Water budget for the TCF pond

By

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Abstract

To determine the impact of various water fluxes associated with the pond at Timbercreek Farm on nitrogen transport through the pond, a water budget was constructed that covered the period from April 2015 to April 2016. The budget included direct measurement of inflow and outflow, precipitation from the Charlottesville-Albemarle airport, and estimates of evaporation made with the Hamon method. The volume of the pond was determined using ArcGIS to be approximately 6800 m^3. Using a datum, the change in volume over time was calculated and groundwater flow was estimated by difference. The total water flux into the pond was 1.64×10^5 m^3/week with 97.5% of the inputs as the surface water and 2.5% precipitation. The total water flux out of the pond was 1.84×10^5 m^3/week with 98.6% of the output as surface water through the outlet and 1.4% evaporation. Thus, the most dominant component of the water budget is surface flow, which has been measured in some capacity throughout the project starting in 2013. The difference between the inputs and outputs of the pond was approximately 11% of the output total, which may, at least partially, be accounted for by the groundwater flow into the pond.

1. Introduction

Timbercreek Farm (TCF) is a permaculture farm located near Charlottesville, Virginia, that is committed to "the community driven and environmentally responsible future of agriculture" (Tcofarm.com). Permaculture farming avoids using pesticides, herbicides, fertilizers, or antibiotics (Jungck, 1985). The goal of permaculture farming at TCF is to create an environment for the animals and grasses to thrive and to determine the viability of sustainable farming practices (Leach, 2014). Utilizing permaculture livestock production may be one way to lower the carbon and nitrogen footprint of such a farm and improve the sustainability of the food production.

All life forms require nitrogen in some form. Humans ingest their nitrogen through food. Growing food, requires the use of nitrogen. Excess nitrogen lost to the environment can cause a myriad of environmental and human health problems including but not limited to "smog, acid rain, climate change, eutrophication, stratospheric ozone depletion, biodiversity loss" and possible degradation of the human immune system leading to an increase in the prevalence of diseases including malaria, West Nile virus, cholera, and schistosomiasis (Galloway et al., 2008; Leach, 2014). Since nitrogen is a necessary part of food production, it is imperative to find ways to effectively increase production while mitigating nutrient loss and detrimental environmental and human health problems (Galloway et al., 2008).

A study was begun at TCF in 2013 comparing the nitrogen use efficiency of Timbercreek Farm to conventional farms (Leach, 2014). Leach's study encompassed the analysis of the farm nitrogen budget through the use of intended N inputs including animal feed, legume biological fixation, and purchased livestock as well as looking at the virtual nitrogen factors (VNF), which are composed of the N lost to the environment during the various stages of the food production process (Leach, 2014). She established sampling sites for her project, which collected water samples from the streams flowing through the property to calculate the inorganic N flux created from June 2013 to April 2014 (Figure 1).

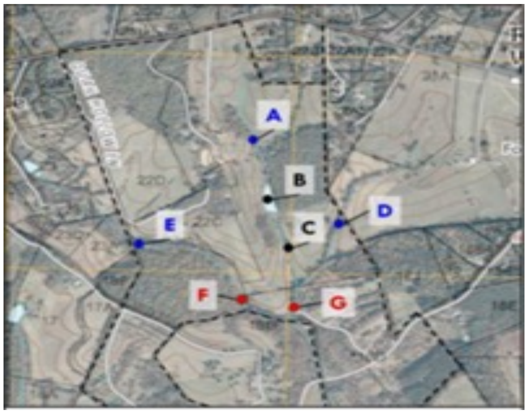


Figure 1. The sampling sites A, B, C, D, E, F, and G established in 2013 with the beginning of the project in 2013 (Leach 2014).

Leach (2014) reported a lower nitrogen (N) flux at sites F and G (near where the stream exits the TCF property, (see locations G and F, Figure 1) for 62% of the 13 sampling dates relative to the flux from sites thought to represent surface water inflows to the property (locations A, D, and E in Figure 1) as evidence that the farm acted as a sink for nitrogen during the period of her study. She also calculated an overall nitrogen budget for the farm to evaluate the N dynamics of the farm and continues to provide a context for research at the farm (2014). One possibility proposed by Leach (2014) to explain the lower N flux in streams leaving the farm is that the pond may either be storing nitrogen in the sediment, or it may be providing a location for denitrification of nitrate to N_2 before the stream flow reaches the outflow sites.

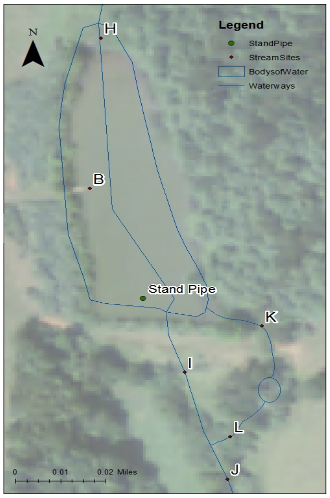


Figure 2. The current sampling sites around the pond are shown here. H is the inflow site. Site B is where the pond datum is located. J is the outflow sites.

Determination of a N budget for the pond requires measurement of N concentration in the water (C_N, M/V) and the discharge (Q, V/T) of water. The flux of N over the time period, then is $C_n \times Q$. This project developed the pond's water budget. A complete water budget includes stream inflow, direct precipitation, groundwater inflow, groundwater outflow, direct evaporation, and stream outflow (Figure 2) (Nath and Bolte, 1998). The biggest input and output from the pond are assumed to be the surface water inflow and outflow due to the consistent stream flow.

Thus, the focus of my thesis is to investigate the hydrology of the farm pond through construction of its water budget. The specific objective of this research was to determine a water budget for the pond by measuring the inputs, outputs, and change in storage over the period between April 2015 and April 2016.

2. Methods

My research uses the methods described by Leach (2014) and Kozuch (2014) to determine the discharge at sites H and J (Figures 1 and 2). For my project, the focus is on inflow site H and outflow site J (Figure 2). Using a mass balance approach I estimated water budget components for the pond (Figure 3 and Equation 1), including surface water inflow, precipitation, in-pond storage, surface water outflow, evaporation and net groundwater flow. A water budget for a body such as a farm pond can be expressed as:

$$dv/dt = p + r_{si} + r_{gi} - r_{so} - r_{go} - e, \tag{1}$$

where dv/dt is the change in volume in m^3/week, p is amount of the precipitation in m^3/week, r_{si} is the amount of surface inflow in m^3/week, r_{gi} is the amount of groundwater inflow in m^3/week, r_{so} is the amount of surface outflow in m^3/week, r_{go} is the amount of groundwater outflow in m^3/week, and e is the amount of evaporation in m^3/week. I assume that overland runoff is a negligible part of the total surface flow, thus, r_{si} and r_{so} represent stream flow. Groundwater inputs, r_{gi}, and groundwater outputs, r_{go}, are included in the budget, but direct measurements were not made. Instead, imbalances in the water budget were attributed to net groundwater flow.

