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The Effects of Withdrawals on the Hydrology of Samish Lake and Upper Friday Creek

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THE EFFECTS OF WITHDRAWALS ON THE HYDROLOGY OF SAMISH LAKE AND UPPER FRIDAY CREEK

by

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ABSTRACT

Samish Lake, the headwaters of Friday Creek, supplies water for approximately 440 residences. These residents withdraw about 140 acre-ft./year of water from the lake. Continued development around the lake will require more withdrawals. Although withdrawals consume only a small portion of the 32,000 acre-ft. of water stored in the lake, they do effect streamflow in Friday Creek, especially low flows in late summer.

Present withdrawals reduce the mean-annual streamflow of Friday Creek from about 31.7 cfs to 31.3 cfs (cubic feet/sec). During a normal year, the lowest streamflow is reduced from about 0.44 cfs to 0.38 cfs. The lake withdrawals have their greatest effect for a period of about six days, usually in August. Withdrawals cause lowest streamflow to occur about three days earlier and to last about three days longer than under natural conditions. Increasing withdrawals by 2.5 times would cause a small additional reduction in minimum streamflow and would increase the duration of minimum flow by another two days.

Simulations indicate that a dam controlling lake outflow could store water for additional withdrawals and for augmenting flow in Friday Creek during the low flow period. Simulations also indicate that augmenting Friday Creek by pumping from lake storage would allow for additional withdrawals while maintaining adequate streamflow. Pumping would, however, lower the late-summer lake level slightly below the natural level.

ACKNOWLEDGEMENT

This study could not have been accomplished without the assistance of Mr. Dave Jenkins, a long time resident of the Samish Lake community. Mr. Jenkins collected daily observations of precipitation, lake level, and stage of Friday Creek. He also provided much interesting information and background on the development history of the lake, past flooding, and the control of beaver and their dams. I also thank Mr. David Johnson, manager of Water District 12, for providing precipitation and sewer records for Samish Lake. Peer review was provided by Linton Wildrick and Robert Garrigues.

INTRODUCTION

Samish Lake is the headwaters of Friday Creek, a tributary to the Samish River. The lake is also the domestic water supply for most residents around the lake. According to a recent tally there are 426 houses or mobile homes on the lakeshore or directly across the road from the lake and about 18 others scattered in the uplands (Jenkins and Ellingson, 1989). The residents withdraw about 0.40 acre-ft./day or about 140 acre-ft. annually (Larson, 1988). Much of this water is exported from the watershed via the sewer system.

Friday Creek drains the lake through a series of wetlands and beaver ponds on the lake's southern end. Although streamflow exceeds 500 cubic-ft./sec. (cfs) during winter storms, the late-summer low streamflow approaches zero. The low streamflow reduces fish habitat and concerns the state's wildlife and fisheries agencies. The low flows occur naturally, but are exacerbated to some extent by the lake withdrawals. In addition, the low flows are reduced by beaver activity.

Construction of new homes requires domestic withdrawals from Samish Lake as there is presently no alternate source of water. Because the volume of water in Samish Lake controls the streamflow in upper Friday Creek, increased withdrawals will further reduce streamflow.

PURPOSE

The demand for additional withdrawals has highlighted the conflict between out-of-stream and in-stream uses of water. The major purpose of this study was to estimate the magnitude of the effects of additional withdrawals on streamflow. In this study, I concentrated on answering three questions:

1. What is the present streamflow regime of Friday Creek?
2. What are the effects of current lake withdrawals on Friday Creek streamflow? and
3. What would be the effects of additional withdrawals?

Answers to these questions are necessary before an informed decision can be made on future water appropriations from Samish Lake and the amount of protection to give Friday Creek.

SITE

Samish Lake is located in southwest Whatcom County about ten miles southeast of Bellingham (Figure 1). It lies in a depression between Chuckanut Mountain on the west and Lookout Mountain to the east. The lake, approximately 810 acres in area, is surrounded by a 7055 acre watershed. The combined drainage area from headwaters to the lake outlet is 7865 acres. Although the lake outlet is at 260-feet in elevation, the ridge line to the west rises to nearly 1800 feet and Lookout Mountain to the northeast peaks near 2700 feet. The average elevation of the watershed is about 1200 feet. The majority of the watershed is forested and slopes steeply toward the lake. Residential development is generally restricted to the near vicinity of the lake shore.

Samish Lake is sharply divided into two basins, a smaller, deep west arm and a shallow, but larger, east arm. The average depth of the west arm is 71 feet with a maximum depth of about 140 feet. The larger east arm has an average depth of 31 feet and a maximum depth of about 75 feet. The present lake was probably gouged out by an advancing glacier during the most recent glaciation approximately 12,000-plus years ago. Filling of the lake occurred as the glacier retreated some 10,000 years ago.

The lake, covering about ten percent of its watershed, contains roughly 32,000 acre-ft. of water in dead storage below the level of the lake outlet. During a typical winter, the lake rises five feet or more with the stored volume increasing to 37,000 acre-ft. The annual flow through the lake is about 22,000 acre-ft. (based on this study).

Geology

The Samish Lake depression overlies the contact between the Chuckanut formation on the north and the Darrington Phyllite to the south (Easterbrook, 1976). The Chuckanut formation is composed of sandstone, conglomerate, and shale, interspersed with minor amounts of coal. These sediments, laid down as the area subsided between 50- and 70-million years ago, rest upon the Darrington Phyllite, a fine-grained, dark-colored metamorphic rock, with associated greenschist and slate. The phyllite, formed from the recrystallization of shale, is greater than 200-million years old.

Both formations are well cemented, consolidated, and generally not water bearing except along fractures. Ground water in sufficient quantities for domestic use is found only in recent alluvium around the lake. Much of this ground water is probably in hydraulic continuity with the lake.

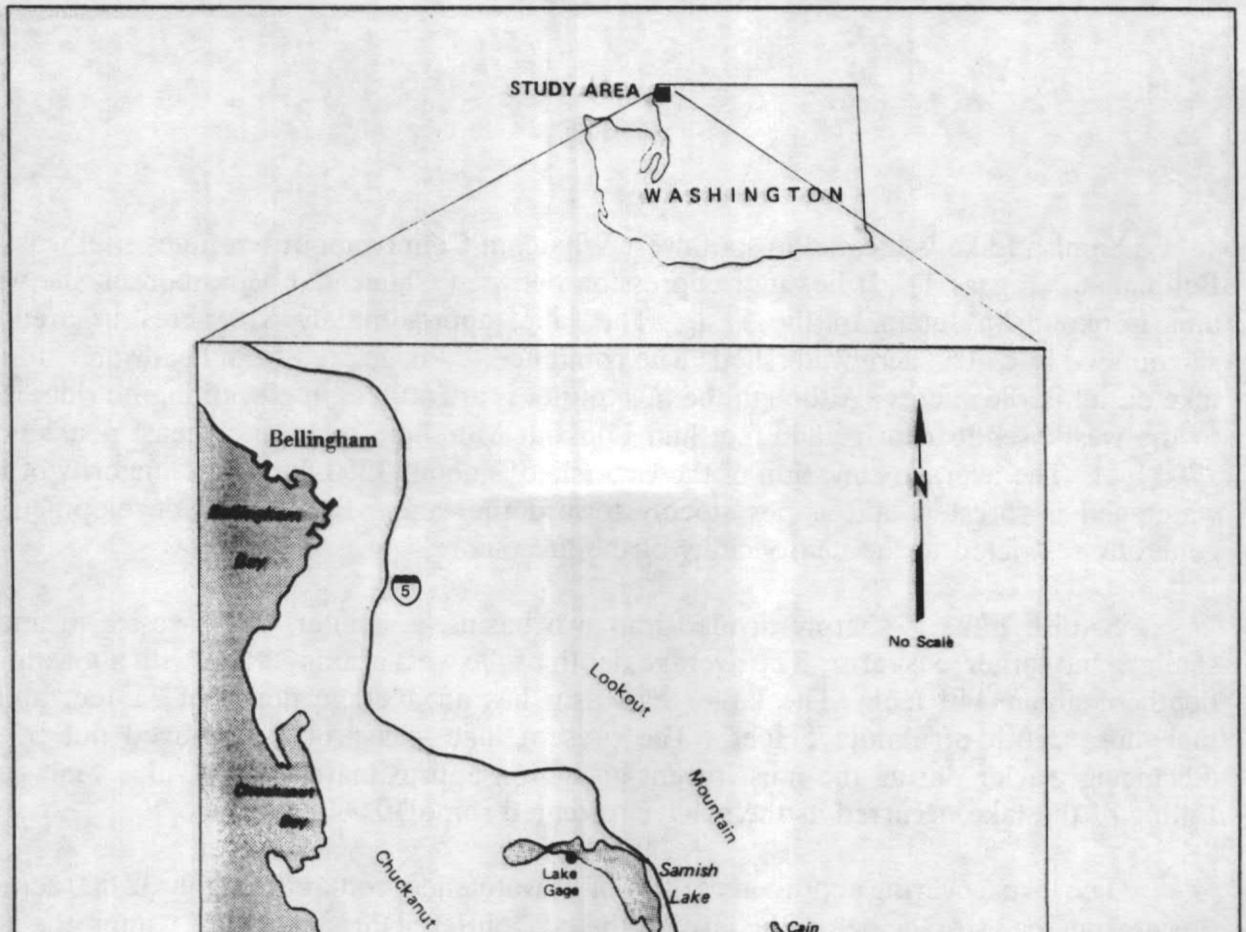

Figure 1. Location Map of Samish Lake and Friday Creek.

Climate

Samish Lake has a maritime climate, with warm, dry summers and cool, wet winters. Extremes in temperature are buffered by the nearby Pacific Ocean, which also contributes heavy winter precipitation. The average maximum temperature recorded at the Bellingham airport (a NOAA climate station), about 20 miles north of the lake, is 71 degrees F. during July and August. The average low temperature is 31 degrees F. occurring during January (winter highs average 43 degrees).

Annual precipitation at the Bellingham airport averages 36 inches. This is about one-half the unofficial precipitation recorded at several locations around Samish Lake. Water District 12 has measured precipitation near the south end of the lake since at least 1979. The average precipitation recorded by the Water District during the past 11 years is 84 inches.

The majority of precipitation falls as rain. Although snow is common, it usually melts within days and only persists on surrounding peaks. Snow accumulation may exceed three or four feet on the highest ridge lines but rarely exceeds 12 inches around the lake. The spring snowmelt is not an important contribution to lake storage.

In the summer, Samish Lake is subject to large evaporation losses. Annual evaporation (potential) at Bellingham approaches 30 inches with as much as 7 inches occurring in July. Thirty inches of evaporation is equivalent to about 2,000 acre-ft. of water from Samish Lake. Over 400 acre-ft. may be evaporated in July alone.

Beaver

Beaver have probably resided in Samish Lake for thousands of years, perhaps more than ten-thousand. During an inspection of Friday Creek from the Nulle Road bridge upstream to the lake (August 23, 1990), I counted five beaver dams, at least one of which was actively maintained. All dams were, however, breached at the time of the inspection, most likely by local residents.

One dam, probably quite old, is located at the edge of the open water where the lake begins its transition into vegetated wetlands. This dam, about 40-feet long and several feet wide, had the appearance more of a mud sill than a dam. However, the water depth increased rapidly to three feet or greater on either side although the depth of water over the structure was only 6 to 8 inches. At the time of the visit, this was the level controlling outflow from the lake. As previously mentioned, dams farther downstream had been breached, many in prior years, but at least one recently, and were not effectively controlling streamflow in Friday Creek.

The older dam leads me to speculate that beaver activity may have raised the level of the lake several feet during past centuries. It is possible that the beaver dams, combined with siltation of beaver ponds, have raised the lake even during recent time. Local folklore indicates that the lake no longer drops as much as it did in years past. Of course, such observations are confounded by the many manipulations man has made to Friday Creek since settling the area.

The greatest dam-building activity occurs in September and October while streamflow is at its lowest and the beaver strive to maintain the level of water in their ponds.

STUDY OVERVIEW

The first step in this study was obtaining streamflow information for Friday Creek. To understand the streamflow regime of Friday Creek and its relationship to storage in Samish Lake, a long-term record of observed streamflow for Friday Creek and long-term records of storage in Samish Lake would be ideal. Unfortunately, except for a few miscellaneous measurements, neither upper Friday Creek nor Samish Lake had been gaged.

Thus, it was necessary to begin streamflow and lake level gaging. I collected data for only one year, from September 1989 through September 1990. Most of the errors in this study can be traced to the short time span of actual gaging. With these observations and precipitation and air-temperature data from the NOAA weather station at the Bellingham airport, I estimated the average, long-term, daily and annual streamflow for Friday Creek using multiple regression and computer modeling. Because climate data at the Bellingham airport has been collected since 1950, it was used in this study rather than the short-term local records.

Because my interest was not in streamflow per se, but rather the relationship between the volume of water in Samish Lake and streamflow, I used lake-level data rather than streamflow data as the primary input to the regression model. I used observed streamflow only to develop the relationship between the volume of water in Samish Lake, as indexed by lake level, and the corresponding streamflow of Friday Creek.

I regressed lake level for 1989-90 with precipitation and air-temperature to get an equation predicting daily lake level from the prior day's lake level, recent rainfall, and the air temperature. I also regressed streamflow for 1989-90 with lake level for the same period to get an equation predicting streamflow from lake level. By combining these two equations, I was able to simulate streamflow from the climatic variables.

Using these equations and the Bellingham climatic data, I simulated the past 40 years of Friday Creek streamflow (1950-1990). This provided a good representation of wet, dry, and average years. I then estimated 10-day-average streamflow at the 10, 50, and 90 percent exceedance frequencies using a log-Pearson Type III analysis of the 40 years of simulated streamflow. The simulated streamflow and streamflow frequencies represent current conditions including the 0.40 acre-ft./day of lake withdrawals.

I simulated streamflow that would have occurred <u>without lake withdrawals</u> by returning the withdrawals to the lake before each successive day's streamflow simulation. That is, I added a depth of water equivalent to the 0.40 acre-ft. of daily withdrawal onto the lake level before predicting the next day's lake level. Then I recalculated the exceedance frequencies for streamflow without lake withdrawals.

