Effects of Residence Time and Depth on Wet Detention System Performance

Harvey H. Harper, Ph.D., P.E.
Environmental Research & Design, Inc.
3419 Trentwood Blvd., Suite 102
Orlando, FL 32812

Abstract

Wet detention ponds are a commonly used stormwater management technique throughout the State of Florida. Current presumptive design criteria for wet detention ponds vary widely with respect to depth and residence time, ranging from shallow ponds (4-12 feet deep) with short residence times (14 days during wet season) to deep ponds (12-20 feet deep) with long residence times (> 100 days). Existing literature related to wet detention ponds suggest a strong correlation between residence time and removal efficiency for both total phosphorus and total nitrogen in wet ponds, with performance efficiency increasing as residence time increases.

A water quality monitoring program was conducted from 2001-2004 in seven wet detention ponds in southeast Orange County which were constructed to a maximum depth of 20 feet. No significant decreases in dissolved oxygen were observed at the pond outfall, even following rain events in excess of 4 inches. Similarly, no statistically significant differences were observed in mean values of dissolved oxygen, conductivity, ammonia, total nitrogen, SRP, or total phosphorus in samples collected following each rain event.

Engineers should be encouraged to design deep (20 feet) wet detention ponds with long residence times (> 100 days). Construction of deep ponds would not only increase the performance efficiency but also provide a substantially larger storage volume for accumulated sediments in an area where resuspension of the material appears to be unlikely.

Introduction

Both man-made and natural waterbodies have been used for stormwater treatment within the State of Florida for over 100 years. Today, wet detention systems are one of the most popular stormwater management techniques, particularly in areas with high groundwater tables. Pollutant removal processes in wet detention systems occur through a variety of mechanisms, including physical processes such as sedimentation, chemical processes such as precipitation and adsorption, and biological uptake from algae, bacteria, and rooted vegetation. These removal processes are regulated by predictable laws of physics, chemistry, and biology, regardless of whether the waterbody has a natural or man-made origin.

A schematic diagram of a wet detention system is given in Figure 1. A wet detention pond is simply a modified detention facility which is designed to include a permanent pool of water with a depth that varies from approximately 6-30 feet. The water level in a wet detention system is controlled by an orifice located in the outfall structure from the pond. The facility is designed with a required treatment volume based upon a specified depth of runoff over the contributing drainage basin area. The treatment volume represents a relatively small portion of the overall volume of the pond and regulates primarily how rapidly water discharges from the pond following a storm event. Inputs of stormwater runoff equal to or less than the treatment volume exit the pond slowly through an orifice in the outfall structure or through percolation into the surrounding groundwater table. Stormwater inputs into the facility in excess of the treatment volume can exit from the pond directly over a weir included in the pond outfall structure. A littoral zone is typically planted around the perimeter of a wet detention facility to provide additional biological uptake and enhanced biological communities.

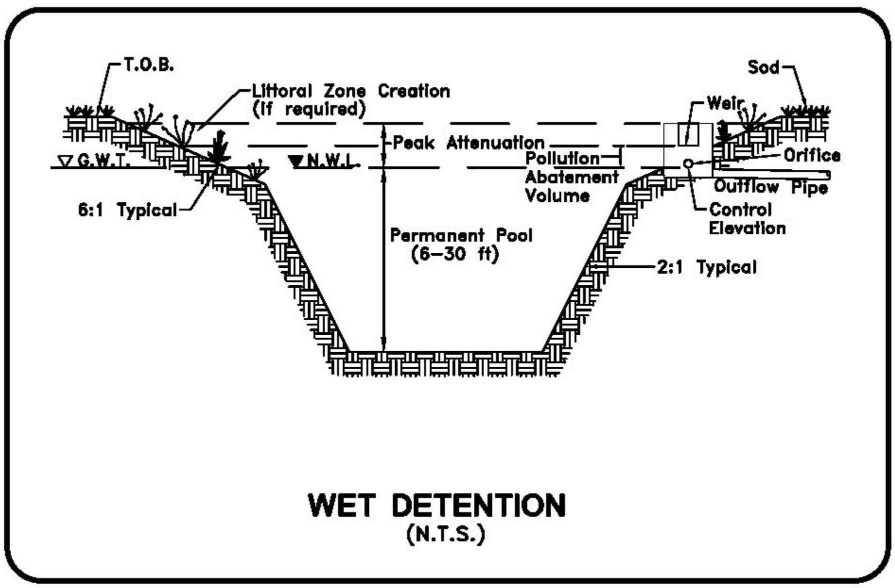

Figure 1. Schematic of a Wet Detention System.

