Quantifying Water Budgets to Evaluate the Hydrologic Performance of Two Stormwater Detention Ponds in Coastal South Carolina

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Abstract

Due to their ability to reduce local flooding and protect receiving waters from intense stormwater pulses, stormwater detention ponds are commonly used stormwater management practices. Stormwater engineers construct ponds to moderate peak flow intensities and to allow residence time of the water within the pond to enhance nutrient removal prior to discharging into downstream ecosystems. Yet rarely, if ever, is the functionality of these ponds verified post-construction. This study aimed to compare hydrologic performance of two stormwater detention ponds located in coastal South Carolina to theoretical design plans by assessing a high resolution water budget. Inflow components of the water budget include surface inflow (sheetflow runoff and engineered drainage networks), groundwater inflow, and direct precipitation. Outflow components include evaporation, surface outflow, and irrigation withdrawal (for the pond located at Cold Stream Cove). Interactions between groundwater and pond water are an important, yet often oversimplified component of water budgets due to their temporal and spatial complexities. We use naturally occurring ^{222}Rn as a tracer to constrain groundwater inputs to the ponds due to its high concentration in groundwater compared to receiving surface waters (often 2-4 orders of magnitude). During rain events, groundwater contributions are minimal in comparison to surface water contributions. However, over the course of the entire study, groundwater represented 4% of all water inputs to the pond at Cold Stream Cove and 30% of all water inputs to the pond at Summerall Oaks. This indicates volumetric contributions are certainly significant. Additionally, runoff generated from rain events showed a correlation to water table height, further emphasizing the importance in understanding groundwater contributions to stormwater ponds. The two studied ponds were designed under the same management regulations but each contains unique characteristics (e.g., weir designs, impervious coverage percentages, topography, pumping for irrigation) by which they respond differently to rain events. We found that the design manuals for both ponds underestimated the inflow values for our monitored rain events, implying the design plans may be significantly underestimating inflow values associated with the rain events after which they were modeled. This may result in the ponds containing post-development discharge values higher than pre-development discharge values for large-scale events.

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Introduction

Coastal areas provide amenities such as employment, recreation, tourism, commerce, energy, and natural resource production. As a result, they are experiencing significant pressure from population growth. Coastal counties represent 17% of the nation's total land area, but in 2003, they accounted for more than half of the population. As a result, coastal counties contain densities more than five times those in the interior of the country (Beach, 2002). This rate continues to rise as southeastern coastal counties alone have experienced a growth of 58% since 1980 (Crossett et al., 2004). Specifically, over the last decade, South Carolina's population has increased by 15%, with coastal Horry County (which contains the urban center to Myrtle Beach and surrounding areas) experiencing residential population growth at more than twice this rate, more than any other county within the state of South Carolina (US Census Bureau, 2010).

Urban development radically alters natural hydrology patterns, with many natural elements having been replaced and altered by man-made facilities. Increased population density leads to greater areas of impervious surfaces (e.g., parking lots, roadways, and rooftops) which can have a significant impact on the flow intensity, runoff magnitude, and timing of stormwater transfer to receiving waters (Hancock et al., 2010). Runoff from these impervious surfaces can be up to 16 times higher than that from natural, more pervious areas (Schueler, 1994). This poses a significant challenge to stormwater managers to store the flood volume that runs off these impervious surfaces and mitigate the impact of terrestrial and human-induced pollutants on downstream receiving ecosystems.

To meet this critical need, managers often employ the use of stormwater ponds, which are intended to intercept, receive, and detain hydrologic flow before discharging into downstream receiving waters. This allows time for natural attenuation processes to clean the water before releasing the flood pulse through conveyance systems (e.g., pipes, culverts, and ditches) to the coastal ocean. Stormwater ponds provide several amenities including flood control, pollutant removal, increased property value, recreational amenities, enhanced aesthetics, wildlife habitat, and irrigation for local golf courses and residential landscaping. Within South Carolina alone, Siewicki et al. (2007) reported there to have been 8,114 stormwater ponds at the time of their study, with this number increasing at an annual rate of 13%. The high population density within Horry County contributed to this area containing the highest density of residential stormwater ponds within South Carolina's coastal zone (U.S. Census Bureau, 2010).

There are three main types of stormwater ponds: (1) wet detention ponds, which contain a permanent pool of water designed to store stormwater temporarily before being discharged into surrounding water bodies; (2) dry detention ponds, which contain a temporary pool of water designed to store stormwater before being discharged into surrounding water bodies; and (3) retention ponds, which contain a pool of water used for stormwater storage with no discharge. Wet detention ponds are the most commonly used stormwater pond. The permanent pool prevents resuspension of trapped sediments, with optimal depths being between one and three meters (US EPA, 1999). Wet detention ponds must be constructed in areas with sufficient precipitation to maintain the pool of water. Highly permeable soils may be compacted or overlain with clay blankets to prevent infiltration from draining the reservoir. Typically, soils with permeabilities between 10^{-5} and 10^{-6} cm/sec are adequate to prevent substantial infiltration, in which case runoff is detained in the pool until being displaced from the next storm event (US EPA, 1999).

Regulations stipulate stormwater ponds must have post-construction runoff rates equal to or less than pre-construction runoff rates. Wet detention ponds are also designed to store and release a minimum of one-half inch (1.3 cm) of runoff from the drainage basin over a 24-hour period (Code of Ordinances, 1985; SC DHEC, 2002). Generally, stormwater management practices advise controlling two to four cm of rainfall and remove 85% of total suspended solids (Weinstein et al., 2008). Stormwater ponds are commonly used due to their ability to reduce local flooding and protect receiving waters from intense stormwater pulses.

Stormwater ponds provide improvements to water quality by natural physical, biological, and chemical processes. Pollutants such as dissolved metals and nutrients are removed by algal uptake, photosynthesis, and bacterial decomposition. The removal efficiency of a pond is primarily dependent upon the pond's hydraulic residence time (HRT): the average time a water molecule resides in a reservoir before being transferred to another reservoir (Fitts, 2013). Stormwater engineers construct ponds based on theoretical plans to moderate peak flow intensities and to allow residence time of the water within the pond to enhance pollutant removal (Starzec, 2005), but rarely, if ever, do they confirm the design actually performs as planned.

Stormwater ponds are often constrained in possible layouts and design considerations based on the available natural and human-influenced terrain. This may lead to stormwater ponds being constructed in dimensions and locations which are less than ideal for their hydraulic intentions (Wong, 1999). If improperly maintained or designed, stormwater ponds may have low HRT's and potentially adverse effects on water quality conditions, despite their theoretical design parameters. In these occasions, they can accumulate large masses of algae, become sites for fish kills, accumulate debris, and exhibit high concentrations of nutrients, bacteria, and chemical contaminants.

By determining the water budget for a pond over time, an evaluation of the hydraulic effectiveness can be determined, and therefore the operational effectiveness can be compared to the theoretical design plans. A water budget is an accurate accounting of all water inflow and outflow components that result in a net change in water volume over time. Inflow components can consist of surface inflow (from sheetflow runoff and engineered drainage networks), groundwater inflow, and direct precipitation to the pond. Outflow components can consist of surface outflow, evapotranspiration, pumping for irrigational purposes, and recharge to terrestrial aquifers.

Interactions between groundwater and pond water are an important, yet often ignored, component of water budget estimations. Schueler (2000) found that two stormwater ponds in Florida received 38% and 47% of their water budgets from groundwater. Additionally, Dimova et al. (2013) showed that five of seven studied Florida lakes contained high to moderate groundwater inflow. In areas with high water tables, such as the coastal plain of South Carolina, groundwater often interacts with surface water and can be a significant factor in hydrologic budgets; yet due to temporal and spatial complexities, groundwater inputs are often overlooked or oversimplified. Technologies have emerged to now allow a more quantitative measure of groundwater inputs to surface bodies. Naturally-occurring ^{222}Rn (radon, half life=3.8 days) has been identified as an ideal natural tracer of groundwater discharge, due to its high concentration in groundwater relative to receiving surface waters (often 2-4 orders of magnitude). ^{222}Rn is also ideal because it is chemically conservative, so remains unaffected by biological and chemical processes. Corbett et al. (1997) concluded that a water balance of a simple system with limited inflows and outflows benefits from application of ^{222}Rn within the water budget.

Due to the scarcity of field-based evaluations of stormwater pond performance, we aimed to assess the hydrologic performance of two stormwater detention ponds by calculating and examining high resolution annual water budgets. Doing so provides source-specific quantification of input and output variabilities associated with changing rainfall and water table conditions. These objectives are part of a larger on-going South Carolina Sea Grant Consortium project designed to provide resource managers and engineering professionals critical information with respect to both pond hydrology and pond performance regarding nutrients, sediments, and bacteria remediation potential. This will provide insight regarding the extent to which stormwater ponds within coastal South Carolina aid in protecting coastal water quality.

Methods

Study Sites

Two stormwater ponds in Horry County, South Carolina were selected for this study based on varying degrees of development within their drainage basins (Figure 1). Summerall Oaks (33°36'15.23"N 79° 1'13.84"W) and Cold Stream Cove (33°35'12.96"N 79° 3'59.34"W) are residential neighborhoods that contain stormwater detention ponds. These ponds were chosen in collaboration with the Horry County Stormwater Department, Horry County Watershed Planner, and Horry County Stormwater Engineers.

Cold Stream Cove is a multi-family condominium (high-density) development (Figure 1A). The pond within this development has a perimeter of 245 m and contains a six-unit building adjacent to the northeastern side of the pond. The drainage basin (44,560 m^2) of the pond at Cold Stream Cove contains 62% impervious surface cover and 8.5% pond coverage. This pond also contains a surface water fountain and irrigation pumps, components of many residential ponds for visual and practical purposes. A 62,000 m^2 wetland complex lies adjacent to this pond on the west side. Summerall Oaks is a standard, single family (medium-density) development (Figure 1B). The stormwater pond within this development has a perimeter of 193 m and is surrounded by 17 single family homes. The total drainage basin (46,420 m^2) of this pond consists of 44% impervious surface cover, with the pond comprising 4.3% of the drainage basin. Both ponds contain single outlet structures regulated by weirs and discharge into Collins Creek which ultimately connects to the Waccamaw River.

Research Approach

Our approach to constraining the hydrologic water budget of these stormwater detention ponds involves constructing a continuous water budget at 30 minute intervals from April 2014 through June 2015. Our water budget assesses the change in pond volume over time, as a function of the various inputs (surface inflow, groundwater inflow, direct precipitation) and outputs (surface outflow, evaporation, and recharge to the terrestrial aquifer) (Figure 2). This water budget is expressed as:

$$\Delta V = I_s + I_g + P - O_s - E - O_g \tag{1}$$

where ΔV is the change in pond volume, I_s is surface inflow, I_g is groundwater inflow, P is direct precipitation, O_s is surface outflow, E is evaporation, and O_g is recharge to the terrestrial aquifer (Figure 2). We measure or quantify all parameters of Eq. 1 except for I_s, which we solve for by rearranging to:

$$I_s = \Delta V - I_g - P + O_s + E + O_g \tag{2}$$

We assume water table heights to be consistently elevated above the pond surfaces, indicating the groundwater hydraulic gradient was into the pond. Thus, we do not consider any recharge of pond volume to the local aquifer, so the term (O_g) is neglected in our water budget. Below, we discuss how each parameter of the water budget (Eq. 2) is measured.

Pond Volume

To calculate the total volume of the studied ponds, we conducted a bathymetric survey using single beam sonar and Real Time Kinematic (RTK) Global Positioning System (GPS). Based on the resulting three-dimensional digital elevation model of the bathymetry for each pond, the Triangulated Irregular Networks (TIN) to level model in HYPACK was used to compute pond volumes across a range of water levels. A linear regression relates the pond water elevation to the volume of the pond (Figure 3). HOBO Water Level Loggers (Onset Corp.) were deployed at constant elevations in each pond and continuously monitored water levels (5 minute intervals). Using the linear regression (Figure 3), pond volumes were calculated for each measured water level. Change in pond volume (ΔV; Eq. 2) was then calculated as the change in pond volume between each set of contiguous water level measurements.

Groundwater Inputs

Concentrations of ^{222}Rn in groundwater are often orders of magnitude higher than surrounding surface waters. This difference makes ^{222}Rn an ideal tracer for quantifying groundwater discharge. We used the geochemical tracer ^{222}Rn as a proxy for groundwater inputs by continuously monitoring radon activities in the pond to use in a box model accounting for sources and sinks of radon (Corbett et al., 1999; Burnett and Dulaiova, 2003; Peterson et al., 2010) (Figure 4). A RAD7 radon-in-air monitor (Durridge Co.) was installed in each pond near the outlet weirs. These RAD7s were connected via a closed air loop to an air-water equilibrium spray chamber (RAD-AQUA) into which pond water was constantly pumped via a submersible pump situated ~20 cm above the pond bottom (Burnett et al., 2001). The air from this exchanger was then pumped through desiccant to the RAD7 where ^{222}Rn activities were measured via alpha decays over 30 minute intervals (Burnett et al., 2001).

Groundwater inputs were quantified with a ^{222}Rn mass balance model, as per Corbett et al. (1997) and Dimova and Burnett (2011):

$$\frac{\Delta Rn_p V_p}{\Delta t} = Q_s Rn_s + \lambda Ra_p V_p + J_{benthic} + Q_{gw} Rn_{gw} - J_{atm} - Q_o Rn_p - \lambda Rn_p V_p \qquad (3)$$

where $\frac{\Delta Rn_p V_p}{\Delta t}$ represents the change in total radon activity within the pond (determined as the difference between two consecutive products of ^{222}Rn concentration in the pond [Rn_p] multiplied by pond volume [V_p] over each 30 minute interval [t]); $Q_s Rn_s$ is radon delivered via surface runoff [as radon activity in runoff water (Rn_s) multiplied by runoff volume (Q_s)]; $\lambda Ra_p V_p$ is the production of radon from its parent (^{226}Ra) dissolved in the water (where λ is the radon decay constant and Ra_p is the dissolved ^{226}Ra activity); $J_{benthic}$ accounts for diffusional inputs of radon from bottom sediments (as per Burnett et al., 2003); $Q_{gw}Rn_{gw}$ is the groundwater input [as the volume of groundwater discharge (Q_{gw}; the unknown we are solving for) multiplied by the radon concentration in discharging groundwater (Rn_{gw})]; J_{atm} accounts for the loss of radon to atmospheric degassing (as per MacIntyre et al., 1995); Q_oRn_p is radon loss from pond drainage (as pond discharge rate (Q_o) multiplied by pond radon activity (Rn_p)); and $\lambda Rn_p V_p$ is radioactive decay losses of radon (Figure 4; Table 1). Surface runoff inputs sourced from precipitation and conveyed through drainage pipes and sheetflow are assumed to contain negligible ^{222}Rn, so the Q_sRn_s term is neglected here. This equation is thus rearranged to solve for groundwater inputs:

$$Q_{gw} = \frac{\frac{\Delta Rn_p V_p}{\Delta t} - \lambda Ra_p V_p - J_{benthic} + J_{atm} + Q_o Rn_p + \lambda Rn_p V_p}{Rn_{gw}} \tag{4}$$

Ingrowth of ^{222}Rn from ^{226}Ra decay ($\lambda Ra_p V_p$) was analyzed by passing large volumes (~62 L) of pond water through acrylic fibers impregnated with MnO_2 (Moore and Reid, 1973). MnO_2 fibers adsorb ^{226}Ra which was quantified on a radon extraction line following methods outlined by Peterson et al. (2009). Multiplying the dissolved ^{226}Ra activity (dpm/m^3) by the pond volume yields the total ^{226}Ra activity in the pond. We then multiply the total ^{226}Ra activity in the pond by the ^{222}Rn decay constant (λ; 0.0038 30 min^{-1}) to quantify the ^{222}Rn production rate (dpm/30 minutes) from ^{226}Ra decay.

Diffusive inputs of ^{222}Rn from bottom sediments ($J_{benthic}$) are quantified using the empirical relationship describing diffusive input rate as a function of sedimentary ^{226}Ra ($^{226}Ra_{sed}$) activity as per Burnett et al. (2003):

$$Rn\ Diffusion\ (dpm\ m^{-2}\ day^{-1}) = 495(^{226}Ra_{sed}) + 18.2 \tag{5}$$

$^{226}Ra_{sed}$ was measured in the Environmental Radioactivity Measurement Laboratory at Florida State University via gamma spectroscopy on replicate sediment samples from each pond. The average $^{226}Ra_{sed}$ values were 1.34 dpm/g for sediments collected from the pond at Cold Stream Cove and 1.53 dpm/g for sediments collected from the pond at Summerall Oaks. These values are multiplied by the surface area of each pond (3,809 m^2 and 1,987 m^2, respectively), and converted into dpm/30 minutes, resulting in constant $J_{benthic}$ values of 5.41×10^4 dpm/30 minutes for Cold Stream Cove and 3.21×10^4 dpm/30 minutes for Summerall Oaks.

A major source of ^{222}Rn to the ponds is through groundwater discharge ($Q_{gw}Rn_{gw}$), as radon activity in the discharging groundwater (Rn_{gw}) multiplied by the groundwater inflow rate (Q_{gw}) - the component of the radon mass balance model we aim to determine. Radon activities in groundwater were measured weekly by collecting 250 mL samples directly from six 1" PVC piezometers arranged in pond-normal transects at each site. Samples were collected in glass bottles (WAT-250 system; Durridge Co.) and measured using standard RAD7 protocols. For our mass balance equation, we selected endmembers by averaging the radon activities measured weekly around each pond and applying the closest measurement in time to the water budget equation.

The radon inventory is then corrected for sinks including atmospheric evasion losses, loss of radon via water discharging over the weirs, and loss of radon via radioactive decay.

Atmospheric losses (J_{atm}) are calculated based on an air-water gas exchange equation presented by MacIntyre et al. (1995):

$$J_{atm} = K \times (Rn_p - \alpha \times Rn_a) \quad (6)$$

where K is the gas transfer coefficient, Rn_p is the ^{222}Rn concentration in the pond, α is the Ostwalds solubility coefficient, and Rn_a is the ^{222}Rn concentration in the air (assumed to be a constant 262 dpm/m^3 based on prior local measurements). The gas transfer coefficient (K) is a function of the air-water interface, particularly dependent on turbulence, water viscosity, and the molecular diffusion coefficient of radon:

$$K = {0.45 \times u^{1.6} \times \left({Sc}/{600}\right)^{-0.5}}\Big/{100} \quad (7)$$

where μ is wind speed measured by the meteorological station deployed at Summerall Oaks and Sc is the Schdmit number. The Schdmit number is a ratio of the kinematic viscosity (v) to the molecular diffusion coefficient of radon (D_m). Ostwalds solubility coefficient (α) is determined by the following temperature dependent equation:

$$\alpha = 0.105 + 0.405 \times e^{(-0.05 \times T)} \quad (8)$$

These equations are described in further detail by MacIntyre et al. (1995) and Turner et al. (1996).

Radon loss from pond discharge over the weir (Q_oRn_p) is calculated by multiplying the pond discharge rate by the radon activity within the pond. Additional ^{222}Rn losses occurred at Cold Stream Cove via the irrigation pump which ran during the summer and fall months (May through November). The water pumped out of the pond was used to irrigate both the drainage basin at Cold Stream Cove and the neighboring development. This is accounted for by multiplying the pumping rate (17.94 m^3/30 min) by the radon concentration within the pond during the hours the pump was functioning (00:00-09:30 on Mondays, Wednesdays, Fridays, and Saturdays; 00:30-3:00 on Tuesdays, Thursdays, and Sundays; dependent on rain conditions).

Finally, the radioactive decay loss of radon ($\lambda Rn_p V_p$) is calculated by multiplying the decay constant of ^{222}Rn (λ; 0.0038 30 min^{-1}) by the total radon activity in the pond (as $Rn_p V_p$).

An additional correction to the radon mass balance is applied at Cold Stream Cove where a fountain runs continuously, posing the potential to degas the water. We collected 6 L grab samples (as per Stringer and Burnett, 2004) in the pond near the fountain intake as well as the water falling from the fountain. The sprayed water was approximately three-fold lower in radon activity than the pond water, so we corrected each radon activity measured from the continuous RAD7 deployment by a factor of 2.88. We acknowledge this is a significant source of uncertainty in this pond.

Direct Precipitation

To account for direct precipitation (P) to the ponds for the water budget in Eq. 2, automated ISCO samplers and accompanying rain gauges were deployed at each study site. Local precipitation accumulation measurements allowed direct rainfall input to the pond to be calculated by multiplying the precipitation rate (m/30 min) by the pond surface area (m^2). These inputs were considered separately from precipitation-derived surface runoff volumes.

Surface Outflow

Each of these ponds was constructed with a weir to control the outflow rate and maintain a relatively constant volume of water within the ponds. The pond at Cold Stream Cove contains a broad-crested weir (Figure 5), whereas the pond at Summerall Oaks contains a combined 90^o v-notch weir (Figure 6). Discharge (Q_o) over the broad-crested weir at Cold Stream Cove was calculated per Hornberger et al. (1998) (Figure 6):

$$Q = \left(\frac{8}{27}g\right)^{1/2} h_{weir}{}^{3/2} w_c \tag{9}$$

where h_{weir} is the height of water flowing over the weir crest and w_c is the width of the weir over which the water is flowing (1.22 m at Cold Stream Cove).

Discharge (Q_o) over the combined v-notch weir at Summerall Oaks was calculated by merging the broad-crested weir equation (with w_c value of 0.36 m) with the following 90^o v-notch equation (Figure 6):

$$Q = (2.49 \times ({}^{h_{weir}}/_{0.3048})^{2.48}) \times 0.028 \tag{10}$$

where h_{weir} is the height of the water flowing over the weir (USBR, 1997). We measured h_{weir} at each weir as the elevation of water within each weir box relative to the elevation of the weir crest, monitored by elevation-corrected Onset Water Level Loggers deployed in each weir box.

The pond at Cold Stream Cove contains an additional water loss via irrigation pumping which was accounted for by considering the pump rate (17.94 m^3/ 30 min) over the times when the pump was in use.

Evaporation

The studied ponds do not contain a vegetated buffer zone, so transpirational losses from the system are not considered. A meteorological weather station was deployed at Summerall Oaks monitoring weather parameters such as air temperature, solar radiation, relative humidity, and wind velocity. Daily evaporation losses were then accounted for using Valiantzas' (2006) version of the Penman equation:

$$E = 0.051(1-0.08)R_s\sqrt{T+9.5} - 2.4\left(\frac{R_s}{R_a}\right)^2 + 0.052\,(T+20)(1-\frac{RH}{100})(1-0.38+0.54u) \quad (11)$$

where R_s is the measured solar radiation (MJ/m^2/day), R_a is extraterrestrial radiation (calculated per Valiantzas 2006), T is temperature (°C), RH is relative humidity (%), and μ is wind speed (m/s). These daily evaporation losses were converted to our 30-minute time scale by multiplying the total daily evaporation loss by the percent solar radiation over the desired 30-minute interval.

Surface Inflow

After accounting for all other parameters of the water budget, we compute the amount of surface water inflow needed to balance the water budget (Eq. 2). This surface water inflow value was broken down further into the amount of water entering the system between the inlet pipes (I_p) and sheetflow runoff (S_R):

$$I_s = I_p + S_R \quad (12)$$

Water volumes entering the system through drainage pipes (I_p) were quantified using the Manning's equation summarized by Camp (1946):

$$I_p = (1.00/n)(A)({R_h}^{2/3})(S^{1/2}) \quad (13)$$

where n is Manning's coefficient values (0.013 for the centrifugally spun concrete pipes at Summerall Oaks and 0.025 for the corrugated plastic pipe at Cold Stream Cove), A is the cross-sectional area of flow normal to the flow direction in m^2, R_h is the hydraulic radius, and S is the bottom slope channel. The hydraulic radius (R_h) was determined by dividing the wetted perimeter by the cross sectional area, where the wetted perimeter of the pipe was determined by elevation corrected HOBO loggers deployed in each pipe box (with one inlet pipe located at Cold Stream Cove and three inlet pipes located at Summerall Oaks). The bottom slope channel (S) was determined by RTK GPS survey points. Sheetflow runoff (S_R) was lastly determined by difference between total surface discharge (I_s) and the piped inputs (I_p).

Results

Here, we present the water budget of two ponds located in coastal South Carolina. The complete water budget was recorded at thirty minute intervals from May 2014 through June 2015. Both ponds average a depth of 1.4 m yet the pond at Cold Stream Cove contains a surface area nearly twice the size of the pond at Summerall Oaks (Cold Stream Cove: 3809 m^2, Summerall Oaks: 1987 m^2). The pond at Cold Stream Cove reached a maximum volume of 7,131 m^3 and a minimum volume of 4,502 m^3 throughout this period, with an average volume of 5,516 ± 321 m^3 (Table 2). The pond at Summerall Oaks reached a maximum volume of 4,397 m^3 and a minimum volume of 2,674 m^3, while averaging 2,836 ± 62.6 m^3 throughout the study (Table 2). Both ponds reached minimum volumes during summer months, particularly in June (Figure 7). The difference between the maximum and minimum pond volumes is nearly twice as high at Cold Stream Cove compared to Summerall Oaks, which is attributed to the pond at Cold Stream Cove being used as a source of irrigation, wherein water is pumped daily out of the pond at far greater rates than it is resupplied. Since Summerall Oaks does not have such an anthropogenic water removal mechanism, its minimum volume remains much more constant throughout the study.

The water input parameters measured at each site include direct precipitation, surface inflow (piped and sheetflow), and groundwater discharge. The maximum rate of rainfall during our study was 30.2 mm/30 min, with an average rain intensity across all rain events of 1.5 ± 2.9 mm/30 min. The average volumetric input of direct precipitation to the ponds throughout the entire study was 0.3 ± 2.5 m^3/30 min for Cold Stream Cove and 0.2 ± 1.1 m^3/30 min for Summerall Oaks (Table 2 and Figure 8). Over the course of our study, a total of 5,523 m^3 and 3,168 m^3 entered the ponds via direct precipitation at Cold Stream Cove and Summerall Oaks, respectively. Despite the different volumes of direct precipitation, the percent contribution of direct precipitation to the total inputs was similar at these sites (13.3% at Cold Stream Cove and 11.4% at Summerall Oaks) (Figure 9A).