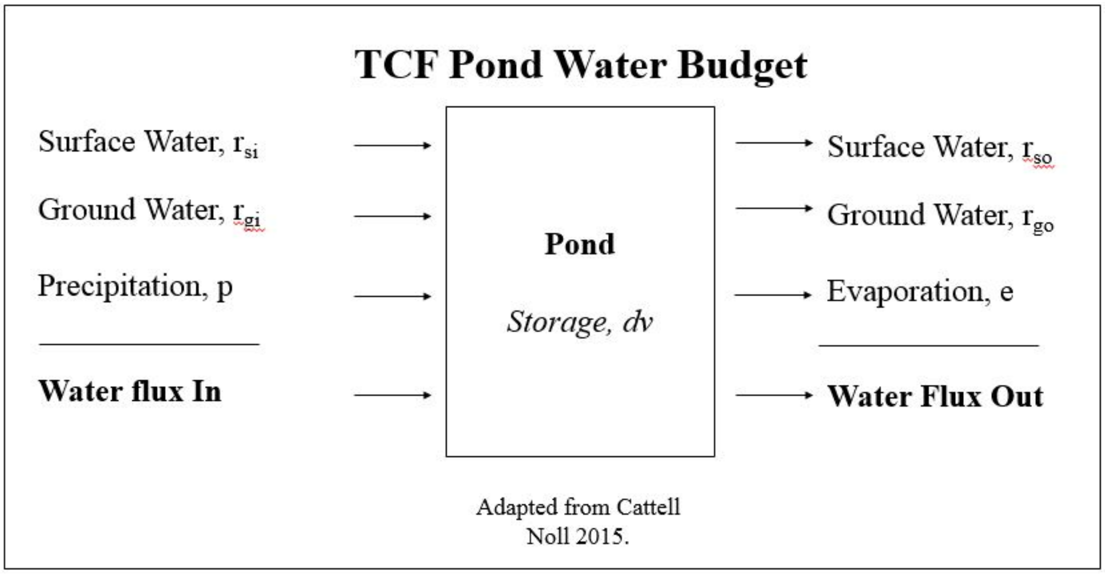


Figure 3. Water Budget for the pond adapted from the nitrogen budget in Cattell Noll 2015.

2.1 Inflows into the pond

Beginning in April 2015, the surface water inflow was measured at sampling site H at the inlet of the pond (Figure 2). Discharge was calculated from the velocity measured with a Marsh-McBirney electromagnetic current meter and from width and depth measurements made with a meter stick according to the method of Rantz et. al (1982). Discharge is determined as

$$Q = \sum_{i=1}^{N} U_1 \times w_i \times z_1 , \qquad (2)$$

where Q is the discharge, U_i is the current velocity, w_i is the width of the measurement section, and z_i is the mid-depth of that section. In order to calculate discharge using the mid-section velocity method (Equation 2), 2-4 measuremnets across the cross-section of the streams were made (Department of Environmental Sciences, 2015). Beginning in July, 2015, a pressure transducer was installed in a stilling well at the inflow site to measure the water depth (stage) at that location. Measurements of stage were made at 6 min. (0.1 hr) intervals. The transducer data were converted to discharge through a rating curve, which was established using the transducer stage readings and point discharge measurements.

To calculate the direct precipitation into the pond, daily rainfall data were obtained from the Charlottesville-Albemarle airport (10.6 km away). The surface area of the pond was determined with ArcGIS to allow scaling of the rain over the entire pond surface. The precipitation input to the pond is represented by p in Equations 1 and 6. Comparisons to on-site data from a rain gauge located at the evaporation pan were made to assess the differences in recorded precipitation between the airport and the study site. Direct surface runoff from precipitation into the pond was not entered in the calculation because I assumed that overland flow was negligible, and that any other rain inflow would be part of the groundwater inflow.

2.2 *Outflows from the pond*

Stream outflow was calculated using the same method as the inflow. The data were obtained from bi-weekly discharge measurements at site J (Figure 1) with the current meter.

Evaporation from April 2015 to April 2016 was estimated by the Hamon method using the total precipitation, temperature, saturation vapor pressure, and length of day (Hamon, 1963, NOAA and US Naval Observatory, 2015). The results were then adjusted to a weekly time scale to generate e in Equation 1. The equation is determined as

$$PET_H = 29.8D\left(\frac{e_a^*(T_a)}{T_a+273.2}\right) \tag{3}$$

where PET_H is potential evapotranspiration (which was taken to be the evaporation from the pond surface), D is day length, $e_a^*(T_a)$ is the saturation vapor pressure corresponding to the average daily temperature and T_a is the daily mean temperature (Hamon, 1963). The saturation vapor pressure at the mean daily temperature was determined using the Clausius-Clapeyron Equation:

$$ln\left(\frac{e_s}{6.11}\right) = \frac{M_V L_{1\to2}}{R^*}\left(\frac{1}{273} - \frac{1}{T}\right) \tag{4}$$

where e_s is the saturation vapor pressure, M_V is the molecular weight of water vapor, R^* is the water vapor gas constant, $L_{1\to2}$ is the latent heat of vaporization and T is the temperature in K (Trewartha and Horn, 1980). Starting in October 2015, evaporation was measured via an evaporation pan that was checked on a weekly timescale and is represented by e in Equation 6. Pan evaporation is calculated as

$$e = \Delta h_{pan} + p, \tag{5}$$

where e is the pan evaporation in centimeters, Δh_{pan} is the change in height of the water surface in the evaporation pan in centimeters and p is the precipitation in centimeters. Using a hook gauge, the change in depth from the top of the stilling well to the water surface was measured on a bi-weekly basis. A rain gauge attached to the evaporation pan provided the precipitation data, and the water level and precipitation data were used to calculate the amount of pan evaporation through Equation 5. When the water level was too high or too low due to precipitation or evaporation, water was added or removed to keep the water level within the mid-range volume capacity of the pan to allow room for additional evaporation or rainfall. This change to the water level was recorded and accounted for in the calculations.

2.2.1 Groundwater flux

The final part of Equation 1, is the net groundwater flux (r_{go}-r_{gi}). This flux was not measured directly, rather it was calculated by difference. Because each of the other components of the budget was measured, imbalances in the overall water budget for the pond were assumed to be the net groundwater flux (Equation 6)

$$r_{go} - r_{gi} = p + r_{si} - r_{so} - et \pm dv/dt \tag{6}$$

2.3 Storage of water in the pond

Pond volume was estimated by creating a bathymetric map in ArcGIS to calculate volume given the water surface elevation at a particular time. The bottom profile and the water surface elevation were set relative to a single datum located at site B. The bottom profile was determined with a sounding line cast from a small boat at 62 GPS-located points in the pond. The depth of water at each point was then set relative to the permanent datum. Using the depth data from the day that the datum was at forty-six centimeters, the volume of the pond was calculated. The weekly measurements of the pond water level relative to the datum, was used to scale the pond volume to see how the different inputs and outputs of the water budget affected the pond volume through a calculation in ArcGIS based on elevation.

