CHAPTER VII HYDROLOGIC BUDGET

A. SURFACE AND GROUNDWATER HYDROLOGY

The hydrologic budget for a lake equates the total water input to the total water output for specified time increments during a specified period. The water flow rates through the lake are thereby quantified. The development of a hydrologic budget is essential in calculating the loading (mass per unit time) of eutrophying nutrients as well as in evaluating a lake's tolerance to these nutrients. The balance between hydrologic inputs and outputs influences the nutrient supply to the lake, the lake's water residence time, and consequently the lake's productivity and water quality. An accurate and detailed hydrologic budget will thus permit an accurate determination of current trophic status and provide a sound basis for evaluating the effectiveness of watershed and in-lake management strategies for improving trophic status.

The quantification of the components of the Great Pond hydrologic budget was based on an intensive one-year stream gaging and precipitation measurement program. A budget for the gaging period (November 1994 through October 1995) was developed as a basis for a complete hydrologic year and phosphorus budget. The budget quantifies the monthly and annual water inflow from each source to Great Pond. Additionally, the monthly variations in the lake's hydraulic retention time and fraction of exchanged lake water volume are specified.

In conjunction with the hydrologic budget for Great Pond, mean monthly surface water discharge volumes for each station in the watershed were calculated and tabulated for the gaging year. This information is valuable for comparing the relative hydrologic (and hence nutrient) contributions from various tributary areas within the watershed. Section B describes the field monitoring program. Section C presents the hydrologic budget and other hydrologic data, and discusses their development.

The Stevens 420 Level Logger consists of a sensitive pressure transducer connected to computerized data logger. The system operates in a low power “sleep” mode most of the time, at a preprogrammed interval it wakes up, takes a depth reading from the stream, stores the data on a removable memory card, and the logger then goes back to sleep. For the purpose of the study we used a one hour interval for collecting data. The readings are collected by removing the memory card and replacing it with an empty one. A computer reads the memory card data, which is then transferred into a DES database.

As implemented in this study the Stevens Level Logger functions as an automated staff gage. The advantage of level loggers is that they can be programed to record hourly water depth, allowing biologists to monitor flow in the stream more closely. Like a staff gage the Stevens Level Loggers need to be calibrated in order to provide us with useable flow data. This was done by taking a reading from the Level Logger and the staff gage when the streams are flowed by DES personnel. The Stevens Level Loggers are then calibrated by calculating a correlation curve using the DES flow data (Appendix VII-I).

B. FIELD MONITORING PROGRAM

Field investigations and data collection occurred from October 1994 through November 1995. The actual gaging year budget presented in this chapter encompasses a complete year, beginning November 1, 1994, and ending October 31, 1995.

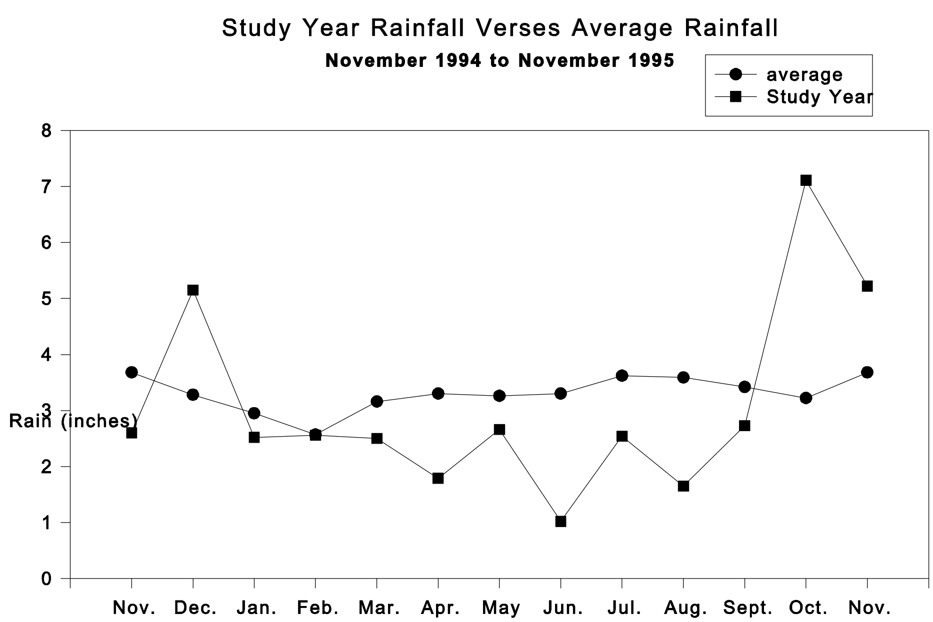
1. Stream Gaging and Precipitation Monitoring

Five in flowing tributaries, three seasonal tributaries, and one outlet station were monitored for flow within the Great Pond watershed. To determine the stage-discharge relationships at each station, measurements of flow were obtained using current meters three or four times per month (depending on time of year and station where flow warranted). Stage-discharge relationships and discharge summaries for each station can be found in Appendix VII-1 and VII-2 respectively.