Surface inflow (Figure 10), comprised of both piped inflow and sheetflow, dominated the water inputs (Figure 9A). The maximum total surface inflow rate was 867 m^3/30 min at Cold Stream Cove and 831 m^3/30 min at Summerall Oaks and occurred during a rain event on July 15^{th}, 2014 (78 mm of rain recorded at Cold Stream Cove and 89 mm of rain recorded at Summerall Oaks). The average total surface inflow rate was 1.3 ± 15.4 m^3/30 min at Cold Stream Cove and 5.3 ± 36.8 m^3/30 min at Summerall Oaks (Figure 10). There is one large pipe transferring surface inflow to the pond at Cold Stream Cove and three smaller pipes transferring surface inflow to the pond at Summerall Oaks. Using Equation 13, we calculate the amount of this total surface inflow that is transferred through engineered piped drainage systems. The maximum piped inflow rate was 478 m^3/30 min at Cold Stream Cove and 636 m^3/30 min from the three pipes at Summerall Oaks. The average piped inflow rate was 1.2 ± 14.9 m^3/30 min at Cold Stream Cove and 0.7 ± 11.3 m^3/30 min from the three pipes at Summerall Oaks (Table 2 and Figure 11). Piped inflow accounted for 63% of total inputs at Cold Stream Cove and 35% at Summerall Oaks (Figure 9A).

Sheetflow contributed a smaller portion of surface water into the reservoirs (Figure 12). Sheetflow accounted for 19% of the total water inputs to Cold Stream Cove and 24% of the total water inputs in Summerall Oaks (Figure 9A). The maximum sheetflow rate was 428 m^3/30 min at Cold Stream Cove and 621 m^3/30 min at Summerall Oaks. The average sheetflow rate was 0.38 ± 4.45 m^3/30 min at Cold Stream Cove and 1.67 ± 22.21 m^3/30 min at Summerall Oaks (Table 2 and Figure 12). The higher contribution of sheetflow at Summerall Oaks may be due to the reservoir being completely surrounded by single family homes directing rainfall from rooftops towards the ponds via gutters that eject rainwater onto lawns.

Groundwater contributions vary between the two ponds. The maximum groundwater discharge rate was 2.1 m^3/30 min at Cold Stream Cove and 21 m^3/30 min at Summerall Oaks. The average groundwater discharge rate was 0.09 ± 0.14 m^3/30 min at Cold Stream Cove and 0.39 ± 1.10 m^3/30 min at Summerall Oaks (Table 2 and Figure 13). The difference in groundwater discharge rates cause the total contribution of groundwater to be lower at Cold Stream Cove (contributing 4% of the total inputs) compared to Summerall Oaks (contributing 30% of the total inputs) (Figure 9A).

The output parameters measured at each site include evaporation and weir discharge, with irrigation withdrawal as an additional output parameter at Cold Stream Cove. As expected, evaporation values were highest during summer months and lowest during winter months (Figure 14). The total volumetric loss due to evaporation throughout the study was 9060 m^3 at Cold Stream Cove and 4903 m^3 at Summerall Oaks with maximum evaporation rates of 4.0 m^3/30 min and 2.1 m^3/30 min at Cold Stream Cove and Summerall Oaks, respectively. The average evaporation rate was 0.46 ± 0.72 m^3/30 min at Cold Stream Cove and 0.24 ± 0.38 m^3/30 min at Summerall Oaks (Table 2). Evaporation values were twice as high at Cold Stream Cove compared to Summerall Oaks due to the surface area of the pond at Cold Stream Cove (3,809 m^2) being nearly twice that of Summerall Oaks (1,987 m^2). Despite Cold Stream Cove undergoing higher evaporative losses, this sink had a lower contribution to the total water loses of the reservoirs. At Cold Stream Cove, evaporation contributed 11% of the total water losses, whereas it accounted for 20% of the total water losses at Summerall Oaks (Figure 9B). This is due to irrigation withdrawal being an additional export source at Cold Stream Cove.

Weir discharge rates are influenced by the type and design of the weir structure (in this study: broad crested or compound v-notch) and the respective reservoir holding capacities prior to the rain event. The total water loss throughout the study due to weir discharge was 19,905 m^3 at Cold Stream Cove and 15,532 m^3 at Summerall Oaks. Despite the differences in weir structures and reservoir holding capacities, both ponds had similar maximum discharge rates (592 m^3/30 min at Cold Stream Cove and 633 m^3/30 min at Summerall Oaks; Figure 15). However, the average weir discharge rates were more distinct between the ponds, with Cold Stream Cove discharging on average 1.1 ± 11.6 m^3/30 min and Summerall Oaks discharging 6.7 ± 39.7 m^3/30 min (Table 2 and Figure 15). Weir discharge accounts for only 25% of the total water losses at Cold Stream Cove but 81% of the total water losses at Summerall Oaks (Figure 9B) despite Cold Stream Cove containing a higher overall weir export value. This is again due to the irrigation system at Cold Stream Cove adding a significant component of water loss. The irrigation system pumped out a total of 52,549 m^3 (accounting for 65% of the water losses) at Cold Stream Cove over the study despite it only occurring from May-October. No such irrigation system exists at Summerall Oaks.

Discussion

Stormwater detention ponds have been shown to be efficient at removing and retaining pollutant loadings. However, very few of these studies provide estimates of performance efficiency calculated on a mass removal basis (which requires an accurate accounting of water fluxes). The vast majority of wet detention pond studies simply examine changes in pollutant concentrations of waters entering the pond compared to those that exit the pond. Despite the copious amount of literature on pollutant remediation, many stormwater ponds are designed based upon their ability to function hydraulically. Additionally, the hydraulic performance of these ponds directly influences the pollutant remediation capabilities, yet little field-based research has been conducted evaluating their hydraulic performance.

We assess the hydraulic performance of these two coastal stormwater detention ponds by evaluating their water budgets. We begin by further examining the groundwater component of the water budget; an input source that is often overlooked or estimated in the literature, leading to high uncertainties from these assumptions. We then investigate the pond performances during a typical, representative rain event as well as during all recorded rain events.

Groundwater

The hydrology of lakes and wetlands can be strongly influenced by adjacent groundwater systems (Winter, 1983; Cherkauer and Nader, 1989; Corbett et al., 1997). Work by Corbett et al. (1997) emphasizes the importance of understanding the complete hydrologic budget of a system, including groundwater contributions, for water management strategies. In coastal settings, even though the volumetric groundwater contributions are small in comparison to surface water, the concentration of solutes (e.g., nutrients) delivered via groundwater discharge can be just as significant as surface water runoff (Johannes, 1980; Moore, 2010; Santos et al., 2008;

Swarzenski et al., 2007). Despite this, groundwater contributions to stormwater ponds have historically been an overlooked or oversimplified component of computed water budgets, so it is unclear as to whether similar contributions of solutes from groundwater sources are as important in coastal pond systems. This study used a radon mass balance model to geochemically characterize groundwater inputs to the ponds, and this section examines the environmental variables that had a significant impact on those radon mass balance calculations.

The basis of the radon mass balance was a continuous record of ^{222}Rn activities in the stormwater ponds. Rn-222 activities in the pond at Cold Stream Cove ranged from 0 to 6.10 dpm/L (averaging 1.48 ± 0.86 dpm/L throughout the study), whereas ^{222}Rn activities in the pond at Summerall Oaks ranged from 0.067 to 32.26 dpm/L (averaging 6.94 ± 5.22 dpm/L; a factor of 5 higher than the average at Cold Stream Cove; Figure 16). The two sites are assumed to be well-mixed; an assumption that was confirmed based on 18 5-L grab samples (Stringer and Burnett, 2004) collected simultaneously around the perimeter of the ponds during February and March of 2014 (data not shown).

These ^{222}Rn activities observed in the ponds are the manifestation of the variable sources and sinks of radon from the system (as outlined in Eq. 3). The heterogeneity of groundwater ^{222}Rn activities (Rn_{gw}), serving as the mass balance endmember, often leads to this term being the largest source of uncertainty among studies applying a ^{222}Rn mass balance (Corbett et al., 1997; McCoy et al., 2007; Santos et al., 2009; Dimova and Burnett, 2011). The fluctuation in endmember activities may be due to multiple variables. For example, work by Corbett et al. (2000) showed a variation in ^{222}Rn groundwater activities due to sediment depth, as the gaseous property of Rn can cause it to diffuse into air within the vadose zone and ultimately escape to the atmosphere. Additionally, more compacted sediments tend to have higher ^{222}Rn values due to higher solid:fluid ratios (Dimova et al., 2013). Another influence of endmember variation is due to higher ^{222}Rn activities being associated with longer groundwater residence times (i.e., slower flow velocities) (Corbett et al., 1998). Finally, assorted lithologies can attribute different ^{222}Rn to groundwater, so the geologic flowpath of groundwater may influence the endmember value.

In an effort to best constrain this uncertainty within our calculations, weekly samples were analyzed from two 3-well transects at each site. Samples were averaged for each sampling period and the nearest sampled event in time was applied for the groundwater equation within the water budget calculations (Eq. 3). Endmember activities at Cold Stream Cove ranged from 2.9×10^5 dpm/m^3 to 1.8×10^6 dpm/m^3 with an average of $8.6 \times 10^5 \pm 3.4 \times 10^5$ dpm/m^3, whereas the endmember activities at Summerall Oaks ranged from 1.4×10^5 dpm/m^3 to 8.2×10^5 dpm/m^3 with an average of $4.1 \times 10^5 \pm 1.3 \times 10^5$ dpm/m^3 (Figure 17). The endmember activities showed more variation and were, on average, higher by a factor of 5 at Cold Stream Cove compared to Summerall Oaks (Figures 17 and 18).

A secondary term containing lower variability within our groundwater mass balance model is ^{222}Rn loss to the atmosphere. Atmospheric diffusion fluxes are related to the gas transfer coefficient (a function of the air/water interface), measured radon activities within the pond, Ostwalds solubility coefficient and the ^{222}Rn concentration in the air (assumed to be a constant 262 dpm/m^3 based on local measurements) (Eq. 6). Of these variables, atmospheric loss is shown to be most sensitive to wind speed and ^{222}Rn activities within reservoirs (Corbett et al., 2000). Both ponds are in close proximity, therefore the same wind speeds were used at each site. Any observed differences between the atmospheric losses are thus accredited to ^{222}Rn activities being significantly higher within the pond at Summerall Oaks compared to the pond at Cold Stream Cove. The pond at Cold Stream Cove contained J_{atm} values ranging from 190.9 dpm/30 min (0.1 dpm/m^2.hr) to 1.80 x 10^5 dpm/30 min (94.5 dpm/m^2.hr), averaging 1.42 x 10^4 ± 1.62 x 10^4 dpm/30 min (7.5 dpm/m^2.hr) whereas the pond at Summerall Oaks contained J_{atm} values ranging from 99.6 dpm/30 min (0.1 dpm/m^2.hr) to 5.14 x 10^5 dpm/30 min (517.1 dpm/m^2.hr), averaging 3.99 x 10^4 ± 5.31 x 10^4 dpm/30 min (40.2 dpm/m^2.hr) (data not shown). Additional variables influencing the radon mass balance including benthic diffusion (based on $^{226}Ra_{sed}$), production of ^{222}Rn from its parent ^{226}Ra, and decay loss of ^{222}Rn to its daughters are listed within Table 1 and discussed in further detail within the methods section.

Based on these parameters affecting the radon mass balance, we calculated groundwater discharge rates to the ponds (Eq. 4). The pond at Cold Stream Cove was found to receive groundwater discharge rates up to 2.08 m^3/30 min (averaging 0.07 ± 0.14 m^3/30 min) (Figure 19), whereas the pond at Summerall Oaks received groundwater discharge rates up to 20.92 m^3/30 min (averaging 0.42 ± 1.1 m^3/30 min) (Figure 20). The difference in groundwater contribution for the two study sites is further illustrated when normalizing the discharge to the surface area of each pond (3,809 m^2 for Cold Stream Cove and 1,987 m^2 for Summerall Oaks) to derive an apparent groundwater velocity. This groundwater velocity averaged 2.36 x 10^{-5} m/30 min for Cold Stream Cove and a factor of 5 higher at 1.61 x 10^{-4} m/30 min for Summerall Oaks.

Our reported groundwater velocities are in the same range as values reported in the literature for similar reservoirs. A study by Corbett et al. (1997) quantified groundwater velocities into Par Pond, a former thermal cooling reservoir for a nuclear power plant in Savannah, Georgia. Our values agree with the average radon mass balance velocity measurements in Par Pond of 6.25 x 10^{-5} m/30 min as well as the water budget method resulting in groundwater velocity measurements with an upper extreme of 1.65 x 10^{-4} m/30 min. Our groundwater velocity values are also comparable to groundwater velocities at Lake Shipp and

Lake Haines, both located within coastal Florida, which experience groundwater velocities of 2.08×10^{-5} m/30 min and 2.08×10^{-4} m/30 min, respectively. An additional groundwater study conducted at Lake Haines used seepage meters in which the groundwater velocities were determine to be between 4.87×10^{-5} m/30 min and 1.50×10^{-4} m/30 min (Dimova et al., 2013). While those reservoirs were not designed to be stormwater catchments, they are of similar topography as the coastal plain of South Carolina, and undergo rates of groundwater input on the same order as those determined for our stormwater ponds.

Over the course of this study, the cumulative groundwater contribution to the pond at Cold Stream Cove was 1,632 m^3 and 4,729 m^3 to the pond at Summerall Oaks – a factor of almost 3 difference between the ponds. These cumulative discharge volumes equate to an average discharge rate of 0.07 m^3/30 min (3.36 m^3/day) at Cold Stream Cove and 0.42 m^3/30 min (20.16 m^3/day) at Summerall Oaks. Surface water inputs (sheetflow and piped inflow) are higher than these groundwater inputs by a factor of 10 at Cold Stream Cove (with a cumulative volumetric input of 17,091 m^3 throughout the study, averaging 1.3 ± 15.4 m^3/30 minutes) and a factor of 2 at Summerall Oaks (with a cumulative surface inflow volume of 10,712 m^3, averaging 5.3 ± 36.8 m^3/30 minutes) (Figure 9A). This is logical considering stormwater ponds are designed to route surface flow into the ponds via sloped topography and piped discharge. Based on the average rate of groundwater discharge, 0.06% of the pond volume at Cold Stream Cove and 0.47% of the volume at Summerall Oaks is replaced daily by groundwater inputs. Therefore, if groundwater was the only input to these ponds, the replacement time would be approximately 46 months for the pond at Cold Stream Cove and 5 months for that at Summerall Oaks. Dimova et al. (2013) found similar ranges for groundwater replacement times (between 2 and 40 months) for six shallow lakes in Florida.

These two seemingly similar ponds along the coastal plain of South Carolina exhibit substantially different groundwater contributions. These differences may be attributed to the relative height of the water table surrounding the ponds during dry periods and topography of the drainage basins which serves to create a hydraulic gradient between the aquifer and the pond. In addition to the hydraulic gradient, it is widely accepted that groundwater flow velocities are influenced by the permeability and transmissivity of the aquifer materials.

The water table elevation at Summerall Oaks (average of 4.79 m above NAVD88) was consistently higher than the elevation of the water table at Cold Stream Cove (average of 1.98 m above NAVD88) (Figures 21B and 22B). When comparing the relative difference between the water table elevation and the elevation of the pond, a slightly higher gradient is observed on average at Cold Stream Cove (0.01 to 0.05 averaging 0.03 ± 0.01) compared to Summerall Oaks (-0.01 to 0.07 averaging 0.01 ± 0.02) (Figures 21C and 22C). The lowest hydraulic gradients are observed when the water table elevation is the lowest (particularly May-July and October-December) and correlate with our lowest groundwater discharges (Figures 21 and 22). The negative gradient observed at Summerall Oaks indicates that a small amount of groundwater recharge from the pond volume may be occurring during these months, a hydrological process we neglected within our water budget. If this is indeed occurring, it would lead to a slight overestimation in sheetflow values until large scale events can replenish the aquifer, driving a shift in the negative hydraulic gradient to a positive one.

Although the hydraulic gradient is on average larger at Cold Stream Cove there is a higher frequency of oscillation and variation observed with the hydraulic gradient at Summerall Oaks, indicating the soils at Summerall Oaks are more permeable. Large scale events drive the change in hydraulic gradients at Cold Stream Cove whereas at Summerall Oaks, the aquifer is responsive to lower magnitude events as well as the large scale events (Figures 21C and 22C). In order to further investigate geologic differences as the driver of differing groundwater inputs to these ponds, we conducted pump tests in December 2014 from the groundwater wells to compute the hydraulic conductivity values around each pond. Hydraulic conductivities around the pond at Summerall Oaks were found to range from 7.58×10^{-3} m/min to 3.73×10^{-1} m/min (averaging $1.05 \times 10^{-1} \pm 1.1 \times 10^{-2}$ m/min), whereas hydraulic conductivity values around the pond at Cold Stream Cove were nearly five times lower, ranging from 9.21×10^{-3} m/min to 2.43×10^{-2} m/min (averaging $2.4 \times 10^{-2} \pm 1.8 \times 10^{-1}$ m/min). This further indicates groundwater can move through sediments with more ease at Summerall Oaks than Cold Stream Cove. Therefore the difference in geologic materials within the drainage basins likely exerts a substantial influence on groundwater sources to these ponds.

During rain events, groundwater contributions are minimal in comparison to surface water contributions, as the water budget sources are dominated (as per design) by focused surface water inputs. However, groundwater seepage consistently occurs into the ponds during periods of no rainfall, serving as the only input mechanism throughout a substantial fraction of time. Groundwater contributions are an often overlooked or oversimplified component of pond water budgets. The question here is of a temporal scale: if the only consideration is how the water budget of these ponds is affected during rain events, then groundwater contributions can likely be neglected. However, groundwater can transport a substantial volume of water (likely impacting solute loadings) to stormwater ponds when considering both wet and dry periods. We found that over the course of the study, groundwater represented 4% of all water inputs to the pond at Cold Stream Cove and 30% of all water inputs to the pond at Summerall Oaks (Figure

9A). We believe these volumetric contributions are certainly not insignificant and recommend that this source should be considered in future pond water budgets.

Selected Rain Event

We examine how these ponds behave hydraulically during a single rain event in order to gain a more complete understanding of the entire water budget. For this analysis, we classify the beginning of a rain event at the onset of precipitation and the termination of the event as the cessation of weir discharge.

On August 23rd, 2014, a medium intensity rain event passed through both study sites following dry antecedent conditions (date of last rainfall: August 18th). This rain event lasted for 6 hours at Cold Stream Cove and 23 hours at Summerall Oaks. The duration of this and many rain events during this study is related to the configuration of the respective weirs at the ponds. The weir design at Summerall Oaks (Figure 6) does not allow as high a discharge rate (particularly at low values of h_{weir}) as the one at Cold Stream Cove (Figure 5), so the weir design controls both the length of the event as well as the rate of discharge in these ponds.

During this rain event, the rain gauges recorded 25.3 mm of rain accumulation at Cold Stream Cove (at an average intensity of 5.1 mm/30 minutes) and 35.6 mm at Summerall Oaks (at an average intensity of 7.1 mm/30 minutes). Considering the surface areas of the ponds, Cold Stream Cove received 96.3 m^3 of direct precipitation and the pond at Summerall Oaks received 70.7 m^3 of direct precipitation (Figure 23). Direct precipitation accounted for 17% of the total inputs at Cold Stream Cove but only 5% of the total inputs at Summerall Oaks. Assuming this rain was homogenous over the entire drainage basin, 1,165 m^3 fell across the basin at Cold Stream Cove and 1,993 m^3 fell on the basin at Summerall Oaks.

Prior to the rain event, the pond volume at Cold Stream Cove was 5439 m^3 and 2835 m^3 at Summerall Oaks (Figure 24). The pond at Cold Stream Cove reached its peak volume of 5,892 m^3 approximately one hour following the beginning of the event, whereas the pond at Summerall Oaks did not reach its peak volume of 3,346 m^3 until 5 hours following the beginning of the rain event. These peak volumes represent a 453 m^3 and 511 m^3 increase from the starting volumes at Cold Stream Cove and Summerall Oaks – values that reflect 39% and 26% of the total drainage basin precipitation accumulations, respectively. We examine more thorough measures of the hydraulic effectiveness of the different drainage basins in the section to follow.

As per design, surface water dominated the water inflow at both ponds. The pipe at Cold Stream Cove contributed 447 m^3 of surface inflow during the rain event, peaking at a discharge of 250 m^3/30 min (Figure 25A). Combined, the three pipes at Summerall Oaks contributed 1,079 m^3 of surface inflow during the rain event, peaking at a discharge of 425 m^3/30 min (Figure 25B). Despite the volumetric differences in piped inflow between the ponds, the piped systems contributed the same percentage of input volume to the total inputs (81% of the total inputs at Cold Stream Cove and 82% of the total inputs at Summerall Oaks). It is logical that the two sites received the most inflow through the piped systems considering that runoff from impervious surfaces is designed to be routed to the ponds via stormwater pipes.

Sheetflow runoff is an additional contributor of surface inflow to the ponds. Sheetflow runoff values were considered during times of precipitation and 30 minutes following the events. Sheetflow totals varied between the two sites, with 5.8 m^3 and 124 m^3 of sheetflow entering the ponds at Cold Stream Cove and Summerall Oaks, respectively (Figure 26), contributing 1.3% of the total inputs at Cold Stream Cove and 9.4% of the total inputs at Summerall Oaks. The surroundings of a pond strongly influence sheetflow potential and are likely the cause of the differences between sites. The pond at Summerall Oaks is nearly completely surrounded by 17 single family homes, whereas Cold Stream Cove only has a single 6-unit condominium adjacent to the reservoir. These rooftops contain gutter systems that funnel rain landing on the pond-side of the structure to the yards, where it can be routed towards the pond as sheetflow runoff (Figure 27). Together, surface inputs (comprised of piped inflow and sheetflow) dominated the rain event by contributing 82.3% of the total inputs at Cold Stream Cove and 91.4% of the total inputs at Summerall Oaks.

During this rain event, the least volumetric source of inflow at both ponds was groundwater. Total groundwater contributions at Cold Stream Cove was 1.0 m^3 (0.2% of the total inputs), substantially lower than groundwater contributions at Summerall Oaks of 40 m^3 (3% of the total inputs) (Figure 28). Our definition of a rain event encompassed more time for groundwater to enter the pond at Summerall Oaks (23 hours) than at Cold Stream Cove (6 hours), however the average groundwater seepage rate into the pond at Cold Stream Cove was still lower than the average groundwater discharge rate into the pond at Summerall Oaks (0.17 m^3/30 minutes and 0.85 m^3/30 minutes, respectively). Normalizing to the surface area of each pond removes the size difference of the ponds, further indicating more intensive groundwater seepage to the pond at Summerall Oaks (4.5 x 10^{-5} m/30 min for Cold Stream Cove and 4.3 x 10^{-4} m/30 min for Summerall Oaks).

The two mechanisms of water export from the ponds during this event are evaporation and weir discharge. The total evaporation during this rain event was 3.0 m^3 at Cold Stream Cove and 13.3 m^3 at Summerall Oaks (Figure 29). Instantaneous evaporation values were twice as high at Cold Stream Cove compared to Summerall Oaks due to evaporation being a function of the surface area of the ponds – yet, cumulative evaporation totals were higher at Summerall Oaks than at Cold Stream Cove due to the length of the event (6 hours at Cold Stream Cove and 23 hours at Summerall Oaks). Regardless, evaporation comprised a minimal component of the water budget exports (1.9% of outputs at Cold Stream Cove and 0.8% of outputs at Summerall Oaks).

Weir discharge dominated water outputs throughout this event, with the reservoir at Cold Stream Cove discharging 145 m^3 and Summerall Oaks discharging 1,610 m^3 (Figure 30). This comprised 98% of the total water exported at Cold Stream Cove and 99% of the total water exported at Summerall Oaks. In addition to exporting the most water, Summerall Oaks experienced water discharging over the weir for a longer duration (21.8 hours) than Cold Stream Cove (5.3 hours). The duration and magnitude of weir discharge is influenced by the weir design as well as pre-event conditions, particularly the pond volume. The pond at Cold Stream Cove contained a volume deficit (i.e., volume below the 'full' volume at which discharge over the weir occurs) of 321 m^3, whereas the pond at Summerall Oaks contained a volume deficit of only 82 m^3 prior to the event. Therefore, much more runoff volume at Cold Stream Cove was used to replenish the pond volume prior to discharge, reducing the duration and volume of runoff that actually discharged out of the pond. Both sites had the last discharging event five days prior to this event, attributing the difference in the holding volumes to pumping for irrigational purposes at Cold Stream Cove.

Although it is beneficial to examine the behaviors of our study sites in response to a single event, rain events vary in magnitude and duration. Due to this, it is imperative to understand how these reservoirs react to events which occurred throughout the year. This selected rain event provides a representative perspective of how the ponds behave to all rain events sampled, which are cumulatively considered in the following section.

Assessment of Pond Performance

Stormwater ponds within Horry County are designed to specifications based on 24-hour rainfall accumulations representing two year (11.43 cm), ten year (17.02 cm) and twenty-five year (19.30 cm) storms. However, these ponds experience rain events across a spectrum of magnitudes, durations, and pre-event characteristics which are much more common than these intense storms. Over the course of this study, rain events large enough to drive discharge over the weir were observed 42 occasions at Cold Stream Cove and on 45 occasions at Summerall Oaks, and spanned a large range from short, intense storms to long showers. Rain intensities ranged from 0.38 mm/hr to 12.7 mm/hr (averaging 3.02 ± 3.0 mm/hr) at Cold Stream Cove and 0.34 mm/hr to 14.22 mm/hr (averaging 3.68 ± 3.6 mm/hr) at Summerall Oaks. During our study, a two year 24-hour storm event (11.43 cm; the lowest magnitude in which these stormwater ponds were designed to capture) never occurred at our sites. Dry periods between discharging events varied from 0.5 to 60 days at Cold Stream Cove (averaging 8 ± 11 days) and from 0.5 to 25 days (averaging 6 ± 6 days) at Summerall Oaks. Examining how these ponds respond to varying conditions provides a more comprehensive assessment of the hydrologic behaviors of coastal plain stormwater ponds.

Surface Inflow Characteristics

As wet detention ponds are designed to capture stormwater runoff, it is logical that surface inflow dominated the inputs to the ponds during rain events in these ponds. Higher rainfall accumulations led to a greater dominance of surface inputs within the total inputs. Likewise, less intensive rain events allow for direct precipitation and groundwater inflow to comprise a larger percent of the total inputs to the ponds due to smaller surface inflow volumes (Figure 31). Despite this, rarely do surface flowpaths (combined piped and sheetflow) contribute less than half of the inputs into the ponds (which occurred only once at Cold Stream Cove and twice at Summerall Oaks). The apparent exponential relationship between rainfall accumulation and relative dominance of surface water flowpaths to the pond water budgets suggests that only for events of very small magnitude (i.e., less than 15 mm rain accumulation) do direct precipitation and groundwater combined contribute more than 20% of the total inputs to the ponds and increasingly larger events show diminishing dominance of surface inflows.

