Table 12. Particle size and organic content of sediment core samples collected in October 1993. DP-Depth of sample and # = sample number. See Figure 3 for sample locations.

Sediment Cores for October 1993						
#	DP (in)	Location	SAND %	SILT %	CLAY %	ORGANIC CONTENT %
1	1	SWALE	92	0	8	2.27
	4		96	3	2	0.43
2	1	N.DITCH	54	12	34	7.74
	4		75	8	17	4.29
3a	1a	INFLOW	81	7	12	2.37
	4a		83	5	13	2.63
3b	1b	DUPLICATE	79	5	17	3.90
	4b		76	0	24	4.56
4	1	MID-POND	72	5	24	5.18
	4		NA	NA	NA	NA
5	1	LITTORAL E	74	12	14	4.83
	4		72	4	24	4.88
6	1	N. POND	61	25	15	10.66
	4		48	29	23	5.89
7	1	DEAD OUT	75	7	18	6.63
	4		98	0	2	0.31
8	1	OUTFLOW	74	8	18	5.21
	4		79	2	19	3.13

Table 13. Particle size and organic content of sediment core samples collected in January 1995. DP-Depth of sample and # = sample number. See Figure 3 for sample locations.

Sediment Cores for January 1995						
#	DP (in)	Location	SAND %	SILT %	CLAY %	ORGANIC CONTENT %
1	1	SWALE	94	3	3	1.14
2	1	N.DITCH	73	15	11	10.03
3	1	INFLOW	75	9	16	3.45
4	1	MID-POND	72	5	24	4.41
5	1	LITTORAL E	74	7	19	4.79
6	1	N. POND	73	6	20	NA
7	1	DEAD OUT	94	2	4	0.88
8	1	OUTFLOW	71	21	8	3.68

Organic content usually shows a reduced percentage with depth. Surface layers in the pond generally ranged between 2 and 5 percent organic matter except in the east ditch which was colonized by a substantial stand of cattails and measured over 7 percent for both years. The grass swale (site 1) had the least organic matter content.

Constituent Concentrations

Nutrients and metals in the sediments are compared to concentrations of constituents in the water columns for October 1993 (Table 14) and January 1995 (Table 15). Field measurements in the water column are included for comparison purposes. Field conditions reflect the different seasons of the collection dates and measured much cooler temperatures and supersaturated conditions for dissolved oxygen in January of 1995. Some spatial relationships as well as comparisons between sediments and the overlying water column are discussed below.

Nitrogen concentrations in the sediments, measured primarily as organic nitrogen (TKN), were much lower in the swale and pond than in the vegetated east ditch and the vegetated littoral shelf at the outflow in 1993 (Table 14). Also the concentration of both inorganic nitrogen and TKN in the water column exhibited the same pattern as that in the sediments indicating an exchange between the sediment water interface during the quiescent no flow conditions in 1993 (Appendix N-1). A similar pattern for the sediments was seen for 1995 except sites 6 and 7 had considerably less TKN in the first inch of the core (Table 15). A shift of nitrogen concentrations in the water column in 1995 can be explained by rainfall patterns. For 1993, no storm with precipitation greater than 0.25 inches had fallen for at least two weeks before sampling took place, while in 1995, the week before the cores were collected, several storms greater than an inch occurred and water was still flowing out of the pond.

Phosphorus concentrations show more accumulation in the pond sediments and the vegetated east ditch than at the inflow swale or the outflow of the pond. Sedimentation is a major pathway for removal of phosphorus and these results show this taking place. Unlike nitrogen, phosphorus concentrations in the water column exhibit no consistent pattern with concentrations in the sediments but a negative correlation exists with dissolved oxygen (DO) concentrations ($R^2=0.40$) during the quiescent conditions of 1993, when wide variations in DO were measured (Appendix N, Figures 3, 4 and 5). The spatial relationship between DO and total phosphorus (TP) also helps explain the lower TP median values in the water column in December 1995 (0.053 mg/l) when DO saturation was over 100 percent compared to October 1993 (0.083 mg/l). This result is consistent with other researchers who have observed a several-fold increase of dissolved P associated with anaerobic sediments (Yousef *et al. 1986*). Phosphorus is not directly altered by changes in redox potential but is indirectly affected in sediments by association with several elements that are reduced (have a valency change).

Table 14. Spatial water quality and sediment concentrations for nutrients and metals in the "Tampa Office" stormwater management system. Samples were collected October 20, 1993, six months after the pond was recontoured. H2O=Water quality sample and SED=Sediment sample. Arsenic, antimony, selenium, silver and thallium were tested for but not found. Sampling locations are in Figure 3. Sediment sample depth (DP) means cores taken from the sediment surface (1) and four inches below the surface (4). Water samples were taken above the same locations. See Appendix R for abbreviations.

OCTOBER 1993			KJELDAHL NITROGEN		INORGANIC NITROGEN		TOTAL PHOSPHORUS		ORTHO PHOS.	TOTAL ZINC		TOTAL COPPER		TOTAL LEAD		TOTAL CADMIUM		BE	NICKEL	CR	IRON	MN	TSS
Constituent => Sediment or Water => #	DP (in)	Location	TKN SED (mg/kg)	TKN H20 (mg/l)	NOx H20 (mg/l)	NH3 H20 (mg/l)	TP SED (mg/kg)	TP H20 (mg/l)	OPH H20 (mg/l)	ZN SED (mg/kg)	ZN H20 (mg/l)	CU SED (mg/kg)	CU H20 (ug/l)	PB SED (mg/kg)	PB H20 (ug/l)	CD SED (mg/kg)	CD H20 (ug/l)	BE SED (mg/kg)	NI SED (mg/kg)	CR SED (mg/kg)	FE H20 (mg/l)	MN H20 (mg/l)	TSS H20 (mg/l)
1	1	SWALE	350	NA	NA	NA	100	NA	NA	8.2 J	NA	U	NA	U	NA	U	NA	0.4 I	U	U	NA	NA	NA
	4		91				54			9.4 J		U		U		U		0.6 I	U	U			
2	1	N. DITCH	2000 J	1.238	0.020	0.101	1200 A	0.163	0.072	132.0 J	0.165	U	0.8	12.0 I	1.16	U	0.04	U	6 I	18 I	0.795	0.036	11.87
	4		700 A				0			5.3 J		U		7.9 I		U		U	5 I	13 I			
3a	1a	INFLOW	150 A	0.578	0.007	0.046	150	0.083	0.020	14.0	0.015	U	0.3	U	0.69	U	0.00	U	U	U	0.278	0.012	6.89
	4a		110				150			8.2		U		U		U		U	U	U			
3b	1b	DUPLICATE	210	NA	NA	NA	940 J	NA	NA	9.2	NA	U	NA	U	NA	U	NA	U	4 I	29 J	NA	NA	NA
	4b		360 A				1100 A			8.3		U		10.0 I		U		U	U	13 I			
4	1	MID-POND	270 A	0.541	0.011	0.054	1400 A	0.054	0.012	9.1 J	0.006	U	0.2	17.0 I	0.85	U		U	5 I	27 J	0.225	0.004	3.16
	4		NA				NA			NA		NA		NA		NA		NA	NA	NA			
5	1	LITTORAL E	300	0.567	0.020	0.055	1000	0.061	0.013	U	0.007	U	3.3	U	0.99	U	0.00	U	4 I	36 J	0.178	0.004	4.86
	4		270				1300			U		U		12.0 I		U		2	4 I	27			
6	1	N. POND	2200	1.435	0.018	0.187	730	0.268	0.037	26.0 J	0.003	U	0.6	14.0 I	0.81	U	0.00	1 I	6 I	8.5 I	0.324	0.026	6.63
	4		380				400			U		U		U		U		1 I	4 I	U			
7	1	DEAD OUT	1400	0.652	0.014	0.058	680	0.090	0.019	10 I	0.006	U	0.7	U	1.58	U	0.09	U	U	10 I		0.007	11.94
	4		110				100 J			U		U		U		U		U	U	U			
8	1	OUTFLOW	990	0.479	0.003	0.067	320	0.063	0.025	24	0.021	U	1.5	U	1.22	U	0.00	U	U	7.6 I	0.161	0.012	4.03
	4		98 J				240 J			U		U		U		U		U	U	U			

FIELD CONDITIONS IN WATER COLUMN WHEN SOIL SAMPLES WERE TAKEN

OCTOBER 1993 Location		SAMPLE DEPTH inches	VEG. TYPE	TIME	TEMP deg C	D.O. mg/l	COND ms/cm	pH su	REDOX volts	%SAT %	T.D.S g/l
1	SWALE	2	grass	------------ -no samples taken ---------------							
2	N.DITCH	11	cattail	8:11	24.33	2.21	0.54	7.26	358	26	0.35
3	INFLOW	16	none	13:14	28.90	12.15	0.426	7.84	390	158	0.27
4	MID-POND	24	Chara sp	------------ -no samples taken ---------------							
5	LITTORAL E	15	algae	7:40	25.23	8.09	0.291	7.78	415	98	0.19
6	N.POND	12	pickerel	7:55	23.92	1.31	0.372	7.11	371	15	0.24
7	DEAD OUT	31	none	7:32	25.41	8.07	0.304	8.07	396	89	0.20
8	OUTFLOW	15	none	13:51	25.85	2.94	0.359	7.26	408	36	0.23

ABBREVIATIONS FOR SOIL SAMPLES.

J = ESTIMATED VALUE
I = VALUE REPORTED IS LESS THAN THE MINIMUM QUANTITATION LIMIT (REFERENCE ONLY) AND GREATER THAN OR EQUAL TO THE MINIMUM DETENTION LIMIT.
A = VALUE REPORTED IS THE MEAN OF TWO OR MORE DETERMINATIONS.
U = MATERIAL WAS ANALYZED FOR BUT NOT DETECTED.
NA = NOT ANALYZED

ABBREVIATIONS FOR FIELD MEASUREMENTS

TEMP=Temperature
D.O.=Dissolved Oxygen
COND=Sp Conductance
REDOX=Oxidation Reduction Potential
%SAT=Saturation of Oxygen
T.D.S.=Total Dissolved Solids

Table 15. Spatial water quality and sediment concentrations for nutrients and metals in the "Tampa Office" stormwater management system. Samples were collected January 17, 1995, eight months after the pond was recontoured. H2O=Water quality sample and SED=Sediment sample. Arsenic, antimony, selenium, silver and thallium were tested for but not found. Sampling locations are in Figure 3. Sediment sample depth (DP) means cores taken from the sediment surface (1) and four inches below the surface (4). Water samples were taken above the same locations. Duplicate soil cores were taken at site 6. See Appendix R for abbreviations.

JANUARY 1995	KJELDAHL NITROGEN		INORGANIC NITROGEN		TOTAL PHOSPHORUS		ORTHO PHOS.	TOTAL ZINC		TOTAL COPPER	
Constituent => Sediment or Water => # DP Location (m)	TKN SED (mg/kg)	TKN H20 (mg/l)	NOx H20 (mg/l)	NH3 H20 (mg/l)	TP SED (mg/kg)	TP H20 (mg/l)	OPH H20 (mg/l)	ZN SED (mg/kg)	ZN H20 (mg/l)	CU SED (mg/kg)	CU H20 (ug/l)
1 1 SWALE	1000 A		0.002	0.025	210 A	0.049	0.038	31 I	0.080	4 I	3.70
4	110 A				76 A			12 U		3 I	
2 1 N. DITCH	900	0.940	0.051	0.004	820 A	0.107	0.034	18 J	0.024	2 I	0.8
4	1900				320 A			4 I		2 I	
3 1 INFLOW	450 A	1.078	0.002	0.009	260 A	0.053	0.040	13 U	0.023	2 U	0.3
4	53 A				86 A			11 U		2 U	
5 1 LITTORAL E	360 A	0.921	0.004	0.008	480 A	0.056	0.040	14 I	0.022	2 U	0.2
4	370 A				640 A			23 I		2 U	
6 1 N. POND	430	0.460	0.004	0.010	1300 J	0.023	0.010	15 J	0.008	2 I	3.3
4	360				1000 A			14 J		2 U	
6b 1 N. POND-D	330				1100 A			14 J		2 U	0.6
4	310 A				1300 J			13 J		2 U	
7 1 DEAD OUT	450	0.250	0.012	0.010	230 A	0.020	0.010	9 J	0.010	1 U	0.7
4	220				200 A			4 I		1 U	
8 1 OUTFLOW	1800 A	0.827	0.004	0.005	450 A	0.104	0.071	94	0.018	5 I	1.5
4	92 A				230 A			17 I		2 U	

JANUARY 1995	TOTAL LEAD		TOTAL CADMIUM		BE	NICKEL	CR	FE	MN	AL	TSS
Constituent => Sediment or Water => # DP Location (m)	PB SED (mg/kg)	PB H20 (ug/l)	CD SED (mg/kg)	CD H20 (ug/l)	BE SED (mg/kg)	NI SED (mg/kg)	CR SED (mg/kg)	FE H20 (mg/l)	MN H20 (mg/l)	AL SED (mg/kg)	TSS H20 (mg/l)
1 1 SWALE	16 I	3.30	1.0 U	0.20	0.4 I	4 I	9 I	0.92	0.349	3090	22
4	6 U		0.3 U		0.0	0	13 I			2560	
2 1 N. DITCH	10 I	1.16	1.0 U	0.20	0.0	0	27	1.37	0.065	10400	21.64
4	5 I		0.9 U		0.0	0	14			4730	
3 1 INFLOW	6 U	0.69	0.0	0.40	0.3 I	3 I	16	0.18	0.005	5040	6.09
4	6 U		1.0 U		0.3 U	2 U	10 I			3400	
5 1 LITTORAL E	6 U	0.85	1.0 U	0.00	0.4 I	4 I	26	0.24	0.005	9760	9.96
4	6 U		1.0 U		0.6 I	6 I	43			13300	
6 1 N. POND	13 I	0.99	0.8 U	0.00	0.0	0	45	0.48		15400	1.07
4	10 I		1.0 U		0.0	0	39 A			12700	
6b 1 N. POND-D	11 I	0.81	1.0 U		0.0	0	46			15700	
4	14 I		1.0 U		0.0	0	58			19700	
7 1 DEAD OUT	5 U	1.58	1.0 U	0.00	0.0	0	6 I	0.04	0.002	1680	0.41
4	5 I		0.9 U		0.0	0	12			3540	
8 1 OUTFLOW	10 I	1.22	2.0 U	0.20	0.5 I	4 I	19 I	0.44	0.001	6860	3.25
4	6 U		1.0 U		0.3 I	2 I	13 I			5790	

