THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

ESTIMATING FRESHWATER RUNOFF INTO GLACER BAY, ALASKA USING GIS METHODS

SUZANNE CIAVOLA
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Reviewed and approved* by the following:

David F. Hill
Associate Professor of Civil and Environmental Engineering
Thesis Supervisor

Patrick M. Reed
Assistant Professor of Civil and Environmental Engineering
Honors Advisor

*Signatures are on file in the Schreyer Honors College.

ABSTRACT

Flow values were estimated for Glacier Bay, Alaska using three sets of regression equations developed by the United States Geological Survey. By manipulating a digital elevation model of the Glacier Bay area using a geographical information system, point source and line source watersheds were created. Once these watersheds were delineated, their physical characteristics were extracted including centroid, area and mean elevation. Land cover data was obtained and used to determine the percent water cover, percent snow and ice cover, and percent forest cover of each watershed in the Glacier Bay domain. Average annual precipitation and mean minimum January temperature for each watershed were also calculated through spatial interpolation using information from eleven surrounding weather stations.

All of the watershed characteristics were input into the three sets of regression equations which include peak flow statistics, annual high-flow statistics, and seasonal low-flow statistics. The results show that the majority of flows are resulting from the point source watersheds rather than the line source watersheds.

Flow measurements were obtained for four small watersheds in Glacier Bay in a recent visit. These four watersheds were analyzed in the same manner as the larger watersheds in the bay and entered into the same regression equations. Flow statistics were also calculated for three gaged watersheds in Southeast Alaska. These three watersheds have known average discharge values on the days when discharge was measured for the four small watersheds in Glacier Bay. Thus all seven values were

superimposed onto a graph of each watershed's low-flow and high-flow statistics. The exceedance probabilities for each known flow value was then estimated from this figure and compared. As a result, the exceedance probabilities for all of the watersheds on a given day were unfortunately not the same. They were however not far off and fit into the low-flow and/or high-flow range of values. This allows a certain level of confidence in the resulting freshwater discharge estimates.

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I want to thank everyone who has given me moral support throughout this year: my two roommates Erin and Krystal, who always give me comic relief; Joe, who has been my civil engineering buddy for four years; and of course my parents without which I would not have the tools, motivation or means to be where I am today.

Chapter 1

Introduction

There is a great desire amongst scientists and the National Park Service in Glacier Bay National Park to understand the currents and tides that drive marine processes. Modeling the water movements in the bay would allow more in-depth studies to be undertaken on this highly unique and complex environment. To make such a model, the freshwater flows in the bay must be estimated. Without the help of any flow gages within the bay, these flows were estimated using previously developed equations for Southeast Alaska.

1.1 Glacier Bay Description

Glacier Bay is located in Southeast Alaska, northwest of Juneau. Figure 1.1 shows the layout of the bay. There are two main arms: the West Arm and the east arm or Muir Inlet that join at the central bay. Bartlett Cove, park headquarters, is on the east side of the lower bay. The bay reaches its southern limit where it is joined by Icy Strait, which ultimately empties into the Gulf of Alaska.

For the purpose of this study, the main bay area as well as parts of Icy Strait were analyzed. The complete domain used is shown in Figure 1.2

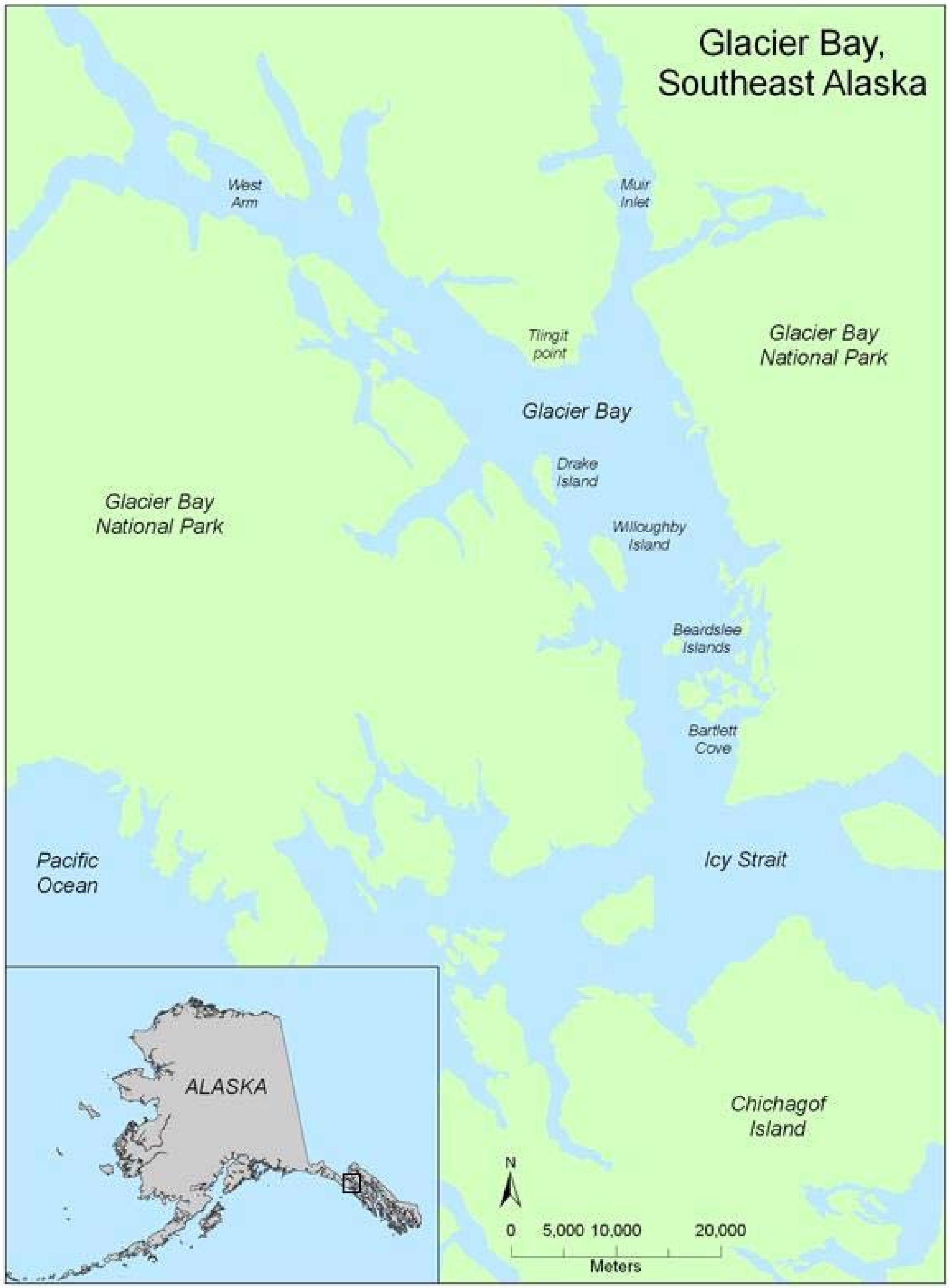


Figure 1.1: Map of Glacier Bay, Alaska

Picture modified from: http://pubs.usgs.gov/of/2006/1081/images/fig1.html

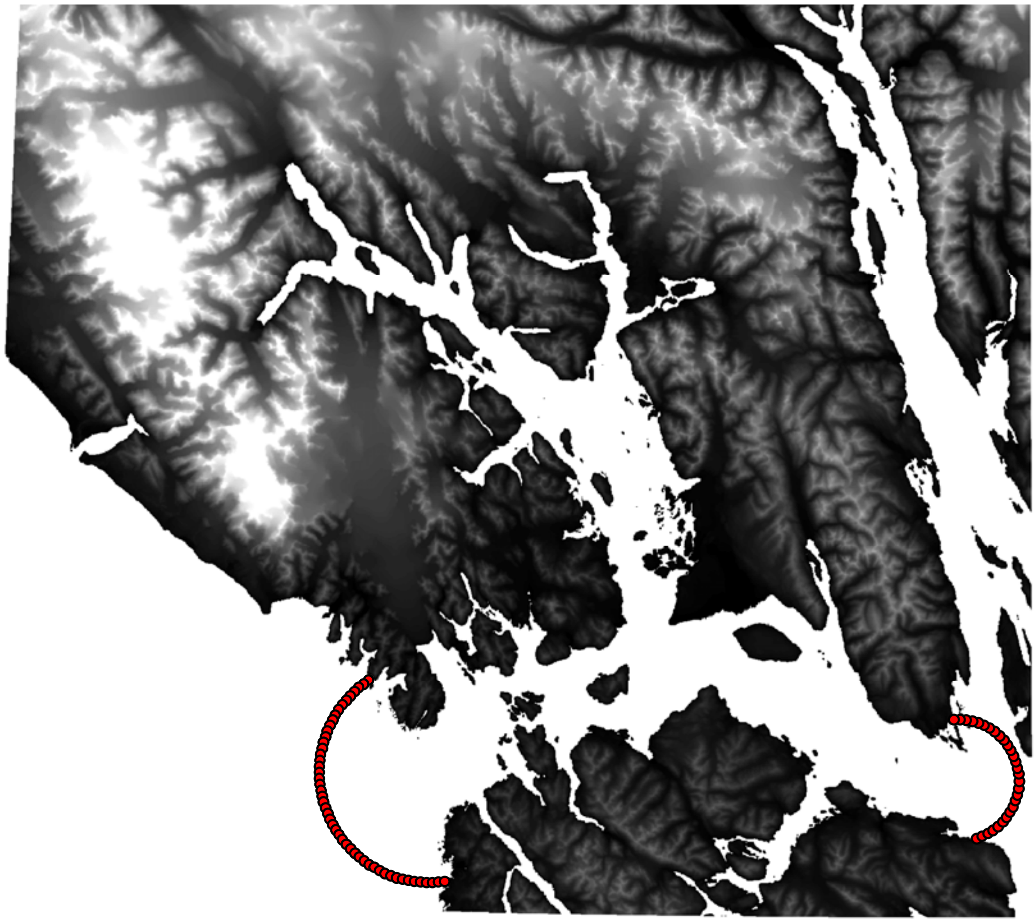


Figure 1.2: The Glacier Bay domain includes all of the main bay as well as parts of Icy Strait enclosed by each of the two arcs.

1.1.1 History

In 1794, George Vancouver was the first to explore and document Glacier Bay. At the time it wasn't a bay but a small indent in the ice along Icy Strait. Less than 225 years later, the glaciers have retreated at one of the fastest rates ever recorded [**2**] sixty-five miles into the bay. This retreat is shown in Figure 1.3. **.**

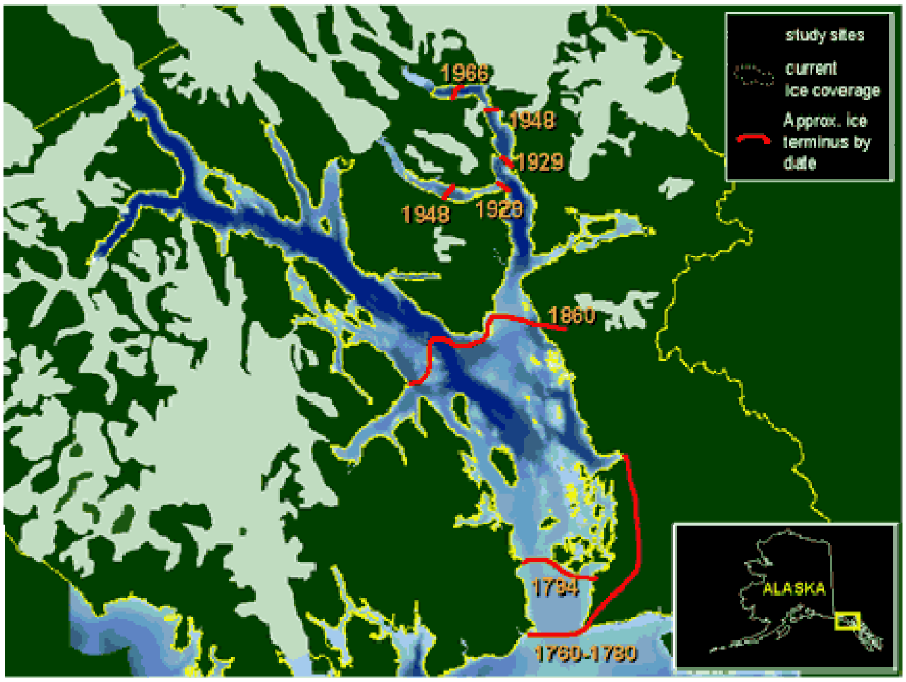


Figure 1.3: Glacial retreat in Glacier Bay
Source: http://www.absc.usgs.gov/research/Fisheries/genetics/genetics.htm

Currently there are still sixteen major glaciers surrounding the bay and twelve of these are actively receding. This glacial retreat has been followed by the progression of terrestrial floral and fauna on the recently uncovered landscape. It is this constant motion that creates a constantly changing state in the bay that is truly unique.

1.1.2 Climate

Glacier Bay experiences a somewhat moderate maritime climate. The coldest temperatures occur in winter with a mean of -2.5°C in January. Temperatures get warmer in spring with the warmest temperatures occurring in July and August with the mean temperature for these months of 13.4°C [**2**]. Due to these variations in temperature, snow-melt starts around May with ice-melt and the most snow-melt in the summer.

Like most of Southeastern Alaska, Glacier Bay receives substantial amounts of rain from the air masses that have collected moisture in the Gulf of Alaska. In Bartlett Cove, the annual precipitation is 1.9m [**4**]. The highest amount of precipitation usually occurs in autumn accompanied by high amounts of freshwater runoff. An Aleutian low dominates then as well as in spring and winter, whereas a high pressure system dominates in the summer months.

1.1.3 Landscape

The glaciers that once covered the bay left behind a beautiful and dramatic landscape. The bay itself is actually a fjord system surrounded by towering mountaintops such as the Fairweather range with mountains as high as 4,600m [**4**]. The central bay, west arm, and east arm were all carved out slowly by retreating tidewater glaciers. These glaciers carved some deep trenches but also left a number of sills or shallower areas that are remnants of the glaciers' terminal morraines. The sill at the entry of the bay is about

25m deep contrasting with the numerous basins that are up to 458m deep[**4**]. The result is a very complex bathymetric situation with varying depths and widths throughout the bay.

To further complicate things, Glacier Bay also experiences somewhat drastic tides. The average difference between high and low tide at Bartlett Cove is 3.7m [**4**], which means that half of the time this difference is even higher than that.

1.2 Present Model Efforts and Needs

Glacier Bay is a constantly changing environment that creates challenges for those trying to understand it. Particularly in the bay itself, a comprehensive model of the oceanography has never been created. Understanding the currents and tides within the bay will provide an important starting point to understanding many different ecological and biological behaviors that occur in this complex environment.

1.2.1 Modeling Capabilities

Currently there is a great dearth of data in Glacier Bay. Due to the harsh climate and conditions there, data collection can be a daunting and impossible task. Given the small amount of data that exists, modeling must be done using data that do exist such as precipitation and air temperature [**2**].

One of the best available methods for modeling the currents and tides in the bay is a tidal circulation model called the Advanced Circulation model or ADCIRC (www.adcirc.org) that incorporates tidal information, wind data, and freshwater inflows. The bathymetry of the bay as well as the coastline of the bay can be input into this model with the three other factors mentioned to create a two or three-dimensional output of the water velocities throughout the bay. For a more in depth description of this model as well as the results of the modeling of Glacier Bay using ADCIRC, refer to Hill, 2007 [**3**].

1.2.2 Importance of a tidal circulation model

Using a tidal circulation model, the trajectory path of a floating object in the water can be predicted. This knowledge would be extremely helpful for the Park Service as well as other scientists. If a boat were to leak any chemical or contaminant into the water, the Park Service could base its actions off of this model to minimize damages. Also certain animals and their larvae float with the tides and currents; this model would open new doors for marine life research.

In such a complicated fjord ecosystem like Glacier Bay, understanding the dynamics in the water is a challenging but important task. Knowing the physical processes within the bay may be the only way to understand the biological processes and patterns [**2**].

1.2.3 Importance of freshwater to the model

One of the inputs, in the form of a boundary condition, to the ADCIRC model is the freshwater inflow. If freshwater inflows into a particular water body were found to be small, they could be omitted. But for Glacier Bay, freshwater appears to play a large role in the tidal circulation. According to Wang et al. [**7**], freshwater discharge has a greater impact on water in subpolar regions such as Glacier Bay than in subtropical or tropical areas. Another study conducted close to Glacier Bay, in the Gulf of Alaska, shows that precipitation and freshwater runoff greatly affect water circulation [**5**]. Besides altering circulation patterns, freshwater flows affect other important factors such as the salinity gradients in the bay and sediment loads.

The biology of Glacier Bay is greatly affected by the different environments occurring in the bay. First of all, the salinity in the waters dictates which animals can tolerate the environment. These density differences caused by differences in salinity can then cause new circulations that again affect biological movement. Movement of a species, its waste products, and nutrients it needs are all affected by these currents. As mentioned in Etherington et al. [**2]**, the abundance of a number of species such as chlorophyll-a and phytoplankton is affected by density changes. Sediment load introduced by freshwater flows can also affect an organism's habitat and again dictate its abundance and spatial distribution.

Understanding the magnitude of the freshwater being input into the bay each year provides a wealth of information not before available. Besides acting as an important input to an ADCIRC model, knowing these flow quantities can be a useful tool for understanding biological movements throughout the bay.

1.3 Purpose and Scope

This main goal of this thesis is to reasonably estimate the magnitude of freshwater flowing into the Glacier Bay domain. Using geographic information system techniques, watersheds will be created and characterized. These characteristics will then be entered into three sets of existing regression equations. This will provide a range of high-flow and low-flow values that can be expected from each watershed as well as from the whole Glacier Bay domain.

An accurate estimate of freshwater flows will act as an input into a tidal circulation model that will help characterize the bay. Both the circulation model and the freshwater input values will shed light on many topics that are of particular interest to scientists.

These estimates of freshwater flow will, however, not have a high degree of accuracy. For a more accurate estimate, the freshwater sources into the bay would have to gaged, which they are not. There is also only one meteorological staion in all of Glacier

Bay providing rain and temperature data. This severe lack of data makes freshwater estimation a very difficult task. To truly quantify the amounts of freshwater flowing into the bay, flow data must be collected. Until reliable flow data is obtained, methods, such as the following, must be implemented to estimate freshwater flows in Glacier Bay.

Chapter 2

Watershed Delineation using ArcGIS

The following is a summary of the watershed delineation process, but for a more detailed procedure, see Appendix A. For the first step, a digital elevation model (DEM) of Glacier Bay was obtained from the United States Geological Survey at http://seamless.usgs.gov (Figure 2.1).

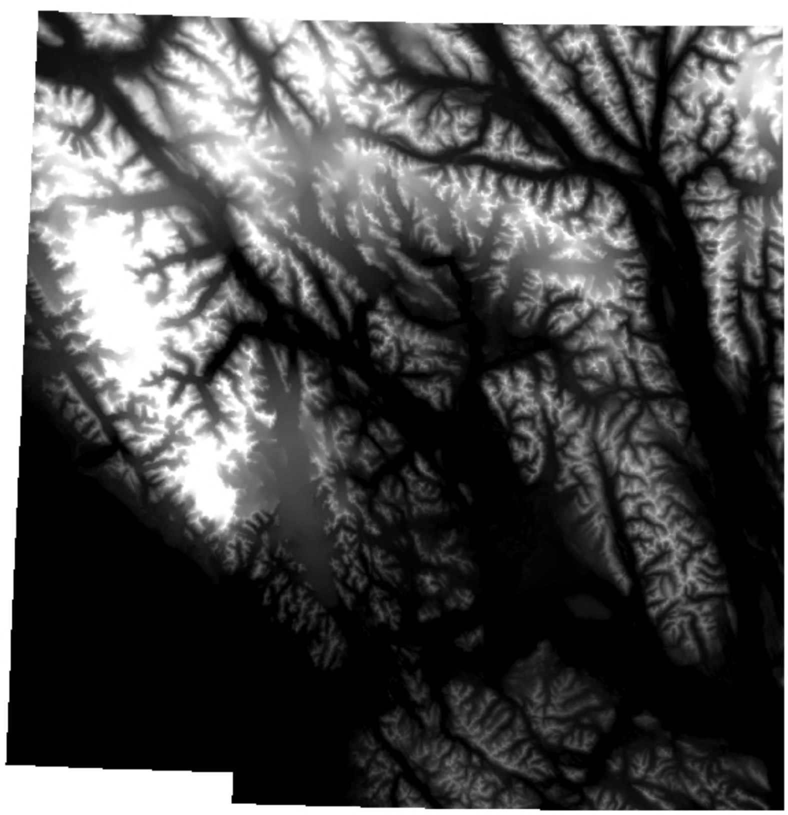


Figure 2.1: The Digital Elevation Model of Glacier Bay used for analysis

This DEM then had to be projected to a flat surface using the Universal Transverse Mercator coordinate system (zone 8). To make calculations faster, the cell size of the DEM was changed to 100 m by 100 m instead of the original cell size of approximately 60 m by 60 m. The cells that represented water originally had raster values below or equal to zero. These water cells will complicate the subsequent watershed analysis, so these cells were reclassified with a value of “NoData”, thus eliminating them, see figure Figure 2.2

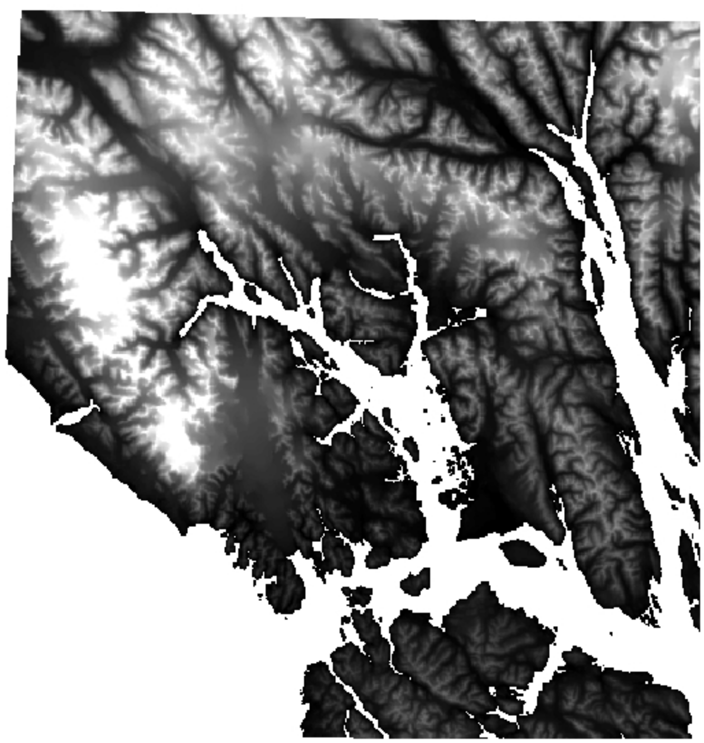


Figure 2.2: Reclassified DEM of Glacier Bay with water cells shown in white.