Though our results indicate that surface runoff largely dominates the water budget for these ponds during rain events, they do not give an indication of how efficiently the drainage basin conveys this rainfall into the ponds. For this, hydrologists often calculate a runoff coefficient, which relates surface runoff volume to the total precipitation landing on the drainage basin. For this analysis, we used the GIS-delineated drainage basin surface areas to estimate the total volumetric rainfall within the drainage basin, and calculate a runoff coefficient by dividing the surface runoff volume for each rain event by this volumetric rainfall across the drainage basins. Event runoff coefficients can range from 0.0 to 1.0 with low values representative of small storms and/or dry soil conditions (leading to minimal surface runoff) and higher values representative of more intense storms and/or saturated soil conditions (producing maximum surface runoff) (Figure 32). Runoff coefficients vary from 0.06 to 0.93 for the basin within Cold Stream Cove and 0.02 to 0.86 for the basin within Summerall Oaks (Figure 32). These trends follow a statistically significant linear relationship ($p<0.01$) for both ponds throughout our study. Runoff coefficients have been reported to increase with increasing urbanization within a watershed (Pawlow, 1977; Leopold, 1991), and this relationship holds true for our study sites with the more impervious Cold Stream Cove demonstrating higher average runoff coefficients (0.45) compared to the less impervious drainage basin at Summerall Oaks (0.18).

The runoff coefficient provides an integrated assessment of how efficiently stormwater is transported via all surface flowpaths, without regard for the various pathways the water may follow (e.g., transfer through pipes and sheetflow runoff). Figure 33 examines the relative influence of sheetflow into the studied ponds by comparing the cumulative sheetflow volumes for each event to the total rainfall within the drainage basins. In this case, data points falling along the dashed 1:1 line would indicate that all of the rainfall within the drainage basin is transferred to the pond via sheetflow, so the slope of the regression curve provides a general basin measure of the relative likeliness to convert rainfall to sheetflow. At Cold Stream Cove, no significant relationship was found with rain falling on the drainage basin flowing into the pond as sheetflow (in fact, most rain events did not produce any sheetflow), whereas 16% of rain falling on the drainage basin at Summerall Oaks flows into the pond as sheetflow (Figure 33). The significantly linear relationship ($p < 0.01$) at Summerall Oaks suggests that more intensive rain events produce more substantial sheetflow volumes.

The difference in these sheetflow conversion values likely results from different drainage basin characteristics. The pond at Summerall Oaks is nearly completely surrounded by single family homes, with elevated lots designed to funnel sheetflow to swales between the houses and ultimately toward the pond. Conversely at Cold Stream Cove, only one six-unit condominium is adjacent to the reservoir, with a small lawn that can serve as a catchment for sheetflow runoff.

The relatively low conveyance via sheetflow compared to total surface inflows indicate that pipes are the main conveyance mechanism for surface flow to the ponds. Figure 34 is similar to Figure 33, except plots cumulative piped inflow to the ponds as a function of volumetric rainfall within the drainage basins, wherein the slopes of the regression curves represent the efficiency by which rainfall is transferred to the ponds via engineered piped flowpaths. At Cold Stream Cove, 51% of the rain which lands on the drainage basin flows through the pipe into the pond ($p<0.01$), whereas at Summerall Oaks, only 26% of the rain which lands on the drainage basin flows through the three pipes into the pond ($p<0.05$; Figure 34).

The difference in piped percentages may be attributed to the drainage basin at Cold Stream Cove being more impervious (62% at Cold Stream Cove compared to 44% at Summerall Oaks). Also, the nature of the pipe engineering at Summerall Oaks allows more holding capacity within the junction boxes where drainage pipes meet. These junction boxes at both ponds are topped by grated manhole covers (e.g., Figure 35), so are subjected to evaporative losses during relatively dry periods. However, the outlet pipes in the three junction boxes at Summerall Oaks are elevated 50 to 55 cm above the bottom of the junction box, whereas the outlet pipe in the single junction box at Cold Stream Cove is only ~5 cm above the junction box bottom. Therefore, evaporation of standing water from inside the junction boxes at Summerall Oaks lowers the water level in the box below the outlet pipe, creating a small storage capacity potential prior to discharging a stormwater pulse into the pond. Additionally, these grated structures may also convert sheetflow to piped inflow. The location and topography surrounding these grated manhole covers offers the possibility of intercepting sheetflow pathways and therefore converting would-be sheetflow into piped discharge.

Inflow and Outflow Hydrograph Characteristics

Human modification of hydrologic flowpaths due to urbanization has caused an increase in surface runoff volume and peak discharge values. This increased volume creates hydrographs which peak prior to when they would under natural conditions. As a result, these stormwater ponds are designed to extend the stormwater hydrograph, reduce peak discharge values, and lengthen the duration between inflow and outflow periodicities. To validate these design plans with our observed data we calculated the percent in which the outflow hydrograph was elongated by subtracting the outflow duration from the inflow duration and dividing by the inflow duration (as illustrated by Figure 36A). The inflow duration was on average 47% of the duration of the outflow at Cold Stream Cove and 18% of the duration of the outflow at Summerall Oaks (Table 3). Additionally, we calculated the peak reduction by a similar equation where the peak outflow is subtracted from the peak inflow and divided by the peak inflow (as illustrated by Figure 36B). The peak inflow was reduced by an average of 75% for the pond at Cold Stream Cove and 71% for the pond at Summerall Oaks (Table 3). Without the implementation of these stormwater ponds, the high intensity surface inflow volumes would be more intensely directed into surrounding streams and rivers, potentially causing erosion and scouring.

We further evaluate the inflow to outflow characteristics by the centroid lag time. The centroid lag time is an assessment of the time difference between the inflow midpoint discharge hydrograph to the outflow midpoint discharge hydrograph (Hancock et al., 2010; Dingman, 2002) (as illustrated in Figure 37). The minimum centroid lag times are 20 min and 30 min with maximum centroid lag times of 5 hours and 12 hours for Cold Stream Cove and Summerall Oaks, respectively (Figure 38).

Centroid lag time variability between the two ponds is impacted by weir characteristics, soil compaction, watershed geology, and land use (Dingman, 2002). A higher variability on an event scale is observed among centroid lag time values for the pond at Summerall Oaks compared to the pond at Cold Stream Cove (Figure 38). Event centroid lag time variability may also be influenced by variables such as the antecedent event conditions (Kang et al., 1998), peak rainfall intensity (Askew, 1963), and precipitation volume and duration (Pawlow, 1977). Throughout our study, no statistically significant correlation was observed between these individual characteristics and event lag time. This may be attributed to storm "piggybacking" (Hancock et al., 2010). In the event that discharge to/from a pond in response to a rain event has not completed prior to the onset of a subsequent event, the second rain event will further intensify the pond elevation and discharge hydrograph. This enhanced elevation creates additional outflow, elongating the event time and changing the associated midpoint time. The additional inflow also causes a variation in the midpoint time for the inflow which can result in the centroid lag time changing on a scale of minutes to hours (as illustrated in Figure 39). The frequent occurrence of storm "piggybacking" likely contributed to the lack of a distinct correlation between centroid lag time and potential influencing variables.

In addition, continually varying outflow discharge rates can result in different water residence times within the ponds. Due to the stormwater detention ponds not containing steady-state conditions (i.e., constant volume and outflow), we assess the holding time by evaluating a turnover time for each rain event. We calculated turnover time by dividing the time in which discharge is occurring by the cumulative weir discharge and then taking this value and dividing it by the pond volume. For both ponds, the longest turnover times (approximately 1.5 years for the pond at Cold Stream Cove and 3 years for the pond at Summerall Oaks) coincided with low magnitude rain events, with the shortest turnover time (30 min for the pond at Cold Stream Cove and 12.5 hours for the pond at Summerall Oaks) coinciding with higher magnitude rain events (Figure 40). The negative exponential relationship between pond turnover time and rain event intensity suggests turnover times respond more so to small variations in low-intensity rainfall events than larger storms. Despite the pond at Cold Stream Cove encompassing a larger basin, its turnover time was on average 60% lower than turnover times observed for the pond at Summerall Oaks for low magnitude rain events (under 30 mm). However, for higher event magnitudes (above 30 mm), the pond at Cold Stream Cove experiences turnover time values which are on average 3 times higher than the turnover times observed for the pond at Summerall Oaks. As the rain event magnitude increases, the difference in discharge values lessens between the ponds, causing the pond volume and pre-event characteristics to have a more significant impact on turnover times.

Antecedent Conditions

The pond volume deficit prior to a rain event (i.e., the volume difference between the pre-event volume and the 'full pond' volume at which discharge over the weir occurs) also has a significant impact on the outflow duration and turnover time for each pond. Longer turnover times are associated with larger pond volume deficits, and therefore higher storage capacity of the pond (i.e., more stormwater runoff is needed to refill the pond prior to discharge occurring). We assess this notion by calculating a percent of the rainfall volume that is retained in the pond, which is primarily a function of the precipitation volume and the pond water level prior to the event. Lower rainfall magnitudes lead to less runoff received and therefore retained by the ponds (Figure 41). Both ponds, particularly the one at Cold Stream Cove, retain a higher percent of rainfall during the summer/fall months (Figures 41 and 42). This is due to larger pond volume deficits during this time, which likely results from enhanced evaporation during the summer (Figure 43) and for the case of the pond at Cold Stream Cove, from the pond serving as a re-use pond for irrigation purposes from May-October when daily irrigation pumping significantly increases the storage capacity for the pond. The pond at Summerall Oaks does not contain such anthropogenic water removal system. The pond at Cold Stream Cove has also shown to retain a higher percentage of rainfall volume during the winter months compared to the pond at Summerall Oaks (Figure 42). We suspect this is attributed to the pond at Cold Stream Cove containing a larger evaporative loss (due to its larger surface area) as well as a lower groundwater contribution compared to the pond at Summerall Oaks.

Although both ponds were designed based on the same management regulations, they each contain unique characteristics by which they respond differently to rain events. The weir structure at Summerall Oaks has shown to serve better for the lower magnitude rain events compared to the weir structure at Cold Stream Cove by elongating the outflow duration, thereby increasing the turnover time. The pond at Cold Stream Cove being a re-use pond for irrigation purposes significantly aids that pond in retaining runoff during the pumping season. The pond at Summerall Oaks contributed larger sheetflow values due to it being completely surrounded by single family homes; however, the higher impervious surfaces within the drainage basin at Cold Stream Cove contributed higher piped inflow values. These varying characteristics cause each pond to respond uniquely to rain events despite being close in proximity and designed under the same engineered guidelines.

Comparison to Engineered Inflow Values

Differing drainage basin characteristics are taken into consideration when engineers design stormwater ponds and their associated structures for moderating runoff rates. When constructing a stormwater best management practice (BMP) a stormwater plan must be created to compare pre-development runoff rates to post-development rates. The Soil Conservation Service (SCS) hydrologic method is the most widely used method for predicting stormwater runoff discharge rates. The SCS method calculates stormwater runoff per the following equation (Horry County Stormwater Management Design Manual, 2000):

$$Q = (P - 0.2S)^2/(P + 0.8S) \tag{14}$$

where Q is the accumulated runoff (mm), P is the accumulated rainfall (mm), and S is the potential maximum soil retention. The soil retention is derived from the following equation (Horry County Stormwater Management Design Manual, 2000):

$$S = \left(\frac{25400}{CN}\right) - 254 \qquad (15)$$

where runoff curve number (CN) indicates the runoff potential of the drainage basin area. References such as Horry County's Stormwater Management Design Manual (2000), indicate runoff curve numbers based on hydrologic soil groups, land use, and the location of these characteristics with respect to the stormwater pond (Figure 44). These curve number values range from 0-100 representing infinite soil retention (0) to fully impermeable characteristics (100). Although engineers use site-specific parameterization, CN values are calculated from empirical tables which include assumptions that may not produce realistic results (Epps et al., 2013).

The stormwater plan for Cold Stream Cove reports a curve number value of 79, whereas the stormwater plan for Summerall Oaks reports a curve number value of 84. It is logical that stormwater engineers would assign a higher curve number value to the pond at Summerall Oaks due to the pond being in the center of the drainage basin and closer in proximity to impervious surfaces compared to the pond at Cold Stream Cove. In comparing the theoretical inflow values resulting from the assigned curve numbers for these ponds with our observed stormwater inflow values, we find that the values reported within the stormwater plans are too low to accurately represent our observed inflow values (Figure 45).

Based on our observed stormwater inflow values, we can rearrange Equations 14 and 15 to derive a more accurate CN based on observational data (Hawkins, 1993):

$$S = 5 \times \left[P + 2Q - \sqrt{4Q^2 + 5PQ}\right] \tag{16}$$

where S is then used to identify the observed CN values. Our derived CN values range from 75 to 98 (averaging 92 ± 5.5) for the pond at Cold Stream Cove and 77 to 98 (averaging 90 ± 5.3) for the pond at Summerall Oaks. The derived CN values are not statistically significant from each other; however the measured values are significantly different from the engineered CN values at both ponds (one-way ANOVA; $p<0.01$). Our average CN values suggest the stormwater engineers used an under representation of the CN by 13 at Cold Stream Cove and by 6 at Summerall Oaks. This is a 14% and 7% variation for the CN values associated with the pond at Cold Stream Cove and Summerall Oaks, respectively. The CN is the least certain variable within the runoff calculation and small deviations in the assigned CN may produce unrealistic runoff estimates. As rain event magnitude increases, the difference between the predicted runoff and our observed runoff increases (Figure 45). Specifically, Boughton (1989) reported that a 15-20% change in the curve number will produce inflow values varying by a factor of two. Based on our observed data and interpretations, we suggest that the ponds will experience discharge values significantly higher than those predicted for the two year, ten year, and twenty-five year storm events after which these ponds were modeled. This may result in post-development discharge values being higher than the pre-development discharge values, in which case the ponds do not function as expected from the design regulations.

The SCS method may lack true representation of runoff by neglecting changing storage retention characteristics. Water table elevations are variable between rainfall, evapotranspiration and antecedent rain conditions. This, in turn, affects variability associated with estimating surface runoff (Epps et al., 2013). A significant correlation ($p<0.01$) was observed between our derived curve numbers based on event-specific observations and the adjacent water table elevations for both ponds (Figure 46). This correlation was more prominent for the pond at Summerall Oaks, suggesting that groundwater conditions have a larger influence on the surface water contribution for the pond at Summerall Oaks compared to the pond at Cold Stream Cove. This coincides with our observations of the pond at Summerall Oaks receiving higher groundwater responses to rain events in comparison to the pond at Cold Stream Cove. These results further emphasize the significance and importance in understanding groundwater contributions to stormwater ponds.

Conclusions

Stormwater ponds are implemented as best management practices to reduce pollution and downstream flooding. Modeling programs are used when designing the stormwater ponds, yet few field based evaluations are completed following construction to ensure that ponds are performing as designed. By monitoring a high resolution annual water budget for two coastal stormwater detention ponds, an evaluation of stormwater pond hydraulic effectiveness was performed. The water budget used in this study consists of inflow components including sheetflow runoff, piped inflow, groundwater inflow, and direct precipitation with outflow components consisting of surface outflow, evaporation, and pumping for irrigation purposes (for the pond at Cold Stream Cove).

Groundwater contributions are an often overlooked or over simplified component in water budget equations, particularly for stormwater ponds. When evaluating groundwater contributions during rain events, they were shown to be minimal in comparison to surface water inputs; however, during periods of no rainfall, groundwater seepage serves as the only input mechanism. This resulted in groundwater representing 4% of all water inputs to the pond at Cold Stream Cove and 30% of all water inputs to the pond at Summerall Oaks. This is likely related to the soils showing a higher hydraulic conductivity at Summerall Oaks as well as stronger peak hydraulic gradients when compared to Cold Stream Cove. Additionally, groundwater has been shown to be a significant carrier of solutes to surface water bodies indicating these total volumetric groundwater contributions may have large scale biogeochemical implications. Our study also showed a significant correlation between surface runoff values and adjacent water table elevations, further emphasizing the importance in understanding the impact groundwater contributions have on stormwater ponds.

As wet detention ponds are designed to capture stormwater runoff, it is logical that surface inflow (comprised of both piped inflow and sheetflow) dominated the water inputs for both the study season and individual rain events. When designing stormwater ponds, engineers estimate surface runoff discharge rates using the Soil Conservation Service (SCS) hydrologic method which requires a site-specific estimated Curve Number (CN). Our total observed surface inflow values were shown to be higher than the estimated inflow values for the ponds located at Cold Stream Cove and Summerall Oaks. This overestimation is a result of the stormwater plans using an under-representation of the CN value (14% and 7% variation for Cold Stream Cove and Summerall Oaks, respectively). It is widely understood the CN value is the least certain variable within this method; however, this under-representation may result in post development discharge values being higher than pre-development discharge values. This suggests our studied ponds may not function hydrologically according to their design plans.

Stormwater ponds are designed to extend the stormwater hydrograph, reduce peak discharge values and lengthen the duration between inflow and outflow periodicities. The duration and magnitude of water export from the ponds is influenced by the weir design and pre-event conditions, particularly the pond volume. The combined v-notch weir design at Summerall Oaks has shown to respond more efficiently to lower magnitude events compared to the broad crested weir design at Cold Stream Cove. This increased the turnover time for the lower magnitude events at Summerall Oaks, providing more time for natural physical, biological, and chemical processes to improve the water quality. Both ponds retained a higher percentage of rainfall runoff from May-October compared to November-April due to enhanced evaporation during summer and fall months and, for the case of the pond located at Cold Stream Cove, from the pond serving as a re-use pond for irrigation purposes. Both ponds were shown to be effective in extending the stormwater hydrograph and reducing peak discharge values. Without the implementation of these stormwater ponds, the high intensity surface inflow volumes would be directed into surrounding receiving waters potentially causing erosion scouring.

It is important to bear in mind this study is reflective of two ponds out of over 8,000 located in South Carolina. Additionally, the pond at Cold Stream Cove and the pond at Summerall Oaks discharge into Collins Creek and the impact of a series of ponds discharging into the same adjacent surface water body is still not widely understood both from a hydrological and biogeochemical perspective. Further evaluation of the downstream effect that stormwater ponds have on receiving waters would aid in understanding the impact stormwater ponds have on rerouting surface flow towards the coastal ocean.

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Tables

Term	Description	Units	Value
Rn_p	Radon in pond	dpm/m^3	Variable
V_p	Volume of pond	m^3	Variable
Q_s	Surface Runoff	$m^3/30$ min	Variable
Rn_s	Radon activity of surface runoff	dpm/m^3	Assumed to be 0
λ	Radon decay constant	$30\ min^{-1}$	$0.0038\ 30min^{-1}$
Ra_p	Production of radon from radium	dpm/m^3	CSC: 86.2 dpm/m^3 SO: 197.09 dpm/m^3
$^{226}Ra_{sed}$	Sedimentary ^{226}Ra activity	dpm/g	CSC: 1.34 dpm/g SO: 1.53 dpm/g
SA	Surface area of pond	m^2	CSC: 3,809 m^2 SO: 1,987 m^2
Q_{gw}	Groundwater discharge	$m^3/30min$	Variable
Rn_{gw}	Groundwater endmember activities	dpm/m^3	Variable
u	Wind speed	m/s	Variable
v	Kinematic viscosity of water	m^2/s	Variable; $1.0043 \times 10^{-6}\ m^2/s$ at 20^oC
D_m	Molecular diffusion coefficient	m^2/s	Variable; $1.16 \times 10^{-7}\ m^2/s$ at 20^o C
T	Water temperature	^oC	Variable
Rn_a	Radon concentration in air	dpm/m^3	262 dpm/m^3
Q_o	Weir discharge	$m^3/30min$	Variable

Table 1: Groundwater mass balance parameter descriptions and units used for Cold Stream Cove and Summerall Oaks pond study. Radon sources and sinks are shown in Figure 3.

	Parameter	Average	Range
Cold Stream Cove	Pond Volume	5473 ± 321 m^3	4502 -7131 m^3
	Direct Precipitation	0.3± 2.5 m^3/30min	0.0 – 115.2 m^3/30min
	Piped Inflow	1.2 ± 14.9 m^3/30min	0.0 - 478 m^3/30min
	Sheetflow	0.38 ± 4.45 m^3/30min	0.0 - 428m^3/30min
	Groundwater	0.09 ± 0.14 m^3/30min	0.0 - 2.1m^3/30min
	Evaporation	0.46 ± 0.72 m^3/30min	0.0 - 4.0 m^3/30min
	Weir Discharge	1.1 ± 11.6 m^3/30min	0.0 - 595 m^3/30min
	Sprinkler Loss	2.9 ± 6.6 m3/30min	0.0 – 17.9 m3/30min
Summerall Oaks	Pond Volume	2836 ± 62 m^3	2674 - 4397 m^3
	Direct Precipitation	0.2 ± 1.1 m^3/30min	0.0 – 61.32 m^3/30min
	Piped Inflow	0.7 ± 11.3 m^3/30min	0.0 - 636 m^3/30min
	Sheetflow	1.67 ± 22.2 m^3/30min	0.0 - 621 m^3/30min
	Groundwater	0.39 ± 1.1 m^3/30min	0.0 - 21 m^3/30min
	Evaporation	0.24 ± 0.38 m^3/30min	0.0 - 2.1 m^3/30min
	Weir Discharge	6.7 ± 39.7 m^3/30min	0.0 - 633 m^3/30min

Table 2. Parameters and associated values measured from the Cold Stream Cove and Summerall Oaks pond study.

	Parameter	Average	Range
Cold Stream Cove	Outflow Elongation	47 ± 21%	15 - 80%
	Peak Reduction	75 ± 19%	19 - 99%
	Centroid Lag Time	1.7 ± 0.9 hours	0.33 – 5 hours
Summerall Oaks	Outflow Elongation	18 ± 13%	2 - 47%
	Peak Reduction	71 ± 28%	6 - 99%
	Centroid Lag Time	2.7 ± 2.3 hours	0.5 – 12 hours

Table 3. Outflow to inflow characteristics. Outflow elongation represents the percent inflow duration compared to outflow duration, peak reduction represents the percent in which the inflow was reduced compared to the outflow, and the centroid lag time is the time difference between the inflow midpoint discharge hydrograph to the outflow midpoint discharge hydrograph.

Figures

Figure 1. Aerial images of selected study site ponds. A) Cold Stream Cove; high-density condominium housing developmental area with a drainage basin consisting of 14 multi-unit complexes, B) Summerall Oaks; medium density developmental area with a drainage basin consisting of 50 single family homes.

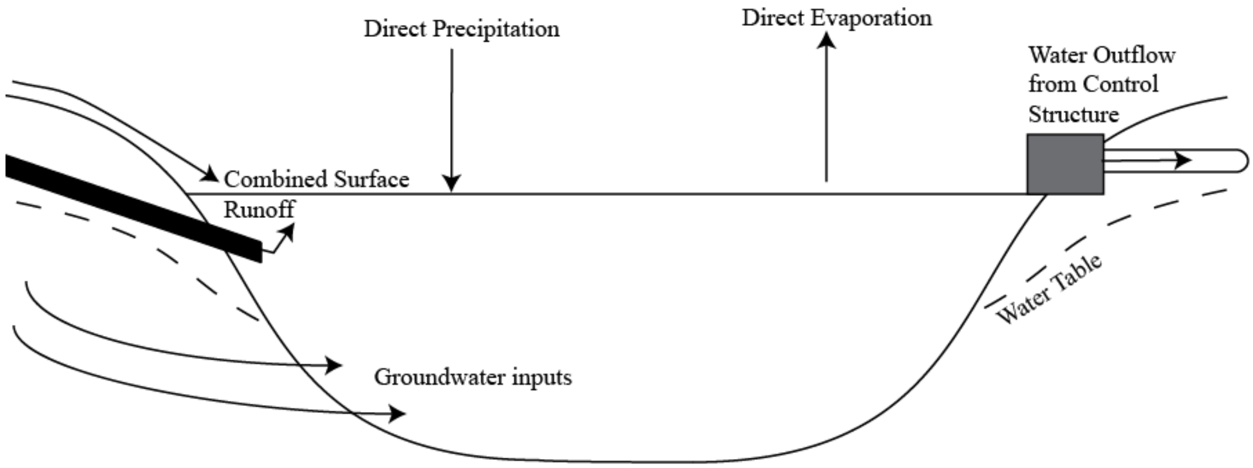

Figure 2. Schematic representation of the pond water budget components. Water inputs were considered from precipitation, combined surface runoff (overland sheetflow and stormwater pipes), and groundwater inputs. Water outputs were considered from evaporation and outflow from the engineered control structure. The measured water table relative to the pond implies negligible groundwater infiltration as an outflow source.

