Chapter 5

fort.20 File - Freshwater Inflows

The inclusion of freshwater inflows is an important feature of the ADCIRC model. As discussed in Chapter 3, the fort.14 file contains information about the boundaries of the domain. To this point, we have considered only two types of boundaries:

1. No-flow boundaries, such as the main coastline or islands. For this type of boundary, water is not allowed to flow perpendicular, or normal, to the boundary.

2. Open boundaries, one in the Gulf of Alaska, the other in Lynn Canal. For this type of boundary, the elevation of the water surface is specified for all times.

There is another type of boundary, called a non-periodic normal-flow boundary. The main coastlines and islands are essentially non-periodic normal-flow boundaries where the normal flow is always zero. In other words, the land forms a solid boundary through which water can not flow.

A more general non-periodic normal flow boundary is one where the normal flow is prescribed to be some non-zero value. This, for example, is what occurs when a river discharges into the bay. Across a section of the boundary (the width of the river), the normal flow is set by the river flow.

Given the very large precipitation amounts in southeastern Alaska, it is very natural to question to what extent freshwater inflows will change the predictions of water surface elevation and velocity in Glacier Bay. Answering this question is one of the main objectives of the current project.

5.1 Inflow Data

The best case scenario would have numerous river gaging stations located in Glacier Bay so that the freshwater inflows could be measured directly and then input in the ADCIRC model. The reality is that very little data on streamflow exists within Glacier Bay. According to the Alaska Science Center (http://alaska.usgs.gov/science/water/index.php), data in the park are available only on the Kahtaheena River (1999 - 2004), near Gustavus. Within the model domain, the fact is that there are hundreds of streams contributing freshwater inflow to the bay. Further complicating matters is the presence of many glaciers, including several large tidewater glaciers. The traditional river gaging methods employed by the USGS do not allow for the measurement of the substantial submarine discharge coming from these tidewater glaciers.

5.2 Estimation / Modeling of Inflows

In order to run ADCIRC simulations to assess the relative significance of inflows, it was determined to try several strategies for estimating the discharges. Interested readers are directed to Ciavola (2007) for a complete discussion of this subject. Only an outline of the methodology will be provided here.

The ‘output’ of a hydrological study of Glacier Bay will consist of information about the magnitude and the timing of flows into the bay. Given the severe lack of requisite ‘input’ data, which will be elaborated upon below, it is unrealistic to expect a hydrological model that will accurately predict hourly and daily flows. Rather, the author is more interested in mean monthly flows, peak discharges, and annual flow statistics.

5.2.1 Obtaining Data

Precipitation and Temperature Data

Precipitation and temperature data were drawn from the National Climatic Data Center for numerous stations in the vicinity of Glacier Bay (Fig. 5.1). Data coverage over the past 50-60 years was found to be highly variable. Stations such as Yakutat and Juneau had reliable data every year while other stations had 10 to 20 years worth of data. The mean annual precipitation

(MAP) and mean minimum January temperatures (MMJT) for these stations are summarized in Table 5.1. Brief inspection of the precipitation data indicates that significant spatial gradients occur. Stations near the coast, such as Pelican and Yakutat receive around 12 feet of rain per year while inland stations such as Haines and Juneau receive around 4 feet per year.

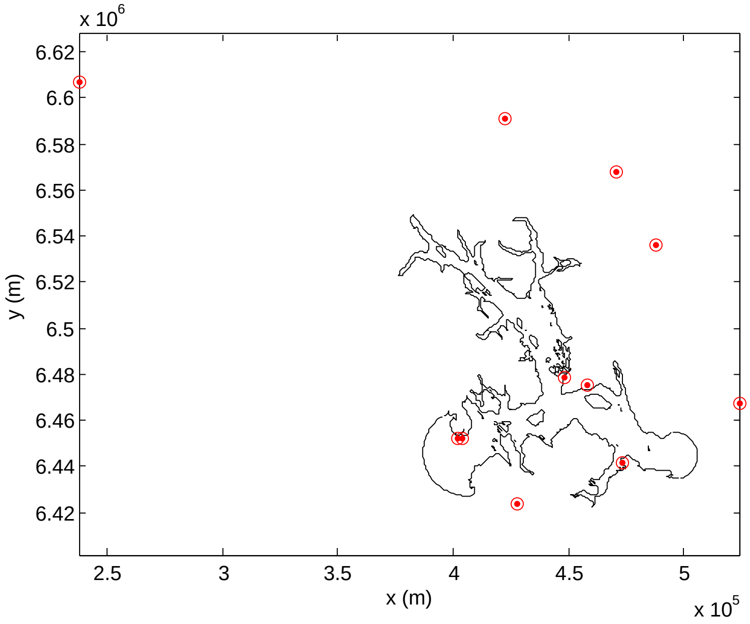

Figure 5.1: Locations of weather stations used in determining rainfall and temperature values.

Elevation Data

Digital elevation data are readily obtained from the USGS (http://seamless.usgs.gov/). Using their web-based interface, it is possible to zoom in on a general region of interest, draw a polygon around a specific region of interest, and then download data on a (roughly) 30 m grid. A grayscale raster image of this data is given in Fig. 5.2.

Station	Latitude	Longitude	MAP (in)	MMJT (°F)
Cape Spencer	58.2	-136.63	100.01	28.2
Eldred Rock	58.96	-135.21	46.56	21.32
Elfin Cover	58.2	-136.66	103.41	29.51
Glacier Bay	58.45	-136.66	70.34	22.96
Juneau	58.35	-134.58	56.89	19.25
Haines Airport	59.25	-135.51	49.21	17.78
Haines 40 NW	59.45	-136.36	49.68	10.02
Gustavus	58.41	-135.71	54.3	20.8
Hoonah	58.11	-135.45	64.46	25.45
Yakutat	59.51	-139.63	146.55	18.88
Pelican	57.95	-136.21	141.74	25.3

Table 5.1: Mean annual precipitation (MAP) and mean minimum January temperature (MMJT) values for weather stations in the vicinity of Glacier Bay.