To simulate streamflow following an increase in lake withdrawals, I developed a deterministic computer model of Samish Lake that treated lake withdrawals as direct reductions in lake volume and calculated streamflow as a function of the remaining volume. I examined the effects on low streamflow of additional withdrawals by increasing the withdrawal rate from the current 0.40 acre-ft/day to 1.00 acre-ft/day, a 2.5 fold increase in water diversions.

The model also allowed the impoundment of water behind a simulated dam and the extraction of dead storage by pumping. Controlling the lake storage allowed me to examined the potential for augmenting low streamflow in conjunction with increased withdrawals.

The effects of beaver dams on lowflow were also examined and subsequently removed from the predicted streamflow to the extent possible. I did not have adequate data to simulate beaver activity but rather found it expedient to subtract their effects from the streamflow record. In essence, although I discuss the present effects of beaver damming during low flow, the effects of beaver have been removed and/or ignored in the modeling. The regression equations and the lake model simulate streamflow that would occur without beaver dams.

DATA COLLECTION AND ANALYSIS

To monitor the level of Samish Lake, I installed a float gage in September, 1989. The gage was installed on the dock of Mr. Dave Jenkins located along the upper, western lake shore. Mr. Jenkins recorded the lake level daily to the nearest 0.01 feet. The zero level was set slightly below the level at which outflow from the lake ceased.

When the study period began, in September 1989, Samish Lake was at a level of 0.72 feet. It declined to a low of 0.49 feet by late October before it began to refill. A storm in November 1989 raised the lake level to 5.07 feet and a second storm in February 1990 raised the level to 5.55 feet. Both storms caused some flooding along the lake shore. During the time between these storms and during the remainder of the winter, the lake fluctuated between a level of two and four feet.

Following a relatively wet June 1990, the lake level began dropping rapidly and reached a low of 0.52 feet near the end of September. The water in Samish Lake began its annual rise on October 3, 1990, with the advent of fall rains (Appendix 1. - Lake level 1989-1990). The lake level did not drop below the zero level of the gage during the study period.

I monitored Friday Creek streamflow with a staff gage installed at the Nulle Road bridge, just downstream of the lake outlet. The staff was installed in August 1989 and streamflow monitored through September 1990. Mr. Jenkins recorded the stage daily to the nearest 0.01 foot. I assumed the daily reading represented the mean discharge for the day, a reasonable assumption considering the buffering of streamflow by the lake and the resulting slow rise and fall of stream discharge.

Fluctuations in stage and related streamflow of Friday Creek closely parallel changes in lake level (Figure 2, Appendix 2. - Friday Creek streamflow 1989-1990). The stream was essentially dry in late September and early October 1989 when the study began, with flow less than 0.01 cfs. Streamflow began to rise with the fall rains in late October and exceeded 400 cfs during the November storm and 625 cfs during the February storm. Snowmelt as well as precipitation likely contributed to the high flow of the later storm.

A wet spring maintained high streamflow through mid-June 1990. Streamflow steadily declined from July through September. Flows in August and September were less than 0.05 cfs, not quite as low as the previous fall, but essentially only a trickle of water flowing between distinct pools. Streamflow began rising in October 1990.

The mean discharge of Friday Creek during 1989-1990 was 44.6 cfs with an annual runoff of 49.3 inches. This October through September water year was wetter than average,

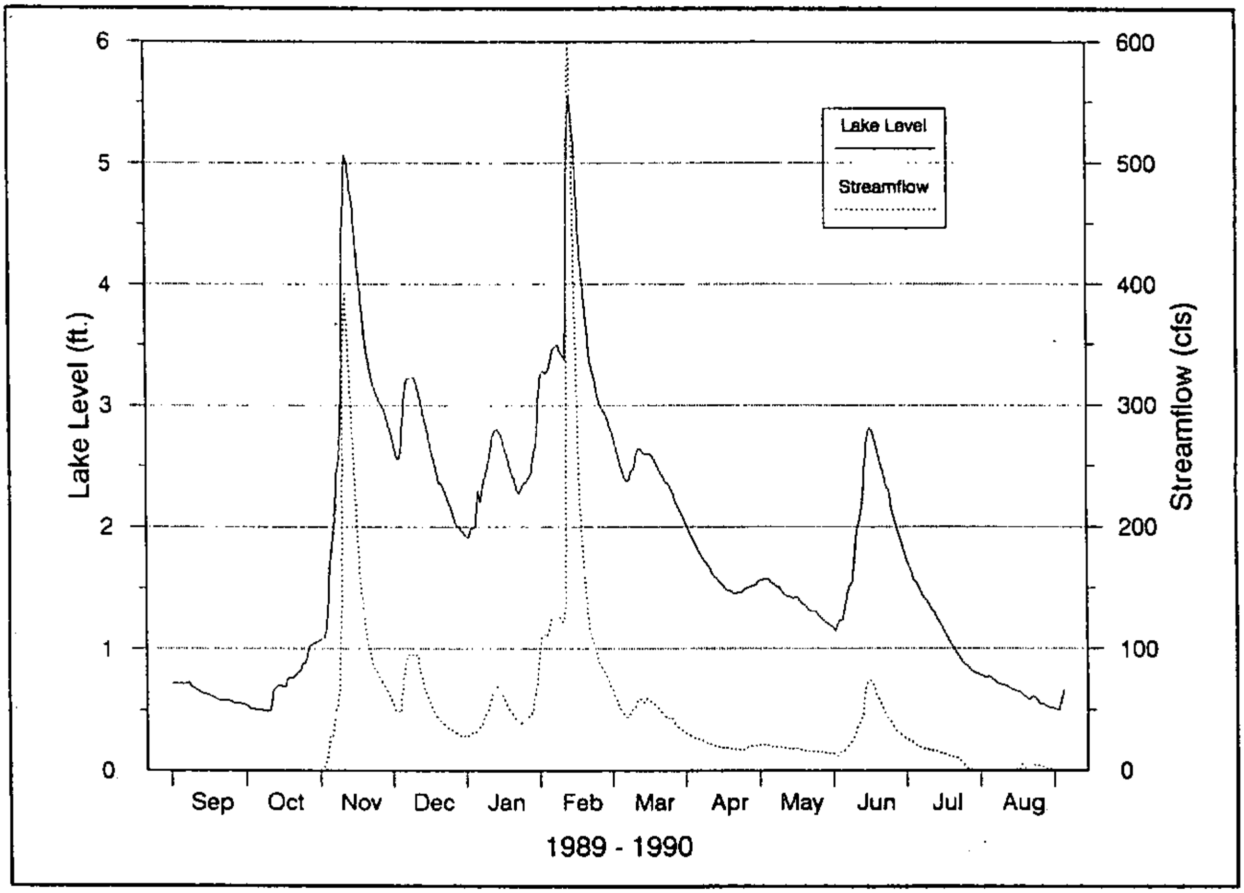

Figure 2. Comparison of Friday Creek streamflow and the water level of Samish Lake.

with Bellingham receiving 41 inches of precipitation as compared to its normal 36 inches. The precipitation recorded by Mr. Jenkins on the west side of the lake, during the same period, was 81 inches, the water district recorded 76 inches.

This can be compared with the driest year of the past 40 years, 1973, with 24.6 inches of precipitation recorded at Bellingham, and the wettest year, 1976, with 47.6 inches. In the latter part of this report, I select 1973 and 1976 for discussion of a dry and wet year, respectively.

The Stage-Discharge Rating

I converted the daily stage records to stream discharge using a set of rating equations. Discharge was measured at ten stages ranging from a low of 4.06 to a high of 7.15 feet. Zero streamflow occurred at a stage of about 3.95 to 4.00 feet. Measured discharge ranged from 0.06 to 162 cubic-ft./second (cfs) (Table 1).

Table 1. Measurements of stream discharge, Friday Creek at Nulle Road.

Date	Time	Staff (ft.)	Discharge (cfs)
zero flow		3.95	0.00
estimate		4.00	0.01
9/27/90	1315	4.06	0.06
10/23/89	1200	4.10 *	0.07
8/23/90	1500	4.35	2.1
7/13/89	1700	4.43 *	5.3
6/30/89	1300	4.49	10.2
7/10/90	1200	4.75	15.8
4/26/90	1400	4.91	21
6/05/90	1400	5.00	24
1/16/90	1415	5.87	52
11/17/89	1430	7.15	162

* staff adjusted by +0.07 feet to compensate for channel filling following the November, 1989 storm.

To develop rating equations relating discharge to stream stage, I plotted the measured streamflow in cfs against the respective staff-gage reading in feet (Figure 3). I divided the resultant curve into four straight-line segments, calculating a rating equation for each line. The first equation predicts discharge for stages between 4.00 and 4.35 feet, the second between 4.35 and 4.50 feet, the third between 4.50 and 5.00 feet, and the fourth, stages greater than 5.00 feet. The equations are presented, along with their correlation coefficients (r), in Figure 3. Additional measurements may show that fewer equations are necessary. The major break in the curve occurs at about 4.50 feet when the channel bottom becomes fully submerged.

I measured stream discharge with a Swoffer Instruments model 2100 current-velocity meter and a top-setting wading rod. Velocity was measured at 0.6 of the stream depth and discharge calculated by the midsection method (Buchanan and Somers, 1969). I generated continuous records of streamflow by passing the daily recorded or simulated stage through the rating equations.

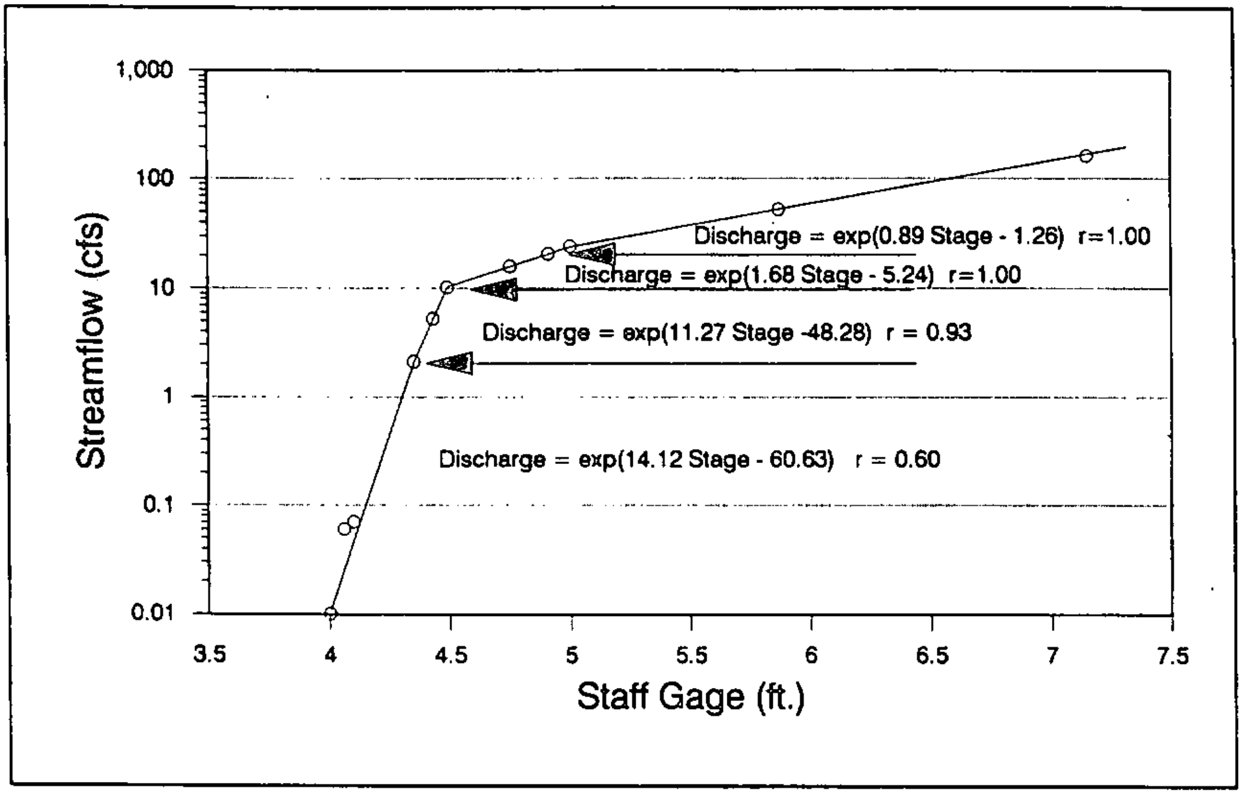

Figure 3. Discharge rating curve and equations for Friday Creek at Nulle Road.

Simulation Of Streamflow From Lake Level

To predict streamflow from lake level, I regressed the Friday Creek stage records against their respective lake-level records. I used data collected between November 4, 1989, and August 31, 1990, removing from the analysis any data known or believed to be affected by beaver dams. Beaver activity was first noted at a lake level of about 0.87 feet, thus data before November 1990 and from July 22 through August 13, 1990, were not used in the regression.

The regression used 279 data pairs and covered lake levels ranging from 0.49 to 5.55 feet and stream stage from 4.12 to 8.65 feet. This included the full range of lake rise and fall and all but the lowest of the stream stage records. The regression equation is:

$$\text{staff gage} = (0.89730 \times \text{lake level}) + 3.59832$$

The regression had a correlation coefficient of 0.97 and a coefficient of determination of 0.92.

Once I had developed the relationship between the lake level and stream stage, I simulated stream discharge by running the estimated stage through the discharge rating equations. Figure 4 indicates how well this technique simulates streamflow. The solid line in the figure depicts the observed streamflow as calculated from the daily stage records, and the dashed line depicts the streamflow as calculated from the daily lake level.

The match between the two streamflow estimates is very good. The mean-daily discharge based on the lake-level regression was 44.2 cfs as compared to the observed 44.6 cfs. Using the lake level as a predictor of streamflow works quite well except during periods of beaver activity.

