek Watershed. Both the Kanawha River Basin and the Little Miami River Catchment are in the U.S. Midwest area, and both are a part of the larger Ohio Creek Watershed. Therefore, these two watersheds are also more likely to have similar characteristics. Thus, the homogeneity of low order streams in the Salmon Creek Watershed could related to the size of the watershed, or it could be related to the physical location of this watershed on the West Coast.

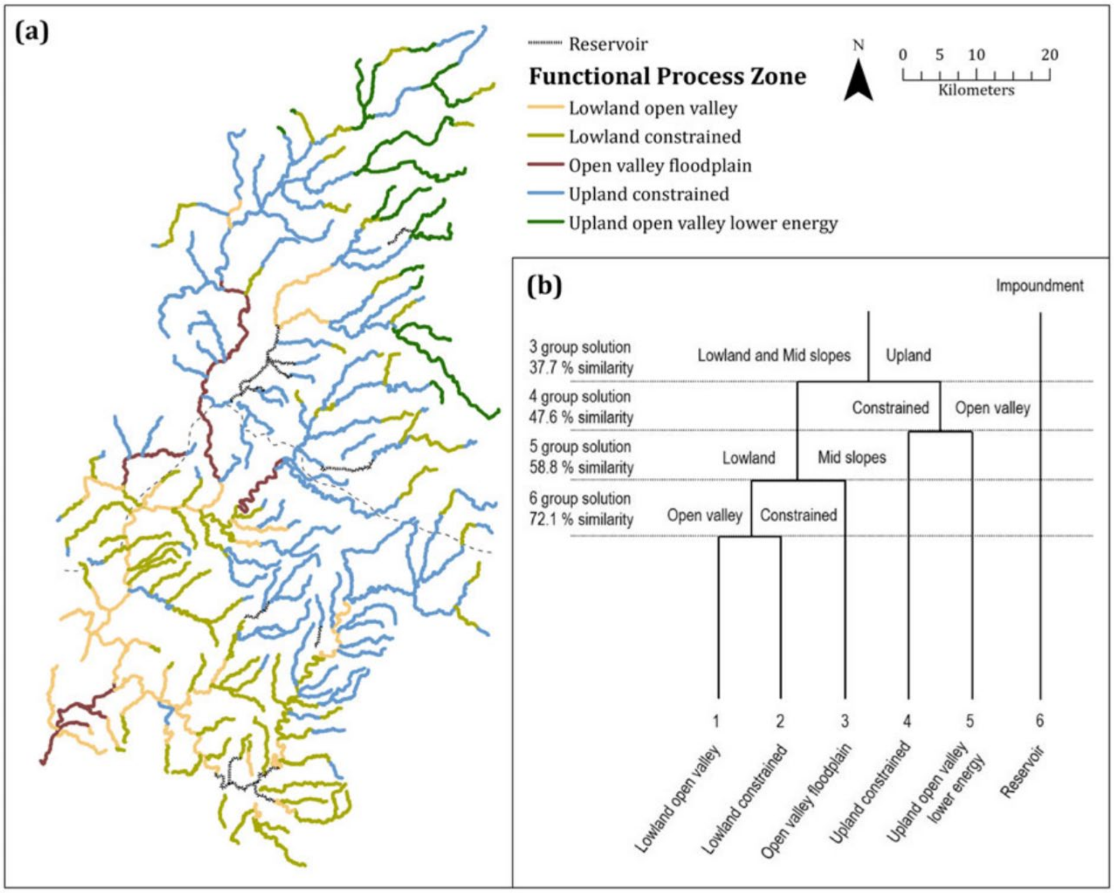


Figure 17. Little Miami River FPZ Model (Thoms 2018). This figure comes from a FPZ study done on the Little Miami River of the Ohio River Basin. Figure 17a shows the FPZs identified for the watershed. Figure 17b shows the results of their model given different levels of similarity.