Upon entering a wet detention facility, stormwater inputs mix rapidly with existing water contained in the permanent pool. Physical, chemical, and biological processes begin to rapidly remove pollutant inputs from the water column. Water which leaves through the orifice in the outfall structure is a combination of the mixture of partially treated stormwater and the water contained within the permanent pool. In general, the concentrations of constituents in the permanent pool are typically much less than input concentrations in stormwater runoff, resulting in discharges from the facility which are substantially lower in concentration than found in raw stormwater. As a result, good removal efficiencies are achieved within a wet detention facility for most stormwater constituents. Although the littoral zone can provide enhanced biological uptake, previous research has indicated that a vast majority of removal processes in wet detention facilities occur within the permanent pool volume rather than in the littoral zone vegetation (Harper, 1985; Harper 1988; Harper and Herr, 1993).

Beginning in the early-1980s, design criteria were established for stormwater treatment ponds to ensure a minimum level of pollutant attenuation. The two most significant design criteria for wet detention ponds are the treatment volume, which regulates the pond size and water level fluctuation, and pond depth, which is directly related to the permanent pool volume and residence time of the pond. A summary of current design criteria for wet detention ponds in three primary water management districts in Florida is given in Table 1. The required treatment volume is similar between the three water management districts. However, substantial differences exist with respect to criteria for pond depth and minimum residence time. The St. Johns River Water Management District (SJRWMD) specifies a minimum wet season residence time of 14 days, with a maximum pond depth of 12 feet and a mean depth ranging from 2-8 feet. The Southwest Florida Water Management District (SWFWMD) also requires a minimum 14-day residence time, but places no limitations on pond depth other than the bottom of the pond cannot breech an aquitard. The South Florida Water Management District (SFWMD) has no specific design criteria for either residence time or pond depth.

TABLE 1

SUMMARY OF DESIGN CRITERIA FOR WET DETENTION PONDS IN FLORIDA

PARAMETER	DESIGN CRITERIA		
	SJRWMD	SWFWMD	SFWMD
Treatment Volume	1 inch of runoff	1 inch of runoff	1 inch of runoff
Pond Depth	Maximum: < 12 ft Mean: 2-8 ft	--[1]	--[2]
Minimum Residence Time (Days)	14[3]	14[3]	--[2]

1. Cannot breech aquitard
2. Not specified
3. Minimum wet season residence time

Of the design parameters listed in Table 1, the most important criteria with respect to overall performance of the stormwater management system are pond depth and residence time. However, the significance of residence time on wet detention pond performance has been clearly reported by several researchers. Rushton, et al. (1997) documented a substantial improvement in wet detention pond performance by increasing the mean pond retention time from 2 days to 14 days. Significant increases in removal efficiencies were observed at the higher residence time for TSS, total organic nitrogen, ammonia, NO_x, SRP, total phosphorus, total iron, and total zinc. Toet, et al. (1990)

report that settling may be the most significant removal process for constituents in wet detention ponds. Settling efficiency is dependent on the residence time which is related to the permanent pool volume provided. Toet, et al. concluded that increasing the permanent pool volume has a direct impact on removal efficiency of all components. Harper and Herr (1993) documented increases in removal efficiencies for total phosphorus and total nitrogen with increases in detention time from 7-43 days in a wet detention facility receiving a combination of commercial and residential runoff.

Pond depth is also a significant factor impacting the performance efficiency of a wet detention system since pond depth is directly related to permanent pool volume. Unfortunately, virtually no previous research has been performed to quantify the performance characteristics of relatively deep (> 20 feet) wet detention ponds. Current limitations on the allowable depth of wet detention ponds are based primarily on inferences from studies intended for other purposes.