FIELD CONDITIONS IN WATER COLUMN WHEN SOIL SAMPLES WERE TAKEN

JANUARY 1995 Location	SAMPLE DEPTH inches	VEG TYPE	TIME	TEMP deg C	D.O. mg/l	COND ms/cm	pH su	REDOX volts	%SAT %	T.D.S. g/l
1 SWALE	3	grass	13:00	16.58	13.84	2.56	6.99	501	NA	NA
2 N.DITCH	6	cattail	11:13	14.01	8.90	0.80	7.75	372	88	0.51
3 INFLOW	NA	none	13:45	18.13	11.23	0.43	8.26	414	116	0.27
5 LITTORAL E	9	grass*	14:45	19.27	10.56	0.36	8.41	406	116	0.23
6 N.POND	20	grass*	13:28	18.52	12.66	0.41	8.82	400	134	0.26
7 DEAD OUT	32	Chara	11:41	15.00	10.02	0.42	8.25	423	98	0.27
8 OUTFLOW	11	none	16:01	19.57	10.22	0.43	8.14	422	111	0.28

*Torpedo grass and chara sp. as well as other planted vegetation such as pickerel weed

ABBREVIATIONS FOR SOIL SAMPLES.
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A = VALUE REPORTED IS THE MEAN OF TWO OR MORE DETERMINATIONS.
U = MATERIAL WAS ANALYZED FOR BUT NOT DETECTED.
NA = NOT ANALYZED

ABBREVIATIONS FOR FIELD MEASUREMENTS
D.O.=Dissolved Oxygen
COND=Sp Conductance
REDOX=Oxidation Reduction Potential
%SAT=Saturation of Oxygen
T.D.S.=Total Dissolved Solids

Metal concentrations in the sediments of these newly constructed ponds were usually measured below the quantification limit (I) or not detected at all (U). Chromium was the one metal measured above the quantitation limit. It should be noted that only low levels of chromium were measured in the water column (see Table 10). One explanation for the higher concentrations of chromium in the sediments is that chromium is naturally occurring in the soils. This observation makes use of the fact that a natural relationship exists between metals and aluminum. Therefore, aluminum is sometimes used to normalize sediment metal concentrations when used to identify anthropogenically enriched sediments (Livingston *et al.* 1995). Although the procedure has not been perfected for fresh water systems in Florida and the sediment samples in this study did not receive the rigorous laboratory methods recommended for definite quantification, our results do indicate that the higher concentrations of chromium at sites 5 and 6 are associated with higher levels of aluminum and are probably not enriched from stormwater input.

Comparison to Standards

Since sediments tend to integrate contaminant concentrations over time they may represent a much better method for determining when conditions are toxic to organisms. For this reason, several government agencies are working on standards to assess possible toxic levels detrimental to aquatic organisms. Some of these standards are listed in Table 16. Also compared in Table 16 are standards used to determine safe levels in soils. Soils are considered non-toxic (clean) in Florida (Chapter 62-775 FAC) as long as concentrations do not exceed those listed in column (a). Stormwater pond sediments are considered clean for disposal purposes if they meet these standards (Livingston and Cox 1995). This means that if sediments are removed from wet detention ponds, and they meet these standards, they can be disposed of on site or used for cover material in lined landfills; and thus, do not create a disposal problem.

Table 16. Sediment water quality criteria giving threshold concentrations (mg/kg) where constituents have the lowest effect level (Possible) and the limit of tolerance level (Probable). See text for a more complete explanation.

Constituent	Soil (a)	Freshwater (b)		Estuarine (c)	
		Sediments		Sediments	
	Toxic	Possible	Probable	Possible	Probable
Cadmium	37	1	10	1	8
Lead	108	31	250	21	160
Zinc	na	110	800	68	300
Copper	na	25	114	28	170
Chromium	50	31	111	33	240
Total Phosphorus	na	545	4800	na	na
Kjeldahl Nitrogen	na	600	2050	na	na

(a) Soil Thermal Treatment Facilities, Chapter 62-775 FAC
(b) Development of Sediment Quality Guidelines (Persud *et al.* 1990)
(c) Sediment Quality in Florida Coastal Waters (MacDonald 1993)

Possible biological effects on aquatic animals need more stringent requirements and two levels have been set for aquatic sediment in several states and Canada (Giesy and Hoke 1990). Informal sediment contamination guidelines have been published for freshwater sediments in Canada which identify potentially adverse biological effects (Persuad *et al.* 1990). Possible effects listed in column (b) represent the boundary between the level at which no toxic effects have been observed and the lowest level showing the concentration that can be tolerated by the majority of benthic organisms. The probable effect indicates the level at which a pronounced disturbance to the benthic community occurs. Guidelines for estuarine sediments, column (c), have been established for Florida (MacDonald *et al.* 1993). The lower bounds of the range of concentrations which could potentially be associated with biological effects is the possible effect level while the probable effect level represents concentrations known to be toxic to organisms.

For metals, none of the sediments measured in these newly constructed ponds reached toxic levels and only a few were considered in the range that could potentially be associated with adverse biological effects. These were usually located in the densely vegetated east ditch (2) or the vegetated littoral zone (6) near the outflow. The same pattern was also noted for nutrients where potentially detrimental levels of Kjeldahl nitrogen and total phosphorous were associated with dense vegetation. Entrapment or uptake of these constituents by plants or benthic organisms and burial in the sediments is one process that removes these pollutants from the system. Since these can be released back to the water column under certain conditions more study is needed to establish pond maintenance guidelines or possible removal of sediments once concentrations are a problem.

Organic Priority Pollutants

The increasing dependence of today's society on technology derived from organic chemicals has led to widespread hydrocarbon pollution. Organic compounds are relevant because they can be carcinogenic, bioaccumulate in organisms, cause toxic reactions plus they degrade slowly. Organic priority pollutants are of special concern in stormwater runoff since much of the source material is associated with automobile traffic.

Sediment samples at the site were tested for over 100 organic pollutants, but only those listed in Table 17 were detected. For 1990 only the sediments at the inflow and outflow were sampled while in 1993 and 1995 four to five locations were tested in the pond and two locations were sampled in the inflow ditches. The only locations with detectable concentrations were the inflow swale and the inflow of the pond.

In 1990, the pond had been receiving stormwater runoff for four years and both the inflow and outflow had some detectable levels of organic pollutants. In 1993, four months after the newly constructed pond had been receiving runoff, no organic pollutants were detected in the pond, but measurable concentrations of polycyclic aromatic hydrocarbons (PAH) were measured in the swale near the parking lot which had not been disturbed by construction. In 1995, the concentrations in the swale had increased several fold and the pond, which had been recontoured six months earlier, already showed trace levels of PAHs.

Some PAHs are known to be carcinogenic to man and are formed during the combustion of coal and petroleum. A major source is street dust present as weathered materials of street surfaces, automobile exhaust, lubricating oils, gasoline, diesel fuel, tire particles, and atmospherically deposited materials (Takada *et al.* 1990).

Table 17. Organic priority pollutants (mg/kg) were sampled in the sediments for all three years. Analyses were performed for over 100 pollutants but only the ones listed below were found in any of the three years. (Note 1990 is for Inflow and Outflow while the other years are Swale and Inflow).

Constituent	1990 Inflow	1990 Outflow	1993 Swale	1993 Inflow	1995 Swale	1995 Inflow
Polycyclilic Aromatic Hydrocarbons (PAH)						
benzo(a)anthracene	U	U	0.76 I	U	3.90	0.44 T
benzo(a)pyrene	U	U	U	U	2.30 I	U
benzo(b)fluoranthene	U	U	U	U	6.20	0.44 T
benzo(ghi)perylene	U	U	U	U	1.70 I	0.44 T
benzo(k)fluoranthene	U	U	1.50	U	2.00 I	U
benzo(b+k)fluoranthene	0.66 M	U	U	U	U	U
chrysene	U	U	U	U	1.40 I	U
dubebzi(a,h)anthracene	U	U	U	U	5.10 T	U
pyrene	0.22	0.31	1.30	U	5.20	0.44 T
fluoranthene	0.03 M	0.03 M	1.10	U	6.00	0.44 T
indo(1,2,3-c,d)pyrene	U	U	0.49	U	2.40 I	0.44 T
phenanthrene	U	U	0.38	U	2.50 I	0.44 T
Esters						
di-n-butyl phthalate	U	0.23	U	U	U	U
di-n-ocytl phthalate	0.10	U	U	U	U	U
butyl benzyl phthalate	0.16	U	U	U	U	U
Nitrosamine						
1,2-diphenylhydrazine	U	0.24 M	U	U	U	U
Pesticide						
4,4'-DDE	0.20	U	U	U	U	U

ABBREVIATIONS:

I = Value reported is less than the minimum quantitation limit, and greater than or equal to the minimum detection limit.

T= Value reported is less than the criterion of detection

M= Indicates presence of material was verified but not quantified

U=Material was analyzed for but not detected.

The Nationwide Urban Runoff Program (NURP) evaluated the significance of priority pollutants which produced results consistent with our findings (Cole *et al.* 1984). Although the NURP analyses were conducted on water samples, the patterns were the same as in our study. For example, they detected PAHs more often than any other organic priority pollutant with pyrene, phenanthrene and fluoranthene found in at least 10 percent of samples. NURP data also detected phenanthrene and pyrene in concentrations that might pose a risk to human health. Since organic pollutants accumulate in the sediments and they present a potential risk to aquatic life and to human health if ingested, it is suggested that their accumulation rate be monitored in stormwater systems and appropriate action taken if a risk is detected. In this study a definite upward trend in the accumulation of PAHs was noted, especially for pyrene, fluoranthene and phenanthrene.

Relationship Between Variables

Chemical and physical processes in surface waters influence the concentration of pollutants in stormwater systems. One of the purposes of this study was to analyze the interactions of various constituents and identify relationships between variables in order to better understand how to make these systems work more efficiently. To aid in this analysis, statistical tests were run on the data collected for 87 rain events over a three year period. The data were typical for natural systems with values highly skewed to the right and often containing extreme outliers. Nonparametric procedures, especially the Spearman method, were used to compute correlation coefficients (Appendices O and P). The Spearman coefficient not only makes no assumption of a normal or linear distribution but also gives more reliable information if the data possess a distinct curvilinear relationship (Walpole and Myers 1972).

Direct Rainfall

To put the correlations in perspective, a few facts about the importance of rainfall directly on the pond are reviewed. Depending on the area of the pond, rainfall accounted for 14 to 26 percent of the hydrologic input, while 20 to 30 percent of inorganic nitrogen and 9 to 10 percent of copper entered directly in rainfall (see Table 8). Zinc concentrations were variable between years but perhaps as much as 38 percent entered the pond in rain during the 1993 sampling period. Rainfall was an insignificant pathway for other pollutants during all years.

Correlation analysis identified relationships between variables (Figure 18). Some researchers have found that precipitation tends to contain contaminants at higher concentrations in short storms and when precipitation is infrequent (Mitsch and Gosselink 1993). This suggests that the washout effect, with rainfall purifying the air, occurs during the early part of a storm, while longer duration rain events dilute samples. In this study, only weak correlations ($r = -0.19$ to -0.34) were observed when rainfall characteristics were compared to constituent concentrations. However, much higher concentrations of inorganic nitrogen (> 0.4 mg/l) were measured in storms with less than an inch of precipitation while storms greater than 1.25 inches never had high levels (Figure 18). Closely spaced storms and rainfall intensity probably account for the many low concentrations reported during small storms.

