Article 76

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# A Tale of Two Regional Wet Extended Detention Ponds

Why do some stormwater ponds work, and others don't? How can virtually identical ponds located just a few miles away from each other have dramatically different pollutant removal capability? Some interesting answers to these questions can be gleaned from recent research performed by Robert Borden and his colleagues at North Carolina State University.

The setting for their study is the rapidly growing North Carolina Piedmont. In response to concerns about development's influence on water quality in local water supply reservoirs, many communities employ large regional wet extended detention (ED) ponds to remove pollutants from stormwater runoff generated by new development. State stormwater regulations promote the use of these ponds, on the basis of prior national research that has generally demonstrated they are highly effective in removing many stormwater pollutants of concern (see article 64 for a review). Consequently, regional wet ED ponds were adopted as a central element of a protection strategy for the City Lake reservoir near High Point, North Carolina. Local officials are now implementing a network of 33 regional wet and dry extended detention ponds to remove stormwater pollutants from future development in the 31-square mile watershed that contributes runoff to the drinking water reservoir.

Borden and his colleagues conducted an intensive monitoring study to document the pollutant removal performance of the first two large regional ponds constructed to protect the reservoir. Each pond was a wet extended detention pond that served a watershed nearly two square miles in size, and was built in advance of anticipated watershed development. The first pond was known as Davis Pond and had a rural drainage area of some 1,258 acres, consisting mostly of dairy farms, crops and forest, that will ultimately be converted into low-density residential development. The second pond, called Piedmont, drained a partially developed 1,220-acre subwatershed that included a large petroleum tank farm, industrial development, highways and open land slated for further development.

Intensive sampling at major inflows and outflows to each pond during both baseflow and storm conditions allowed very accurate computation of the mass of pollutants entering and leaving each facility. Over a single year, 22 storms were sampled at Davis Pond and 25 storms sampled at the Piedmont Pond, as well as 12 samples of baseflow conditions. The suite of pollutants measured included sediment, nutrients, carbon, coliform bacteria, and metals. In addition, researchers also intensively sampled water quality conditions occurring within each pond, taking monthly samples of dissolved oxygen, temperature, nutrients, chlorophyll, secchi depth and other parameters at various depths in the pond water column throughout the growing season. Lastly, the research team sought to understand the nutrient and sediment dynamics of the ponds using a series of simple and complex models.

At first glance, the Davis and Piedmont ponds were very similar (Table 1). Both drained about the same drainage area, and were located just a few short miles from each other. Their subwatersheds both had the same fine-grained clay soils for which the region is known. Both ponds had about the same surface area and depth, and had desirable length to width ratios. Both ponds had a similar permanent pool volume, and provided considerable additional extended detention volume. Both ponds stratified during the summer months, and experienced moderate sediment inputs.

At second glance, however, the two ponds could hardly be more different. As noted earlier, Davis pond was rural while Piedmont pond was primarily industrial (and had twice as much impervious cover). Average drawdown time for Davis Pond was nearly 60 hours, while Piedmont had an average drawdown time of less than eight hours. Algal conditions in Davis Pond were hypereutrophic, whereas Piedmont Pond barely registered as eutrophic at all. Incoming phosphorus concentrations were typically three times higher in Davis Pond than Piedmont. And whereas no stormwater practices were located upstream of Davis Pond, nearly half of the total drainage area to the Piedmont Pond (48%) was subject to prior treatment from an upstream stormwater pond at an industrial site. Lastly, the year in which Davis Pond was monitored was a dry year (rainfall only 78% of normal), compared to the relatively normal year monitored at Piedmont (93% of normal rainfall).

The pollutant removal performance observed at the two North Carolina ponds was considerably different (Table 2). On one hand, Davis Pond was found to have an overall pollutant removal just slightly below the national median for stormwater ponds. Davis Pond removed an estimated 60% of incoming sediment, 45 to 60% of phos-

**Table 1: Comparative Profile of the Davis and Piedmont Wet Detention Ponds in North Carolina**

| Feature | Davis Pond | Piedmont Pond |
|---|---|---|
| Drainage Area (acres) | 1258 | 1220 |
| Watershed Imperviousness (%) | 16 | 30 |
| Land Use | Farmland | Industrial |
| Watershed Soils | 70% HSG 'C' | 60% HSG 'C' |
| Pond Surface Area (acres) | 12.7 | 10.0 |
| Mean Pond Depth (feet) | 4.9 | 4.1 |
| Pool Storage Volume (wi)[a] | 0.65 | 0.5 |
| Temp. ED Storage Volume (wi) | 0.74 | 1.17 |
| Average Drawdown Time (hrs) | 59 hours | 7.7 hours |
| Length to Width Ratio | 3.75 : 1 | 7: 1. |
| Pond Area/Drainage Area Ratio | 1.01% | 0.97% |
| Upstream Stormwater Practices? | None | Upstream pond on 48% of DA |
| Year Sampled | 1994 | 1995 |
| Number of Storms Sampled | 25 | 22 |
| Annual Rainfall | 78% of normal | 93% of normal |
| Stratifies During Summer? | Yes | Yes |
| Trophic State [b] | Hypereutrophic | Mesotrophic |
| Storm inflow TSS conc (mg/L) | 145 | 101 |
| Storm Inflow TP conc. (mg/L) | 0.36 | 0.13 |