Table 1. The pond inputs and outputs and the approach to collecting each contributing factor.

Variable	Approach
Inputs	
Surface Flow	Measured in the inflow stream using the velocity-discharge method (Rantz, 1982) (m^3/week).
Groundwater Inflow	Calculated by difference with the water balance equation based upon an estimation of net impact with groundwater outflow (m^3/week).
Precipitation	Precipitation from the Charlottesville-Albemarle Airport multiplied by the surface area of the pond determined with GIS (m^3/week).
Storage Volume	Determined using a basin-filling model (ArcGIS) from water depth soundings made at 62 points located in XY space with a GPS unit. (m^3)
Outputs	
Stream Flow	Measured in the inflow stream using the velocity-discharge method (Rantz, 1982) (m^3/week).
Groundwater	Calculated by difference with the water balance equation based upon an estimation of net impact with the groundwater inflow (m^3/week).
Evaporation	Calculate using meterological data from the Charlottesville-Albemarle Airport, the Hamon equation and the Clausius-Clapeyron equation (m^3/week).

2.4 Rating curve

The stage-discharge relationship at the inflow and outflow sites was used to rate the pressure transducers and to provide a continuous (0.1 hr interval) discharge record. The rating curve was created using the flow-meter-based discharge readings taken bi-weekly and the coordinating stage data at that time for the period starting when the stilling wells were first introduced on July 9, 2015 until the end of the sampling period on April 4, 2016. The stage-discharge data were modeled with a best-fit line, and the parameters of the resulting equation were used to convert the stage readings from the transducers to discharge values. The discharge values were then compared to the bi-weekly readings.

3. **Results**

3.1 Inputs and outputs

Stream discharge data for the inflow and outflow sites were collected on thirty dates from April 2015 to April 2016. Surface-water flux showed a strong seasonal pattern with decreased stream flow during the summer, and discharge increased during the fall and spring (Figure 4). In

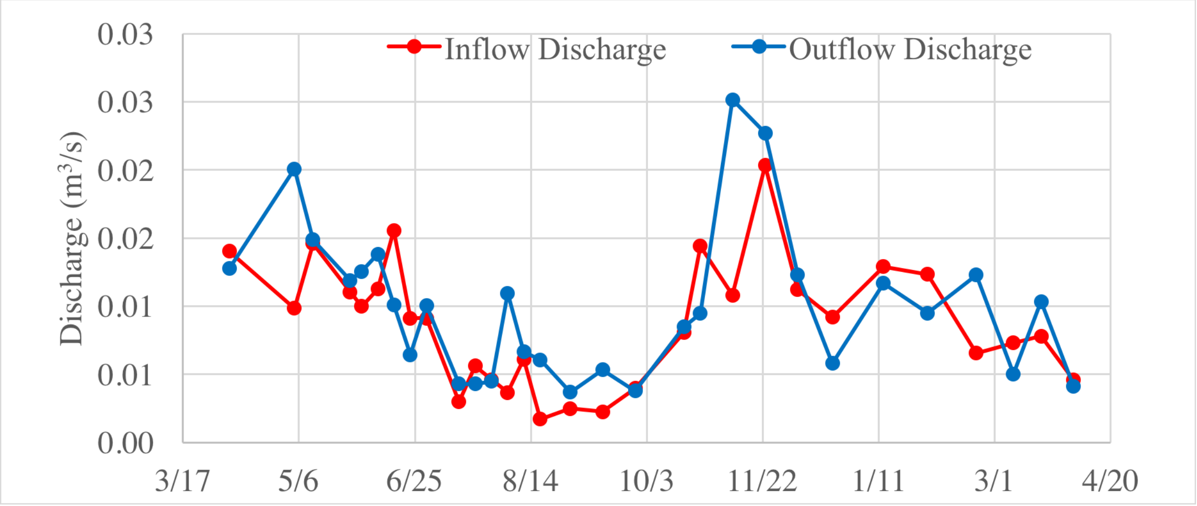


Figure 4. Stream discharge for the inflow site (H) and the outflow site (J) for the period between April 6, 2015 and April 4, 2016.

general, the inflow and outflow matched well, although at some points, outflow exceeded inflow by a substantial amount (e.g., 5/4, 8/4, 11/9 and 2/22). The overall surface water inflow over the year was 1.59 x 10^5 m^3/year, while the overall surface water outflow was 1.81 x 10^5 m^3/year.

Each week at TCF, I recorded the amount of water in the rain gauge. Precipitation values downloaded from NOAA for the Charlottesville-Albemarle airport were summed for each week that sampling occurred and included in the water flux into the pond. When considered on a monthly timescale over the year from April 2015 to April 2016, the data varied over time but followed no seasonal trend (Figure 5). Precipitation data from the airport had a moderate correlation (r^2=.45) to the precipitation data gathered from the rain gauge at the farm (Figure 6a). When excluding the summer months (which commonly have higher variability in storm intensity) (data points from April 2015, and then October 2015-April 2016), the data displayed a stronger, correlation (r^2=.69) and a closer relation to the 1:1 line (Figure 6b).

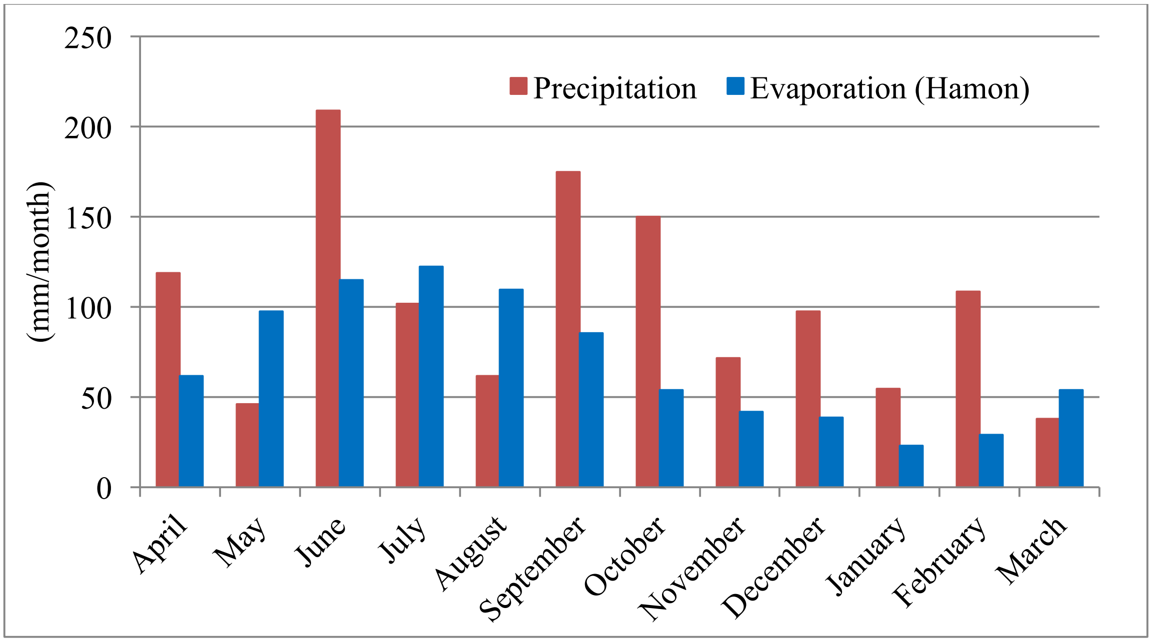


Figure 5. The average monthly precipitation (red) and Hamon evaporation (blue) shown from April 2015 through March 2016 in millimeters per month.