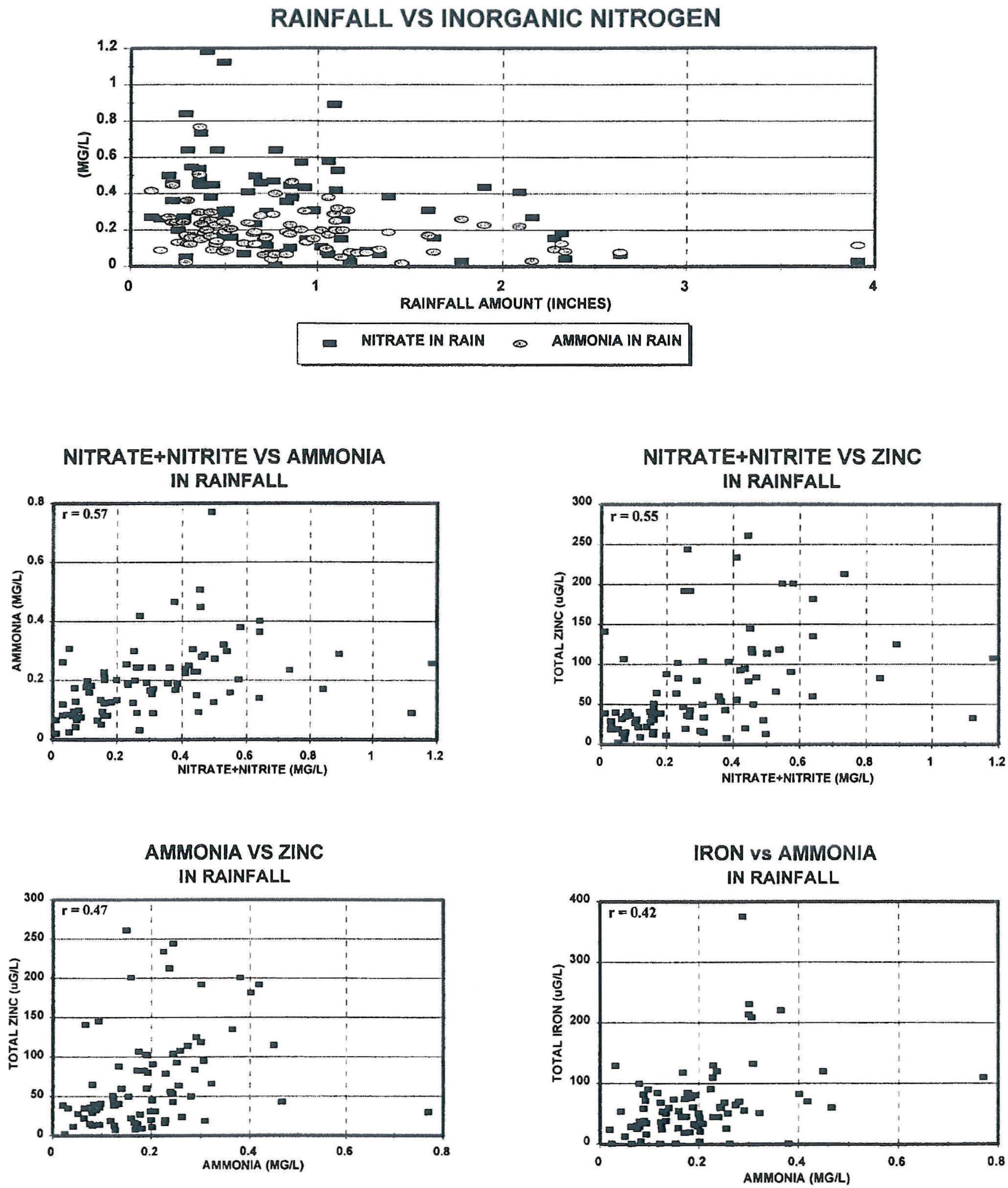


Figure 18. Scatter plots for concentrations of constituents measured in rainfall indicating variables which had a tendency to vary together. r=Spearman correlation coefficient.

The few constituents in rainfall measured in high enough concentrations to analyze statistically are graphed together for descriptive purposes and imply a joint relationship rather than a cause and effect dependency (Figure 18). The Spearman's coefficient of rank correlation identified a few associations demonstrating a tendency for some constituents to increase together. Ammonia, nitrate plus nitrite, zinc and iron showed the strongest positive relationships. Several explanations are discussed below.

A major pathway for the nitrate and ammonia found in rainfall comes from the transformation of nitrogen oxides. Anthropogenic sources of nitrogen oxide contribute a large amount of nitrogen to the atmosphere. In 1985, Florida was listed as the eighth largest nitrogen oxide emitting state based on national rankings of total emissions. Of the total amount of nitrogen oxide discharged, vehicular traffic contributed 50 percent, utilities 35 percent and other industrial sources 5 to 10 percent (Rogers 1990). Another source for the combined nitrogen in the atmosphere is the ammonia released by microbial degradation of terrestrial organic matter that is then partly oxidized to nitrate in the atmosphere (Hutchinson 1944).

It should be noted that rainfall samples at this site had higher concentrations of both zinc and ammonia when compared to two other locations in the Tampa Bay area (Rushton 1993). Explanations include the close proximity of cattle feedlots and industrial activity. Almost 75 percent of the total estimated U. S. Anthropogenic emissions of ammonia come from livestock waste and fertilizer application (Placet *et al.* 1990). The significantly higher zinc levels are attributed to industrial air pollution and the resuspension of particles by highway traffic.

Transport and eventual deposition of aerial pollutants is a complicated process as the ten years of work conducted by the National Acid Precipitation Assessment Program (NAPAP) concluded (Hicks *et al.* 1989). The NAPAP report helps explain the high nitrogen levels found in rainfall. Convective storms remove pollutants efficiently, transform these pollutants into other chemical species, and deposit the products in rainfall. Southwest Florida has the greatest number of convective storms in the United States with 100 per year normal for the region. Gaseous ammonia, due to its high solubility, is rapidly taken up on atmospheric aerosols. Its atmospheric lifetime is short and once deposited it is converted to acidic nitrate in soils. The report further states that urban versus rural studies show urban samples may have up to ten times more sulfates and nitrates for a given storm and about 1.5 times more deposited annually. Wet deposition represents most of the wet plus dry deposition of sulfur and nitrogen while phosphorus is transported primarily as dry deposition (Brezonik *et al.* 1983). It should be noted (see Table 6) that concentrations of inorganic nitrogen in rainfall were always greater than concentrations measured at the inflow of the pond indicating its removal and transformation by overland flow through the large grassed areas in the drainage basin.

Rainfall analysis emphasizes the need to reduce anthropogenic air pollution to help clean up surface water pollution. Nitrogen oxides are emitted into the atmosphere primarily through the combustion processes used in transportation, fossil fuel energy production and waste incineration. The results also points out the importance of vegetated areas in the drainage basin to help utilize and transform nitrogen before it reaches surface waters.

Inflow Data

In a comparison between rainfall, the inflow, and the outflow stations, correlation analysis shows the strongest associations for the inflow data (Appendix O). In general constituents which exhibit a tendency to increase together exhibit much less scatter than the correlations identified in rainfall, although the coefficients are similar. Of all the constituents examined iron and phosphorus proved to be the best predictors for constituent concentrations, although a few of the other metals also varied together. For example, an association exists between zinc and copper ($r = 0.66$). Nitrogen species exhibited the poorest relationships with no coefficients greater than 0.46. Rainfall characteristics were related to each other but were only weakly correlated ($r < 0.50$) to constituent concentrations except for negative correlations with the major ions. Also the major ions show strong relationships to each other (except potassium) and were negatively correlated to some constituents, most often phosphorus, iron and lead.

As mentioned above, some of the best correlations (Figure 19) occurred with iron, the strongest of these are with lead, manganese, suspended solids, and phosphorus (to be discussed later). Although iron is of little direct toxicologic significance, it often controls the concentration of other elements, including toxic heavy metals, in surface waters (Moore 1991). Surface water iron concentrations usually range from 50 to 200 ug/l in aerated aquatic systems (Hutchinson 1975). In this study, iron concentrations increased at the inflow from an average of 555 ug/l in 1990 to 3200 ug/l in 1994, probably caused by the construction activity and resultant soil disturbance. Because iron is so common in the earth's crust, erosion accounts for a majority of the concentrations transported by runoff (Moore 1991). Most iron is present as colloidal particles of ferric hydroxide which is measured here, in part, as suspended solids explaining that relationship (Figure 19). In addition, ions in suspended solids can neutralize the charges on the hydroxide colloidal particles forming a rapidly settling precipitate. Metals, such as copper, can also be adsorbed by and co-precipitated with the ferric hydroxide precipitate (Wetzel 1975). The relationship between iron and copper would undoubtedly have been stronger except for a fertilization and weed control program that occurred at the site between August 1994 and January 1995 and artificially elevated copper and nitrogen levels on some dates during this period. Manganese is chemically similar to iron in its behavior in surface water and similar conditions cause these two elements to vary together. The major ions tend to be inversely correlated with iron and a sodium example is shown in Figure 19.

Phosphorus also shows some significant relationships (Figure 20). It is of considerable environmental concern as a nutrient since, in surface water where it is a limiting factor for growth, inputs of phosphate can result in obnoxious algal blooms. As might be expected since ortho phosphorus is part of total phosphorus, these two constituents vary together (Figure 20). Also in Figure 20 the interrelationship of phosphorus, iron and manganese is evident. This supports the idea that their aquatic transformations (dissolution, transport, distribution, precipitation and accumulation) are interrelated and are interdependent with those of other significant components of natural waters (Stumm and Morgan 1970). Ferric oxides are known to co-precipitate or occlude to phosphorus under aerobic conditions and are, in fact, relatively selective for phosphorus although they also adsorb proportions of metals and other constituents.

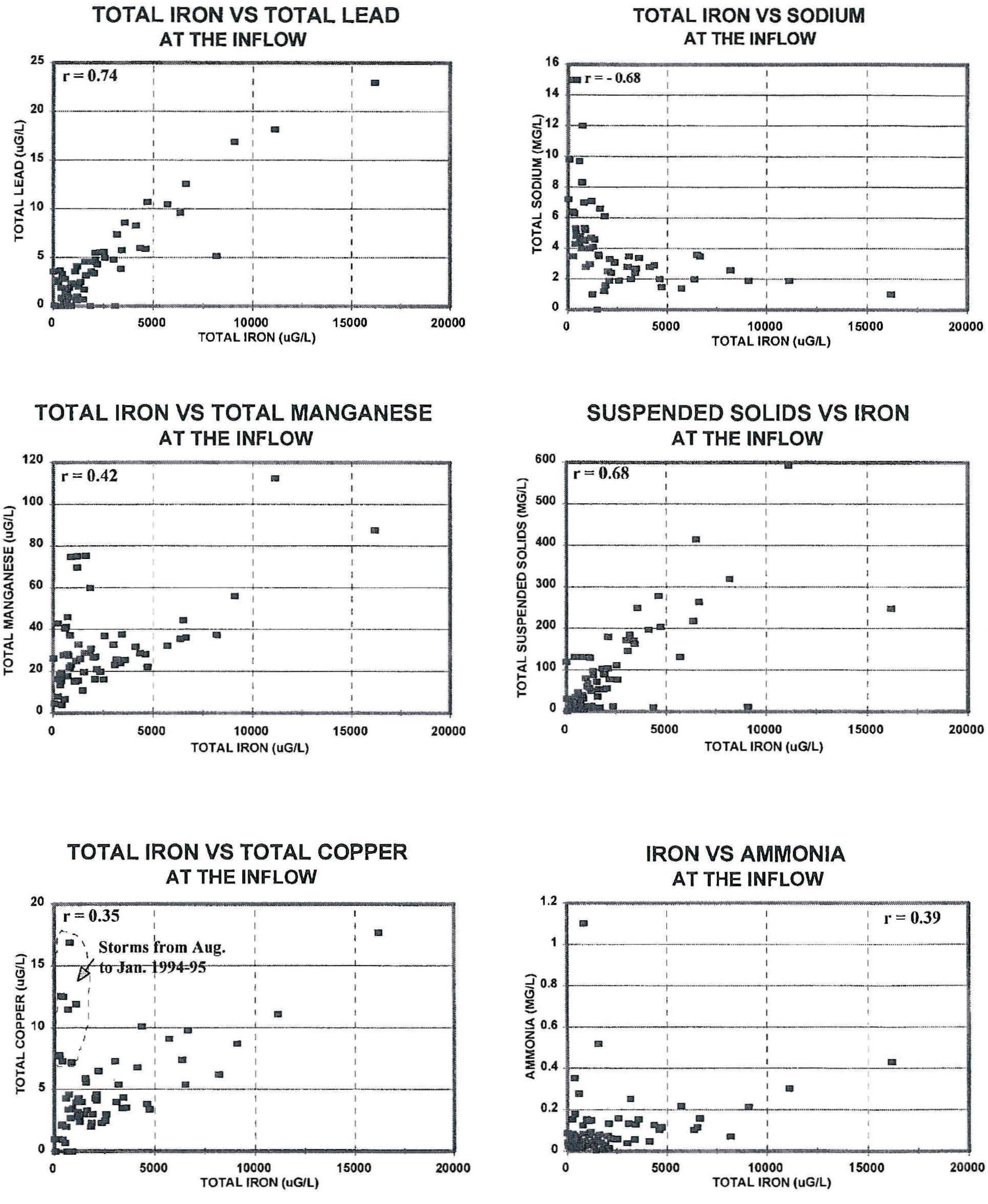


Figure 19. Scatter plots for variables measured at the inflow which had a tendency to vary with iron concentrations. r=Spearman correlation coefficient.