With the DEM properly set up, the first step in delineating the main catchments contributing to the bay was to eliminate depressions in the DEM. When creating watersheds, GIS assumes that water will simply flow downhill. These existing depressions will create sinks which will thwart efforts to create clearly defined basins flowing out into the main bay. With the depressions removed, and using the flow direction tool in ArcGIS, the DEM was transformed into a raster showing which direction water falling on each cell of the DEM will travel according to which of the surrounding cells has the steepest descent.

To demonstrate this process on a smaller scale, Figure 2.3 shows a closer view of the east arm of the bay. Figure 2.4 shows the flow direction raster that was determined for the east arm; each color representing a different flow direction. Each cell is surrounded by eight other cells; the color on this cell represents which of these eight neighboring cells have the lowest elevation and hence where water will flow. Thus each cell is one of eight different colors representing the eight major compass directions: north, south, east, west, northeast, northwest, southeast, and southwest.

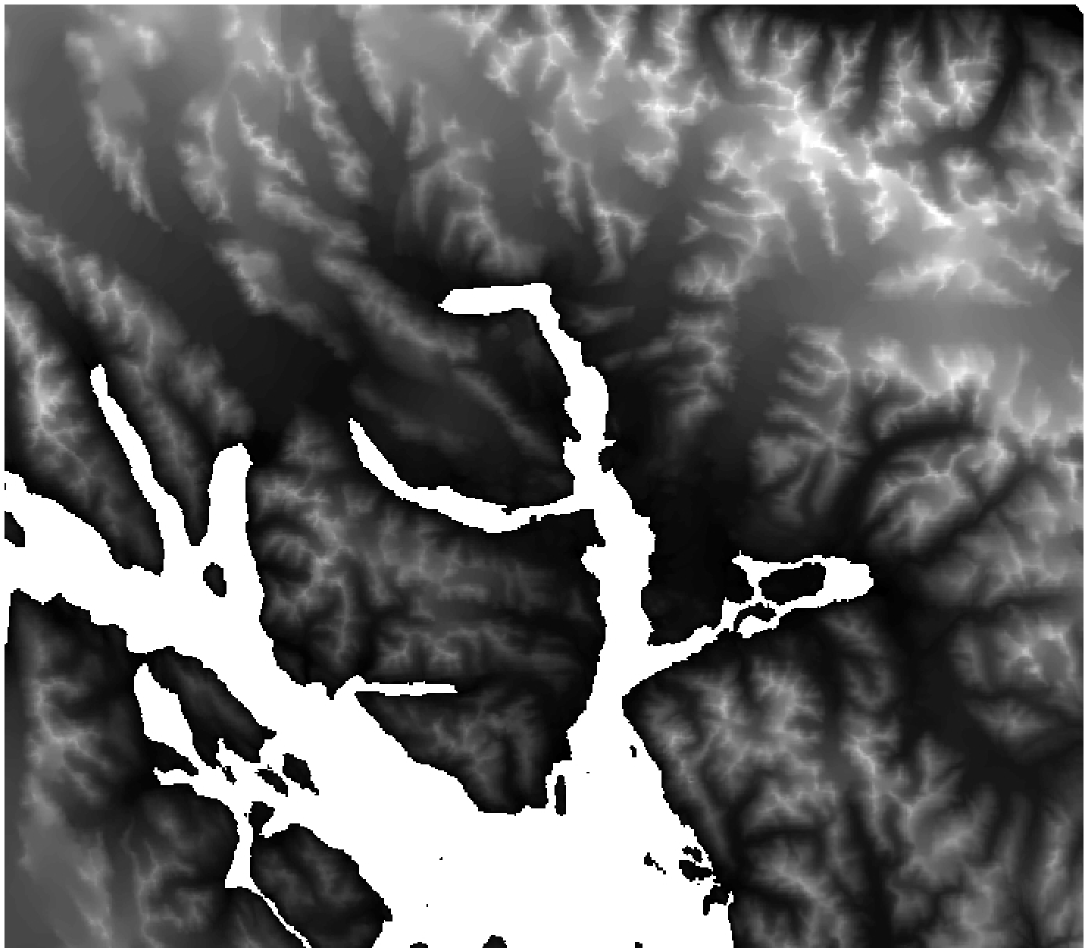


Figure 2.3: DEM of the east arm of Glacier Bay

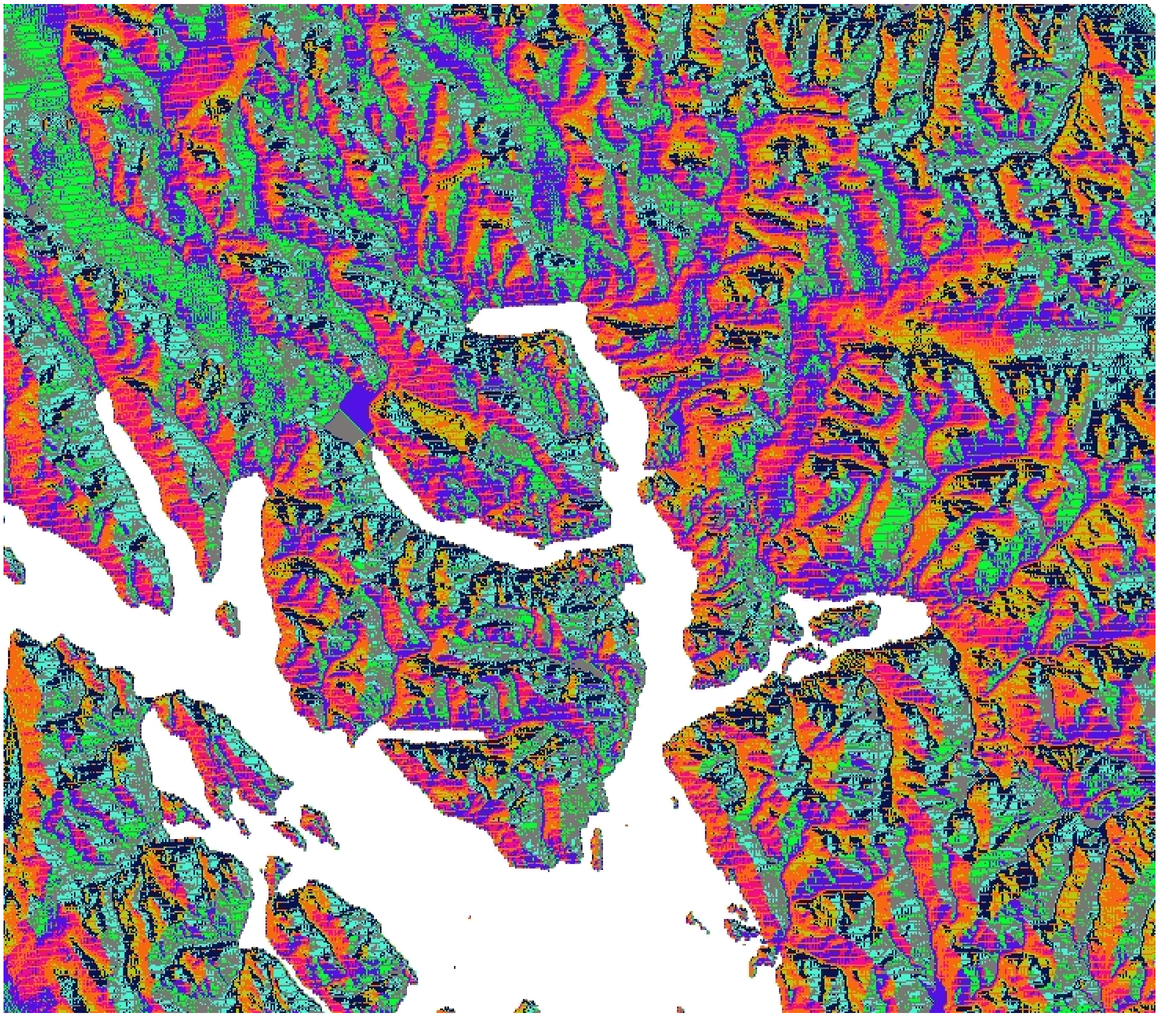


Figure 2.4: Flow direction raster for the east arm of Glacier Bay

Based on this flow direction raster, a flow accumulation tool was applied that calculates how many cells contribute flow to any given cell. For example, lower elevations such as streams or rivers will have the highest flow accumulation values and higher elevations will have little to no flow accumulation. To find only larger streams and rivers, the flow accumulation raster was classified into two different categories: cells with an accumulation value below 5000 and those that are above 5000. Cells in the latter category have at least 5000 cells contributing flow or 50 km^2 of contributing area. The result, shown in Figure 2.5, is a map showing the locations of major streams flowing into the east arm of Glacier Bay.

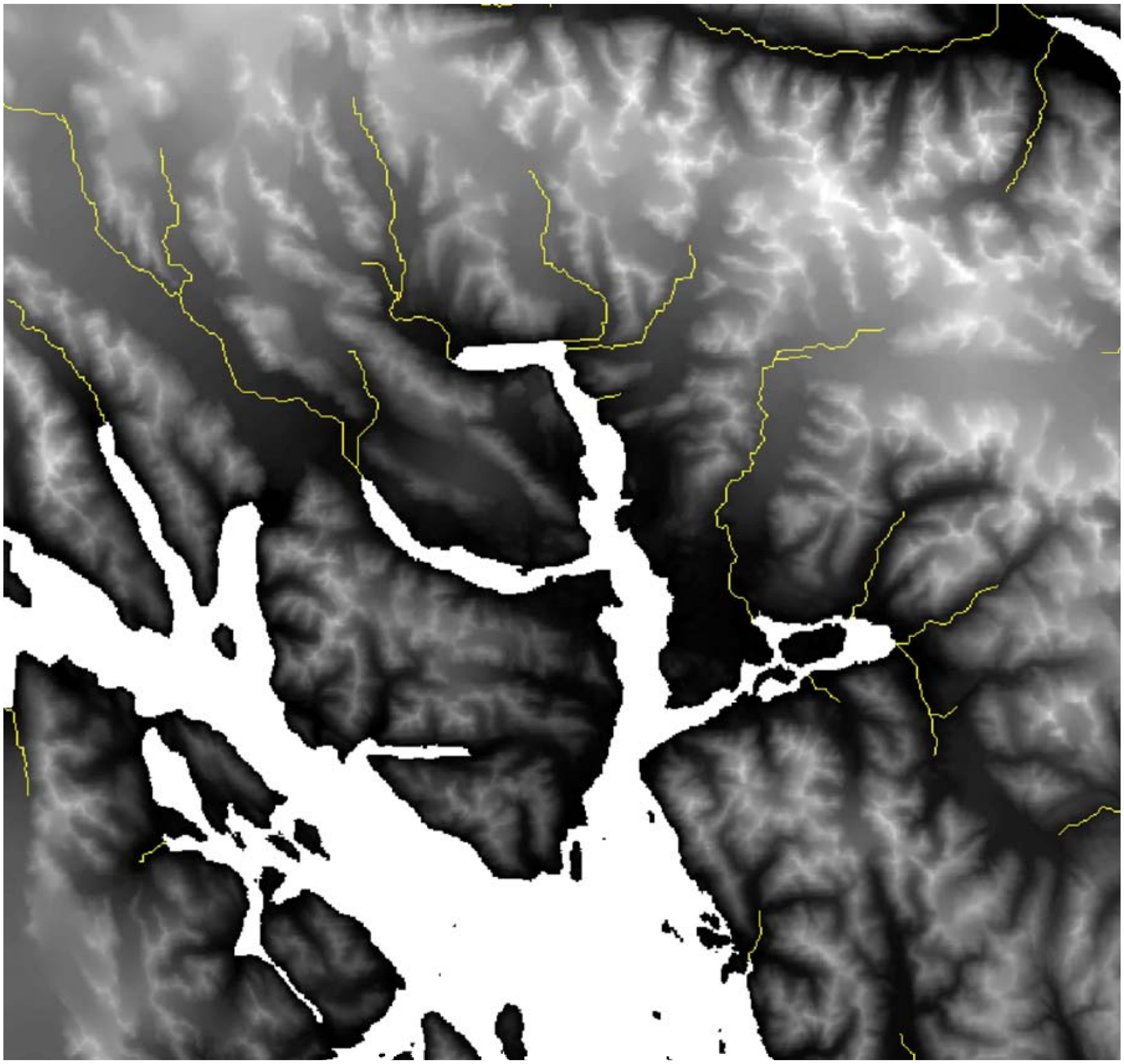


Figure 2.5**:** Classified flow accumulation raster of the east arm of Glacier Bay.

2.1 Point Source Delineation

The flow accumulation raster for the whole bay shows 36 main streams flowing into the domain. Each of these streams defines a point source watershed with a distinct point of entry or pour point into the bay. To create these watersheds within GIS, an empty point shapefile was created. Then the empty point shapefile was edited by adding pour points at the thirty-six locations with the highest flow accumulation values, where the outlet of each of these streams would occur. This is shown for the east arm in Figure 2.6. Each pour point was assigned an individual identification number and then the completed shapefile was converted to a raster. This aligns each pour point with the existing DEM raster grid, overlapping the cell with the highest flow accumulation. Finally, the watershed tool was then run which created point source watersheds by including all cells contributing flow to each pour point. The resulting point watersheds for the east arm are shown in Figure 2.7. For further explanation of the steps taken to delineate a watershed using a DEM, see Simmons' [**6**] description of the same methods.

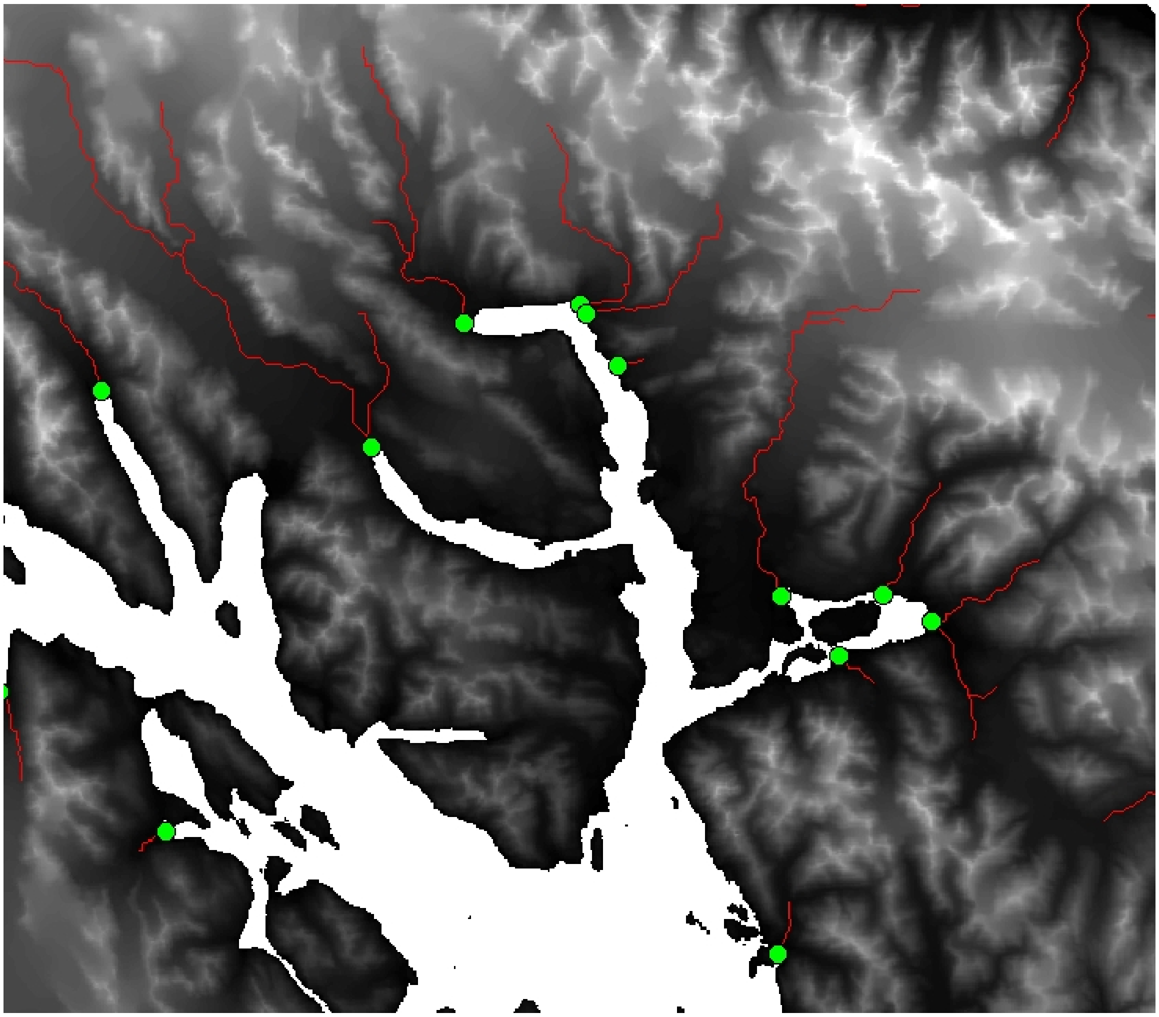


Figure 2.6: Flow accumulation raster of the east arm with pour points added

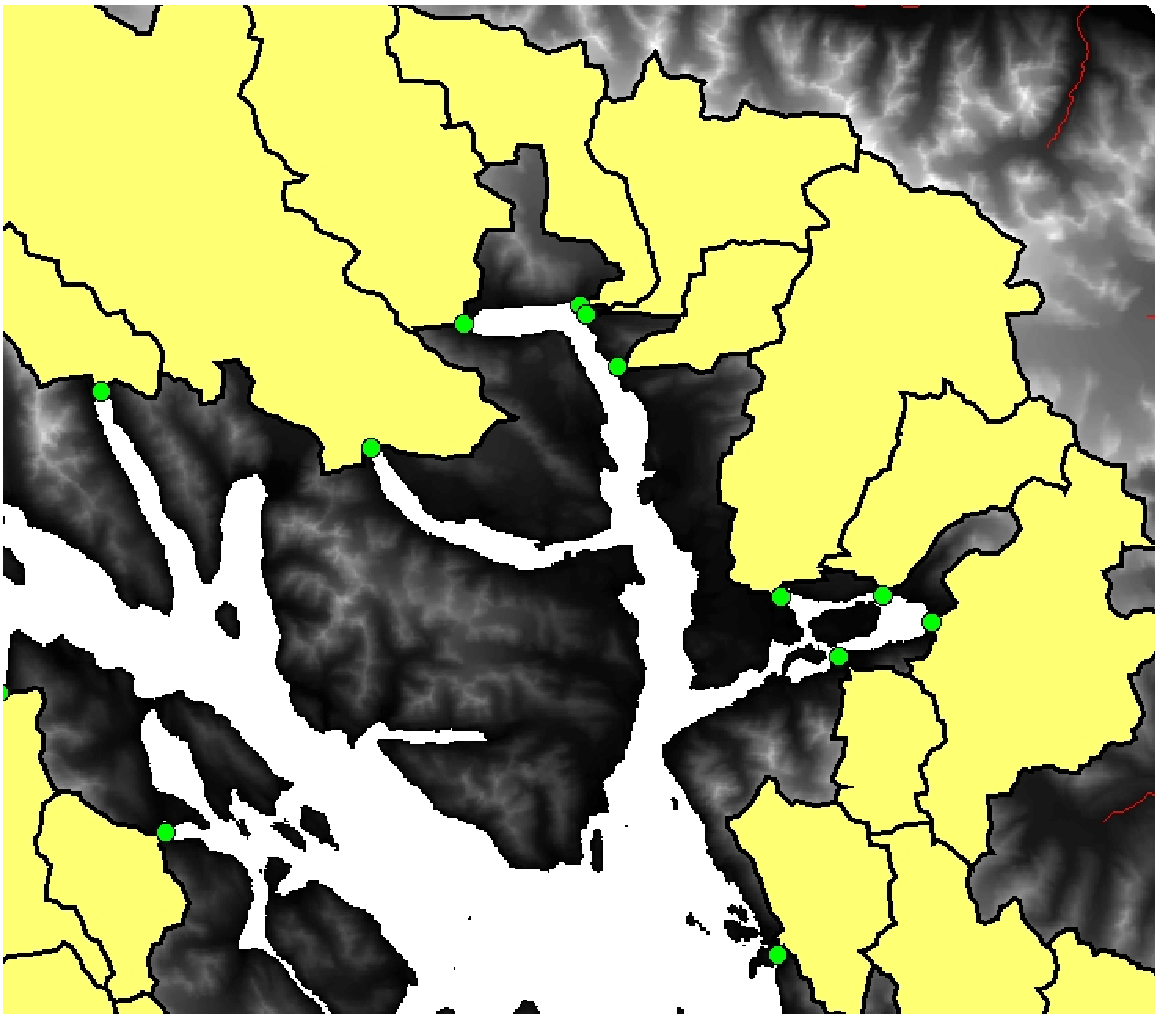


Figure 2.7: Point watersheds in the east arm of Glacier Bay

2.2 Line Source Delineation

The point source watersheds are mainly high elevation areas that drain out through one point or stream into the bay. This leaves a lot of land near the coast that must somehow be included. Realistically these areas of land drain into the bay through countless small streams, gullies, or through overland flow. Modeling this would be extremely tedious and would create an unrealistic amount of minute watersheds. Instead, the coastline was divided into sections that lie between the point watershed pour points. It was assumed that all of the land that contributes runoff to each coastal section distributes this flow evenly along the coast and forms what is called a line source watershed.