Land Cover Data

One of the strategies employed for determining peak flows relies upon knowledge of land cover. Therefore, land cover data were downloaded from the Alaska Geospatial Data Clearinghouse (http://agdc.usgs.gov/data/usgs/erosafo/ak_lcc/ak_lcc.html). Separate files are provided for many different USGS quadrangles. These data files may immediately be loaded into ArcGIS. Note that a careful look at the metadata for each quadrant is warranted, as different land use codes are used for the different quads. With some care, the files from the quads making up Glacier Bay can be merged together into single layers for forests (Fig. 5.3), ice / snow (Fig. 5.4), etc.

Soils Data

Many traditional methods (curve number, etc.) of distributed modeling of runoff require detailed information about soil characteristics. The best location for this data is the NRCS Soil Data Mart, found at http://soildatamart.nrcs.usda.gov/. There, users can request data from the Soil Survey Geographic Database (ssurgo) and the State Soil Geographic Database (statsgo). However, it should be noted that the coverage of Glacier Bay in these databases is inadequate for this type of distributed modeling effort.

5.2.2 Delineating Watersheds

With data in hand, the next step in estimating runoff is the characterization of watersheds in the drainage basin. This analysis was performed using, among other tools, the spatial analyst toolbox in ArcGIS 9.2, and involved the following steps:

1. Filling the digital elevation model (DEM) to eliminate small 'sinks,' or cells of depression.

2. Calculating the flow direction raster, which simply indicates the direction of steepest descent for each cell.

3. Calculating the flow accumulation raster. Essentially, this operation calculates, for every cell in the DEM, the number of cells that flow into that cell.

4. Delineating watersheds. This operation is based upon 'pour points' (stream outlets) defined by the user. Note that, when delineating watersheds that feed into a long coastline, there will be hundreds or thousands, many of them extremely small. Therefore, it was decided to group watersheds into two classes, 'point-source' watersheds and 'line-source' watersheds. Classification as a point watershed is reserved for those watersheds exceeding an arbitrary minimum area. For the present analysis, this was set at approximately 7 km^2. As a result, some 40 point watersheds were identified Each of these represents a fairly major stream emptying into Glacier Bay. A line watershed simply represents the aggregate of all of the minor watersheds that lie between two adjacent major, or point, watersheds. For the purposes of the ADCIRC model, the water that falls on a line watershed will be modeled as running off uniformly distributed over the coastline of the line watershed. This strategy has been previously employed in the modeling of precipitation runoff in southeastern Alaska (Wang *et al.*, 2004). Fig. 5.5 shows, some 40-50 line watersheds are identified in addition to the 40 or so point watersheds for the Glacier Bay domain.

Figure 5.2: Digital elevation data for Glacier Bay National Park.

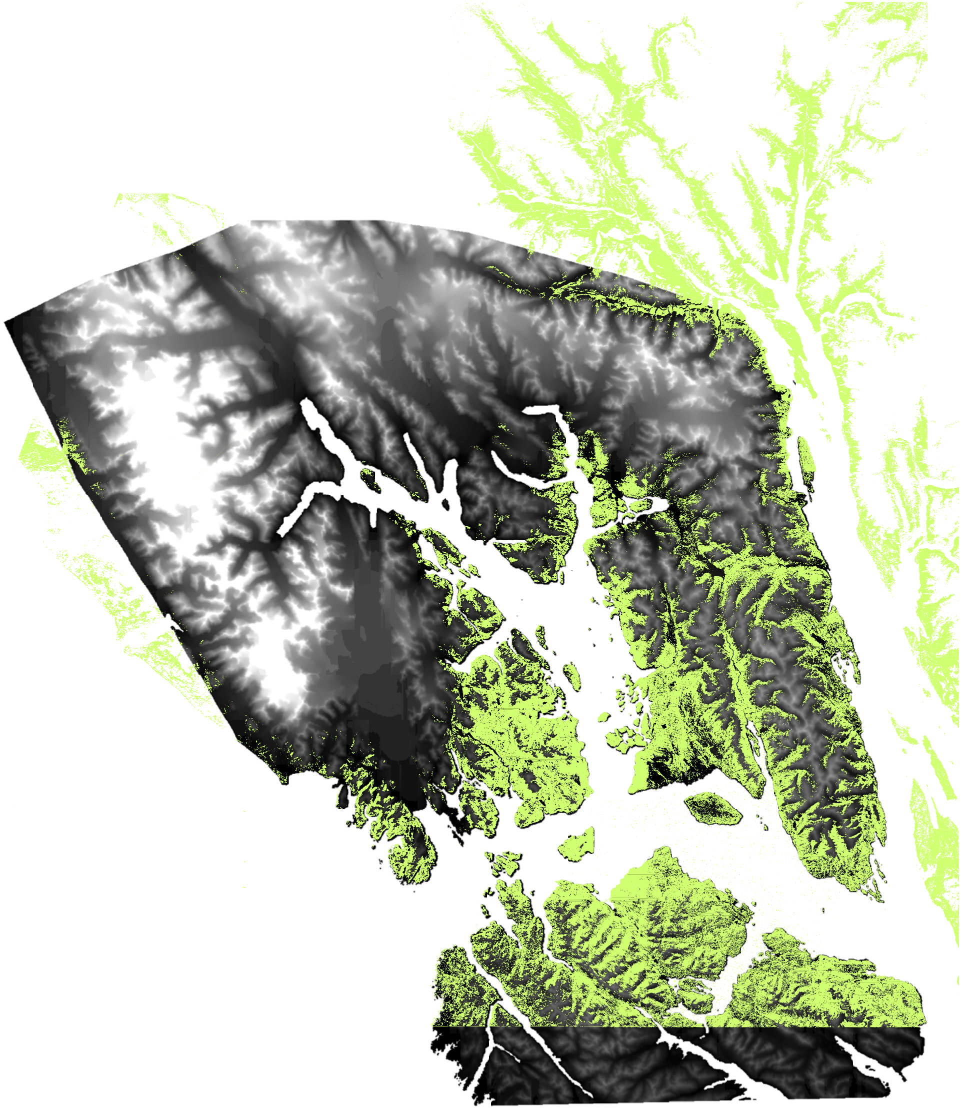

Figure 5.3: Forest cover, superimposed upon the elevation DEM.

