The Water Budget of Great Herring Pond in 2012 and 2013
Measurements, Comments, Residence Time

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Highlights of this study

1. Groundwater wells up from the bottom of Little Herring Pond near its northern end and becomes part of the pond water, which then flows through a flume at the pond's southernmost end to become Carters River. This meandering stream, about one mile long, drops only 2 feet over its entire length before it spills into the northwestern end of Great Herring Pond. Yet it provides about 80 – 90 % of the water in Great Herring Pond, with a flow rate of 4000 – 6000 gallons/minute, varying with the seasons. The remainder of the water in Great Herring Pond originates mostly as rain, and to a small extent as springs at the bottom of the pond.
2. Water flow in Carters River has been more or less stable over more than 30 years despite very significant development in the watershed.
3. The water level of Great Herring Pond is held constant by a concrete barrier and overflow at its southeastern end, which marks the beginning of Herring River. Even after very significant rainfall, the pond returns to its normal level within a few days. Herring River flows through a narrow valley into the Cape Cod Canal after dropping a bit more than 30 feet over a distance of about 1 mile.
4. The residence time of the water in Great Herring Pond has been determined by studying both the water flowing into the pond and the water flowing out of it. The residence time in 2012 and 2013 deduced from water flowing into the pond was 6 – 7 months. The residence time in 2012 deduced from water flowing out of GHP was 11 - 12 months. For 2013 it was 6 – 7 months.

From the middle of 2009 until the beginning of 2014, the Herring Ponds Watershed Association (HPWA) was involved in a study of water flow into and out of Great Herring Pond (GHP), Plymouth, MA. The main goal was to get a deeper understanding of the water budget of GHP: how much water did the tributaries deliver to GHP; how much was supplied by rain/runoff; lost by evaporation; springs and sinks in GHP; how quickly would pollution be flushed away, i.e. what was the residence time of water in GHP.

Water flow in this system is fairly simple. It is dominated by groundwater welling up at the bottom of Little Herring Pond (LHP), an approximately 100 years old shallow (av. depth 3ft) pond to the north of GHP. The groundwater springs are located at the pond bottom, near its northern end. Water flows south until it discharges into a concrete flume marking the southern end of the pond and the beginning of Carters River. Carters River is a small meandering stream approximately one mile long. It empties into the northwestern end of Great Herring Pond. Great Herring Pond, a large, deep (av. depth 22ft) warm water pond, overflows at a concrete barrier on its southern end, and becomes another small stream approximately one mile long, the Herring River, which empties into Cape Cod Canal. There are no other streams into or out of GHP, except two small drainage channels from abandoned cranberry bogs.

Flow data were taken by HPWA volunteers, in collaboration with several people from the River Instream Flow Stewards (RIFLS) program of the Fish and Game Division of Massachusetts, Margaret Kearns and Cindi DelPapa, then Cindi and Laila Parker, and finally Laila. The RIFLS people installed staff gauges at three points: the flume at the south end of Little Herring Pond (LHPo), Carters Bridge at the outflow of Carters River into Great Herring Pond (GHPi), and in Herring River about 100 ft downstream from its beginning , approximately 15 ft upstream of Sandy Pond Bridge (GHPo). They also provided water flow calibrations and frequent re-calibrations of the staff gauges. Readings of the staff gauges were taken mainly by Brian Harrington and myself, with several other occasional volunteers. Daily rain gauge results were collected by me at my residence on a peninsula reaching deeply into Great Herring Pond, fairly close to its center.

This paper shares results from 2012 and 2013 only. I distribute it now, partially to highlight open questions and solicit better ways to look at the data. I will continue to work on the rest of the data, which we took between the middle of 2009 and early 2014.

The day-by-day data are confusing – it’s hard to see the forest for all the trees. Therefore, I summed the data month-by-month. I attach flow graphs for 2012 and 2013. Flow units are given in gallons per minute. Rainfall as shown is converted from the usual inches to gallons/min for the surface area of GHP (376 acres) only. It should be remembered that the whole watershed has an area of about 4450 acres, about half of which is downstream of GHP. Most importantly, I stress that there is a lack of data on the contribution of runoff flowing into GHP or seeping directly into the groundwater. I have no data about springs and sinks in the pond, except qualitative evidence for springs of unknown but probably insignificant flow rate from a few open holes remaining in the ice covering GHP even on very cold days in early winter. The biggest such hole is roughly at GPS N41^0 47.8’; W70^0 33.8’, close to the deepest spot in the pond. The estimate of evaporation is given in gallons/min for the whole pond surface area, and is obtained using a USGS program based on a regional model of Fennessey and Vogel (J. Hydrology 184, 337, 1996). I have to thank Laila for providing the evaporation estimates for 2012. They should also be used for the other years.