Direct discharge measurements do have some disadvantages. Schroeder (1979) and Dennis (1988) point out that periods of peak discharge during storm events and spring melt off may be missed, resulting in lower estimates of inflow and thus nutrient loading. In fact, both spring melt off and storm events could represent a large percentage of the total hydrologic and phosphorus budget in a given watershed. To offset this disadvantage, several sampling stations were equipped with Stevens water level recorders.

A variety of methods have been utilized to calculate runoff and water budgets. Each method has drawbacks. Estimates of flow rates on tributary streams from interpolation of flows from neighboring watersheds can have significant errors. Dillon and Rigler (1974) caution against predicting water budgets through empirical methods using long-term runoff maps. They suggest that measurement versus estimation provides more accurate results and should be utilized where possible. In general, values will usually fall within 25% of those predicted using long-term runoff maps.

Daily rainfall and water equivalent snowfall data (Chapter III) were collected from NOAA climatological stations in Concord and Manchester, New Hampshire. The Manchester station is within 20 miles of the study area. Monthly rainfall and water equivalent snowfall data for Great Pond are presented in Table VII-I, along with the surface volume precipitation upon the lake. Figure VII-I compares the mean annual wetfall in the Manchester area with the study year wetfall. The study year wetfall was well below the mean monthly wetfall from March of 1995 to September of 1995. The dry study year will effect not only the hydrologic budget, but also, the



Source: City of Manchester Water Works Rain Gauge

Figure VII-1 Great Pond study year versus average rainfall annual phosphorus budget. Monthly evaporation volume from Great Pond is presented in Table VII-2.

Table VII-1

Great Pond Monthly Precipitation (Nov '94 - Oct '95)

Water Volume ($10^3 m^3$)

Month	Monthly Total (in)	Monthly Total (m)	Precip (m^3)	Precip ($10^3 m^3$)	Percent
Nov '94	2.60	0.066	54,461	54.5	7.5
Dec '94	5.15	0.131	108,096	108.1	14.8
Jan '95	2.52	0.064	52,108	52.1	7.1
Feb '95	2.56	0.065	53,636	53.6	7.3
Mar '95	2.50	0.064	52,398	52.4	7.2
Apr '95	1.79	0.045	37,132	37.1	5.1
May '95	2.66	0.068	56,111	56.1	7.7
Jun '95	1.02	0.026	21,454	21.5	2.9
Jul '95	2.54	0.065	53,636	53.6	7.3
Aug '95	1.65	0.042	34,657	34.7	4.7
Sep '95	2.73	0.069	56,936	56.9	7.8
Oct '95	7.11	0.181	149,355	149.4	20.5
Total	34.83	0.885		730.0	100

Surface Area=825,163 m^2 Precip (m3)=Monthly (m) X Surface

Table VII-2

Great Pond Monthly Evaporation Rates

(Pan Coef.)(Lake Surface Area)(Monthly Evap.)

Month	Total Evap (in)	Total Evap (m)	Evap (m^3)	Evap ($10^3 m^3$)	Evap (Pan Coef)
Apr '95	1.11	0.028	23,105	23.1	17.8
May '95	3.35	0.085	70,139	70.1	54.0
Jun '95	3.88	0.099	81,691	81.7	62.9
Jul '95	4.31	0.109	89,934	89.9	69.2
Aug '95	4.80	0.122	100,670	100.7	77.5
Sep '95	3.55	0.090	74,264	74.3	57.2
Oct '95	2.31	0.059	48,685	48.7	37.5
Total	23.31	0.592		488.5	376.1

2. Groundwater

One area which is poorly understood, and in which little information exists, is groundwater seepage and its nutrient contribution to surface waters. In many cases, groundwater seepage may represent a significant input of water and nutrients to an aquatic system. Recent, as well as past, field work has demonstrated significant interchange between lakes and groundwater lenses. Many lakes, rather than being isolated from groundwater bodies by lake bottom sediments, are closely connected with them, forming integral parts of dynamic groundwater flow systems (McBride and Pfankuch, 1975). Nitrogen and phosphorus are direct contributors to the productivity of lakes and streams.

These nutrients are often encountered in high concentrations in groundwater and may represent a significant percentage of the nutrient loading to a given lake.

Lee (1972) and Connor (1979) found that seepage flow patterns generally showed an exponential decrease with increasing distance from shore. Shallow groundwater contributes the major volume of seepage to a lake.

Downing and Peterka (1978) and Connor (1979) observed that seepage meters collected more groundwater during rainy periods as compared to drier periods occurring during the summer months. It is speculated that as the water table rises due to rainfall, groundwater is forced by the hydraulic gradient into the lake.