Typical zonation in a pond or lake is illustrated on Figure 2. The upper portions of the water column in a waterbody are typically well mixed, with a relatively uniform temperature. This upper layer, called the epilimnion, is the area in which the majority of algal production occurs. In this zone, photosynthesis exceeds respiration, and near saturation levels of dissolved oxygen are typically maintained. Under certain conditions, lower layers of a deep lake may become isolated from the upper layers as a result of thermal stratification within the waterbody. Penetration of sunlight into these lower layers can be poor, and as a result, little or no algal productivity may occur. In this lower zone, commonly referred to as the hypolimnion, respiration exceeds photosynthesis, and the water column may become void of dissolved oxygen during certain parts of the year.

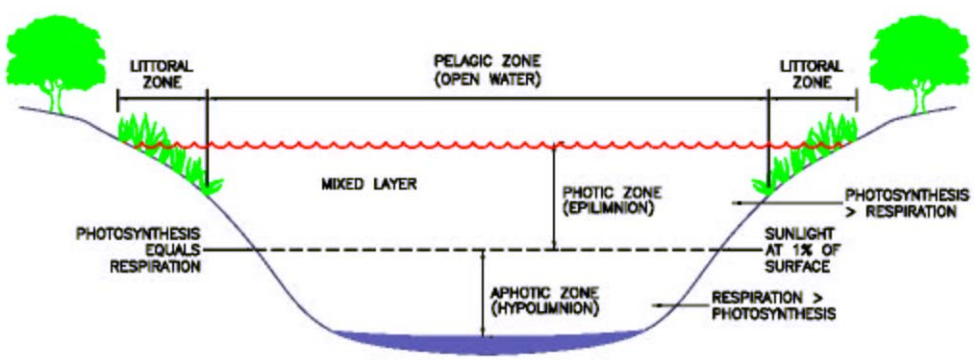

Figure 2. Typical Zonation in a Lake or Pond.

Under stratified conditions, the hypolimnion becomes isolated from oxygen input mechanisms, and anaerobic conditions may develop. Anaerobic conditions, considered to occur when dissolved oxygen concentrations decrease to less than 1 mg/l, may increase the release of ions such as ammonia and orthophosphorus, along with gases such as H_2S and

CO_2, from the bottom sediments into the hypolimnion water. The accumulated constituents in the hypolimnion can then be circulated into the epilimnion as a result of a destratifying event, such as a prolonged windy period or strong storm event, potentially resulting in episodes of reduced water quality and low dissolved oxygen at the pond outfall. However, if penetration of solar radiation is not inhibited, waterbodies as deep as 20 feet or more with low algal production may not experience stratification or anaerobic conditions at deeper water depths.

Impacts of Residence Time on Performance Efficiency

A general literature review was conducted of previous research performed within the State of Florida which quantifies pollutant removal efficiencies for stormwater treatment ponds as a function of residence time. Particular emphasis was given to studies which appear to be scientifically valid, provide a reasonable period of study, include estimates of performance efficiency in terms of mass removal, and provide an estimate of residence time or sufficient information so that a residence time could be calculated. Although studies related to stormwater treatment ponds are relatively common in the literature, very few of these studies provide estimates of performance efficiency calculated on a mass removal basis, and even fewer provide estimates of pond residence time during the period of study. The vast majority of wet detention pond studies simply provide measurements of changes in concentrations during migration through the pond.

A summary of selected stormwater treatment studies identified in the literature is given in Table 2. Thirteen separate studies were selected which provide both mass removal estimates for total nitrogen and total phosphorus and calculated estimates of residence time. The first two ponds identified in Table 2 present the results of stormwater research conducted by Rushton, et al. (1995) and Harper and Herr (1993). Residence times for these ponds range from 2-19 days. As residence times increase, ponds typically become larger in both surface area and volume and are often identified as named waterbodies. The remaining studies summarized in Table 2 reflect studies performed on named waterbodies, utilized primarily for stormwater treatment, as part of a watershed study or water quality improvement project. For each of these studies, the calculated residence time and mass removal efficiencies for total nitrogen and total phosphorus reflect the combined inputs from stormwater runoff, groundwater seepage, and bulk precipitation. Virtually all of these studies reflect urban waterbodies which provide stormwater treatment for large residential and commercial areas. Calculated residence times for the selected studies range from 2-328 days, reflecting a wide range of treatment conditions.