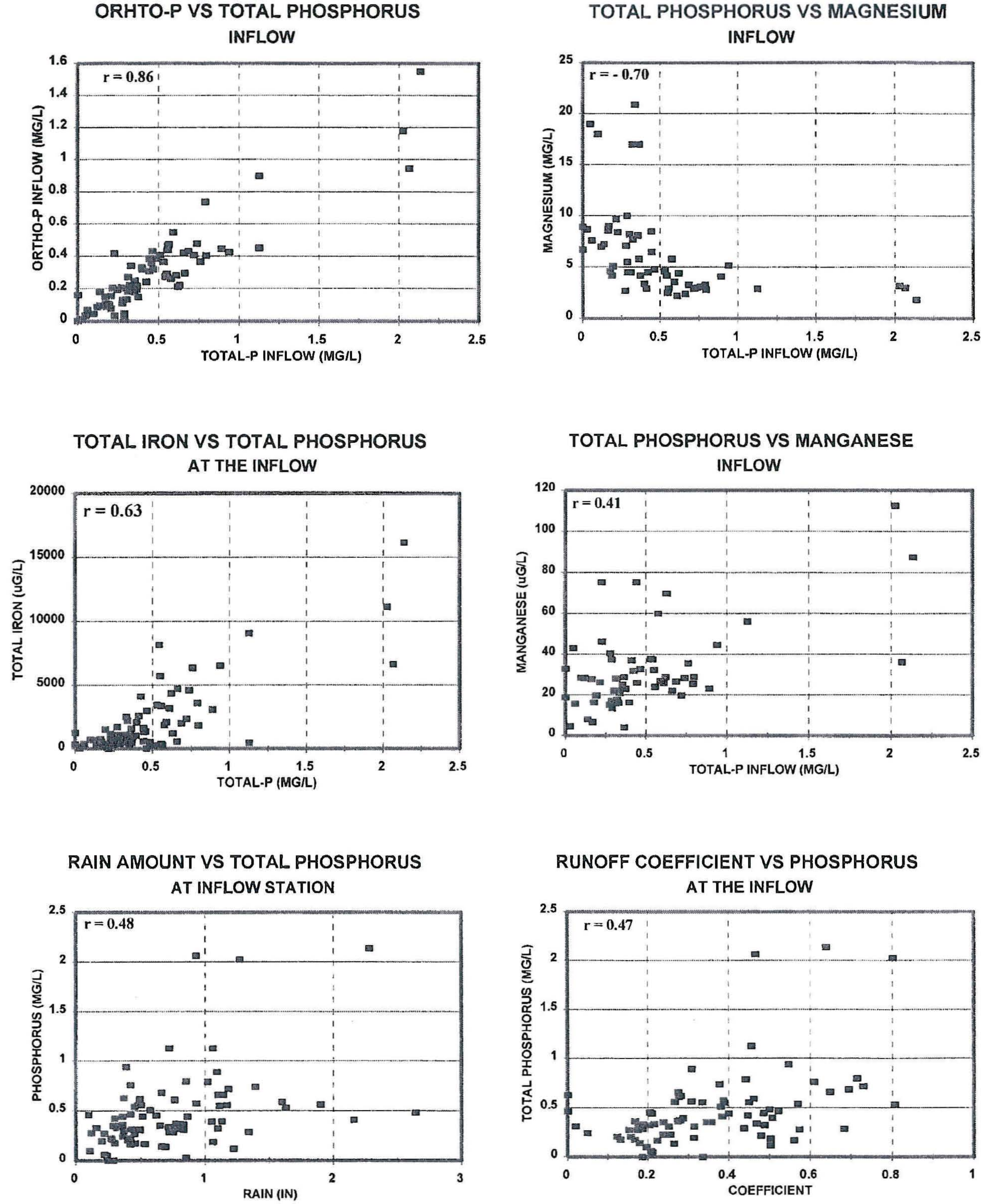


Figure 20. Scatter plots for variables measured at the inflow which had a tendency to vary with total phosphorus. r=Spearman correlation coefficient.

Total phosphorus is also weakly correlated with rainfall amount and negatively correlated with many of the major ions as the example with magnesium demonstrates.

The inflow correlation analysis emphasizes the importance of iron as a controlling mechanism. Since it was measured in above average concentrations, especially in 1994, and since it forms particles that settle easily, it undoubtedly represents an important process leading to the sedimentation and removal of constituents in this study.

Outflow Data

In general the same correlation patterns were seen at the outflow as the inflow (Appendix P), although not as many relationships were identified. Zinc, iron and cadmium were weakly related ($r = 0.45$). Iron was no longer associated with lead, probably because of the extremely low concentrations of lead found in outfall samples with most concentrations below the laboratory detection limit. Nitrogen demonstrated no strong correlations ($r < 0.41$) when compared to other nitrogen species, other constituents, or rainfall characteristics. Major ions were related to each other but demonstrated negative correlations with phosphorus, iron and suspended solids, similar to the patterns found at the inflow.

The most consistent relationships were graphed in scatter plots (Figure 21). As expected, ortho phosphate, which is about 58 percent of total phosphorus, shows good agreement when compared to total phosphorus. One of the major ions, calcium, was plotted as an example of the inverse relationship exhibited by major ions. As discussed above, iron is usually present as ferric oxyhydroxide in aerobic waters, but water at the outflow is sometimes anaerobic after crossing over the wide, heavily vegetated, littoral shelf. Therefore, iron at the outflow may be present in the ferrous form which binds phosphorus and some metals less tightly as was discussed in the sediment section. Also concentrations of iron were significantly less with an average of about 319 ug/l at the outflow compared to 1951 ug/l at the inflow. With a few exceptions, the lower concentrations of constituents make correlations less obvious. One exception, total suspended solids was much better correlated to total phosphorus at the outflow ($r = 0.71$) than at the inflow ($r = 0.47$) indicating a transformation of suspended solids in the pond from inorganic particles to organic forms.

Phosphorus concentrations increased during larger storms at both the inflow and outflow. One explanation for increased concentrations of phosphorus with more intense storms was demonstrated with a study using ^{32}P as a tracer (Ahuja 1990). In that study, rainfall increased the transfer of chemicals from soil solution into surface runoff; with the transfer of phosphorus from the soils likely coming from a pumping action associated with rainfall impacts and accelerated molecular diffusion (Ahuja and Lehman 1983). In our study the effect was much more obvious at the outflow in 1990 when the pond was shallow and often dry (Rushton and Dye 1993).

Correlation analysis provided a basis for drawing conclusions about some of the processes taking place, especially for phosphorus and metals. Phosphorus and iron appear to be controlling factors with increased concentrations of other pollutants increasing with these two constituents. Phosphate species are known to form complexes, chelates and insoluble salts with some metals (Stumm and Morgan 1970).

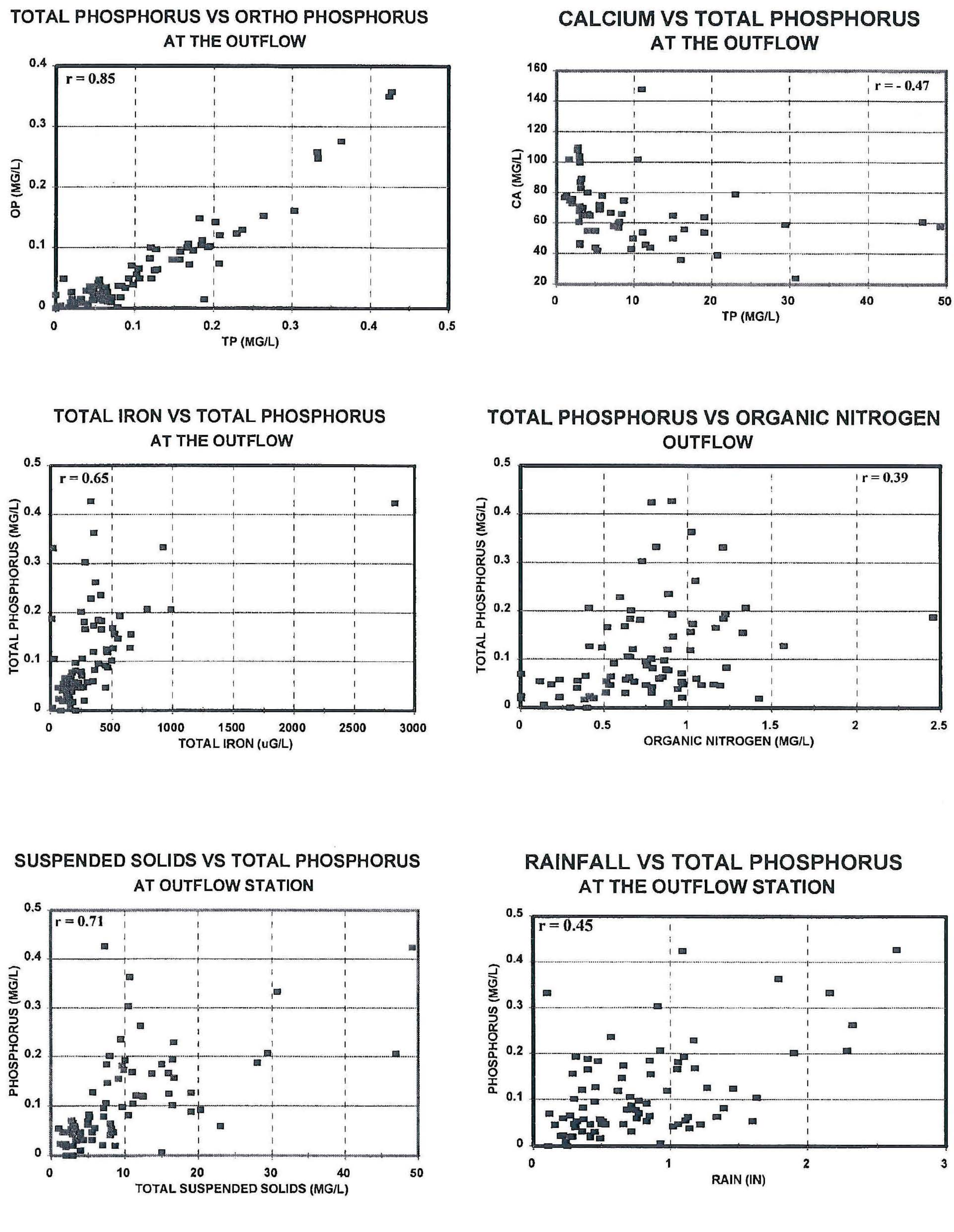


Figure 21. Scatter plots for concentrations of constituents measured at the outflow indicating variables which had a tendency to vary together. r=Spearman correlation coefficient.

Biological Measurements

The preceding sections have investigated the physical and chemical interactions taking place in the wet detention pond. The following section discusses plant and insect measurements made during the final year of the study in 1994 and for vegetation again in 1996.

Vegetation Analysis

Shallow areas, usually around the perimeter of lakes and ponds, which support emergent vegetation are referred to as the littoral zone. They help provide for the biological assimilation of pollutants, and therefore, wet detention ponds built according to SWFWMD rules must include a minimum of 35 percent littoral zone, preferably concentrated at the outfall. The rule also states that the littoral zone shall be no deeper than 3.5 feet below the design overflow elevation. Planting of species is not usually required, but native vegetation that becomes established must be maintained as part of the operation permit. The purpose of this part of the study was to document which plants colonize the littoral zone by natural recruitment and to determine the success of actively planting the littoral zone by increasing the coverage of desirable plants. Also of interest are the processes which allow the invasion of species that tend to form monocultures and have little wildlife value. These are especially serious when they are also aggressive colonizers, such as cattail *(Typha* sp) and primrose willow *(Ludwigia peruviana)* which produce large volumes of organic matter and anaerobic conditions on pond bottoms. Of special concern in this study was the dominance of another noxious species, torpedo grass *(Panicum repen),* which during 1993 and 1994 was a dominant colonizer on the littoral shelf and expanded rapidly into open water by elongated surface runners. This exotic species is difficult to control and is seldom utilized by waterfowl or songbirds (Tarver *et al. 1978).*

A productive littoral zone of desirable plant species helps transform and bury pollutants using a complex variety of biological, chemical and physical processes. For example, Macrophytes remove pollutants by: 1) assimilating them directly into their tissue, 2) providing a suitable environment for microbial activity which in turn remove pollutants, and 3) transporting oxygen into their rhizosphere, thereby stimulating aerobic degradation of organic matter and growth of nitrifying bacteria (Brix 1993, Reddy and DeBusk 1987). Vegetation also slows flow which gives particulates time to settle. In addition a diverse vegetation community attracts macroinvertebrates that also convert constituents and bury them in the sediments. Denitrification, seepage and ammonia volatility are other processes which remove nitrogen. Although senescence of plant parts often release nutrients back to the water column, translocation to the roots essentially removes some nutrients permanently.

Vegetation History at the Site - When first constructed, the original wet detention pond was planted with a variety of species. According to the vegetation plan finalized on January 8, 1987, the following species were to be planted: 206 cypress trees *(Taxodium distichum)*, 950 pickerel weed (*Pontederia cordata)*, and 400 cord grass (*Spartina bakeri*). The cord grass and cypress were planted above the littoral zone and the pickerel weed, spaced on 3.3 foot centers, covered the entire pond area. There was no permanent pool in this early design. By 1990, the first year of this study, the cypress and cord grass were well established around the perimeter of the pond, but cattails had invaded the central portion, although some pickerel weed (*Pontederia cordata)*, water lily (*Nymphaea odorata*) and arrowhead (*Sagittaria lancifolia*) still survived, although hidden, among the cattail.

In 1993, the first year the pond was recontoured, an effort was made to save as many of the cypress trees and as much of the cord grass as possible, still many had to be sacrificed to provide sufficient area for the enlarged pond. Almost all of the desirable species in the pond were either transplanted to another site or plowed under. After construction was completed, the littoral zone was quickly colonized by torpedo grass and later almost the entire volume of the permanent pool was invaded by a macroalga, *Chara* sp. Some of the vegetation near the outfall and a few of the pickerel weed and arrowhead in the littoral zone surrounding the pond survived the construction. In July 1994, about six weeks into the final year of collecting data for this study, the littoral zone was planted with 365 bare root pickerel weed seedlings and 265 bare root arrowhead (*Sagittaria latifolia)* plants.