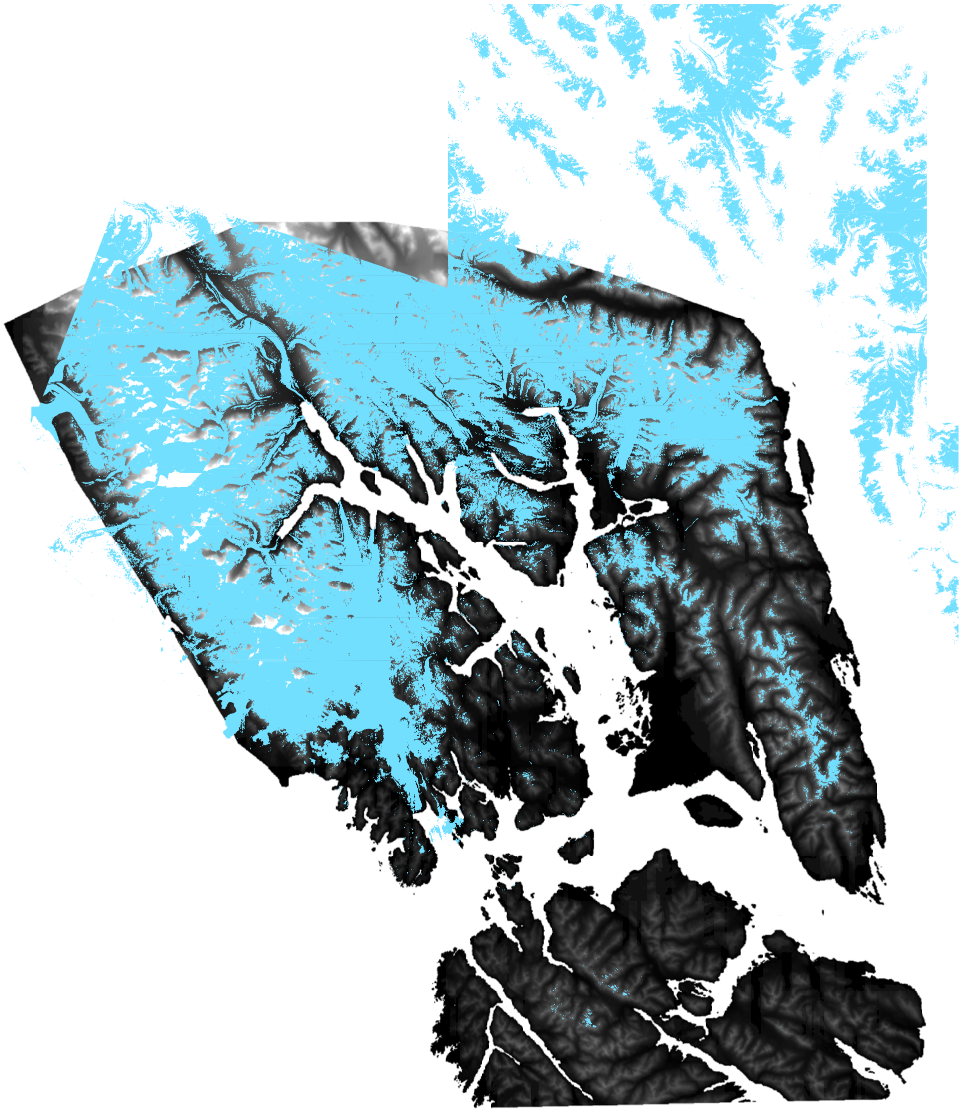

Figure 5.4: Snow / ice cover, superimposed upon the elevation DEM.