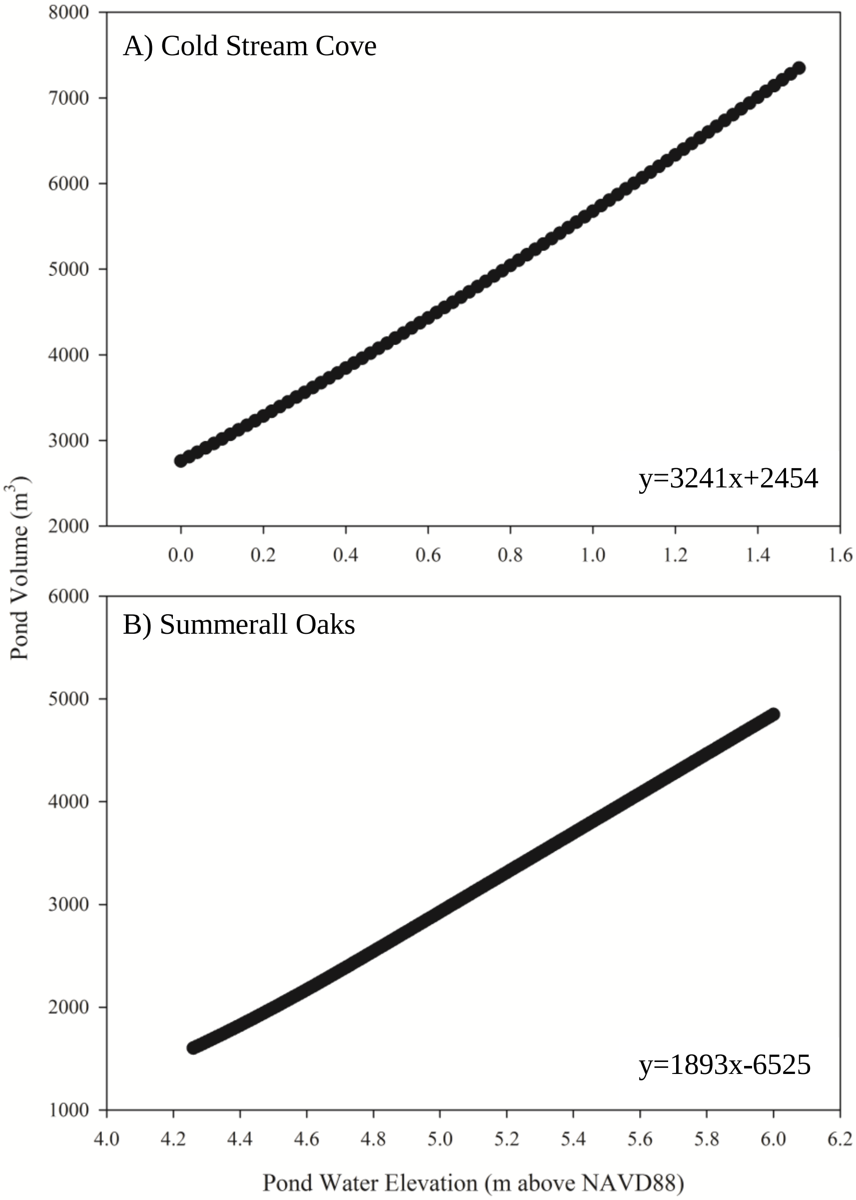

Figure 3. Linear regression trends derived by HYPACK's TIN to Level model used for computing pond volume at Cold Stream Cove (A; R^2=0.99) and Summerall Oaks (B; R^2=0.99)

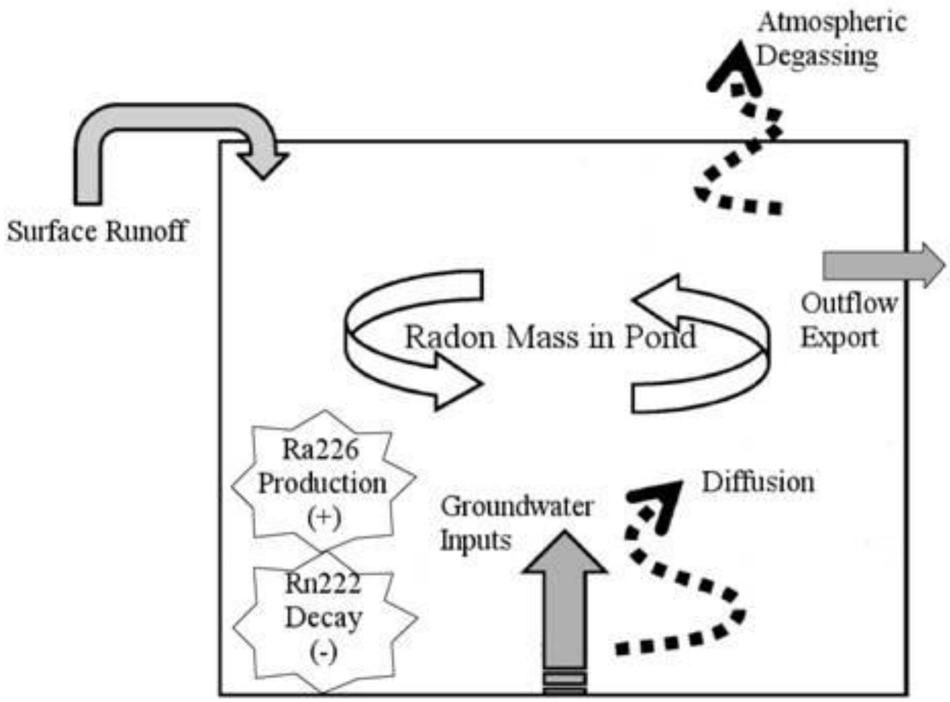

Figure 4. Schematic representation of the ^{222}Rn budget for each pond used to quantify groundwater input rates. The radon activity in each pond represents a balance between sources and sinks within the reservoir. Sources of ^{222}Rn include surface runoff (assumed to be negligible), production from dissolved ^{226}Ra decay, diffusion from bottom sediments, and groundwater inputs. ^{222}Rn sinks include outflow export (including irrigation pump export at Cold Stream Cove), atmospheric degassing, and radioactive decay.

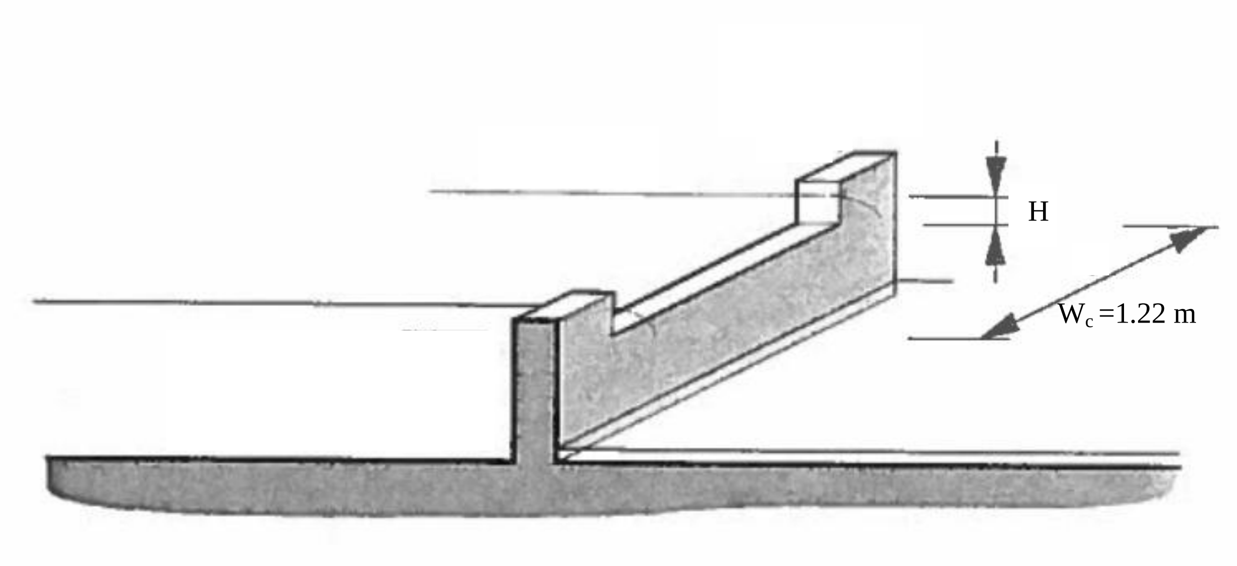

Figure 5. Schematic representation of the broad crested weir (Eq. 9) at Cold Stream Cove (Figure modified from Ferguson, 1998).

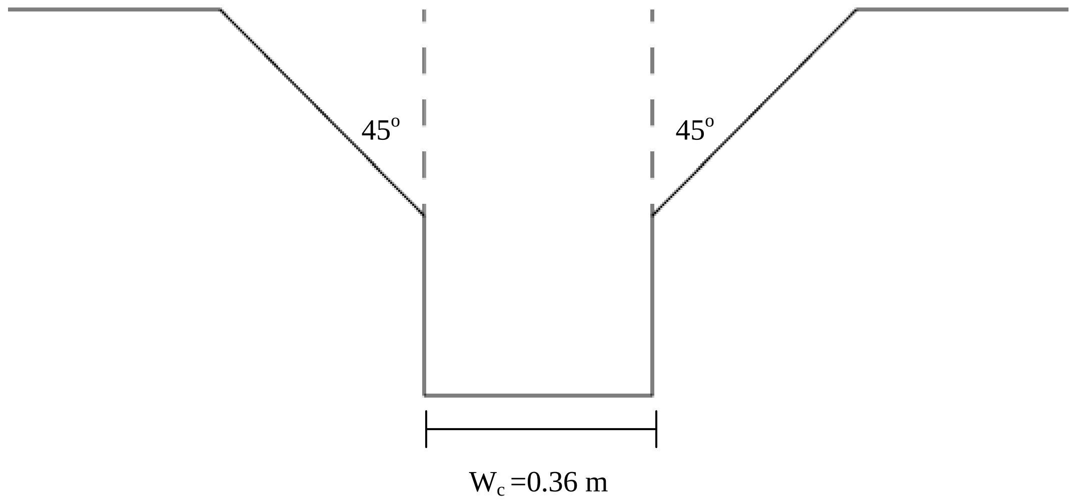

Figure 6. Schematic representation of Summerall Oaks modified weir. Discharge within the dotted lines was calculated using the broad crested weir equation (Eq. 9) and the discharge within the two triangles was calculated using 90° v-notch weir equation (Eq. 10).

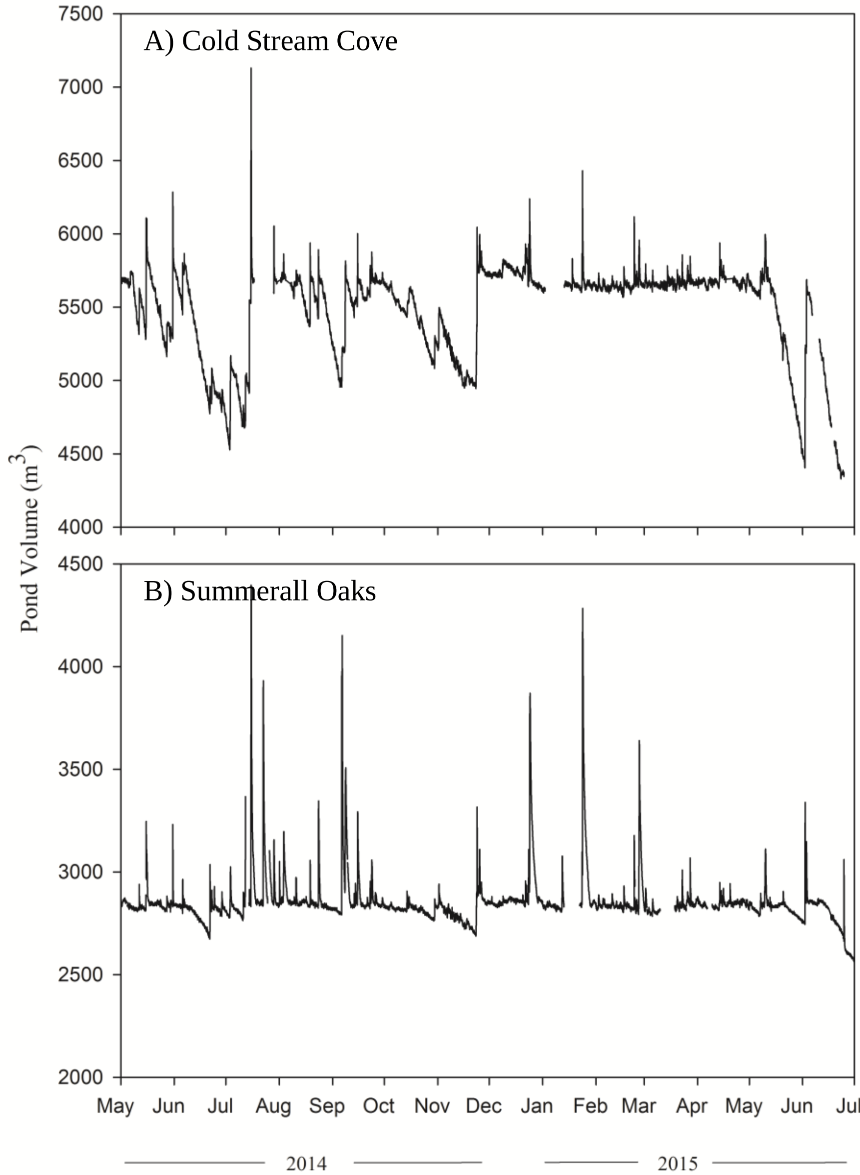

Figure 7. Pond volumes associated with Cold Stream Cove (A) and Summerall Oaks (B) monitored at thirty minute intervals.

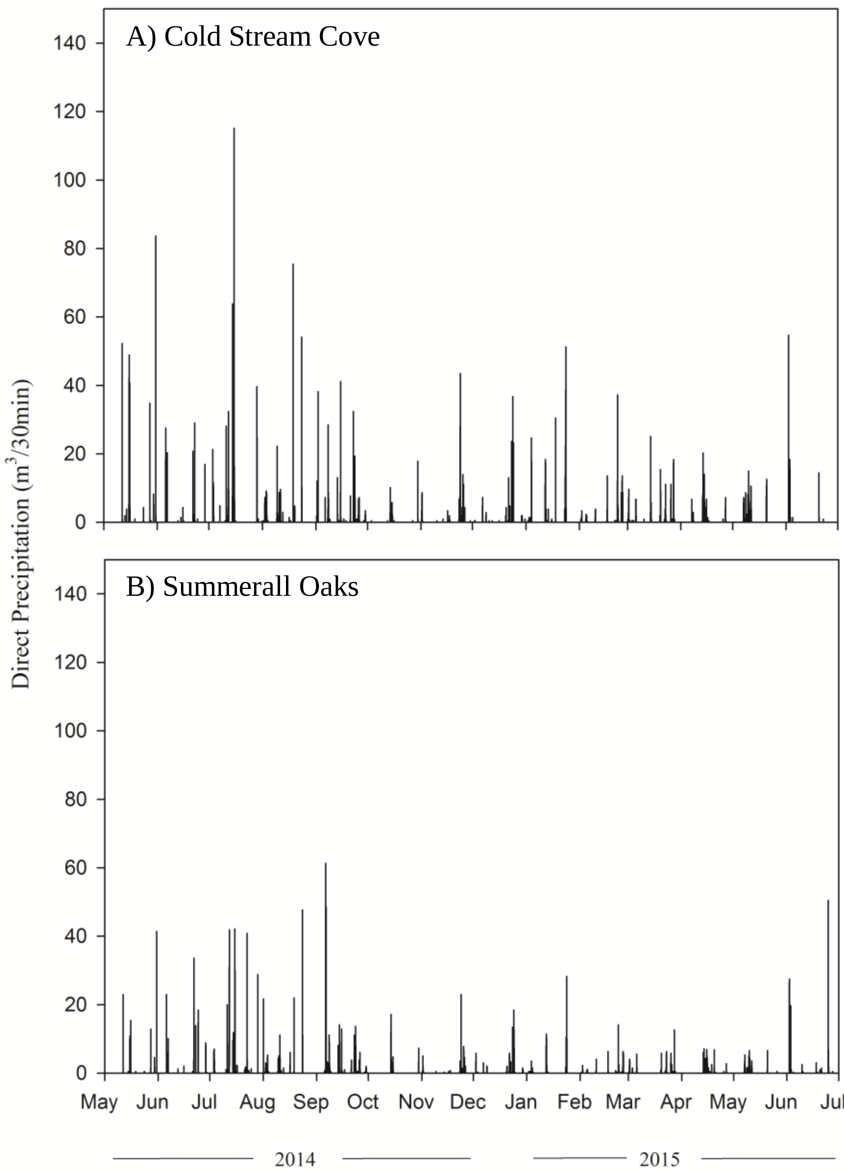

Figure 8. Direct precipitation associated with the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B) monitored at thirty minute intervals

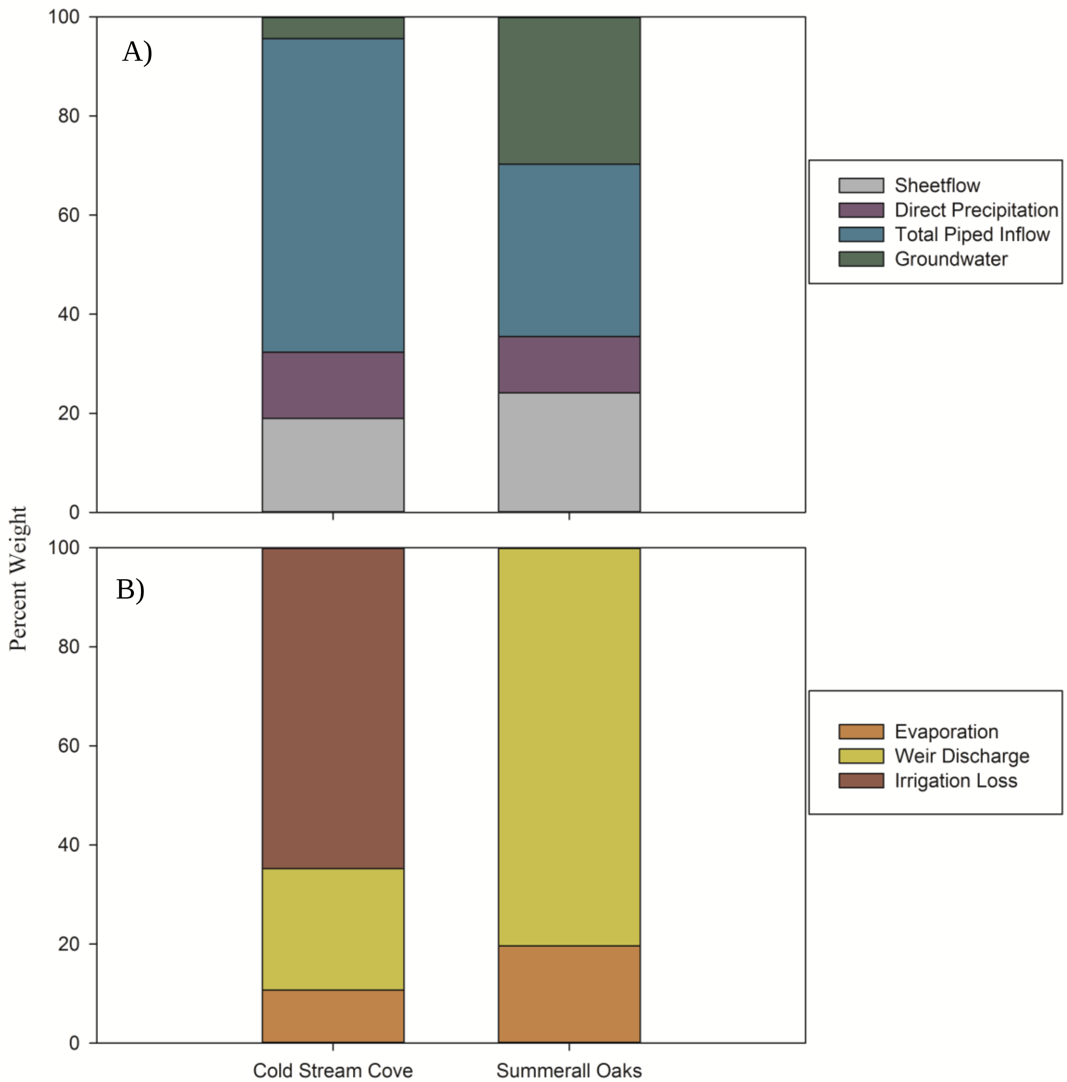

Figure 9. The percent weight of the overall water sources (A) and sinks (B) for the study period. Values were only included when data allowed the complete water budget to be determined. The percent values at Cold Stream Cove represent 92% of the study period and the percent values at Summerall Oaks represent 79% of the study period.

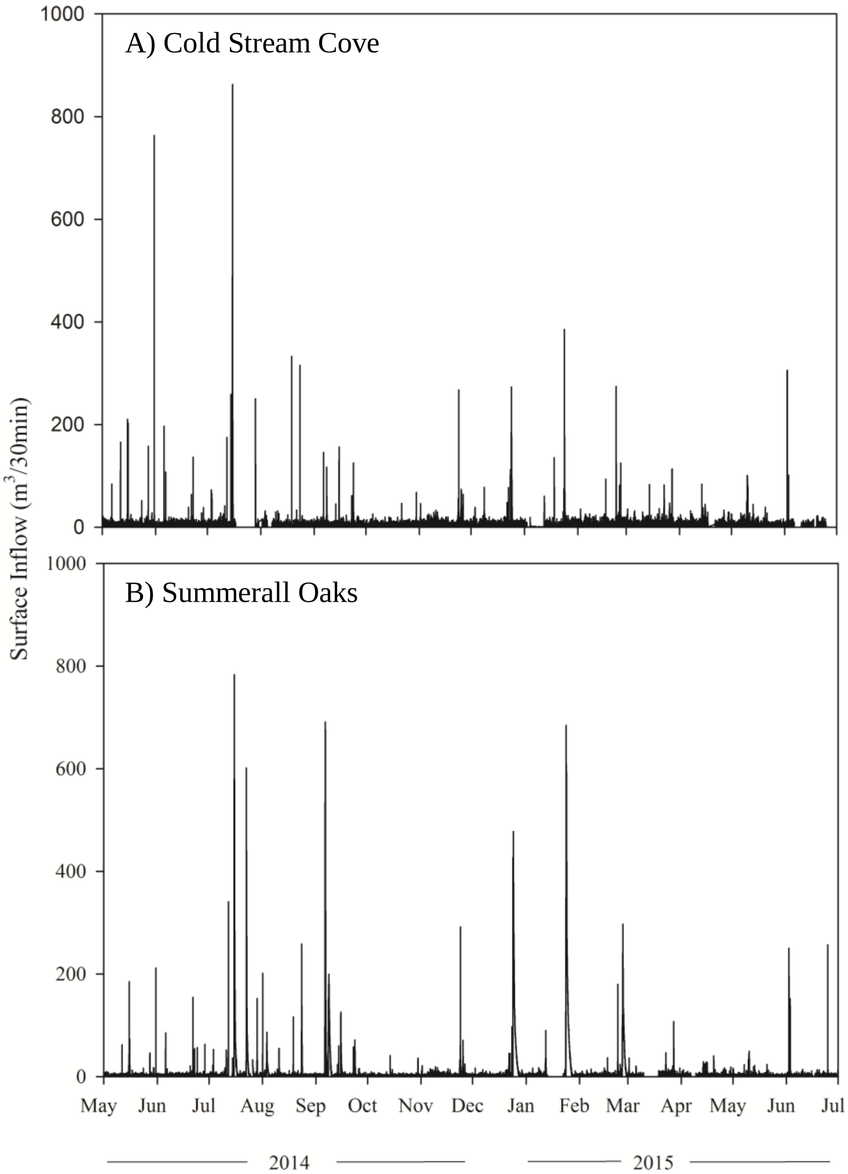

Figure 10. Surface inflow values associated with the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B) at thirty minute intervals.

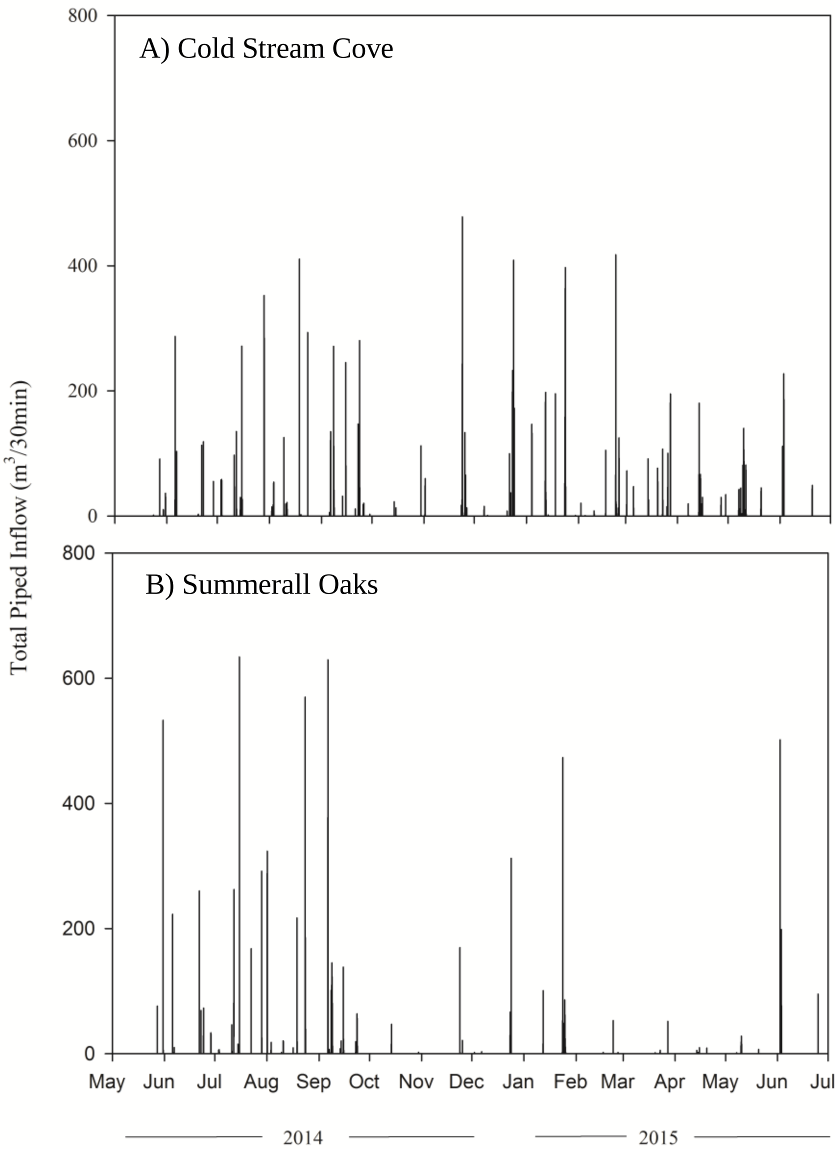

Figure 11. Inlet pipe discharge values associated with the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B) at thirty minute intervals. Piped discharge values are representative of the single pipe directing surface flow at Cold Stream Cove and the three pipes directing surface flow at Summerall Oaks.

