# A TECHNICAL SUMMARY OF PERFORMANCE: LITTORAL SHELF FILTERS AS A WET POND RETROFIT

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## Introduction

Pollution from stormwater runoff continues to be a primary concern, linked to the degradation of streams and lakes in developing areas [1–5]. Wet ponds are one of the most commonly found stormwater control measures (SCMs) throughout the southeastern United States. North Carolina, in particular, has over 20,000 wet ponds used for stormwater management. While wet ponds have been shown to successfully mitigate flooding and remove total suspended solids (TSS) [6–8], their ability to treat stormwater runoff for nutrients and pathogens has been highly varied because of a lack of existing mechanisms to remove pathogens and the dissolved fraction of nutrients [6,7,9]. Consequently, recent efforts have focused on retrofitting existing wet ponds to improve their water quality performance [7,10,11].

Since the mid-2000's, wet ponds in North Carolina, and other states, have been designed and constructed with littoral or aquatic shelves along their perimeters for safety and aesthetics. An attractive area of space for retrofit, recent research in Minnesota explored the possibility of installing media based filters along these shelves as a retrofit [11]. Erickson et al. [11] found that a retrofit sand-based filter incorporating iron filings captured 88% of dissolved phosphorus from runoff routed from the wet pond through the filter. This novel study demonstrated that wet pond performance could be improved through retrofit, particularly with respect to phosphorus removal. Moreover, a filter could also provide treatment for pathogens, a pollutant of particular concern in coastal areas.

Based upon this initial research, North Carolina State University's Stormwater Engineering Group retrofitted three existing wet ponds to include littoral shelf filters to assess the ability of the filters to provide polishing of pond effluent for nutrients and pathogens.

## Materials and Methods

### *Site Descriptions*

#### Sapphire Road

A 3,895 ft$^2$ wet pond receiving runoff from the 7.3-acre Sapphire Road residential area watershed in Rocky Mount, NC, was retrofit with a 408 ft$^2$ littoral shelf filter in October 2017 (Figure 1). The filter was installed along the south bank of the wet pond (Figure 2). The filter was installed at permanent pool elevation with an approximately 4-inch high berm separating the filter surface from the permanent pool surface. The filter was lined with an impermeable liner to prevent seepage of water from the banks of the pond and ensure only stormwater above the permanent pool would be routed through the system. Above the impermeable liner, the filter was backfilled with a 6-inch layer of double-washed #57 stone, a 3-inch layer of double-washed

#87 stone, and 1.5 feet of ViroPhos filter media donated by EnviRemed Environmental Services. The filter was drained through two 4-inch perforated underdrains that were daylighted to a swale outside of the wet pond and fitted to a 1-inch nozzle (Figure 2).

**Figure 1.** Sapphire wet pond in Rocky Mount, NC.

**Figure 2.** Sapphire littoral shelf filter following construction (left) and underdrain (right).

*Bridgewood Road*

A 6,691 ft$^2$ wet pond receiving runoff from the 17.1-acre Bridgewood Road residential area watershed in Rocky Mount, NC, was retrofit with a 354 ft$^2$ littoral shelf filter in October 2017 (Figure 3**Figure *1***). The filter was installed along the western bank of the pond at permanent pool elevation with an approximately 4-inch high berm separating the filter surface from the permanent pool surface (Figure 4). As at Sapphire, the filter was lined with an impermeable liner to prevent seepage of water from the banks of the pond and ensure only stormwater above the permanent pool would be routed through the system. Above the impermeable liner, the filter was backfilled with a 6-inch layer of double-washed #57 stone, a 3-inch layer of double-washed

#87 stone, and 1.5 feet of Bold & Gold® filter media donated by Environmental Conservation Solutions. The filter was drained through two 4-inch perforated underdrains that were daylighted to a stream adjacent to the wet pond and fitted to a 1-inch nozzle.

**Figure 3.** Bridgewood wet pond in Rocky Mount, NC.

**Figure 4.** Bridgewood littoral shelf filter following construction (left) and underdrain (right).

*Wilmington Operations Center*

Lastly, a 1-acre wet pond in Wilmington, NC, receiving runoff from the 30-acre municipal operations center was retrofit to include a littoral shelf filter (Figure 5). The 240 ft$^2$ littoral shelf filter was constructed in August 2016 adjacent to the pond's existing outlet structure and was installed at permanent pool elevation with an approximately 4-inch high berm separating the filter surface from the permanent pool surface (Figure 6). The filter was lined with an impermeable liner to prevent seepage of water from the banks of the pond and ensure only stormwater above the permanent pool would be routed through the system. Above the impermeable liner, the filter was backfilled with a 6-inch layer of compacted double-washed #57 stone, an uncompacted 6-inch layer of double-washed #57 stone, a 3-inch layer of double-washed #87 stone, and 1.5 feet of Bold & Gold® filter media donated by Environmental Conservation Solutions. The filter was drained through two 4-inch perforated underdrains that were daylighted within the existing pond's outlet structure and fitted to a 1-inch nozzle.

**Figure 5.** Wilmington Operations Center wet pond.

**Figure 6.** Littoral shelf filter during construction (left) and following a rain event (right).

### *Data Collection*

Following retrofit, Onset HOBO U20 water level loggers were installed to monitor water levels within the shelf filters and Teledyne ISCO monitoring equipment was installed to monitor hydrology and water quality associated with each retrofit. At Bridgewood and Sapphire, sharp crested v-notch weirs were installed within the catch basin inlets and outlet structures of each pond and within a weir box surrounding each daylighted underdrain. ISCO bubbler modules measured water levels over each weir and flow rates were calculated using stage-discharge relationships. Flow-weighted volumetric water quality samples were collected at each monitoring location (pond influent, pond effluent, and filter effluent) using ISCO programmable automated samplers and were delivered for laboratory analysis within 24 hours of rainfall cessation.