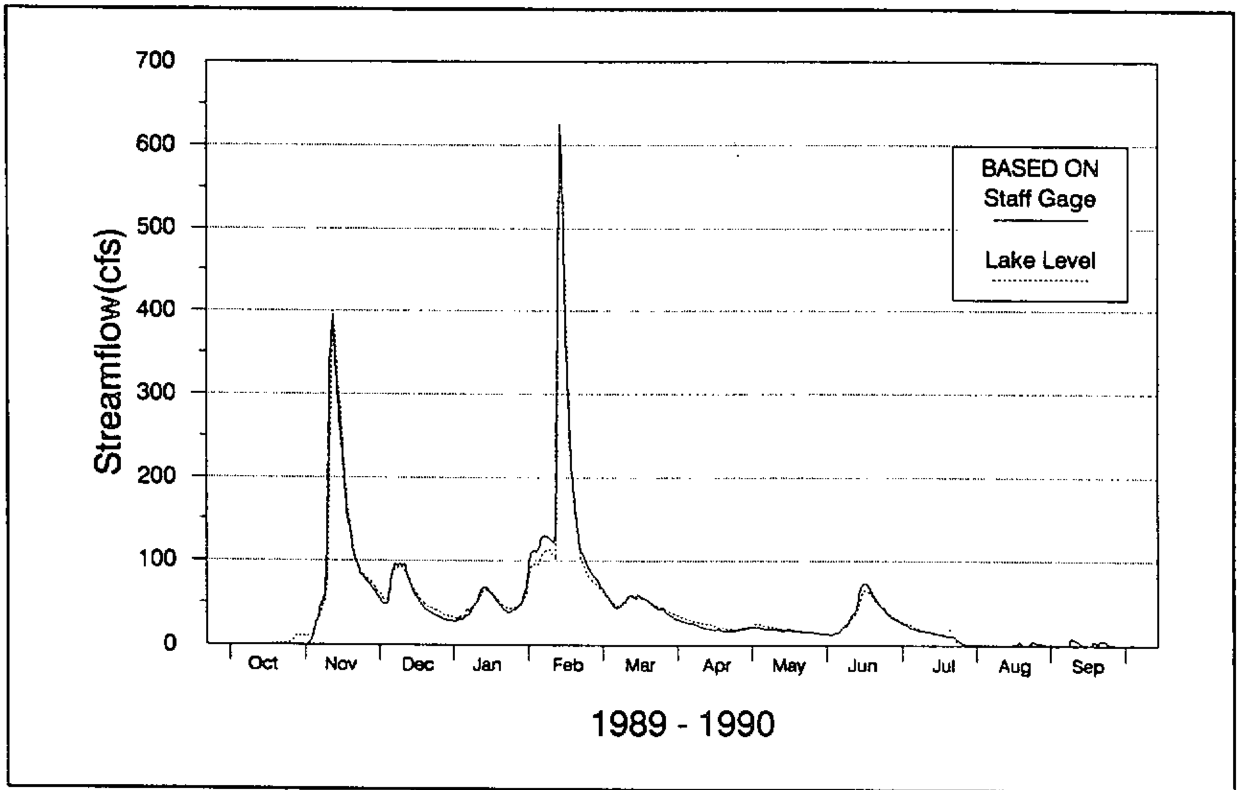

Figure 4. A comparison of streamflow as measured by the staff gage at Nulle Road with streamflow simulated from the water level of Samish Lake.

Simulation Of Lake Level Using Climatic Data

After simulating streamflow from the lake level, I predicted the lake level based on climatic data. To develop a prediction equation, I regressed the daily lake levels, recorded by Mr. Jenkins, with precipitation and air temperature recorded at the Bellingham airport. I used 365 days of data, from September 1, 1989, through August 31, 1990, in the regression.

The dependent variable in the regression was the current day's lake level. I used five independent variables: (1) the prior-day's lake level, (2) the sum of the prior-three-day's precipitation, (3) the current-day's precipitation, (4) the prior-day's precipitation, and (5) the average of the maximum and minimum daily air temperature.

I tried several summations of prior-days' precipitation including 3,4,5,7, and 10 days before deciding on 3 days. The regression using precipitation for the prior 3 days had the lowest standard error.

The initial regression, using air temperature as an independent variable resulted in a standard error of 0.01, a correlation coefficient of 0.995, and a coefficient of determination of 0.991. Additional regression calculations without temperature as a variable resulted in identical statistics. Lake levels predicted from either regression were similar. To simplify the analysis, I dropped temperature from the regression.

The final equation is:

daily lake level = 0.9641 x (prior day's lake level)
+ 0.0496 x (sum of prior 3 day's precipitation)
+ 0.1612 x (day's precipitation)
+ 0.2644 x (prior day's precipitation)
+ 0.0032

Because I was interested in a prediction equation and not a cause-and-effect correlation, I did not concern myself with the co-dependence of lake level and prior-day's lake level.

I tested the regression equation by calculating the daily lake levels during 1989-1990 and comparing them with observed lake levels. The initial lake level was set equal to the actual level and used as the "seed" to start the prediction. From day two onward, the predicted daily level was used as the prior-day's lake level for the next day's prediction. I recalculated the precipitation sums and lags for each day.

The predicted lake level generally matched the pattern of the actual level (Figure 5). The dramatic increase in lake level during the February storm was not well predicted from the Bellingham data, but the summer recession and low levels were adequately simulated. Although it would have been better to verify the equation on data not used in the original regression, I had no additional data.

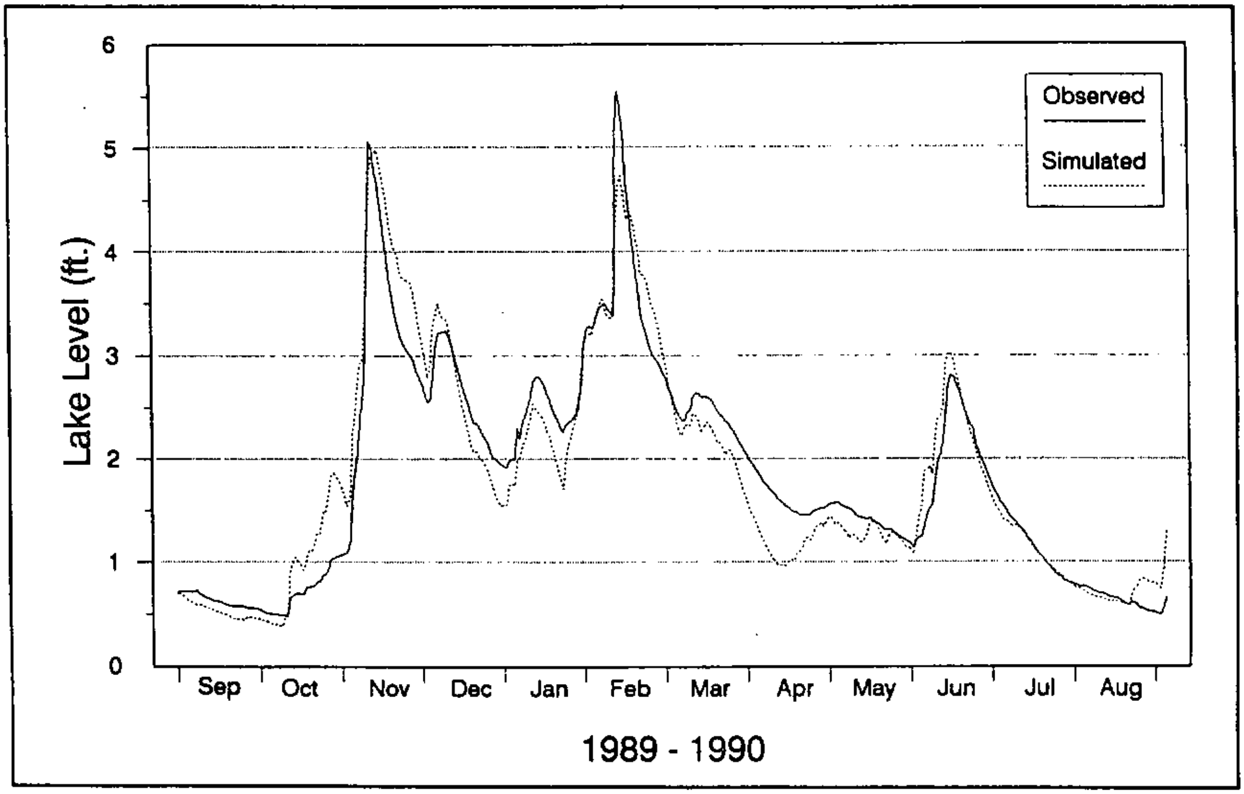

Figure 5. A comparison of the observed and simulated water level of Samish Lake.

STREAMFLOW STATISTICS

Using precipitation from the Bellingham airport for 1950 through 1990, and the regression equations previously discussed, I simulated 40 years of daily lake level and resultant streamflow of Friday Creek. Starting with an assumed lake level of 0.70 feet on October 1, 1949, I simulated Friday Creek streamflow through September 30, 1990. Using these simulated records, I then estimated the statistical frequency of streamflows expected to be equaled or exceeded 10, 50, and 90 percent of the time.

Rather than use the highly variable daily values, I averaged streamflow over 10-day periods before calculating flow statistics. The daily streamflow during each 10-day period (three per month) were averaged for each of the 40 years. This resulted in 36 flow values for each year, one for each of the three periods during a month. The last period of each month with other than 30 days contains either 8, 9, or 11 days rather than 10.

The frequency calculations for each of these 36 period values involved 40 observations (40 years of streamflow) and assumed a log-Pearson Type III distribution (Haan, 1977). The Pearson K-values necessary in this calculation were computed by an equation generally considered reliable for skew coefficients between +1.0 and -1.0 (Harter, 1969). The K-values are based on the standard, normal deviate and not Pearson K-tables.

The simulated streamflow included the effects of current lake withdrawals. To estimate the streamflow of Friday Creek without the lake withdrawals, I added a height of water equal to the daily withdrawals to the prior-day's lake level before predicting the current day's level. Adding 0.00048 feet to the lake level is roughly equivalent to 0.40 acre-ft. added to the lake. Streamflow and exceedence flows were estimated from the adjusted lake level as previously described.

Based on the regression model, the current mean-annual streamflow of Friday Creek is 31.3 cfs. Without current withdrawals, the model predicted a mean-annual streamflow of 31.7 cfs, an increase of 0.4 cfs. Since the current withdrawals are about 0.2 cfs, the model overestimates the actual effects of withdrawals.

The 10, 50, and 90 percent exceedence streamflows for the 36 periods of the year are presented in Table 2 and plotted in Figure 6. These results depict the streamflow as affected by current lake withdrawals because the model is derived from 1989-1990 data. The lowest flows usually occur in mid-August with a minimum flow of 0.38 cfs equaled or exceeded about one-half the time. Minimum flows drop to 0.01 cfs (essentially dry) at least once in ten years. Highest flows occur in late December or Early January, equaling or exceeding 51 cfs about one-half the time.

Table 2. Exceedance streamflow for Friday Creek at Nulle Road (cfs).							
		With Withdrawals			Without Withdrawals		
Month	Period	10%	50%	90%	10%	50%	90%
Jan	1	108.7	51.5	24.8	109.8	52.0	25.1
	2	120.5	44.8	27.0	121.7	45.3	27.4
	3	139.1	50.7	23.0	140.5	51.2	23.4
Feb	1	130.3	44.8	19.7	131.6	45.3	20.0
	2	133.1	42.4	18.7	134.4	42.9	19.0
	3	95.4	30.7	13.9	96.3	31.1	14.2
Mar	1	89.5	36.0	18.4	90.4	36.4	18.7
	2	74.8	33.5	16.1	75.5	33.8	16.5
	3	55.8	29.4	15.5	56.3	29.7	15.9
Apr	1	47.0	27.0	15.2	47.5	27.4	15.5
	2	40.2	26.7	14.2	40.6	27.0	14.6
	3	33.7	27.0	12.4	34.4	27.1	12.8
May	1	31.5	23.2	8.4	32.0	23.5	8.9
	2	31.3	21.8	6.7	31.8	22.1	7.1
	3	29.2	20.9	3.5	29.3	21.4	3.8
Jun	1	30.4	17.1	3.0	30.4	17.7	3.3
	2	34.6	13.4	1.1	34.2	14.0	1.3
	3	30.8	9.0	0.9	30.8	9.5	1.0
Jul	1	29.8	9.8	0.8	29.7	10.3	0.9
	2	41.0	5.9	0.17	40.9	6.3	0.20
	3	25.3	2.2	0.04	26.0	2.4	0.05
Aug	1	10.5	0.57	0.02	11.2	0.66	0.02
	2	7.5	0.38	0.01	8.0	0.44	0.02
	3	18.4	0.53	0.01	19.1	0.61	0.01
Sep	1	33.3	1.1	0.02	34.0	1.2	0.02
	2	32.1	1.8	0.04	32.7	2.0	0.05
	3	35.1	3.2	0.08	35.1	3.5	0.10
Oct	1	47.2	6.2	0.15	47.0	6.6	0.18
	2	56.9	12.2	0.29	56.0	12.9	0.33
	3	40.6	30.7	2.1	40.8	31.2	2.2
Nov	1	55.5	45.5	8.2	55.6	45.9	8.5
	2	83.9	34.9	15.3	84.7	35.2	15.7
	3	87.2	39.2	15.6	88.0	39.6	16.0
Dec	1	107.5	46.3	20.0	108.6	46.7	20.4
	2	107.3	48.5	22.8	108.4	49.0	23.2
	3	107.5	51.3	24.9	108.6	51.8	25.2