Vegetation Survey - In an effort to quantify the result of natural recruitment on species diversity a vegetation survey of the littoral zone was conducted before planting in June 1994 and again two years after planting in June 1996. Meter square quadrat frames were used to estimate percent cover of emergent vegetation in 54 individual quadrats. Where the littoral zone was wide enough, one quadrat was analyzed near shore, the "a" quadrat, and another measurement was made in the deeper zone, the "b"quadrat (see Figure 4 for the exact location of all sampling sites and Appendix Q for all the measurements). Some of the most striking differences between 1994 and 1996 included the large reduction in open water and the increase in species diversity (Table 18). The dominant species in 1994, torpedo grass *(Panicum repens)* and barnyard grass *(Echinoclloa crusgalli*) occupied about the same area during both sampling events, but many other species had also colonized by 1996. These included not only the planted pickerel weed *(Pontederia cordata)* and arrowhead (*Sagittaria latifolia*) but also *Bacopa monnieri* which grew profusely in the upper part of the fluctuating pool and *Rhynchospora corniculata* which had dispersed from a patch near the outfall to produce isolated individual seedlings throughout the littoral zone. Some nuisance species were also increasing, especially cattail *(Typha* sp.) and willow *(Salix caroliniana)* which, as explained above, have the potential to crowd out more desirable species. Alligator weed (*Alternanthera phloxeroides*) was another noxious weed of concern which showed a 69 percent increase from 1994 to 1996.

Submerged Vegetation - The most noticeable nuisance species in 1996 were large patches of filamentous algae. Since submerged species were not counted in the survey, unless a mat broke the surface of the water, the many large clumps below the surface throughout the littoral zone are not included in Table 18. Also, not included in Table 18 was the macroalga *Chara* which occupied about 40 percent of the volume in the deeper water and appears to be shaded out and killed by the filamentous algae mats. *Chara* had been a dominant vegetation type (about 60 percent of the volume of the permanent pool) during the study in 1993, but was almost totally absent in the pond during the vegetation survey in 1994. By 1996 it was once again a dominant

Table 18. Vegetation analysis of the littoral zone using percent cover. Surveys were conducted June 1994 (shaded columns) and June 1996. Exten=dead end extension on west side, West=West side of original pond, East=East side of original pond, New=part of pond excavated in 1994, Shelf=wide littoral shelf at the outflow. See Figure 4 for locations.

SCIENTIFIC NAME	COMMON NAME	LITTORAL ZONE - PERCENT COVER											
		1994	1996	---------- 1994 ----------					---------- 1996 ----------				
				EXTEN	WEST	EAST	NEW	SHELF	EXTEN	WEST	EAST	NEW	SHELF
Open Water		62.09	29.70	66.1	61.3	50.5	75.1	22.1	40.6	23.7	32.5	22.2	14.6
Panicum repens	Torpedo grass	17.78	23.28	20.1	15.4	20.0	2.4	29.3	33.2	11.3	9.3	32.8	3.9
Echinochloa crusgalli	Barnyard grass	5.30	5.43	0.0	8.1	4.8	0.0	19.4	0.0	13.3	10.6	0.8	1.1
Alternanthera phloxeroides	Alligator weed	2.60	4.39	0.0	0.0	0.0	0.0	0.0	5.8	4.1	4.7	0.4	7.3
Rhynchospora corniculata	Horned-rush	1.57	2.87	0.0	0.0	0.0	0.0	12.1	0.0	5.8	0.3	0.2	11.4
Ludwigia repens		1.50	0.44	4.8	3.6	5.5	0.0	8.6	1.1	0.0	0.0	0.7	0.3
Lolium spp ?		1.20	0.00	0.0	0.0	4.5	0.0	2.1	0.0	0.0	0.0	0.0	0.0
Dichromina colorata	White top sedge	0.93	0.83	2.9	0.1	0.0	0.0	1.3	2.1	0.3	0.7	0.5	0.0
Ludwigia peruviana	Primrose Willow	0.57	0.33	1.4	0.0	1.0	0.0	0.0	0.1	0.1	1.4	0.0	0.1
Pontederia cordata	Pickerel weed	0.48	8.02	0.0	1.7	0.0	0.0	0.7	0.2	10.7	3.7	10.9	21.0
Mikania scandens	Hemp vine	0.46	2.30	1.1	0.3	0.1	0.0	0.7	0.4	0.3	6.2	1.5	4.6
Paspalum distichum	Knot grass	0.46	0.00	0.4	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
Spartina bakeri	Cord grass	0.46	0.00	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrocotyle umbellata	Pennywort	0.43	4.83	0.7	0.5	0.2	0.0	0.7	2.1	2.3	6.3	0.4	18.6
Grass (red head)		0.41	0.13	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.7	0.0
Commelina sp.	Dayflower	0.39	0.07	0.0	0.0	1.9	0.0	0.0	0.0	0.1	0.1	0.0	0.3
Polygonium punctatum	Knot weed	0.37	0.56	0.0	1.7	0.0	0.0	0.0	0.0	1.0	0.7	0.0	0.0
Centella asiatica	Coinwort	0.37	0.28	0.4	0.4	0.9	0.0	0.0	0.4	0.5	0.3	0.0	0.1
Ludwigia leptocarpa		0.37	0.09	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.1
Cyperus haspens		0.35	0.00	0.0	0.4	0.4	0.0	1.4	0.0	0.0	0.0	0.0	0.0
Sagittaria lancifolia	Arrowhead	0.28	0.11	0.7	0.0	0.0	0.0	0.7	0.1	0.0	0.0	0.0	0.6
Lythrum alatum	Loosestrife	0.28	0.46	0.4	0.5	0.3	0.0	0.1	0.2	0.7	0.3	0.4	0.6
Lippia nodiflora	Carpet weed	0.26	0.22	0.7	0.0	0.4	0.0	0.0	0.0	0.4	0.4	0.0	0.4
Cyperus oderatus		0.24	0.15	0.0	0.8	0.0	0.3	0.0	0.1	0.0	0.0	0.0	1.0
Pluchea purpurascens	Marsh-fleabane	0.17	0.06	0.1	0.7	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Acer rubrum	Red maple seedling	0.11	0.19	0.1	0.0	0.5	0.0	0.0	0.1	0.4	0.3	0.0	0.1
Floating filamentous algae		0.09	6.93	1.6	0.0	0.0	0.0	0.0	6.8	19.4	1.8	1.9	0.0
Sesbania Vesicaria	Bag-pod	0.09	0.00	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Typha sp.	Cattail	0.07	0.63	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	3.0	0.6
Glabrous Grass		0.04	0.31	0.1	0.0	0.0	0.0	0.0	0.0	0.8	0.5	0.2	0.0
Ampelopsis arborea	Pepper vine	0.04	0.07	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0
Eupatorium capillifolium	Dog fennel	0.04	0.02	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Bacopa monnieri	Water-hyssops	0.00	3.37	0.0	0.0	0.0	0.0	0.0	5.8	4.6	4.2	0.0	0.0
Sagittaria latifolia		0.00	1.78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.8	10.4
Grass	St. Augustine	0.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	0.0	0.0
Ptilimnium capillaceum	Bishop's weed	0.00	0.41	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2	2.4
Cyperus polystachyos		0.00	0.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
Unknown red node		0.00	0.11	0.0	0.0	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.0
Juncus effusus		0.00	0.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
Salix caroliniana	Willow	0.00	0.07	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0
Juncus megacephalus		0.00	0.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
Cyperus distinctus		0.00	0.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Galium sp.	Bed straw	0.00	0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Ludwigia microcarpa		0.00	0.04	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Unknown alternate leaf		0.00	0.04	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Unknown opposite leaf		0.00	0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
Mitreola petiolata		0.00	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Ulmus americana var floridana	Elm seedling	0.00	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
AVERAGE NUMBER OF SPECIES PER SQ. METER		3.67	6.70	4.2	5.3	4.3	1.5	5.1	6.4	6.4	6.6	5.3	9.4

species and since it produces major changes in dissolved oxygen and pH (see Figure 13), its effect needs further study. It may also indicate eutrophication levels.

Chara belongs to the Chaophyceae family, a unique group of nonvascular hydrophytes with worldwide distribution commonly known as stoneworts or brittleworts. They grow best in oligotrophic calcareous waters and disappear when water bodies become eutrophic (Vymazal 1995). *Chara* spp. may be physiologically sensitive to high P concentrations (Forsberg 1964) or as Blindow (1988) found not inhibited by P toxicity but reduced by some other factor such as competition from other vegetation. Competition appears to be the case in this study where light limitation or smothering by filamentous algae seems to cause its demise. Inability to tolerate competition was also evident in the littoral zone in this study since *Chara* was seldom seen in plots next to the shore where other vegetation was present in quantity. A study in the Florida Everglades tends to support this hypothesis. Complete disappearance of both *Chara* and *Utricularia* was seen in plots with added phosphorus of 0.26 g - m^{-2} - wk^{-1} (Steward and Ornes 1975). In another study with lower P additions (4.8 g P- m^{-2} - yr^{-1}) the results showed a decline of *Utricularia* and an increase in *Chara* and the authors concluded that an increase in *Chara* may serve as an early indicator of P enrichment in the Everglades (Craft *et al.* 1995).

Spatial Differences - The vegetation data for each year were further subdivided into the area of the pond where it was found (Table 18). The wide littoral shelf near the outflow (SHELF) had the least percentage of open water for both years and showed the best survival rate for the planted pickerel weed and common arrowhead. It also had the greatest reduction in torpedo grass which in this study did not survive shading by other vegetation. The newly excavated zone (NEW) had the greatest percentage of open water and the least diversity in 1994, but by 1996 the open water had been colonized by torpedo grass and the area near shore by the planted pickerel weed. In 1994, with the exception of the newly constructed area, the dead end extension to the west (EXTEN) had the greatest amount of torpedo grass and open water. The sharp drop off and deeper water in both the dead end and the newly constructed portion of the pond especially favored the dominance of torpedo grass which expands by long floating rhizomes from the shore. The east (EAST) and west (WEST) sides of the pond exhibited similar characteristics with about the same amount of open water and torpedo grass. The west side of the pond and the dead end extension to the west had the largest amount of filamentous algae indicating the prevailing wind may blow it in that direction.

Species Diversity - From 1994 to 1996 species diversity increased by 82 percent overall and as might be expected was greatest in the newly constructed portion of the pond where it increased by 253 percent. In contrast, diversity on the littoral shelf increased by 84 percent and in the rest of the pond by 21 to 53 percent. The littoral shelf exhibited the greatest species diversity on both sampling dates demonstrating the effect of its larger size and more uniform water depth on plant colonization as well as survival of planted species. The survey also demonstrated that planting the shelf with pickerel weed and common arrowhead reduced the amount of torpedo grass (87%). The planting of pickerel weed also reduced the amount of torpedo grass in other parts of the pond but not by as great a percentage since the torpedo grass expanded into the deeper water. It should be noted that pickerel weed was planted in two rows around the perimeter of the pond but only those closest to shore survived while torpedo grass continued to expand into the open water zones demonstrating the effect of proper elevations for establishing target species.

Nuisance Species - By 1996, cattails, an invasive species, had begun to colonize two parts of the pond: 1) on the exposed shore of the newly constructed portion and 2) on some of the soil piled up during the pond excavation on the littoral shelf. After the survey was completed, the cattails were cut off below the water surface to see if they can be controlled in this manner. The number of cattail plants removed on the newly constructed part of the pond included 192 individuals and on the littoral shelf at the outflow, 125 individuals. These plots will be followed to determine if this is an effective method for controlling cattail invasions. During our observation period from 1990 to 1996 no cattails were reduced by any planted vegetation or naturally occurring species colonization. However, caterpillars were observed on almost all cattail stalks in 1996 which may be providing some biological control. Alligator weed (*Alternanthera phloxeroides*) was another noxious weed of concern where heavy grazing by insects may be keeping its expansion under some control. All alligator weed plants measured in 1996 showed severe grazing by insects.

In summary, factors which influenced the colonization of nuisance species in this study included exposed soils after construction which produced conditions favorable to cattail invasions. Steep slopes in the littoral zone favored the expansion of torpedo grass and may indicate that a 3.5 foot maximum depth for the littoral zone is too deep. Of importance is the greater species diversity and survival of desirable planted species which occurred on the large (45 x 45 sq. ft.) and relatively shallow (< 1 ft average depth) littoral shelf at the outflow. Planting desirable species reduced the invasion of torpedo grass when water levels were shallow, however, none of the planted pickerel weed survived in the deeper part of the littoral zone and the planted arrowhead only survived on the wide littoral shelf at the outflow.

Macroinvertebrate Sampling[2]

The diversity and abundance of aquatic macroinvertebrates can be used as a measure of environmental quality. It has been well documented that non-polluted water bodies have a significantly greater diversity and a different taxa composition than polluted systems. To document the changes over the summer in this newly recontoured wet detention pond, dip net and sediment samples were collected weekly from June 18 to August 16, 1994. Open water areas and vegetated littoral zones were sampled with equal intensity and the combined data for each date were recorded.

It was expected that the high pollution loads and the wide fluctuations typical of stormwater ponds would result in an abundance of a few tolerant species and therefore low

[2] Marnie Ward, an undergraduate student in the Department of Zoology at the University of Florida, collected and identified the insects as an independent study project. The information in this section was taken from her report.

species diversity. This was not necessarily the case in this newly constructed pond. Instead the number of species steadily increased while the number of individuals fluctuated sporadically in response to environmental conditions, insect emergence patterns, and disturbance of the littoral zone by the planting of additional vegetation (Table 19). The littoral zone was planted with pickerel weed and other desirable macrophytes on July 20, 1994 (refer to vegetation analysis section), and this disturbance interrupted the upward trend of the number of individuals recorded after this date. No obvious explanation exists for the sudden drop in the number of individuals on August 16th. The greatest abundance of individuals and taxa occurred on August 4th when 165 individuals of 19 taxa were identified and this same pattern continued for the August 11th sampling date. The high number of individuals were the result of one species, *Limnodrilus hoffmeisteri*, which accounted for almost half of the individuals collected on those two dates.