This process is summarized here but is also laid out in more detail in Appendix B. To define the line sources, first a flowlength tool was run on the DEM that calculates the distance from each cell water must travel to reach the bay. Then cells with a flowlength value of zero were extracted from the resulting file. These cells, by definition, lie along the coast where water would not have to flow any distance to reach the bay. Figure 2.8 shows the extracted coast cells for the east arm of Glacier Bay.

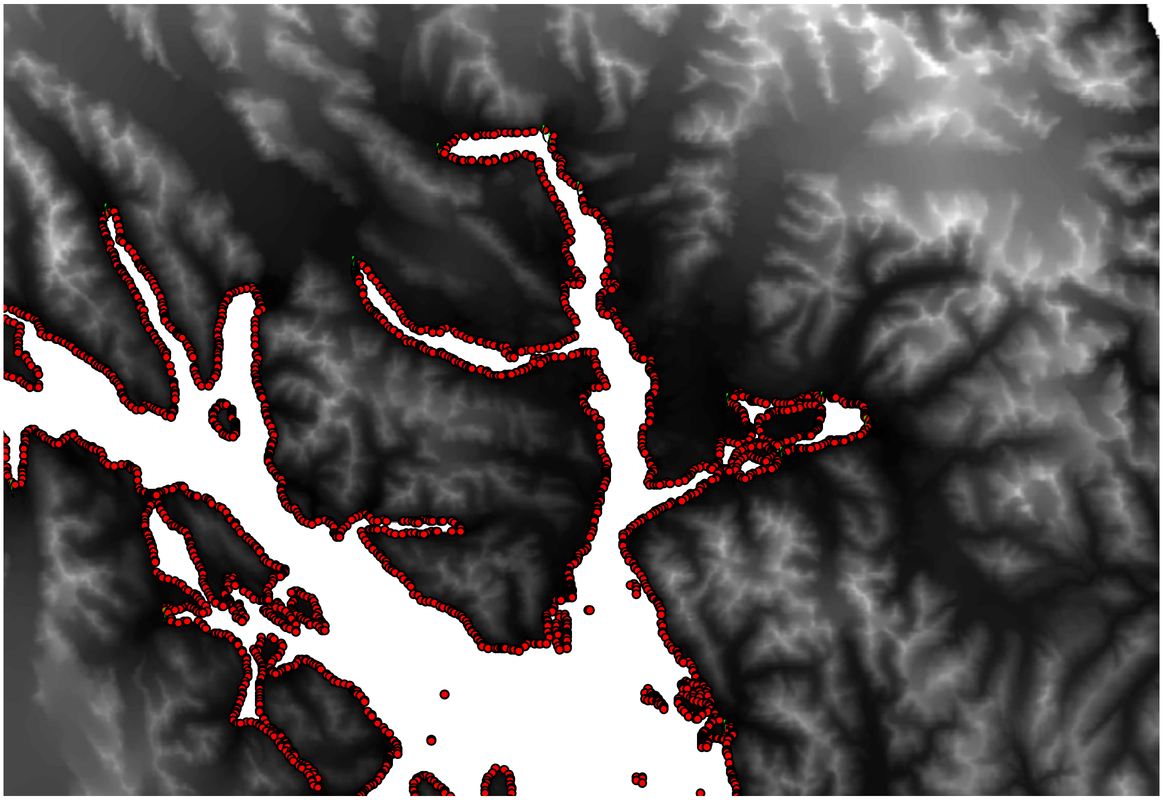


Figure 2.8: Coast cells (in red) and the point watershed pour points (green dots) on the east arm of Glacier Bay

Just like the point sources, some sort of pour point needs to be defined for the watershed tool to be run. The first step in doing this was to create another empty shapefile. On this shapefile, polygons were drawn that overlap all of the coast cells between two major stream outlets as illustrated in figure Figure 2.9. A polygon was also drawn that covering all of the islands so that they will be grouped together.

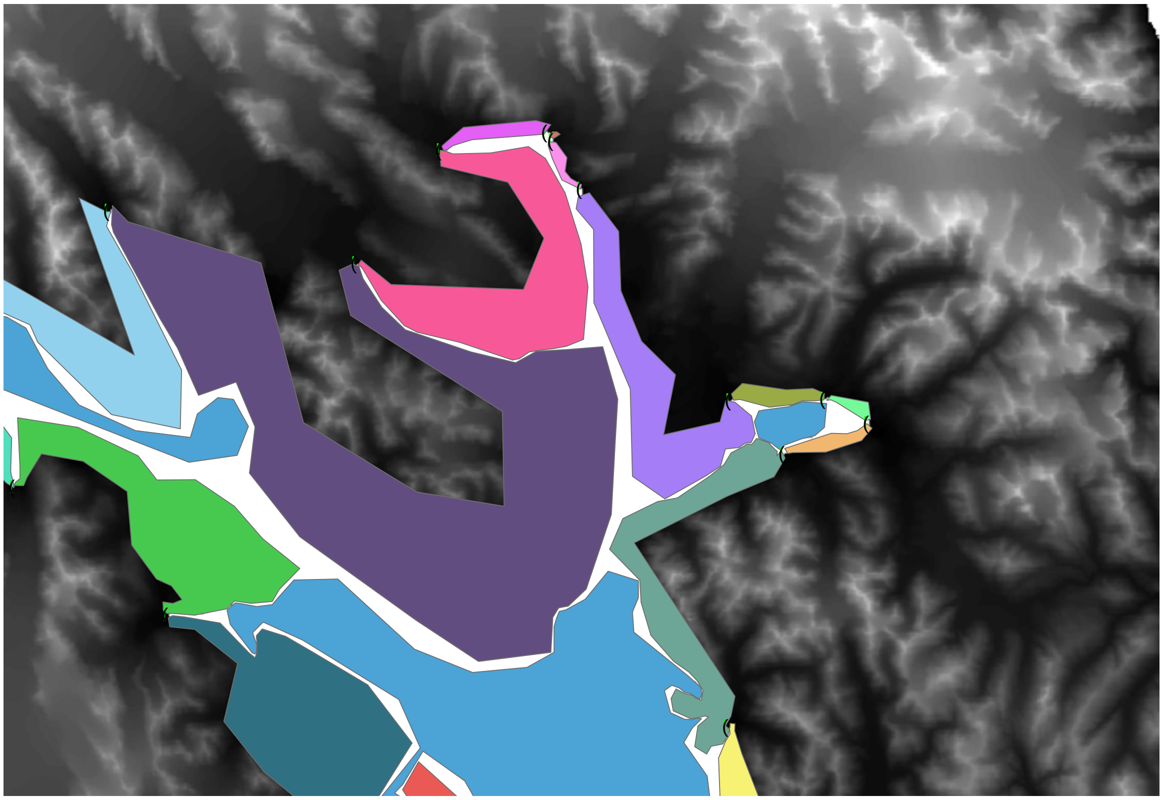


Figure 2.9: Polygons drawn over the coastline of Glacier Bay's East Arm to create line source pour points and the point watershed pour points (green dots)

The coastal edge raster was converted from a raster to an integer and then from an integer to a point shapefile. It was then possible to run an intersection tool that extracted the coast cells covered by each polygon and numbered the cells according to which polygon overlapped them. The coast cells were grouped together in this manner to form thirty-nine different sections of the coast that act as line source pour points for thirty-nine separate watersheds. These coast cells were then converted from the resulting shapefile to a raster so that the watershed tool could be implemented. Using these coast sections as pour points, the watershed tool created the line source watersheds. (See Figure 2.10)

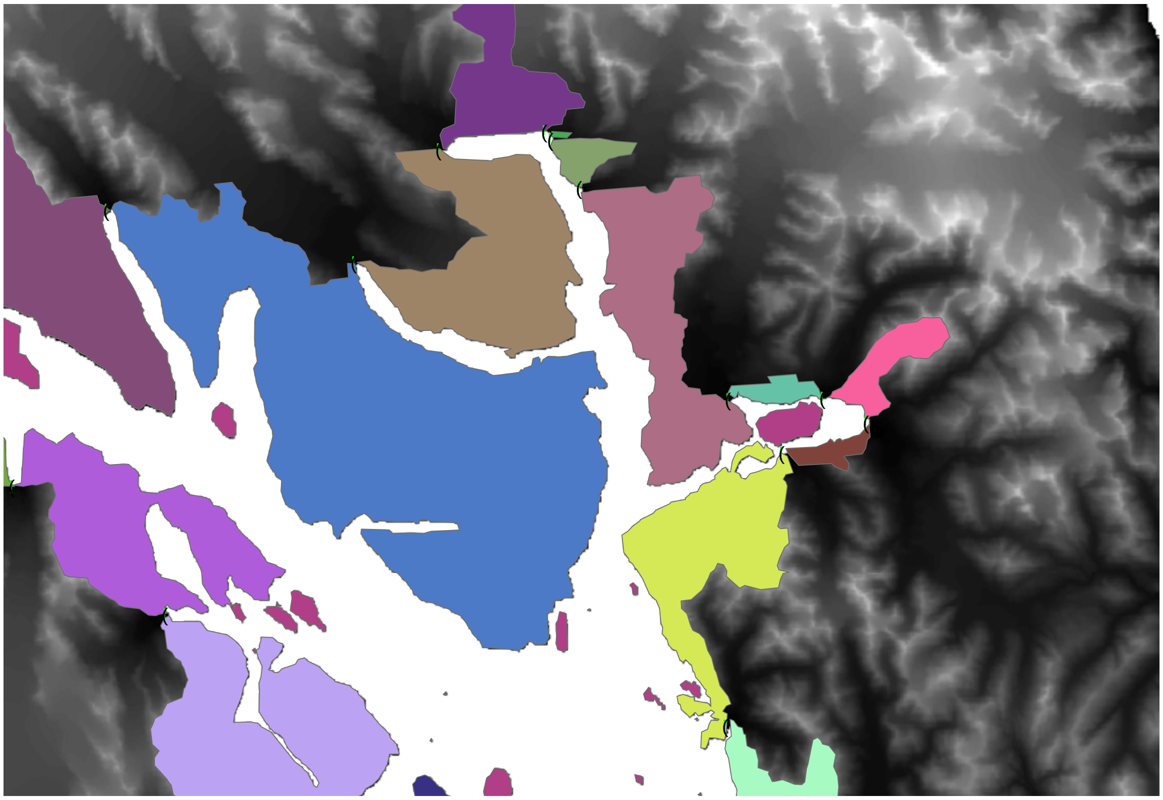


Figure 2.10: Line watersheds and the point watershed pour points (green dots) in the east arm of Glacier Bay

The resulting line and point watersheds for the entire Glacier Bay domain are shown in Figure 2.11 and Figure 2.12 . All of the watersheds are shown in Figure 2.13