Direct measurements of groundwater through the placement of seepage meters can quantify one factor in the hydrologic budget. In the same way, analysis of the seepage can supply important chemical information that can be utilized in nutrient budget calculations.

Groundwater seepage was measured directly in Great Pond. Seepage meters were constructed from fifty-five gallon drums (208.2L) cut to form two sections approximately 44 cm in height for insertion into organic muck sediments. Sterile bacterial whirl packs, secured to one-holed rubber stoppers in the top of the drum by hard plastic tubing, were used as seepage collection devices (Connor and Belanger, 1981). Meters were placed at single site locations and one site had duplicate meters that were used for quality control. Eleven study sites were established within the lake's perimeter as illustrated in Figure VII-2. Samples were collected from May of 1994 through September 1994.

Seepage rates were measured for the hydrologic budget by occluding the tubing of the collect bag, attaching it to the seepage meter tubing and releasing the occlusion clamp. After the measurement interval, the volume of water obtained from the collection device was measured. The seepage rate was calculated by subtracting the initial volume and converting the collected volume (mL) to liters per square meter per day (L/m^2/day). Mean monthly seepage rates were calculated for each of the areas surrounding each seepage meter. The areal addition of individual mean annual seepage rates resulted in total groundwater seepage for the entire sediment area of Great Pond for the study year. Raw seepage meter data, computed from over 100 seepage measurements, are presented in Appendix VII-3.

The greatest mean seepage rate for the study year in Great Pond was recorded at station four with a value of 31.5 L/m^2/day (Table VII-3). The maximum seepage rate of 51.3 L/m^2/day was recorded at station nine. Stations four and nine were established on the north shore and south shore Great Pond. The soils in this region are classified as being well drained with a moderately rapid permeability. The substrate in which the seepage meter were placed had a very sandy consistency with a thin organic layer on the surface. Typically these soils promote the rapid migration of groundwater towards the pond.

Table VII-3

Mean Annual Seepage Rates (L/m^2/Day)

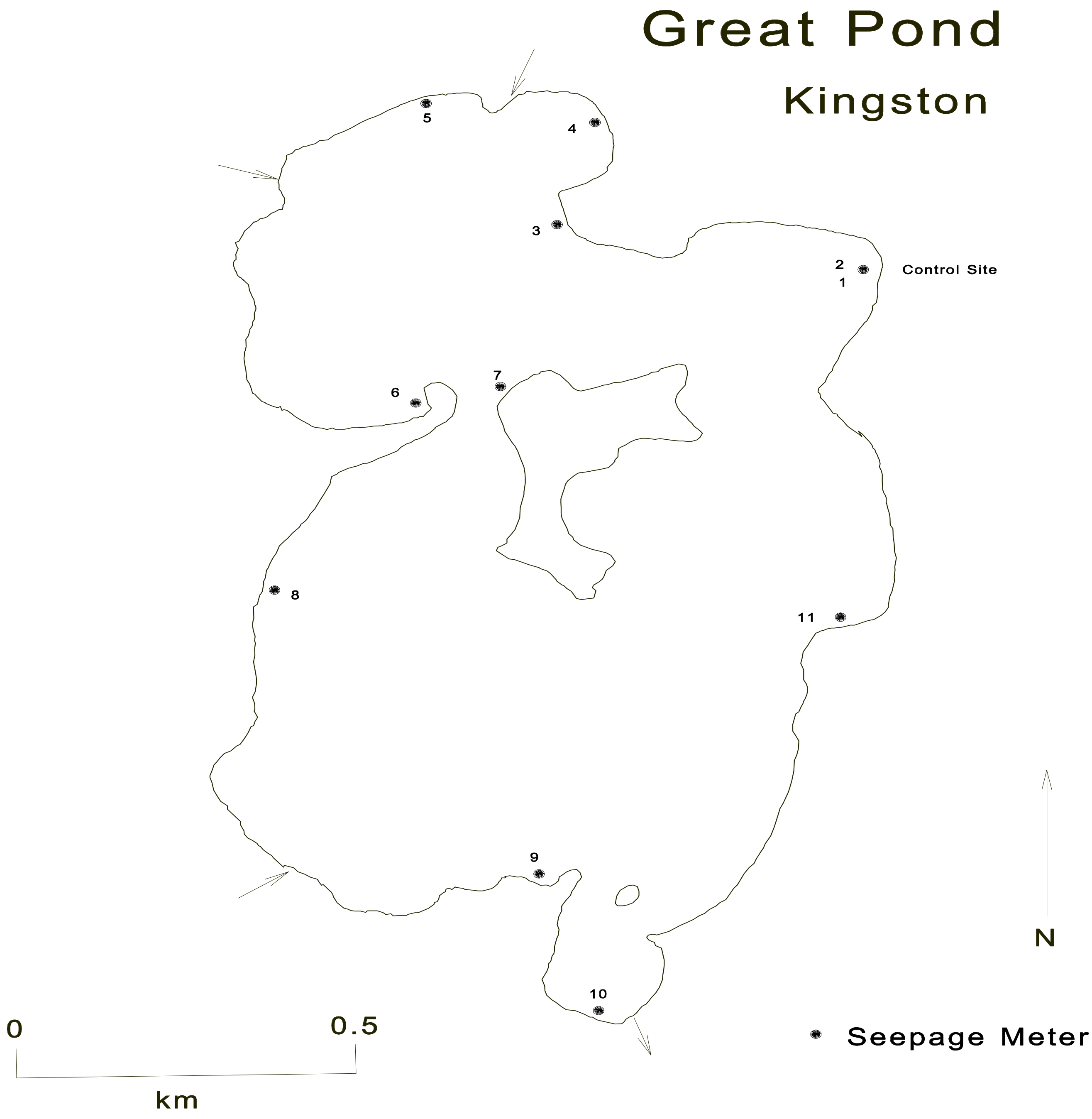
Station	Rate	Station	Rate
1	6.1	7	13.0
2	6.4	8	9.2
3	13.4	9	30.9
4	31.5	10	6.0
5	8.4	11	6.1
6	5.3		