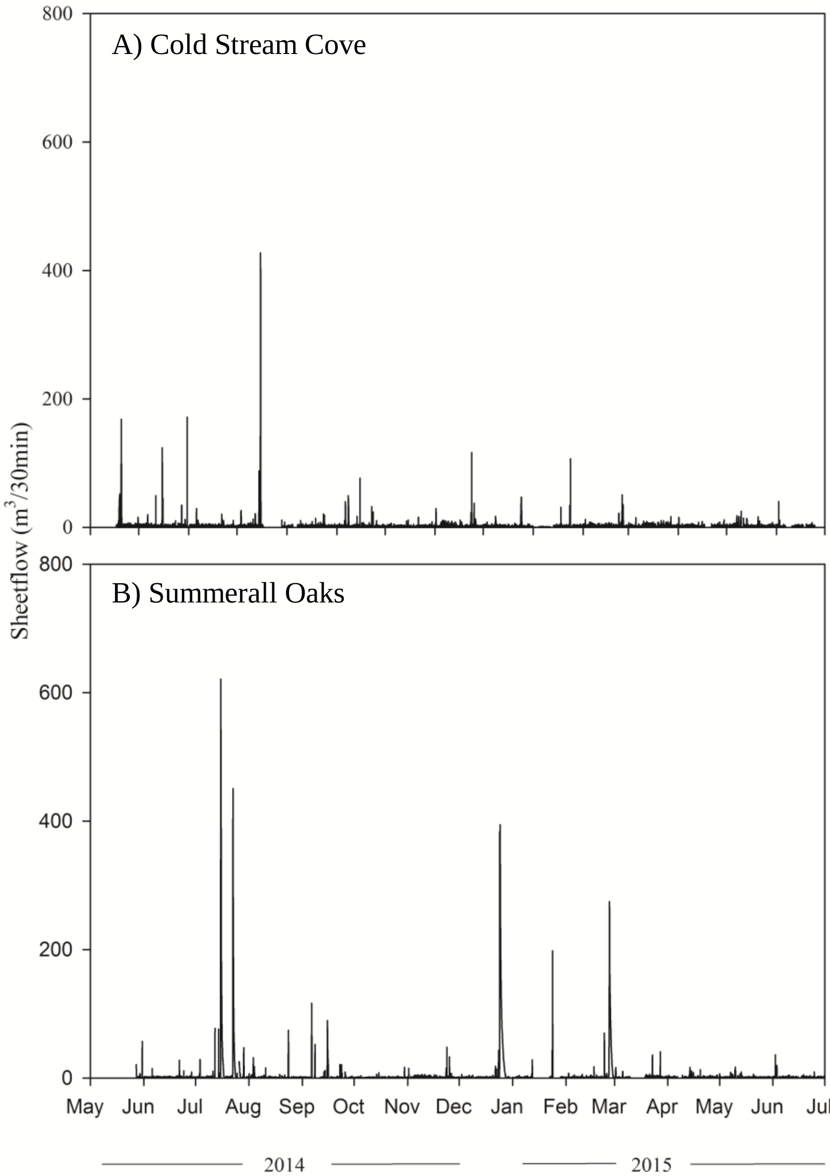

Figure 12. Sheetflow values associated with the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B) at thirty minute intervals.

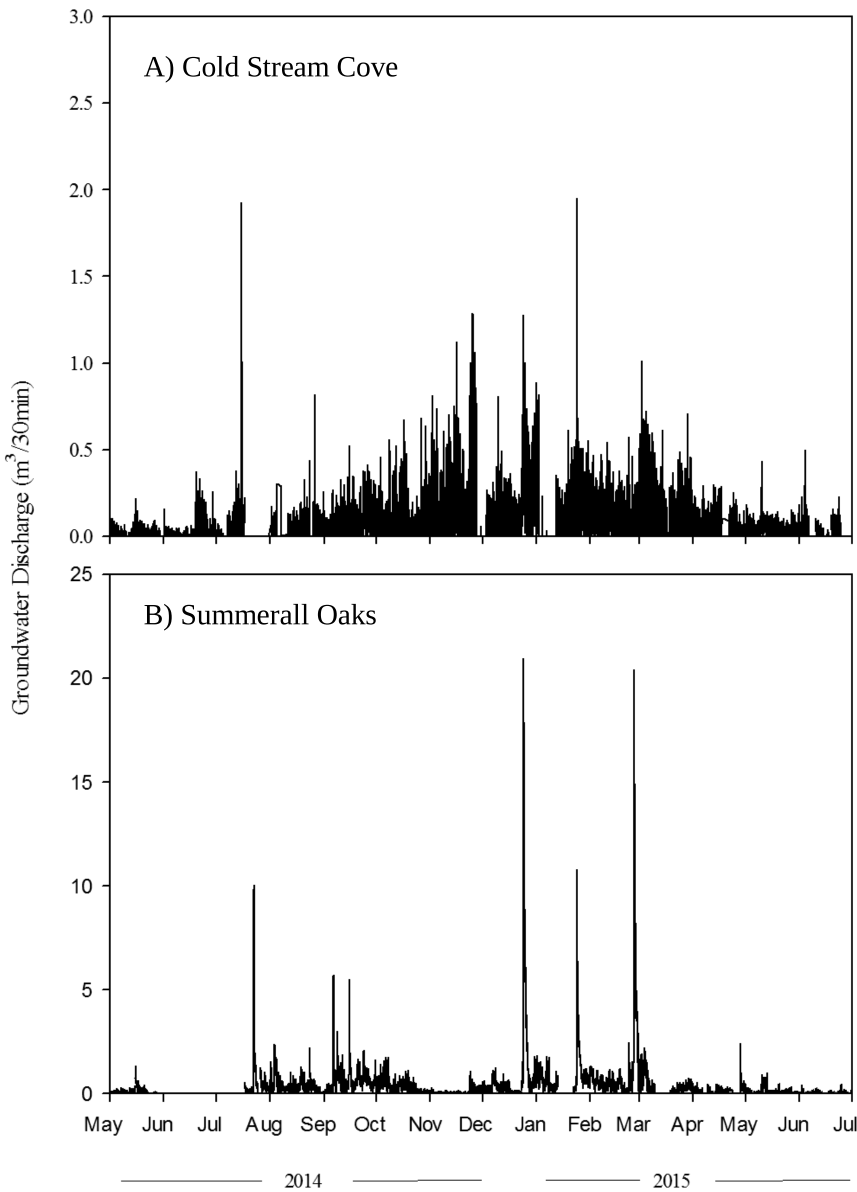

Figure 13. Groundwater discharge values associated with the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B) at thirty minute intervals. Due to instrumentation error, groundwater was not monitored from May 29th, 2014 through July 15th, 2014 at Summerall Oaks. Note the different y-axis scales.

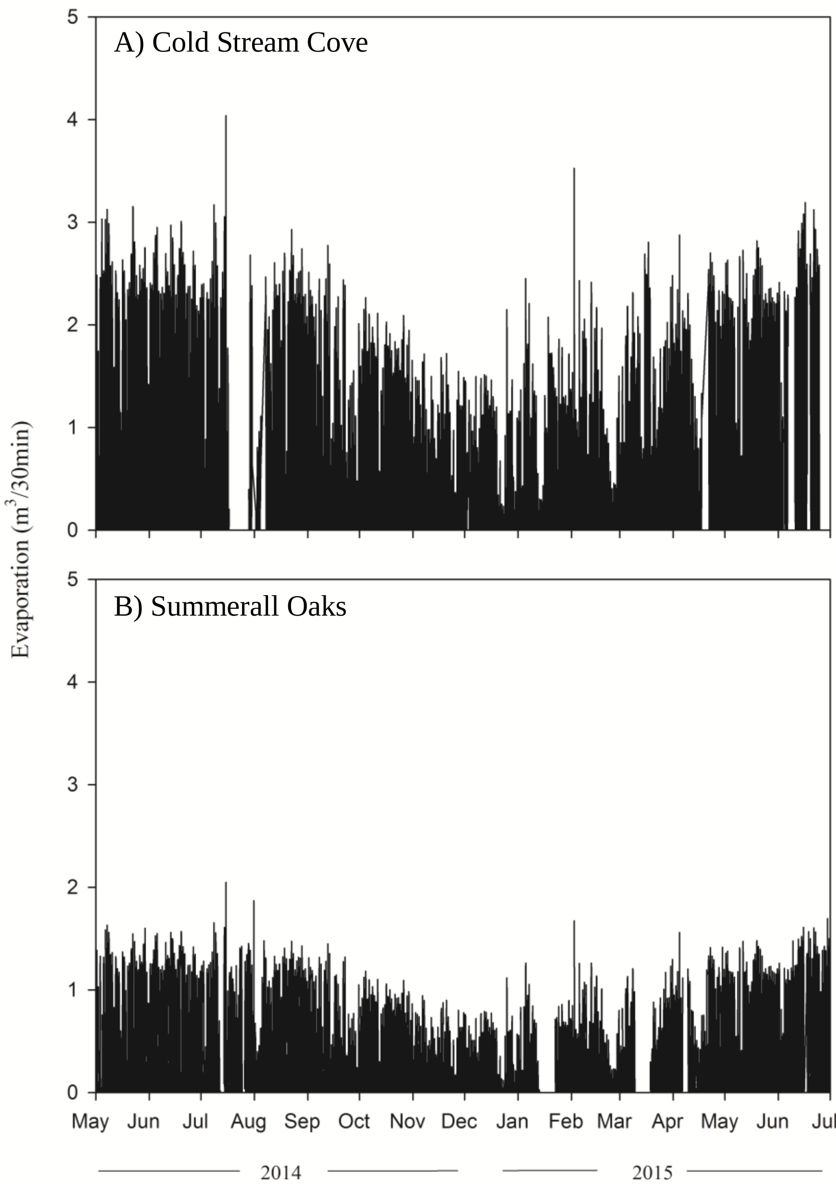

Figure 14. Evaporation values associated with the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B) at thirty minute intervals.

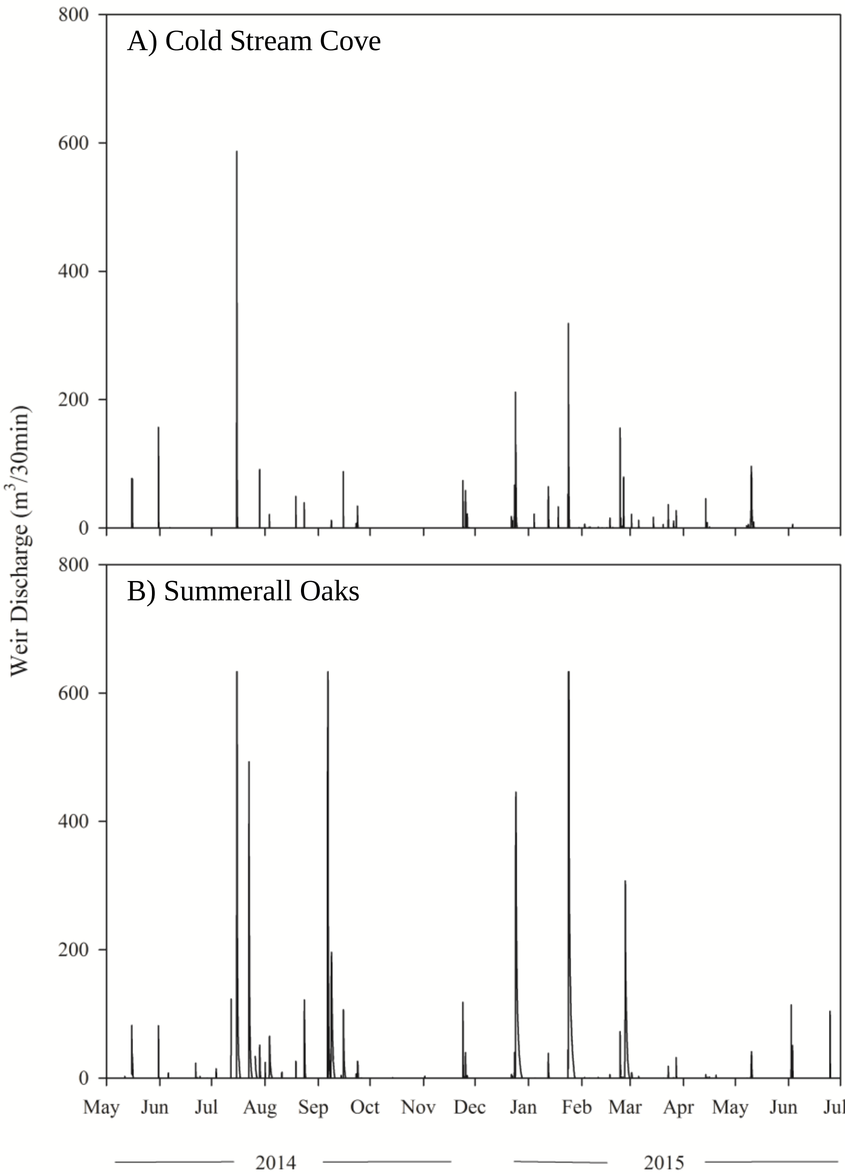

Figure 15. Weir discharge values associated with the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B) at thirty minute intervals.

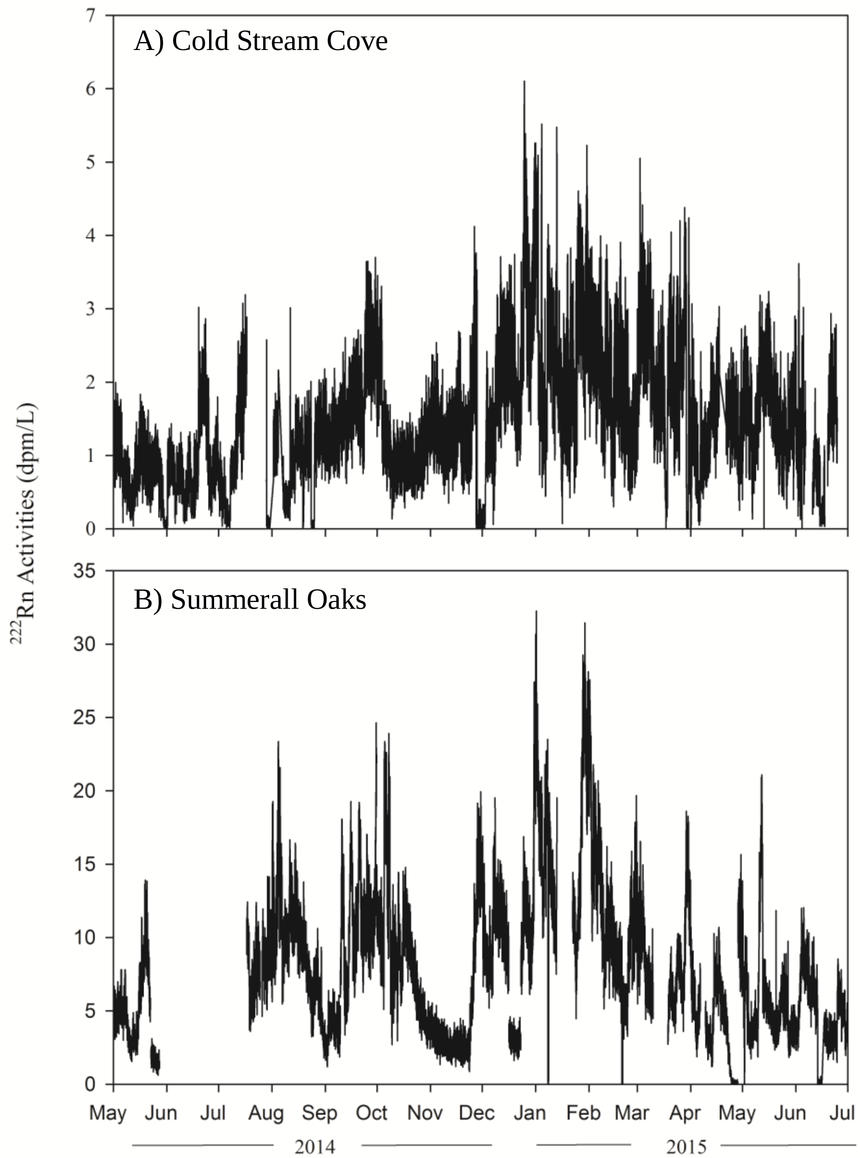

Figure 16. Observed ^{222}Rn activities for the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B).

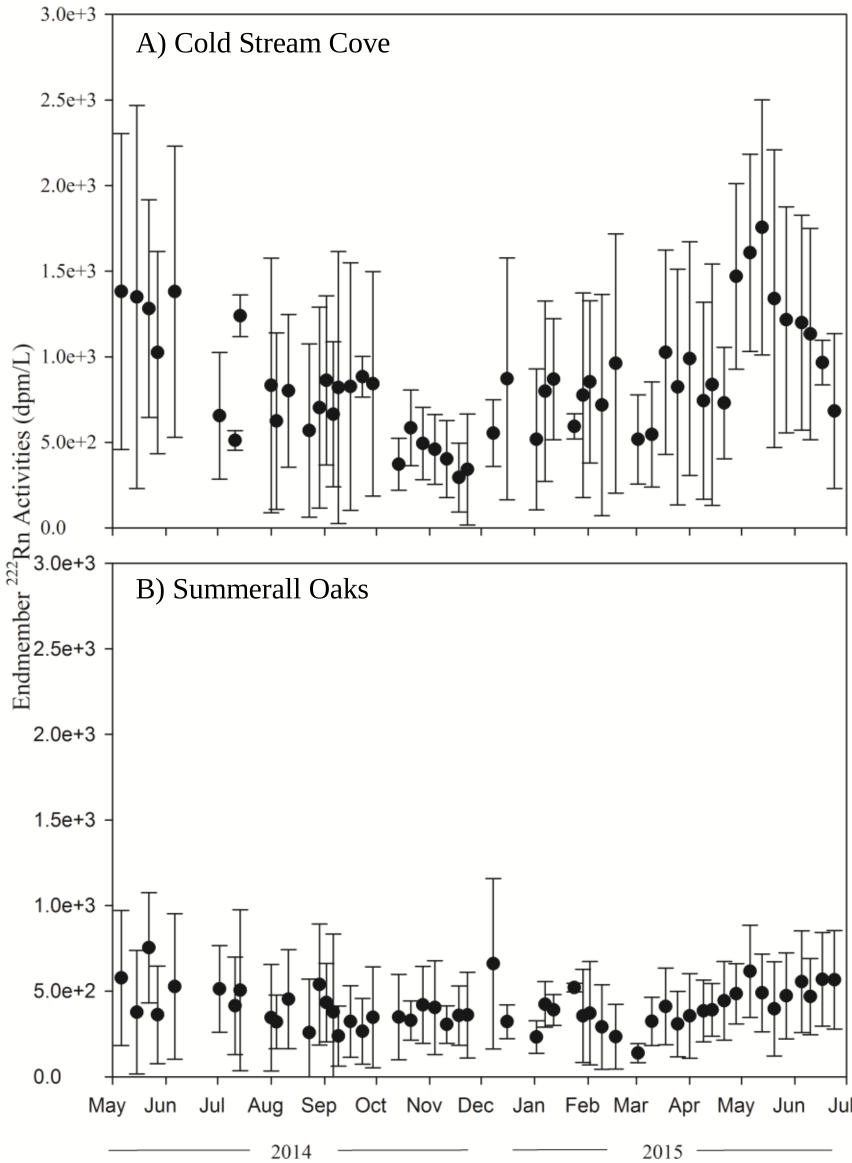

Figure 17. Average groundwater ^{222}Rn activities sampled weekly from two 3-well transects at Cold Stream Cove (A) and Summerall Oaks (B) with associated 1-sigma error bars (n=55).

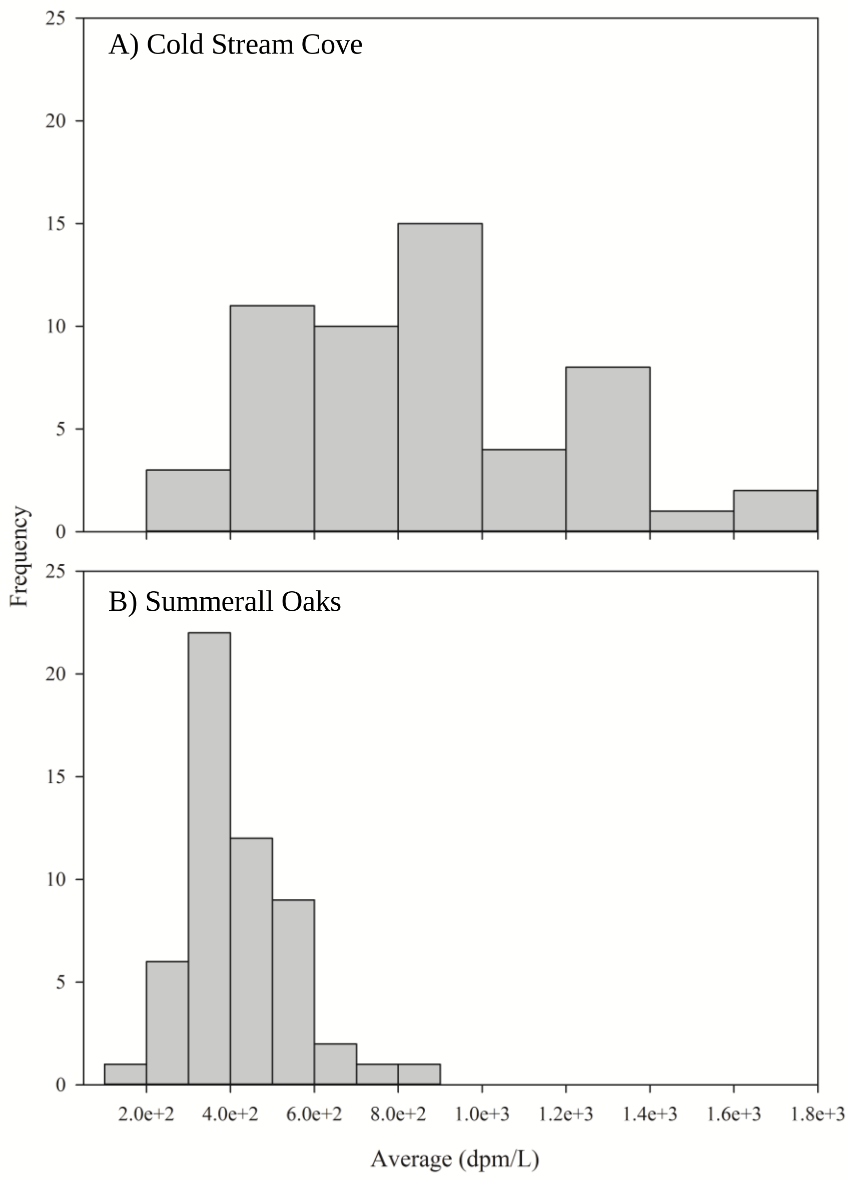

Figure 18. Histogram of radon in groundwater endmember activities measured at Cold Stream Cove (A) and Summerall Oaks (B).

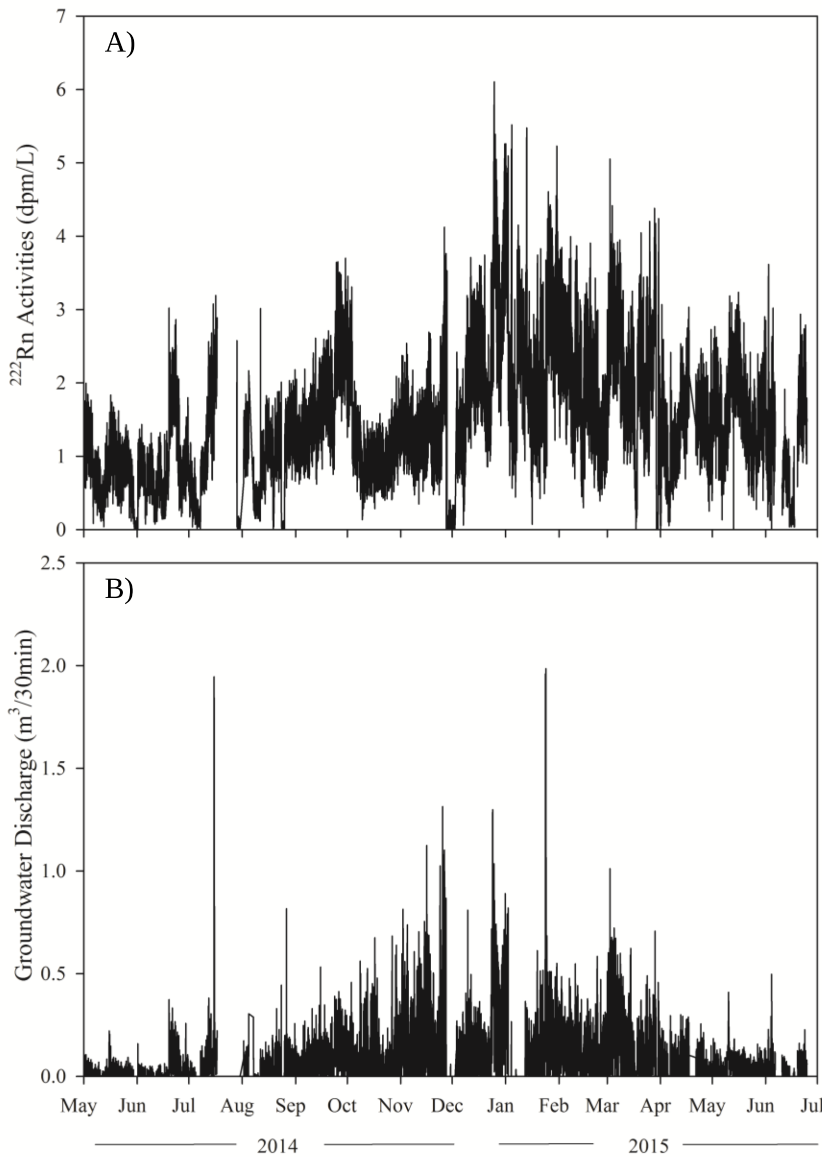

Figure 19. Observed ^{222}Rn activities in the pond at Cold Stream Cove (A) and corresponding groundwater discharges (B) into the pond.

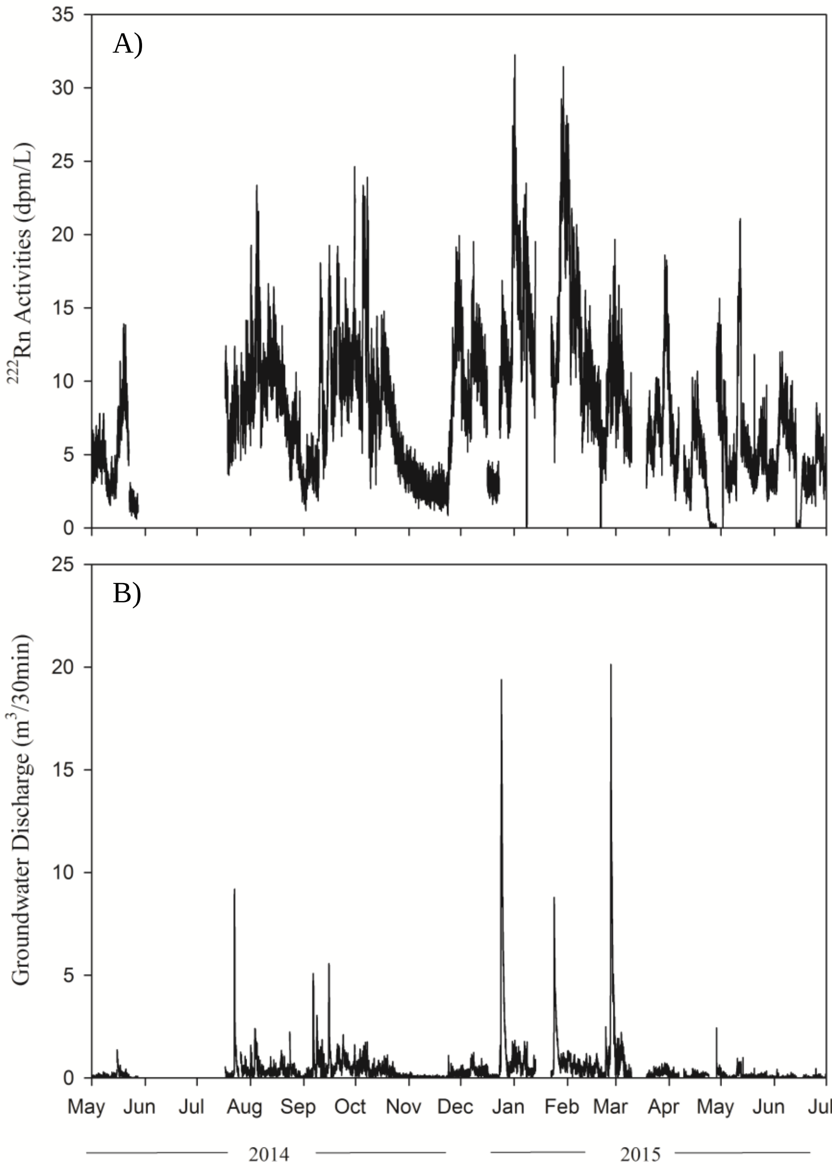

Figure 20. Observed ^{222}Rn activities in the pond at Summerall Oaks (A) and corresponding groundwater discharges (B) into the pond.