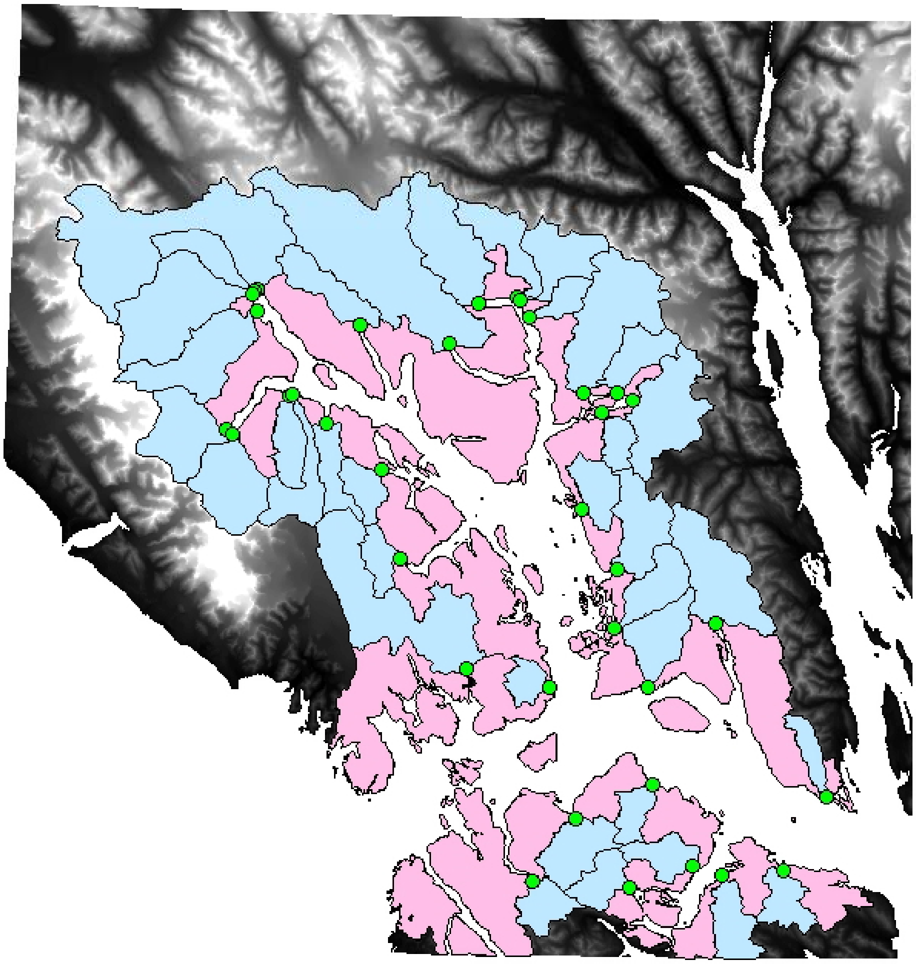

Figure 5.5: Point and line watersheds, ad delineated with GIS analysis, for the Glacier Bay domain.

5.2.3 Characterizing Watersheds

Once the watersheds have been defined, it is straightforward to interrogate them in ArcGIS in order to extract information of interest. Depending upon the type of runoff estimate that is being considered, this information will vary. Items of interest, as will be discussed below, include things such as the area and the centroid coordinates of the watershed, the mean elevation, and percent forest, snow, and water coverage. Specific details on how these data were determined are given in Ciavola (2007) and the interested reader is directed to that thesis.

5.2.4 Estimation of Peak Flows

As the present goal is to understand the extent to which inflows alter patterns of water elevation and velocity in Glacier Bay, it makes sense to initially consider high flow events, such as those following a substantial rainfall event. A report by Curran *et al.* (2003) discusses the development of regression equations for peak flows in Alaska. That report represents an intensive analysis of 361 streamflow-gaging stations in Alaska. In order to improve the accuracy of the derived estimation equations, the stations were grouped into 7 regions (Fig. 5.6). This grouping procedure was based upon hydrologic unit boundaries and regional boundaries developed by the USGS. Some refinement to this grouping scheme was made based upon basin characteristics.

For all of the watershed basins, Curran *et al.* (2003) determined a number of characteristics thought to be relevant to controlling the peak streamflows. In the end, the regression equations included, at most, drainage area, mean basin elevation, area (fractional) of forest, area (fractional) of lakes and ponds, mean annual precipitation, and mean minimum January temperature.

For regions 1 and 3 (Glacier Bay lies in region 1), which include 93 gaging stations, the regression equations for the 2, 5, 10, etc., year peak discharges are given by Table 5.2.

Based upon these equations, the corresponding peak discharges from all line and point watersheds were calculated. Detailed results are tabulated in Ciavola (2007). The summed discharges (total runoff into the Glacier Bay domain) are summarized in Table 5.3. Note that the ‘runoff’ from precipitation that falls directly onto the water surface is not included in these totals. Also note that these values, which are $O(10^5)$ cfs, are the same order of magnitude as typical flows in the Mississippi River.

Q_T	Error	Years
$Q_2 = 0.004119A^{0.8361}(ST+1)^{-0.3590}P^{0.9110}(J+32)^{1.635}$	38	0.88
$Q_5 = 0.009024A^{0.8322}(ST+1)^{-0.3670}P^{0.81280}(J+32)^{1.640}$	37	1.3
$Q_{10} = 0.01450A^{0.8306}(ST+1)^{-0.3691}P^{0.7655}(J+32)^{1.622}$	37	1.8
$Q_{25} = 0.02522A^{0.8292}(ST+1)^{-0.3697}P^{0.71650}(J+32)^{1.588}$	38	2.4
$Q_{50} = 0.03711A^{0.8286}(ST+1)^{-0.3693}P^{0.6847}(J+32)^{1.559}$	40	2.8
$Q_{100} = 0.05364A^{0.8281}(ST+1)^{-0.3683}P^{0.6556}(J+32)^{1.527}$	41	3.1
$Q_{200} = 0.07658A^{0.8276}(ST+1)^{-0.3669}P^{0.6284}(J+32)^{1.495}$	43	3.4
$Q_{500} = 0.1209A^{0.8272}(ST+1)^{-0.3646}P^{0.5948}(J+32)^{1.449}$	41	3.1

Table 5.2: Regression equations (for regions 1 and 3) for various recurrence intervals. Q_T is the discharge in cfs, A is drainage area in square miles, ST is the area of lakes and ponds in percent, P is the mean annual precipitation in inches, J is the mean minimum January temperature in degrees Fahrenheit. Equations are taken from Curran *et al.* (2003).

5.2.5 Annual Flow Statistics

A second set of useful regression equations has been developed by Wiley and Curran (2003). Whereas the peak flow statistics discussed in §5.2.4 were derived from annual peak flows, the statistics discussed in the current section pertain to annual flow statistics based upon daily streamflow data.

The report of Wiley and Curran (2003) shares many characteristics with that of Curran et al. (2003). Many of the same basins were analyzed and many of the same basin characteristics were used in the obtained regression equations. As summarized in Table 5.4, one set of equations is given for the 15, 10, 9,. . ., 1 percent duration flows. As an example, the 1 percent duration flow is exceeded one percent of the time. These equations therefore describe the high flow statistics.

Analysis of low flow statistics is complicated by the fact that, during the winter time, freezing leads to unreliable low flow data. Therefore, and as outlined in Table 5.5, a second set of equations is provided for low flow statistics. However, these equations are strictly valid only for the months of July, August, and September.