A plot of removal of total phosphorus as a function of residence time in stormwater treatment ponds is given in Figure 3. The “best-fit” equation through these points exhibits a logarithmic shape with an R-square value of 0.720, indicating that residence time explains approximately 72% of the variability in removal efficiency for total phosphorus in stormwater treatment ponds. The “best-fit” curve appears to become asymptotic at a removal efficiency of approximately 90% for total phosphorus at a residence time of 300 days, although removal efficiencies as high as 98% were observed within the data set.

TABLE 2

SUMMARY OF REMOVAL EFFICIENCIES FOR SELECTED STORMWATER TREATMENT PONDS IN FLORIDA

POND LOCATION	RESIDENCE TIME (days)	MASS REMOVAL (%)		REFERENCE
		TN	TP	
Tampa	2 14	33 61	62 90	Rushton, et al. (1995)
DeBary	19	26	54	Harper and Herr (1993)
Tallahassee (Lake Arrowhead)	49	52	71	Harper, et al. (2000)
Tallahassee (Gilbert Pond)	77	20	60	Harper, et al. (2000)
Tallahassee (Lake McBride)	168	54	76	Harper, et al. (2000)
Tallahassee (Lake Tom John)	114	34	68	Harper, et al. (2000)
Winter Park (Lake Virginia)	220	44	85	ERD (2000)
Winter Park (Lake Osceola)	102	35	71	ERD (2000)
Winter Park (Lake Maitland)	197	35	79	ERD (2000)
Orlando (Lake Lucerne)	105	53	80	Harper and Herr (1991)
St. Petersburg (Mirror Lake)	114	84	92	ERD (1998)
Lakeland (Lake Morton)	328	43	83	Harper, et al. (2002)
Orlando (Lake Eola)	244	89	98	Harper, et al. (1982)

A plot of removal of total nitrogen as a function of residence time in stormwater treatment ponds is given in Figure 4. Removal of total nitrogen as a function of residence time also appears to exhibit a logarithmic shape, although the R-square value of 0.39 is somewhat less than the R-square value observed for total phosphorus. The removal efficiency for total nitrogen appears to become asymptotic at an efficiency of approximately 55%.

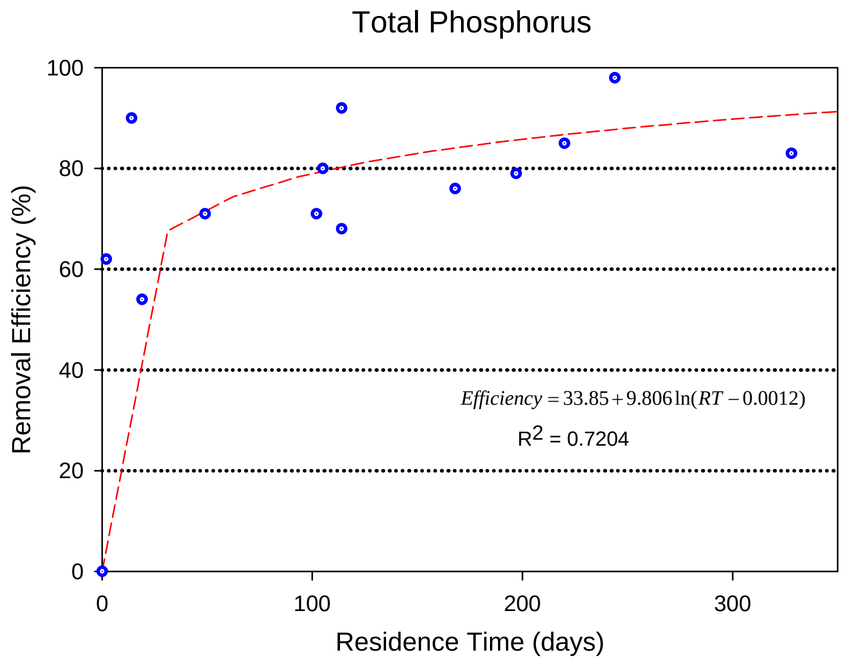

Figure 3. Removal of Total P as a Function of Residence Time.