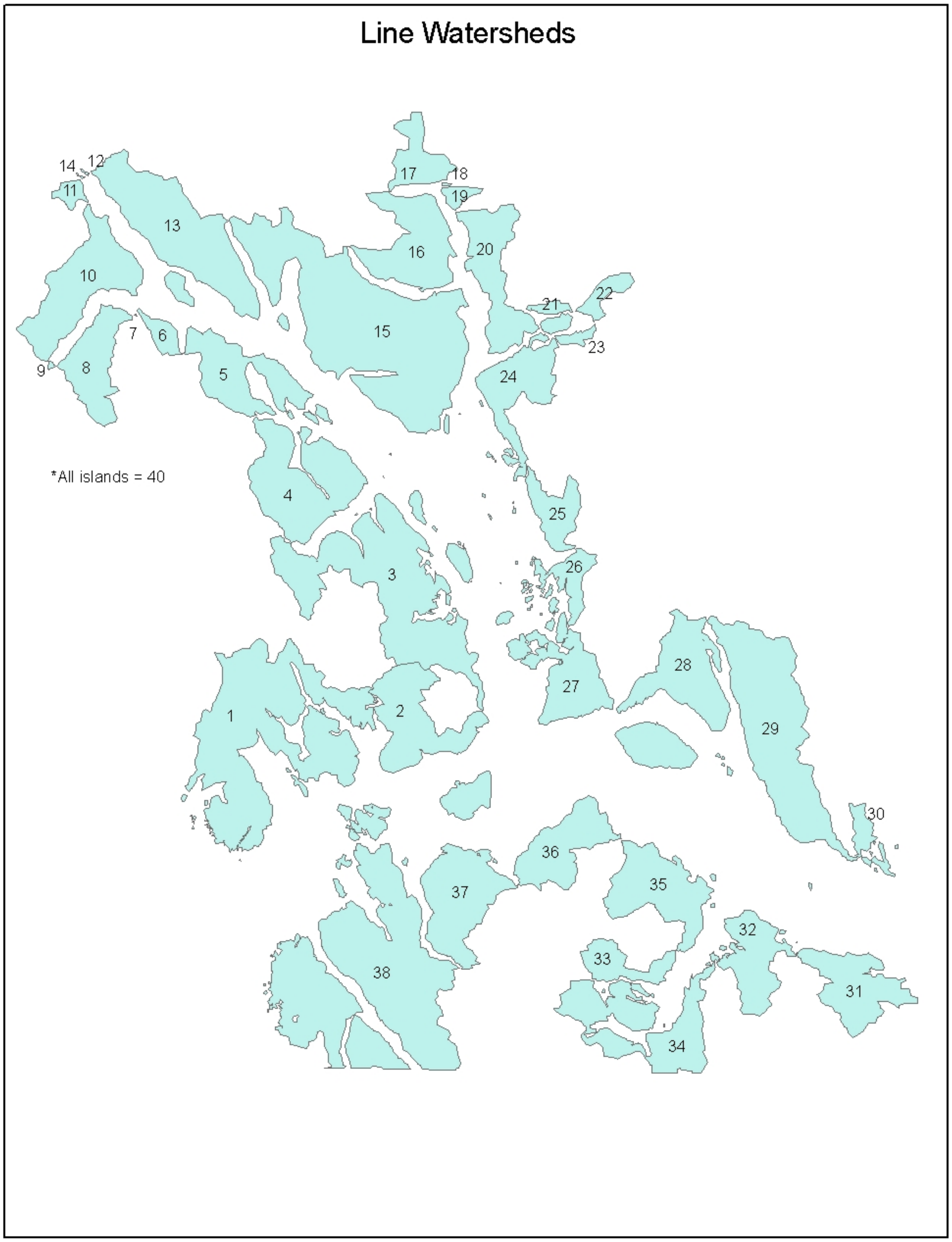


Figure 2.11: Line source watersheds in Glacier Bay

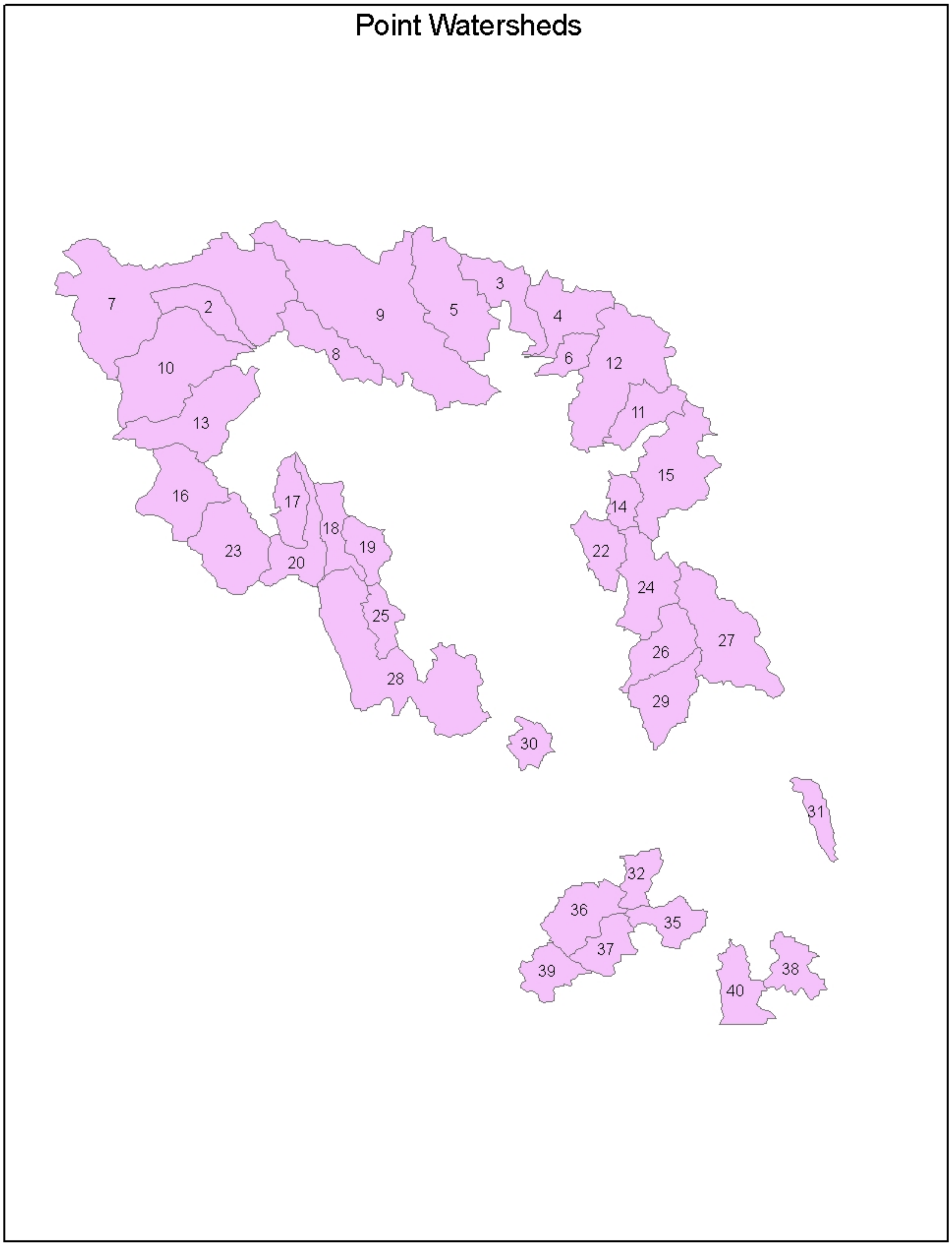


Figure 2.12: Point source watersheds in Glacier Bay

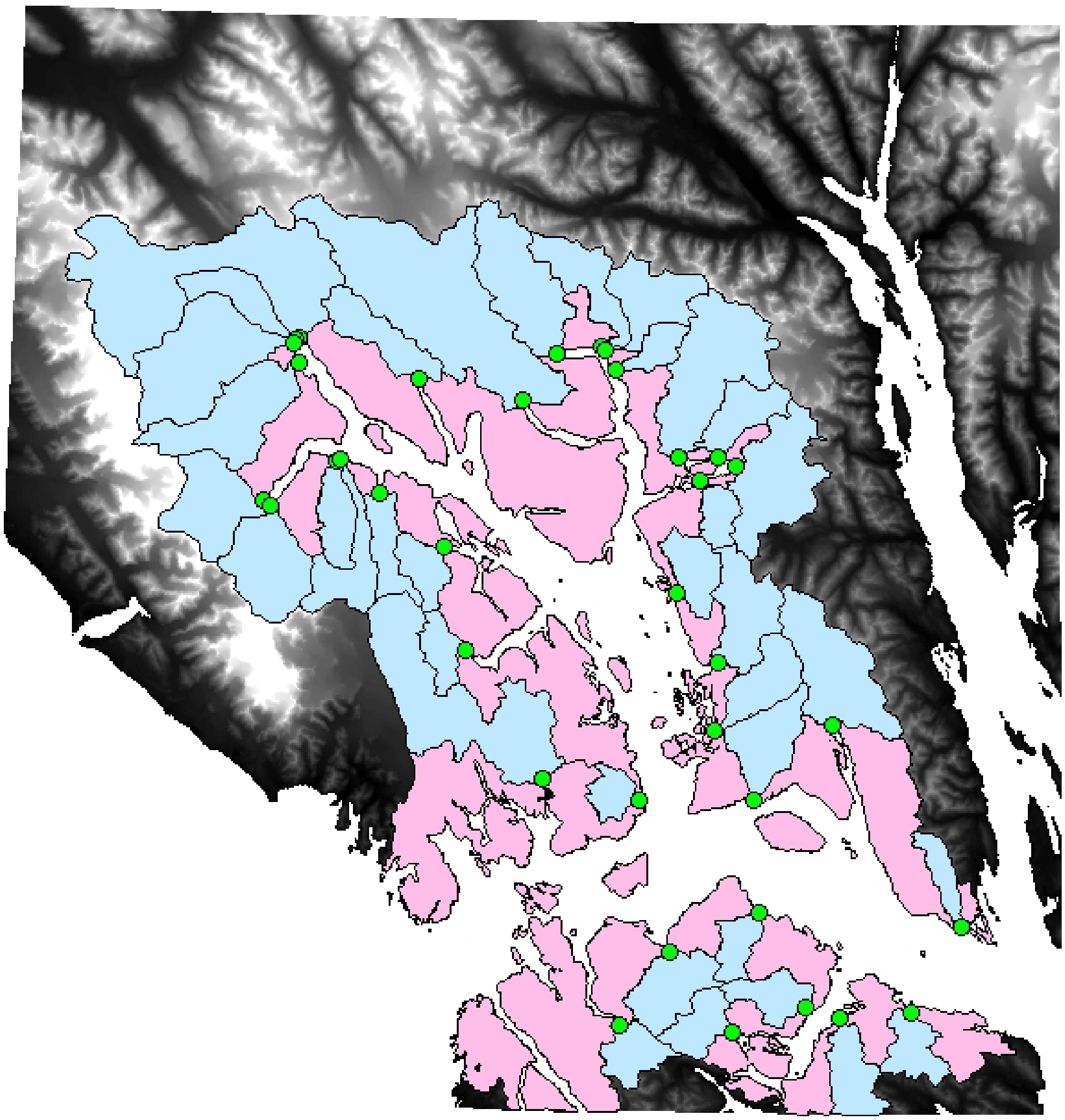


Figure 2.13: All of the watersheds in Glacier Bay

Chapter 3

Determination of Watershed Characteristics

When all of the main watersheds were identified, they then had to be characterized according to size, elevation, location, climate, and land cover for hydrologic analysis.

3.1 Area

Areas of each of the 75 watersheds were determined through ArcGIS. Using some simple coding, the areas of both line and point source watersheds were calculated. For more detail, see Appendix C. Table 3.1 below shows the results.

The total line and point watershed areas are approximately 1710 mi^2 and 2247mi^2 respectively.

Table 3.1: Watershed areas

Point ID	Area (mi²)	ID	Area (mi²)
2	34.71	20	44.91
3	47.27	22	34.43
4	53.08	23	71.98
5	90.47	24	59.74
6	20.20	25	24.03
7	223.84	26	44.03
8	45.68	27	95.31
9	241.03	28	161.95
10	117.60	29	51.08
11	37.85	30	20.68
12	115.04	31	20.98
13	84.35	32	23.54
14	21.19	35	30.77
15	90.01	36	50.22
16	67.82	37	31.61
17	32.15	38	31.75
18	31.90	39	30.84
19	26.87	40	39.02

Line ID	Area (mi²)	ID	Area (mi²)
1	150.20	20	40.61
2	47.36	21	3.06
3	115.97	22	8.00
4	67.10	23	2.93
5	41.50	24	36.13
6	7.06	25	18.99
7	0.01	26	13.86
8	32.95	27	40.59
9	0.31	28	46.48
10	55.14	29	100.25
11	4.65	30	6.43
12	0.13	31	38.78
13	79.19	32	33.03
14	0.08	33	17.18
15	178.79	34	61.02
16	46.85	35	46.18
17	19.65	36	36.64
18	0.18	37	50.57
19	4.20	38	184.81
		40	72.65

3.2 **Mean Elevation**

To extract the mean elevation of each watershed, this was also done through ArcGIS. By running the zonal statistics tool on the DEM raster and the watershed shapefile, and selecting the “mean”, ArcGIS generated a table of mean elevations for each watershed. These results are shown below in Table 3.2 . The average mean elevation of the point watersheds is about 792m, noticeably higher than the average line watershed elevation of 331m.

Table 3.2: Mean watershed elevations

Point	ID	Mean Basin Elevation (m)	ID	Mean Basin Elevation (m)	Line	ID	Mean Basin Elevation (m)	ID	Mean Basin Elevation (m)
	2	928	20	1055		1	235	20	13
	3	1135	22	685		2	213	21	131
	4	1242	23	1506		3	250	22	692
	5	1036	24	552		4	380	23	222
	6	794	25	694		5	327	24	529
	7	1471	26	373		6	435	25	455
	8	1062	27	680		7	37	26	21
	9	997	28	479		8	1095	27	212
	10	1668	29	196		9	30	28	335
	11	756	30	176		10	843	29	505
	12	1020	31	372		11	665	30	130
	13	1627	32	391		12	77	31	203
	14	638	35	341		13	770	32	210
	15	709	36	406		14	79	33	332
	16	1542	37	416		15	463	34	263
	17	990	38	314		16	297	35	246
	18	768	39	490		17	759	36	229
	19	720	40	279		18	121	37	325
						19	357	38	307
								40	98

3.3 Centroids

Determining the centroid of each watershed was an important task accomplished through ArcGIS methods very similar to those used to find the areas of the watersheds. For a more detailed procedure, refer to Appendix D. The results are shown in Table 3.3 . Note that coordinates are given in meters using zone eight of the Universal Transverse Mercator coordinate system. There are also no coordinates given for line watershed forty because the centroid is irrelevant for this watershed representing all of the islands.

Table 3.3: Watershed centroid locations

Point

ID	X (centroid)	Y (centroid)
2	371737	6556825
3	429080	6559382
4	440283	6556457
5	418475	6559074
6	441191	6548164
7	365409	6559549
8	395283	6550206
9	404589	6556130
10	365718	6545988
11	455133	6537328
12	450009	6544782
13	371115	6536730
14	451188	6520463
15	460674	6526574
16	367568	6522376
17	388300	6519918
18	396600	6515224
19	402494	6511705
20	389924	6512174
22	447126	6511442
23	377080	6512124
24	455498	6504774
25	405524	6498139
26	458656	6493123
27	470282	6495080
28	408416	6489703
29	459263	6483342
30	433545	6474657
31	487880	6461420
32	454238	6449334
35	460063	6441178
36	443388	6442371
37	448035	6436406
38	483381	6432248
39	437152	6431523
40	473285	6428059

Line

ID	X (centroid)	Y (centroid)
1	407945	6469603
2	428601	6471965
3	424441	6490533
4	412457	6505940
5	403801	6520889
6	392616	6526715
7	388794	6529500
8	383089	6522498
9	376700	6522353
10	380990	6533694
11	379517	6546835
12	381544	6549877
13	394978	6541554
14	380958	6549307
15	421524	6528321
16	428230	6539708
17	428985	6551946
18	432979	6548125
19	434783	6546631
20	440010	6535359
21	447911	6530546
22	455679	6532523
23	451612	6526338
24	443358	6518952
25	448537	6501622
26	450592	6491933
27	449945	6478342
28	467168	6478516
29	479944	6470765
30	492173	6456323
31	491310	6433792
32	476727	6437661
33	458000	6437158
34	460829	6428638
35	463233	6447600
36	449761	6453878
37	434944	6446339
38	421848	6434923
40	------	------

3.4 Climate

For estimating flow statistics for each watershed, two climatological elements need to be defined: mean annual precipitation and mean minimum January temperature. Ideally, this information could be obtained from weather stations within and around the bay. Unfortunately, due to Glacier Bay's remote location, weather data are very difficult to collect and currently do not exist. Along with a station in the park headquarters, Bartlett Cove (listed as Glacier Bay), data were extracted from ten other weather stations surrounding Glacier Bay. These stations were chosen based on their proximity to the Glacier Bay domain as well as length and completeness of records. Information from these weather stations was obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html). Figure 3.1 illustrates the locations of the eleven stations relative to Glacier Bay.

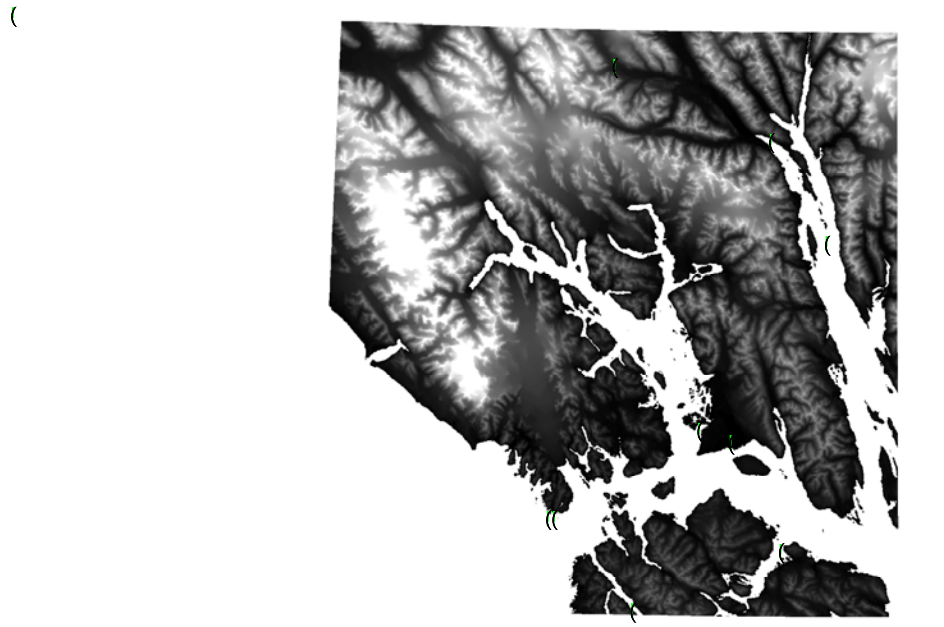


Figure 3.1: Locations of the eleven weather stations used to estimate mean minimum January temperature and mean annual precipitation

The data from each station ranged from 17 years of data to 83, usually with a number of years missing. The full climate data can be found in Appendix E. Table 3.4 shows the different data ranges for each station as well as station location, elevation, mean annual precipitation and average mean minimum January temperature. Both mean precipitation and temperature values are averages of all existing data for each station. This also includes years that were noted as “e” or an estimated total.

It must be noted that there is a lot of temporal variability in these averaged values. Standard deviations of mean annual precipitation values run from 10-20% while standard deviations for mean minimum January temperature values range from 14-70%.

Table 3.4: Summary of each station used for climate data

Station	Data Range	Latitude	Longitude	Elevation	Avg. Precip (in.)	Avg.Mean Min Jan T (°F)
Cape Spencer	1936-1974	58.2	-136.63	27.1	106.5	28.2
Eldred Rock	1943-1973	58.96	-135.21	15.8	46.3	21.3
Elfin Cove	1975-2006	58.2	-136.66	6.1	103.4	29.5
Glacier Bay	1966-2006	58.45	-135.88	15.2	70.3	23.0
Juneau Airport	1949-2006	58.35	-134.58	3.7	56.9	19.3
Haines Airport	1925-1953 & 1973-2006	59.25	-135.51	9.4	49.2	17.8
Haines 40 NW	1989-2006	59.45	-136.36	249.9	49.7	10.0
Gustavus	1923-2006	58.41	-135.71	12.2	55.4	20.8
Hoonah	1972-2006	58.11	-135.45	12.2	64.5	25.4
Yakutat	1948-2006	59.51	-139.63	8.5	147.3	18.9
Pelican	1967-2006	57.95	-136.21	3.7	141.7	25.3

With these data, the mean annual precipitation and mean minimum January temperature for each watershed must be determined. Ideally, stations much closer to Glacier Bay or even within Glacier Bay could be used to account for small scale differences in rainfall and temperature due to topographical changes. Because these data are currently unavailable, the precipitation and temperature values for each watershed were interpolated based on the location of each watershed's centroid with respect to the locations of the eleven stations and their corresponding values of mean annual precipitation and mean minimum January temperature. This was done in Matlab and created the following results in Table 3.5 . The only exception was line watershed number forty, which is all of the islands, where the precipitation and temperature values used were averages of all eleven station. This was done because using the centroid of all of the islands combined to interpolate the climate data would have created arbitrary results.

Table 3.5: Interpolated values of mean annual precipitation and mean minimum January temperature for each watershed

Point	ID	Mean Annual Precipitation (in.)	Mean min. Jan T (°F)
	2	88.2	17.5
	3	55.8	13.7
	4	54.9	15.2
	5	61.6	14.4
	6	56.6	16.0
	7	90.9	17.5
	8	77.2	17.0
	9	70.2	15.6
	10	94.9	19.3
	11	57.3	18.6
	12	56.3	17.4
	13	94.7	20.2
	14	61.3	19.6
	15	58.9	20.2
	16	101.1	22.3
	17	90.3	21.4
	18	87.1	21.5
	19	84.9	21.6
	20	91.8	22.3
	22	63.6	19.9
	23	98.9	23.1
	24	63.9	21.5
	25	87.4	23.2
	26	63.7	22.5
	27	52.5	20.9
	28	88.4	24.2
	29	58.0	21.4
	30	79.6	24.5
	31	58.9	21.7
	32	83.5	23.6
	35	82.9	24.8
	36	104.3	23.9
	37	103.3	24.8
	38	64.5	25.4
	39	122.3	24.8
	40	64.5	25.4

Line	ID	Mean Annual Precipitation (in.)	Mean min. Jan T (°F)
	1	94.8	26.8
	2	83.1	25.2
	3	79.6	23.0
	4	81.2	21.8
	5	81.4	20.3
	6	85.8	20.2
	7	87.1	20.1
	8	92.4	21.3
	9	96.0	21.7
	10	90.1	20.0
	11	87.0	18.4
	12	84.9	17.8
	13	80.0	18.1
	14	85.4	17.9
	15	69.5	18.3
	16	62.4	16.3
	17	58.2	14.7
	18	57.5	15.0
	19	57.6	15.4
	20	59.4	17.0
	21	59.5	18.4
	22	58.3	19.1
	23	60.0	19.2
	24	62.5	18.8
	25	65.6	21.0
	26	67.4	22.1
	27	68.0	22.6
	28	55.0	20.7
	29	56.4	20.6
	30	60.3	22.4
	31	64.5	25.4
	32	64.5	25.4
	33	89.3	25.2
	34	64.5	25.4
	35	72.9	24.2
	36	85.5	22.9
	37	112.4	24.5
	38	127.5	26.0
	40	81.0	21.8

3.5 Land Cover

The final data extracted from each of the 75 main watersheds were land cover statistics. Four quadrants (Juneau, Skagway, Mount Fairweather and Sitka) of land cover information were downloaded from the Alaska Geospatial Data Clearinghouse (http://agdc.usgs.gov/). Each of these quadrants contained raster data showing about thirteen different types of land cover. For the purposes of this analysis, three different types of cover were focused on: forest, snow and ice, and water. To find forest cover, “needeleaf (open)”, “needleleaf (closed)”, “needleleaf forest”, and “needleleaf woodland” were grouped together on each quadrant. For areas covered with snow or glaciers, “barren/snow” and “barren/glacier” were grouped together. And for areas covered with water, “clear water”, “turbid water”, and “turbid/shallow water” were grouped together. This created three different land use rasters for each of the four quadrants.

These were then merged by land type to create one large raster for forest, snow/ice, and water land uses. As an example, Figure 3.2 shows the four quadrants merged to create one forest layer.

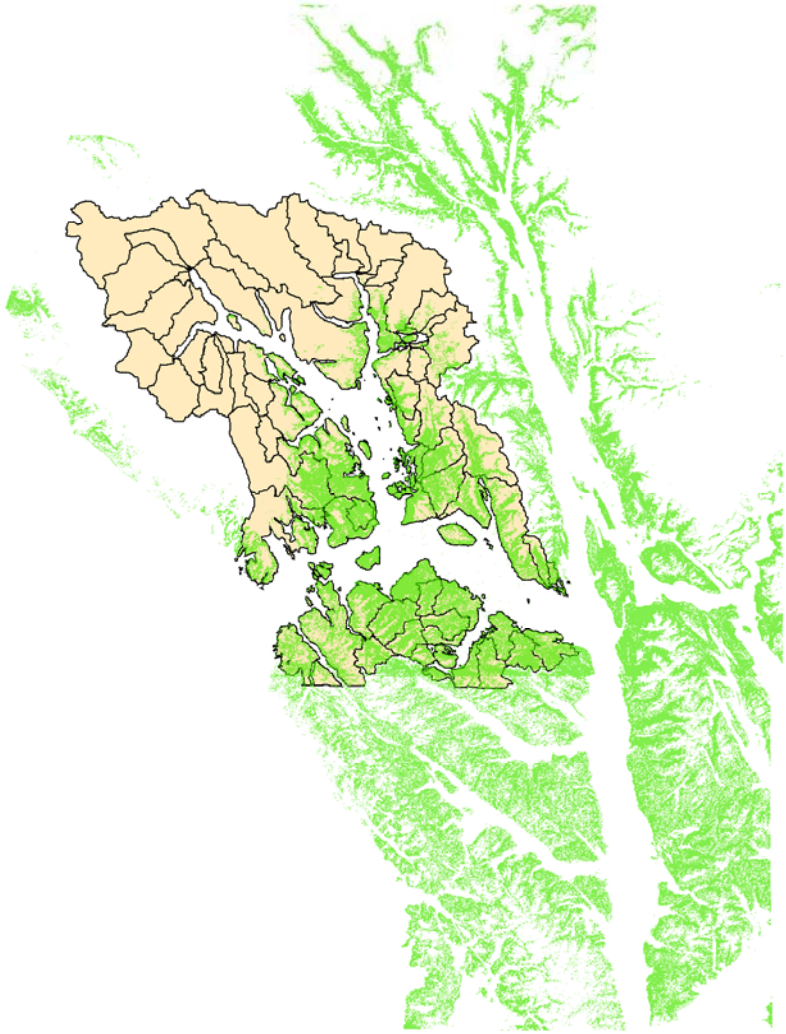


Figure 3.2: Merged forest layer superimposed on the watershed polygons.