Here are some of the 2012 and 2013 results:

1. **The puzzle of water sometimes appearing from seemingly nowhere - comparing the amount of water flowing out of LHP (LHPo) into the mouth of Carters River – with the amount of water discharging at the southern end of Carters River (Carters River Bridge) into GHP (GHPi):** First 2012. Water flow out of Little Herring Pond (LHPo) into Carters River is fairly constant at 4000 +/- 500 gallons/min. 2012 flow out of Carters River into Great Herring Pond (GHPi) is about 5500 g/min in January but drops steadily to about 4000 g/min in July and remains at that level for the rest of the year. Rainfall in the first 4 months is small. It roughly doubles during the last 8 months of the year. During those first 7 months there were up to 1000 g/min more coming out of Carters River than went in, a 15 – 20 % difference. Where did this extra water come from? Is there a calibration problem, or is that real? There doesn't seem to be much correlation between flow and rainfall, but rainfall is only about 10% of the Carters River flow.

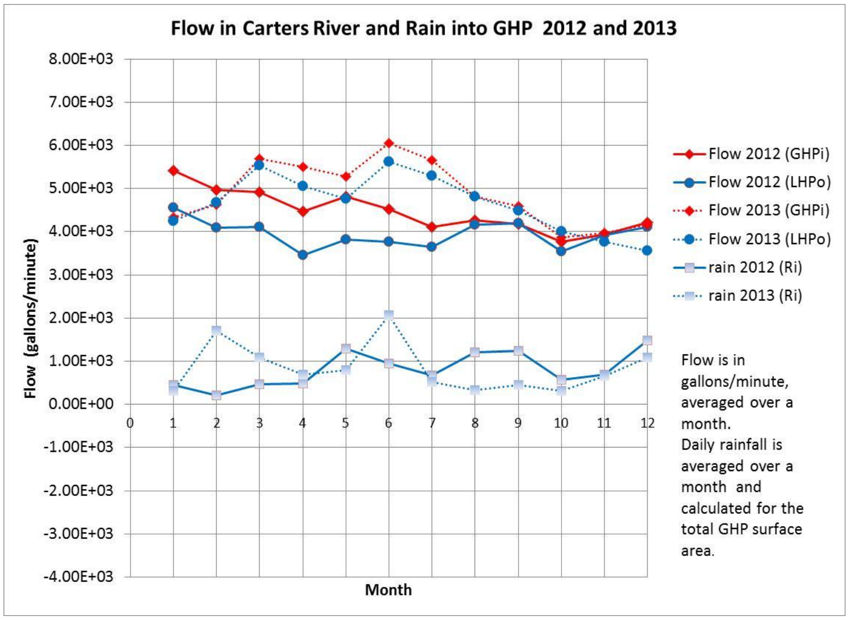

Figure 1. Water flow in gallons/minute out of Little Herring Pond into Carters River (LHPo) and out of Carters River into Great Herring Pond (GHPi) for 2012 (solid lines) and 2013 (dotted lines). Also shown is 2012 and 2013 rainfall in gallons per minute entering the GHP surface area (380 acres).

In 2013, LHPo increases from about 4200 g/min in January to more than 5000 g/min between March and August and then falls steadily to about 3600 g/min in December. Flow out of Carters River GHPi is practically the same, i.e. in 2013 there is no difference between the two flows as there was in the first part of 2012. Rainfall in the first half of the year 2013 is at least twice what it was in the beginning of the previous year but then is low for the next four months, before it increases again. There were two months, February and June, with large spikes of rain during several days close together, of more than 1" per day