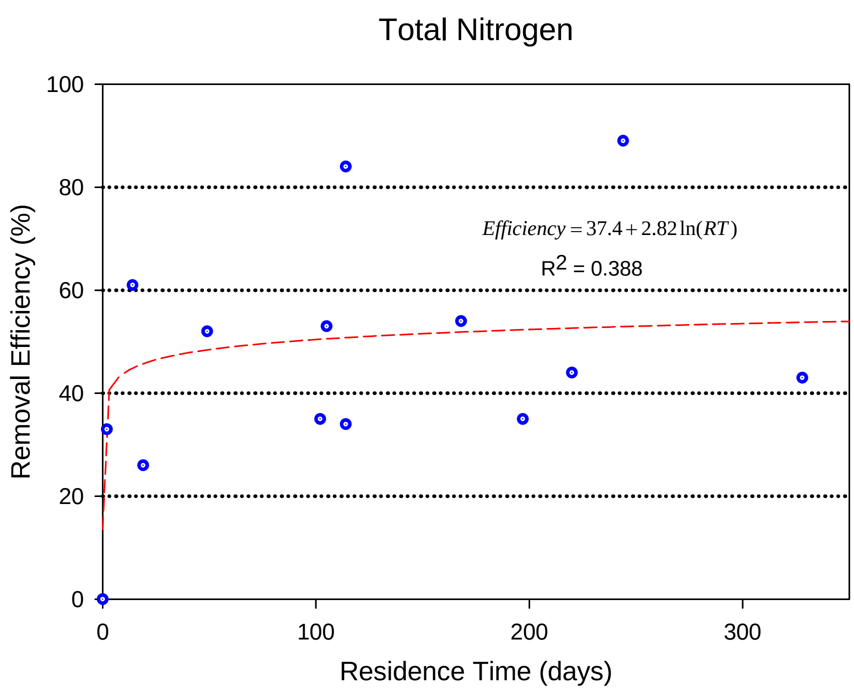

Figure 4. Removal of Total N as a Function of Residence Time

Impacts of Pond Depth on Performance Efficiency

No significant previous studies have been conducted within the State of Florida to evaluate the impact of pond depth on performance efficiency. However, limited water quality monitoring of pond discharges following significant rain events has been required as a permit condition for construction of deep ponds permitted by SJRWMD. A quarterly monitoring program was required by SJRWMD for the Stoneybrook Development, located in southeast Orange County, as part of the permit requirements for construction of seven wet detention ponds to a maximum depth of 20 feet. Characteristics of the constructed deep ponds in the Stoneybrook Development are summarized in Table 3. Pond areas range from 1.23-7.98 acres, with contributing land use consisting of entry road, residential, and golf course areas. Each of these seven ponds was constructed to a maximum depth of 20 feet.

The SJRWMD permit for the project requires water quality monitoring to be performed in each of the seven detention ponds on a quarterly basis after 80% completion of development in each of the watersheds. Water quality samples must be obtained twice daily, at least 6 hours apart, for three days following storm events that produce at least 0.5-inch of rainfall. This monitoring program is designed to detect variability in outfall concentrations of dissolved oxygen, nitrogen species, phosphorus species, and heavy metals following significant rain events which may cause circulation of the entire waterbody to occur. If anaerobic conditions had developed in lower layers of the pond, these conditions would be evidenced by decreases in dissolved oxygen, and increases in species such as ammonia, SRP, and total phosphorus at the pond discharge. The quarterly monitoring program was initiated in 2001 and has continued through 2004, with a total of 11 monitored events.