The least amount of groundwater seepage was measured at stations six and ten. Station ten, located to the northwest, had a seepage rate of 6.0 L/m^2/d while station six, located in the southeast section of the pond had a mean annual seepage rate of 5.3 L/m^2/d.

The eastern pond seepage meters were located in areas of excessively drained soils with 60 inches of cover to bedrock. Seepage rates in these areas averaged 6.0 L/m^2/d. The western pond areas had seepage rates of 9.2 L/m^2/d and were also located in excessively drained soils with 60 inches of cover over bedrock. The island station showed higher seepage rates 13.0 L/m^2/d than rates measured at both the eastern and western shoreline.

Although mean monthly seepage rates were similar between specific stations, generally, seepage rates were greater during June. As we discussed previously, seepage rates increase with high runoff periods and decrease with dry periods. Therefore, it is likely that high seepage rates would correspond to periods of rainfall and when snowmelt and ground thaw has occurred in the watershed.

Statistical analysis of the data collected at each control site indicated there was no statistically significant difference between the data collected from meters one and two. A t-test was performed on calculated seepage rates collected at station one and station two in order to compare the data between seepage meters and determine the validity of the data. Data from station one and two passed both the normality test ($P=0.0987$) and the equal variance test ($P=0.4925$), indicating that usage and interpretation of data from this control site is valid.



C. HYDROLOGIC BUDGET COMPONENTS

The hydrologic budget for the Great Pond watershed, equating all measurable inflowing and outflowing waters over a designated period of time, were determined by the following equation:

Inflow volume = outflow volume

Specifically for Great Pond

$Qi_1 + Qi_2 + \ldots Qi_5 + R + P_{lake} + Gwi = Qo_1 + EV + Gwo$

Where,

Qi_1 = Kelley Brook

Qi_2 = Halfmoon Brook

Qi_3 = Thayer Brook

Qi_4 = Ball Brook

Qi_5 = Lincoln Brook

R = Surface water runoff from the direct drainage area

P_{lake} = Precipitation volume on lake

Gw_i = Groundwater inflow (seepage)

Qo_1 = Great Pond outlet

EV = Lake surface evaporation

GWo = Groundwater outflow (recharge)

Each component of this budget is in volumetric unites of $10^3 m^3$ (1000 cubic meters).

1. Hydrologic Budget for Study Period (1994-1995)

The monthly contributions from the tributaries (Qi) were derived from the aforementioned stream monitoring stations. Groundwater seepage (Gwi) was measured directly the two year study period. Monthly direct runoff rates (R) were calculated by multiplying the runoff coefficient (m/yr) obtained from the Knox and Nordenson Atlas (1955) by the estimated area around the lake which drained directly into the lake.

Stream outflow (Qo) is the measured discharge from the Great Pond outlet. Evaporation from the lake surface (EV) was calculated by multiplying the lake surface area times the evaporation, using a pan coefficient of 0.77.

Groundwater outflow recharge zones (Gwo) are difficult to measure unless reliable seepage meter data, including several meter transacts to the deeper portions of the lake, are available. Groundwater recharge was measured through mass balance equations and was estimated to be a small portion of the water budget. This is because the surrounding groundwater gradients are predominantly oriented into the lake basin, and the zone through which groundwater outflow occurs is small.

The hydrologic budget for each month of the study period for Great Pond is presented in Table VII-4. The months of October and November reflect periods when water storage is decreased by allowing excess water to flow over the outlet structure of Great Pond. This is an annual event that is performed to reduce shore-line damage and erosion from ice and to diminish the possibilities of property damage from flooding as a result of spring snowmelt.