Based upon these two sets of equations, the flow statistics for each watershed were calculated and are tabulated in Ciavola (2007). The summed discharges for the entire Glacier Bay domain are plotted in Fig. 5.7 in the form of a flow duration curve. The results indicate that flows on the order

Recurrence Interval (years)	Peak Discharge (cfs)
2	198,000
5	282,000
10	340,000
25	414,000
50	471,000
100	528,000
200	589,000
500	668,000

Table 5.3: Peak discharge values, for various recurrence intervals, for the Glacier Bay domain.

of 10,000 to 100,000 cfs are expected.

5.2.6 Estimating Annual Hydrograph

Finally, in addition to estimating peak flows and annual flow statistics, it is of interest to consider the annual variation of discharge over a given year. There are many strategies that may be taken towards this goal. As with the previous sections, readers are directed to Ciavola (2007) for a more complete discussion; only a brief review is provided here.

Observed Characteristics of Annual Hydrograph

Royer (1979) gave consideration to runoff, particularly as it impacts circulation patterns in the Gulf of Alaska. He noted the difference between the annual cycles observed in temperature and precipitation. Regarding the former, a peak is observed in the summer months, and regarding the latter, a strong peak is observed in October. He then proposed a simple ‘box model’ wherein precipitation that fell during winter months (November to April) would be largely locked up as snow and precipitation that fell during the rest of the year would run off immediately. Stored snow was then forced to run off under a hydrograph increasing linearly from May to a maximum in September, before dropping off again to zero in November. The result of this model is a hydrograph with a single peak (snowmelt runoff plus immediate runoff) typically in September.

OSn (cfs)	Coefficient of Determination	Standard error of estimate, in percent
$OS15 = 0.1358A^{0.9960}P^{1.016}$	0.97	22
$OS10 = 0.2145A^{0.9472}P^{0.9740}$	0.97	21
$OS9 = 0.2372A^{0.9422}P^{0.9652}$	0.97	22
$OS8 = 0.2670A^{0.9374}P^{0.9550}$	0.97	22
$OS7 = 0.3033A^{0.9307}P^{0.9443}$	0.97	22
$OS6 = 0.3486A^{0.9234}P^{0.9329}$	0.96	22
$OS5 = 0.4120A^{0.9162}P^{0.9179}$	0.96	23
$OS4 = 0.4875A^{0.9074}P^{0.9057}$	0.96	23
$OS3 = 0.6039A^{0.8963}P^{0.8892}$	0.96	24
$OS2 = 0.7960A^{0.8829}P^{0.8697}$	0.95	25
$OS1 = 1.279A^{0.8637}P^{0.8293}$	0.94	27

Table 5.4: Regression equations (for regions 1 and 3) for annual high duration flows. OSn is the discharge, having an n percent exceedence probability, in cfs, A is drainage area in square miles and P is the mean annual precipitation in inches. Equations are taken from (Wiley & Curran, 2003, Table 2)

Wang *et al.* (2004), building upon Simmons (1996), developed a distributed model for estimating runoff into the Gulf of Alaska. This effort delineated point-source and line-source watersheds using a DEM. Forced with daily temperature and precipitation data, their work attempted to reproduce observed runoff patterns by modeling snow storage and melt directly, rather than assuming a snowmelt hydrograph. Empirical parameters for baseflow, routing velocity, and infiltration coefficients were necessary and were used to calibrate the output to observed data.

These approaches are summarized in Fig. 5.8. The hydrograph of Wang *et al.* (2004) closely approximates the annual cycle in temperature (not shown) and not precipitation, suggesting that runoff into the Gulf of Alaska is dominated by snow and glacial melt. The hydrograph of Royer (1979) is best viewed as a balance, or average, between low-lying watersheds dominated by precipitation (immediate runoff) and higher-elevation watersheds dominated by snow storage and melt.

This idea can be explored further by considering runoff data from gaging

J-Sn (cfs)	Coefficient of Determination	Standard error of estimate, in percent
$J-S98 = 2.532 \times 10^{-9} A^{1.142} P^{1.521} E^{1.674}$	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 5.5: Regression equations (for region 1) for annual low duration flows. J-Sn is the discharge, having an n percent exceedence probability, in cfs, A is drainage area in square miles, P is the mean annual precipitation in inches, and E is the mean basin elevation in feet. Equations are taken from (Wiley & Curran, 2003, Table 2)

stations in southeast Alaska. Table 5.6 presents a summary of mean monthly flows for a number of gaged watersheds. The flows have been normalized by the mean annual total for the purposes of comparison. A quick perusal of the data in the table indeed reveal a nearly 'bi-modal' distribution of hydrographs. Many of the watersheds have their peak flows in the summer months; these hydrographs are plotted together in Fig. 5.9a. The remaining watersheds have their peak flows in October, and these hydrographs are plotted in Fig. 5.9b. For the watersheds where mean elevation data were available, these elevations are plotted against the peak-flow-month in Fig. 5.9c. It is clear that watersheds with a mean elevation above roughly 2000 feet are dominated by the snowmelt contribution. Watersheds with a lower mean elevation have a hydrograph dominated by precipitation. Indeed, Fig. 5.9b looks very much like the normalized precipitation curve in Fig. 5.8.

Modeled Glacier Bay Hydrograph

Having demonstrated some attributes of the annual cycle, attention is finally turned to the problem of quantifying discharges. The easiest way to estimate discharge into Glacier Bay, as a function of calendar month is as follows. Note