**Figure 7.** Monitoring equipment installed at the inlet of Sapphire pond (left) and filter underdrain at Bridgewood (right).

In Wilmington, an ISCO Signature Flowmeter and an Area Velocity Module (AVM) were installed within the underdrain nozzle to measure flows leaving the filter. Grab water quality samples were collected from the pond inlet, pond outlet, and filter outlet during storm events to analyze for pathogens. Due to short holding times for pathogens, Wilmington water quality samples were delivered to a local certified laboratory, Environmental Chemists, Inc., for analysis.

### *Sample Analysis*

Sapphire and Bridgewood water quality samples were analyzed at the NC State University Environmental Analysis Laboratory within the Department of Biological and Agricultural Engineering. Samples were analyzed for total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), nitrate-nitrogen, total phosphorus (TP), orthophosphate (OP), and total suspended solids (TSS). Total nitrogen (TN) was calculated as the sum of TAN and nitrate, organic nitrogen (ON) was calculated as the difference of TKN and TAN, and particulate bound phosphorus (PBP) was calculated as the difference in TP and OP. Pond outlet samples represented treatment provided solely by the pond while filter samples were treated by the pond and the littoral shelf filter.

Wilmington water quality samples were analyzed for fecal coliform (FC) and E. coli, two indicator bacteria. Indicator bacteria are used to predict rates of gastrointestinal illness, and their presence is typically indicative of other pathogen presence.

### *Data Analysis*

An efficiency ratio (ER) was calculated to determine removal rates for the pond and filter. For the pond, ER was calculated as,

$$ER_{pond} = \frac{Concentration_{Pond\ In} - Concentration_{Pond\ Out}}{Concentration_{Pond\ In}} \times 100 \qquad (1)$$

where Concentration is either the event mean concentration (EMC) of a nutrient or TSS the geometric mean of FC or E. coli.

As the filters were all located adjacent to each outlet structure, runoff routed through the filters would have already received some degree of treatment by its respective pond; therefore, an additional ER was calculated to compare pond effluent to filter effluent as,

$$ER_{filter} = \frac{Concentration_{Pond\ Out} - Concentration_{Filter\ Out}}{Concentration_{Pond\ Out}} \times 100 \qquad (2)$$

Geometric means were calculated using pathogen results for comparison. Pathogen geometric means and nutrient concentrations at each sampling location were statically compared using R Statistical Software. Differences were significant at $\alpha = 0.05$.

## Results and Discussion

### *Hydrology*

<u>Wilmington Operations Center</u>

At the Wilmington Operations Center pond, hydrologic monitoring using the AVM and water level loggers was intended to allow calculation of flows through the filter underdrain and over the pond outlet structure's weir. While the filter included an impermeable liner to prevent seepage from the pond's banks and allow calculation of inter-event flows, it became apparent shortly after construction that the impermeable liner was compromised during installation. Water remained in the filter regardless of the presence of a rain event with a median depth of 1.1 ft throughout the monitoring period (Fig. 3). As such, constant flows through the underdrain confounded efforts to calculate event based pathogen loads.

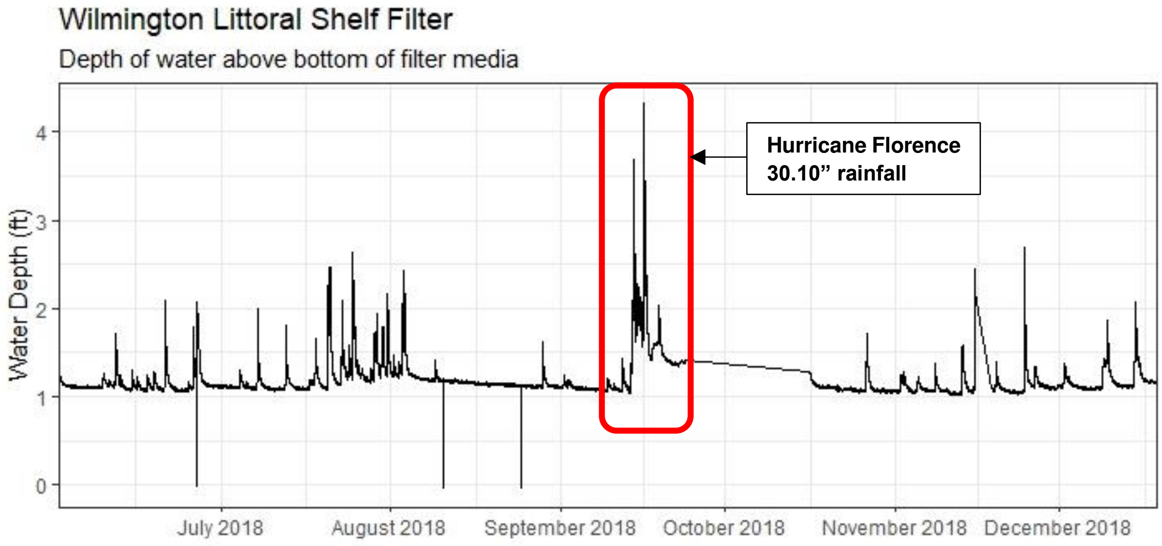


**Figure 8.** Water levels within the filter from June - December 2018.

### Rocky Mount Ponds

At the Sapphire and Bridgewood ponds in Rocky Mount, NC, 57 storm events with rainfall exceeding 0.10 inches were observed between October 2018 – June 2019 with 20 storm events being sampled at each site for water quality. Rainfall ranged from 0.10 to 2.16 inches with a median of 0.54 inches. Of these 20 sampled events, 18 included paired pond influent, pond effluent, and filter effluent.