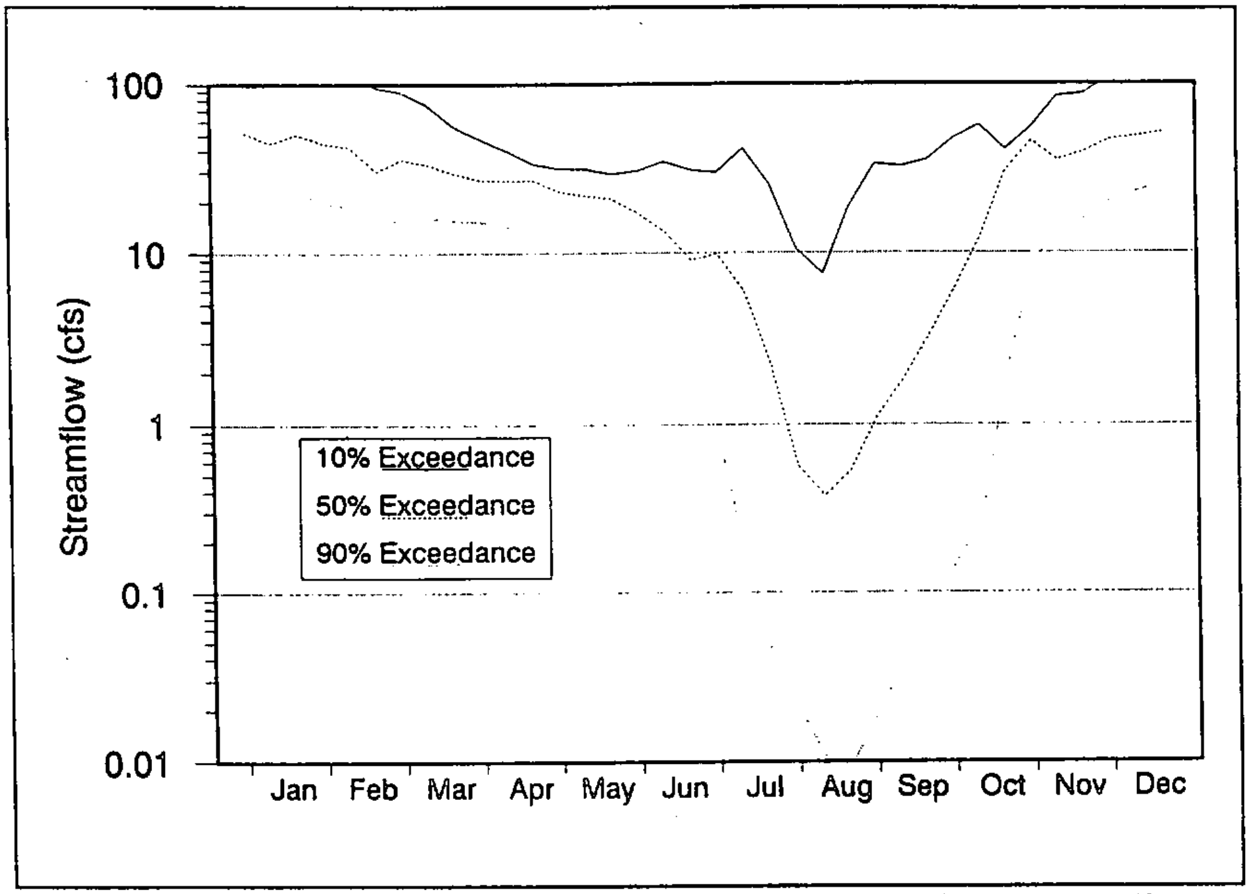

Figure 6. Streamflow equaled or exceeded 10, 50, and 90% of the time, 1950 to 1990.

The exceedance streamflows without lake withdrawals are also shown in Table 2. They did not differ greatly from streamflows with withdrawals and were not plotted. At the scale of Figure 6, the streamflows with and without lake withdrawals would plot as the same line. This is not to say that the lake withdrawals do not effect streamflow, especially lowest flows.

To show the important differences between these two cases, I plotted the 50-percent exceedence streamflow during the lowest flow period, July through September (Figure 7). This figure compares streamflow affected by lake withdrawals to the streamflow not affected by lake withdrawals. The effects of lake withdrawals become important only when streamflow is below about 0.6 cfs.

Present lake withdrawals (0.40 acre-ft./day = about 0.20 cfs) have caused minimum streamflow (50-percent exceedance) to decrease by about 0.06 cfs (from 0.44 to 0.38 cfs). The lake withdrawals have also advanced the date at which the streamflow drops below a given low flow (for example 0.5 cfs) by about three days (see Lag Time, Figure 7).

Similarly, withdrawals retard the rewetting of the stream by a similar lag thus increasing the time of lowest flow. In an average year, the lake withdrawals have their maximum effect for a period of about six days in mid-August. Because the regression model overestimated the effects of withdrawals, I believe these effects are maximum values. The effects of current withdrawals on streamflow may often be less than this.

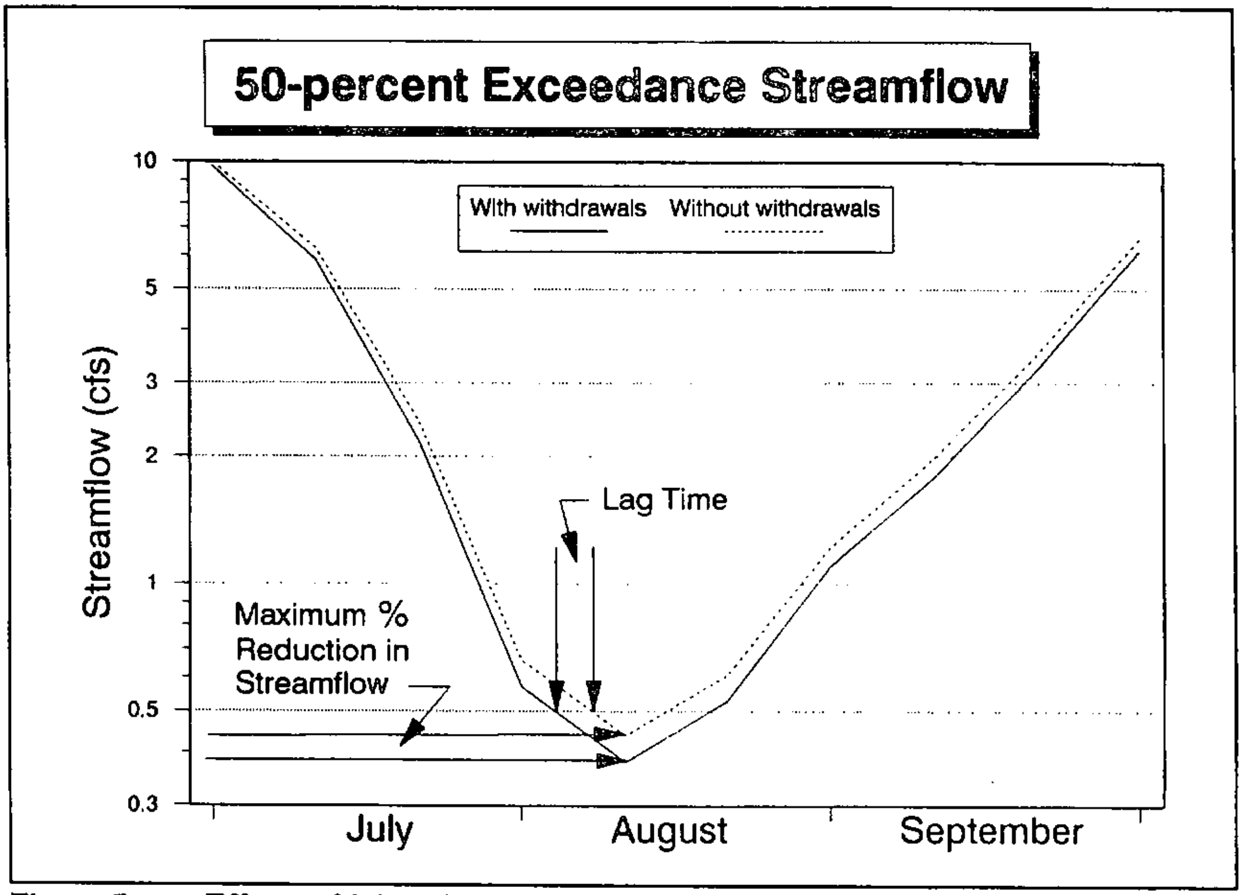

Figure 7. Effects of lake withdrawals on low streamflow in Friday Creek.

THE DETERMINISTIC MODEL

I developed a deterministic computer model to estimate effects of additional lake withdrawals on Friday Creek. The model was based on the retardation of precipitation both in the soil and in lake storage and its slow release as streamflow. Input to the model is precipitation and air temperature at the Bellingham airport.

I calibrated the model using the 1989-1990 data. Bellingham precipitation was increased by a weighting factor during calibration until the predicted mean-annual flow of Friday Creek equaled the observed. I kept this weighting constant throughout the remaining model simulations.

The model routes precipitation through soil storage, extracts evapotranspiration, and passes a portion of the soil water into the lake. The lake volume is increased by the soil moisture inflow and direct precipitation, lake evaporation is removed, and the new level of the lake computed from the remaining volume. Outflow is then generated using the previously described relationship between lake level and streamflow. A flow chart of the model is presented in Figure 8. The model, including a partial listing of the source code, is further described in Appendix 3.

After the model calibration, I simulated streamflow for the 40-year period, 1950-1990, in one continuous model run. The lake storage and soil-moisture conditions at the end of each year were the initial conditions for the following year. However, rather than examine the entire simulation, I selected the wet and dry years, 1976 and 1973 respectively, and 1990 as examples.

In the first model run, the lake withdrawals were set to the 0.40 acre-ft./day current rate. I made a second model run with withdrawals increased to 1.00 acre-ft./day, 2.5 times the current withdrawals. The increase in withdrawals by 0.60 acre-ft. was arbitrary, but would represent more than double the current residential population.

I ran the model a third time, simulating a two-foot dam controlling the lake outflow. Whenever the level of the lake was greater than two feet, the outflow of the lake was simulated as before. However, when the lake level dropped to two feet or less, I controlled the outflow. Although the normal outflow from the lake is about 25 cfs at a lake level of two feet, I arbitrarily reduced the outflow to 8 cfs. The retarding of outflow retained water in the lake for later release.

The dam was designed to have no effect on streamflow or lake level when the lake level was above two feet. However, once the lake declined below the two-foot dam, the

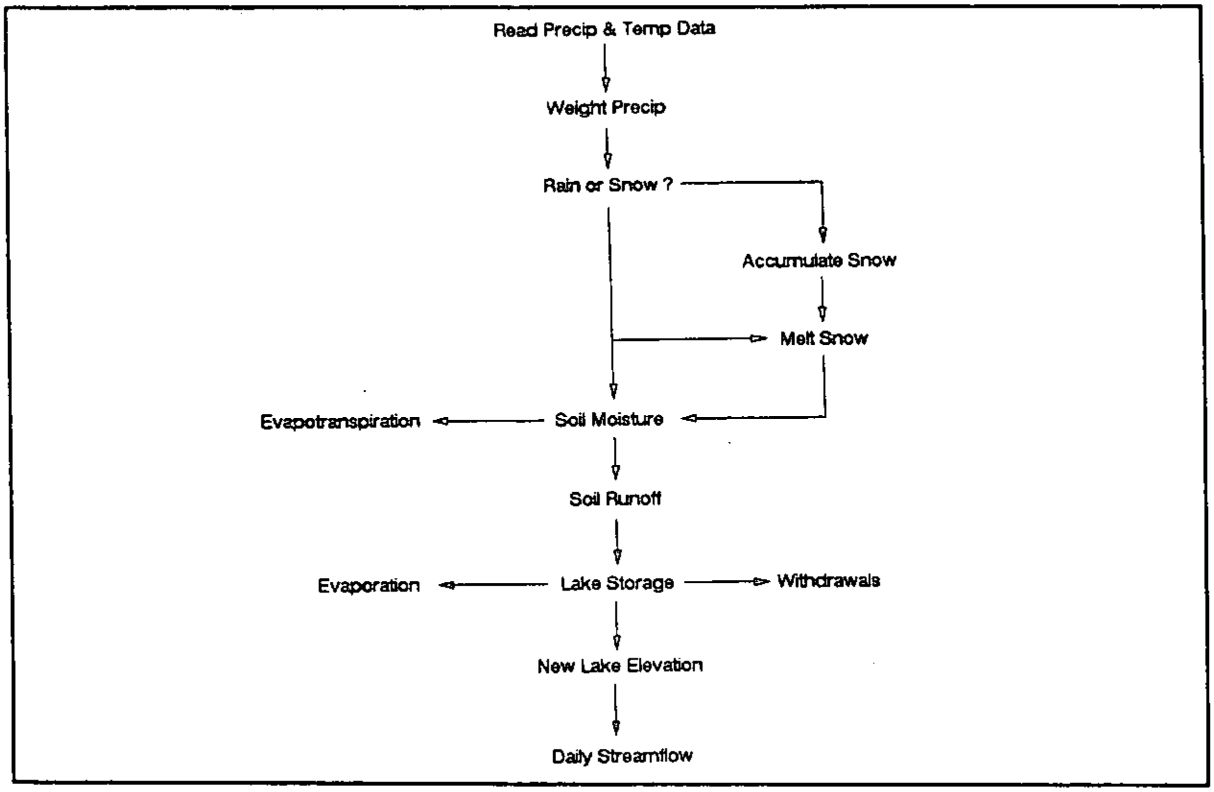

Figure 8. Flow chart of the deterministic computer model.

outflow was slowed and any further decline in lake level retarded. When the lake level had declined to one foot, I arbitrarily reduced the lake outflow to 4 cfs. When the lake level reached zero feet, streamflow ceased.

Both the two-foot height of the dam and the 8 and 4 cfs controlled outflow were selected as examples only. My purpose was only to determine if storage was a practical method of enhancing low streamflow. I did not attempt a gradual lowering of streamflow nor did I investigate the most feasible storage level or the maximum low-flow enhancement. I also did not investigate whether there is enough gradient between the lake and upper Friday Creek to discharge 4 cfs when the lake level approaches zero, only that there was enough water in the lake to maintain this flow assuming the gradient was adequate.

A fourth run was made with the dam in place and the withdrawals increased to 1.00 acre-ft./day. Lake outflow was again clamped at 8 cfs when the lake level was between one and two feet, and at 4 cfs when the level was less than one foot.