With each of these three land use layers complete, they were then converted to polygons so that the intersection tool could be used. This tool extracted all of the land use polygons that overlapped watershed polygons. These three intersection layers are shown in Figure 3.3

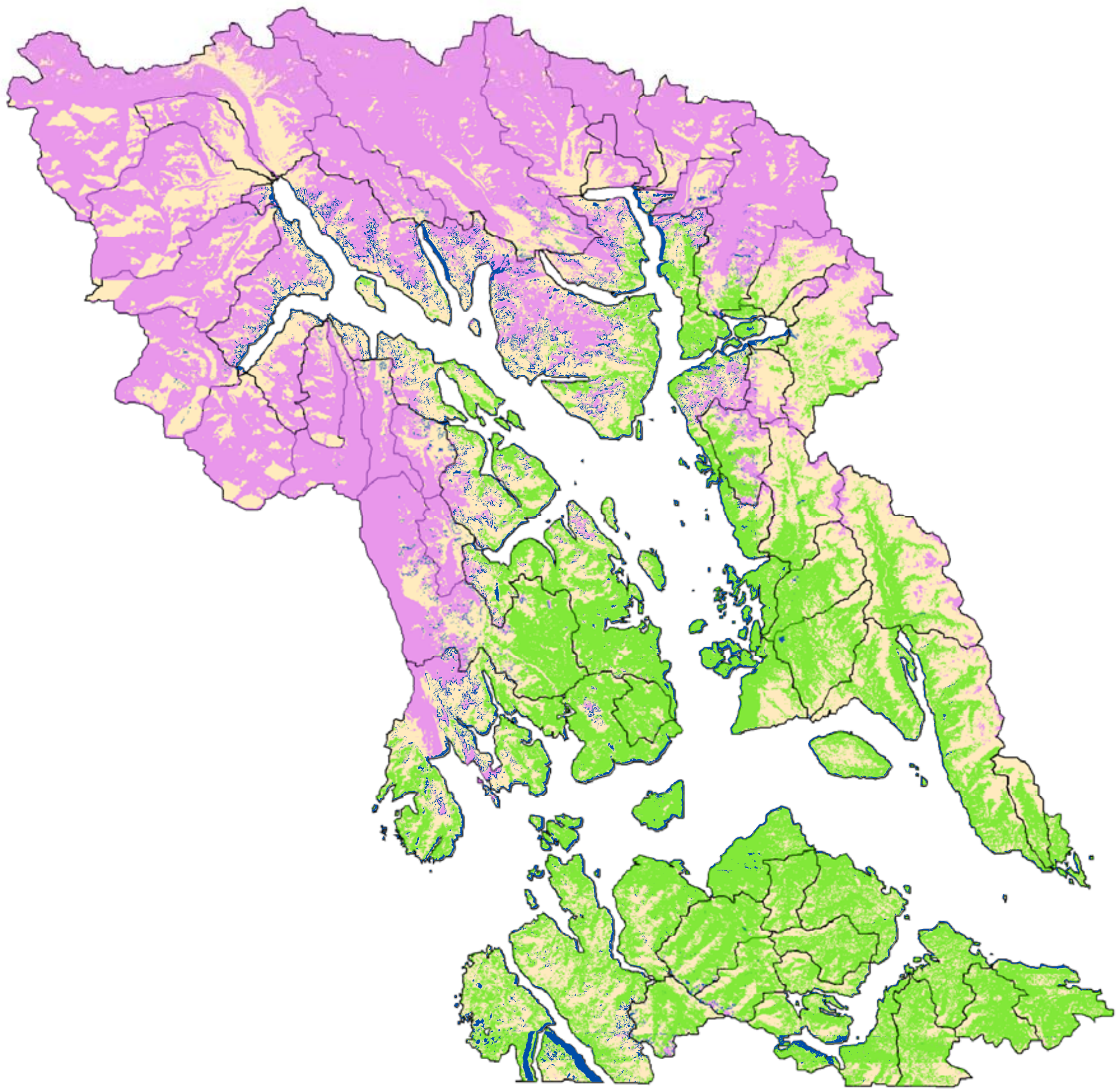


Figure 3.3: Land use polygons showing where forest (green), snow/ice (purple), and water (blue) intersect with each watershed

Each of these layers provided a table listing the area each type of land use intersects with each watershed. These areas are expressed as a percent of the total area of each watershed in Table 3.6. A more detailed procedure for determining land cover statistics can be found in Appendix F.

Table 3.6: Land use percentage of total area of each watershed

Point	ID	Forest % of total area	Water % of Total Area	Snow/Ice % of Total Area	ID	Forest % of total area	Water % of Total Area	Snow/Ice % of Total Area
	2	0.0	0.0	54.9	20	0.0	0.3	91.6
	3	0.0	0.0	91.0	22	34.4	3.8	23.6
	4	0.0	0.0	77.6	23	0.0	0.0	75.8
	5	0.0	0.0	81.0	24	31.9	0.2	9.5
	6	0.2	4.8	63.1	25	0.1	2.3	66.1
	7	0.0	0.0	73.3	26	55.6	0.3	1.3
	8	0.0	0.9	85.4	27	30.4	0.1	7.7
	9	0.2	0.9	86.3	28	27.6	2.4	44.3
	10	0.1	0.0	61.8	29	61.8	0.5	0.0
	11	10.5	0.0	31.0	30	82.8	0.5	0.3
	12	5.5	2.2	77.1	31	48.6	0.0	0.1
	13	0.0	0.4	74.0	32	75.1	0.0	0.0
	14	4.4	1.5	25.5	35	67.5	0.0	0.0
	15	15.4	0.3	21.4	36	72.1	1.8	0.3
	16	0.0	0.6	68.4	37	60.9	2.1	1.6
	17	0.0	0.6	73.7	38	77.4	0.3	0.5
	18	0.0	1.7	79.9	39	53.9	4.2	2.2
	19	0.0	4.1	58.6	40	63.2	0.2	1.1

Line	ID	Forest % of total area	Water % of Total Area	Snow/Ice % of Total Area	ID	Forest % of total area	Water % of Total Area	Snow/Ice % of Total Area
	1	32.0	7.3	15.8	20	48.7	10.0	12.6
	2	74.5	4.4	1.4	21	64.0	8.1	0.7
	3	60.9	4.0	3.7	22	5.5	0.3	33.7
	4	28.0	6.3	11.9	23	26.0	31.7	0.1
	5	21.1	6.6	10.5	24	29.3	12.5	26.9
	6	0.0	11.6	14.9	25	58.5	6.0	5.7
	7	0.0	0.0	72.3	26	84.9	12.0	0.0
	8	0.0	2.1	51.6	27	65.9	8.5	0.0
	9	0.0	44.5	18.4	28	53.6	3.0	0.0
	10	0.0	9.1	52.8	29	46.7	1.8	2.4
	11	0.3	14.5	61.0	30	76.5	0.7	0.0
	12	0.0	0.0	47.3	31	77.0	0.0	0.3
	13	0.9	8.1	52.3	32	70.7	5.6	0.0
	14	0.0	0.0	0.5	33	49.8	1.3	0.0
	15	13.5	8.9	30.1	34	66.2	7.0	0.6
	16	11.2	8.5	32.7	35	71.6	1.9	0.0
	17	0.0	0.0	61.7	36	89.5	3.1	0.0
	18	0.0	30.1	22.4	37	67.8	1.2	0.0
	19	6.6	27.6	26.6	38	47.9	8.1	0.5
					40	59.1	17.2	0.7

Chapter 4

Estimating Flow Statistics

The next step taken in estimating freshwater flows was to calculate three types of flow statistics: peak streamflow values, annual high-flow values, and annual low-flow values. This was done using three sets of regression equations that were developed for Alaska by the U.S. Geological Survey (USGS). The USGS created two separate reports discussing these equations [**1**] [**8**] that are based on the same study undertaken in Alaska and its conterminous basins in Canada. In this study, the USGS examined as many gaged basins as possible around Alaska to develop equations that can then be used for ungaged basins.

A few hundred gaged basins were statistically analyzed to use in these equations. The peak streamflow study examined 301 stations in Alaska and 60 in Canada; the high-flow and low-flow study examined 222 stations. These stations either had at least ten years of records through water year 1999 or they were used in a previous USGS study and only had 8 to 9 years of records. Data from these stations were only used if the data was taken during a period that flow was not regulated through diversions or any conditions not related to the catchment's characteristics.

The basins were divided into seven hydrologically different regions, as shown in Figure 4.1, where basins in each of these regions experience similar weather systems and possess similar geomorphology. In each region, flow equations were developed for the gaged watersheds which can then be used for the ungaged watersheds in the same region.

Nine different basin characteristics (drainage area, main channel length, main channel slope, mean basin elevation, area of lakes and ponds, area of forests, area of glaciers, mean annual precipitation, and mean minimum January temperature) were used as independent variables in a regression model. Based on this model, only the basin

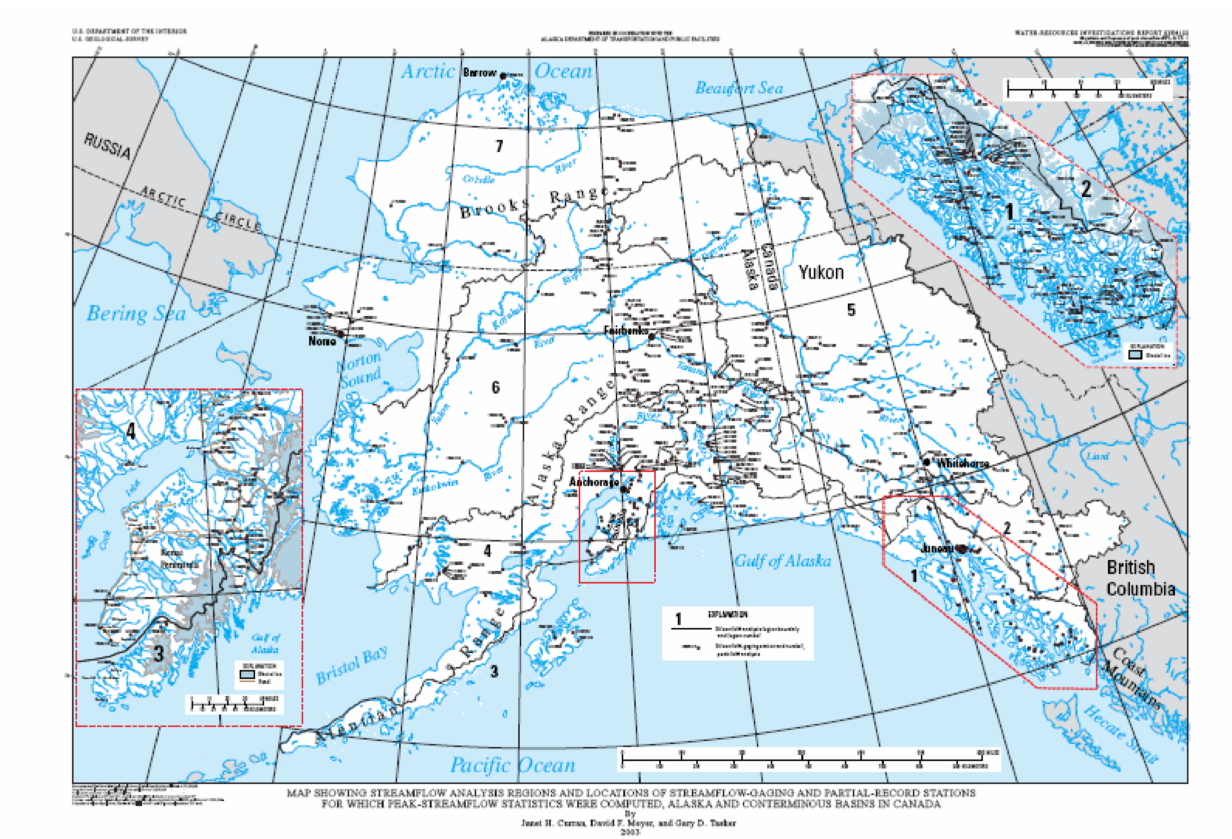


Figure 4.1: The seven zones used for hydrologic analysis by the USGS.
Source: http://pubs.usgs.gov/wri/wri034188/pdf/wri034188.plate_v1.10.pdf

characteristics that were determined to have the greatest effect on flow were used in the resulting regression equations. These resulting equations are to be used for basins which are not regulated by a condition not related to catchment characteristics such as a man-made dam or glacial damming.

4.1 Peak Flows

One set of regression equations, as shown in Table 4.1, describes the peak flows that can be expected at recurrence intervals from 2-500 years given inputs of drainage area [sq. miles], area of lakes and ponds [%], mean annual precipitation [inches], and mean minimum January temperature [°F].

Table 4.1: Regression equations for calculating peak streamflow [**1**]

[A-drainage area in square miles, P-mean annual precipitation in inches,
ST-area of lakes and ponds in percent, J-mean minimum January temperature in degrees Fahrenheit,
E-elevation in feet, F-area of forest in percent]

Estimating Equation	**Average equivalent years of record**	**Average Standard error of estimate, in percent**
Regions 1 and 3 (93 streamflow gaging stations) Applicable range of variables: A: 0.720-571; ST: 0-26; P:70-300; J: 0-32		
$Q_2 = 0.004119\ A^{0.8361}\ (ST+1)^{-0.3590}\ P^{0.9110}\ (J+32)^{1.635}$	0.88	38
$Q_5 = 0.009024\ A^{0.8322}\ (ST+1)^{-0.3670}\ P^{0.8128}\ (J+32)^{1.640}$	1.3	37
$Q_{10} = 0.01450\ A^{0.8306}\ (ST+1)^{-0.3691}\ P^{0.7655}\ (J+32)^{1.622}$	1.8	37
$Q_{25} = 0.02522\ A^{0.8292}\ (ST+1)^{-0.3697}\ P^{0.7165}\ (J+32)^{1.588}$	2.4	38
$Q_{50} = 0.03711\ A^{0.8286}\ (ST+1)^{-0.3693}\ P^{0.6847}\ (J+32)^{1.559}$	2.8	40
$Q_{100} = 0.05364\ A^{0.8281}\ (ST+1)^{-0.3683}\ P^{0.6556}\ (J+32)^{1.527}$	3.1	41
$Q_{200} = 0.07658\ A^{0.8276}\ (ST+1)^{-0.3669}\ P^{0.6284}\ (J+32)^{1.495}$	3.4	43
$Q_{500} = 0.1209\ A^{0.8272}\ (ST+1)^{-0.3646}\ P^{0.5948}\ (J+32)^{1.449}$	3.6	45

These four basin characteristics were entered into each equation for both point source and line source watersheds. The results are shown in Table 4.2 and Table 4.3 .

The average equivalent years of record and average standard error of estimate are both measures of each equation's accuracy. The average equivalent years of record represent how many years of streamflow data is necessary at a given site for the streamflow statistic to have the same accuracy as the estimate obtained from the regression equation. The error of estimate represents the percentage of error in the flow statistics for each ungaged site. Curran et al.[**1**] quotes that two-thirds of the ungaged sites should fall within these standard errors. It must also be noted that certain ranges were noted for each of the four input variables for these equations to be applicable, as shown in Table 4.1. A number of both point and line source watersheds have values that do not fall into these ranges so this may cause a higher degree of error than the average standard error.

Another important thing to note is the five line watersheds that have particularly small areas ranging from 0.01 to 0.31 square miles as shown in Table 4.1. These watersheds all fall between two larger stream sources and hence point source watersheds that are very close to each other leaving a small area of coastline for the line source. These few line watersheds have areas that are too small to be included in the range of acceptable ranges for use in the regression equations and will cause higher degrees of error.

Table 4.2: Line source watershed peak flow values all in ft^3/s

ID	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}	Q_{200}	Q_{500}
1	6287	8668	10306	12384	13979	15529	17202	19378
2	2369	3335	4004	4856	5512	6153	6846	7753
3	4660	6568	7896	9598	10916	12210	13611	15454
4	2516	3535	4248	5165	5877	6579	7341	8348
5	1597	2247	2702	3291	3748	4200	4692	5343
6	316	444	534	650	740	829	926	1055
7	5	7	8	10	11	13	14	16
8	2104	2947	3530	4273	4844	5400	6001	6785
9	17	24	28	35	39	44	49	56
10	1984	2754	3293	3989	4529	5062	5642	6408
11	197	276	332	405	462	518	579	661
12	26	37	45	56	64	71	80	91
13	2353	3302	3973	4844	5526	6203	6942	7927
14	17	25	30	37	42	47	53	60
15	3983	5646	6827	8371	9587	10803	12131	13914
16	1119	1612	1965	2430	2798	3168	3575	4125
17	1079	1598	1967	2450	2829	3208	3620	4173
18	6	9	11	14	16	18	21	24
19	91	131	161	201	232	264	300	349
20	922	1334	1630	2019	2328	2640	2982	3445
21	119	175	214	266	307	348	393	454
22	538	799	983	1222	1408	1592	1794	2061
23	75	109	133	165	190	216	244	283
24	865	1243	1513	1868	2148	2430	2739	3155
25	714	1029	1252	1542	1769	1995	2241	2570
26	466	668	811	996	1142	1286	1445	1656
27	1316	1881	2279	2796	3199	3600	4036	4618
28	1562	2295	2815	3495	4028	4562	5145	5926
29	3450	5055	6190	7668	8827	9982	11240	12921
30	468	692	849	1052	1209	1364	1533	1755
31	2937	4300	5244	6447	7372	8276	9250	10522
32	1304	1881	2285	2807	3212	3614	4050	4627
33	1462	2065	2479	3002	3400	3787	4203	4740
34	2033	2923	3546	4351	4978	5600	6275	7171
35	2492	3571	4320	5278	6017	6742	7527	8555
36	2017	2840	3410	4137	4698	5246	5839	6615
37	4495	6185	7334	8771	9860	10905	12023	13455
38	9295	12429	14569	17255	19301	21266	23378	26094
40	1937	2702	3241	3938	4483	5023	5612	6395

Table 4.3: Point source watershed peak flow values all in ft^3/s

ID	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}	Q_{200}	Q_{500}
2	2792	3962	4774	5809	6606	7384	8223	9319
3	2066	3060	3772	4704	5439	6177	6982	8064
4	2359	3500	4313	5378	6215	7054	7968	9195
5	3994	5847	7163	8879	10225	11569	13030	14987
6	599	877	1077	1341	1549	1760	1991	2303
7	13634	19152	22976	27847	31599	35259	39194	44343
8	2449	3501	4239	5190	5929	6659	7450	8497
9	8607	12333	14966	18386	21063	23724	26612	30467
10	8655	12137	14535	17574	19903	22164	24590	27745
11	2077	3073	3777	4690	5403	6111	6881	7904
12	3328	4868	5966	7405	8540	9679	10922	12596
13	6017	8430	10092	12199	13814	15383	17069	19261
14	1025	1500	1836	2271	2611	2949	3318	3808
15	4235	6219	7615	9421	10830	12227	13741	15752
16	5400	7516	8965	10790	12182	13526	14967	16829
17	2558	3611	4337	5258	5963	6648	7386	8344
18	2058	2904	3489	4236	4810	5371	5976	6767
19	1381	1944	2336	2838	3227	3608	4021	4564
20	3810	5372	6444	7798	8832	9834	10909	12301
22	1264	1830	2230	2750	3157	3563	4006	4597
23	6770	9477	11323	13639	15398	17091	18902	21230
24	3440	5022	6127	7548	8650	9736	10910	12458
25	1592	2244	2695	3268	3709	4138	4601	5205
26	2688	3928	4794	5906	6767	7615	8531	9738
27	4394	6535	8047	10007	11540	13063	14717	16917
28	8015	11201	13398	16187	18330	20416	22663	25592
29	2568	3781	4634	5737	6596	7447	8371	9596
30	1783	2554	3086	3759	4274	4775	5314	6013
31	1450	2146	2633	3262	3749	4231	4752	5440
32	2314	3308	3991	4853	5511	6148	6833	7718
35	2974	4251	5125	6228	7068	7881	8753	9879
36	3740	5174	6155	7390	8331	9239	10215	11473
37	2480	3438	4092	4916	5542	6147	6797	7635
38	2290	3350	4084	5022	5744	6450	7212	8209
39	2366	3212	3789	4513	5062	5590	6157	6885
40	2731	3990	4864	5979	6838	7678	8584	9769

4.2 High flow statistics

The second set of equations used describes high flow statistics. These represent daily mean flows that will be equaled or exceeded x-percent of the time, ranging from 1-15%. These equations are shown in Table 4.4 and only require drainage area [miles] and mean annual precipitation [inches] as inputs.

Like the peak flow statistics, a standard error of estimate if provided. There is also a list of ranges shown in Table 4.4 within which each basin's characteristics must fall for its flow statistic to have the standard error of estimate. Again, some of the basins did not fall within this range and this will cause higher error in the flow estimates. The other measure of error is the coefficient of determination. This is also called an R-squared value which shows how closely the applied model, in this case the regression model, fits.

Table 4.4: Regression equations for calculating annual high-duration flows [**8**]

[A-drainage area in square miles, P-mean annual precipitation in inches]

Estimating Equation	**Coefficient of determination**	**Standard error of estimate, in percent**
Regions 1 and 3 (78 streamflow gaging stations) Applicable range of variables: A: 1.82-571; P: 70-300		
$O\text{-}S15 = 0.1358\ A^{0.9660}\ P^{1.016}$	0.97	22
$O\text{-}S10 = 0.2145\ A^{0.9472}\ P^{0.9740}$	0.97	21
$O\text{-}S9 = 0.2382\ A^{0.9422}\ P^{0.9652}$	0.97	22
$O\text{-}S8 = 0.2670\ A^{0.9374}\ P^{0.9550}$	0.97	22
$O\text{-}S7 = 0.3033\ A^{0.9307}\ P^{0.9443}$	0.97	22
$O\text{-}S6 = 0.3486\ A^{0.9234}\ P^{0.9329}$	0.96	22
$O\text{-}S5 = 0.4120\ A^{0.9162}\ P^{0.9179}$	0.96	23
$O\text{-}S4 = 0.4875\ A^{0.9074}\ P^{0.9057}$	0.96	23
$O\text{-}S3 = 0.6039\ A^{0.8963}\ P^{0.8892}$	0.96	24
$O\text{-}S2 = 0.7960\ A^{0.8829}\ P^{0.8697}$	0.95	25
$O\text{-}S1 = 1.279\ A^{0.8637}\ P^{0.8293}$	0.94	27

Table 4.5 shows the results for line source watersheds and Table 4.6 shows the results for point source watersheds.