During March and April the water inflow to Great Pond exceeded the amount of water that flowed out of the lake via the outlet structure. This is the period of time when water is collected in the lake basin to bring the lake level back to full pond. This is the level which the lake remains from June through September. To account for the discrepancy in flow, an artificial level adjustment of 1100.0 $10^3 m^3$ was added during the month of March.

2. Seasonal Flow Trends

Although seasonal precipitation rates influence the total inflow of water to the lake, seasonal precipitation rates may not follow seasonal inflow distribution patterns. Figure VII-3 shows that the winter and spring seasons were the greatest producers of water to Great Pond, representing 45.1 and 37.3 percent respectively of the seasonal flow of water. During this same period of time, the fall wetfall only accounted for 10.5 percent of the total annual precipitation.

Table VII-4

Great Pond Hydrologic Budget for Gaging Period (Nov '94 - Oct '95)

Water Volume ($10^3 m^3$)

Component	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total Annual	Mean Monthly
Qi_1 - Kelley	389.0	988.0	1979.9	1345.8	1873.7	1181.9	568.9	455.1	53.1	40.3	34.0	60.7	8970.4	747.5
Qi_2 - Halfmn.	51.4	212.0	197.2	150.7	235.2	95.4	30.3	7.3	0.0	0.0	0.0	0.0	979.5	81.6
Qi_3 - Thayer	22.0	196.9	204.8	89.1	129.0	88.1	60.7	22.0	7.5	19.2	0.0	15.2	854.5	71.2
Qi_4 - Ball	29.4	151.4	166.9	61.7	174.5	66.1	37.9	14.7	15.2	18.2	22.0	53.1	811.1	67.6
Qi_5 - Lincoln	0.0	7.6	0.0	0.0	7.5	7.3	0.0	0.0	0.0	0.0	0.0	0.0	22.4	1.9
Tot. Trib. Flow	491.8	1555.9	2548.8	1647.3	2419.9	1438.8	697.8	499.1	75.8	77.7	56.0	129.0	11637.9	969.8
R	31.0	61.5	0.0	0.0	90.2	21.2	31.9	12.2	30.4	19.7	32.4	84.8	415.3	34.6
P_{lake}	54.5	108.1	0.0	0.0	159.2	37.1	56.1	21.5	53.6	34.7	56.9	149.4	731.1	60.9
GW_i	79.0	156.6	76.5	77.6	76.5	53.8	81.3	31.2	77.6	50.3	82.4	216.4	1059.2	88.3
Total Inflow	656.3	1882.1	2625.3	1724.9	2745.8	1550.9	867.1	564.0	237.4	182.4	227.7	579.6	13843.5	1153.6
$Q0_1$	602.4	1840.1	2588.1	1664.8	1630.9	1500.9	776.4	467.3	151.7	94.9	150.2	522.1	11989.8	999.2
Artificial Adj.					1100.0								1100.0	0.0

EV	0.0	0.0	0.0	0.0	0.0	17.8	54.0	62.9	69.3	77.5	57.2	37.5	376.2	31.4
GWO	53.9	42.0	37.2	60.1	14.9	32.2	36.8	34.0	16.4	10.0	20.0	20.0	377.5	31.5
Total Outflow	656.3	1882.1	2625.3	1724.9	2745.8	1550.9	867.2	564.2	237.4	182.4	227.4	579.6	13843.5	1062.0

The spring season typically delivers the greatest amount of water to northern New England lakes. The reason for the seasonal peak discharge is a combination of rainfall, frozen ground, which limits groundwater penetration, and the melting of the stored winter snowpack.

The summer contributed fifteen percent of the seasonal precipitation, but yielded the lowest seasonal inflow distribution to the lake (7.1 percent), often typical in watershed studies. Summer storm events are usually of high intensity and short duration, as such, they are difficult to detect by manual stream monitoring techniques. Since summer inflow distribution is usually underestimated, the placement of automated flow recorders on each tributary and outlet will make hydrologic budgets more precise for future studies.

Another aspect to consider when assessing a storm's significance is the environmental conditions at the time of the storm. July and August are typically hot dry months in the Northeast and are in the middle of the growing season. The land is usually dry, with a low water table, and is primed for absorption of rainfall and runoff. In most instances, the high summer rainfall does not correspond to the low to moderate summer inflow to the lake. This low correlation between rainfall and lake inflow can be explained by higher soil infiltration rates during the summer and because high intensity, short duration rain events are difficult to monitor. The short duration rain events are often missed and not accounted for in the hydrologic or nutrient budgets. Only if an organized summer wetfall event is measured or automated flow equipment is employed, can sophisticated hydrologic budgets be constructed. In this study, only Kelly Brook contained an automated flow device and only for a nine month period.

The fall season contributed only 10.5 percent of the seasonal inflow to the pond. Typically northern New England receives substantial wetfall during the fall season. However, September and November were exceptionally dry for this study year, producing only 15 percent of the total annual wetfall. However, October proved to be more typical of the regional wetfall patterns, accounting for 20 percent of the annual wetfall budget.