Runoff successfully infiltrated the Sapphire filter for the majority of the monitoring period (Figure 9). However, at Bridgewood, sensor fouling precluded the collection of quality internal water level data within the filter. Regardless, during field visits, observations allowed determinations about infiltration to the Bridgewood filter. A concern with the installation of littoral shelf filters is the biologically active nature of wet pond ecosystems and its effect on filter blinding and maintenance in addition to clogging draw down orifices on pond outlet structure. Heavy moss and algal growth was witnessed at the Bridgewood pond during 80% of field visits. This biological activity caused blinding of the filter surface at times and also caused extended periods of inundation when the pond outlet was clogged. However, removing accumulated biological material from the outlet orifice and removal of accumulated material and subsequent raking of the filter surface restored infiltration.

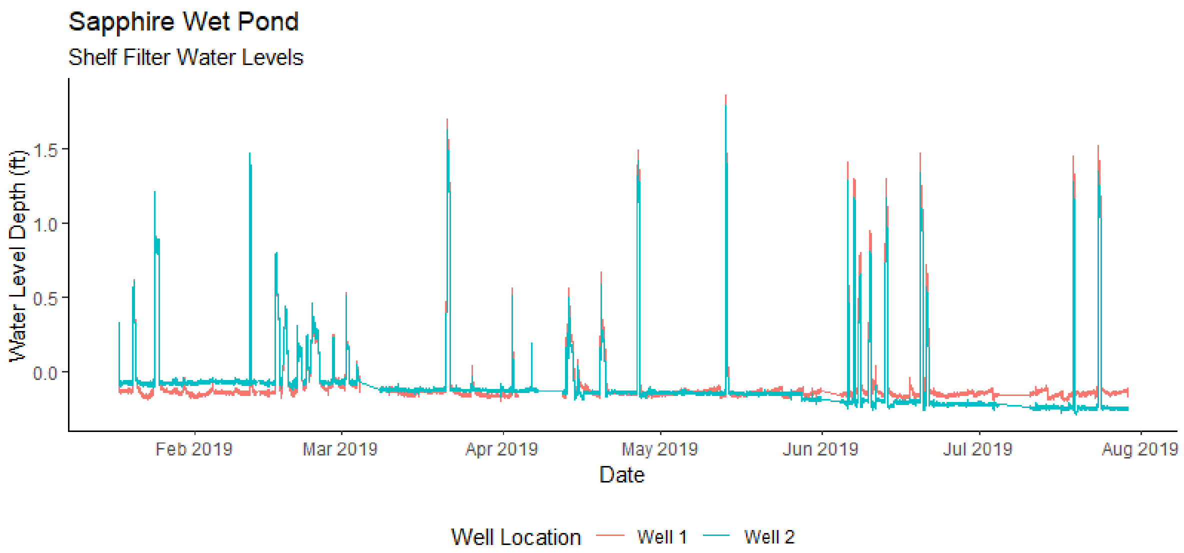


**Figure 9.** Water levels within the Sapphire filter from January - August 2019.

***Pathogens***

While the Wilmington filter remained active even during dry periods, the filter still received stormwater runoff during storm events as evidenced by the spikes in internal water levels during rain events seen in Figure 3. That grab samples were only collected during rain events still allows pathogen removal comparisons.

Nine storm events were sampled for paired pond influent and pond effluent and eight were sampled for paired pond influent, pond effluent, and filter effluent from October 2018 – December 2019. Influent E. coli concentrations ranged from 58 to more than 2,420 CFU/100 mL, pond effluent concentrations ranged from 4 to more than 2,420 CFU/100 mL, and filter effluent concentrations ranged from less than 1 to 659 CFU/100 mL (Table 1). The geometric means of E. coli for influent, pond effluent, and filter effluent were 776, 208, and 11 CFU/100 mL, respectively.

**Table 1.** Individual storm results for E. coli and fecal coliform sampling.

| Date | E. Coli (CFU/100mL) | | | Fecal Coliform (CFU/100mL) | | |
|---|---|---|---|---|---|---|
| | Pond In | Pond Out | Filter Out | Pond In | Pond Out | Filter Out |
| 10/26/2018 | 981 | 4 | | >60,000 | 82 | |
| 11/8/2018 | 173 | 1,047 | 1 | 2,100 | 11,000 | 10 |
| 11/15/2018 | 1,554 | 1,414 | 388 | 15,000 | >60,000 | 12,000 |
| 12/10/2018 | 145 | 291 | 4 | 46 | 245 | 6 |
| 3/21/2019 | 614 | 142 | 120 | 118 | 82 | 19 |
| 4/5/2019 | 438 | 132 | 9 | 360 | 28 | <10 |
| 6/10/2019 | 58 | 28 | 14 | 55 | 64 | 10 |
| 8/16/2019 | >2,420 | >2,420 | 659 | 12,000 | 30,000 | 490 |
| 12/30/2019 | >2,420 | 326 | <1 | 17,000 | 240 | <5 |

Influent FC concentrations ranged from 35 to more than 60,000 CFU/100 mL, pond effluent concentrations ranged from 28 to more than 60,000 CFU/100 mL, and filter effluent concentrations ranged from less than 5 to 12,000 CFU/100 mL (Table 1). The geometric means of FC for influent, pond effluent, and filter effluent were 3,302, 622, and 51 CFU/100 mL, respectively.

E. coli ER was 73% for the pond while the filter improved the performance of the pond by 95%. While the pond alone reduced E. coli by 73%, reductions were not statistically significant. Three of nine sampled events resulted in an export of E. coli from the pond, likely due to the presence of waterfowl inhabiting the pond (Table 1). However, E. coli concentrations were significantly reduced by the filter when compared to both runoff into the pond and pond effluent (Fig. 4).

Similarly, the filter significantly reduced FC concentrations when compared to pond influent and effluent while the pond was not able to significantly reduce FC from stormwater runoff. FC removal in the pond was highly varied with five of nine sampled events representing an export of FC (Table 1). Again, increases in FC within the pond are likely due to the presence of waterfowl inhabiting the pond. FC ER was 81% for the pond while the filter improved the pond's performance by 92%.