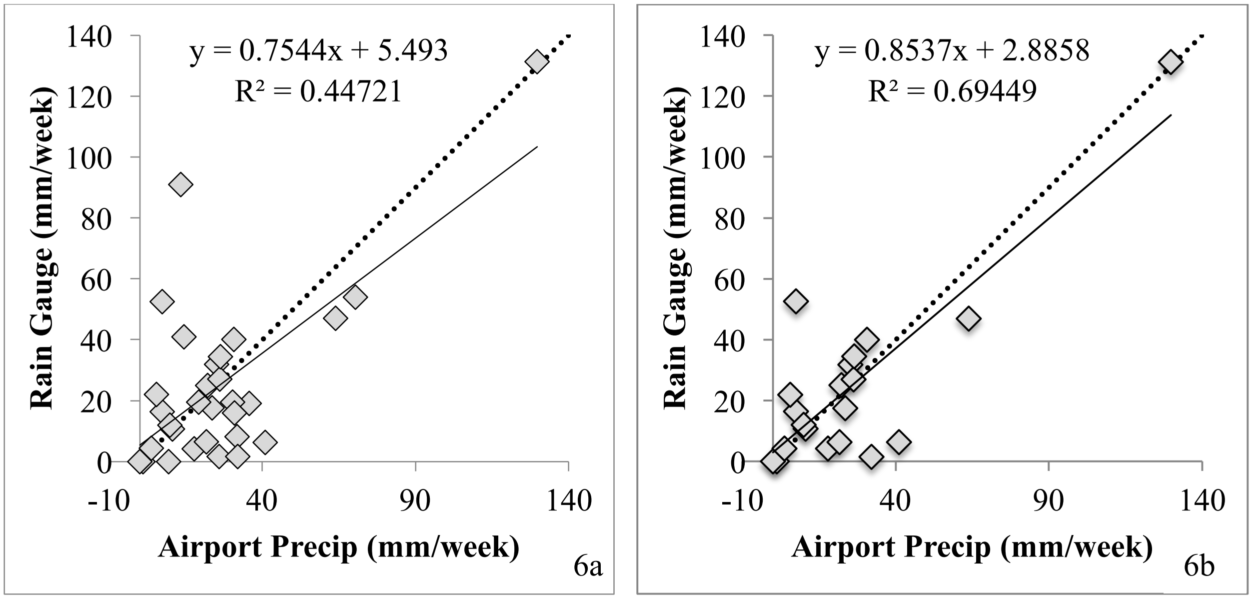


Figure 6. A comparison of site rain gauge data to the reported precipitation data at the Charlottesville-Albemarle Airport. Figure 5a depicts the comparison from April 2015 to April 2016. Figure 6b depicts the same data from April 2015 to April 2016 excluding May-September due to the more variable high intensity storms during summer months.

Evaporation data from the Hamon method followed the expectation that the potential evapotranspiration was higher over the summer and lower in the winter (Figure 5). The estimates of the- evaporation from the Hamon method were found to be similar to the estimates from the evaporation pan, however, no correlation was found between the data (r^2=0.015) (Figure 7). When compared to a 1:1 line, the two methods show no agreement with a slope approaching 0.

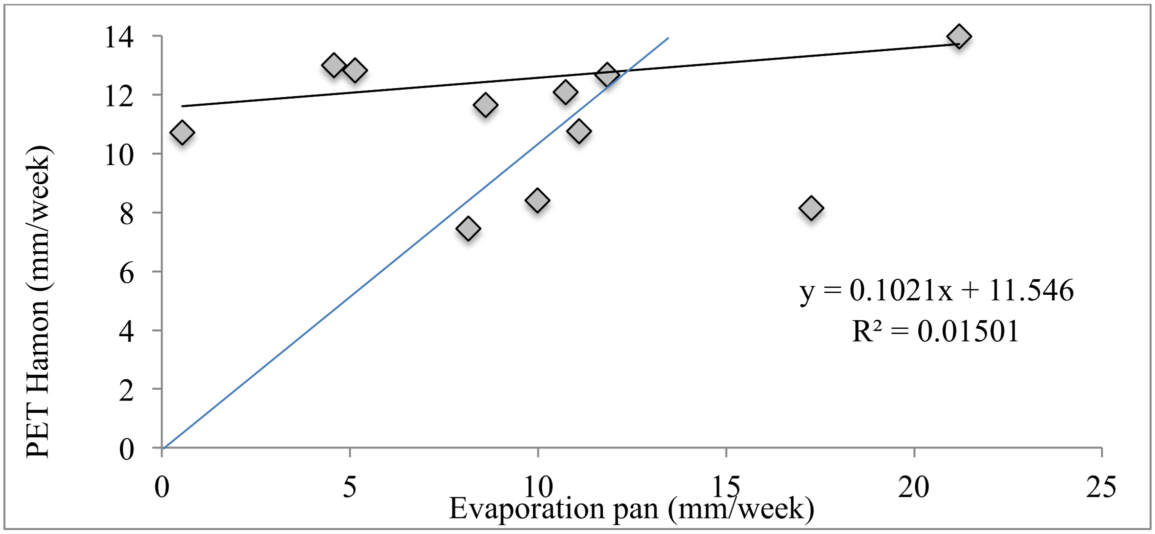


Figure 7. The Hamon calculation for evaporation uses data from the Charlottesville-Albemarle Airport. The evaporation pan measurements are from an onsite evaporation pan at TCF.

Total water flux mirrored the stream water flux both in and out of the pond. Both inflow and outflow showed a seasonal pattern of higher stream flow during the spring and fall (Figure 8). When plotted against each other, the water inputs and outputs showed strong agreement (Figure 9). The total water inputs to the pond were 1.64 × 10^5 m^3/year, and the total outflow was 1.84 × 10^5 m^3/year, yielding a difference of 2.0 × 10^4 m^3/year. Thus outflow exceed inflow by 11% (Figure 10). In the water budget, precipitation directly into the pond makes up 2.5% of the water flux into the pond. The surface water inflow dominated the water flux into the pond and was 97.5% of the estimated inflow. The water flux out of the pond was 1.4% evaporation and 98.6% stream flow. Surface water fluxes in and out of the pond ranged from 1.0 × 10^3 to 1.37 × 10^4 m^3/week. Precipitation fluxes varied from 0-500 m^3/week and evaporation fluxes varied from 30-180 m^3/week (Figure 11). Precipitation and evaporation fluxes were on average 1-2 orders of magnitude smaller than the stream flow.