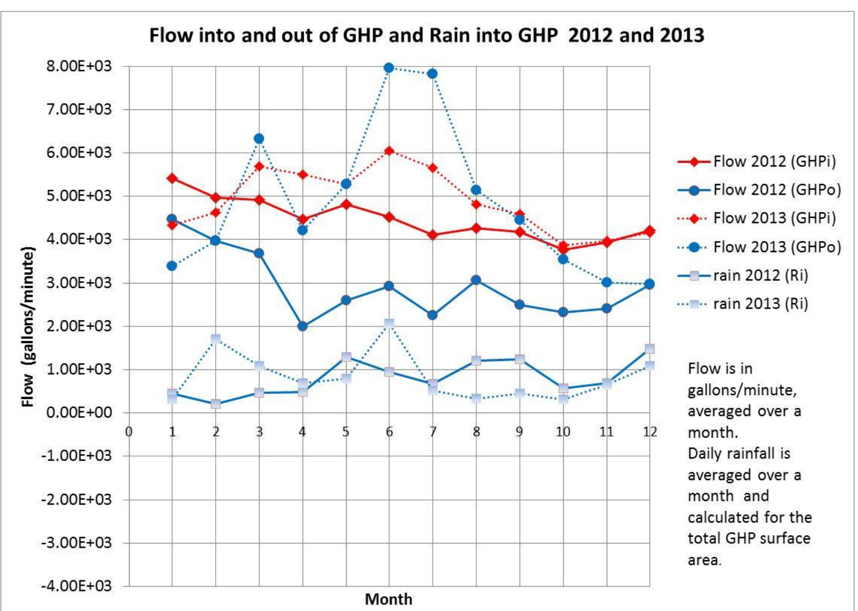

Figure 2. Water flow in gallons/minute from Carters River into Great Herring Pond (GHPi) and from Great Herring Pond into Herring River (GHPo), for 2012 (solid lines) and 2013 (dotted lines). Also shown is 2012 and 2013 rainfall measured in inches/24 hours and converted here to gallons per minute entering the GHP surface area (380 acres).

each. Especially the spike in May is reflected by a large peak in the flow, which takes a surprisingly long two months to peter out. I would have expected the discharge into GHP (GHPi) to always be a bit more than the outflow from LHP, because of rainfall along the river banks. But that might not contribute much and may not be detectable. It is difficult to see where Carters River during 2012/13 could have gained 1000 g/min on its way from LHP to GHP for about 6 months, and then stopped gaining for the next 17 months.

2. **Comparing the water flow into GHP (GHPi) and out of GHP (GHPo):** As discussed already, in 2012 GHPi varies from about 5000 g/min in the first half of the year to about 4000 g/min in the second half. Interestingly, 5000 g/min is the flow rate quoted in data