Great Pond

Seasonal Inflow/Outflow Distribution

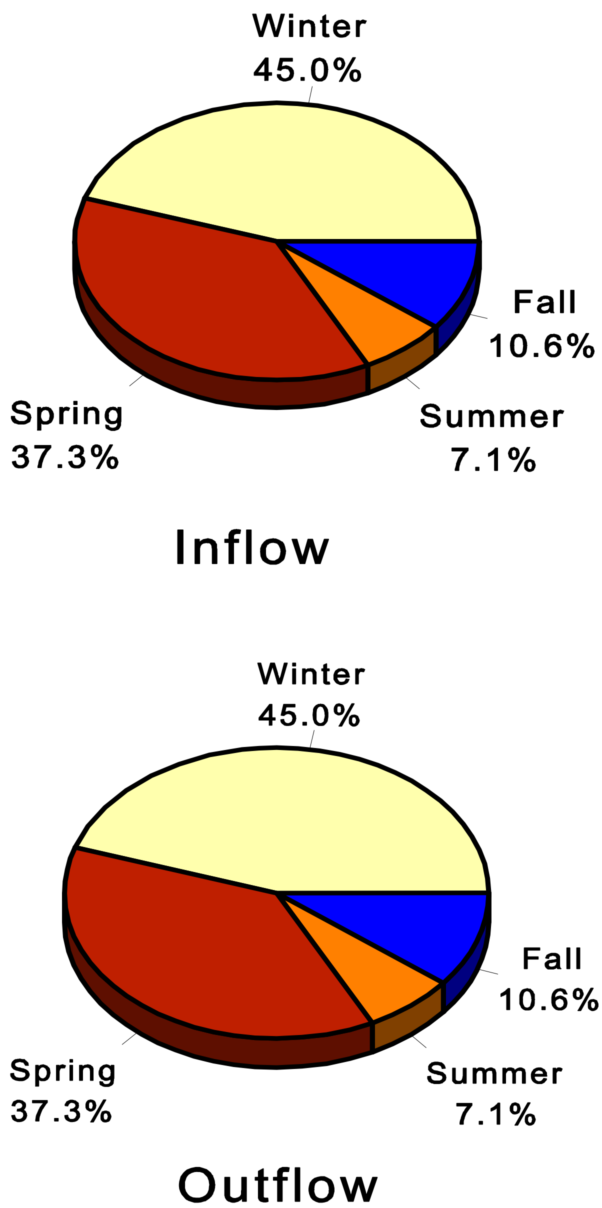


Figure VII-3: Great Pond Seasonal Water Volume Exchanges

The winter season accounted for 45 percent of the hydrologic budget. This contribution is higher than other studies conducted and is attributed to heavy December rainfall and frozen ground that limited the amount of rainfall from infiltrating the ground. High rainfall during this period is also the reason why tributary flow was greatest during the winter, representing 49.5 percent of the tributary supply of water to the lake.

Seasonal outflow characteristics are regulated by a dam structure and may not correspond with the monthly inflow distribution. As the boards to the dam are put into placeduring the spring, the pond retains more water while outlet flow is decreased. During October, the boards to the dam are removed, creating an excess of outflow from the lake. Outflow during this time is greater than tributary inflow.

3. Tributary Flow Contributions

The subwatershed area of the Kelly Tributary (3,513 acres), comprises 55 percent of the Great Pond watershed and contributed 77 percent of the total tributary inflow to the lake (Figure VII-4). The subwatershed of this tributary is characterized by extensive wetland complexes which cover 508 acres or 14.5 percent of the subwatershed area. The drainage patterns in the Kelly tributary watershed are also influenced by 100 acres of open water including Long Pond, Danville (89 acres). Mixed, conifer and deciduous forests comprised 68 percent of the Kelly subwatershed. The Kelly Tributary drains into Great Pond at the southwest section of the pond.

The Ball Road Tributary has a 1070 acre subwatershed that accounted for 7.0 percent of the total tributary inflow during the study year. This subwatershed occupies 17 percent of the Great Pond watershed and provides drainage for only 1 acre of open water. However, the predominant features throughout the subwatershed are the extensive wetlands comprising 124 acres or 12 percent of the total subwatershed area. Much of the watershed is made up of forest (75 percent). Flow volumes and drainage patterns in the Ball Road Tributary watershed are often influenced by beaver activities and impoundments.

The Thayer Tributary and its 491 acre watershed contributed 7.3 percent of the total tributary inflow during the study year. This subwatershed occupies 7.6 percent of the total watershed area for

Great Pond. This subwatershed has extensive surface waters and contains Greenwood Pond, which comprises 53 acres or 11 percent of the subwatershed area. There are 81 acres of wetlands (17 percent) which surrounds Greenwood Pond. The pond outlet meanders through a portion of the wetlands before entering the extreme northern section of Great Pond, west of Kingston State Park.