TABLE 3

CHARACTERISTICS OF DEEP PONDS IN THE STONEYBROOK DEVELOPMENT

POND	SURFACE AREA (acres)	MAXIMUM DEPTH (ft)	CONTRIBUTING LAND USE
2-1	1.23	20	Entry road
2-3	2.09	20	Residential
3-1	7.98	20	Residential
5-1	5.51	20	Residential
8-1	3.91	20	Residential
10	4.60	20	Golf Course
11	7.68	20	Golf Course

A statistical comparison of mean variability in discharges from deep ponds in the Stoneybrook Development following storm events is given in Figure 5. Rainfall depths for the monitored storm events range from 0.5-4.4 inches, with a mean rainfall depth of 2.27 inches for the 11 monitored events. As seen in Figure 5, no significant decreases in dissolved oxygen have been observed at the pond outfall even following rain events in excess of 4 inches. None of the monitored outfall events was observed to have dissolved oxygen concentrations less than the Class III criterion of 5 mg/l outlined in Chapter 62-302 FAC. Similarly, no significant increases in specific conductivity, ammonia, total nitrogen, SRP, or total phosphorus were observed in the initial monitoring performed immediately following the storm event which would suggest negative water quality impacts from anaerobic lower layers. No statistically significant differences are present in mean values of dissolved oxygen, conductivity, ammonia, total nitrogen, SRP, or total phosphorus between the six samples collected following each rain event. Based upon the statistical summary presented in Figure 5, the fact that the ponds were constructed to a depth of 20 feet rather than the 12-ft maximum outlined in the SJRWMD regulations does not appear to have negatively impacted discharges from any of the monitored ponds.

A summary of mean characteristics of discharges from deep ponds in the Stoneybrook Development from 2001-2004 is given in Table 4. Discharges from the ponds have been characterized by near-saturation levels of dissolved oxygen, relatively low levels of total nitrogen, and concentrations of total phosphorus similar to those commonly observed in urban lakes. No exceedances of applicable Class III water quality criteria have been observed for lead, zinc, or fecal coliform bacteria.

TABLE 4

MEAN CHARACTERISTICS OF DISCHARGES FROM DEEP PONDS IN THE STONEYBROOK DEVELOPMENT FROM 2001-2004

PARAMETER	UNITS	MEAN VALUE BY POND						
		2-1	2-3	3-1	5-1	8-1	10	11
Diss. Oxygen	mg/l	8.7	7.4	8.3	8.2	7.6	7.9	8.1
Total N	µg/l	1027	807	782	758	801	751	909
SRP	µg/l	2	2	2	2	2	9	7
Total P	µg/l	39	28	23	35	26	33	37
Lead	µg/l	1.3	1.5	1.3	1.3	1.2	1.2	1.2
Zinc	µg/l	8.1	7.8	6.4	5.8	5.8	5.1	3.3
Fecal Coliform	CFU/100 ml	176	174	74	136	181	126	94