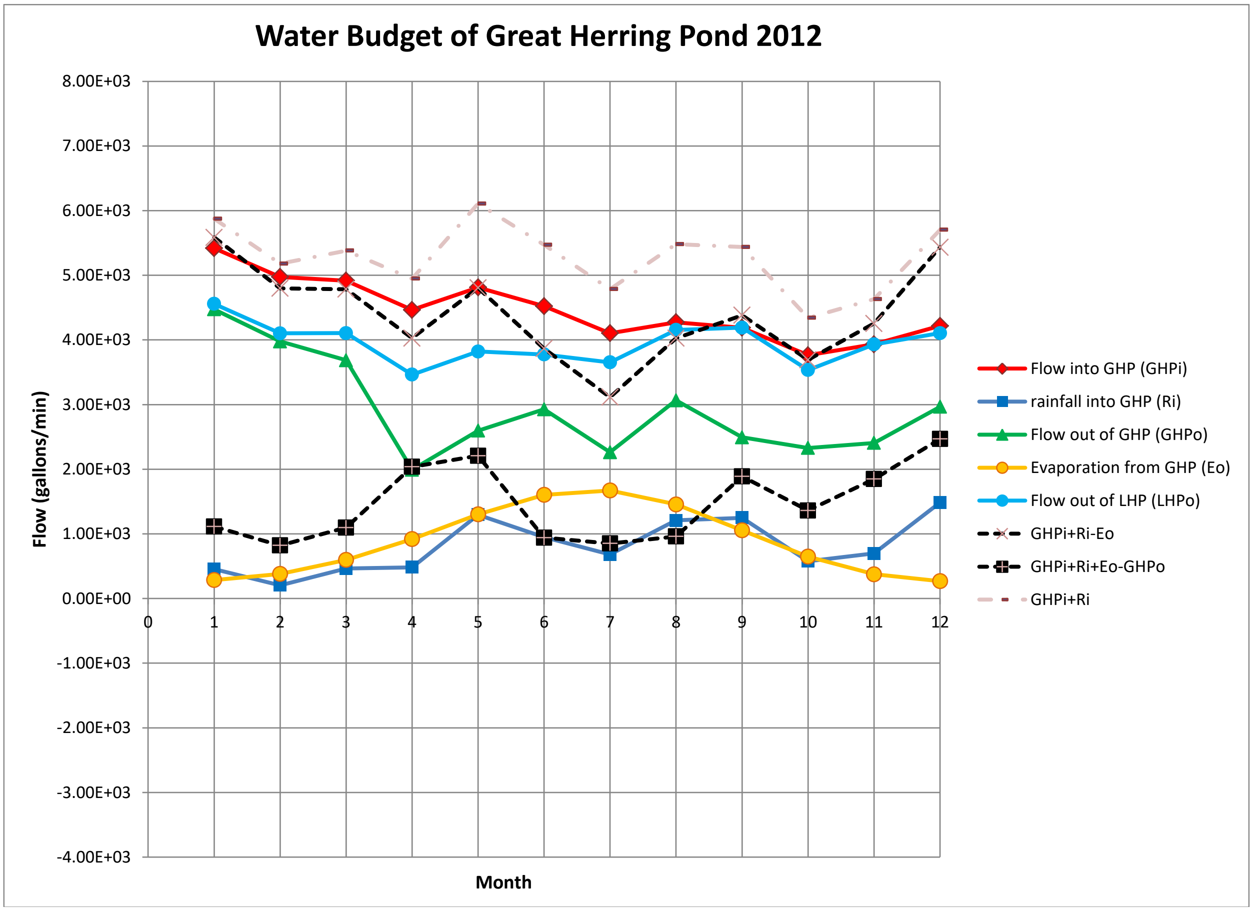

Figure 3. Measured monthly water flows LHPo, GHPi, GHPo, measured rainfall Ri into GHP, estimated water evaporation Eo from GHP. Also shown are sum of waters entering GHP (GHPi+Ri, dash-dot), sum of waters entering minus evaporation (GHPi+Ri-Eo, upper dashed line), and all measured waters entering and leaving GHP (lower dashed line). Not considered were runoff and seepage between pond and ground water. All for 2012.

from 1979/80 *theherringpondswatershed.org/uploads/Great_Herring_Pond_Baseline_Study_Full.pdf.* So the nearby large residential developments of the last thirty years, Ponds of Plymouth and others, seem not to have caused major flow changes in the LHP ground water springs. For most of 2012 the flow out of GHP (GHPo) is about 1000 – 1500 g/min less than the flow into GHP for all of 2012. Where does this water go, especially if we add rainfall into the pond (500 – 1000 g/min, not counting runoff)? We will come back to