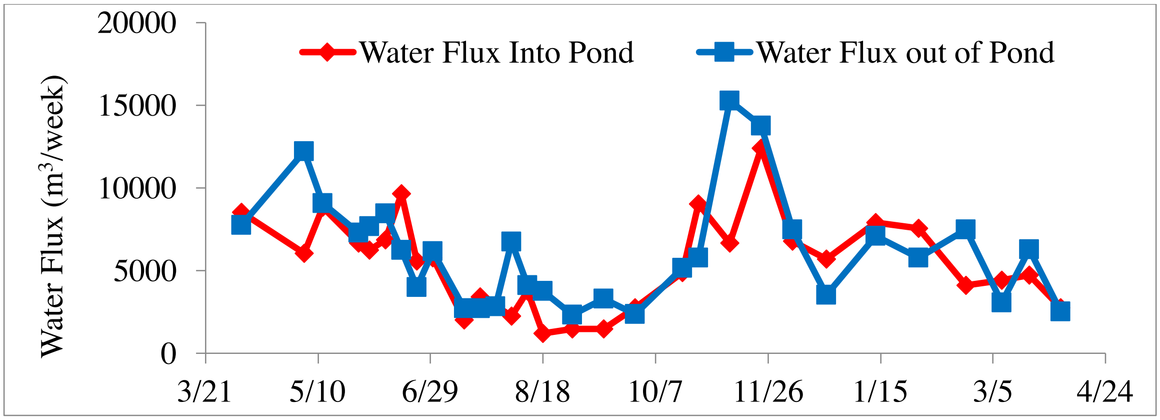


Figure 8. The water flux in (red line) and the water flux out (blue line) of the pond from April 6, 2015 to April 4, 2016 using the data from the surface flow at sites H and J, precipitation, and evaporation data.

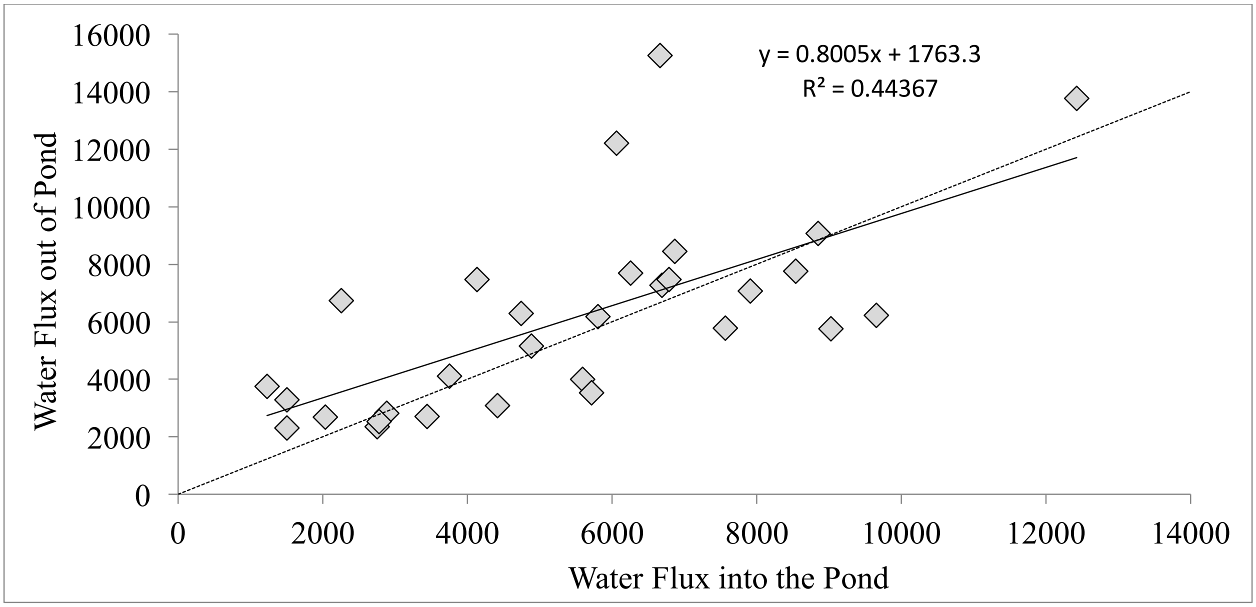


Figure 9. The relation between water flux into and out of the pond as compared to a 1:1 line shows that the water flux out of the pond is higher than the water flux into the pond.

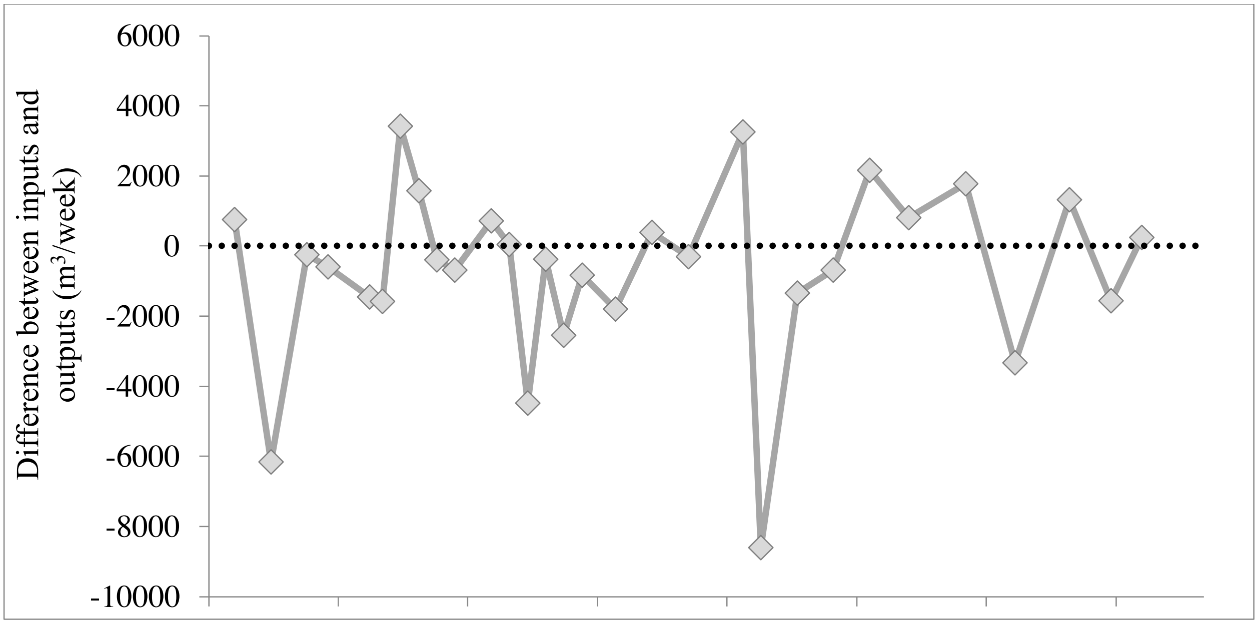


Figure 10. The difference between the water inputs and outputs is thought to be groundwater flow. The points below the dashed line indicate that more water is leaving the pond than entering. Throughout the period between April 2015 and 2016, 11% more water left the pond than entered it through the stream at site H.