		Month											
Station Name	Station ID	1	2	3	4	5	6	7	8	9	10	11	12
ALSEK R NR YAKUTAT AK	15129000	0.01	0.01	0.01	0.02	0.07	0.19	0.24	0.21	0.13	0.07	0.03	0.02
ANTLER R BL ANTLER LK NR AUKE BAY AK	15055500	0.03	0.02	0.02	0.03	0.11	0.2	0.17	0.14	0.14	0.1	0.04	0.05
FISH C NR KETCHIKAN AK	15072000	0.08	0.07	0.06	0.08	0.11	0.1	0.07	0.07	0.1	0.15	0.12	0.09
KADASHAN R AB HOOK C NR TENAKEE AK	15106920	0.07	0.07	0.06	0.1	0.14	0.09	0.04	0.05	0.11	0.16	0.11	0.09
KAKUHAN C NR HAINES AK	15056030	0.01	0.01	0.01	0.02	0.08	0.18	0.23	0.22	0.13	0.08	0.03	0.02
MENDENHALL R NR AUKE BAY AK	15052500	0.01	0.01	0.01	0.01	0.05	0.14	0.22	0.24	0.19	0.1	0.02	0.01
MONTANA C NR AUKE BAY AK	15052800	0.04	0.04	0.04	0.05	0.11	0.13	0.12	0.13	0.15	0.13	0.07	0.05
SITUK R NR YAKUTAT AK	15129500	0.08	0.08	0.07	0.07	0.08	0.07	0.05	0.08	0.14	0.16	0.1	0.12
STANEY C NR KLAWOCK AK	15081497	0.12	0.1	0.09	0.08	0.05	0.03	0.03	0.05	0.13	0.17	0.15	0.16
TAIYA R NR SKAGWAY AK	15056210	0.01	0.01	0.01	0.01	0.07	0.17	0.25	0.25	0.15	0.06	0.03	0.01
TAKU R NR JUNEAU AK	15041200	0.01	0.01	0.02	0.03	0.13	0.22	0.2	0.16	0.12	0.07	0.03	0.02

Table 5.6: Normalized mean monthly flows for several USGS gaging stations in southeast Alaska

that this approach assumes static glaciers, no evaporation, and no infiltration losses.

1. Select an annual precipitation amount for Yakutat, which has served as the reference station.
2. Based upon the network of weather stations at which annual data is available, spatially interpolate this rainfall amount to the centroids of all the watersheds.
3. Depending upon whether the mean elevation of each watershed is less than or greater than 2000 ft, adopt one of the two idealized annual hydrographs as discussed in the previous section.
4. Release this precipitation over the 12 months of the year, allowing for an overall hydrograph for the Glacier Bay domain to be determined. As has been convention, we continue to neglect the rainfall landing on the surface of the water itself.

Sample results, using the mean annual precipitation, are given in Fig. 5.10. The hydrographs for the point and line watersheds are given separately in addition to the overall hydrograph. Several points are worth noting. First of all, the summed hydrograph for the point watersheds is clearly dominated by snow melt. This is because the point watersheds are the larger ones with large mean basin elevations. The summed hydrograph for the line watersheds, on the other hand, is clearly dominated by precipitation. This is due to the fact that these watersheds are close to the coastline and therefore have low mean basin elevations. Third, the division of total discharge between point and line watersheds is found to be fairly close, with about 55% coming from the former and 45% from the latter. Finally, the overall hydrograph is dominated by snow melt (point watersheds), exhibiting a single peak in the summer, but is noticeably 'broadened' by the contribution from the precipitation (line watersheds).