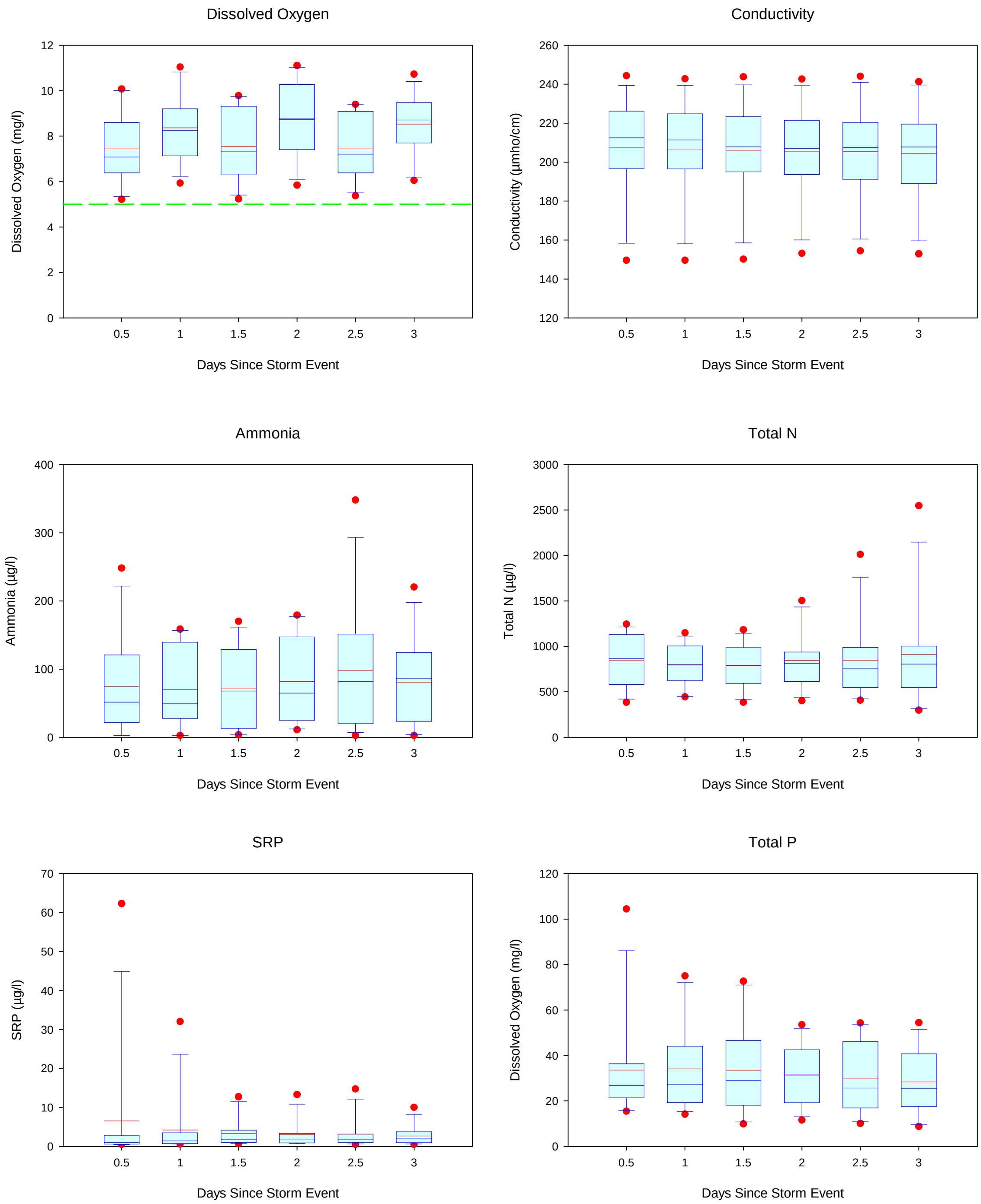

Figure 5. Mean Variability in Discharges from Deep Ponds in the Stoneybrook Development Following Storm Events.

Discussion and Conclusions

Based upon the plots presented in Figures 3 and 4, residence time appears to be significantly correlated with removal efficiencies for both total nitrogen and total phosphorus. Increases in residence time explain approximately 72% of the variability in removal efficiency for total phosphorus, while explaining approximately 39% of the variability in removal efficiency for total nitrogen. The remaining variability in removal efficiencies for total nitrogen is related to differences in the forms of nitrogen present within the pond as well as nutrient limitation dynamics. However, it appears clear that increasing the residence of wet detention ponds can improve removal efficiencies for both total nitrogen and total phosphorus.

Construction of wet detention ponds to a depth of 20 feet does not appear to have a significant negative impact on overall performance of a wet detention system. Circulation of anaerobic water from lower layers of a wet detention pond would be easily observed by substantial variability in concentrations of dissolved oxygen discharging through the pond outfall, particularly during the period immediately following the storm event. The monitoring program performed at the Stoneybrook Development has not revealed any negative water quality impacts associated with ponds constructed to a depth of 20 feet. Further research is recommended to characterize water quality impacts from ponds constructed deeper than 20 feet.

Engineers should be encouraged to design deep wet detention ponds, up to 20 feet in depth, to increase residence time and improve treatment effectiveness. In addition, deeper ponds provide storage for accumulated pollutants in an area of the pond where resuspension is unlikely. The larger permanent pool volume also provides additional protection from shock loads.

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