Other taxa collected during the study indicate the stormwater pond is suitable for habitation by aquatic species that are considered pollution intolerant. For example, mayflies have long been classified as an indicator of good water quality, due in part to the large gill surface area they expose to the environment (Fleming 1964, Gaufin 1973). Also studies of heavy metal pollution indicate mayflies are sensitive to heavy metal contamination (Winner 1980). In some studies hydracarinids in the order Arachnida were found to be sensitive to environmental stress because of their low tolerance to physio-chemical changes, especially pH fluctuations (Smith and Cook 1991, Havens 1993). In our study hydracarinids were represented in all collections after July 15th. Also in the order Diptera, *Cryptotendipes* sp. is listed as a taxa intolerant of pollution (Hulbert 1989), although other Diptera in the pond, *Cryptochironomus* spp., *Glyptotendipes paripes, Tanypus* spp. and *Chaoborus punctipennis*, are taxa tolerant of degraded conditions (Hulbert 1989).

Diversity indices are an additional tool for measuring the quality of the environment. Although estimates of diversity improve with increased sample size and are not accurate with less than 100 specimens, they are used here to give an indication of the status of the system. The Shannon-Weaver diversity index measures both richness of species and the distribution of individuals among species. For this study values ranged between 2.74 measured on the first sampling date to 3.49 calculated for July 29. For pooled data which included all sampling dates the diversity index increased to 4.53 (Table 19). When Wihm (1970) evaluated Shannon-Weaver diversity numbers calculated from data collected by numerous authors for a variety of polluted and unpolluted waters, he found that in unpolluted water the diversity index was usually between 3 and 4, but in polluted waters the index was less than 1. Using this yardstick the stormwater pond falls in the slightly polluted category. However, in the southeastern United States, EPA biologists found that where degradation is slight to moderate, the diversity index lacked the sensitivity to detect the differences (USEPA 1973).

Another measurement, equitability (USEPA 1973), is much more sensitive to pollution. Equitability usually ranges from 0 to 1 except in the unusual situations where samples contain only a few specimens represented by several taxa. That situation occurred in this study on collection days with less than 55 individuals and 16 taxa (Table 19). In unpolluted streams equitability generally ranges between 0.6 and 0.8, and even slight levels of degradation have

Table 19 . Insect taxa collected at the Tampa Office Pond - Summer 1994

	Jun 18	Jul 8	Jul 15	Jul21	Jul 29	Aug 4	Aug 11	Aug16	TOTALS
Odonata (dragonflies)									
Crocothemis servilia		1							1
Perithemis tenera		1							1
Brachymesia gravida		1							1
Orethemis ferruginea		2	2	1	4				9
Pachydiplax longipennis			2		3	3	4		12
Erythemis simplicicollis		3		1			1		5
Coryphaeschna ingens					1				1
Analagma doubledaye							2	1	3
Pantala flavescens								1	1
Odonata (damselflies)									
Ishnura posita		18	11	2	3	2	5		41
Ishnura ramburii			6		1				7
Hemiptera (true bugs)									
Belostoma lutarium					1				1
Belostoma testaceum	3	1	7		2		3	1	17
Ranatra nigra							3	1	4
Ranatra fusca						1			1
Pelocoris femoratus		3	9		5	9	8		34
Ephemeroptera (mayflies)									
Cloeon sp.	3								3
Baetis pigmaeus	2					4	3		9
Baetis intercalaris							4		4
Ephemerellidae				6	14				20
Isonychia sp.					2				2
Baetisca sp.					1	1			2
Caenis diminuta				4		15	2		21
Coleoptera (water beetles)									
Lissorhoptrus simplex	7	1	2	1			2	1	14
Derallus altus	1	2						1	4
Stenus sp.	2								2
Tropisternus lateralis	3					1			4
Haliplus mutchleri		1		1	2				4
Haliplus punctatus				3		1	1		5
Dineutus emarginatus		2	43			1			46
Oligochaeta (worms)									
Limnodrilus hoffmeisteri		1	5			80	67		153
Arachnida (water spiders)									
Hydracarina (green)				2		23	8		33
Hydracarina (red)				2	2	2	1	2	9
Tricoptera (stoneflies)									
Oecetis sp.						2	3	4	9
Diptera (midges)									
Odontomyia sp.				1			1	2	4
Chaoborus punctipennis								1	1
Cryptochironomous sp.				1	4	10			15
Cryptotendipes sp.						2			2
Glyptotendipes sp.	1				8	5		2	16
Polypedilum sp.						1		1	2
Procladius sp.							1	1	2
Tanypus sp.			2		1		1	1	5
Tanytarsus sp.						2		14	16
Number of individuals	22	37	89	25	54	**165**	**120**	**34**	**546**
Number of taxa	8	13	10	13	16	**19**	**19**	**15**	**43**
Diversity Index	**2.74**	2.76	2.49	**3.27**	**3.49**	**2.73**	**2.68**	**3.11**	**4.53**
Equitability	**1.14**	**0.71**	**0.75**	**1.06**	**1.01**	**0.48**	**0.47**	**0.83**	**0.79**

been found to reduce the level below 0.5. Polluted water is generally in a range of 0.0 to 0.3. The lowest values (0.47 and 0.48) calculated during early August in this study occurred when an explosion of *Limnodrilus hoffmeisteri* dominated the collection effort. The dominance of this one species may be an indication of increased pollution levels during the height of the rainy season, or more likely, the manifestation of its life cycle and the emergence of its young.

Although relatively high levels of degradation had been expected in the stormwater pond, both species composition and diversity measurements indicate only slightly degraded water quality. Since this was a newly constructed pond, it was reasoned that it may not be representative, therefore, a comparison site which had been receiving stormwater for over ten years was added to the study. It was sampled on August 18, two days after the last collection date at the Tampa Office pond. The purpose was to examine similarities and differences between the old and the new pond. The comparison pond had been included in a previous study conducted by SWFWMD where 24 wet detention ponds that had received permits from the District were compared after storm events for water quality (Kehoe 1992). In that study the pond was identified under the pseudonym GTEDS. The GTEDS pond is 3.69 acres in size with an average depth of 10 feet. It receives runoff from 54 acres covered mostly by paved parking lots and rooftops. Like the Tampa Office pond, the bottom is clayey with a littoral zone of healthy macrophytes around the perimeter. At the time of the invertebrate sampling the water clarity was poor. Sampling was accomplished using the same proportional distances and methods as the Tampa Office pond. The comparison of the species collected at the Tampa Office pond on August 16th with the other much larger wet detention pond GTEDS on August 18th are listed in Table 20. Although only about 24 to 28 percent of the same taxa were found in both ponds, the number of individuals and species are almost the same.

Table 20. Insect taxa at two wet detention ponds during August 1994.

Order	Genus Species	Tampa Office Pond (3 mo old)	GTEDS (10 yrs old)
Odonata	*Pantala flavescens*	1	
	Analagma doubledayi	1	
	Lestes sp. 1		1
	Lestes sp. 2		1
	Ophiogomphus sp		2
	Erythemis simplicicollis.		2
Hemiptera	*Belostoma testaceum*	1	1
	Ranatra nigra	1	
	Ranatra fusca		4
	Pelocoris femoratus		4
	Pelocoris carolinensis		7
Arachnida	*Hydracarina* (green)		7
	Hydracarina (red)	2	1
Tricoptera	*Oecetis* sp.	4	
	Unidentfied Leptoceridae (Family)		1
Coleoptera	*Lissorhoptrus simplex*	1	
	Derallus altus	1	

Table 20 (continued)

Order	Genus Species	Tampa Office Pond (3 mo old)	GTEDS (10 yrs old)
Diptera	*Odontomyia* sp.	2	
	Chaoborus punctipennis	1	
	Glyptotendipes sp.	2	1
	Polypedilum sp.	1	
	Procladius sp.	1	
	Tanypus sp.	1	
	Tanytarusus sp.	14	1
	Unidentified Tanypodinae (Family)		1
	Number of Individuals	**34**	**34**
	Number of Species	15	14

This limited study spanning a two month period indicates that stormwater ponds are not dominated by an abundant number of individuals representing a few tolerant taxa, as might be expected, but instead are quite diverse including some species intolerant of pollution. Since insects integrate chemical, physical, and ecological aspects of water quality, this implies that stormwater ponds may be relatively good wildlife habitat when properly built and maintained. However, it needs to be emphasized that heavy metals and organic pollutants can be concentrated up the food chain. In a study funded by the St. Johns River Water Management District, fish collected from stormwater ponds contained significantly higher concentrations of heavy metals then fish from a control site (Campbell 1993).

A recent visit to the Tampa Office pond in June 1996 revealed that the pond has an even more diverse insect community than when sampled in 1994. Many different varieties of dragon flies, mayflies and water spiders were seen in abundance. Also several large bass and many other species of fish were evident in the clear water. More detailed studies of insects in wet detention ponds would provide useful information for making these systems better wildlife habitats, although more information is needed about the bioaccumulation of toxic pollutants in species that use these systems.

ANALYSIS

The results of this study clearly demonstrated the improvement in pollution removal made by the Conservation Wet Detention design. Features such as a fourteen day residence time, a permanent pool for maximum mixing and a littoral zone for biological treatment increased mechanisms for pollution removal. This section will discuss some of the processes that help improve water quality.

Pollutant Removal Mechanisms

Whenever site conditions allow, stormwater management systems should be designed to achieve maximum onsite storage (and even reuse) of stormwater by incorporating infiltration practices throughout the remaining natural and landscaped areas (Livingston 1995). Also conditions in the pond should be manipulated if necessary to maximize pollution removal.

Landscape Techniques

Good stormwater management includes strategies for removing pollutants as soon as rainfall reaches the ground and designs should incorporate a series of opportunities for assimilation, transformation and recycling of stormwater. Some of the mechanisms for good stewardship which were used in this project include taking advantage of the entire drainage basin. Various processes which were or could be incorporated into the landscape design at the Tampa Office are illustrated in Figure 22 and discussed below.

Preserving Existing Wetlands - The pond was excavated between two degraded wetlands which had been impacted by construction of the Tampa By-Pass Canal. Although no direct exchange of water between the pond and the wetlands exist during normal rain events, data from the surrounding wells show how the mound of water under the pond also raises the water table under the wetlands after rain events (Rushton and Dye 1993). Placing the two systems in close proximity also increases the potential for wildlife utilization. Additionally, planting cypress trees around the pond shaded the littoral zone reducing algae and other nuisance species and the increased transpiration by trees helped to cleanse and recycle stormwater.

Parking Lot Design - Grassed areas around the parking lot provided some treatment for runoff by acting as grass buffer strips. To be effective the strip must be at least 20 feet wide, have a slope of 5 percent or less and be stabilized (Bell 1995). Under ideal conditions, grass buffer strips can remove 5 to 25 percent of suspended solids provided the flow is kept shallow and slow (Urbonas 1994). It was shown by Wanielista *et al.* (1978) that shoulder areas of highways were very effective for the removal of hydrocarbons, metals, and solids.

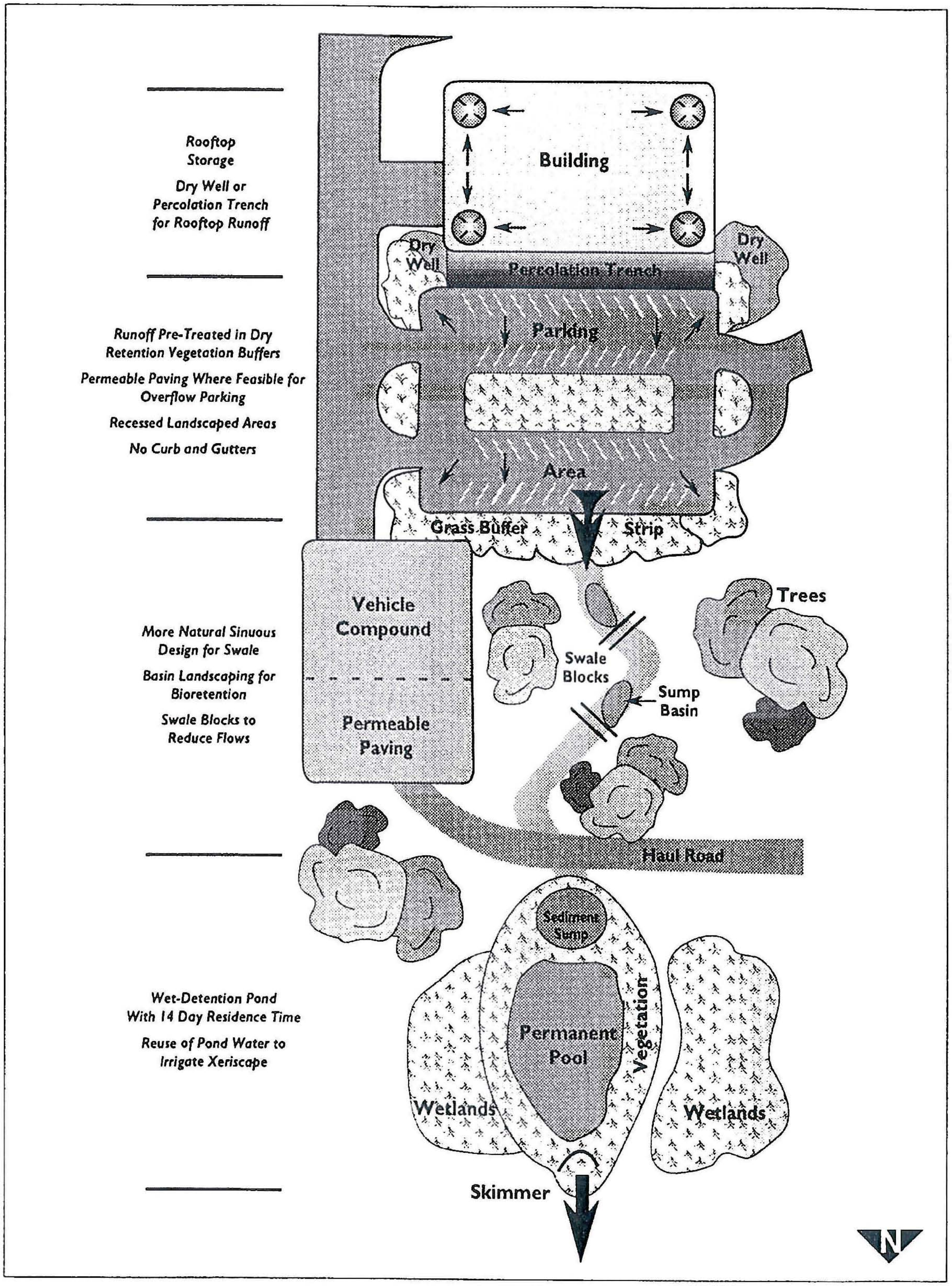


Figure 22. Idealized Basin Design for Stormwater Treatment.