Because the lake contains about 32,000 acre-ft. of dead storage below its outlet level, streamflow augmentation, very similar to that provided by dam storage, could be accomplished with pumps. Results would differ only in the final lake levels. For similar volumes of streamflow augmentation, pumping would result in lower lake levels than using dam storage.

To test a pumping scenario, I made three final runs with 0.40 acre-ft. of withdrawals, no dam, but with a simulated pump augmenting lake outflow. Streamflow was augmented to maintain flows of 0.50, 1.00, and 2.00 cfs. To maintain these flows, I withdrew water from the lake and added it to the lake outflow whenever the natural streamflow dropped below these flow limits. If necessary, I pumped from dead storage using water from below the lake level at which streamflow would have naturally ceased.

Calibration

The 1989-1990 streamflow simulated by the computer model closely matched the observed streamflow except during the major February storm (Figure 9). The model, relying on the assumption that Samish Lake precipitation is a constant proportion of precipitation at the Bellingham airport, poorly simulated this event. Proportionately much greater precipitation probably occurred on the Samish Lake watershed than was estimated from the Bellingham precipitation.

Although poorly estimating the peak flow event of the year, the model adequately simulated the recession and baseflow occurring in July, August, and September. In this study, I was most interested in the low-flow period (see lower plot in Figure 9). Fortunately, because of the buffering effect that the lake storage has on streamflow, the model was not sensitive to changes in the soil storage parameters or estimates of evapotranspiration. Thus, even though the model was crude, the resulting streamflow reasonably simulated actual flow, especially during low-flow periods.

Increased Withdrawals

A comparison of the simulated streamflow with withdrawals set at 0.40 acre-ft./day and at 1.00 acre-ft./day is presented in Figure 10. Streamflow during the low-flow period, June through September, is presented for 1990, 1976, and 1973. The model predicted that, with current withdrawals, 1990 streamflow would practically cease by mid-August. The model simulated 25 days in 1990 with streamflow less than 0.01 cfs. The increase in withdrawals to 1.00 acre-ft./day caused the streamflow to cease about two days sooner, and increased the number of days with flow less than 0.01 cfs to 27.

The streamflow simulations were similar for the dry year, 1973, except that streamflow ceased near the end of July. By the end of the 1972-73 water year, lake storage was lower than at the start by 754 acre-ft. Increasing the withdrawals from 0.40 to 1.00 acre-ft./day reduced the annual runoff from 25.4 to 25.2 cfs and increased the number of days with streamflow less than 0.01 cfs from 59 to 61 days. The additional withdrawals also caused the lake storage at the end of the year to decline another 27 acre-ft.

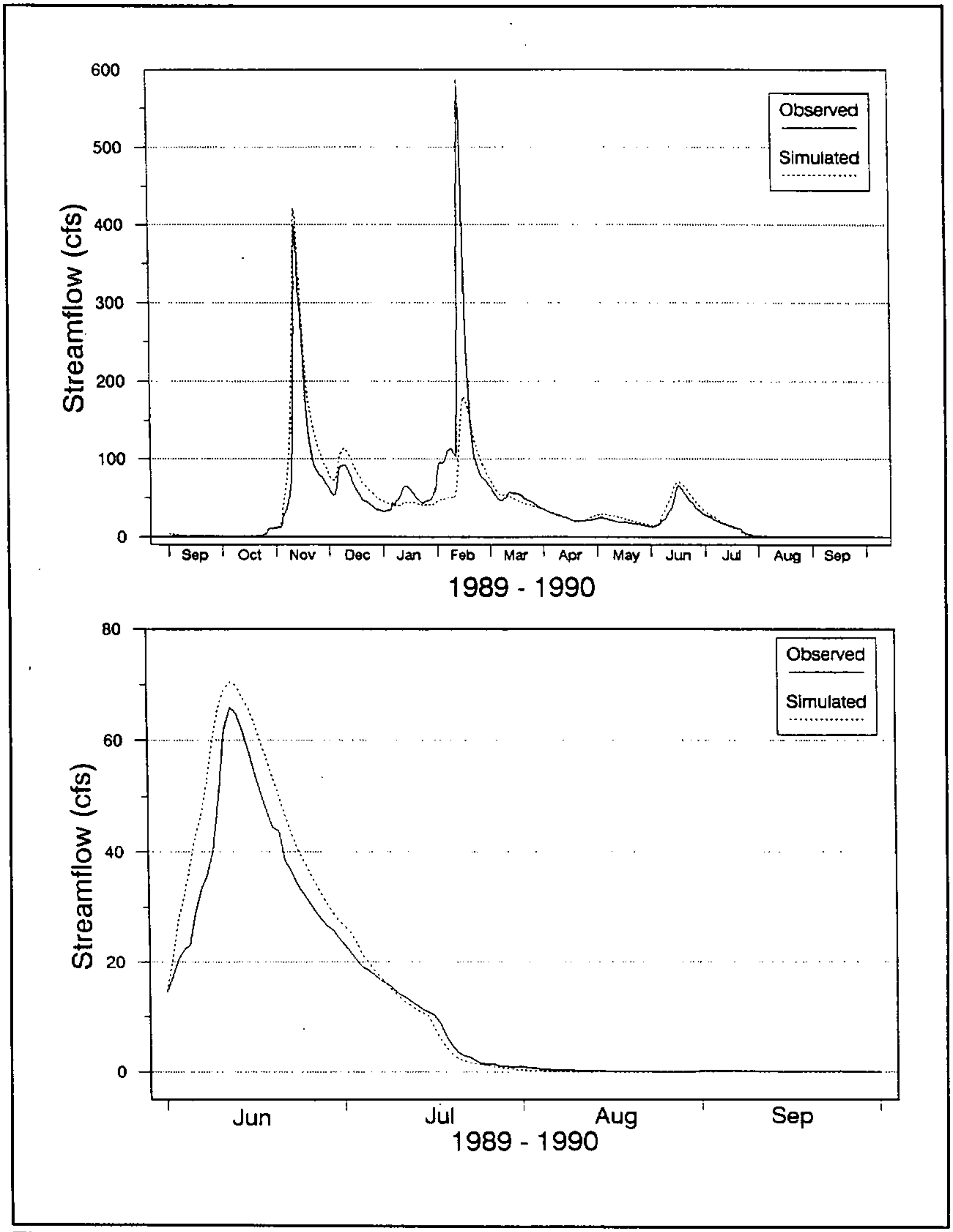

Figure 9. A comparison of the simulated and observed streamflow of Friday Creek

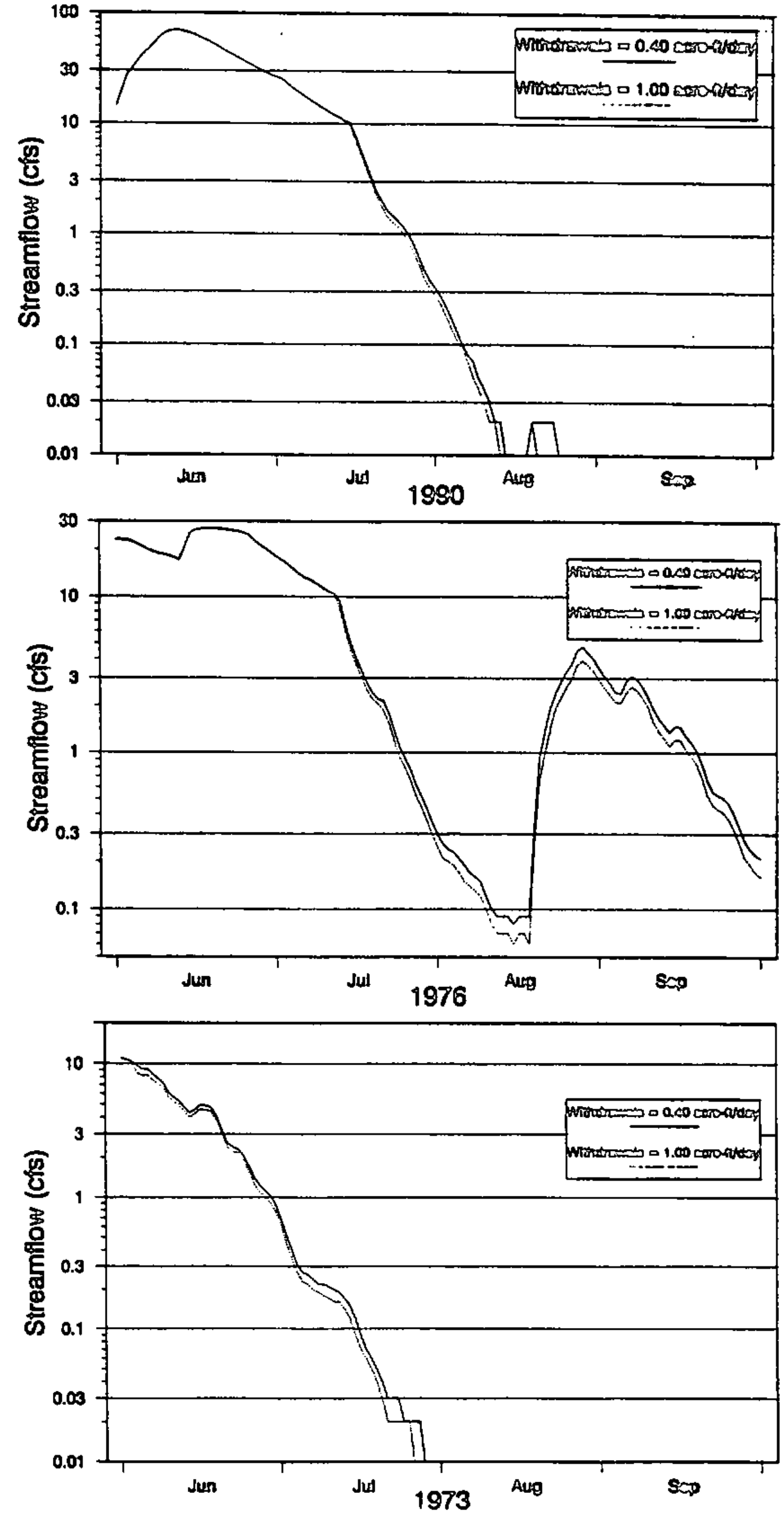

Figure 10. Simulated streamflow with 0.40 acre-ft./day lake withdrawals compared to simulated streamflow with 1.00 acre-ft./day lake withdrawals.

Simulated streamflow did not cease during the wetter 1976. Flows were low for about one week in August before rising to reflect rainfall and a wet September. Even though the year was wet, lake storage was down 245 acre-ft. at the end of the year as compared to the beginning. The final lake level was 0.65 feet and the annual runoff was 43.9 cfs.

Increasing the 1976 withdrawals to 1.00 acre-ft./day decreased the annual runoff to 43.6 cfs and the final lake level to 0.63 feet. It also caused the lake storage at the end of the water year to be 12 acre-ft. lower than the prior case. Increasing the withdrawals caused the lowest flow to decrease from about 0.08 to 0.06 cfs.

Simulated Dam

With the addition of a dam and controlled outflow, the streamflow in Friday Creek was markedly enhanced. A comparison of simulated streamflow with and without a dam is presented in Figure 11. Streamflow during the low flow summer period is shown for 1990, 1976, and 1973.

During 1990, the dam maintained a streamflow of 8 cfs through July and a flow of 4 cfs through the remainder of the year. In contrast, without the dam the streamflow ceased in mid-August. Likewise, during the wetter year, 1976, streamflow was maintained at 8 cfs through most of August and 4 cfs through September. However, enhancing streamflow during 1976 did cause the lake storage to be 640 acre-ft lower at the end of the year than without the dam.

This reduction in lake storage is an artifact of dam operation. Friday Creek dries up when the lake level drops to about 0.40 feet. After adding the dam, however, I allowed the outflow to continue until the lake level reached zero feet. In effect, I lowered the outflow level and allowed some of the dead storage to be converted to streamflow. This was not intentional, I only realized it after studying the model results. Placing the outlet of the dam at the lowest practical elevation will, however, minimize the overall height of the dam.

The dam also greatly enhanced streamflow during the dryer 1973. Streamflow of 8 cfs was maintained until mid-July, and 4 cfs until mid- September. Although the stream dried up in September, flow was maintained for 42 days beyond that which would have occurred without the dam. Days with streamflow less than 0.01 cfs were reduced from 56 to 14 days. Streamflow could have been maintained all summer if the initial controlled flow had been reduced from 8 cfs.

Figure 12 presents information similar to Figure 11 except that withdrawals have been increased to 1.00 acre-ft./day. Even with the increased withdrawals, streamflow is markedly enhanced by the storage control. During 1990, streamflow is maintained at 4 cfs for all but the last three days of the year. Even with the added withdrawals, this is 21 days longer than without the dam.