Table 4.5: Line source watershed annual high-duration flow values in ft^3/s, where O-Sx is the mean daily discharge with an x-percent chance of exceedance.

ID	O-S15	O-S10	O-S9	O-S8	O-S7	O-S6	O-S5	O-S4	O-S3	O-S2	O-S1
1	1755	2084	2168	2265	2370	2493	2654	2843	3090	3485	4231
2	503	614	643	677	714	759	817	885	976	1121	1399
3	1144	1375	1435	1503	1578	1667	1783	1918	2097	2381	2926
4	688	835	874	918	967	1025	1100	1189	1307	1495	1855
5	434	531	557	586	620	659	710	771	852	980	1228
6	83	104	110	117	125	135	147	162	183	215	278
7	0	0	0	0	0	0	1	1	1	1	1
8	395	483	506	533	564	600	646	701	775	893	1117
9	5	6	7	7	8	8	9	11	12	15	21
10	633	768	803	844	889	943	1012	1094	1203	1377	1708
11	56	71	76	80	86	93	102	112	127	150	196
12	2	2	3	3	3	3	4	4	5	6	9
13	796	963	1007	1056	1112	1178	1263	1363	1496	1708	2114
14	1	1	2	2	2	2	2	3	3	4	6
15	1514	1815	1892	1981	2077	2190	2340	2512	2739	3101	3800
16	372	460	483	509	540	575	622	676	749	866	1093
17	150	189	199	211	225	242	263	289	323	378	487
18	2	2	2	3	3	3	3	4	5	6	8
19	33	43	46	49	53	58	63	71	80	96	127
20	309	383	403	425	451	482	521	568	631	731	928
21	25	33	35	38	41	44	49	55	62	75	100
22	63	81	86	91	98	106	116	128	145	171	224
23	25	32	34	37	39	43	47	53	60	73	97
24	290	360	379	400	424	453	491	535	595	689	875
25	164	205	216	229	244	262	284	312	349	407	522
26	124	156	165	175	187	201	219	240	269	316	407
27	354	437	459	484	512	546	590	642	712	822	1038
28	325	403	424	448	475	507	549	598	665	770	977
29	701	857	898	944	996	1057	1138	1231	1356	1553	1940
30	53	68	72	77	82	89	98	108	123	145	191
31	321	397	417	440	467	498	539	587	652	754	954
32	275	341	359	379	402	429	465	507	564	654	831
33	203	252	265	280	298	318	344	376	419	488	619
34	497	610	639	673	712	757	816	885	978	1125	1411
35	430	528	554	584	617	657	708	769	850	979	1229
36	405	495	520	547	578	615	663	720	796	917	1149
37	729	877	916	961	1011	1070	1145	1235	1355	1546	1904
38	2897	3384	3508	3650	3802	3980	4212	4487	4842	5415	6470
40	742	899	940	987	1039	1101	1181	1276	1401	1601	1983

Table 4.6: Point source watershed annual high-duration flow values in ft^3/s, where O-Sx is the mean daily discharge with an x-percent chance of exceedance.

ID	O-S15	O-S10	O-S9	O-S8	O-S7	O-S6	O-S5	O-S4	O-S3	O-S2	O-S1
2	396	485	508	535	566	602	649	705	779	898	1124
3	335	416	437	462	490	523	566	616	684	792	1005
4	369	457	480	507	537	573	620	674	748	865	1095
5	694	847	887	932	983	1043	1122	1214	1336	1530	1909
6	149	188	199	211	225	241	263	288	323	378	487
7	2471	2917	3030	3161	3299	3463	3679	3928	4254	4776	5765
8	451	552	579	609	644	685	738	801	885	1018	1275
9	2041	2432	2532	2647	2769	2913	3105	3324	3612	4072	4959
10	1386	1653	1722	1801	1887	1989	2121	2277	2482	2808	3425
11	278	346	364	385	408	436	473	516	574	666	847
12	799	974	1020	1072	1130	1198	1288	1392	1530	1750	2181
13	1003	1204	1257	1317	1383	1461	1562	1682	1840	2091	2567
14	170	213	225	238	254	272	296	324	362	423	543
15	659	806	844	888	937	995	1071	1159	1277	1464	1830
16	868	1044	1090	1142	1200	1269	1358	1463	1603	1825	2244
17	376	461	484	509	539	573	618	671	743	856	1073
18	360	442	464	489	517	551	594	645	715	824	1034
19	297	366	385	406	430	459	495	539	599	693	873
20	529	643	673	708	746	793	852	922	1017	1166	1451
22	282	350	368	389	413	441	477	520	579	671	852
23	900	1081	1129	1183	1243	1314	1406	1515	1659	1888	2321
24	482	593	621	655	692	736	794	861	952	1096	1376
25	275	339	356	376	398	425	459	500	556	643	812
26	358	442	464	490	519	553	598	651	722	834	1053
27	620	761	797	840	887	942	1016	1100	1214	1393	1748
28	1756	2088	2174	2271	2377	2501	2665	2854	3104	3502	4258
29	376	465	488	515	546	582	629	684	759	877	1108
30	216	269	283	299	317	339	367	401	447	520	660
31	161	203	214	227	242	260	282	309	346	405	520
32	257	318	334	353	374	400	432	471	524	607	768
35	331	407	428	451	477	509	549	597	662	765	962
36	671	810	847	888	935	991	1062	1147	1260	1439	1777
37	425	518	542	570	602	640	689	747	825	948	1182
38	264	328	345	365	387	414	448	489	544	631	802
39	492	596	624	655	690	733	786	851	937	1075	1331
40	322	399	419	443	469	501	542	590	655	758	959

4.3 Low Flow Statistics

The final set of equations used was the seasonal low-flow equations. These are denoted as J-Sx, representing the daily mean discharge that will be equaled or exceeded x-percent of the time for July through September. These low-flow equations are only valid for the season July-through-September because low-flow data collected in the winter months is compromised by ice effects. These equations require drainage area [miles], mean annual precipitation [inches], and mean basin elevation [feet] as inputs and are shown in Table 4.7 .

Table 4.7: Regression equations for calculating seasonal low-duration flows [**8**]

[A-drainage area in square miles, P-mean annual precipitation in inches, E-mean basin elevation in feet above sea level]

Estimating Equation	Coefficient of determination	Standard error of estimate, in percent
Region 1 (65 streamflow gaging stations) Applicable range of variables: A: 1.82-571; P: 70-300; E: 358-3,900		
J-S98 = $2.532 \times 10^{-9} A^{1.142} P^{1.521} E^{1.674}$	0.93	66
J-S95 = $7.423 \times 10^{-9} A^{1.104} P^{1.485} E^{1.612}$	0.94	55
J-S90 = $2.479 \times 10^{-8} A^{1.080} P^{1.451} E^{1.520}$	0.95	49
J-S85 = $5.016 \times 10^{-8} A^{1.058} P^{1.380} E^{1.506}$	0.95	45
J-S80 = $8.813 \times 10^{-8} A^{1.044} P^{1.347} E^{1.477}$	0.96	43
J-S70 = $2.456 \times 10^{-7} A^{1.028} P^{1.300} E^{1.407}$	0.96	39
J-S60 = $6.997 \times 10^{-7} A^{1.013} P^{1.264} E^{1.323}$	0.97	35
J-S50 = $2.089 \times 10^{-6} A^{0.9961} P^{1.226} E^{1.232}$	0.97	32

Table 4.8 and Table 4.9 show the results of the low-flow analysis for Glacier Bay. Note that these values have the same errors as the high-flow values. The majority of the watersheds' statistics should fall within the standard error shown in Table 4.7 with the

exception of those watersheds that do not fall into the proper ranges of area, elevation and/or mean annual precipitation also shown in Table 4.7 .

Table 4.8: Line source watershed seasonal low-duration flow values in ft^3/s, where J-Sx is the mean daily discharge with an x-percent chance of exceedance.

Line: ID	J-S98	J-S95	J-S90	J-S85	J-S80	J-S70	J-S60	J-S50
1	54	73	100	120	139	182	233	294
2	10	14	21	25	30	41	54	70
3	34	47	65	79	92	121	157	198
4	38	52	70	85	99	128	160	197
5	17	24	33	41	48	63	81	102
6	4	6	8	10	12	16	21	26
7	0	0	0	0	0	0	0	0
8	120	157	195	236	269	323	373	419
9	0	0	0	0	0	0	0	0
10	134	176	220	266	302	367	430	492
11	5	7	10	13	15	20	25	30
12	0	0	0	0	0	0	0	0
13	145	189	239	288	328	401	473	545
14	0	0	0	0	0	0	0	0
15	127	166	216	261	300	377	461	551
16	11	16	22	28	33	44	58	74
17	18	25	33	42	49	62	76	91
18	0	0	0	0	0	0	0	0
19	1	1	2	3	3	4	6	8
20	0	0	0	0	0	0	1	1
21	0	0	0	0	1	1	1	2
22	5	8	11	14	17	22	27	33
23	0	0	1	1	1	2	2	3
24	22	30	40	51	60	77	95	116
25	9	12	17	22	26	34	43	54
26	0	0	0	0	0	0	1	1
27	6	9	13	16	20	27	36	47
28	11	16	22	28	33	44	57	73
29	55	74	98	121	141	180	221	267
30	0	0	1	1	1	2	2	4
31	5	7	11	13	16	22	30	40
32	4	6	9	12	14	20	27	35
33	7	11	15	19	22	29	38	48
34	13	18	26	32	38	51	67	86
35	10	15	21	26	31	41	54	70
36	9	13	18	23	27	36	47	62
37	34	48	65	78	91	117	147	183
38	167	219	290	337	383	482	597	723
40	4	6	10	12	15	21	29	40

Table 4.9: Point source watershed seasonal low-duration flow values in ft^3/s, where J-Sx is the mean daily discharge with an x-percent chance of exceedance.

Point: ID	J-S98	J-S95	J-S90	J-S85	J-S80	J-S70	J-S60	J-S50
2	90	119	150	182	208	254	297	340
3	89	118	147	182	209	256	298	338
4	116	151	186	231	264	319	369	416
5	187	240	296	362	412	498	577	651
6	19	26	35	44	52	66	80	95
7	1707	2047	2360	2734	3000	3426	3752	3981
8	126	164	204	248	283	342	396	448
9	654	809	974	1153	1289	1530	1745	1934
10	1079	1314	1518	1775	1956	2232	2438	2581
11	36	50	64	81	94	119	143	170
12	209	267	329	402	458	554	643	726
13	706	872	1018	1200	1329	1528	1681	1794
14	16	22	29	37	44	56	69	84
15	92	121	155	191	220	273	328	384
16	555	692	815	961	1067	1232	1363	1463
17	95	126	158	192	219	265	309	351
18	58	78	101	123	142	175	209	244
19	41	56	73	90	104	130	156	184
20	158	206	255	307	348	417	480	540
22	33	45	58	73	85	107	131	156
23	553	689	813	959	1065	1232	1365	1469
24	43	58	77	95	111	141	173	208
25	36	49	64	79	91	114	138	163
26	16	22	30	38	45	59	75	94
27	77	102	131	162	188	235	284	335
28	173	225	290	344	393	488	591	699
29	5	8	12	15	18	25	33	44
30	3	4	6	7	9	13	17	23
31	6	9	12	15	19	25	32	41
32	12	18	25	31	36	47	60	75
35	13	19	26	33	38	50	65	81
36	44	61	81	98	113	144	179	218
37	27	37	50	61	72	92	114	140
38	8	12	17	21	25	34	44	56
39	44	61	80	97	111	140	171	205
40	9	12	17	22	26	35	46	59

To summarize all of the statistics shown above, Table 4.10, Figure 4.2 and Figure 4.3 show the peak-flow, high-duration flow and low-duration flow statistics for all of the line source watersheds, point source watersheds, and for all of the watersheds combined.

Table 4.10: Summary of all three flow statistics with flow values in cfs.

	Line	**Point**	**Total**
J-S98	1080	7135	8214
J-S95	1447	8909	10356
J-S90	1902	10655	12557
J-S85	2303	12645	14948
J-S80	2658	14143	16801
J-S70	3357	16649	20005
J-S60	4130	18852	22982
J-S50	4983	20786	25769
O-S15	17495	21820	39315
O-S10	21146	26413	47559
O-S9	22101	27613	49714
O-S8	23194	28986	52180
O-S7	24411	30515	54926
O-S6	25850	32321	58171
O-S5	27717	34669	62386
O-S4	29919	37429	67347
O-S3	32851	41106	73957
O-S2	37509	46943	84451
O-S1	46454	58178	104632
Q_{2}	69195	129904	199099
Q_{5}	97339	185246	282585
Q_{10}	116960	223739	340699
Q_{25}	142132	272978	415110
Q_{50}	161626	311010	472636
Q_{100}	180794	348297	529091
Q_{200}	201574	388547	590121
Q_{500}	228938	441405	670342

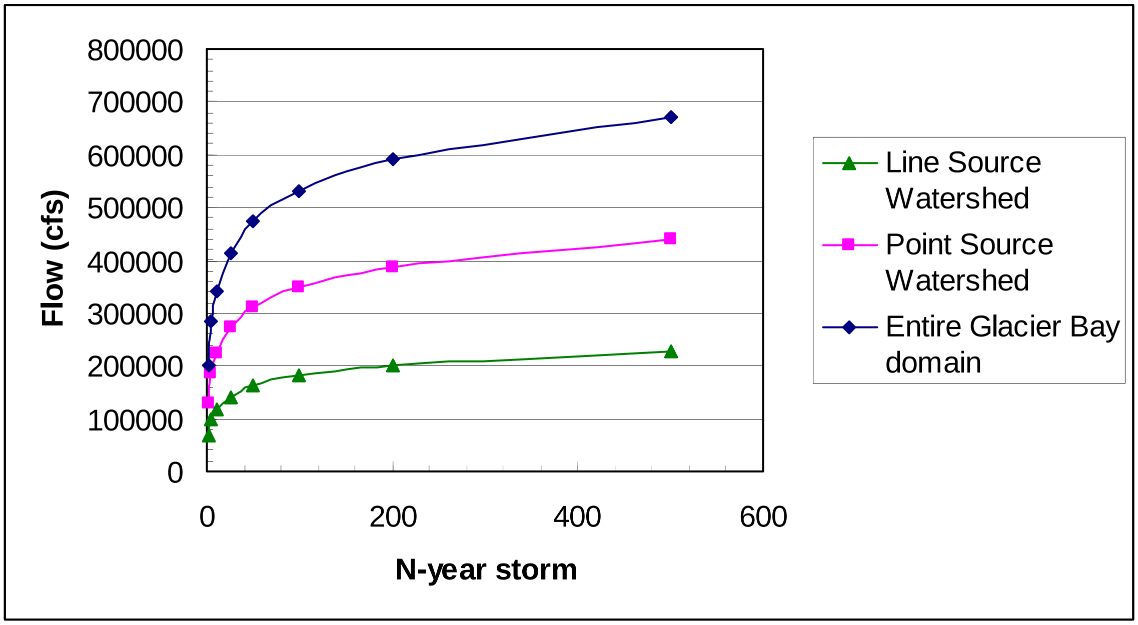
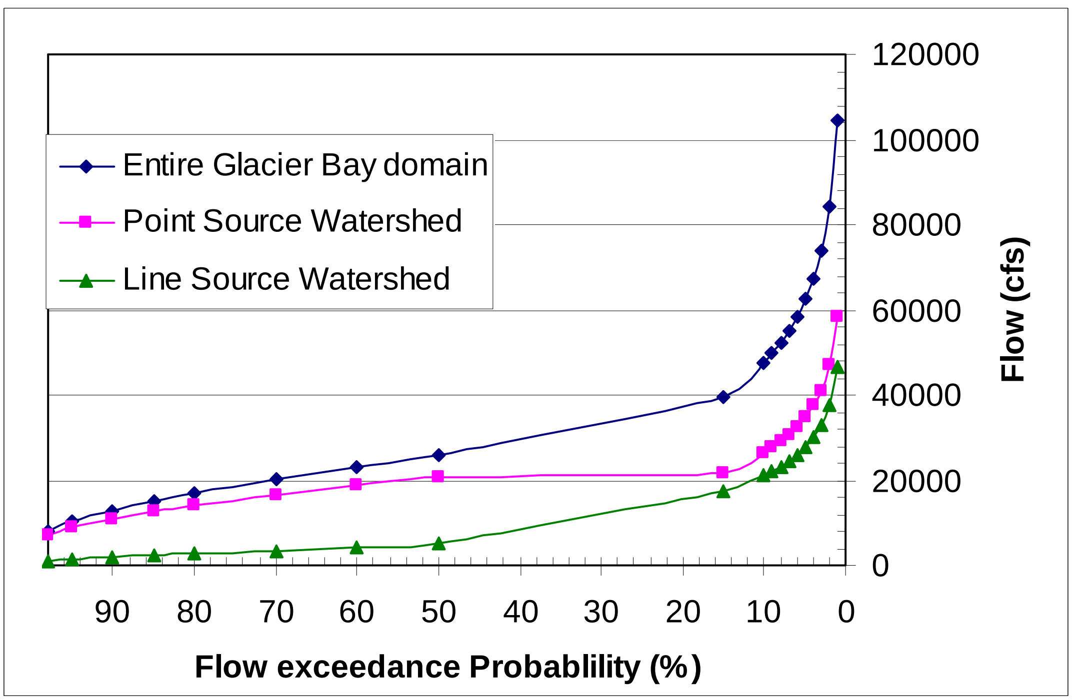


Figure 4.2: Summary graph showing peak flows vs. the n-year event..



4.3: Summary graph showing flow vs. flow exceedance probabilities obtained from the high-duration and low-duration flow values.

These figures show the approximate magnitudes of flow created by the two different types of watersheds. The point watersheds are always responsible for the majority of the discharge having averages of 84%,56%, and 66% of the total low-flows, high-flows, and peak-flows respectively. The daily average flow for the entire Glacier Bay domain varies greatly from around 8,000cfs for a 98 percent probability of exceedance to about 105,000cfs for the one percent exceedance probability. The peak flows for the domain do not vary as drastically and stay within the same order of magnitude ranging from about 200,000 cfs to 670,000 cfs. However, these peak flows are rather sizable; to compare, the Mississippi River at New Orleans has an average discharge of 600,000 cfs according to www.nps.gov.

Chapter 5

Data Validation

All of the flow values that were estimated have variable and somewhat high amounts of possible error. So it would be informative as well as encouraging if these data could be verified somehow. In a trip to Glacier Bay, discharge values were collected for four small watersheds. These four watersheds as well as five United States Geological Survey gaged watersheds in Alaska were input into the three sets of regression equations and then compared. Ideally the exceedance probabilities for all of the watersheds on a given day would be the same or similar to prove that these equations are consistent. The complete process and results are described below.

5.1 Glacier Bay Flow Data

During a trip up to Glacier Bay at then end of May, 2007 discharge values were collected for four small streams around the bay. These sites and their recorded locations are as follows:

North Fingers South Stream	N 58°34’37.2” W 136°13’2.7”
Rush Point	N 58°28’18.0” W 136°05’50.8”
Ice Valley	N 58°48’10” W 136°13’2.7”
Berg Bay South	N 58°30’17.1” W 136°13’2.7”

Flow values were gathered using standard wading survey for all of the sites except for Rush Point, where an acoustic Doppler current profiler was used. The average discharge values measured as well as the time of measurement is shown in Table 5.1

Table 5.1: Approximate time of data collection and average discharge values measured at four sites in Glacier Bay.