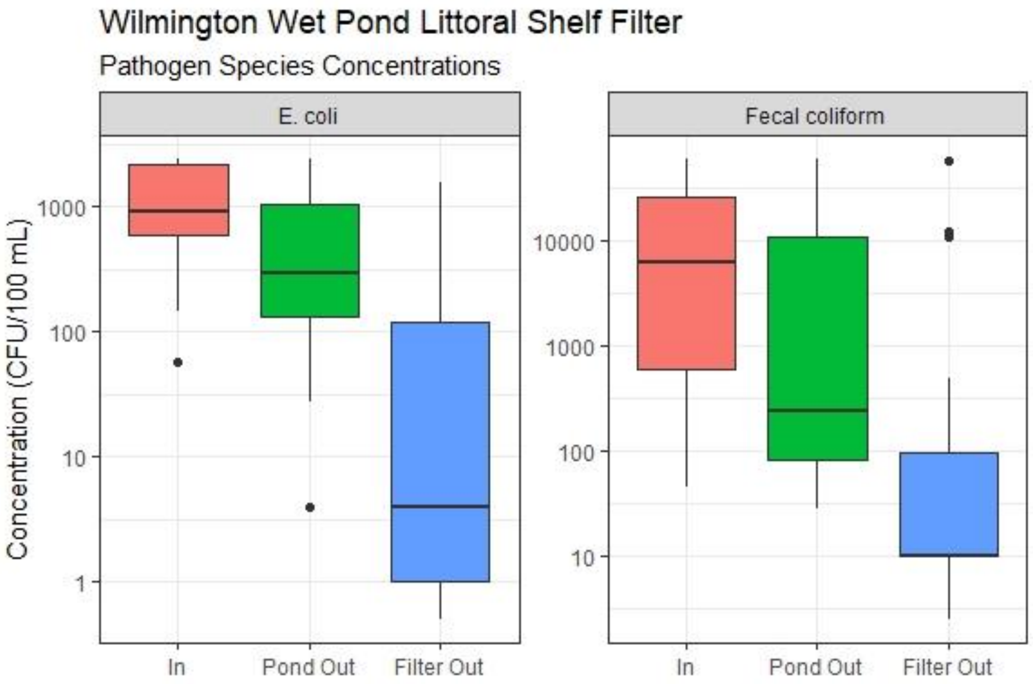


**Figure 10.** Pathogen species concentrations.

### *Rocky Mount Nutrients Study*

#### Nitrogen

Overall nitrogen results indicate why retrofits to wet ponds can provide significant improvement to nutrient removal in North Carolina. One of the key drivers for this research is the inability of ponds to reliably provide nitrogen and phosphorus removal. This is evidenced by the difference in nitrogen removal seen at the two Rocky Mount ponds. While the Sapphire pond itself was able to reduce nitrogen concentrations by a median of 65%, the Bridgewood pond struggled to remove any nitrogen (median removal rate of 0%). However, both filters were able to significantly reduce TN concentrations when compared to pond effluent. When combined, the filters were able to reduce influent TN concentrations by a median of 48%.

At the Sapphire Pond, influent TN concentrations ranged from 0.86 to 2.92 mg/L, pond effluent TN concentrations ranged from 0.58 to 1.99 mg/L, and filter effluent TN concentrations ranged from 0.28 to 2.18 mg/L. Median TN concentrations for pond influent, pond effluent, and filter effluent were 1.67, 0.93, and 0.77 mg/L, respectively (Table 2). The Sapphire filter was able to reduce influent TN concentrations by a median of 49%. When compared to pond effluent, filter effluent TN concentrations were reduced for 78% of events. The pond was able to significantly reduce TN concentrations with a median $ER_{pond}$ of 38% while the filter provided an additional significant reduction with a median $ER_{filter}$ of 11%.