[a] wi = watershed inches
[b] As computed using the North Carolina Trophic State Index

phorus forms, and 70 to 90% of fecal coliforms. Removals of organic carbon, nitrogen and total copper was rather low (approximately 20%), and zinc and lead removal was also fairly modest.

On the other hand, the Piedmont Pond ranked as one of the lower performers on record, particularly given its large design volume. Only 20% of sediment was removed as it passed through Piedmont, and the pond appeared to slightly export bacteria. Removal of dissolved phosphorus was also disappointing (15%). On the positive side, Piedmont was fairly effective in removing soluble nitrate, but showed very modest ability to remove organic carbon or total nitrogen (approximately 30%).

Thus, despite their design similarities, the two ponds have clearly different removal dynamics and capabilities. Borden and his colleagues diagnosed why the two ponds behaved differently by analyzing internal pond water quality data and applying models. Several key factors appeared to explain their wide divergence in pollutant removal performance.

The first key factor involved algal production. Davis Pond, by virtue of its higher phosphorus loading and long residence time experienced very high algal production. Monitoring revealed high chlorophyll a and shallow secchi depth readings throughout the growing season, and the pond was classified as hyper-eutrophic according to the North Carolina Trophic State Index (Table 3). Modeling showed that incoming nutrients were taken up by the pond algae, incorporated into biomass, and eventually settled to the bottom sediments of the pond. The high algal production, coupled with the pond's shallow depth, create a very strong vertical stratification in the water column during the summer. While nitrogen uptake was also strong in the summer months, ammonia nitrogen produced by decomposition of bottom sediments tended to be trapped and accumulated in the bottom waters of the pond (known as the hypolimnion). Once pond stratification broke down with the onset of cooler weather, much of this ammonia mixed through the water column and was then discharged from the pond, which may account for the mediocre removal of total nitrogen noted at Davis. Also, not all algae produced in the pond settled with the sediments; a substantial portion was discharged from the pond, as evidenced by the export of chlorophyll a seen in Table 2.

While Davis pond was an algae factory, Piedmont was not. Incoming phosphorus concentrations were often too low to stimulate algal growth. Secchi depth readings averaged three feet, and the average chlorophyll a level was a mere 10 µg/L during the growing season. Inorganic nitrogen and phosphorus levels within the pond were frequently below detection limits during the summer, clearly limiting algal growth. Consequently, Piedmont was classified as only mildly eutrophic using the NCTSI technique. Since algal production was so low within Piedmont pond, nutrient uptake was not a major removal mechanism within the pond.

The second key factor explaining the divergent removal capability was the particle size distribution of incoming sediments. The research team showed that the particle size distribution of sediments generated from both subwatersheds were exceeding hard to settle out (Table 4). Sixty percent of the incoming sediments to both ponds had measured settling velocities of one foot per second or less, which is near the limit for meaningful sediment removal. The higher sediment removal reported for other stormwater ponds is simply due to the fact that they receive more sediment mass in heavier fractions that are much easier to settle out. The fine clay soils eroded from the subwatershed limited the capability of both North Carolina ponds to achieve a higher sediment removal rate. Since Davis Pond had a much longer drawdown time (59 hours compared to

**Table 2: Pollutant Removal of North Carolina Ponds**
**Percent Annual Mass Removal (including baseflow and stormflow conditions)**

| Monitored Parameter | Davis Pond (%) | Piedmont Pond (%) | National Median (%) |
|---|---|---|---|
| **Total Suspended Solids** | 60 | 20 | 67 |
| **Total Organic Carbon** | 22 | 27 | 41 |
| **Total Phosphorus** | 46 | 40 | 48 |
| **Dissolved Phosphorus** | 58 | 15 | 52 |
| **Total Nitrogen** | 16 | 30 | 31 |
| **Nitrate-Nitrogen** | 18 | 66 | 24 |
| **Fecal Coliform** | 48 [a] | (-5) | 65 |
| **Copper** | 15 (-30.3) [b] | nd [c] | 57 |
| **Lead** | 51 | nd | 73 |
| **Zinc** | 39 (60.5) [b] | nd | 51 |
| **Chlorophyll *a*** | (-193) | neg [c] | nd |

[a] Average monthly removal ranged from 70 to 90%, annual mean influenced by a single outlier.
[b] Numbers in parentheses indicate removal of soluble metal fraction.
[c] nd = no data, or data were below detection limits neg= negative removal rate.