	Date/Time of data collection	**flow [cms]**	**flow [cfs]**
North Fingers South Stream	May 31, 2pm	5.6	199.3
N. Rush Point Stream	May 29, 3 pm	9.1	321.2
Ice Valley	June 1, 12 pm	3.0	106.5
Berg Bay South Stream	May 31, 11am	4.9	174.7

The location of each site was then added to a point shapefile in ArcGIS. This was superimposed onto the flow accumulation layer (created previously for Glacier Bay) to determine which stream on that layer corresponded to the stream that was measured. Then, using the same process described in Chapter 2, the four watersheds for the four small streams visited in Glacier Bay were delineated. These are shown in Figure 5.1

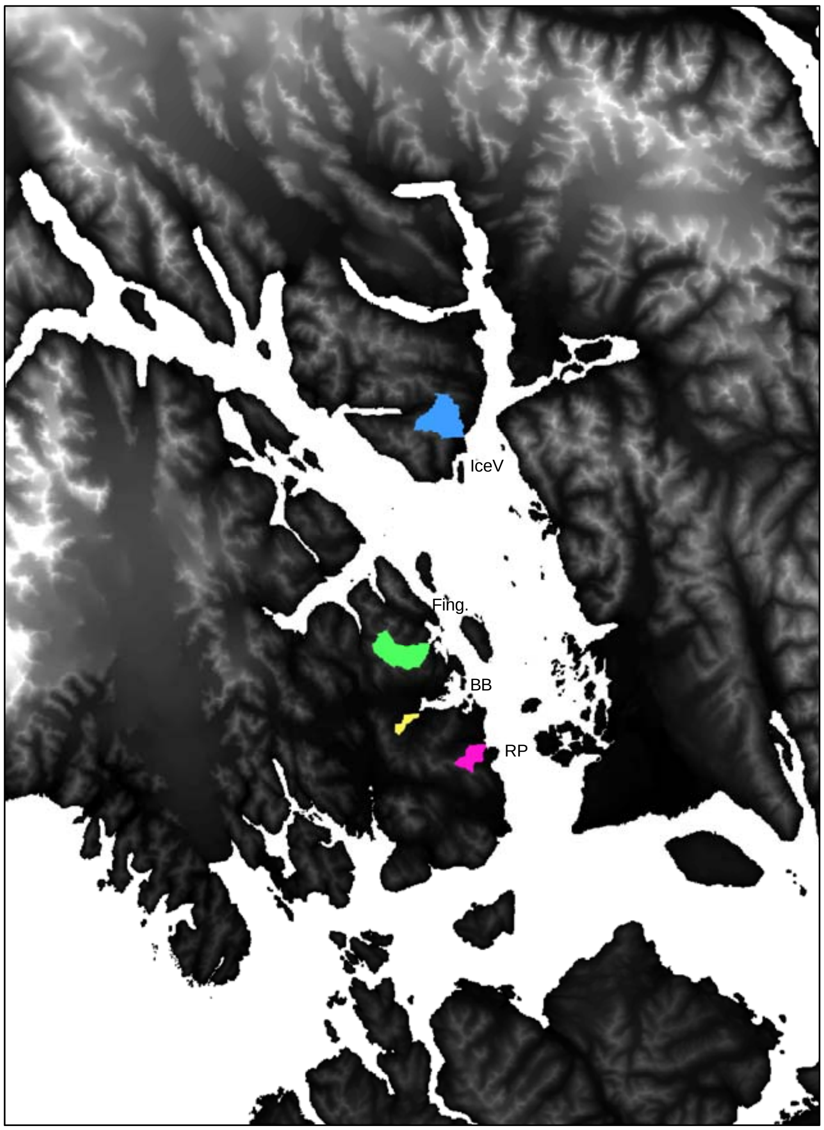


Figure 5.1: Location of four watersheds that were visited in Glacier Bay. (IceV = Ice Valley, Fing. = North Fingers South Stream, BB = Berg Bay South Stream, RP = N. Rush Point Stream)

The next step in using the regression equations was to extract the necessary characteristics of each watershed. This was done through ArcGIS using the same procedure described in Chapter 3. Table 5.2 shows the results.

Table 5.2: Watershed characteristics for four small watersheds in Glacier Bay

	Area [Sq. mi]	X Centroid	Y Centroid	Mean Elevation [ft]
North Fingers South Stream	7	425902	6492680	1083
N. Rush Point Stream	3	434355	6480270	637
Ice Valley	7	430896	6520280	979
Berg Bay South Stream	1	426509	6484340	288

	% Water	% Forest	% Snow/Ice	P (mean annual precip.) [inches]	J (mean min. Jan temp) [°F]
North Fingers South Stream	1%	53%	1%	78	23
N. Rush Point Stream	0.4%	83%	1%	77	24
Ice Valley	5%	35%	9%	67	19
Berg Bay South Stream	0.1%	95%	0%	80	24

Then, using the three sets of regression equations shown in Chapter 4, flow statistics were calculated with the results shown in Table 5.3 . However, it must be noted that three of the values used in the regression equations did not fall within the acceptable ranges. Berg Bay's area is too low for both low and high flow regression equations, Ice Valley's average annual precipitation falls below acceptable precipitation range for all of the regression equations and Berg Bay's elevation is below the minimum elevation value of 358ft. All of these values are not far out of the acceptable range but this will still cause a greater percentage of error.

Table 5.3: Flow statistics, in cfs, for four small watersheds in Glacier Bay

		North Fingers South Stream	**N. Rush Point Stream**	**Ice Valley**	**Berg Bay South Stream**
Peak Flow Statistics	Q_{2}	744	336	607	161
	Q_{5}	1076	488	890	234
	Q_{10}	1305	592	1088	284
	Q_{25}	1596	725	1344	348
	Q_{50}	1819	827	1542	396
	Q_{100}	2035	925	1738	443
	Q_{200}	2269	1032	1950	494
	Q_{500}	2572	1169	2230	559
High-flow Annual Statistics	**O-S1**	247	105	234	49
	O-S2	190	79	179	36
	O-S3	161	66	152	30
	O-S4	143	58	134	26
	O-S5	129	52	122	23
	O-S6	119	47	111	21
	O-S7	110	44	103	19
	O-S8	103	41	96	18
	O-S9	97	38	90	17
	O-S10	91	36	85	15
	O-S15	72	28	67	12
Low-flow Seasonal Statistics	**J-S50**	16	3	13	0.5
	J-S60	12	2	10	0.3
	J-S70	9	2	7	0.2
	J-S80	7	1	5	0.1
	J-S85	6	1	4	0.1
	J-S90	4	1	3	0.1
	J-S95	3	0	2	0.0
	J-S98	2	0	2	0.0

5.2 USGS Gaged Station Flow Data

Three gaged stations and their contributing watersheds in Southeast Alaska were also anaylzed. Without gaging stations in Glacier Bay, gaging stations that were as close as possible to Glacier Bay had to be examined. These stations and the watershed characteristics were found at http://waterdata.usgs.gov/nwis/rt. The stations used are as listed in Table 5.4 and are shown geographically in Figure 5.2.

Table 5.4: Location and relevant watershed characteristics for the three USGS stations in Southeast Alaska.

	Kadashan R AB Hook C Near Tenakee, AK	**Fish C Near Ketchikan, AK**	**Montanta C Near Auke Bay, AK**
Station ID	15106920	15072000	15052800
LAT (N)	57.66	55.39	58.4
LONG (W)	135.18	131.19	134.61
Mean Elevation [ft]	1020	1300	1500
% Water	0	0.14	0
Area [Sq. mi]	10.2	32.1	14.1
P (mean. Annual precip.) [inches]	100	180	100
J (mean min. Jan temp) [°F]	26	28	22

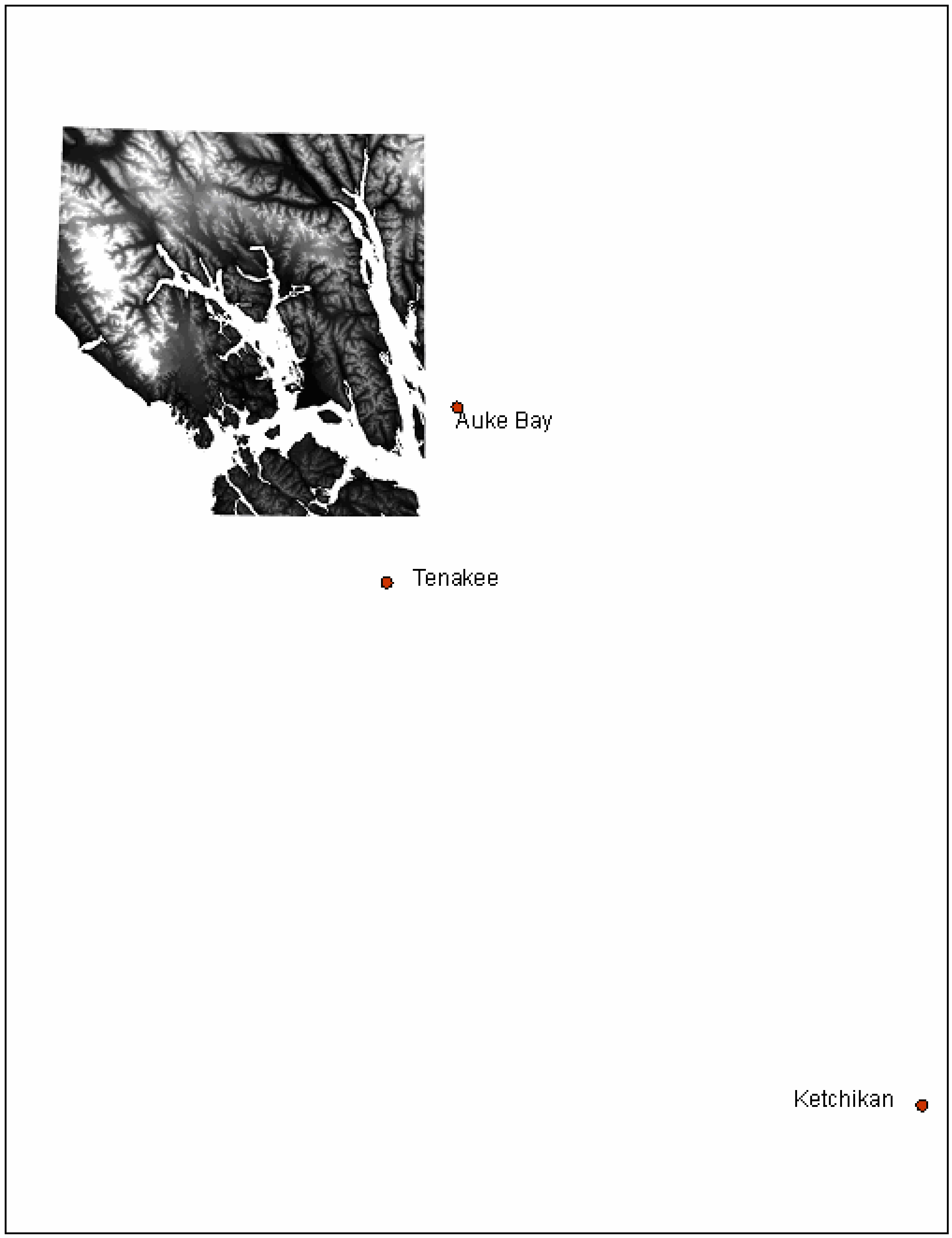


Figure 5.2: Locations of the three USGS stations in Southeast Alaska.

The values for daily mean discharge were also available from the USGS and were extracted for same days that discharge measurements were made in Glacier Bay: May 29, May 31, and June 1. Table 5.5 shows these values.

Table 5.5: Measured flow values for the three USGS stations in Southeast Alaska

	Flow [cfs]		
	29-May	**31-May**	**1-Jun**
Tenakee	234	135	133
Ketchikan	569	559	556
Auke Bay	200	233	177

Flow statistics were then calculated using the characteristics given for these three watersheds. The results are shown below in Table 5.6 .

Table 5.6: Flow statistics, in cfs, for the three USGS stations in Southeast Alaska

		Tenakee	Ketchikan	Auke Bay
Peak Flow Statistics	Q2	1456	6543	1699
	Q5	2053	8659	2391
	Q10	2457	10052	2863
	Q25	2961	11736	3457
	Q50	3340	12974	3908
	Q100	3704	14121	4342
	Q200	4092	15331	4808
	Q500	4587	16820	5406
High-flow Annual Statistics	O-S1	433	1898	573
	O-S2	339	1557	452
	O-S3	291	1370	389
	O-S4	260	1252	348
	O-S5	237	1162	319
	O-S6	219	1090	295
	O-S7	204	1032	275
	O-S8	191	983	259
	O-S9	181	940	246
	O-S10	172	902	233
	O-S15	138	758	188
Low-flow Seasonal Statistics	J-S50	30	264	68
	J-S60	24	219	55
	J-S70	18	179	44
	J-S80	14	143	34
	J-S85	11	125	29
	J-S90	9	106	23
	J-S95	6	80	17
	J-S98	4	58	12

5.3 Comparing the results

The last and most important step in this process is comparing the data calculated for both sets of watersheds. What is most important is the approximate exceedance probability calculated by the high-flow and low-flow equations that corresponds to actual flow values on May 29th, May 31st, and June 1st. These probabilities should be relatively similar for all watersheds on a given day. This would show that the equations are successfully estimating flows.

First, the high-flow and low-flow values for all nine watersheds (four in Glacier Bay and the three USGS watersheds) were graphed according to their exceedance probabilities. Then the measured flow values were added to this graph to show the approximate exceedance value that would correspond with each flow value. Figure 5.3 shows this for the four watersheds in Glacier Bay. Figure 5.4 shows the same graph for the three USGS watersheds.

A number of important conclusions can be drawn from these two figures. It is clear that there is no definite agreement on the probability of exceedances. Fortunately, the four watersheds in Glacier Bay are all very close and consistantly show high flows. Some are quite high and are a good amount higher than the value estimated for the one percent exceedance flow. A possible explanation for this could be difference in the type of flow estimates being used; the high-duration flow values correspond to daily mean flows whereas the discharge values used for these four watersheds are measurements taken once during the day and do not represent the mean flow for the day. These measurements were mostly taken within a one hour period and by no means represent the mean discharge value for the day.

Still there are many other sources of error that can lead to discrepancies in the flow values for the four Glacier Bay watershed. For example, all of the layers used to extract watershed characteristics in ArcGIS have a grid size that is 100m x 100m. This grid unit may be too large to obtain the degree of accuracy required for these smaller watersheds. There was also a degree of uncertainty in the choosing of the pour points for these watersheds. Using the recorded geographical positions, each location where measurements was taken was added to a shapefile in ArcGIS that was placed over the flow accumulation layer. For most watersheds, this clearly showed which stream on the flow accumulation raster was the correct stream. In the case of Berg Bay, two streams' outlet cells were next to eachother, making the correct choice unclear. Finally, these smaller watersheds could be affected by local differences in rainfall or glacial melting. Considering that these measurements were taken on different days, it may have rained on one or all of these watersheds between May 29th and June 1st, causing higher flows on a given day.

Unlike the relative agreement found in the Glacier Bay flow statistics in Figure 5.3**,** Figure 5.4 shows less agreement. The exceedance probabilities cover a wider range, from about 5.5 to 26%. They also don't follow any chronological patterns; some watersheds had increasing flows over the four day period, whereas others had decreasing flows. This implies that these basins may have been experiencing different conditions such as differing ice melt rates or precipitation rates. This can be expected because all of these sites are rather spread out. Some of these values are rather unreliable as well because any flow value that is below the estimated value for a fifteen percent exceedance probability falls into a range predicted by the low-flow regression equations. These equations are only meant to apply to the months July through September and these flow values occurred in late May and early June.

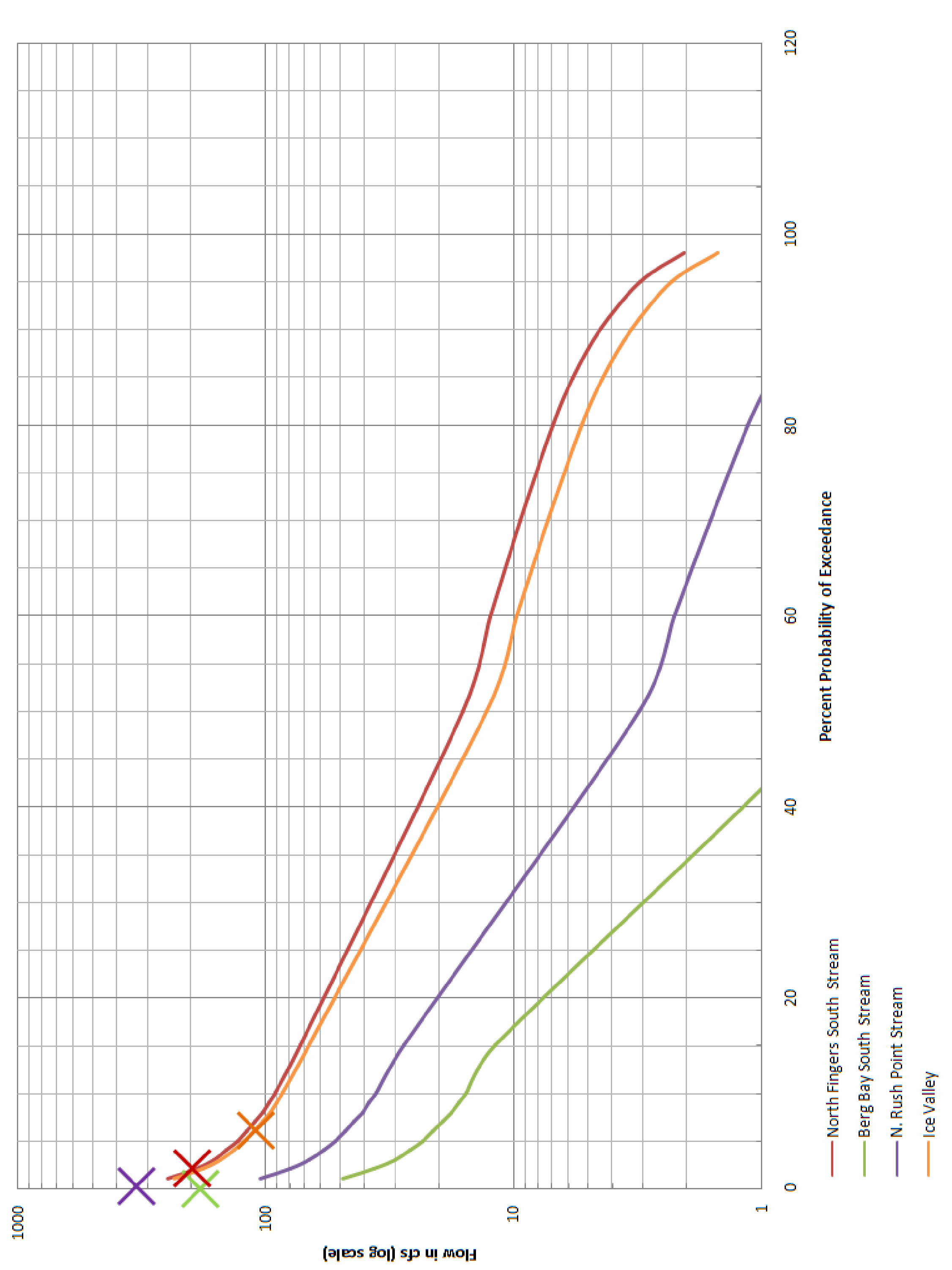


Figure 5.3: High-flow estimates, low-flow estimates, and measured flows (colored “x”s) for four small watersheds in Glacier Bay

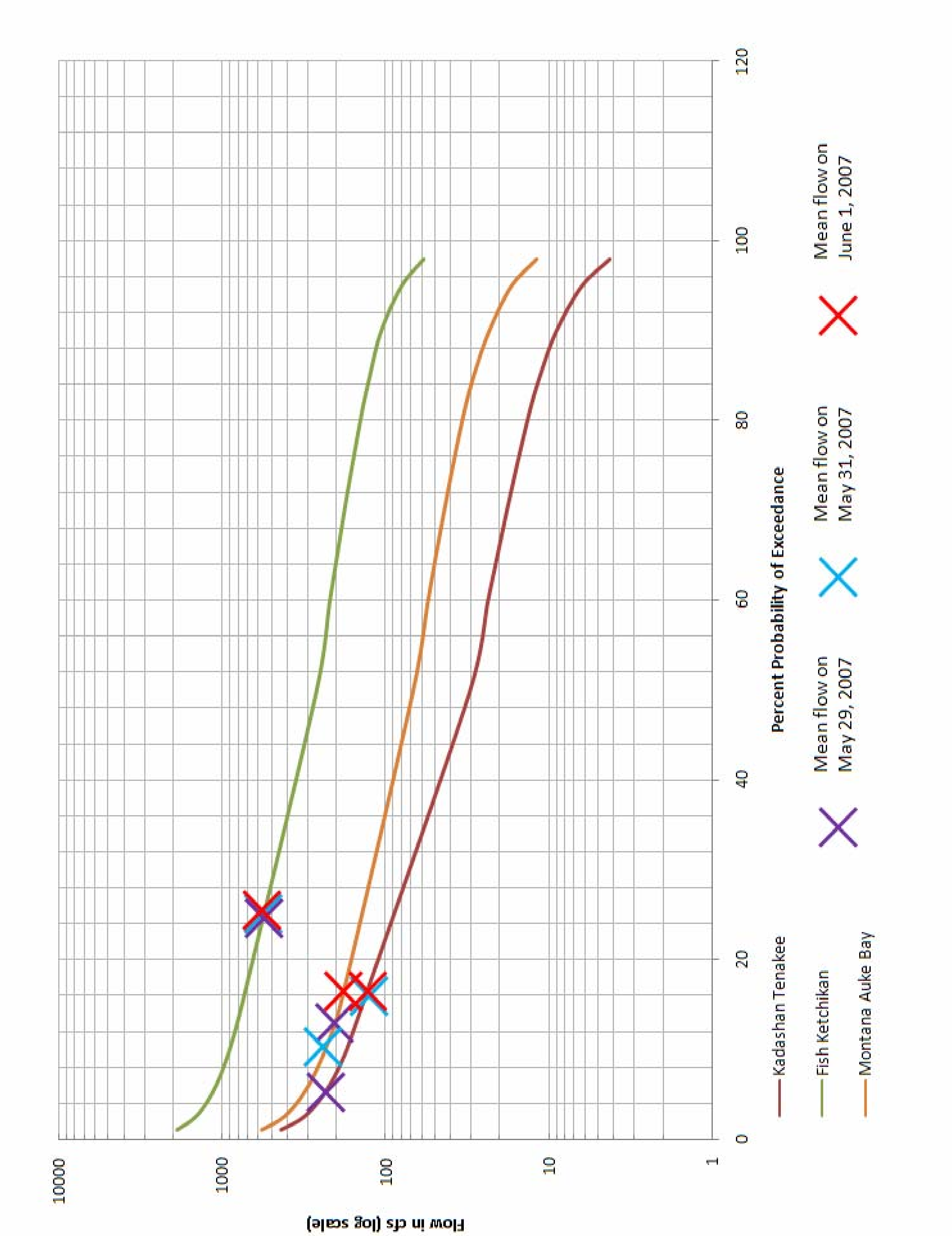


Figure 5.4**:** High-flow estimates, low-flow estimates, and measured flows for the three USGS stations in Southeast Alaska.