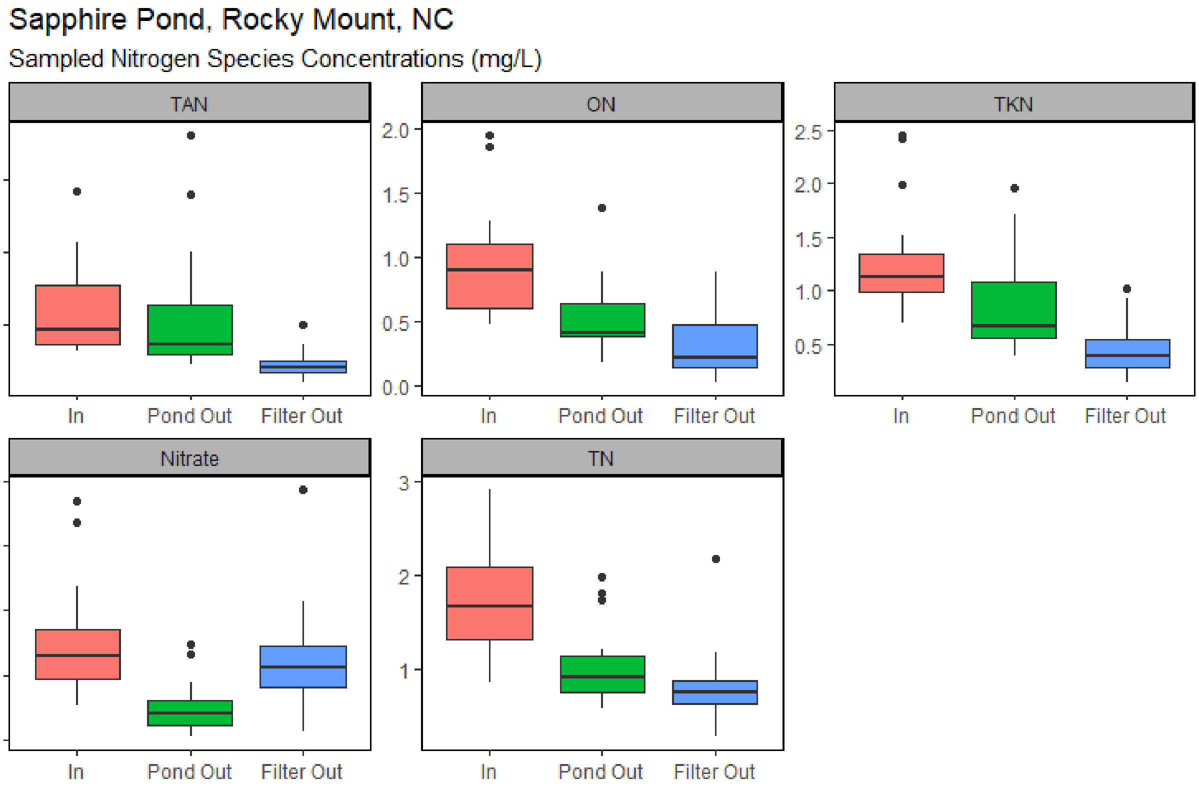


**Figure 11.** Nitrogen species concentrations (mg/L) at each monitoring location at Sapphire wet pond in Rocky Mount, NC.

At Bridgewood, TN concentrations were more varied, with influent concentrations ranging from 0.47 to 3.50 mg/L. Overall, median TN concentrations were 1.29, 1.34, and 0.65 mg/L for pond influent, pond effluent, and filter effluent, respectively (Table 2). The pond itself did not remove nitrogen (median TN removal rate of 0%), demonstrating why retrofits are needed. The retrofit filter significantly reduced TN when compared to the pond itself with a median removal rate of 54%.

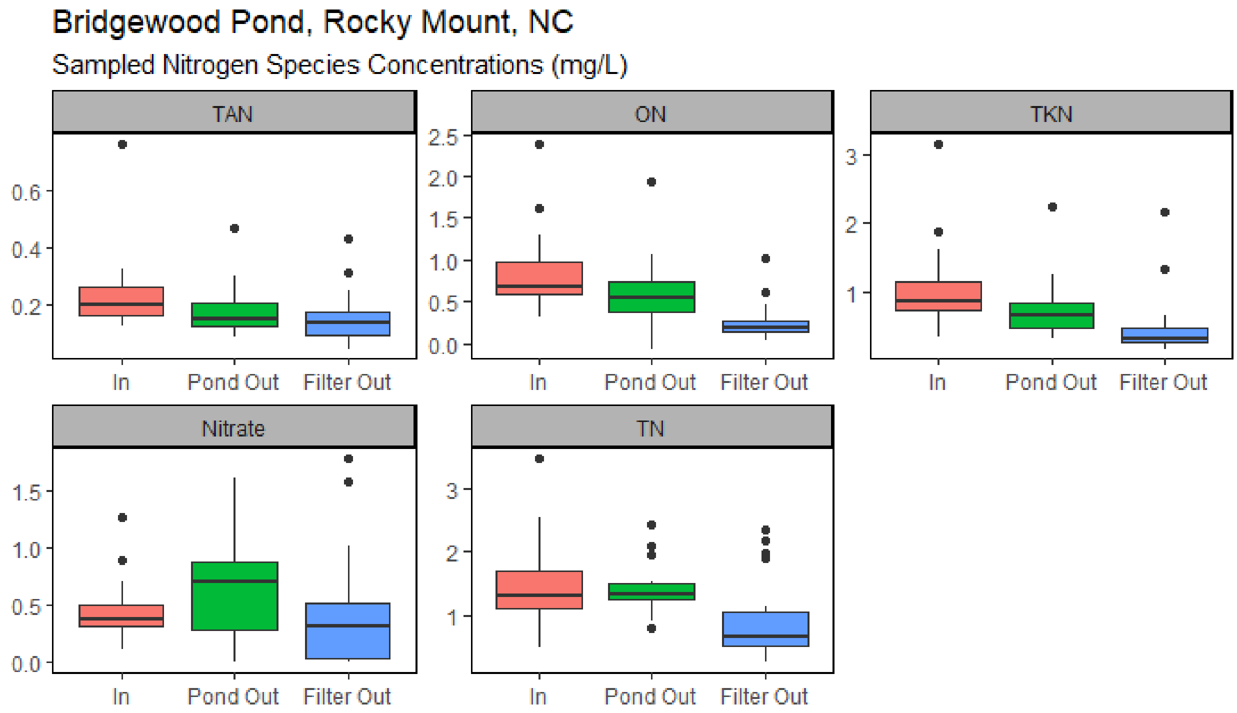


**Figure 12**. Nitrogen species concentrations (mg/L) at each monitoring location at Sapphire wet pond in Rocky Mount, NC.

**Table 2**. Median concentrations and efficiency ratios for nitrogen species.

| Site | Sample Location | Median Value | | | | |
|---|---|---|---|---|---|---|
| | | TKN | TAN | ON | Nitrate | TN |
| Bridgewood | Pond In | 0.87 | 0.20 | 0.68 | 0.38 | 1.29 |
| | Pond Out | 0.66 | 0.15 | 0.54 | 0.71 | 1.34 |
| | ER$_{Pond}$ | 17% | 25% | 12% | -53% | 0% |
| | Filter Out | 0.34 | 0.14 | 0.18 | 0.32 | 0.65 |
| | ER$_{Filter}$ | 48% | 0% | 65% | 56% | 54% |
| Sapphire | Pond In | 1.14 | 0.28 | 0.90 | 0.39 | 1.67 |
| | Pond Out | 0.66 | 0.22 | 0.40 | 0.13 | 0.93 |
| | ER$_{Pond}$ | 36% | 25% | 48% | 65% | 38% |
| | Filter Out | 0.40 | 0.12 | 0.22 | 0.34 | 0.77 |
| | ER$_{Filter}$ | 40% | 59% | 38% | -92% | 11% |

Of all species, the filters performed well at reducing TKN, likely due to the transformation of TAN and ON to nitrate. Surprisingly, nitrate results were mixed with Bridgewood reducing concentrations when compared to the pond outlet by a median of 52%; however, while impressive, this reduction was not statistically significant and was very similar to inlet nitrate concentrations. Similarly, inlet and filter effluent concentrations at Sapphire were very similar, but nitrate concentrations leaving the filter were significantly higher than concentrations leaving the pond outlet (Fig. 5). This significant increase in nitrate is attributed to the aerobic environment within the filter supporting the aforementioned transformation of TAN to nitrate. However, filtration of particulate-bound ON and some possible sorption of N still produced significant removal of TN at Sapphire.