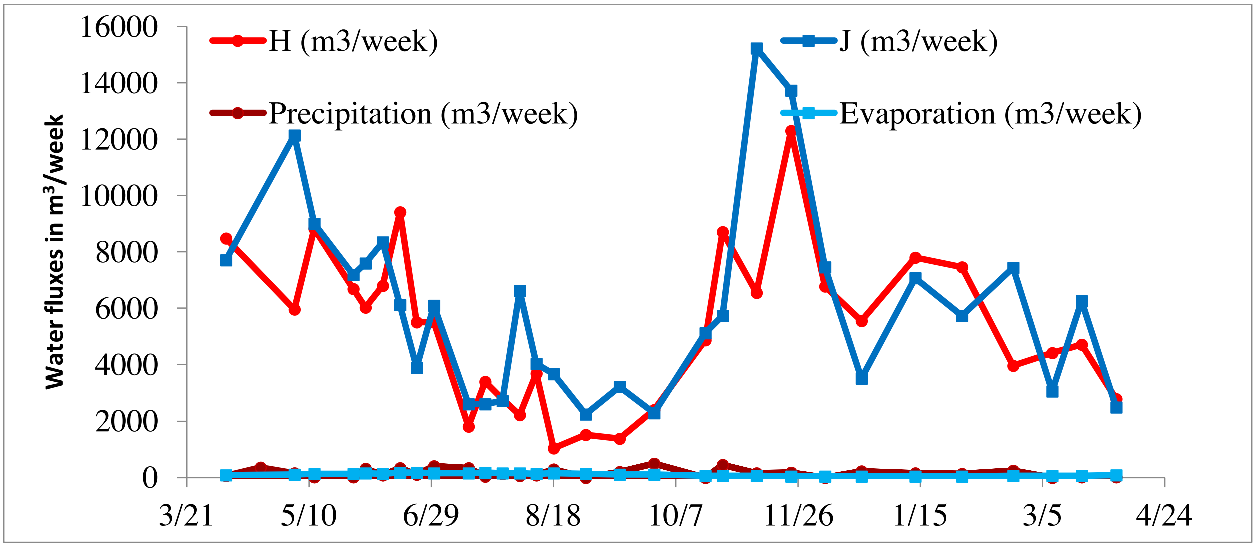


Figure 11. The composition of water fluxes to and from the pond at Timbercreek Farm. The red components represent inputs to the pond, and the blue components are the outputs from the pond.

3.2 Storage Volume of the Pond

The volume and the surface area of the pond was calculated using the water depths collected on October 6, 2015. They were to 6820 m^3 and 6380 m^2, respectively. The overall average depth of the pond was 1.1 meters with a range from .2 meters to 2.7 meters (Figure 12). Using the different volumes found using the calculations in ArcGIS based off the changing elevation of the datum, the difference in volume of the pond remained within the same order of magnitude as evaporation and precipitation during sampling except the week of March 9, 2016 where the volume of the pond cut from 7010 m^3 to 3370 m^3 (Figure 13). It is important to note that this means that the change in volume also was 1-2 orders of magnitude less than the surface water inflow and outflow.

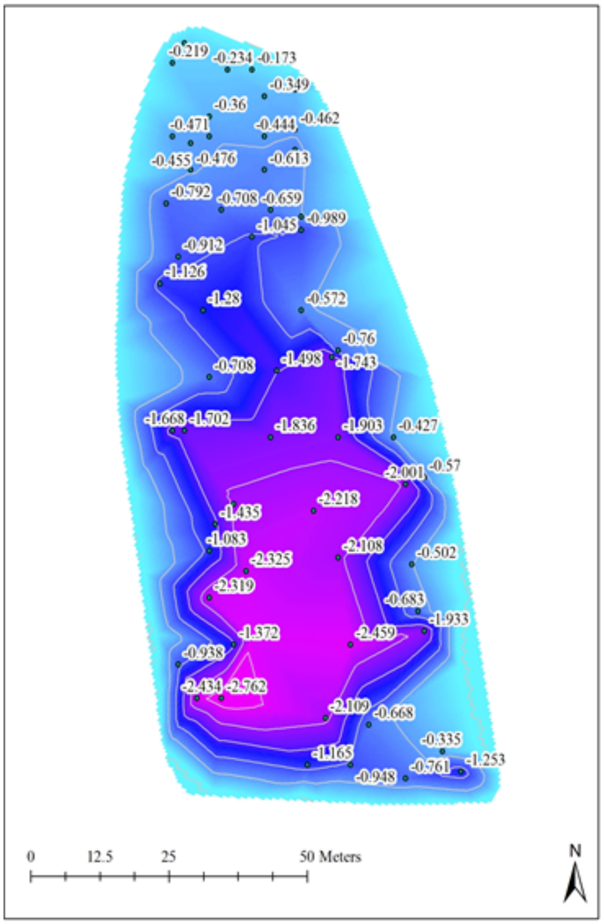


Figure 12. The bathymetric map of the pond constructed using ArcGIS and the depths for the 62 waypoints for which depth was sounded on October 6, 2015. The depths are indicated as meters below the water surface.

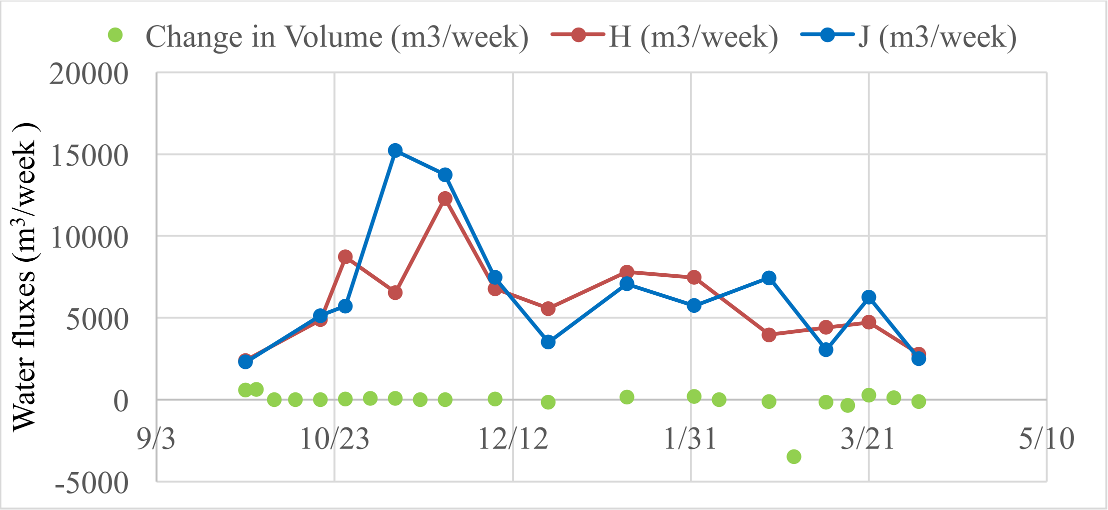


Figure 13. Pond water fluxes in terms of m^3/week from September 2015-April 2016. The red line is the surface inflow and the blue line is the surface outflow. The green line represents the weekly change in volume of the pond.