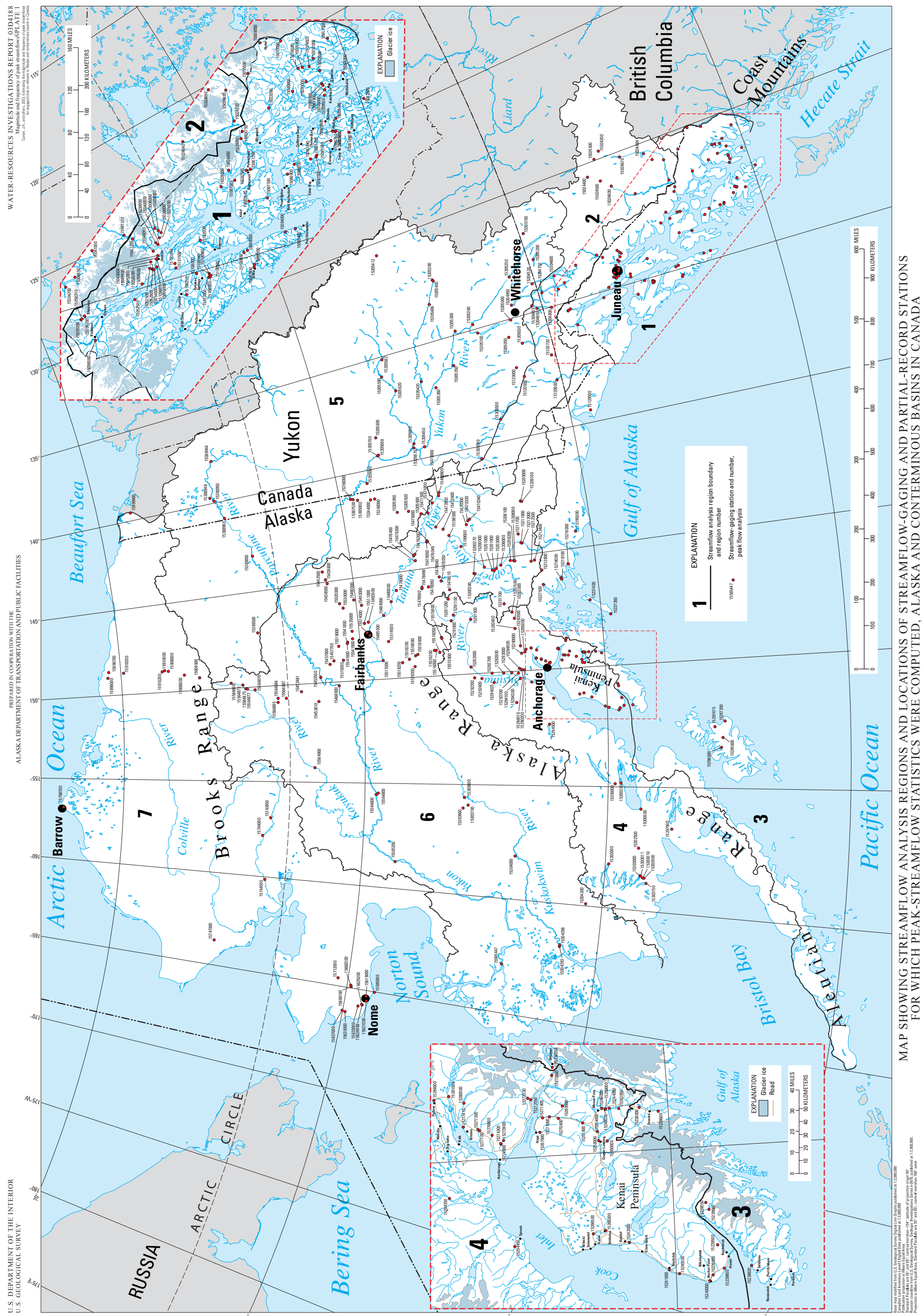

Figure 5.6: Streamflow analysis regions for Alaska. Figure reproduced from Curran *et al.* (2003).

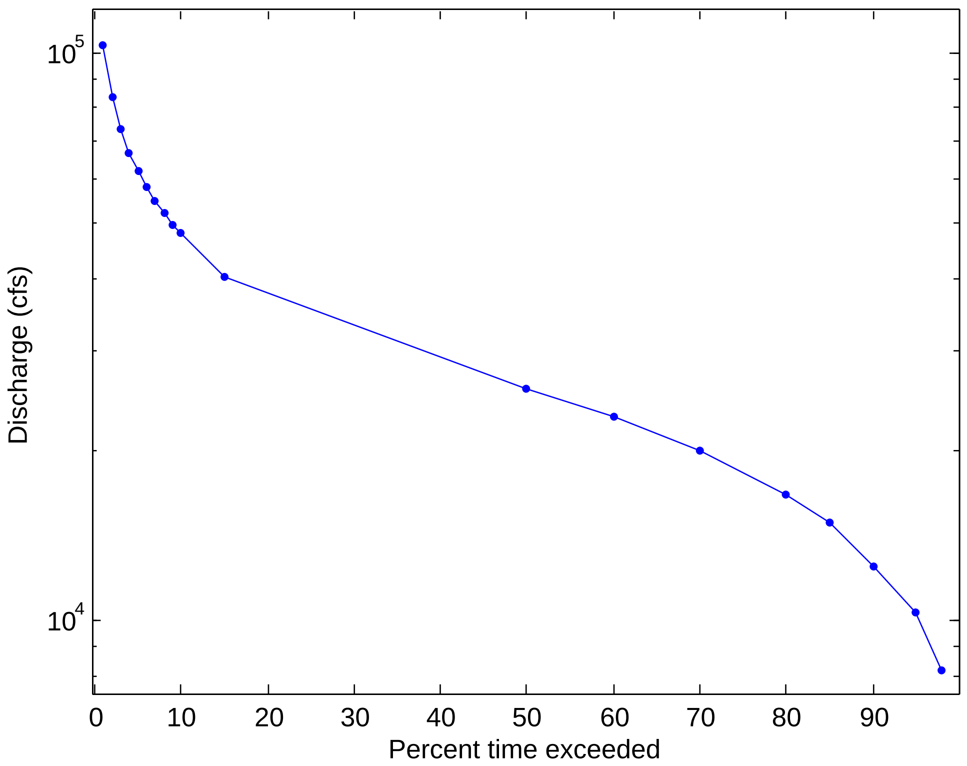

Figure 5.7: Flow duration curve for the Glacier Bay domain.

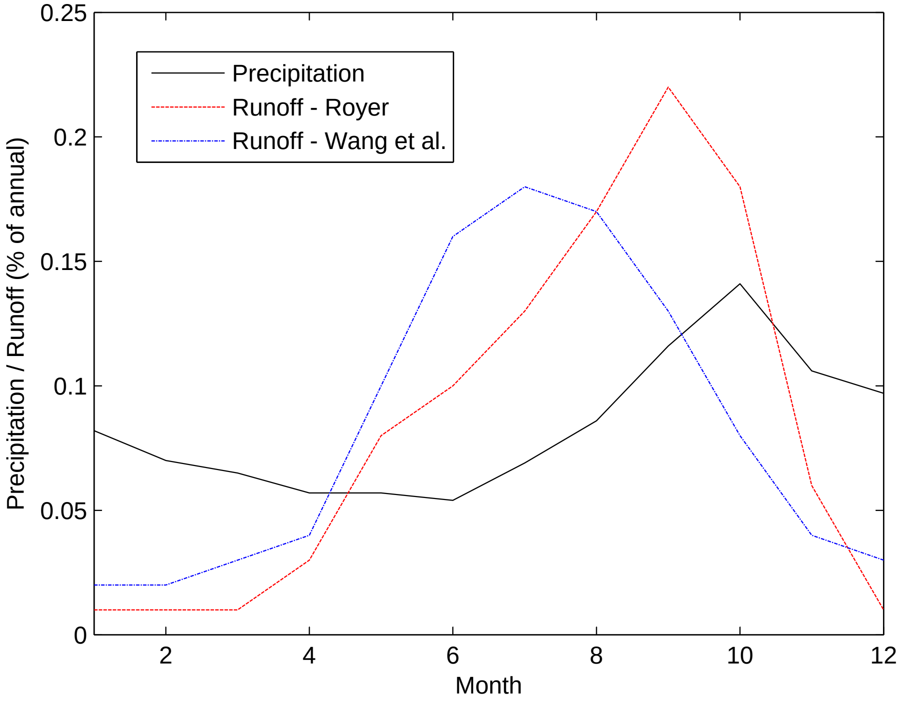

Figure 5.8: Normalized annual precipitation and runoff for the Gulf of Alaska from Wang *et al.* (2004). The hydrograph of Royer (1979), as determined from the meteorological data in Wang *et al.* (2004) is also shown.