Overall, both filters provided significant reductions of influent TN. When both data sets were combined, the median reduction of TN was 48%. When compared to the TN credit that NCDEQ assigns wet ponds (1.22 mg/L), littoral shelf filter retrofits can provide a significant benefit with an overall median effluent TN concentration of 0.71 mg/L [12].

### *Phosphorus*

Phosphorus removal via the retrofit littoral shelf filters was also very promising. Both filters were able to significantly reduce TP concentrations from runoff into the pond with a combined median 58% reduction of influent TP concentrations. At Sapphire, effluent concentrations from the filter were significantly less than the pond's effluent, demonstrating the nutrient removal potential of the retrofit. At Bridgewood, the pond itself provided significant treatment of TP from runoff. While TP concentrations from the filter at Bridgewood were significantly higher than from the pond outlet, median TP concentrations of 0.034 mg/L from the pond and 0.057 mg/L from the filter are almost irreducible. Interestingly, median effluent TP concentrations from both Sapphire and Bridgewood filters were 0.06 mg/L and 0.057 mg/L, respectively, demonstrating great agreement.

Median TP concentrations at Sapphire were 0.17, 0.12, and 0.06 mg/L for the pond inlet, pond outlet, and filter outlet, respectively. The pond significantly reduced TP concentrations with a median removal rate of 32% while the filter provided an additional significant reduction of TP when compared to pond effluent with a median additional removal rate of 62%.

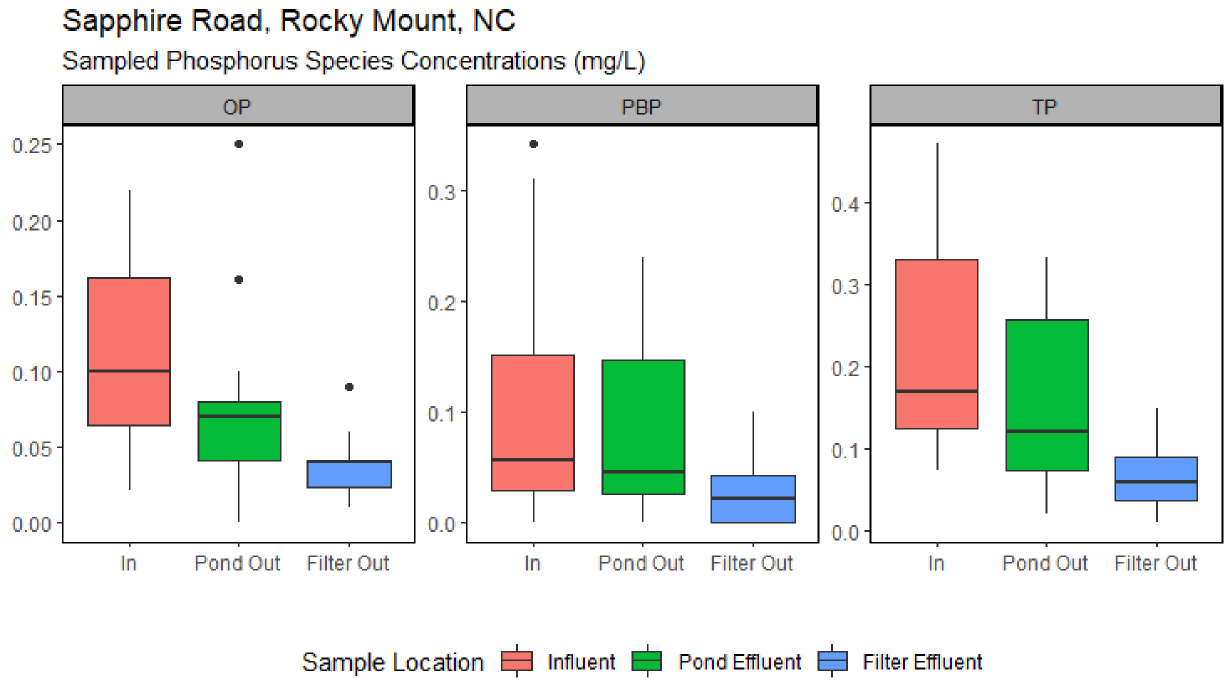


**Figure 13.** Phosphorus species concentrations (mg/L) at each monitoring location at Sapphire wet pond in Rocky Mount, NC.

At Bridgewood, the filter significantly increased TP concentrations when compared to the filter, with a median removal rate of -14%. However, the pond was very efficient at removing TP, with a median TP reduction of 65%. While a significant increase when compared to pond effluent (median TP concentration = 0.03 mg/L), filter effluent TP concentrations were still low (median TP concentration = 0.06 mg/L) and significantly less than influent TP concentrations (median = 0.15 mg/L).