3.3 Rating Curve

The rating curve from the discharge and the stage as measured with pressure transducers at sites H and J fit best along the power function (Figure 14). The continuous discharge values calculated by using the rating curves to process stage date from the pressure transducers in place at the pond inflow (site H) and outflow (site J) were often higher than the discharge found during the bi-weekly measurement especially for the time periods between September 28 to October 19, December 22 to January 13 and February 1 to February 22 (Figure 15).

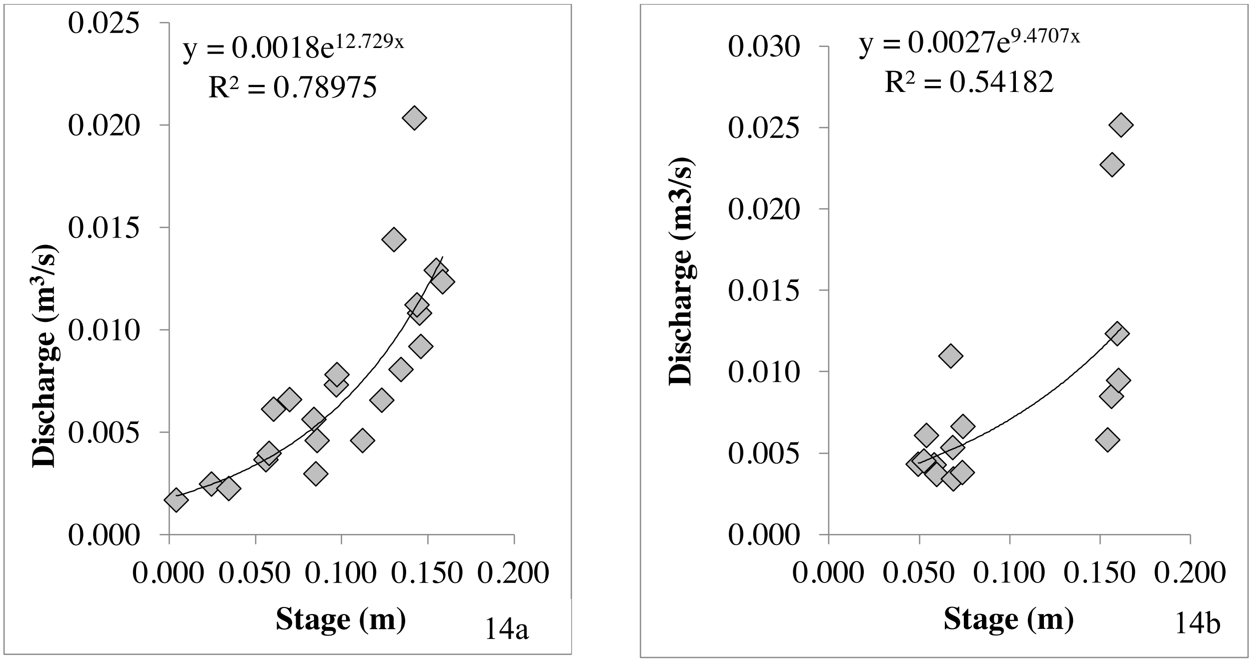
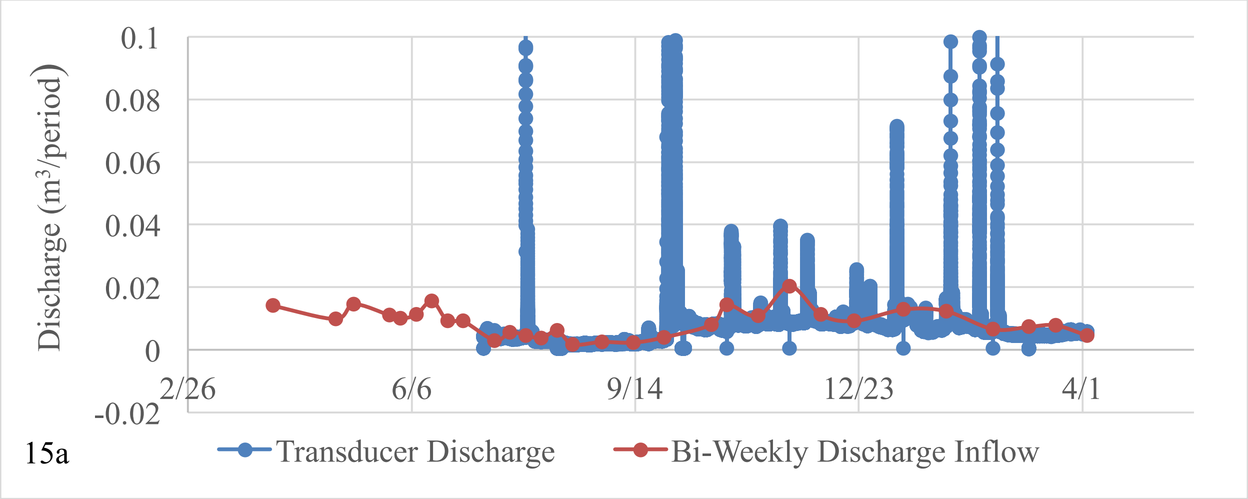
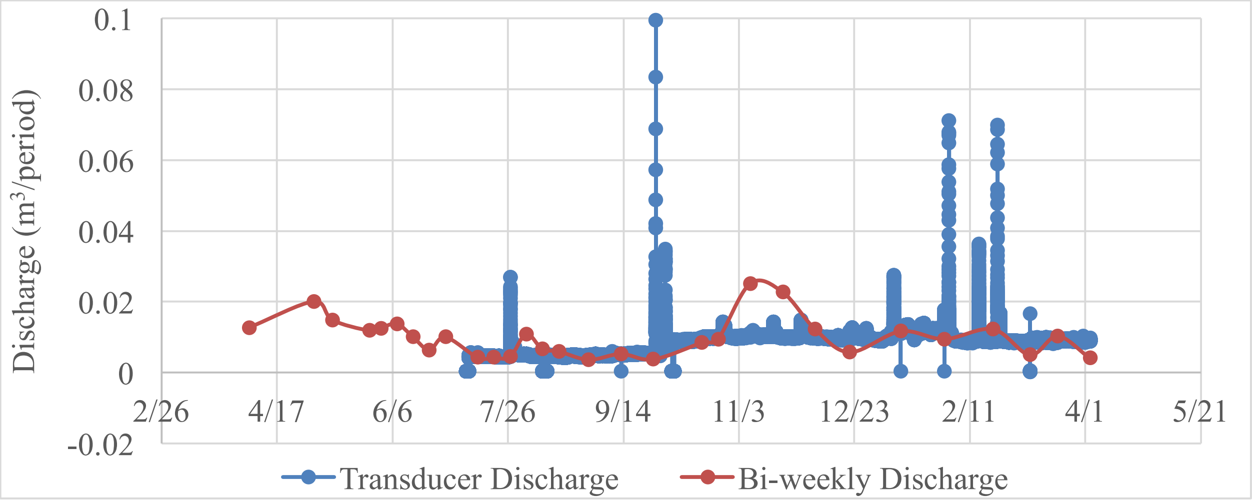