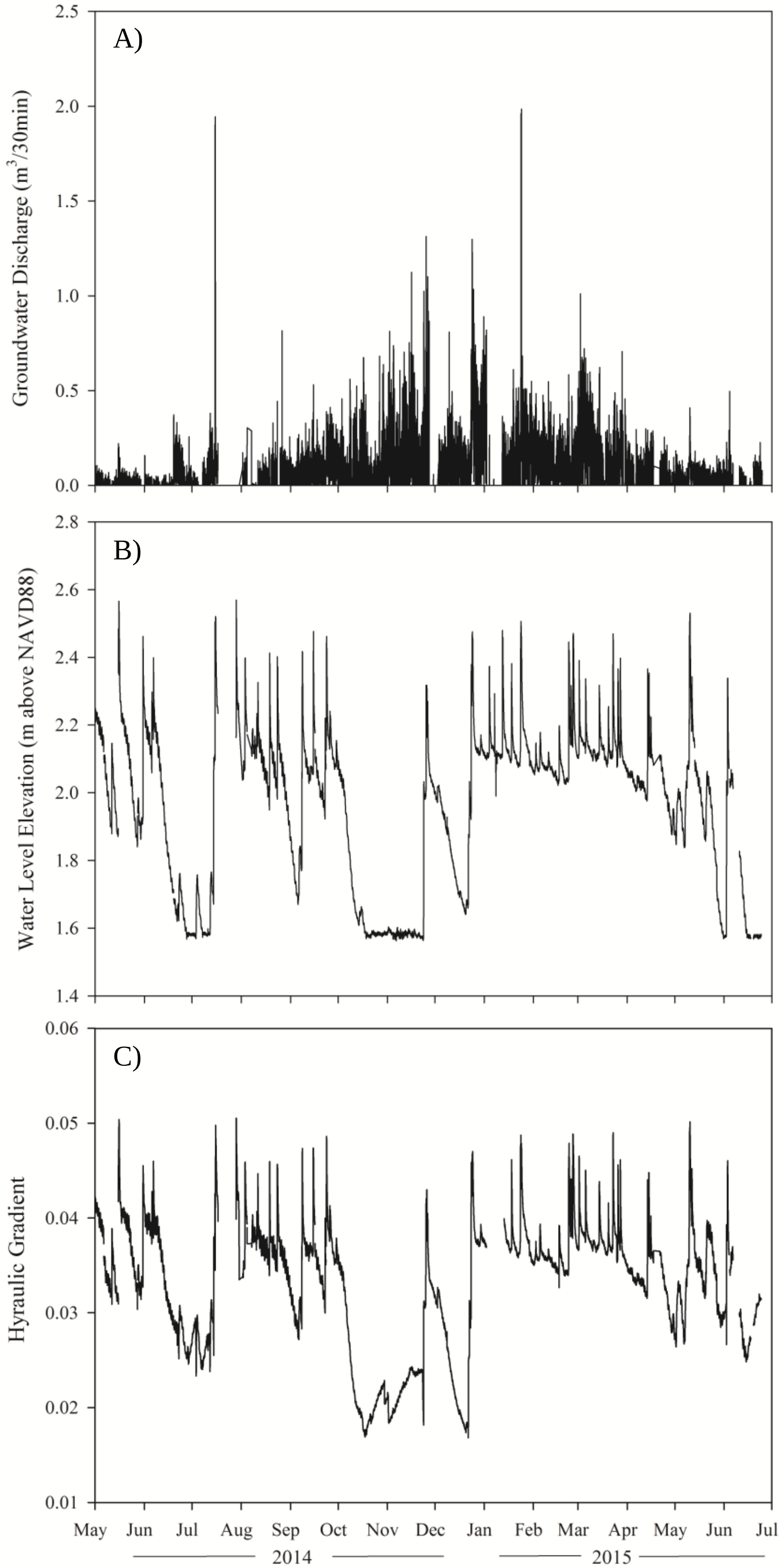

Figure 21. Groundwater discharge rates (A), water table elevation (B), and corresponding hydraulic gradient from a well approximately 25 m from the pond at Cold Stream Cove. Water table elevations below 1.6 m were unable to be resolved.

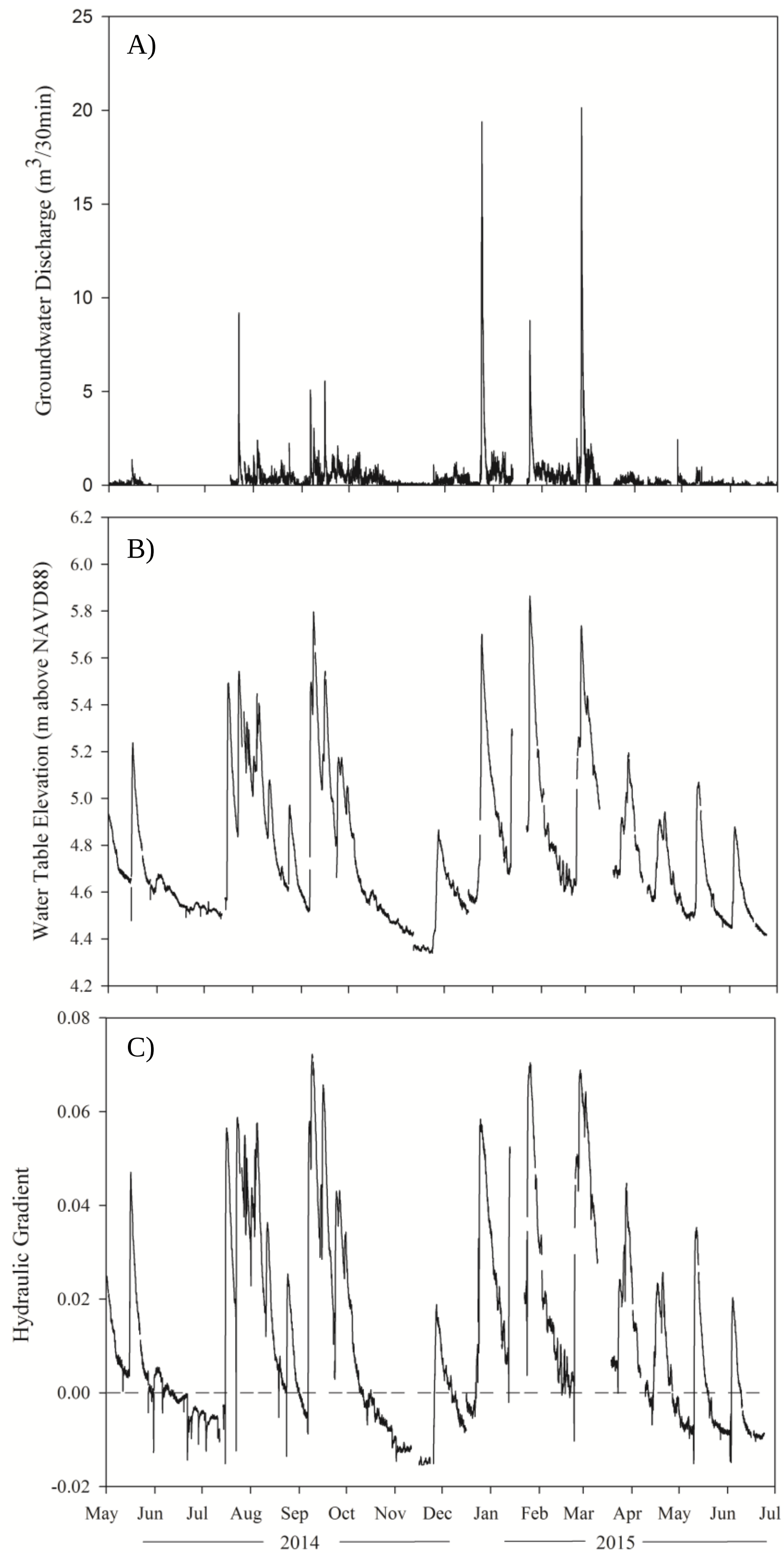

Figure 22. Groundwater discharge rates (A), water table elevation (B), and corresponding hydraulic gradient from a well approximately 13 m from the pond at Summerall Oaks.

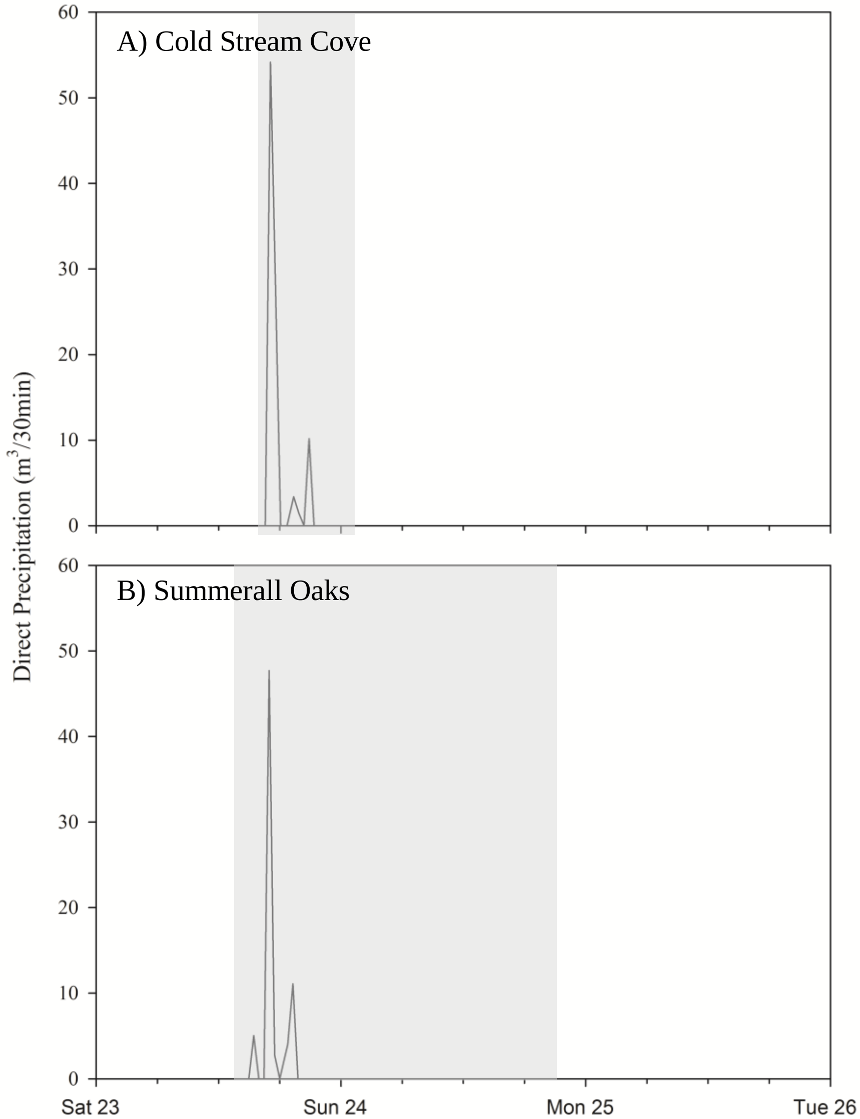

Figure 23. Direct precipitation rates at Cold Stream Cove (A) and Summerall Oaks (B) in response to a rain event occurring on August 23rd, 2014. The event duration is shown in gray.

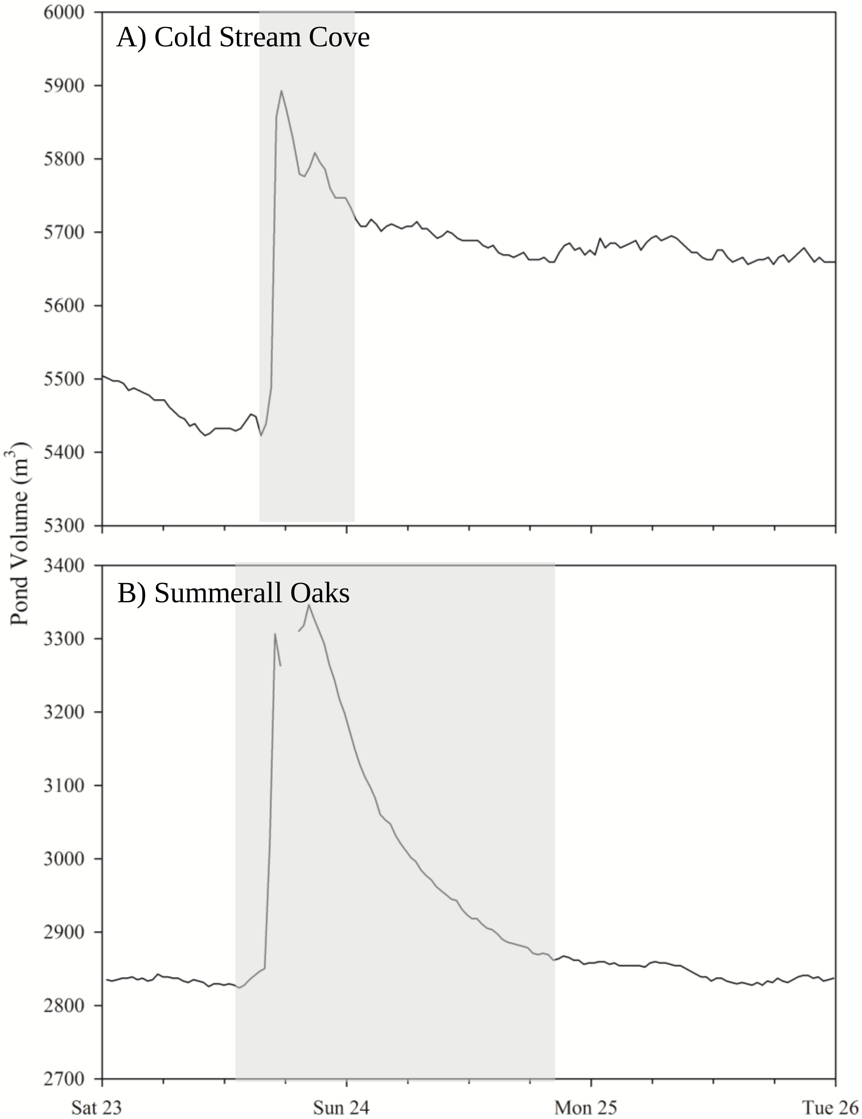

Figure 24. Pond volume at Cold Stream Cove (A) and Summerall Oaks (B) in response to a rain event occurring on August 23rd, 2014. The event duration is shown in gray.

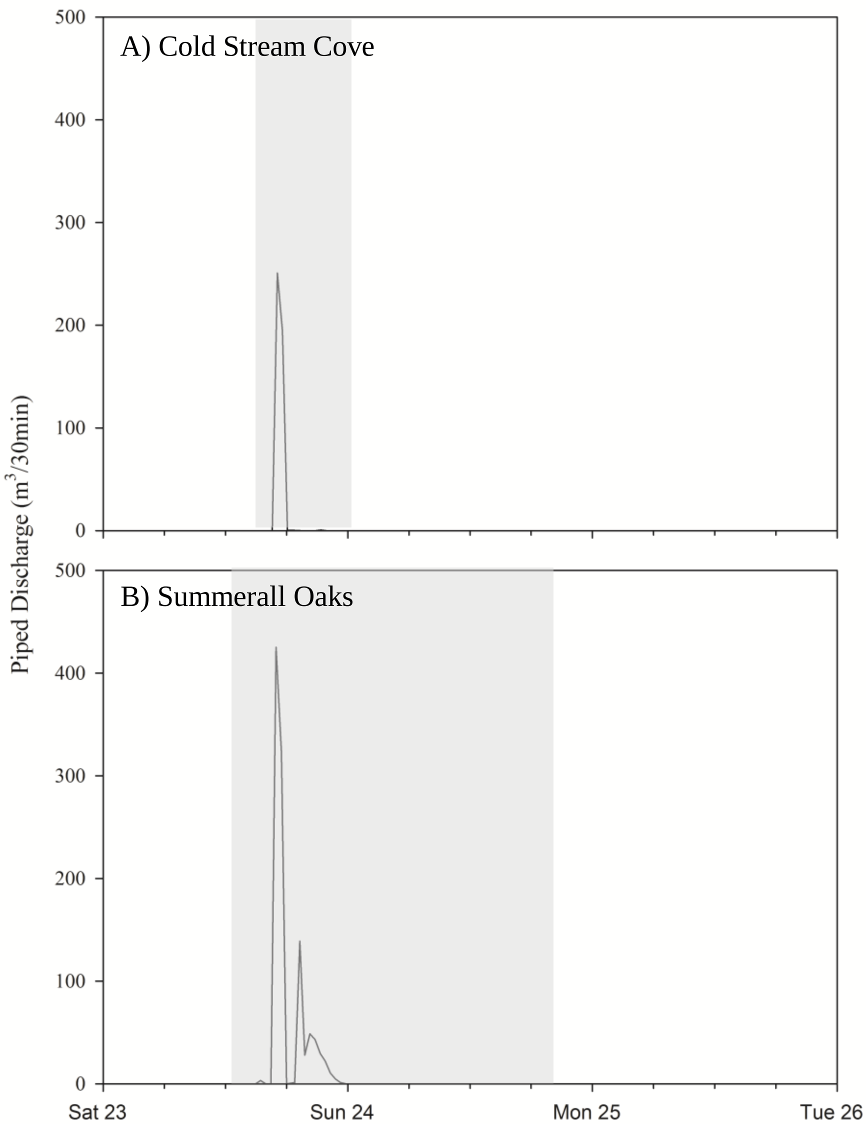

Figure 25. Piped discharge at Cold Stream Cove (A) and Summerall Oaks (B) in response to a rain event occurring on August 23rd, 2014. The event duration is shown in gray.

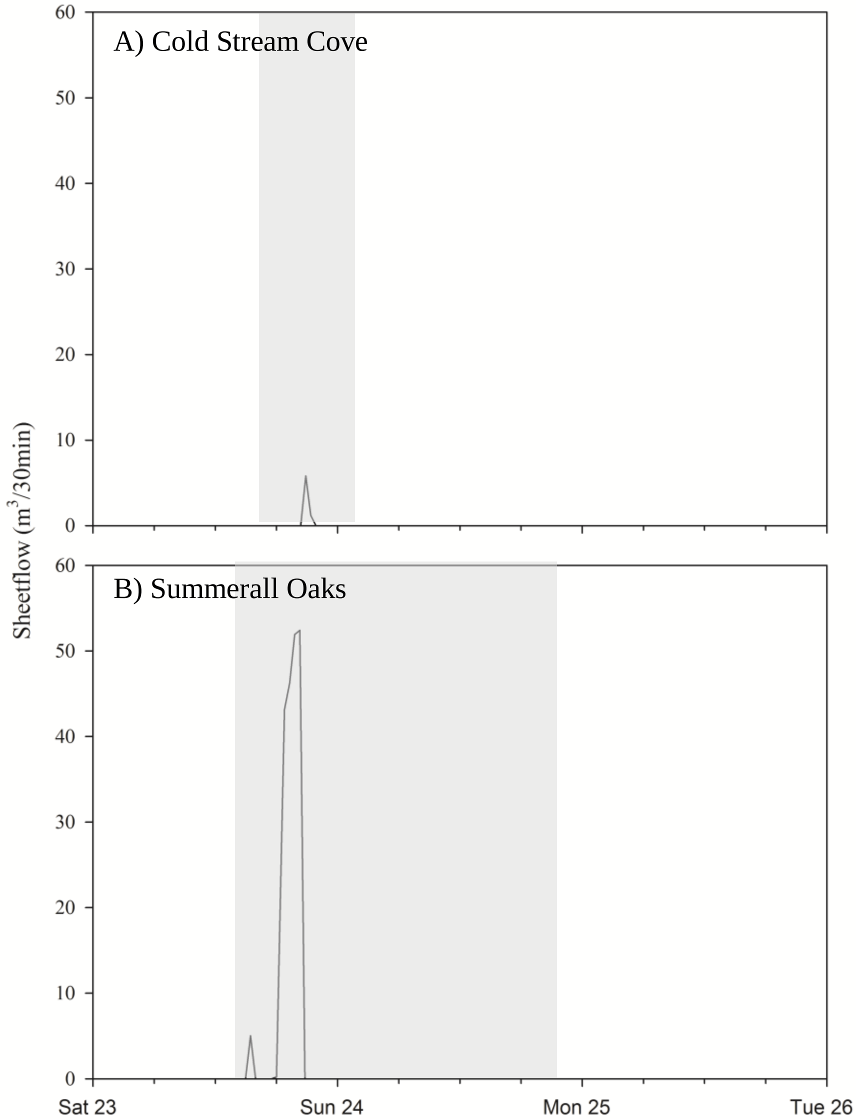

Figure 26. Sheetflow values at Cold Stream Cove (A) and Summerall Oaks (B) in response to a rain event occurring on August 23rd, 2014. The event duration is shown in gray.

Figure 27. Photographs of the steep rooftops at Summerall Oaks (A) and the drainage pipes directing runoff towards the pond in the form of sheetflow across the yards surrounding the pond at Sumerall Oaks (B). Similar drainage pipes are observed for the single condominium adjacent to the pond at Cold Stream Cove.

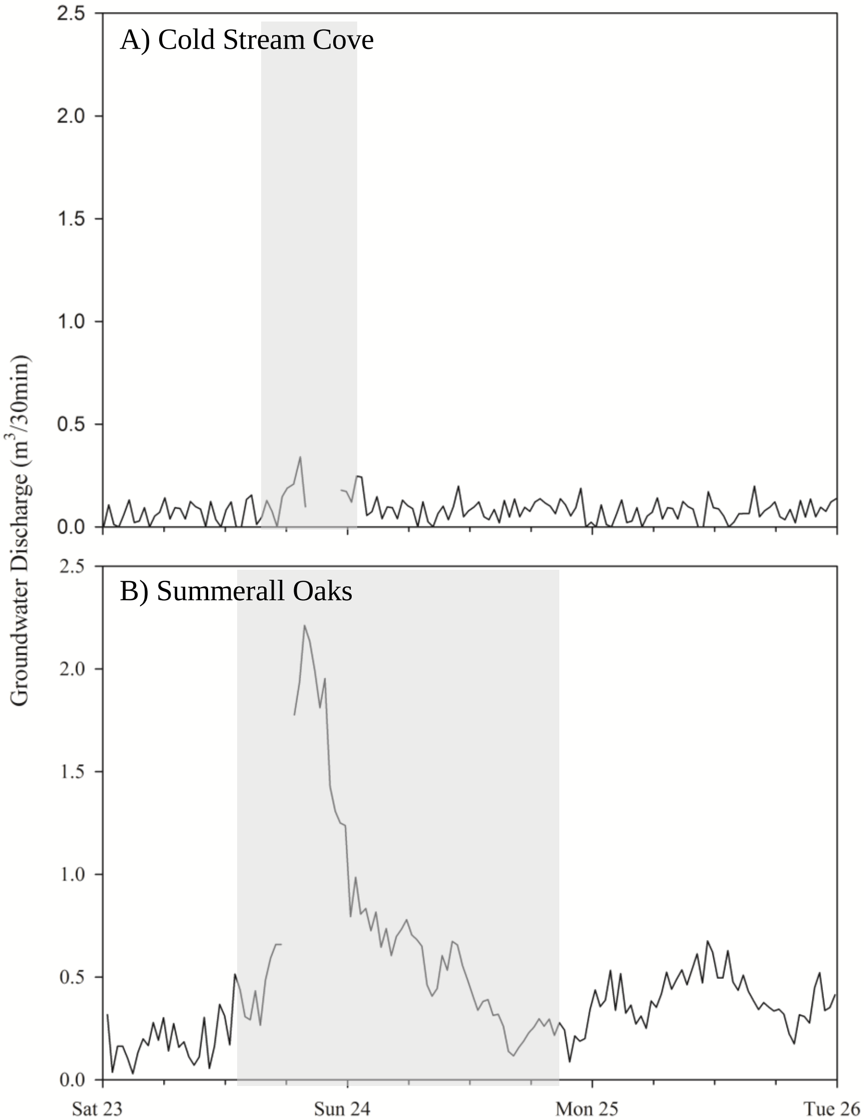

Figure 28. Groundwater discharge rates at Cold Stream Cove (A) and Summerall Oaks (B) in response to a rain event occurring on August 23rd, 2014. The event duration is shown in gray.