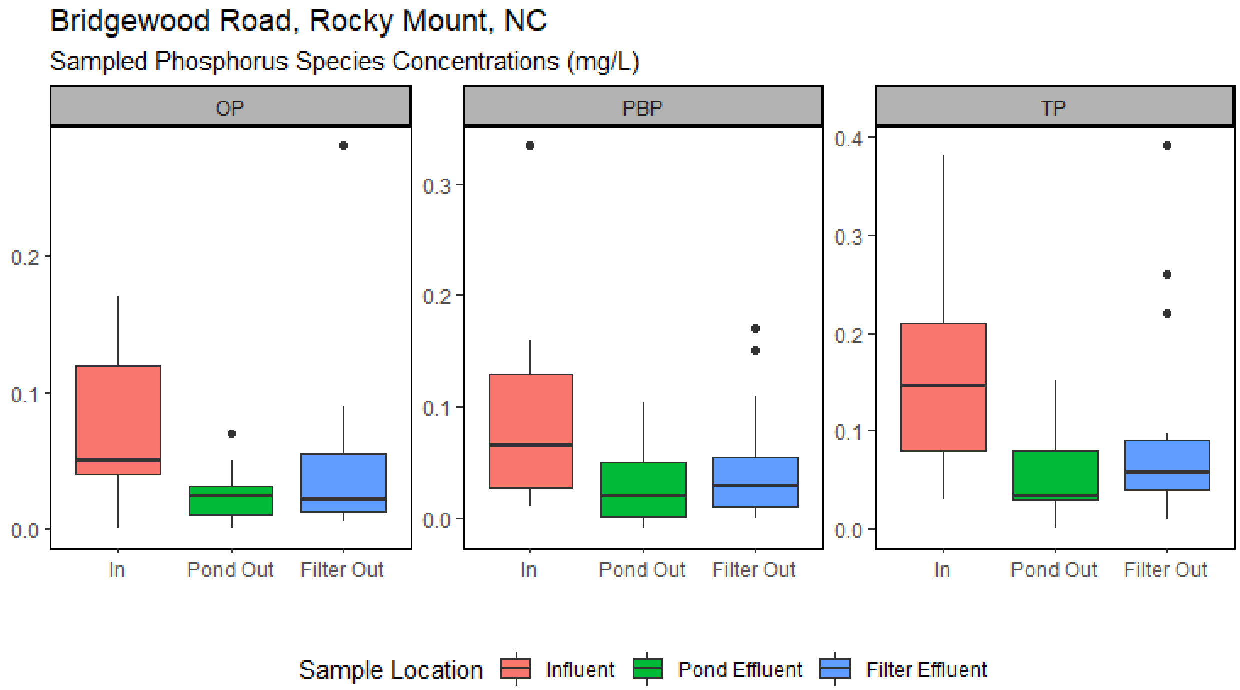


**Figure 14.** Phosphorus species concentrations (mg/L) at each monitoring location at Bridgewood wet pond in Rocky Mount, NC.

**Table 3**. Median concentrations and efficiency ratios for phosphorus species and TSS.

| Site | Sample Location | Median Value | | | |
|---|---|---|---|---|---|
| | | TP | OP | PBP | TSS |
| Bridgewood | Pond In | 0.15 | 0.05 | 0.07 | 14.59 |
| | Pond Out | 0.03 | 0.02 | 0.02 | 7.23 |
| | ERPond | 65% | 60% | 77% | 52% |
| | Filter Out | 0.06 | 0.02 | 0.03 | 1.42 |
| | ERFilter | -14% | 0% | 0% | 92% |
| Sapphire | Pond In | 0.17 | 0.10 | 0.06 | 41.75 |
| | Pond Out | 0.12 | 0.07 | 0.05 | 9.37 |
| | ERPond | 32% | 48% | 20% | 75% |
| | Filter Out | 0.06 | 0.04 | 0.02 | 4.21 |
| | ER Filter | 62% | 50% | 82% | 52% |

Naturally, as a filter, the best P species removal by the filters should be associated with PBP; however, as ponds already perform well as reducing sediment and particulate matter, at Bridgewood, PBP concentrations were already very low. The dissolved fraction, OP, provided the most promising results for both ponds. At Sapphire, the filter provided an additional significant removal of OP. At Bridgewood, OP concentrations were already very low as the pond worked very well at reducing OP. Regardless, filter effluent concentrations of TP were both 0.06 mg/L, well below the 0.15 mg/L effluent credit given to new wet ponds by NCDEQ [12].

### *TSS*

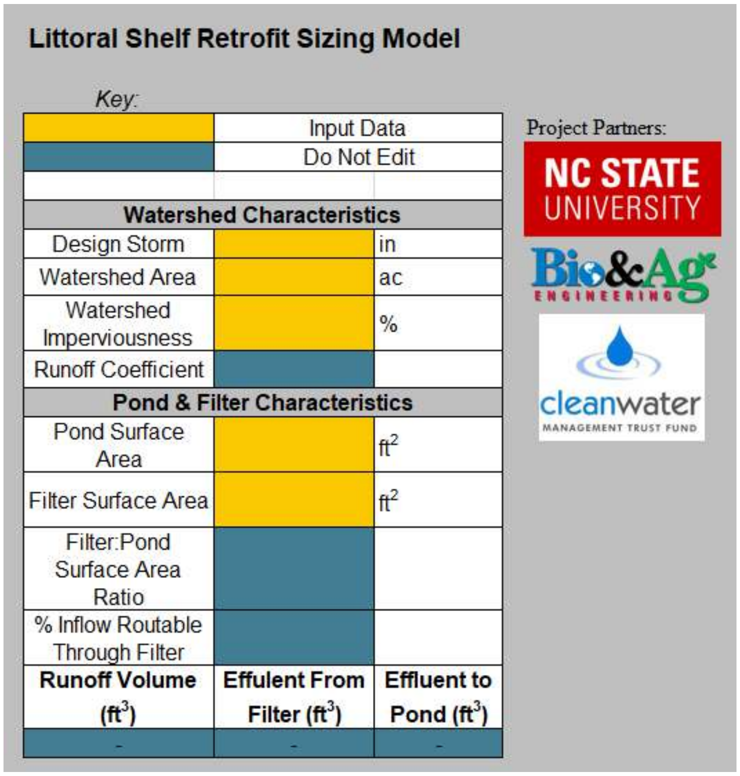
Not surprisingly, both filters excelled at polishing TSS from the ponds. At Bridgewood, the median removal rate for TSS by the pond itself was 52% while the filter removed an additional 92% when compared to the pond effluent. At Sapphire, the wet pond performed better, with a median removal rate of 75% while the filter provided an additional median removal rate of 52% over the pond's effluent.