Figure 14. Using the data from the pressure transducers and the weekly discharge ratings, a rating curve was produced for the pond inflow and outflow. Site H (inflow) is depicted in 14a and site J (outflow) is depicted in 14b.





15b

Figure 15. The discharge values derived from the rating curves in Figures 14a and 14b were used to create a comparison of discharge among the bi-weekly measurements and the pressure transducer readings. Figure 15a depicts the stream inflow discharge and Figure 15b displays the stream outflow discharge.

4. Discussion

The Timbercreek Pond water budget from April 2015 to April 2016 was developed using the stream water discharge measured at sites H and J, precipitation data and evaporation data. A total of 1.64×10^5 m^3 entered the pond and 1.84×10^5 m^3 exited between April 2015 and April 2016. During this time, the total difference between the two was 2.0×10^4 m^3, which means that more water left the pond than entered over that year. One possible explanation is that groundwater inputs to the pond are large. Another possibility is that there was some error in determining one or more of the other components of the water budget, or that one or more of our assumptions (i.e. overland flow being negligible) were inaccurate.

The discharge data measured during the bi-weekly measurements clearly shows that during the base flow conditions, the majority of the water transport through the pond occurs through the surface flow (Figure 11). Using the discharge data and the volume of the pond, the average

15b

residence time of the pond is approximately two weeks (the rate of which is mainly determined by the surface water flux). This supports the hypothesis that the main transport of water into and out of the pond is through surface water flow and suggests that the surface water flux has the most significant role in determining the nitrogen flux into the pond. In addressing the nitrogen problem, it is important to understand the water budget in order to examine the N budget through the pond. Understanding both the water and nitrogen flux is key to understanding the sustainability of the agricultural practices of the farm.

The discharge showed a downward trend throughout the summer (Figure 4). One explanation for this is the increased evaporation during the summer months (Figure 7). However, the fact that evaporation only makes up 1.4% of the water flux out of the system makes this unlikely. Another possible explanation is that an increased amount of water was leaving the watershed through evapotranspiration during the summer. With the increased amount of plant growth during the summer, more water will be taken up by the roots (most of which is transpired back to the atmosphere) from the groundwater. Thus, enhanced ET in the summer could contribute to a significant decrease in both the water entering and leaving the pond through the stream at sites H and J. Since groundwater contributes to stream water base flow, if more precipitation goes towards evapotranspiration, then less reaches groundwater or eventually stream flow.

The precipitation data from the Charlottesville-Albemarle Airport showed a strong correlation (r^2=.69) with the rain gauge data during the spring, fall, and winter months and demonstrated its ability to replace the on-site data during these months if the on-site data are not available. During the summer months, on-site data should preferably be used in order to catch the localized rain storms produced through convective precipitation (Trewartha and Horn, 1980).

The data obtained thus far from the evaporation pan indicates that there is no correlation between the results produced by the Hamon method and the data recorded from Timbercreek Farm, therefore, I propose the continued use of the Hamon method for estimation because it provides reasonable estimates based off of precipitation, temperature, saturation vapor pressure, and the length of day (Figure 7).

The amount of excess outflow (over inflow) for the period from April 2015 to April 2016 was approximately 11% of the inflow (Figure 10). Evapotranspiration might affect the total discharge to and from the pond, but it should not affect the measured differential in inflow versus outflow. The other possible source of the excess outflow water is inputs to the pond from groundwater. As the volume of the pond remained relatively constant over the study period (except for the obvious decrease in volume when the standpipe broke, thus lowering the water level in the pond), the difference might partially be accounted for by assuming that enough groundwater entered the pond to make up the excess outflow. Given that the pond is at the bottom of a steep grade (an elevation difference of about 21 meters from the surface of the pond to the top of the adjacent hillslope), there could be a substantial groundwater flow to the pond from the adjacent upland. A quick calculation, that requires several assumptions, can increase confidence in the conclusion that groundwater inputs to the pond account for much if not all of the 11% excess outflow. If it is assumed that the values of evapotranspiration computed with Hamon's method can be extrapolated to the upland area, and further assuming the precipitation values reported, along with the results of the Hamon-method calculation, in Figure 4 apply to the entire watershed, then the amount of water not evaporated or transpired, i.e., available as overland flow or groundwater flow, can be estimated. Summing the precipitation for the year from the data in Figure 4 yields approximately 1.236 meters of precipitation in that year. By observation, the ET reported is on the order of 50% of the precipitation, leaving 0.618 meters of precipitation to surface and subsurface flow. For simplicity, I will assume no overland flow, and route all the water through the subsurface (groundwater), although for purposes of balancing the budget, either flow is acceptable. From digitizing a topographic map of the area, the portion of the watershed that discharges directly to the pond mostly by way of the steep adjacent slope is approximately 28,700 m^2. When multiplied by the depth of precipitation minus ET to yield the volume of water for groundwater flow, the result is approximately 17,000 m^3. With this crude approximation, reasonably good correspondence with the excess outflow is obtained, in support of groundwater (with some overland flow) as making up the difference in the budget.

4.1 Potential Improvements and Further Research

A problem during the project was the reliability of the equipment and the availability. This thesis depended heavily on the use of the Marsh McBirney flow meter, the pressure transducers, the depth finder, the rain gauge, the evaporation pan, and the hook gauge all working properly. In the beginning of the September, the Marsh McBirney flow meter kept listing negative velocity readings for many of the sites. We tested the flow meter against several other flow meters and we determined that it was not properly calibrated and from then on used a different flow meter from the SWAS laboratory.

Further research, can expand upon the knowledge of water transport through the pond through the nitrogen budget. Applying this data on a multiple year scale would be the next step to understanding the nitrogen flux through the pond and on a larger scale throughout the entire watershed of Timbercreek Farm.

5. Acknowledgements

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