The watershed design in this study would be improved by also including landscaping treatment. Trees and shrubs absorb the energy of falling rain, their roots hold soil particles in place, vegetation helps maintain absorptive capacity of the soils, and vegetation slows the velocity of runoff and acts as a filter to catch sediments. One method being tested to reduce runoff in Maryland, is Rain Gardens. These are shallow landscaped gardens that mimic a forest environment and manage stormwater through bioretention. It is estimated that 19% to 38% of nitrogen loading and 18 to 73% of phosphorus loading could be removed if a mature forest was created for bioretention (Coffman 1993). Rain Gardens can also be designed so that they reduce discharge to predevelopment levels, a condition that is not achieved with wet detention ponds alone (Coffman 1995). All stormwater retained and recycled on site, reduces pollutant loads downstream by allowing more time for infiltration and evapotranspiration. Vegetative control is usually accomplished in parking lots by using recessed landscape areas with raised storm sewer inlets and curb cuts.

Roof Runoff - At the Tampa Office site, roof drains discharge directly to the parking lot surface which increases flow and pollutants to the pond. Bioretention would have been useful in treating the roof runoff, especially if some kind of dry well or infiltration trench had been incorporated into the design to take care of excess runoff. When percolation trenches are properly operating they can remove up to 99% of the particulates (Urbonas 1994). This also reduces surface runoff which, in turn, reduces surface water pollutants. The major concern is groundwater pollution. Studies have shown that possible metal pollution from stormwater which has percolated through soils does not migrate more than a few inches and follows an exponential decline with depth (Harper 1988, Yousef *et al.* 1991). Nitrate-nitrogen, however, is highly mobile and could create higher concentrations in groundwater, this possibility needs further study. A major concern associated with infiltration/exfiltration systems is filter clogging and maintenance.

Pre-Treatment Swales and Ditches - Placing the wet detention pond some distance away from the parking lot increased the potential for stormwater treatment before runoff entered the pond. This minimized the directly connected impervious surfaces such as asphalt parking lots and building rooftops and therefore reduced pollutant loads. Surface runoff from storms less than about 0.15 inches was virtually eliminated because of the opportunity for infiltration and depression storage. Also the runoff that did occur had the opportunity for treatment. Some field measurements showed removal efficiencies of 30 to 50% for metals by swales 200 feet long, although the swales perform poorly in reducing concentrations of nutrients (Harper 1988). This is consistent with data collected during this study. In 1991 composite grab samples for two storm events were collected from parking lot runoff to estimate the amount of treatment given by the ditches (Rushton and Dye 1993). Removal efficiencies were similar or somewhat higher than Harper's (1988) with about 50% removal for total suspended solids and 10 to 30% for nutrients except for organic nitrogen which increased. The higher concentrations of priority pollutants measured in sediment cores collected in the swale compared to concentrations at the inflow of the pond is another indication that the swale is effective for removing petroleum hydrocarbons (see Table 17). Maintenance may present a challenge, however, and sump basins may be a solution.

Sump Basins - Although a few wide places in the swales and ditches collected some water and slowed flow in this study, sump basins designed for this purpose would have been more effective. Sediment sumps, forebays or interceptor basins are depressions in the runoff collection stream which may also be a cost effective maintenance strategy. Maintenance of stormwater systems has not been adequately addressed and the value of collection areas where sediments can be easily removed and the area restored appears to be an attractive alternative. Most stormwater sediments meet State Clean Soil Criteria (Rule 62-775) and can be disposed of in permitted lined landfills and used for landfill cover (Livingston and Cox 1995). Since these sediments also contain elevated concentrations of nutrients, they can also be used on site as a soil amendment. Yousef *et al.* (1991) recommends that sediments accumulating in wet detention ponds be removed every 25 years based on sediment accumulation rates. Fernandez and Hutchinson (1992) indicate that the longer sediments accumulate in wet detention systems the more likely the sediments may exceed clean soil criteria. Cleaning out an entire pond is an expensive proposition and destroys existing ecosystem values. Sump basins would intercept much of the heavier particles and although they would have to be cleaned more often, the process would be less expensive and cause less environmental damage. A sediment sump collecting runoff from a roof top and a parking lot in a commercial development demonstrated its effectiveness in capturing and retaining zinc and copper (Carr and Rushton 1995).

Packed Bed Filters - Packed bed filters use vegetation planted in rock media to filter and treat stormwater. Experiments conducted to determine the efficiency of packed bed filters indicate good removal for metals, organic nutrients and total suspended solids with averages usually between 50 and 90 percent (Egan *et al.* 1995). Dissolved nutrients were not as easily removed, however, and were often increased. Depending on flow rate, nitrate and phosphorus often increased and ranged between -55 percent to +57 percent, and ortho-P ranged between -49 percent to +4 percent. The study showed that low flow was most effective for removing cadmium, chromium, TKN, nitrate, nitrite, total dissolved solids and total suspended solids; while copper, lead, zinc, ammonia, total phosphorus, fecal coliform, and total organic carbon were removed better at higher flow rates (Egan *et al.* 1995).

Pollutant removal in dry systems such as most of those described above are limited by: Resuspension of previously deposited material, short settling times which then export fine-grained particles, and insufficient biological contact time for uptake of soluble nutrients. Therefore they are more suitable for removal of large particle sized pollutants and for reduction in stormwater volume before more intensive treatment. Wet ponds, on the other hand, are effective in removing both small particulates and soluble pollutants provided they have sufficient volume in relation to the contributing watershed and effectively utilize the biogeochemical cycle (Schueler and Helfrich 1989).

Wet Detention Basins

The primary objective of our research project was to analyze the effectiveness of three wet detention designs for pollutant removal efficiency and the following section investigates some of the mechanisms which affected pollution removal. Two main processes are taking place in wet detention ponds to reduce pollutants (Hartigan 1989): One relies on solids settling theory and assumes pollutants are removed by sedimentation, and the other views the wet detention pond as a lake achieving a controlled level of eutrophication in an attempt to utilize biological and physical/chemical processes. Both approaches suggest that pollutant removal efficiency is positively related to hydraulic residence time (Figure 23).

Hydraulic Residence Time (HRT) - One of the main differences between the three design alternatives was an increase in residence time from 2.5 days in 1990, to 5 days in 1993 and finally to 14 days in 1994. HRT is the average amount of time water is stored in the permanent pool, and is the reciprocal of the water renewal rate. Chemical and biotic properties are often influenced by the openness of the system, and the renewal rate is an index of this process since it indicates how rapidly the water in the system is replaced (Mitsch and Gosselink 1993). A model developed by Walker (1987) to determine the optimal residence time necessary to reduce nutrient levels to acceptable levels, calculated that it takes two to three weeks for the removal of dissolved nutrients (Hartigan 1989). Field investigations have also identified residence time as a key parameter as determined in an analysis of several mechanisms studied at a natural wastewater wetland treatment site (Knight *et al.* 1987). Based on the parameters measured in their study, residence time is the primary causative factor influencing the reduction of P concentrations. Residence time was also shown to increase the removal of pollutants in laboratory experiments using both calcareous and organic soils. The nitrate concentration of the water column was decreased by 15 and 54 percent for a residence time of 12 and 24 days respectively for both soil types; and for ammonium the reduction was 75 percent in 12 days compared to 93 percent in 24 days in organic soils, and 53 percent in 12 days and 98 percent in 24 days for calcareous soils (Reddy and Graetz 1981). This shows that under ideal conditions in the laboratory, residence time is an important process for removing nitrogen and phosphorus from the water column. Our field study substantiates these results for wet detention ponds (see Table 7 and Figure 8).

But, infinitely long residence times are not the answer. Apparently in natural systems there is an optimal residence time depending on the size of the system before degraded nutrient enriched water is a problem. Low removal rates of nutrients have been recorded when ponds become stagnant. It is well documented in the limnology literature that increased water residence time leads to higher algal abundances in systems constrained by temporal, rather than nutrient limitations (Soballe and Kimmel 1987). Hvitved-Jacobsen (1990) also noted that algae problems in wet detention ponds were dependent on residence time. He concluded that long residence times supported by external as well as internal nutrient loads may increase algal biomass and that detention pond volume for pollution removal has to be weighed against tolerance for eutrophication levels. Increased algal production was also noted in a study of 24 wet detention ponds where grab samples were collected at the outfall after rain events. In that study, using log transformed data, total suspended solids concentrations were negatively correlated with discharge frequency ($r = -0.62$) (Kehoe 1992). The 14-day residence time used during our study appears to be of sufficient duration to remove nutrients, but not long enough to affect removal rates (see Table 7).

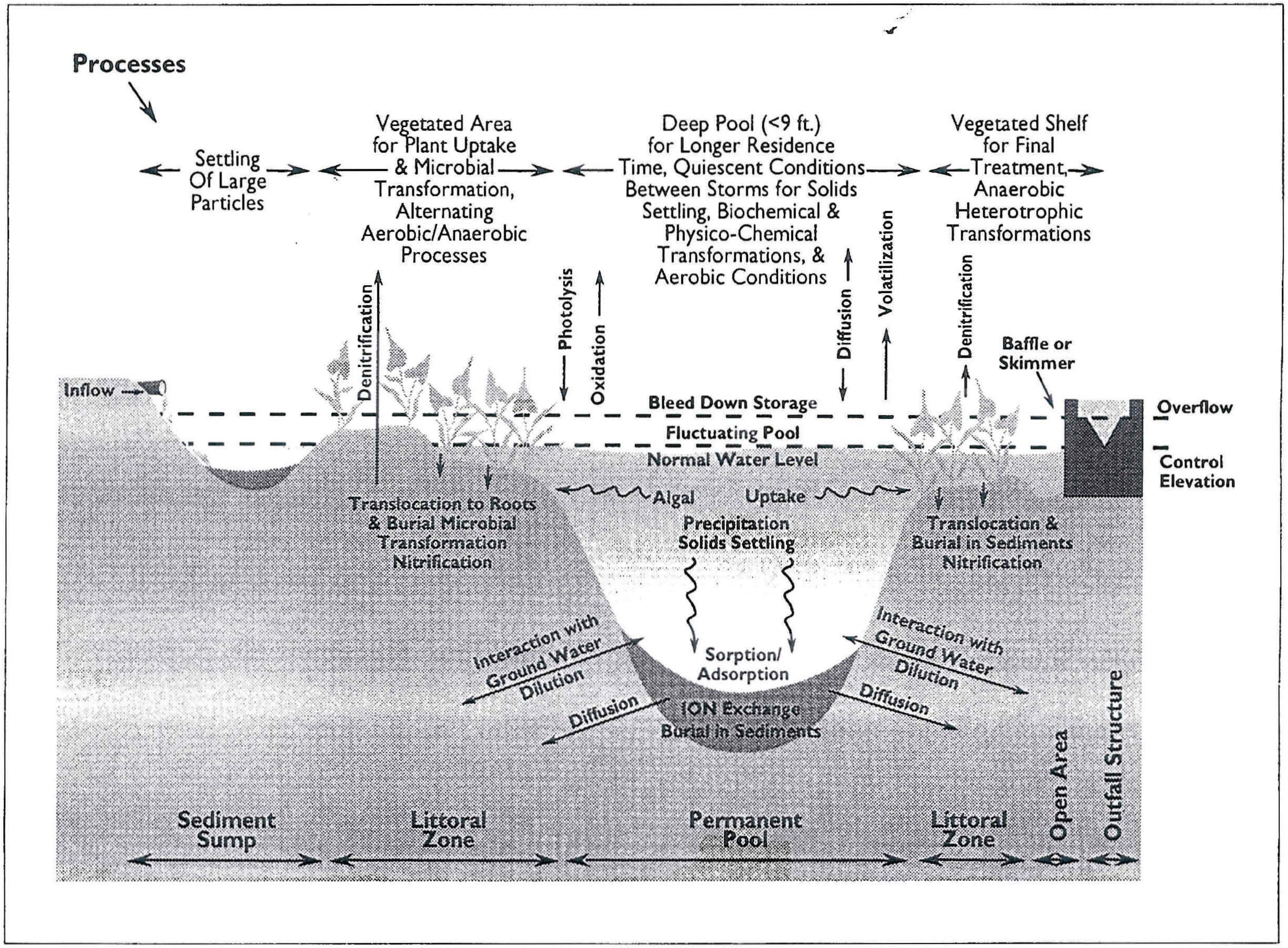


Figure 23. Idealized Wet Detention Pond

Permanent Pool - One of the most important features of a wet detention basin is the permanent pool (Hartigan 1989), and one of its major functions is to allow time for gravitational settling and transformations. Most pollution removal occurs during quiescent periods between storm events therefore the permanent pool must have sufficient volume to treat storm runoff. Ideally the "treated water" from the previous storm will be displaced by the next rain event. During the intervening time the permanent pool provides conditions where sedimentation of particulate matter is most likely to occur. Settleability of particulates has been studied in the laboratory by Whipple and Hunter (1981) and Randall *et al.* (1982). Results show that TSS and lead are the most efficiently removed while about half of BOD and phosphorus were reduced and more than a third of selected metals settled out (Table 21). These values indicate how much pollution removal is theoretically possible by sedimentation alone. During the third year of our study much better removal rates that those in Table 21 were documented (see Table 7) indicating that other processes besides sedimentation were reducing pollutants.