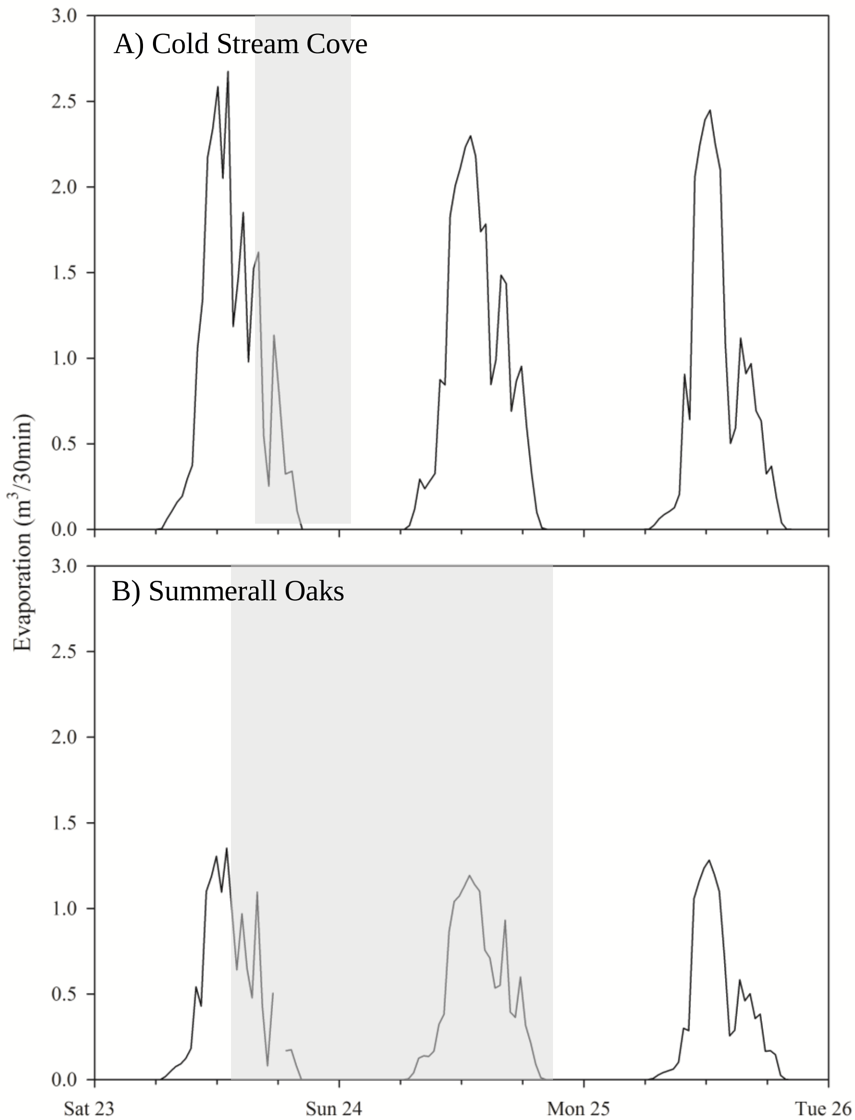

Figure 29. Evaporation rates at Cold Stream Cove (A) and Summerall Oaks (B) during a rain event occurring on August 23rd, 2014. The event duration is shown in gray.

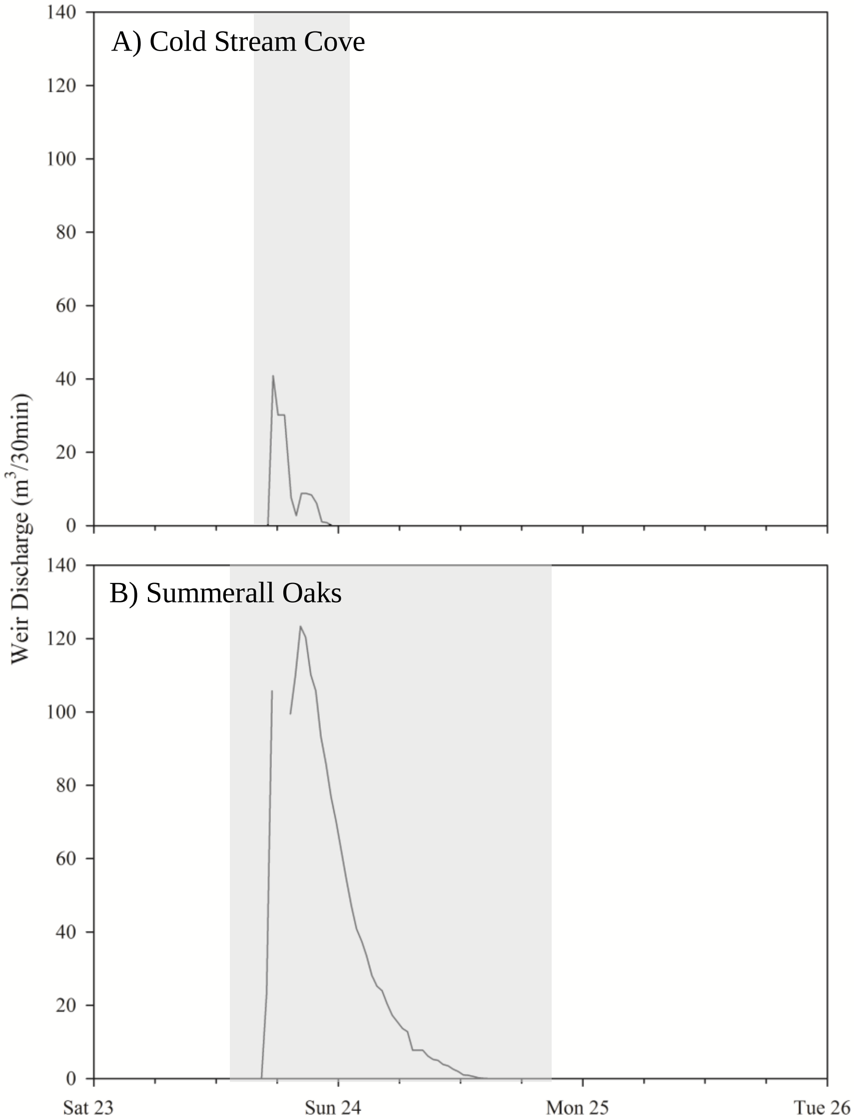

Figure 30. Weir discharge rates at Cold Stream Cove (A) and Summerall Oaks (B) in response to a rain event occurring on August 23rd, 2014. The event duration is shown in gray.

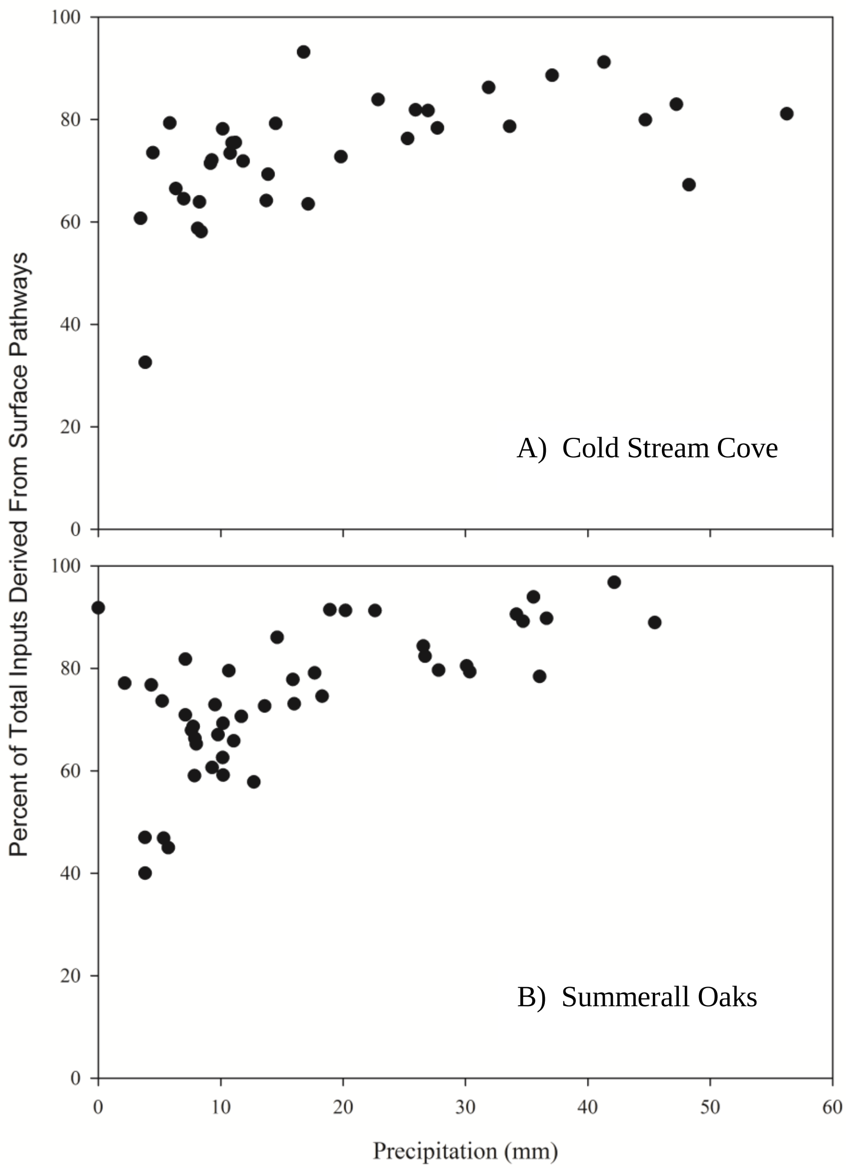

Figure 31. Percent of total inputs derived from surface pathways as a function of rainfall accumulation for the pond at Cold Stream Cove (A) and Summerall Oaks (B).

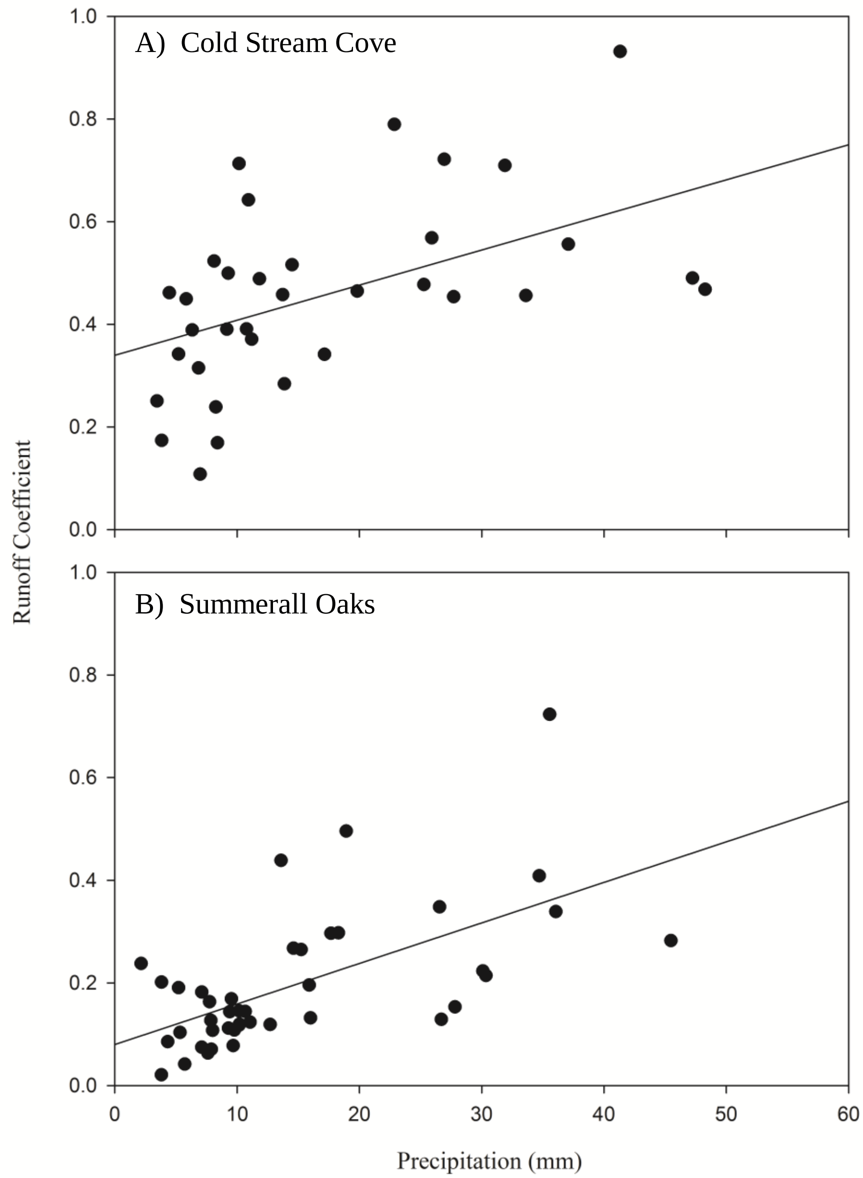

Figure 32. Runoff coefficients as a function of rainfall accumulation for the pond at Cold Stream Cove (A; R^2=0.437, n=42, p<0.01) and the pond at Summerall Oaks (B; R^2=0.360, n=45, p<0.01).

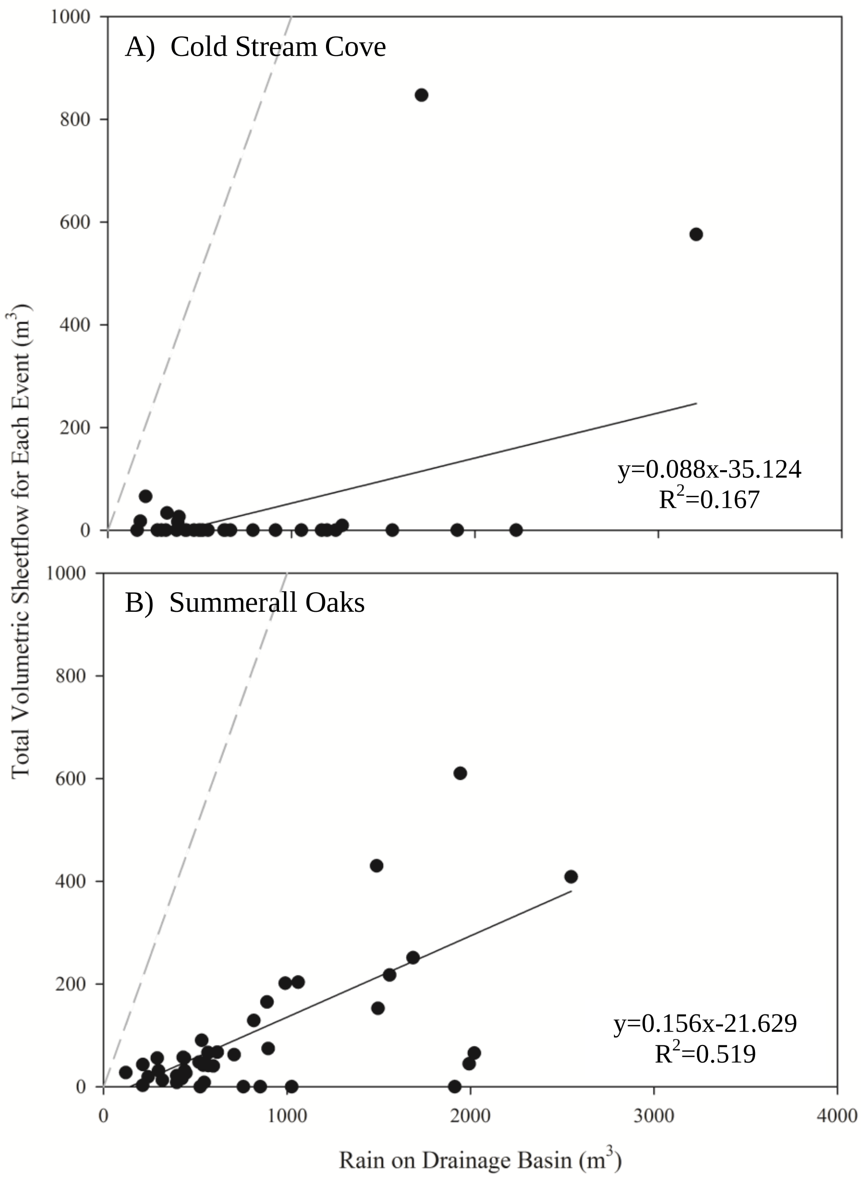

Figure 33. Total volumetric sheetflow for each event as a function of volumetric rainfall in the drainage basin at Cold Stream Cove (A; R^2=0.17, n=42, p>0.1) and Summerall Oaks (B; R^2=0.52, n=45, p<0.01). The dashed line represents the 1:1 ratio.

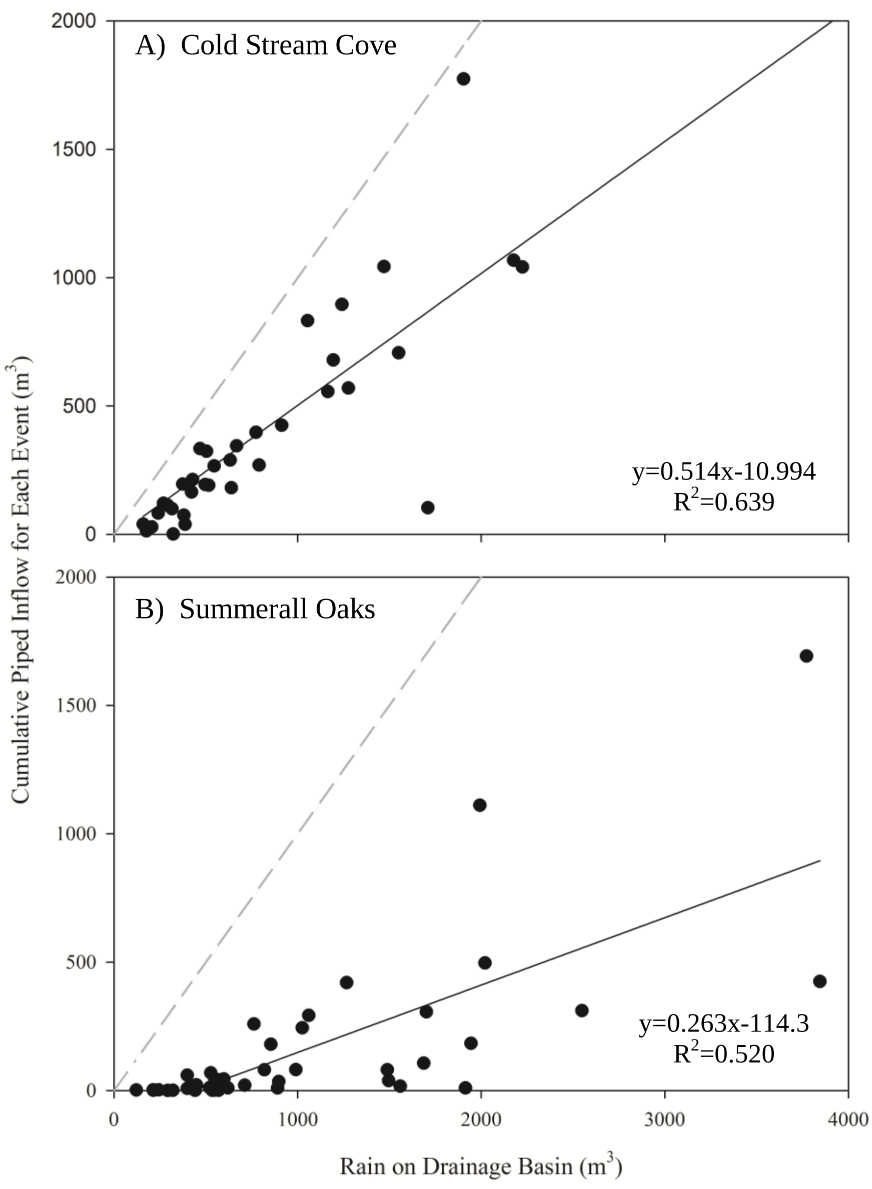

Figure 34. Cumulative piped inflow for each event as a function of volumetric rainfall in the drainage basin at Cold Stream Cove (A; R^2=0.64, n=42, p<0.01) and Summerall Oaks (B; R^2=0.52, n=45, p<0.05). The dashed line represents the 1:1 ratio.

Figure 35. Photograph of grated manhole covers located in the yards of Cold Stream Cove and Summerall Oaks. The water which flows into these manholes travels to the pond via stormwater piped systems.

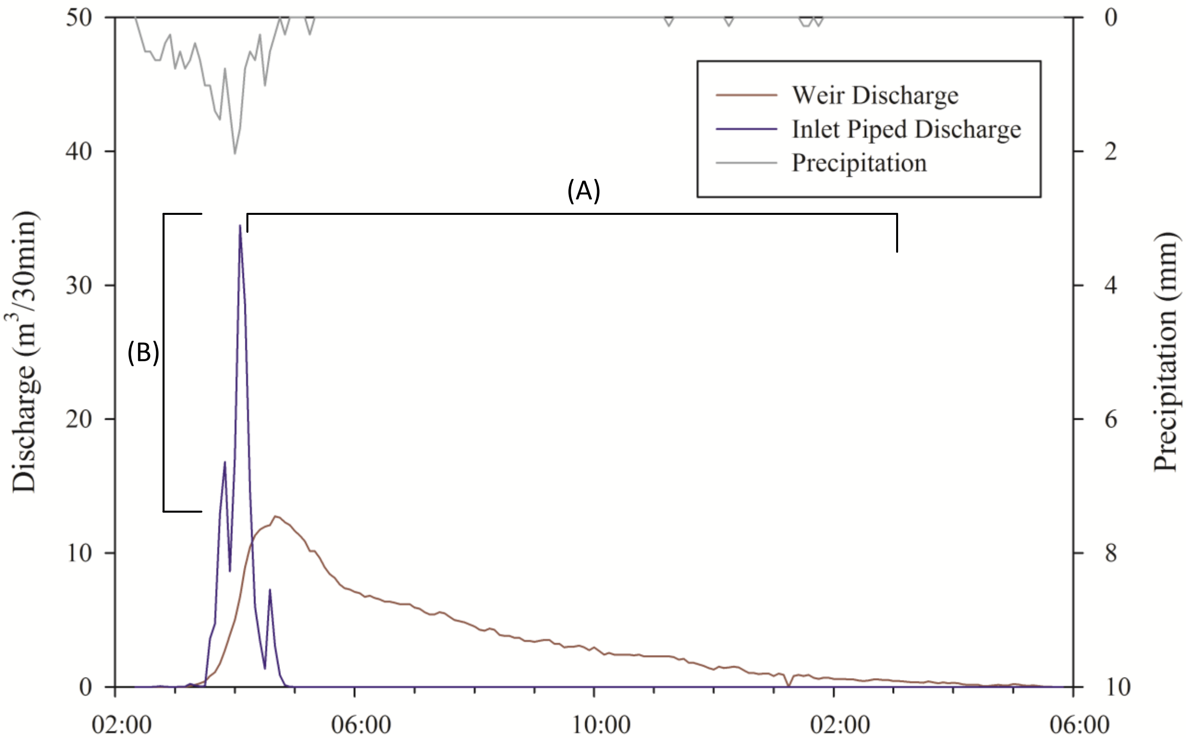

Figure 36. Example of elongation (A) and peak flow reduction (B) based on an event which occurred at the pond at Summerall Oaks on February 23rd, 2015. In this event the inflow duration was 14% of the outflow duration and the peak flow was reduced by 65%.

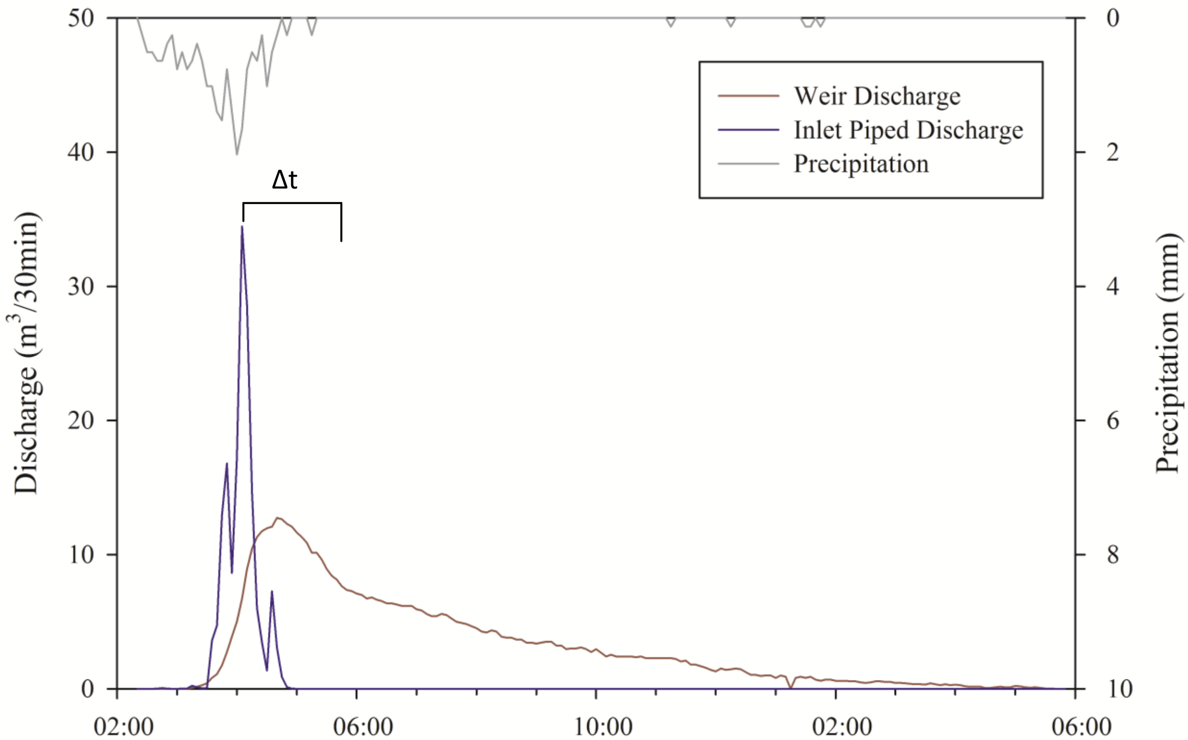

Figure 37. Example of calculating centroid lag time based on an event which occurred at the pond at Summerall Oaks on February 23rd, 2015. The midpoint for the piped inflow occurred at 04:05 and the midpoint for the weir discharge occurred at 06:25, creating a lag time of 2.33 hours.