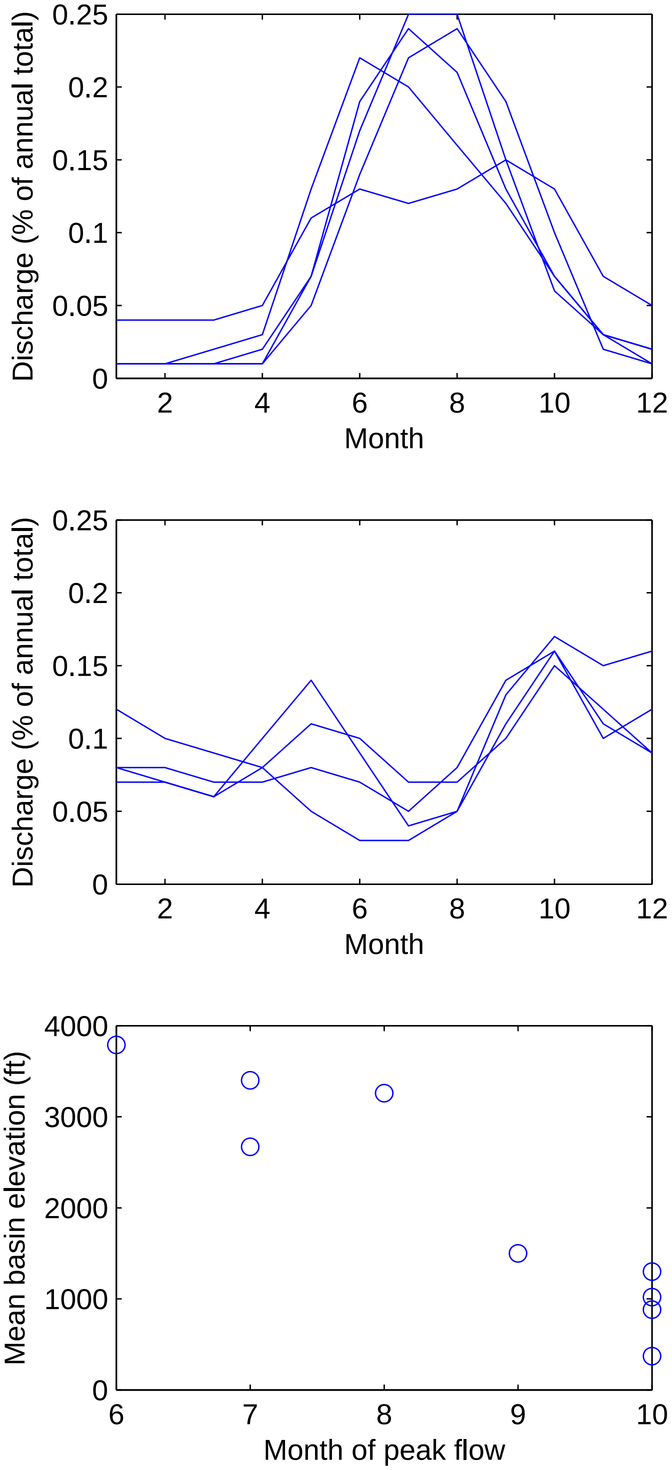
Discharge (% of annual total)
0.25
0.2
0.15
0.1
0.05
0
2
4
6
8
10
12
Month
Discharge (% of annual total)
0.25
0.2
0.15
0.1
0.05
0
2
4
6
8
10
12
Month
Mean basin elevation (ft)
4000
3000
2000
1000
0
6
7
8
9
10
Month of peak flow

Figure 5.9: .

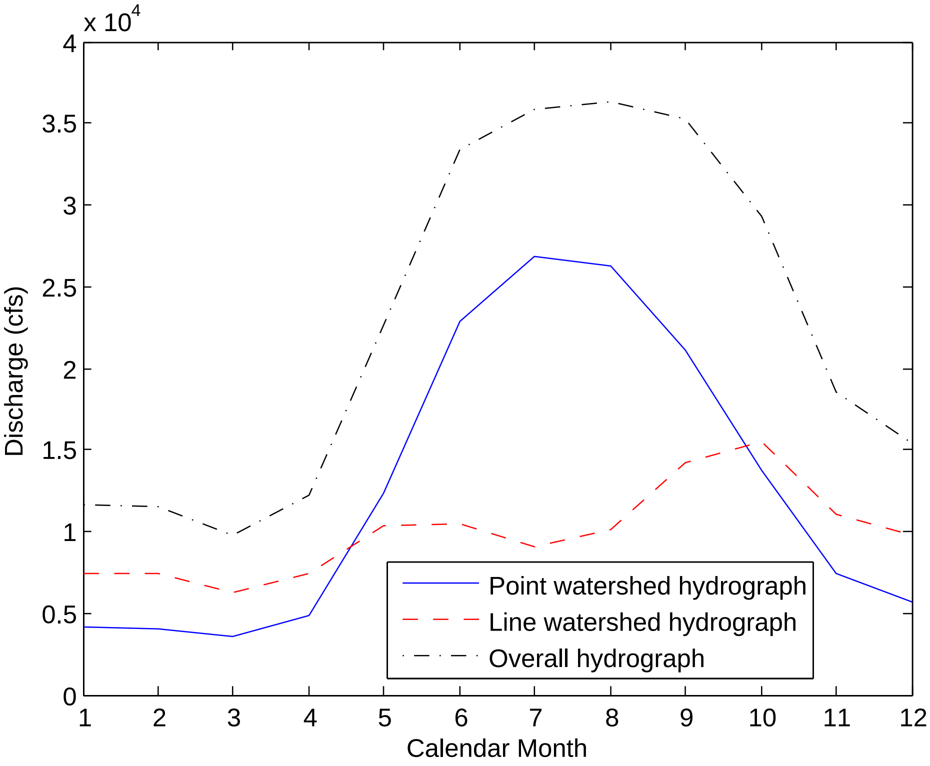

Figure 5.10: Modeled annual hydrograph for Glacier Bay Domain.