**Table 3: The Trophic State of Two Stormwater Ponds**

| | Davis Pond (1994) | | Piedmont Pond (1995) | |
|---|---|---|---|---|
| Constituent | Annual Mean | NCTSI Score | Annual Mean | NCTSI Score |
| **Secchi Disc (in.)** | 22 | 0.92 | 36 | 0.41 |
| **Chlorophyll *a* (µg/L)** | 61 | 1.52 | 9.1 | -0.07 |
| **Total P (mg/L)** | 0.151 | 1.92 | 0.037 | 0.32 |
| **Total Organic N (mg/L)** | 1.23 | 2.03 | 0.291 | -0.33 |
| **INDEX TOTAL** | | 6.38 | | 0.32 |

The North Carolina Trophic State Index (NCTSI) provides a quantitative index of eutrophication, based on the total score derived from four lake-wide annual mean variables: concentrations of total organic nitrogen and total phosphorous (mg/L), chlorophyll-a (micrograms/ L) and average secchi disk depth ( in inches). A index score of less than -2 indicates oligotrophic conditions, -2 to 0 indicates mesotrophic conditions, 0 to 5 eutrophic conditions, and a score more than 5 indicates hypereutrophic conditions.

eight at Piedmont), however, it had a longer time frame to settle fine-grained sediments.

The last key factor relates to upstream treatment. As noted earlier, nearly half of the Piedmont subwatershed was also served by an upstream pond. Although no actual monitoring data was available to assess the effectiveness of the upstream pond, it appeared to have a strong influence in reducing inflow concentrations to the downstream pond. Borden noted that inflow concentrations were routinely two to four times lower at Piedmont than Davis. In addition, it was speculated that coarse sediment particles were preferentially removed in the upstream pond, making it that much more difficult to settle sediments in the downstream pond.

Researchers tested a series of simple and complex models to explain the sediment and nutrient removal dynamics of the Davis and Piedmont Ponds. Three models were found to be poor predictors of sediment removal at the test ponds: Brune's empirical curve, Heinemann's curve and Driscolls stochastic sedimen-

**Table 4: Settling Velocity Fractions for Stormwater Sediments in Feet per Second**

| Sediment Size Fraction | % of Sediment by Mass | National | North Carolina Region | Study Area |
|---|---|---|---|---|
| 1 | 0 to 20% | 0.03 | 0.01 | 0.04 |
| 2 | 20 to 40 | 0.30 | 0.08 | 0.44 |
| 3 | 40 to 60 | 1.50 | 0.40 | 0.93 |
| 4 | 60 to 80 | 7.00 | 1.80 | 1.9 |
| 5 | 80 to 90 | 65.00 | 6.00 | 4.44 |

tation model. A complex continuous lake simulation model adapted from the Minnesota Lake Water Quality Model (MINLAKE — Riley and Stefan, 1988) aptly predicted seasonal trends in pond dynamics and produced relatively accurate predictions of sediment and nutrient removal. Interesting, a very simple empirical equation developed by Reckhow (1988) to predict nutrient behavior in Southeastern lakes also proved to be reasonably accurate in predicting annual nutrient removal rates for large stormwater ponds. The Reckhow equations predict phosphorus and nitrogen trapping efficiency for phosphorus and nitrogen in lakes based on simple parameters

$$K_p = 3.0\, P_{in}^{\,0.53}\, T_w^{\,-0.75}\, z^{\,0.58}$$

$$K_n = 0.67\, T_w^{\,-0.75}$$

$K_p$ = trapping efficiency for phosphorus

$K_n$ = trapping efficiency for nitrogen

$P_{in}$ = mean annual influent TP concentration (mg/l)

$T_w$ = hydraulic residence time (years)

$z$ = mean depth (meters)

The predictive value of the simple Reckhow model is shown in Table 5. A quick review of the first equation shows the importance of inflow phosphorus concentration and increased residence time in pond or lake removal efficiency.

***—JSB/TRS***

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**Table 5: Comparison of Observed and Predicted Nutrient Removal for North Carolina Stormwater Ponds Using the Reckhow Equations**

| Annual Nutrient Removal (%) | Davis Pond | | Piedmont Pond | |
|---|---|---|---|---|
| | Total P (%) | Total N (%) | Total P (%) | Total N (%) |
| Observed | 46 | 16 | 40 | 36 |
| Predicted | 51 | 24 | 30 | 21 |