To further visualize these results, Table 5.7 was created to show the approximate exceedance probabilities that correspond to all of the discharge measurements for each watershed.

Table 5.7**:** Daily comparison of exceedance probabilities that correspond to the measured flow values for the four Glacier Bay watersheds and the three USGS watersheds in Southeast Alaska.

	29-May		31-May	
Site	**Discharge [cfs]**	**Approximate Probability of Exceedance [%]**	**Discharge [cfs]**	**Approximate Probability of Exceedance [%]**
North Fingers South Stream	----	----	199	1.8
N. Rush Point Stream	321	<1	----	----
Ice Valley	----	----	----	----
Berg Bay South Stream	----	----	175	<1
Tenakee	234	5.5	135	16*
Ketchikan	569	26*	559	26*
Auke Bay	200	12.5	233	10
	1-Jun			
North Fingers South Stream	----	----		
N. Rush Point Stream	----	----		
Ice Valley	106	7		
Berg Bay South Stream	----	----		
Tenakee	133	16*		
Ketchikan	556	26*		
Auke Bay	177	16*		

*Probabilities higher than 15 only apply to July-September

These probabilities of exceedance were roughly extracted from Figures 5.3 and 5.4 and are not very precise. They do however clearly show the range of values and highlight the lack of chronological patterns.

Fortunately, all of the measured flow values are within the range of flows described by the combination of the low-flow and high-flow regression equations. This verifies the ability of the equations to calculate flows that are of the same magnitude as the actual flows. All of the exceedance probabilities are all below 30% as well which suggests a higher degree of agreement. Considering the numerous sources of error throughout this process, the results of this comparison are somewhat reassuring. They are not strong enough to prove the accuracy of these equations, but they are certainly not strong enough to disprove it either.

Chapter 6

Conclusions and Recommendations

The following summarizes the results of this thesis as well as suggests ideas for future research.

6.1 Conclusions

This thesis characterized the watersheds in Glacier Bay using GIS methods as well as quantified freshwater inflows. The values resulting from the USGS regression equations show large amounts of freshwater being input into the bay daily on the order of thousands of cfs. It also shows that most of this flow is emanating from large streams and rivers rather than the smaller flow sources summarized by line watersheds.

There is a reasonable amount of uncertainty incorporated into these values that are a product of the regression equations, the resolution use in ArcGIS, and most importantly the severe lack of data. Without any known flow values in the bay, there is no way of confirming the validity of the calculated flow values. Performing a few flow measurements on smaller watersheds in Glacier Bay and subsequently analyzing these did provide a degree of assurance. But this by no means proves the correctness of the flow values.

6.2 Recommendations

The most obvious extension of this work would be to collect flow and/or meteorological data around Glacier Bay. This would serve to verifty these flow values and provide more accuracy. For truly reliable flow data, a gaging system would have to be set up that would collect daily flow measurements. Currently, there are existing weather stations around the bay that measure precipitation and temperature (D. Lawson, Cold Region Research and Engineering Lab, unpubl. Data). Adding this data to the watershed characterization would greatly strengthen the two meterological parameters that were interpolated.

Having these freshwater estimates gives an idea of flow magnitudes but it does not provide an outlook on when these flows can be expected througout the year. If these flow estimates were fit onto some form of hydrograph this could provide a better understanding of temporal distribution of freshwater flows.Further exploration into freshwater flows can provide a better understanding of ciruclation patterns in the bay and any resulitng ecological patterns.

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Appendix A

Watershed Delineation

1. First, if the DEM has not already been projected, it must be projected using the "Project Raster Tool" in the Data Management Tools toolbox in ArcGIS. In this case, the NAD27, Zone 8N projection was used.
2. In the projection step, the "Output cell size" option can also be filled out to choose what cell size the DEM will have. One hundred meters was used on the Glacier Bay DEM.
3. To reclassify water cells so that they have no elevation values, use the "Reclassify" tool in the Spatial Analyst Tools toolbox. Make the old cell values the minimum cell value through zero. Make the new cell value "NoData".
4. To eliminate depressions in the DEM, execute the "Fill" tool, which is under the Hydrology section of the Spatial Analyst Tools toolbox. Run this tool on the projected and reclassified DEM raster.
5. Then run the "Flow Direction" tool which is also in the Hydrology tool set. Use the filled DEM as the input surface.
6. Run the "Flow accumulation" tool in the Hydrology tool set.
7. To classify the flow accumulation layer, right-click the layer and select its properties. Then select Symbology. Select the Classified option and create two classes. Then select the button next to the number of classes that says "Classify" and adjust the break values to the desired values.

8. The next task is creating the pour points. A point shapefile must be created using ArcCatalog.
9. Add this new point shapefile to the map in use on ArcGIS.
10. Use the “Identify” tool in ArcGIS to find the points of highest flow accumulation, or the river outlets.
11. Pour points need to be placed on these outlets. Do this by selecting the “Start Editing” option in the editor. Select the location of the empty point shapefile.
12. Then, using the Sketch tool, add pour points at the desired locations, making sure to stay within the boundaries of the grid square on the flow accumulation raster.
13. When all pour points have been added, open the pour point layer’s attribute table and give each added point a unique ID.
14. Save the edits and stop editing (All in the Editor menu).
15. The pour points need to be converted to a grid that matches the grid used on all previous layers; this is done using the “Feature to Raster” tool in the Conversion Tool toolbox.
16. Run the watershed tool, from the Hydrology tool set, selecting the correct flow direction raster and pour point raster. This should successfully create watersheds from each pour point.
17. Finally, this is not necessary but is required to perform other tools on the watershed layer; the watershed layer can be converted to a polygon shapefile by running the “Raster to Polygon” tool in the Conversion Tools toolbox.

Appendix B

Determining Pour Areas for Line Source Watersheds

1. Start out with the flow direction raster obtained from steps 1-5 in Appendix A. Then run the “Flow Length” tool in the Spatial Analyst Tools toolbox under the Hydrology heading.
2. Run the “Extract by Attributes” tool that is in the Spatial Analyst Tools toolbox. Use the flow length raster as the input raster and enter “Value = 0” for the “Where clause”. This should create a layer showing coastal cells where the flow length is zero.
3. Next, create a polygon shapefile in ArcCatalog using the same projection as before.
4. Add this shapefile to the current map in ArcGIS.
5. Make sure to add the pour point file created for the point watersheds to the map.
6. Start an editing session from the editor menu, selecting the polygon shapefile as the layer to be edited.
7. Using the sketch tool, draw polygons around all of the points on the flow length layer that are between two adjacent point source pour points.
8. When all of the polygons have been drawn, open the polygon shapefile layer’s attribute table and give each polygon an individual ID number.
9. Save the edits and stop editing (both options are under “Editor”).

10. Convert the coastal raster into an integer file using the “Int” tool under “Math” in the Spatial Analyst Tools toolbox.
11. Now that the coastal file is an integer, convert it into a point shapefile using “Raster to Point” tool in the Conversion Tools toolbox.
12. Run the “Intersect” tool under “Overlay” in the Analysis tools toolbox. Input the coastal point shapefile and the polygon shapefile.
13. Turn this layer into a raster using “Feature to Raster” in the Conversion Tools toolbox and make sure to keep the correct grid size that is consistent with all of the other layers. Also make sure that the “Field” in the dropdown box is set to the field that lists into which of the polygons each overlapping coast cell falls.
14. The final step is to run the watershed tool, from the Hydrology tool set, selecting the correct flow direction raster and pour point raster created in step 13. This should create all of the line source watersheds. This raster can also be converted into a shapefile if desired, as is shown in step 17 of Appendix A.

Appendix C

Determining Watershed Areas

1. To find the areas of the individual watersheds in a layer, the first step is to right-click on the name of the watershed polygon layer and open the attribute table.
2. Click on the "options" button and then select "add field".
3. Give the field a name, i.e. "area".
4. Choose "Double" as the type.
5. Under precision and scale, any numbers can be entered depending on how much precision is desired.
6. Select okay and exit out of the attribute table.
7. Open an editing session by selecting "start editing" within the editing toolbar so that the watershed layer can be edited.
8. Reopen the attribute table of the watershed layer.
9. Right-click the area field that was just created and select "calculate values".
10. Check the box labeled "advanced".
11. Enter the following code into the first text box:

```
Dim dblArea as double
Dim pArea as IArea
Set pArea = [shape]
dblArea = pArea.area
```

12. In the second text box below the first enter: *dblArea*.
13. Click ok and the area field should be filled with values for each watershed.

Appendix D

Determining Watershed Centroids

14. To find the x and y coordinates of the centroids of the individual watersheds in a layer, the first step is to right-click on the name of the watershed polygon layer and open the attribute table.
15. Click on the “options” button and then select “add field”.
16. Give the field a name, i.e. “x_centroid”.
17. Choose “Double” as the type.
18. Under precision and scale, any numbers can be entered depending on how much precision is desired.
19. Select okay and exit out of the attribute table.
20. Open an editing session by selecting “start editing” within the editing toolbar so that the watershed layer can be edited.
21. Reopen the attribute table of the watershed layer.
22. Right-click the field that was just created and select “calculate values”.
23. Check the box labeled “advanced”.
24. Enter the following code into the first text box:

```
Dim dblX as double
Dim pArea as IArea
Set pArea = [shape]
dblX = pArea.Centroid.X
```

25. In the second text box below the first enter: *dblX*.
26. Click ok and the area field should be filled with values for each watershed.

27. Repeat steps 1-13 for the y-value of the centroid, replacing all x-values with y-values in the code in step 11.

Appendix E

Complete Weather Station Data

Annual Precipitation (in inches x 100)

	1923	1924	1937	1938	1939	1940	1941	1942	1943	1944
Yakutat Airport										
Glacier Bay										
Hoonah										
Eldred Rock										4127
Haines Airport										
Pelican										
Haines 40 nw										
Elfin Cove										
Cape Spencer			10267	12570		10334				11620
Gustavus		5618				5214	5312	6027	7028	6300
Juneau Airport										

	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956
Yakutat Airport				13111				13404	11004	9158	12907	15731
Glacier Bay												
Hoonah												
Eldred Rock								6484			2780	3959
Haines Airport												
Pelican												
Haines 40 nw												
Elfin Cove												
Cape Spencer	12499			15433	15381		8195	10508	10755	7591		10952
Gustavus	5370	5203	6205	5935	5516		3918	6265	5474	4851	4451	6329
Juneau Airport							3780	6573	5447	4118	4889	6797

1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
9527	11545	13530	15626	13803	14161	17944	16834	18788	11923	12683	11649
									7546	7511	6840
3198	3975	5149	5277	6425	3900	4663	6404	4002	4785	4691	4800
											12612
8526		10612	11575	13321	10393	10708	11255	10901	11501	10439	7891
4289	5326	5130	5333	6380	5781	6098	5157	4956	5331	5032	
4011	5156	5570	5777	6811	6183	5739	5828	4788	5830	5007	4802

1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
11463	12653	13626	11496	11435	14623	13940	18170	14467	14049	14936	14857
6954	7543	6704	7588	6402	8394	6971	7131	5985	7466	6565	7147
										6502	8272
4795	5793	4075	3300								
					7004	4285	5929	3989	4591	3601	6179
12985	13986	10881	8854	9861	17066	14718			18036	15408	17581
						8669	10853	10065	11590	9577	11443
7085	9553	9684	9720	8849							
								5275	5259		
5100	5318	4863	5367	4586	6385	4632	5641	4718	4608	4929	6188

1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
17654	12072	13635	13779	16923	18129	25024	19804	16045	17176	21948	23233
7034	5242	6210	6275	6967	7738			6671	8236	7889	
5879	3668	4651	4576	6136				3817	4145		5048
16191	11907	13467	14269		13323						
									3827	4929	6243
10182	8335	8915	9587	11769		12722	10448			11718	10828
				5706				5013			
5433	4112	4155	5768			5879	6077	4688	5688	8515	7930

1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
13817	16287	13898	12487	17229			16508	12612	11284	11711
6618										6071
		4608			4531	8865	5885	6461		
4518	4749	4212	3206	5496	4810	7316	5808	5528	4222	4600
9473	11381	7840	8883	10619	8097	12482	10641	11027		9260
							5468			
7159	6889	4644	6045	7462	5320	7899	6897	5939	6227	5413

2004	2005	Average (100*in.)	Average (in.)	STDEV (100*in.)	STD % of Avg
14315	16287	14733.96	147.34	3228.504	21.91
7715	7535	7033.857	70.34	722.1361	10.27
		6446.286	64.46	1660.792	25.76
		4629.1	46.29	1064.783	23.00
	5245	4921.438	49.21	1037.945	21.09
18554	15430	14173.83	141.74	2760.486	19.48
5051		4967.667	49.68	1013.852	20.41
11664	11133	10340.78	103.41	1344.728	13.00
		10647.07	106.47	2012.875	18.91
7145	6341	5543.886	55.44	701.7125	12.66
6522	7402	5688.755	56.89	1075.845	18.91

Mean Minimum January Temperature (in °F *10)

	Range									
Cape Spencer	1936-1974		302	303	318	331	306		252	333
Eldred Rock	1941-1973					298	184	310	235	199
Glacier Bay	1966-2006	128	232	196	101	218	146	154	209	184
Gustavus	1923-2006		249	171	335		246	236	297	162
Haines 40 NW	1989-2006		75	53	220	55	104	139	-44	50
Hoonah	1972-2006		126		231	188	357			
Haines Airport	1925-1953 & 1973-2006		106	154	198	276	175	155	111	305
Yakutat	1948-2006	260			12	162	80	167	149	258
Juneau	1949-2006		-28		129	75	145	151	288	125
Pelican	1967-2006		216	142	229	165	167	227		
Elfin Cove	1975-2006	234	282	345	279	270	222	363	197	308

Cape Spencer	345	287	242	325	287	216		254	211	200	245	338	264	285	344
Eldred Rock		187	145	168	195	289	185	230	311	156	272	311	244	228	281
Glacier Bay		279	331	239	219	177	333	154	269	288	329		295	240	196
Gustavus	305	276	242	158	282	201	-2		138	99	159	165	299	127	140
Haines 40 NW	80	43	62	242	151	167	72	108	127						
Hoonah		305	317		252	174	251	248	247	248	342	289		242	
Haines Airport	65	160	223	308	285	273	210	149	187	199	304	157	204	235	104
Yakutat	169	167	268	169	195	249	209	268	242	148	18	105	103	-46	176
Juneau	140	280	128	228	257	212	227	254	178	2	169	119	-15	165	65
Pelican		358	267	251	199	331	186	283	295	342	317	305			237
Elfin Cove	326	346	328	322	306	262		287	348	273	297	315	227	272	285

Cape Spencer	270	323	347	301	315	315	261	231	291	268	205	278		224	275
Eldred Rock	201	139	225	197	107	224	115	141	193						
Glacier Bay	234	218	310	189	246	238	141				212	326	270	265	200
Gustavus	283	148	225	256	209	235	255	199	63	221	188		311		
Haines 40 NW															
Hoonah															
Haines Airport	180	-75				168	200			323	168	208	192	77	287
Yakutat	81	77	134	92	179	206	323	194	164	181	363	130	251	265	344
Juneau	89	125	81	187	238	325	192	143	140	333	79	256	282	332	314
Pelican	256	286													
Elfin Cove	290	274	352	312	349	277	290	311							

260															
223	275														
120			263	318	295		210	209		198	319		210	48	
115	64	110	110	124	112	187	217	204	198	298	139	267	246	217	108
298	264	205	145	203	165	294	111	244	165	65	210	221	195	316	269
293	223	212	220	184	325	178	241	218	100	209	193	221	221	328	263

								Average (°F*10):	**Avg. (°F)**	**STDEV**	**% STDEV of avg**
								282.000	28.20	4.26	15.09
								213.214	21.32	5.99	28.11
								229.556	22.96	6.04	26.31
	-48	225	342		182	188	236	208.020	20.80	8.42	40.48
								100.235	10.02	6.98	69.64
								254.467	25.45	6.22	24.43
255	164	108		102	60	102		177.782	17.78	7.86	44.24
255	177	218	228					188.772	18.88	8.32	44.08
269	205	205	255					192.509	19.25	8.66	45.00
								252.950	25.30	6.22	24.59
								295.129	29.51	4.09	13.85

Appendix F

Determining Watershed Land Cover Statistics

<u>Organizing the Land Cover Data</u>

1. First download the land cover quadrants, which in this case were Juneau, Skagway, Mount Fairweather and Sitka from the Alaska Geospatial Data Clearinghouse (http://agdc.usgs.gov/).
2. Add these quads on ArcGIS and project them to the coordinate system; UTM zone 8 was used for Glacier Bay.
3. Next extract the forest, snow/ice, and water data. This is done using the "Extract by Attributes" tool in the Spatial Analyst toolbox.
4. Run this tool on each of the quads and where it says 'where clause', click on the icon on the right side of that box where the query value can be set to "VALUE = 5 or VALUE = 6" depending on which values need to be extracted.

The following values were extracted from each quadrant:

Juneau- Forest: 5-needleleaf (closed), 6-needleleaf (open), 11- needleleaf (open)
Snow/ice: 10-barren/snow, 13- barren/glacier
Water: 1-Clear water, 2-Turbid water, 3- Turbid water, shallow water, some mud/gravel flats\

Mt. Fairweather- Forest: 1-Needleleaf (closed), 2-Needleleaf (open), 3-Needleleaf forest (woodland)
Snow/ice: 11-Ice/snow, 12-Mountain shadow
Water: 8-Clear water, 9-Turbid/shallow water

Skagway- Forest: 5-Needleleaf (closed), 6-Needleleaf (open), 11- Needleleaf (open)
Snow/Ice: 10-Barren/snow, 13-Barren/glacier
Water: 1-Clear water, 2-Turbid water, 3- Turbid water

Sitka- Forest: 6-Needleleaf (closed), 7-Needleleaf (open), 14- Needleleaf (woodland)

Snow/Ice: 12-Snow/ice
Water: 1- Clear water, 2- Turbid water

5. Repeat step 4 entering which values correspond to the land cover type that you wish to extract. The result of steps 3-5 will be different rasters for each quad showing a different kind of land cover.
6. The new rasters will have all of the different types of forest or ice extracted with different values, but they must be reclassified as one value. This is done by running the 'Reclassify' tool in the Spatial Analyst toolbox and giving all of the values in the raster the same value.
7. Repeat step 6 for each different kind of land cover and make sure that each quadrant's raster of the same type of land cover has the same id number so that all of the forests will have an id of say 1 and the snow will have an id of 2.
8. With four different quadrant rasters for each type of land cover, they must now be joined. Run the 'Mosaic to new raster' tool in the Data Management Tools toolbox and add the four different rasters for the forest or water cover.
9. Repeat step 8 for each type of land cover. The result will be three rasters showing the forest, snow and ice, and water cover over the entire domain.
10. Next convert these rasters into polygons using the 'Raster to Polygon' tool in the Conversion Tool toolbox.

Finding the Land Cover Intersection Areas

1. Use the 'Intersect' tool in the Analysis Tools toolbox on the watershed polygon layer as well as each land cover polygon layer.

2. Repeat step one for each type of land cover as well as each set of watersheds (line source and point source).
3. Open the attribute table of the new intersection layers and calculate the area of all of the intersecting polygons created in the new layer.(see Appendix A)
4. The attribute table now lists how many different polygons of each type of land cover intersects each watershed. These are listed in the different id numbers in the table. These areas can be added up to show the total area of forest, snow and ice, and water that is in each watershed.