The Halfmoon Pond Tributary has a drainage basin on 186 acres and represents 2.9 percent of the total watershed. Forests represent 58 percent of the subwatershed land use. Halfmoon Pond represents almost 11 percent (20 acres) of the subwatershed while surrounding wetlands make up 22 percent (41acres) of the drainage basin. The Halfmoon Tributary flows into the West section of Great Pond and like the other sampled tributaries, is influenced by beaver activity.

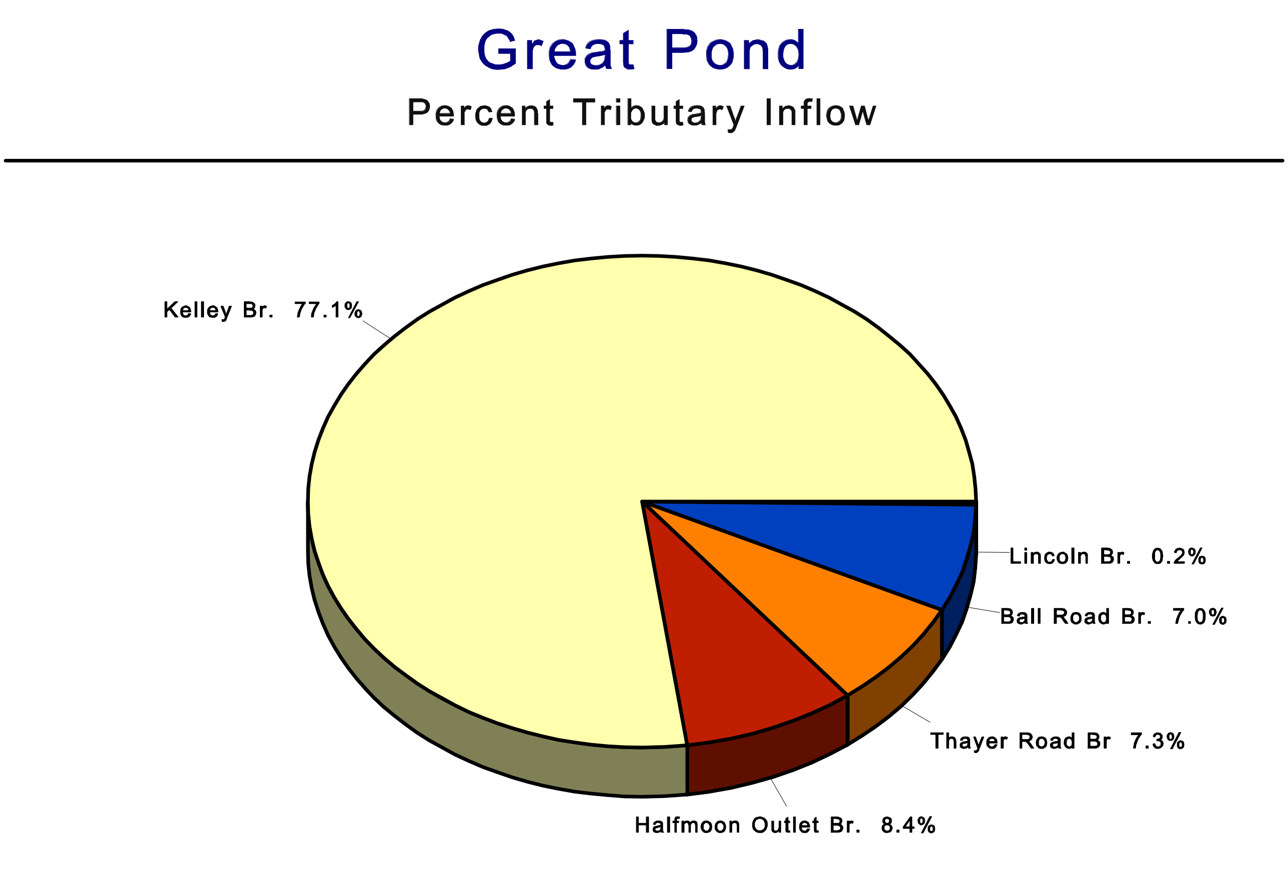


Figure VII-4: Percent Tributary Inflow

4. Total Annual Inflow and Outflow Budget Contributions

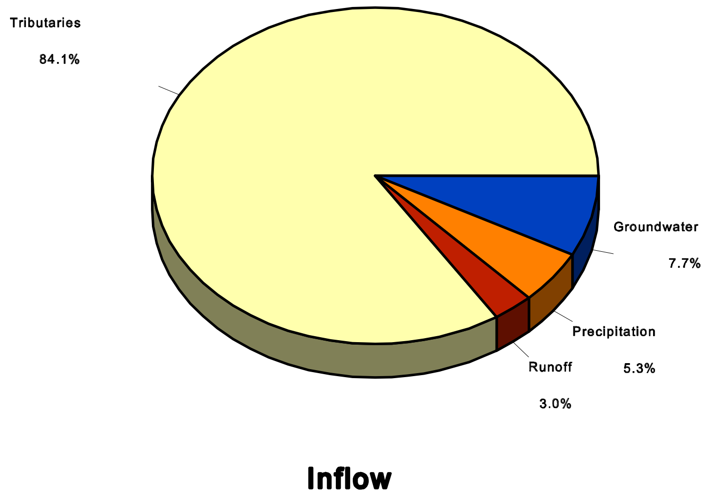
Figure VII-5 depicts the relative annual volumes of each inflowing and outflowing component of the Great Pond hydrologic budget. Tributary flow accounted for 11637.9 $10^3 m^3$ of the total 13,843.5 $10^3 m^3$ flow, or 84.1 percent of the total water budget of Great Pond. Direct precipitation to the lake accounted for 5.3 percent of the budget. Direct outflow or discharge represented 94.5 percent of the outflow budget for the same year. Evaporation accounted for 2.7 percent of the outflow and water recharge into the groundwater was estimated to be 2.8 percent of the total discharge from the lake

.5. Storm Event Hydrology

Stormwater runoff is a principal cause for degradation of rural lakes where urban runoff is present (Cooke et. Al, 1986). Runoff water will likely contain the impurities in precipitation plus debris and other impurities deposited on the ground surface. Pollutants diffuse over the surface of the land and eventually enter the aquatic system (Wanielista, 1978).

Two types of storm events are important to the hydrologic and nutrient budget. High intensity, short duration storm events can represent a high percent of the total water budget and a significant percent of the phosphorus export to a lake. Since less water is able to percolate into the ground in high intensity storm events, more unfiltered surface runoff and more erosional material is carried to the lake and its tributaries.