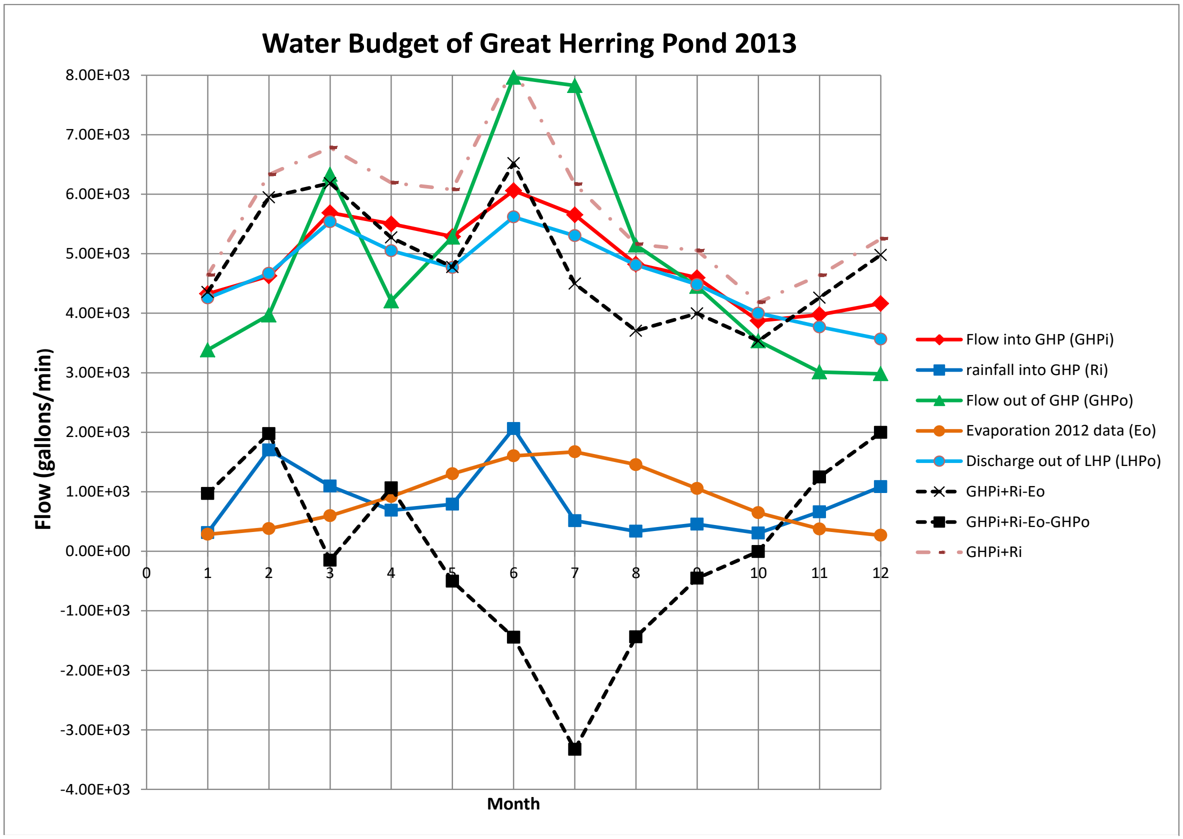

Figure 4. Measured monthly water flow rates, LHPo, GHPi, GHPo, measured rainfall Ri into GHP, estimated water evaporation Eo (2012 estimate) from GHP. Also shown are sum of waters entering GHP (GHPi+Ri, dash-dot), sum of waters entering minus evaporation (GHPi+Ri-Eo, upper dashed line), and all measured waters entering and leaving GHP (lower dashed line). Not considered were runoff and seepage between pond and ground water. All for 2013.

this question below. Not so for 2013. Both the flow into GHP and out of GHP, but especially out of GHP, show strong correlations with massive rainfall peaks of more than 1 inch (up to 2.7 inch) per day during several successive days that dominate the flow between March and September. Only towards the end of the year does the deficit of the outflow compared to the inflow go back to the 1000 g/min of the previous year. In June /July the inflow goes up to about 6000 gallons/min, and the outflow reaches 8000 gallons/min, indicating that groundwater and/or runoff must contribute at times up to 4000 gallons/minute. It is significant that after the large amount of rain, which occurred within just a few days, the flow out of GHP stays high for about one month. Some of the water took that long to find its way into and then out of the pond. This implies water storage in the watershed rather than the pond, inferred from an event in 2009, when 6 inches of rain occurred in a period of a few hours. This caused the pond surface to be lifted by about a foot, but it returned to its previous height not within weeks or months, but within about 3 – 5 days, indicating no restrictions of water flow out of the pond which might retain the water in the pond for a long time. It seems that the watershed is sometimes able to store a significant amount of water temporarily, before releasing it into GHP.

3. **Rainfall:** In 2012, rainfall contributes between 10 and 20 % of new water to GHP, with the bulk (80 – 90%) of new water coming from Carters River, i.e. from the groundwater springs in LHP. In the first 7 months of 2013, the contribution from rain is somewhat larger, because of snow melting/rain in March and the unusual June rain spikes. In the last three months of 2013, it returns to looking similar to 2012. Overall there is about 20% more precipitation in 2013 than in 2012.
4. **Evaporation:** I am grateful to Laila for running the evaporation estimates for 2012. According to these data, evaporation peaked in July at about 1700 gallons/minute. This would indicate that during that month about 40% of the water contributed to GHP by Carters River evaporated.
5. **Flow into GHP (GHPi) plus Rainfall (Ri):** This is the faint dash-dot line, the top line in Figures 3 and 4. No surprises here.
6. **Flow into GHP (GHPi) plus Rainfall (Ri) minus Evaporation (EO), and the same quantities minus additionally the flow out of GHP (GHPo):** Please note the 2012 evaporation estimate is used for both 2012 and 2013 because I do not have the 2013 estimate. The first quantity is the net new water into GHP, if we assume negligible runoff and no significant springs in GHP. This quantity appears as the upper dashed line in the two graphs. If we also subtract the flow out of GHP (GHPo) we get the lower dashed line in the graphs. I call this the water budget GHPi +Ri –Eo – GHPo. It should be zero under the assumptions, which are that the pond water level stays the same all year long, and runoff and springs are insignificant. In 2012 that is clearly not the case, but varies between +1000 and +2000 g/min. So maybe we ought to make a wild guess which works reasonably well for 2012: unaccounted springs in GHP add 1000 g/min and runoff does the rest, although the runoff is somewhat time-delayed compared to the rainfall. There's also the unexplained huge dropoff in flow GHPo by almost a factor two, from 4000 g/min to 2000 g/min, between March and April, which is very puzzling. Afterwards, this flow stays below 3000 g/min for the rest of the year, which raises calibration questions, because the other two gauges don't show such a dramatic change. If it were the end of snow melting, shouldn't we see something similar in GHPi and LHPo? Indeed there is a small effect in both these quantities – but nowhere near a factor two. So this remains unexplained.