### *Loads*

As Sapphire had the most reliable hydrology data, load comparisons were calculated to assess pounds of nitrogen saved by the Sapphire filter. Assuming the volume of water routed through the filter would have instead passed through the pond outlet, loads were calculated for two scenarios: (1) the pond as-is without a littoral shelf filter and (2) the post-retrofit pond. For both scenarios, the nitrogen and phosphorus load from the watershed would be unchanged at 122.3 lb N/yr and 12.9 lb P/yr. In the scenario without a littoral shelf filter, the pond would export 45 lb N/yr and 6.1 lb P/yr. With a littoral shelf filter, the pond exported 44.1 lb N/yr and 5.4 lb P/yr, representing a 30-year savings of 27.3 lb of N and 20.6 lb of P.

## ***Future Littoral Shelf Filter Retrofit Sizing***

Guidance on sizing future littoral shelf filter retrofits was developed using hydrologic data collected during this project. As the Wilmington shelf filter ran continuously, its data was excluded from this analysis. Furthermore, the Bridgewood pond experienced the most clogging of any pond outlet which confounded efforts to discretize flows between events. Consequently, data from Sapphire was used to develop the sizing model. Using the Sapphire data and design information, the attached spreadsheet tool was developed to assist designers in determining how large their littoral shelf filter should be to treat a target percent of inflow treated (Figure 15).



**Littoral Shelf Retrofit Sizing Model**

*Key:*

| | | |
|---|---|---|
| 🟨 | Input Data | |
| 🟦 | Do Not Edit | |
| | | |
| **Watershed Characteristics** | | |
| Design Storm | 🟨 | in |
| Watershed Area | 🟨 | ac |
| Watershed Imperviousness | 🟨 | % |
| Runoff Coefficient | 🟦 | |
| **Pond & Filter Characteristics** | | |
| Pond Surface Area | 🟨 | $ft^2$ |
| Filter Surface Area | 🟨 | $ft^2$ |
| Filter:Pond Surface Area Ratio | 🟦 | |
| % Inflow Routable Through Filter | 🟦 | |
| **Runoff Volume ($ft^3$)** | **Effulent From Filter ($ft^3$)** | **Effluent to Pond ($ft^3$)** |
| - | - | - |

Project Partners:

**Figure 15**. Screenshot of littoral shelf retrofit sizing tool interface.

In an effort to promote future implementation and simplify the design process, the design tool is based on the ratio of permanent pool surface area of the pond to the surface area of the littoral shelf filter. At Sapphire, the filter-to-pond surface area ratio (F:P) was 10.5%. Using the hydrologic monitoring data, a median ratio of filter flow volume:inlet flow volume (F:I Flow) was 11.2%. Future designs will be based on the observed ratios and placed on a sliding scale.

### *Maintenance Recommendations*

Maintaining adequate infiltration of the filter media is essential to littoral shelf filter functionality and performance. While the Wilmington filter presented constant discharge, volunteer vegetation rooted into the filter media and sediment from the pond accumulated on the filter surface. In Rocky Mount, sediment from the developing watershed at the Sapphire pond resulted in sediment accumulation on the littoral shelf filter surface leading to areas of clogging (Figure 16).

**Figure 16.** Biological blinding of the shelf filter observed at the Sapphire pond (left) remedied by raking of the filter surface (right).

As aforementioned, the Bridgewood pond was highly active with biological material and became regularly clogged with moss and algae (Figure 17). However, clogging of the surface layer was easily remedied by raking accumulated material (both biological and sediment). Following removal of material and raking of the surface layer of media, infiltration of filters was restored. While an easy fix, regular maintenance of the filter surface area (particularly during the growing season) needs to be planned and budgeted for successful future implementation.

**Figure 17**. Clogging of the Bridgewood filter with biological material (left) and restoring infiltration by removing and raking the filter (right).

To prevent issues with clogging in future implementations, a maintenance schedule of semi-annual media surface raking is recommended. For wet ponds similar to Bridgewood, where biological activity is particularly present, more frequent maintenance will be required. For these ponds, pre-installation maintenance to treat the cause of moss and algal growth is recommended to reduce the post-installation maintenance burden and prolong the life of the filter media in the littoral shelf filter.

## Conclusions

As improving pond performance with respect pathogen and nutrient removal is imperative, significant reductions in FC, E. coli, TN, and TP provided by polishing pond effluent through the retrofit littoral shelf filters is very promising. When comparing filter effluent to pond influent, combined dataset median reductions were 48% for TN, 58% for TP, and 98% for both FC and E. coli, making the littoral shelf filter a viable retrofit for providing cleaner water to North Carolina's streams, recreational waters, and shellfishing waters.

An important caveat in this study is the degree of treatment received with respect to total runoff volume entering the pond. While the filter significantly reduced TN and TP concentrations, and will offset almost a pound of N and P per year at the Sapphire pond, the amount of water treated (and thus load reduction) can be greatly increased by installing larger filters. However, while oversizing future installations of retrofit littoral shelf filters may allow greater treatment capacity, it may prove to (1) be cost prohibitive, (2) negatively affect the hydraulics of the pond with respect to flood mitigation, or (3) both. In order to realize substantial load reductions, future research will need to explore optimizing filters to maximize the percent of inflow treated while minimizing impacts to flood mitigation.

Lastly, maintenance requirements should be carefully considered as biological activity may result in blinding of littoral shelf filters. As such, maintenance requirements may be extensive dependent upon vegetative characteristics of individual sites.

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