The second type of rain event is the long duration, low intensity event. This type of event usually has lower priority for stormwater sample events. Generally, long duration, low intensity storms have lesser impacts on surface water quality from phosphorus, bacteria or solids loading. Wetfall from this type of event often infiltrates into the ground rather than travel overland. Less overland flow results in less turbidity and less phosphorus load to the lake.



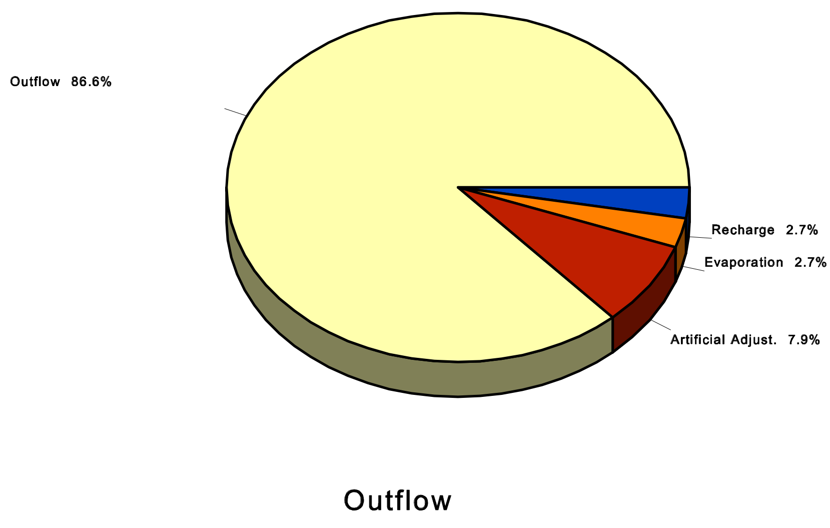


Figure VII-5: Great Pond Inflowing/Outflowing Component Distribution

The sample year rainfall total for Great Pond was 34.83 inches. This is below the 20 year mean for the state, which shows an average yearly rainfall value of 38.07 inches. Although 50.8 percent of the rainfall occurred during the growing season, from the months of May through October, many of the rain events were of long duration and low intensity and 20 percent occurred in October. Because of the drought during the hydrologic growing season, high intensity storm events occurred infrequently.

On October 6, 1995, biologists and volunteers monitored a low to moderate intensity storm event at Great Pond, for approximately seven hours. The watershed was dry and little runoff was measured at each station. Many of the tributaries were dry at the time of the event and maximum water flows during the peak storm event flow were minor compared to other seasonal flow trends. As Table VII-5 shows, peak flow times ranged from 4:00am at the Ball Road Tributary, to 8:00am at the Halfmoon Tributary. Approximate maximum discharge resulted in only 0.06 CFS at Halfmoon, 0.18 CFS at Ball Road, and 0.70 CFS at the largest tributary, Kelley Brook.

Table VII-5
Storm Event Peak Flow Times and Discharge
For Each Station

Station	Peak Time	Approximate Discharge (CFS)
Kelly Tributary	4:30 am	0.70
Halfmoon Tributary	8:00 am	0.06
Ball Road Tributary	4:00 am	0.18