   Furthermore, 2012 and 2013 are quite different. First, I note that rainfall is much heavier in the first half of 2013. In February, there is a rain spike, several days, close together, when daily rainfall is around 1 inch. It may be exacerbated by snow melt. There is a similar spike in June, another few days with daily rainfall of up to 2.7 inches. Only in July does rainfall settle down to average dailies near 10% of the river flow volumes until November when rain starts increasing again. As discussed already, these rain spikes show up dramatically in the flow out of GHP. But GHPi+Ri –Eo – GHPo, the water budget, has an enormous deficit, peaking in July at between -3000 g/min and - 4000 g/min, which must be made up by some combination of runoff and groundwater entering GHP. That the rain peaks produce a lot of runoff and also may make the groundwater rise significantly is not surprising. However, that it takes several months for things to settle down was very surprising to me, because it means that the water is stored temporarily, and the question is how much in GHP, how much elsewhere. A one inch rise in the pond water level corresponds to 1×10^7 gallons, or about 1/3% of the total amount of water stored in GHP. I have no systematic data on the daily or weekly rise and fall of the pond's water level, but I doubt, from observations, that it fluctuates by more than a couple of inches, except after an exceptionally large rainfall. Therefore storage as pond water is insignificant.

7. **Water residence in GHP.** GHP contains about 2.9×10^9 gallons of water. Once pollutants are in the pond, how long will it take for them to be flushed out by new water entering the pond, under the assumption that the new water is clean? This question can be answered by studying the amount of water flowing out of GHP into Herring River. For simplicity we'll assume that brisk wind and waves mix the water continuously, and that any pollutant remains distributed well over the whole pond. This may not be a totally adequate assumption, because there are bays and sometimes there is stratification, and the actual flushing time may therefore be much longer, for some parts of the pond, but it may be adequate for an estimate.
   For mathematics lovers, this is a classical exponential problem, characterized by a single number, the halflife, here also called residence time. If there is a steady flow of clean water into the pond, only half the pollution will be left in the pond after one halflife. That is the definition of halflife. Wait for another halflife, and half of the remaining pollution will be left, i.e. only ¼ of the original pollution is remaining. After another halflife, 1/8 of the pollution is left. In other words, the remaining pollution in the pond will be ($½^1$=1/2), ($½^2$=1/4), ($½^3$=1/8), ($½^4$=1/16), ….. after 1, 2, 3, 4, … halflives. Our flow data result in a halflife of 12 months for the year 2012, and 7 months for 2013.
   In principle, the same result can be obtained, not by measuring the outflow of contaminated water, but by studying the amount of clean water added to GHP each month. I note that, for 2012, evaporation, which removes clean water from GHP, is more or less cancelled by rainfall, which adds clean water. This can be seen by consulting Figure 3. Therefore, the flow GHPi represents the clean water replacing the polluted water GHPo, except in the first six months it is between 1000 and 2000 g/min more than GHPo. Where does this extra water go? It must end up in the ground. So some of the pollution enters the groundwater. For 2013, the (accidental) agreement between evaporation and rainfall is much worse, but those quantities are both much smaller than the flow GHPi and will be ignored. With these simplifications, the residence times for

both 2012 and 2013 by this method are between 6 and 7 months, in agreement with the earlier results.

8. Additional Comments and Questions.

- As already mentioned, I am puzzled by the data showing the outflow of Carters River into GHP sometimes being much larger than its inflow from LHP. Is there sometimes a sizeable bypass of water around the flume at the southern end of LHP?
- In hindsight, perhaps I should have summarized the daily data in weekly or biweekly batches, for easier comparisons.
- Does any information on springs and sinks in GHP exist?
- If these measurements are continued in the future, it might be helpful to record daily or weekly pond water levels.
- I welcome comments. Please send to e.vongoeler@neu.edu.