Number of FPZs

I identified four FPZs in Salmon Creek. Both the Kanawha River Basin and the Little Miami River Catchment studies identified six FPZs. One reason that Salmon Creek may have fewer zones is because it is a much smaller watershed. Another reason could be that the type of model that I used. I used a cluster analysis with a cut off at 80% dissimilarity but looking and the results of the cluster analysis (Figure 10), it looks like there could be two or three clusters within the cluster for the constrained zone. If I had used a different model, then the number of FPZs could have been different. The Miami River catchment analysis (Figure 17b) shows that in their model, different cut offs could be used to create models with different numbers of FPZs. In the model that I used, the differences within the constrained zone cluster were not large enough to differentiate it into multiple clusters.

Relationships between FPZs and Variables

I also wanted to see which of the 9 variables I collected were the most important for defining each FPZ. I also want to see if the same variables were important in other studies. By looking at the results of the results of the PCA, I found that the constrained zone is mostly defined by high RVS, LVS, DVS, and PRE as well as low SIN. Open-valley upland has high VW and VFW and low RVS and LVS. Open Valley Lowland has high SIN and low PRE and DVS. Lowland alluvial has alluvial geology and low PRE.

I compared these with the variable found in FPZs in the Kanawha River Basin (Williams 2013), where many of the same FPZs were identified. In this watershed, upland and lowland constrained zones were also found to have high RVS and LVS as well as low VW and VFW. Upland open-valley had high VW and VFW and low RVS, LVS, and DVS. Lowland alluvial had alluvial geology, high VFW, and low RVS, LVS, and DVS. The Kanawha River Basin analysis also measured four additional variables: channel belt width, channel belt sinuosity, channel planform, and ratio of valley width to valley floor width. Of these variables, only ratio of valley width to valley floor width was mentioned as important for determining FPZs. This variable was found to be high in constrained zones and low in lowland alluvial and upland open-valley zones. This watershed did not have a lowland open-valley zone.

Limitations

Because my data all came from online sources, I was limited by the resolution of the data available. This particularly meant that the accuracy of valley dimension measurements was limited by the 10-meter resolution of the DEM. This resolution issue was especially challenging in areas will very narrow valley floors. Because each site had to be measured by hand, it was very time-consuming to measure 9 valley dimensions. This time constraint limited the number of points that could be sampled, and I was unable to use a previously developed automation process in Williams et al. (2013) because the code was outdated. I was also unable to go visit the site in person to see if there were any visible differences between the FPZs and to verify if there were any structures such as roads that may have affected stream flow.

Future Directions

One possible line of further research is to look at the distribution of wildlife, such as benthic macroinvertebrates along Salmon Creek to see if their distribution can be related to the FPZs I identified. Maasri et al. (2019) found similarities in benthic macroinvertebrate distributions across multiple watersheds and comparing the organisms in this watershed with others could explain stream function differences between agricultural and natural watersheds. I would also be interesting to look at how this watershed differs from urban watersheds which may experience different types on pollution and even more channelization. A new FPZ model of this watershed could also be conducted with the addition variable ratio of valley width to valley floor width, since the variable was important for describing FPZS in other studies.

Broader Implications

I found that the FPZ model for Salmon Creek was more homogeneous for low order streams compared to models for other watersheds. Although I identified a fewer number of FPZ than other studies, this was due to the type of model I used and not the nature of the watershed. The variables that I found to be important in determining my FPZs were similar to those identified in the Kanawha River Basin model, although this study used four additional variables. This model summarizes the physical properties of the stream. Knowing the FPZ of a particular stream means that you have a general understanding of its physical properties without needing to look at individual variables. This can help inform management of the watershed by helping to identify suitable breeding areas of the diminishing steelhead population in the watershed (Hammack 2006) or find ways to protect certain ecosystems services along the watershed (Ryan 2003).

ACKNOWLEDGEMENTS

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