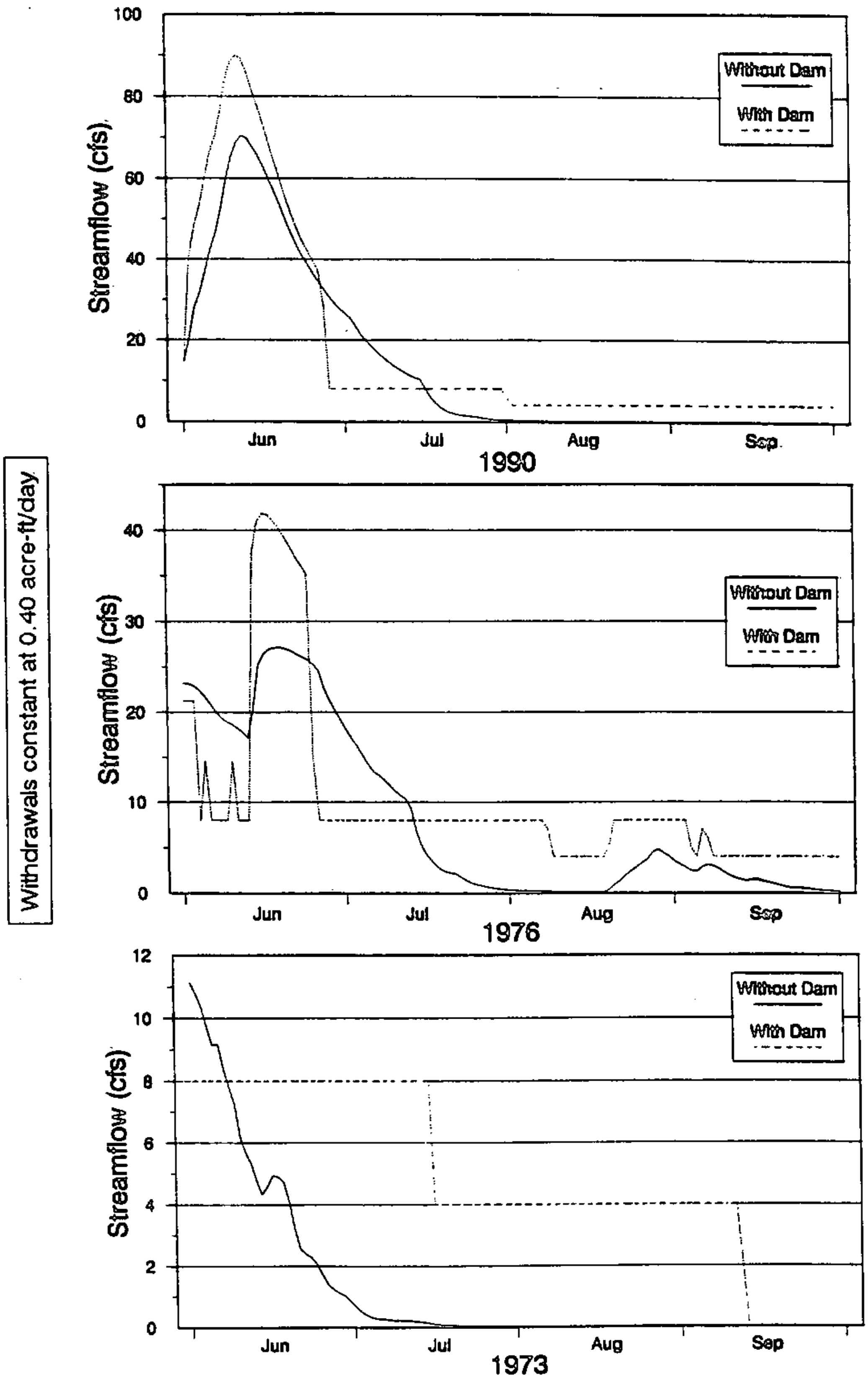

Figure 11. A comparison of simulated streamflow with a dam to that without.

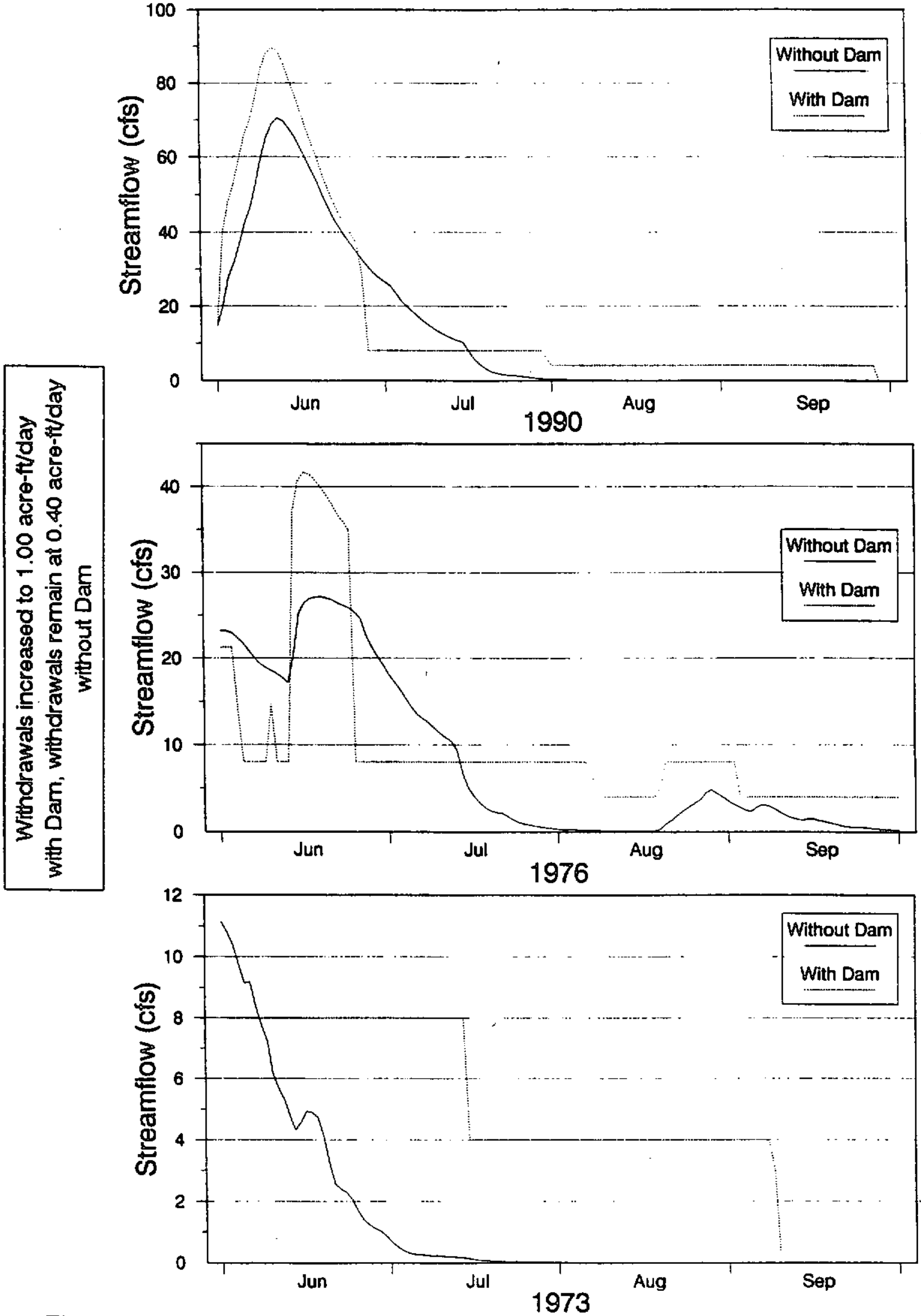

Figure 12. A comparison of simulated streamflow with and without a dam after lake withdrawals are increased to 1.00 acre-ft./day.

The additional withdrawals have little effect during the wetter 1976. At least 4 cfs is maintained throughout the summer. During the drier 1973, the additional withdrawals caused three days more zero streamflow than a dam with current withdrawals. However, again the stream is kept flowing for 39 days longer than without the dam.

Simulated Pumping

By simulating augmentation of streamflow by pumping, I maintained streamflow at either 0.5, 1.0, or 2.0 cfs throughout the low flow season. Contrary to the dam, which maintained a higher lake level by retarding runoff early in the summer, pumping, which was implemented only after streamflow was low, caused the lake level to decline. The higher the augmentation volume, the more water I pumped from Samish Lake and the lower the resultant lake level. Because of this, I have focused this discussion on lake level rather than streamflow. Streamflow is maintained at the selected rate. Results of the model runs are summarized in Table 3.

Table 3. Pumping from Samish Lake to augment low streamflow of Friday Creek.

Year	Max Pumping Rate (cfs)	Lowest Lake Level (ft.)	Lake [1] Lowered (ft.)	Days Pumped	Lake [2] Storage Used (acre-ft.)
1990	0	0.19	0	0	0
	0.5	0.12	0.07	84 [3]	40
	1.0	0.05	0.14	87 [4]	78
	2.0	-0.08	0.27	96 [5]	169
1976	0	0.58	0	0	0
	0.5	0.57	0.01	25	4
	1.0	0.55	0.03	40	19
	2.0	0.49	0.09	65	87
1973	0	-0.09	0	0	0
	0.5	-0.17	0.08	93	50
	1.0	-0.26	0.15	96	95
	2.0	-0.45	0.36	103	181

[1] Difference between lowest lake level with pumping and without.

[2] Volume pumped from lake in excess of the natural lake outflow.

[3] 22 days in the fall, 1989 and 62 days in the summer, 1990.

[4] 22 days in the fall, 1989 and 65 days in the summer, 1990.

[5] 25 days in the fall, 1989 and 71 days in the summer, 1990.

Simulated pumping during 1990 to maintain a flow of 0.5 cfs consumed 40 acre-ft. of lake storage. Pumping was necessary for 22 days in the fall of 1989 and 62 days during late summer of 1990. Pumping caused the lowest lake elevation to decline by 0.07 ft., from 0.19 ft. (no pumping) to 0.12 ft. (pump 0.5 cfs). Increasing the augmentation to 1.0 cfs consumed 78 acre-ft. of lake storage and extended the pumping time in late summer to 65 days. The lowest lake elevation was 0.14 ft. lower than without pumping. Augmenting streamflow to 2.0 cfs required 169 acre-ft. of lake storage. To maintain the 2.0 cfs streamflow, it was necessary to pump 25 days in the fall of 1989 and 71 days in the late summer of 1990. The lake level was lowered by 0.27 ft. to a low of -0.08 ft.

During the wetter year, 1976, only 4 acre-ft. of lake storage were required to maintain streamflow at 0.5 cfs. Pumping was necessary for 25 days and the lowest lake level declined by 0.01 ft. Forty days of pumping and 19 acre-ft. of lake storage were required to augment streamflow to 1.0 cfs. The additional pumping caused the lake level to decline to 0.55 ft., a reduction of 0.03 ft. over the no pumping case. Sixty-five days of pumping and 87 acre-ft. of lake storage were required to augment streamflow to 2.0 cfs. This higher volume of streamflow augmentation lowered the lowest lake level by 0.09 ft.

Considerably more pumping and lake storage were required to augment streamflow during the drier year, 1973. Ninety-three days of pumping and 50 acre-ft. of lake storage were necessary to maintain streamflow at 0.5 cfs. The lowest lake level was lowered from -0.09 to -0.17 ft., a decrease of 0.08 ft. (lake levels are relative to the float gage on Mr. Jenkins dock). Increasing the augmentation volume to 1.0 cfs required 96 days of pumping and 95 acre-ft. of lake storage. The lowest lake level was -0.26 ft. Augmentation at 2.0 cfs required 103 days of pumping, 181 acre-ft. of lake storage, and lowered the lowest lake level by 0.36 ft. (to -0.45 ft.).

THE EFFECTS OF BEAVER

Although I have only limited information on beaver activity in Friday Creek, their impacts on the streamflow regime as well as Samish Lake are important. Local custom, for at least the past 40 years, has been to remove the beaver dams and clear the channel in early summer to reduce the lake level (personal communications Dave Jenkins, 1989). To keep the beaver from rebuilding, the dams were periodically removed during the summer.

Dam control maintained a lower lake level and in some cases improved streamflow in Friday Creek. A lower lake level was desired both to increase the amount of beach and to prepare the lake for storing winter stormflow. In recent years, channel cleaning has declined and during 1989-1990 it appears that the dams were removed more to demonstrate their effects on streamflow than to lower the lake level.

Some of the effects that beaver (and man) have on Friday Creek streamflow are shown in Figure 13, an enlargement of the summer and fall periods of Figure 4. The figure compares streamflow simulated from lake level (with beaver activity removed) with the actual streamflow observed at the staff gage. Beaver were active during these time periods and the beaver dams were destroyed several times by local residents.

The trend of the simulated streamflow during both the fall of 1989 and late summer 1990 was a continual recession, normal for late summer streamflow, with small increases in streamflow reflecting rainfall. In contrast, the observed streamflow drops rapidly, beginning about mid-July. The decline in streamflow was caused by damming of Friday Creek by beaver. Subsequent removal of the beaver dams throughout the summer resulted in rapid rises in streamflow until the beaver repaired the damage, followed by rapid declines in streamflow.

The beaver dams were removed so often in August and September, 1990 that streamflow was a continual series of surges. The ups and downs had no relationship to precipitation or actual lake water available for runoff.

During September 1989, the beaver activity caused streamflow to virtually cease whereas the simulated streamflow continued, albeit at a low rate.