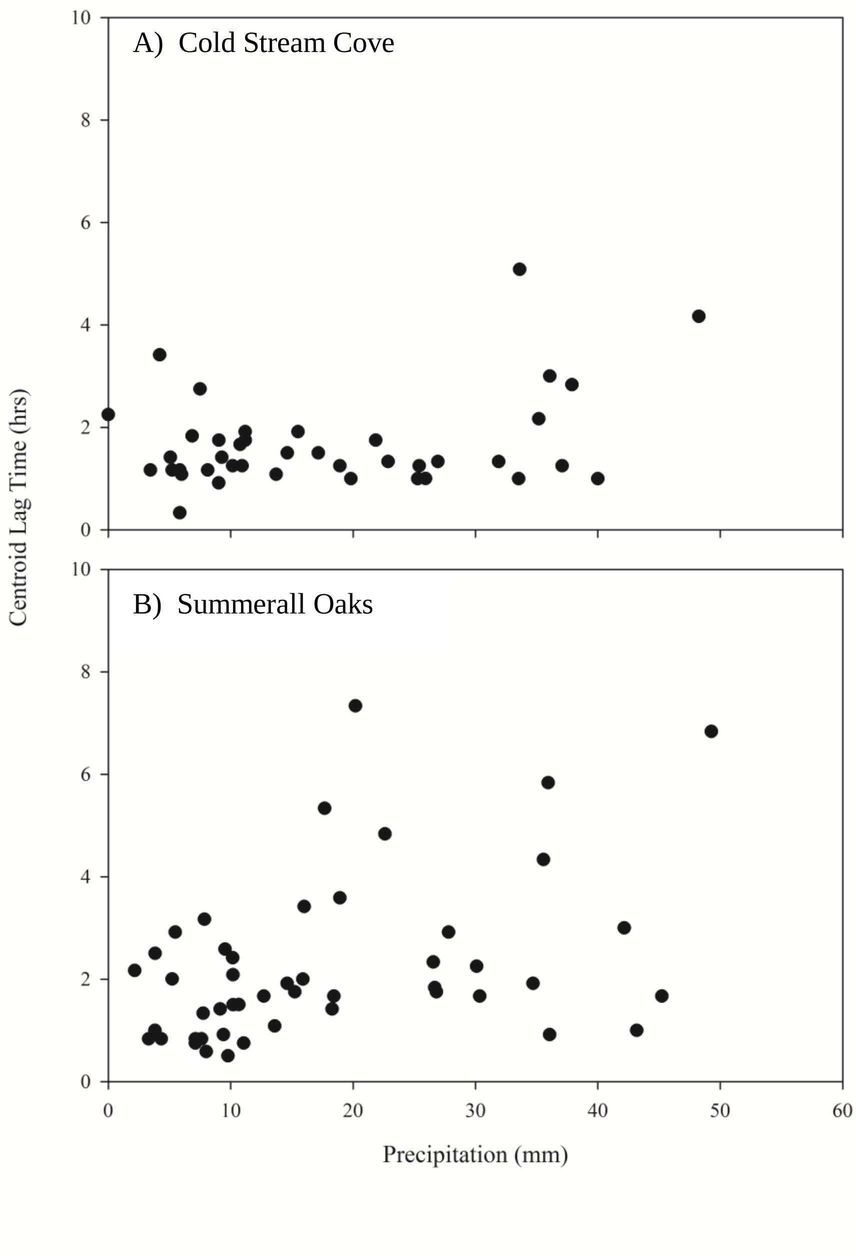

Figure 38. Centroid lag time values as a function of rainfall accumulation for the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B).

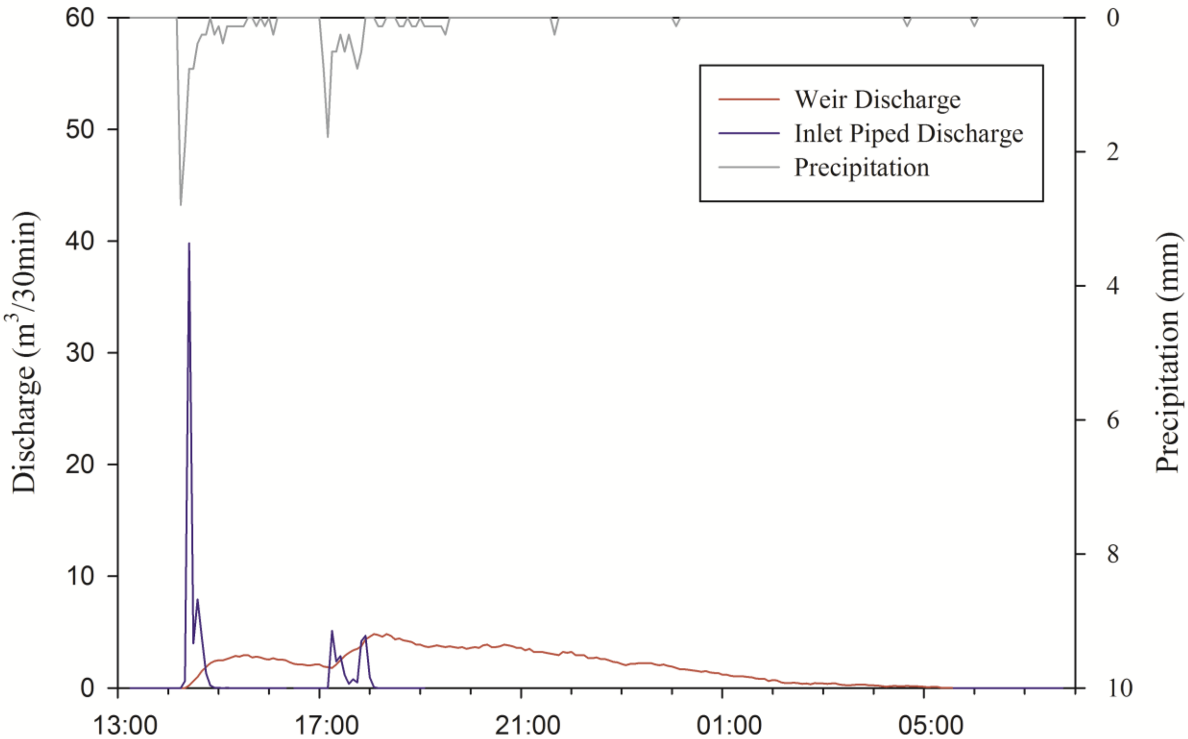

Figure 39. Example of when storm "piggybacking" influences the calculated centroid lag time. This example is an event which occurred at the pond at Summerall Oaks on September 23rd, 2014. The midpoint for the piped inflow occurred at 14:25 and the midpoint for the weir discharge occurred at 19:45 creating a lag time of 5.33 hours. If the inflow was more intense during the second band of rain, it could have resulted in the centroid lag time having shortened by up to three hours.

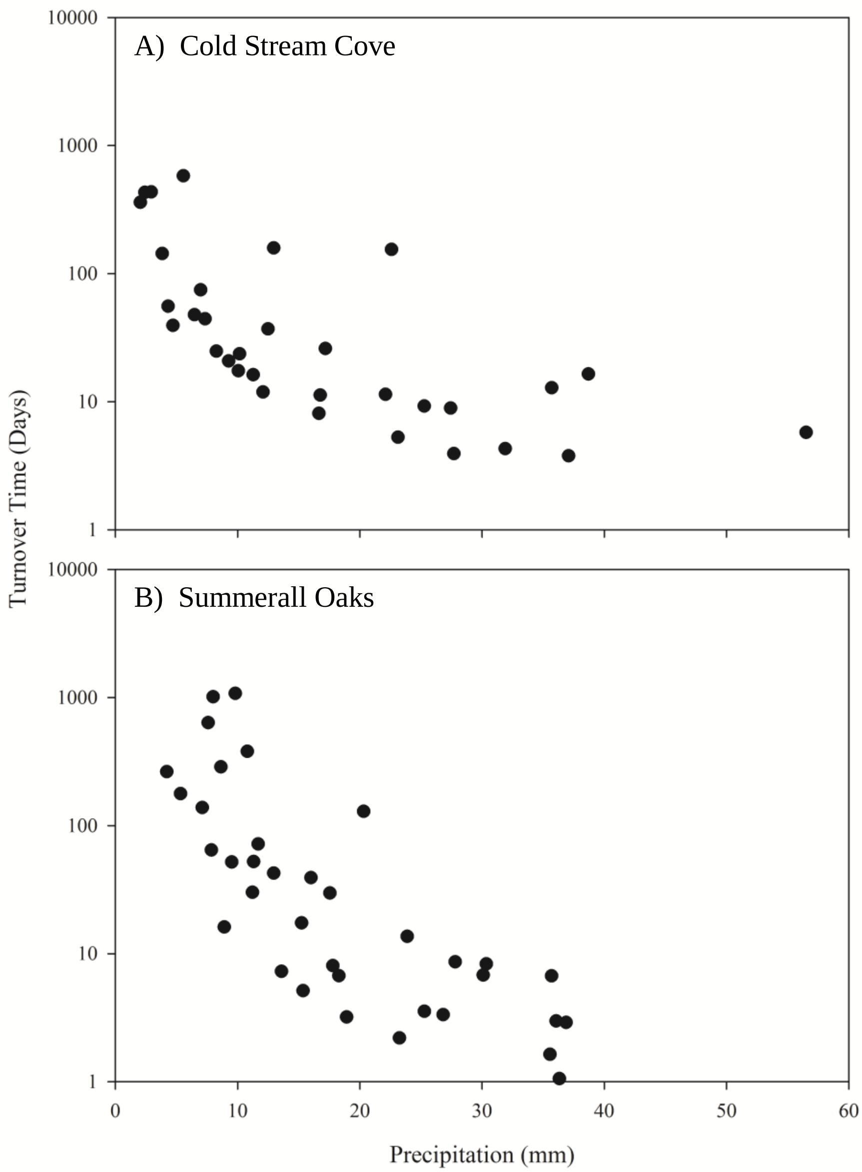

Figure 40. Calculated turnover times as a function of rainfall accumulation for the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B). Note the logarithmic y-axis scale.

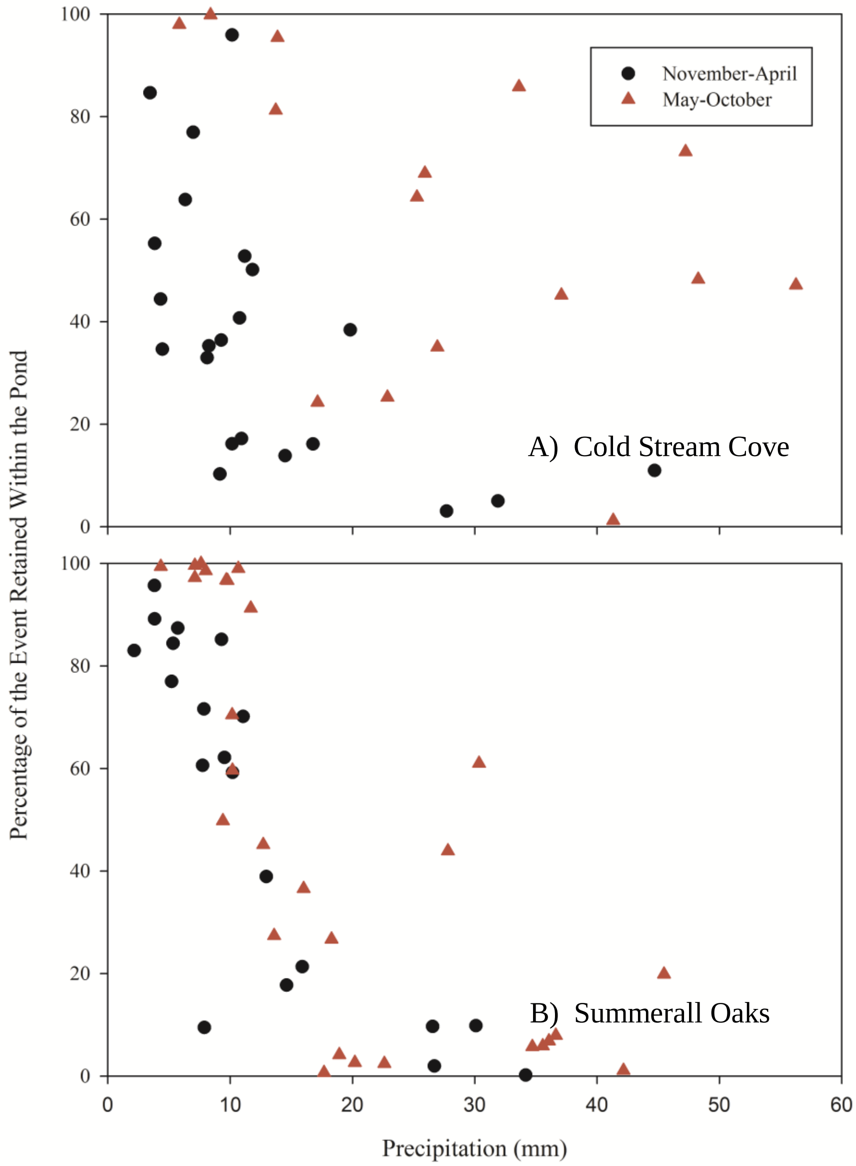

Figure 41. Seasonality related to the percentage of the event retained within the pond as a function of rainfall accumulation for the pond at Cold Stream Cove (A) and the pond at Summerall Oaks (B).

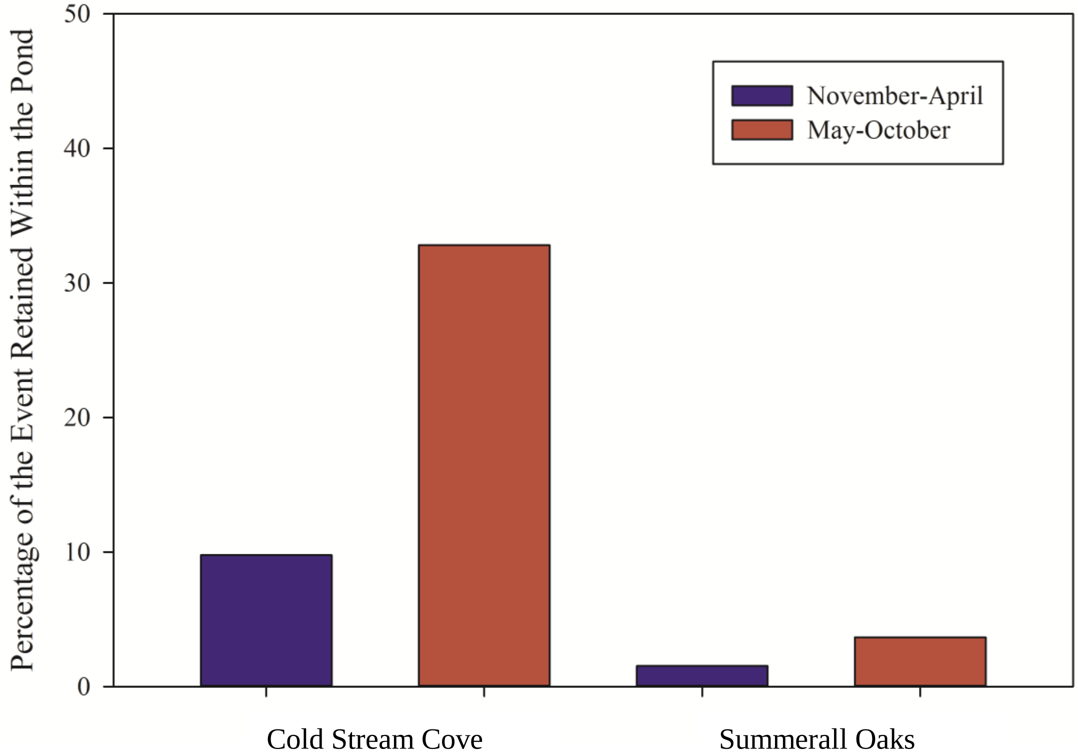

Figure 42. Influence of seasonality on the percentage of the event retained within the pond.

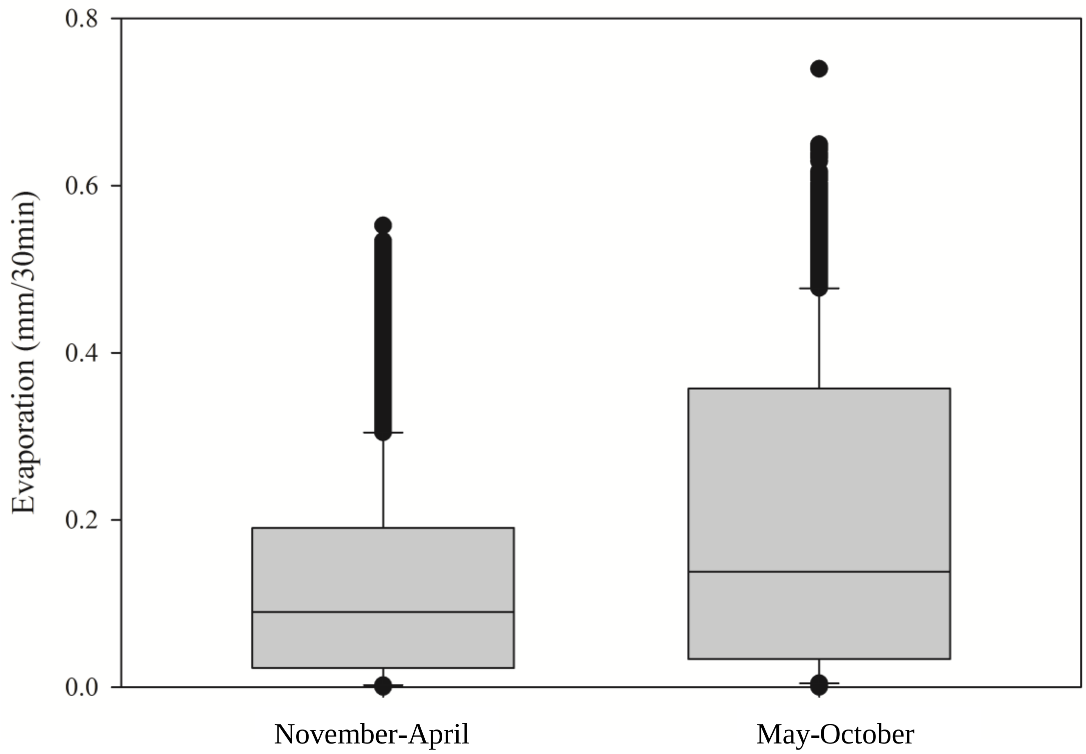

Figure 43. Box and whisker plot of evaporation rates for November-April compared to May-October. These rates were derived from the weather station located at Summerall Oaks and applied to both ponds for direct evaporation values.

Table 2-6 Runoff Curve Numbers[1]

Cover description: Cover type and hydrologic condition		Average percent impervious area[2]	Curve numbers for hydrologic soil groups: A	B	C	D
Cultivated land:	without conservation treatment		72	81	88	91
	with conservation treatment		62	71	78	81
Pasture or range land:	poor condition		68	79	86	89
	good condition		39	61	74	80
Meadow: good condition			30	58	71	78
Wood or forest land:	thin stand, poor cover		45	66	77	83
	good cover		25	55	70	77
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]						
Poor condition (grass cover <50%)			68	79	86	89
Fair condition (grass cover 50% to 75%)			49	69	79	84
Good condition (grass cover > 75%)			39	61	74	80
Impervious areas:						
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)			98	98	98	98
Streets and roads:						
Paved; curbs and storm drains (excluding right-of-way)			98	98	98	98
Paved; open ditches (including right-of-way)			83	89	92	93
Gravel (including right-of-way)			76	85	89	91
Dirt (including right-of-way)			72	82	87	89
Urban districts:						
Commercial and business		85%	89	92	94	95
Industrial		72%	81	88	91	93
Residential districts by average lot size:						
1/8 acre or less (town houses)		65%	77	85	90	92
1/4 acre		38%	61	75	83	87
1/3 acre		30%	57	72	81	86
1/2 acre		25%	54	70	80	85
1 acre		20%	51	68	79	84
2 acres		12%	46	65	77	82
Developing urban areas and Newly graded areas (pervious areas only, no vegetation)			77	86	91	94

[1] Average runoff condition, and $I_a = 0.2S$

[2] The average percent impervious area shown was used to develop the composite CNs. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. If the impervious area is not connected, the SCS method has an adjustment to reduce the effect.

[3] CNs shown are equivalent to those of pasture. Composite CNs may be computed for other combinations of open space cover type.

Figure 44. Excerpt from the Horry County Stormwater Management Design Manual (2000) showing curve numbers associated with various hydrologic soil groups and land uses.

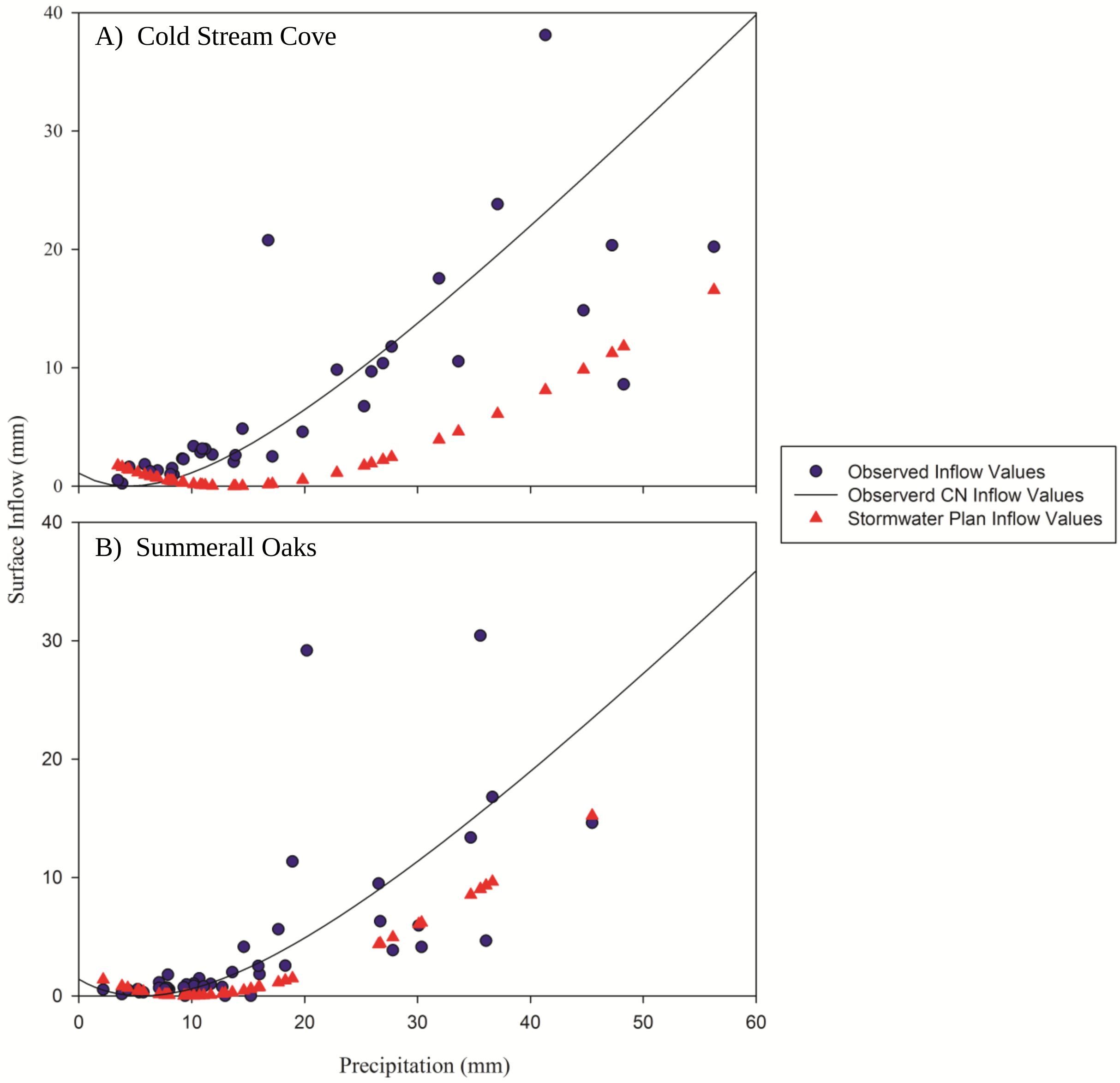

Figure 45. Observed inflow values, inflow values related to observed CN, and stormwater inflow values based on engineered plans as a function of rainfall accumulation for the drainage basin at Cold Stream Cove (A) and the drainage basin at Summerall Oaks (B).

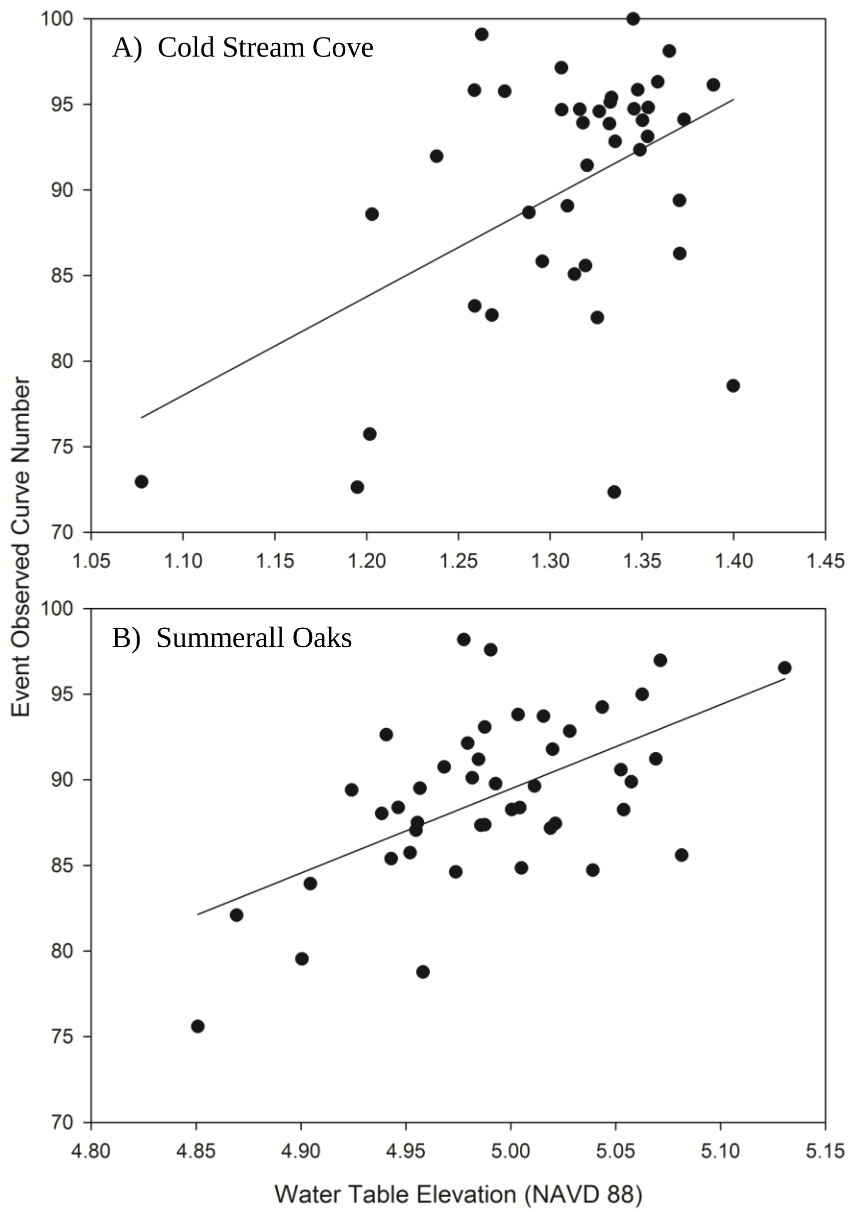

Figure 46. CN values derived from our event-specific observations plotted against adjacent water table elevations for the pond at Cold Stream Cove (A; R^2=0.229, n=42, p<0.01) and the pond at Summerall Oaks (B; R^2=0.330, n=45, p<0.01).