The primary purpose of a beaver dam is to create an artificial pond that the beaver uses for refuge when moving about and feeding. Usually, the beaver have a series of dams, each backing water up to the base of the upstream dam. The series of ponds hides the natural gradient of the stream. Large dams may be built on year after year by many different generations. As food is depleted around the margins of the pond, the dam is

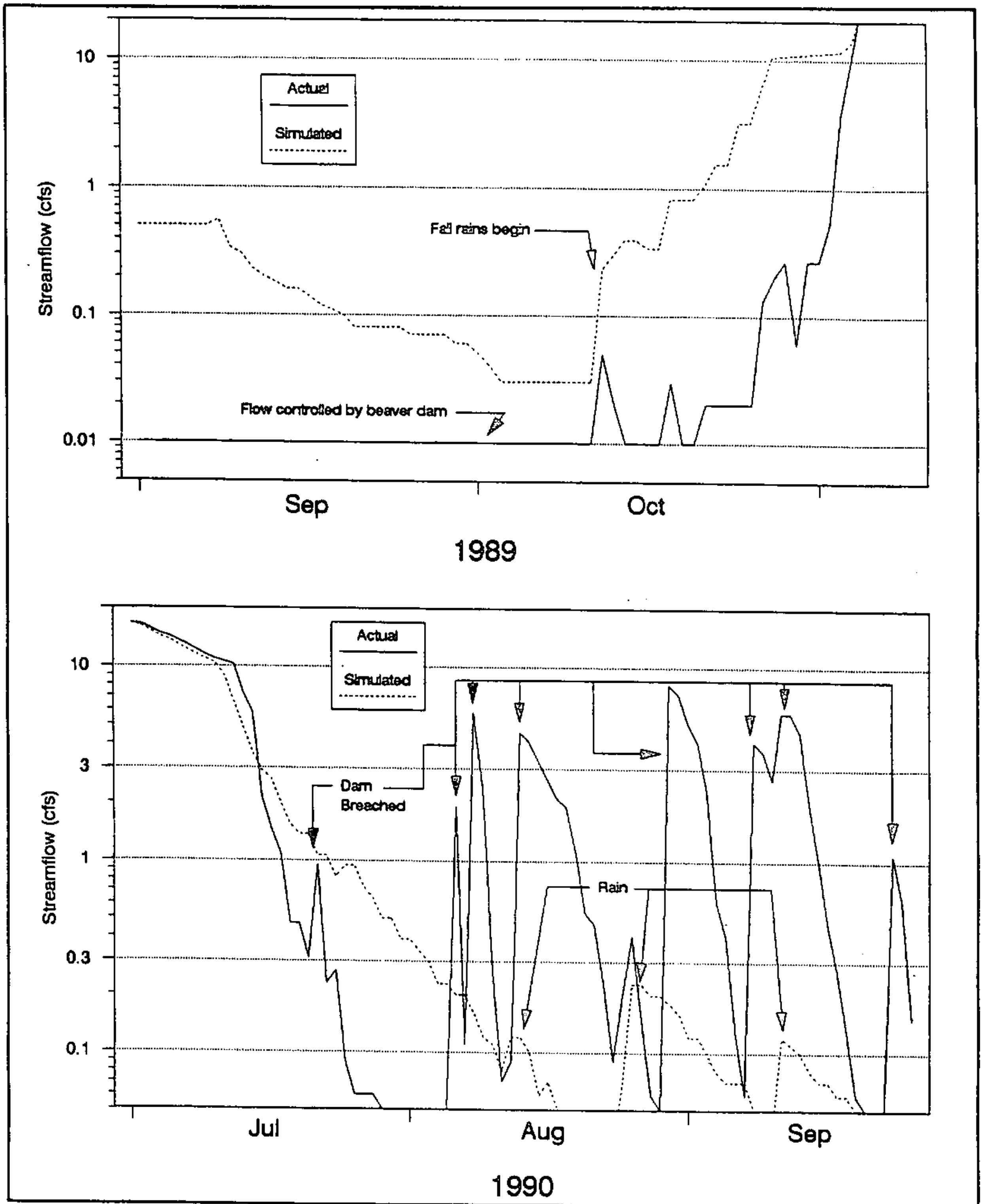

Figure 13. The actual streamflow of Friday Creek, complete with beaver activity and man's actions, as compared with the streamflow simulated without any effects of beaver.

raised to extend the pond. This may continue until physical conditions limit the extent of the pond, or until some calamity, either man caused or natural, sets the evolution back to stage one.

I can only guess what streamflow would be like if beaver dams were not disturbed, but left to develop to an equilibrium stage. It is possible that the size of the dams and their ensuing ponds would eventually stabilize. Once filled the ponds would continuously pass inflow to outflow and have little effect on streamflow.

Unfortunately, Friday Creek has not been left undisturbed. Dams have been alternately breached and rebuilt. With enough disturbance the beaver abandon a dam and move elsewhere, only to have a new generation move back and repair the dam once disturbance ceases.

I suggest that over the past 40 years the beaver have acted to reduce low streamflow in a manner similar to that shown in Figure 13 (Oct 1989). The beaver have been extensively disturbed and the ponds are probably less than their maximum extent. As a result, the beaver are continuously raising or repairing their dams to deepen the ponds. Low streamflow never reaches an equilibrium stage, possibly equivalent to the simulated streamflow of Figure 13. Instead streamflow remains in a reduced state interspersed with periods of high flow when dams are breached, followed by periods of even lower flow as the beaver strive to reestablish pond water levels.

I believe that the interactions of man and beaver have done more to disturb the low-flow regime of Friday Creek than have lake withdrawals.

SUMMARY

The water level of Samish Lake fluctuates four or five feet during a normal year. Likewise outflow via Friday Creek varies between a few tenths of a cfs in August to several hundred cfs during winter storms. The estimated, natural mean-annual flow of Friday Creek is 31.7 cfs. This is reduced to 31.3 cfs with the current 0.40 acre-ft./day lake withdrawals.

Minimum lake level and lowest streamflow usually occur in August. With current lake withdrawals of 0.40 acre-ft./day, the lowest streamflow expected to be equaled or exceeded once in two years is about 0.38 cfs. This is 0.06 cfs lower than would be expected without lake withdrawals. In addition to the lower flows, the lake withdrawals have advanced the average onset of minimum streamflow by about three days and extended the median period of low flow by another three days.

Increasing withdrawals from 0.40 to 1.00 acre-ft./days will affect streamflow in the same way that the earlier withdrawals affected natural streamflow. Minimum streamflow will occur about two days sooner than at present with minimum streamflow a few hundredths of a cfs lower.

Damming the lake outflow allows early summer runoff to be stored for later release. The dam increased low streamflow at least 10-fold over natural conditions. Significant streamflow augmentation is possible even with increased lake withdrawals.

Likewise, pumping from the lake to augment low streamflow provides significantly more water in the stream. With current withdrawals, pumping maintained streamflow at 2.0 cfs during the driest year while drawing the lake level down less than 0.5 ft. below its normal level. Pumping would usually be required for between 30 and 90 days during July through October. Pumping could also mitigate additional withdrawals with only slight declines in lake level.

Although the lake withdrawals exacerbate minimum streamflow in upper Friday Creek, the lowest flows are caused by beaver. The beaver, through their dam building activities, have reduced flows in late summer below those that would occur if the lake were allowed to drain without dams.

APPENDIX 1. Lake level of Samish Lake (ft.), 1989 - 1990.

Day	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	0.72	0.54	1.08	2.62	1.98	3.26	2.69	1.94	1.57	1.24	1.57	0.77	0.66
2	0.72	0.53	1.09	2.55	1.99	3.29	2.63	1.90	1.58	1.24	1.55	0.75	0.65
3	0.72	0.51	1.20	2.57	2.00	3.38	2.54	1.86	1.56	1.35	1.51	0.74	0.65
4	0.72	0.51	1.66	2.79	2.30	3.46	2.47	1.81	1.54	1.47	1.46	0.72	0.64
5	0.72	0.50	1.85	3.09	2.19	3.48	2.40	1.77	1.53	1.52	1.42	0.72	0.62
6	0.72	0.50	2.05	3.22	2.35	3.50	2.37	1.74	1.51	1.55	1.40	0.70	0.61
7	0.72	0.50	2.42	3.22	2.41	3.44	2.38	1.71	1.51	1.76	1.37	0.70	0.61
8	0.73	0.49	2.56	3.23	2.49	3.41	2.46	1.68	1.48	1.96	1.33	0.69	0.59
9	0.69	0.49	3.08	3.23	2.60	3.37	2.47	1.65	1.45	2.05	1.31	0.68	0.58
10	0.68	0.49	4.38	3.17	2.75	4.87	2.60	1.61	1.43	2.19	1.27	0.66	0.57
11	0.66	0.50	5.07	3.08	2.79	5.55	2.64	1.59	1.43	2.46	1.23	0.66	0.56
12	0.65	0.66	5.01	2.99	2.80	5.41	2.63	1.57	1.42	2.73	1.20	0.65	0.56
13	0.64	0.68	4.78	2.89	2.77	5.15	2.60	1.54	1.41	2.81	1.16	0.65	0.54
14	0.63	0.70	4.67	2.80	2.72	4.67	2.60	1.53	1.43	2.79	1.12	0.63	0.53
15	0.63	0.70	4.44	2.70	2.64	4.35	2.60	1.50	1.41	2.72	1.08	0.61	0.53
16	0.62	0.69	4.18	2.60	2.59	4.09	2.59	1.48	1.38	2.65	1.05	0.60	0.61
17	0.61	0.69	3.98	2.53	2.50	3.85	2.56	1.48	1.37	2.56	1.02	0.58	0.60
18	0.60	0.76	3.74	2.43	2.43	3.62	2.52	1.46	1.35	2.48	0.98	0.61	0.59
19	0.59	0.76	3.56	2.35	2.38	3.37	2.47	1.45	1.32	2.40	0.95	0.61	0.58
20	0.58	0.76	3.40	2.35	2.31	3.28	2.43	1.44	1.31	2.32	0.92	0.59	0.57
21	0.58	0.78	3.29	2.3	2.26	3.21	2.40	1.43	1.31	2.30	0.89	0.55	0.56
22	0.58	0.81	3.18	2.25	2.32	3.10	2.36	1.42	1.31	2.14	0.87	0.56	0.55
23	0.58	0.81	3.12	2.20	2.35	3.01	2.35	1.43	1.28	2.08	0.86	0.54	0.55
24	0.58	0.88	3.06	2.15	2.37	2.97	2.30	1.44	1.26	2.00	0.83	0.53	0.55
25	0.57	0.88	3.02	2.07	2.40	2.94	2.26	1.46	1.24	1.94	0.81	0.52	0.54
26	0.56	0.94	3.00	2.01	2.44	2.90	2.20	1.47	1.22	1.87	0.80	0.52	0.54
27	0.56	1.03	2.94	2.00	2.47	2.83	2.16	1.48	1.21	1.80	0.80	0.51	0.54
28	0.56	1.04	2.85	1.97	2.70	2.78	2.11	1.50	1.19	1.74	0.78	0.50	0.54
29	0.56	1.05	2.79	1.95	3.11		2.07	1.53	1.18	1.68	0.78	0.49	0.53
30	0.55	1.06	2.73	1.93	3.27		2.03	1.57	1.14	1.64	0.76	0.57	0.52
31	0.55	1.07		1.91	3.28		1.98		1.20		0.77	0.67	

APPENDIX 2. Friday Creek Streamflow (cfs), 1989-1990.

Day	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	0.01	0.01	0.54	50	31	110	60	28	21	15	22	0.06	0.15
2	0.01	0.01	3.7	49	30	115	57	27	21	15	21	0.06	0.06
3	0.01	0.01	10	48	33	127	51	27	21	18	20	0.06	0.05
4	0.01	0.01	28	68	35	129	48	26	20	21	19	0.05	8.1
5	0.01	0.01	28	86	37	129	45	26	19	23	18	0.05	7.3
6	0.01	0.01	48	96	43	127	44	25	19	25	17	0.05	5.2
7	0.01	0.01	57	94	47	125	46	23	19	30	17	0.05	4.1
8	0.01	0.01	66	96	50	122	50	22	19	36	17	0.05	2.4
9	0.01	0.01	144	94	60	137	51	22	19	39	16	0.05	0.62
10	0.01	0.01	338	96	67	483	58	21	18	45	16	0.05	0.41
11	0.01	0.01	394	81	68	625	59	20	18	65	15	0.05	0.13
12	0.01	0.05	351	75	68	528	59	19	17	73	14	1.9	0.06
13	0.01	0.02	304	67	65	383	56	19	19	75	14	0.11	4.1
14	0.01	0.01	259	60	60	293	60	18	18	73	13	5.8	3.7
15	0.01	0.01	225	57	57	223	58	19	17	67	12	2.4	2.6
16	0.01	0.01	180	50	52	188	56	19	17	61	11	0.27	5.8
17	0.01	0.01	151	47	49	155	55	18	17	58	11	0.07	5.8
18	0.01	0.03	137	43	46	129	53	17	16	52	11	0.09	4.6
19	0.01	0.01	115	41	42	112	50	17	16	48	10	4.6	1.9
20	0.01	0.01	103	39	40	106	47	17	16	45	7.3	4.1	0.95
21	0.01	0.02	96	37	38	101	45	17	16	42	5.8	3.3	0.47
22	0.01	0.02	84	35	40	92	43	17	16	38	2.1	2.6	0.27
23	0.01	0.02	83	34	42	87	43	18	15	35	1.5	2.1	0.13
24	0.01	0.02	77	33	43	83	44	19	15	32	1.1	1.9	0.06
25	0.01	0.02	75	31	47	79	39	21	15	31	0.47	1.1	0.05
26	0.01	0.13	72	30	48	76	37	20	14	29	0.47	0.54	0.04
27	0.01	0.20	67	29	59	69	35	21	14	27	0.31	0.47	0.04
28	0.01	0.27	64	29	71	67	33	21	14	26	0.95	0.23	1.1
29	0.01	0.06	59	28	99		31	21	14	25	0.23	0.09	0.62
30	0.01	0.27	55	28	110		30	21	12	24	0.27	0.20	0.15
31		0.27		29	112		29		12		0.09	0.41	

APPENDIX 3. Samish Lake Deterministic Model.

A deterministic computer model was written specifically for the Samish Lake basin. The model, while using general concepts, is not a general purpose watershed model. The Samish Lake model calculates daily streamflow of Friday Creek from daily values of precipitation and maximum and minimum air temperature. The model also tracks daily lake storage (acre-ft.) and lake level (ft.). Weather Service climate data from the Bellingham airport is used as input.

The model first reads the input data for a day, increasing the Bellingham precipitation by a weighting factor to compensate for the higher precipitation at the Friday Creek watershed. After several calibration runs of the model, I selected a weight of 1.0 for daily precipitation less than 0.5 inches, a weight of 1.5 for daily precipitation between 0.5 and 1.0 inches, and a weight of 2.0 for daily precipitation greater than 1.0 inches. This progressive weighting was necessary to get the model to respond adequately to the larger storm events without over reacting to the smaller events.

The model divides the day into four periods, each receiving one-quarter of the daily rainfall. I assumed the average temperature for the first period of each day, beginning at midnight, was equal to the minimum daily temperature. The average temperature for the second and fourth periods was assumed equal to the average of the maximum and minimum temperature, and the average temperature for the third period was equal to the maximum temperature.

After precipitation is read and weighted, the model determines whether it should be treated as rain or accumulated as snow. Using an air temperature lapse rate of -0.001 degree/ft., the model converts the Bellingham temperature (recorded at 140 ft. elevation) into an estimated temperature at the mid-elevation of the watershed (1200 ft.). The resultant lapsed air temperature is then compared with 32.0 degrees F., and if below, the precipitation is assumed snow. Snow is accumulated until melted by rain or warmer temperatures. Although snow is accumulated on the land surface (7055 acres), snow falling on the lake (810 acres) is immediately added to lake storage.

Accumulated snow is melted whenever rain or warmer temperatures occur. If raining on snow, the quantity of snow melted is equal to the rain-melt-rate (0.074 inches melt/degree day) multiplied by the difference between the lapsed air temperature and 32 degrees F. multiplied by the rainfall. If not raining, melt is calculated as the dry-melt-rate (0.025 inches melt/degree day) multiplied by the difference between the lapsed temperature and 32 degrees F.

The snow routines in this model did not accumulate large volumes of snow and had little effect on the streamflow of Friday Creek during model calibration.

I did not model the hydrologic effects of watershed vegetation, but treated the land surface as a simple delay function. The land receives precipitation and snowmelt, delays it in a soil moisture reservoir, evaporates and transpires some of the soil moisture, and allows the remaining soil moisture in the reservoir to slowly flow into the lake. The streams feeding the lake are not explicitly modeled.

The model estimates evaporation based on an empirical relationship between the daily evaporation recorded in Bellingham and the maximum daily air temperature. The Bellingham records indicate that evaporation is not significant when the air temperature is less than about 60 degrees F. Using linear regression, I obtained the following equations relating potential evaporation to air temperature:

1. If temperature is > 60 degrees F. but < 74 degrees F. then
   Evaporation = (Temperature-60) x 0.01667
2. If temperature is > 74 degrees F. then
   Evaporation = ((Temperature-74) x 0.00778)+0.23

Daily lake evaporation was assumed equal to the potential evaporation as estimated from maximum air temperature. However, evapotranspiration (ET) from the land surface was limited to less than the potential depending on the status of the soil moisture. Initially, I based ET on the ratio of soil moisture to a maximum soil moisture storage value. That is, ET was greatest when the soil was wettest and progressively declined as the soil dried. In practice, this consistently underestimated the ET. Early model runs predicted an annual ET less than 10 inches. Actual ET in the Bellingham area is in the 18-20 inch range. On final model runs, I allowed the ET to equal the potential evaporation whenever soil moisture was adequate, when the potential evaporation exceeded the available soil moisture, I allowed ET to equal and thus consume the remaining soil moisture. This resulted in more realistic ET values.

After ET is removed from the soil moisture, the model determines the amount of remaining soil moisture to release to the lake. The volume of water released is calculated as the soil moisture multiplied by a drainage rate coefficient (a fraction between 0 and 1.0) and multiplied by the ratio of soil moisture to a maximum-retard-storage value. The drainage rate coefficient and the maximum retard storage value are empirical coefficients determined by model calibration. The values used in final model runs were 20 inches for maximum-retard-storage and 0.10 for the drainage rate coefficient.

The model next adds the soil runoff and the precipitation falling on the lake to the lake storage. The lake volume (acre-ft.) is updated and a new lake level calculated. An equation relating lake level to lake volume was developed from a bathymetric map of Samish Lake: Lake Elevation = 32.255 x ln(Lake volume, acre-ft.) - 334.5.

Based on the new lake elevation, the model calculates the daily streamflow using the lake-level-to-stream-stage relationship and the discharge-rating equations described in the main body of this report.

Daily streamflow is the main output from the model, although daily lake volume and lake level are tracked.

Dam

The model has the capability to simulate a dam across the lake's outflow and to store and release lake water. A dam is simulated by substituting a specified lake outflow (streamflow) for the normal streamflow when the lake level falls below a preset dam height. As long as the lake level stays above the dam height the model simulates normal streamflow. When the lake level falls below the dam height, streamflow is kept constant (at the specified rate) as long as there is adequate water behind the dam. The lake volume and level are updated continuously to reflect the lake outflow. The streamflow rate is specified in the model input and may be either a constant flow or a series of declining flows related to the declining lake level. Water in excess of the specified streamflow is retained as storage within the lake for later release.

Pumping

In addition to a dam, the model includes a simulation of pumping from lake storage to augment streamflow. An augmentation rate, 2.0 cfs for instance, is input to the model. Whenever streamflow drops below this rate, the model transfers additional water from lake storage to the stream to makeup the deficit. The model keeps track of depletions from lake storage and impacts on lake level.

Program listing - LAKEMOD.PAS

The following is a partial listing of the Turbo Pascal source code for the deterministic model. Only the main routine and important subroutines are included. Routines to print, graph, or otherwise manipulate the input or output data are not presented.

```
Program LakeMod;  {simple watershed model for the Lake Samish watershed}

{globals}
const
  Periods=4;                      {periods in a day}
  LandArea:real = 7055;           {land area of the watershed in acres}
  LakeArea:real = 810;            {area of the lake in acres}
```

```
  FreezeTemp:real =32;               {average daily temperature below which rain=snow}
  DryMeltRate:real = 0.025;          {inches of melt per degree day temperature}
  RainMeltRate:real = 0.074;         {inches of melt/degree day when raining}
  TempElev:real = 140;               {elevation in ft. of the base temperature station}
  MidElev:real = 1200;               {mid elevation of the watershed for lapse of temp}
  LapseRate:real = -0.001;           {temp decline per foot of increased elevation}
  StartSoilMoisture:real = 1.0;      {initial soil moisture in inches}
  MaxSoilMoisture:real = 10.0;       {limit to the available soil moisture for ET (in)}
  MaxRetardStorage:real = 20.0;      {limit to retardation moisture storage}
  DrainageRate:real = 0.10;          {fraction between 0 and 1.0 to retard soil runoff}
  StartLakeStorage:real = 32800;     {initial lake storage in acre-ft}
                                     {note: lake storage at elev 0 = 32,000 acre-ft}
  DivertDaily:real = 0.40;           {daily diversion from lake in acre-ft}
  DamHt:real = 2.0;                  {dam height}
  FixedRunoff:real = 8.0;            {controlled runoff when dam in effect}
  PumpRate:real = 2.00;              {cfs to pump}
  LakeControl = 0.82;                {lake elevation to start pump}

  {rating equation constants}
  a1=-60.63;  b1=14.12;
  a2=-48.28;  b2=11.27;
  a3=-5.24;   b3=1.68;
  a4=-1.26;   b4=0.89;

var
  df,outf:text;                      {file with daily precipitation and temperature}
  water:real;                        {general purpose real variable, several uses}
  Snow:real;                         {amount of snow on ground in inches water}
  Melt:real;                         {amount of snow melted during any period}
  SoilMoisture:real;                 {soil moisture storage in inches}
  SoilRunoff:real;                   {period runoff from soil in inches}
  LakeStorage:real;                  {storage in the Lake in acre-ft}
  LakeElev:real;                     {elevation of the lake level in feet}
  DailyRunoff:real;                  {daily lake outflow in cfs}
  AnnualPrecip:real;                 {summation of annual weighted precipitation}
  AnnualRunoff:real;                 {annual lake runoff in cfs converted to inches}
  ActualAnnual:real;                 {actual annual lake runoff to calibrate volume}
  Days,SummerDays:integer;           {count of days of data read in from file}
  TotalLandET:real;                  {total annual evapotranspiration from land}
  TotalLakeET:real;                  {total evaporation from lake}
  DeltaSoil:real;                    {change in soil moisture over time span - inches}
  DeltaLake:real;                    {change in lake storage over time - inches}
  PrecipWeight:real;                 {precip weighting factor}
```

```
{input variables to be read from data file}
  Precip:real;                    {period precipitation in inches}
  MinTemp,MaxTemp:real;           {daily minimum and maximum temperature degrees F}
  ActualElev:real;                {actual lake elev if it exists for comparison}

{subroutines}

{compute the temperature of the mid-elevation for snow determination}
{based on a lapse rate and max and min air temperatures}
function TempLapse:real;
  var temp:real;
  begin
  case periods of
    1:temp:=MinTemp;
    2:temp:=(MinTemp+MaxTemp)/2;
    3:temp:=MaxTemp;
    4:temp:=(MinTemp+MaxTemp)/2;
    end;  {case}
  TempLapse:=temp+LapseRate*(MidElev-TempElev);
  end;

{compute the snow melt in inches when raining}
function PrecipMelt:real;
  var Temp:real;
  begin
  PrecipMelt:=(RainMeltRate+0.007)*Precip*(TempLapse-FreezeTemp);
  end;

{compute the snow melt in inches if not raining}
function DryMelt:real;
  begin
  DryMelt:=DryMeltRate*(TempLapse-FreezeTemp);
  end;

{compute the period potential ET based on max daily temperature}
function PotET:real;
  begin
  if MaxTemp>60 then
    begin
    if MaxTemp>74 then PotET:=(((MaxTemp-74)*0.00778)+0.23)/periods
    else PotET:=((MaxTemp-60)*0.01667)/periods;
    end
  else PotET:=0;
  end;
```

```
{compute the soil ET based on soil moisture and potential ET for period}
function SoilET:real;
  begin
  if PotET<SoilMoisture then SoilET:=PotET else SoilET:=SoilMoisture;
  { ORIGINAL ATTEMPT ** SoilET:=PotET *(SoilMoisture/MaxSoilMoisture);}
  end;

{compute the soil moisture to release to soil runoff}
function SoilMoistureRelease:real;
  begin
  SoilMoistureRelease:=SoilMoisture*((SoilMoisture/MaxRetardStorage)*DrainageRate);
  end;

{compute the period evaporation from the lake surface in acre-ft}
function LakeET:real;
  begin
  LakeET:=LakeArea*PotET/12;
  end;

{compute new lake elevation based on lake storage}
function NewElev:real;
  begin
  {test if lake goes dry, then halt}
  if LakeStorage<1 then
    begin
    writeln('lake storage low',days);
    c:=readkey; halt;
    end;
  NewElev:=32.255*ln(LakeStorage)-334.5;
  end;

{compute the lake outflow for the period given the lake elevation}
function LakeOutflow(LakeElev:real):real;
  var a,b,stage:real;
  begin
  {relationship between lake elevation and friday creek gage}
  Stage:=(0.89730*LakeElev)+3.59832;
  {upper friday creek rating equation}
  if Stage<4.35 then begin a:=a1; b:=b1; end
  else if stage<4.50 then begin a:=a2; b:=b2; end
       else if stage<5.00 then begin a:=a3; b:=b3; end
            else begin a:=a4; b:=b4; end;
  LakeOutflow:=exp((b*Stage)+a);
  end;
```

```
{MAIN program segment}

var i:integer;

BEGIN

  OpenFiles;
  SoilMoisture:=StartSoilMoisture;
  AnnualPrecip:=0; Snow:=0;
  LakeStorage:=StartLakeStorage;
  AnnualRunoff:=0; ActualAnnual:=0;
  TotalLandET:=0; TotalLakeET:=0;
  days:=0; SummerDays:=0;
  LineCount:=0;

  {repeat for each day}

  While not eof(df) do
    begin
    {read the daily data values}
    ReadData;
    if precip<0.5 then PrecipWeight:=1.0
      else if precip<1.0 then PrecipWeight:=1.5
        else PrecipWeight:=2.00;
    AnnualPrecip:=AnnualPrecip+(Precip*PrecipWeight);
    inc(days);
    DailyRunoff:=0;

    {repeat for the periods in a day}

    for i:=1 to periods do
      begin

      {check if rain should be stored as snow}
      if TempLapse<=FreezeTemp then
        begin
        Snow:=Snow+(Precip*PrecipWeight/periods);
        Precip:=0;  {do not pass the precip on as rainfall}
        Melt:=0;
        writeln('snow: ',snow:6:2,'  day: ',days,TempLapse:10:2);
        end
```

```
{melt any snow on ground during the period}
else
  if Snow>0 then
    begin
    if Precip>0 then Melt:=PrecipMelt/periods
    else Melt:=DryMelt/periods;
    if Melt>=Snow then
      begin
      Melt:=Snow;
      Snow:=0;
      end
    else Snow:=Snow-Melt;
    end
  else Melt:=0;

{add period snow melt and weighted precipitation to soil moisture}
SoilMoisture:=SoilMoisture+Melt+(Precip*PrecipWeight/periods);
if SoilMoisture>MaxRetardStorage then
  begin
  {excess water directly to runoff}
  SoilRunoff:=SoilMoisture-MaxRetardStorage;
  SoilMoisture:=MaxRetardStorage;
  end
else SoilRunoff:=0;

{subtract ET from soil moisture - inches}
water:=SoilET;
SoilMoisture:=SoilMoisture-water;
TotalLandET:=TotalLandET+water;

{add water released from soil to runoff}
water:=SoilMoistureRelease;
SoilRunoff:=SoilRunoff+water;

{update the soil moisture}
SoilMoisture:=SoilMoisture-water;

{add runoff to lake, converting from inches to acre-ft}
LakeStorage:=LakeStorage+(LandArea*SoilRunoff/12);

{add direct precipitation to lake - acre-ft}
LakeStorage:=LakeStorage+(LakeArea*Precip*PrecipWeight/periods/12);
```

```
    {subtract lake ET from lake storage in acre-ft}
    water:=LakeET;
    LakeStorage:=LakeStorage-water;
    TotalLakeET:=TotalLakeET+water;

    {if diversions then subtract from lake storage for each period}
    if Diversions then LakeStorage:=LakeStorage-(DivertDaily/periods);

    {compute new lake elevation}
    LakeElev:=NewElev;

    {compute the daily lake runoff in cfs}
    if Dam and (LakeElev<DamHt) and (LakeElev>0) then
      begin
      if LakeElev>DamHt/2 then water:=FixedRunoff
      else water:=FixedRunoff/2;
      end
    else if pump and (LakeElev<=LakeControl) then water:=PumpRate
      else water:=LakeOutflow(LakeElev);
    DailyRunoff:=DailyRunoff+water;

    {update the lake storage, converting runoff back to acre-ft}
    LakeStorage:=LakeStorage-(water*60*60*24/Periods)/43560;

    end;  {FOR - end of period repeat loop}

  DailyRunoff:=DailyRunoff/Periods;
  AnnualRunoff:=AnnualRunoff+DailyRunoff;

  end;  {WHILE - end of daily repeat loop}

END.
```

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