Table 21. Comparative settleability of pollutants in urban runoff as determined by laboratory settling experiments. Percent removal of pollutants.

	TSS	TOC	TP	TN	ZINC	LEAD	COPPER	BOD
(1)	90	34	56	33	44	86	---	64
(2)	68	---	50	---	30	65	42	40

(1) Randall *et al.* 1982 (48 hour settling time)
(2) Whipple and Hunter 1981(32 hour settling time)

Aquatic Plants - Vegetation in a stormwater treatment system is important both for uptake of nutrients and as a carbon and litter source for the sediments. The carbon, in part, fuels the immobilization of phosphorus and nitrogen by microorganisms. Vegetation coverage was a major difference between the three pond designs. In 1990 the entire pond was colonized by cattail and the depth of the pond was about one foot. For 1993 and 1994 only one-third of the pond area included a littoral shelf allowing pollution treatment by both a permanent pool and vegetation. The dominant vegetation was torpedo grass and the maximum depth of the littoral zone was up to three feet. These differences in vegetation cover affect processes in the pond.

Vascular plants are important in pollution removal since they assimilate and store contaminants, transport oxygen to the root zone, and provide a substrate for microbial activity. In a literature review of the role of aquatic plants in the removal of pollutants the following processes were identified (Reddy and DeBusk 1987). Nitrification-denitrification reactions are the dominant mechanism for nitrogen although some quantities of N can be removed by plant uptake. The nitrification process is enhanced beneath stands of plants which transport large quantities of oxygen such as pennywort. Nitrate-N thus formed, diffuses into reduced microenvironments in the pond system, where it is utilized as an electron acceptor by facultative anaerobic bacteria and lost from the system as nitrogen gas, however, differences between plant species is impressive. Denitrification rates in excess of 1 g m^{-2} d^{-1} have been reported in experiments with pennywort. As a comparison, pennywort transported 2.49 to 3.95 mg O_2 g^{-1} hr^{-1} while cattails only transports 0.19 to 1.39 mg O_2 g^{-1} hr^{-1} (Reddy and DeBusk 1987).

Although phosphorus is also removed from water by plant uptake and microbial assimilation, reduction depends mostly on precipitation with cations, such as calcium, magnesium, iron, manganese and adsorption onto clay and organic matter. This helps explain the much better removal of total phosphorus compared to total nitrogen in the Tampa Office pond since higher than average concentrations of calcium and iron were measured.

Removal rates of 13 to 75 percent of total nitrogen and 12 to 75 percent of total phosphorus have been recorded for vegetated plots (Reddy and Debusk 1987). High plant surface area and soil organics are important for the microbial decomposition of oxygen demanding pollutants, petroleum hydrocarbons and synthetic organics (Horner 1995). Plant uptake and microbial transformations at the Tampa Office pond undoubtedly were responsible for removal of pollutants, but plants also affected the amount of dissolved oxygen in the water column which introduces another process which affects pollution removal.

Aerobic/Anaerobic conditions - Biogeochemical cycling in wetlands holds the key to improving designs for pollutant removal efficiency, and dissolved oxygen levels with its associated redox reactions are often implicated in that process. One mechanism for the removal of pollutants in the second and third year of this study, as compared to the first year, was the fact that more than one process for pollution removal was available. These included both aerobic and anaerobic conditions with well oxygenated open water expanses in the permanent pool and more anaerobic vegetated littoral zones (see Table 11). Nitrogen removal is enhanced by alternating oxidizing and reducing conditions which maximize nitrification during the aerobic phase and denitrification during anaerobic (reducing) conditions, however, denitrification is reduced if carbon supplies are low (Hammer and Knight 1994). Ammonium loses were more complicated with an initial increase of ammonium caused by the mineralization of organic nitrogen, followed by a rapid decrease during the 29 day experiment. Ammonium loss (99 percent) in the aerobic water was due to nitrification and ammonia volatilization. The loss in the anaerobic water columns (83%) was due to the ammonia volatilization process alone (Reddy and Graetz 1981). Ammonification needs moderate temperatures and pH, microbial attachment substrates, and adequate supplies of oxygen (Hammer and Knight 1994). These conditions were met using the Conservation Wet Detention design (1994) in our study.

The phosphorus cycle is fundamentally different from the N cycle since there is no valency change, no gaseous phase, and the soil-litter compartment contains the major P pool. Although phosphorus is unaffected by redox reactions anaerobic conditions still releases P to the water column since the adsorbed and occluded P is released when Fe^{3+} is reduced to Fe^{2+} (Faulkner and Richardson 1989). As an example of the effect of redox reactions on P removal, Yousef *et al.* (1986) conducted isolation chamber experiments and measured a decrease of phosphorus in the water column under aerobic conditions, and an increase, under anaerobic conditions. They concluded that soluble phosphorus was decreased because of sorption by the sediments and the control of its release in an aerobic environment. Masscheleyn *et al.* (1992)

found soils equilibrated under oxidized to moderately reduced conditions (+500 to +200mV) removed from 90 to 98 percent of added P depending on P load; but under reduced conditions (0 to -200mV), only 28 percent (low loads) to 74 percent (high loads) of phosphorus was removed by the soil. One explanation for the difference is given by Patrick and Khalid (1974) who found anaerobic soils released more phosphate to soil solutions low in soluble phosphate and sorbed more P from soil solutions high in soluble P than did aerobic soils. They theorized that the greater surface area of the gel-like reduced ferrous compounds in an anaerobic soil results in more soil phosphate being solubilized where solution phosphate is low and more solution phosphate being sorbed where solution phosphate is high. This same tendency was seen during quiescent conditions (one sampling event) at the Tampa Office pond where stations with low dissolved oxygen had higher total phosphorus concentrations (see Appendix N-4). Also, when DO concentrations in the bottom waters were less than 2 mg/l, total phosphorus concentrations were 0.16 and 0.27 mg/l; while DO levels greater than 8 mg/l had P concentrations that ranged from 0.06 to 0.09 (see Table 14).

An anoxic sediment-water interface typically exhibits a negative redox potential and easily releases metals such as iron, copper, zinc and cadmium (Guilizzoni 1991). More research is needed to investigate the interaction between soil redox conditions and soil pH and how it affects metal chemistry. Special attention should focus on the rhizosphere effects where an oxidizing soil environment exists immediately around the root zone and in close proximity to strongly reduced soils, a condition which influences metal chemistry and availability (Gambrell 1994). Reduction of carbon oxygen demand, petroleum hydrocarbons, and synthetic organics are all promoted by aerobic conditions (Horner 1995). The fact that both aerobic and anaerobic conditions existed in the pond during our study (see Appendix M) undoubtedly improved the efficiency of the pond since several processes were available to remove pollutants.

Soil Type - Pollution removal in wetlands works best on a medium to fine textured soil (Horner 1995). Also the soil is the primary removal mechanism for phosphorus which is attributed to soil sorption, biomass and accreting sediments (Kadlec 1994). The type of sediments may determine if wetland soils act as a source or a sink for P. For example, calcareous soils low in organic matter but high in $CaCO_3$ removed more added phosphorus than organic soil (Reddy and Graetz 1981). They further concluded that flooded organic soil may function as a source by increasing the soluble P concentration in the overlying aerobic water column while phosphorus reduction over the calcareous soils was probably a result of precipitation of P with calcium compounds and physical sorption by the underlying soil. Laboratory experiments showed a maximum reduction (65%) in the ortho-P concentration in the water column with a 24-day residence time, whereas for organic soil, maximum reduction (36%) in ortho-P levels was observed with the residence time of 6 days and reduction was less for longer residence times (Reddy and Graetz 1981). Other researchers have also found greater phosphorus sorption potential in predominately mineral swamp forest soils compared to organic freshwater marsh soils (Masscheleyn *et al.* 1992). The calcareous sandy soils with low organic matter content at the Tampa Office pond (see Tables 12 and 13) probably contributed to the 90 percent phosphorus removal rates exhibited with increased residence time.

Since phosphorus is primarily removed by soil sorption processes, the fact that soils have a finite P capacity is of concern. Data indicate that high initial removal rates of phosphorus by freshwater wetlands will be followed by large exports of P within a few years. Sorption is enhanced, as mentioned above, by high calcium concentrations and is also improved by oxalate-extractable iron and aluminum. Therefore, wetland types with predominately mineral soils and high amorphous aluminum content are better P sinks than peatlands but sill retain much less P than terrestrial ecosystems (Richardson 1985). Gale *et al.* (1993) also measured more rapid nitrogen removal in wetlands with mineral soils than organic soils and they concluded that soil type has a significant effect on nitrogen removal from floodwater. In addition dissolved metal adsorption is enhanced by sediments with a high soil cation exchange capacity (Horner 1993).

In the Tampa Office study the higher levels of calcium in the water column (72 mg/ l) in 1994 compared to 50 mg/l in 1993 may have helped account for the increased efficiency for phosphorus removal in 1994 (see Figure 8). Also the increased iron measured at the inflow (555 ug/l in 1990, 1517 ug/l in 1993 and 3,200 ug/l in 1994) may have enhanced precipitation of phosphorus and then incorporation with iron oxide in the sediments. Additionally, the mineral soils and the higher levels of aluminum in the sediments of the permanent pool probably increased the removal of heavy metals, nitrogen and phosphorus (see Table 15). Since attachment sites on soil particles suitable for the uptake of P are finite, the phosphorus potential may decrease over time and this potential needs more study. However, the wetland biogeochemical cycle can operate to accrete new soils and sediments which contain phosphorus and these soil building processes can provide a more permanent storage of phosphorus (Kadlec 1994).

pH - At near-neutral to somewhat alkaline pH levels, metals tend to be effectively immobilized as are metals complexed with large molecular weight organics (Gambrell 1994). A circumneutral pH advances microbially mediated processes such as decomposition and nitrification-denitrification and avoids the mobility of certain pollutants at extreme pH (Horner 1993). The neutral to slightly alkaline pH measured in our study is ideal for metal immobilization and the nitrification-denitrification process (see Table 11) .

In Summary - The Tampa Office pond in 1994 which used the Conservation Wet Detention design (TP/SWP-022) performed well for removing pollutants during the first eight months after construction. Factors which likely contributed to this result were pre-treatment opportunities in the watershed, increased residence time with good flushing characteristics, a vegetated littoral shelf concentrated at the outfall, aerobic conditions in the permanent pool, mineral soils, increased iron runoff and a circumneutral pH. Features which might help the pond even more would be a better landscape design incorporating trees, a sediment sump to collect large particle pollutants, littoral zone plants selected specifically for their proven ability to remove stormwater pollutants by pumping oxygen to the rhizosphere, and better control of fertilizers and pesticide use. Improved use of the entire drainage basin would help reduce runoff to pre-development levels. This is a newly constructed pond and additional research as the pond matures should indicate long term removal capabilities and determine maintenance requirements.

COMPARISON DATA

Additional insight about wet detention ponds can be gained by comparing the data to other studies that have been conducted in the region.

Treatment Efficiencies

A major objective of this study was to determine how well wet detention ponds reduced pollutants from the inflow to the outflow using different residence times. The efficiency of the system is relevant to the State Water Policy (Chapter 62-40 FAC) which has a goal for new stormwater systems of 80 percent reduction in annual loads. The data from this study as well as comparable data from other studies in Florida demonstrate the wide range of efficiencies exhibited by different stormwater management designs (Table 22).

Table 22. Percent reduction of mass loads (efficiency) for various wet detention ponds and natural wetlands in Florida.

	MEAN REMOVAL EFFICIENCIES (%)											
	This Study				Comparative Studies of Wet Detention Treatment							
	1990	1993	1994		a	b	c	d	e	f	g	h
Total Lead	----	----	92		32	90	83	----	----	----	60	85
Total Zinc	56	32	87		10	96	84	----	----	----	85	90
Total Cadmium	55	42	87		----	79	88	----	----	----	----	----
Total Iron	40	76	94		----	92	5	87	85	----	----	----
Total Copper	----	1	55		----	90	79	19	22	----	40	50
Ammonia-N	54	-31	90		54	99	79	89	90	----	----	----
Organic-N	30	15	51		9	96	29	7	-8	----	----	----
Nitrate+Nitrite	64	61	88		----	95	94	92	95	87	50	70
Ortho Phosphate	69	39	92		37	97	67	83	89	82	40	60
Total Phosphorus	62	57	90		33	91	70	75	75	60	60	70
Suspended Solids	71	67	94		16	82	86	77*	69*	64	85	85

Comparative Studies

- a Martin 1988 (Mixed Urban) SHORT RESIDENCE TIME, NO PRE-TREATMENT
- b Harper 1988 (Residential) NO PRE-TREATMENT, RETENTION 80%
- c Carr and Rushton 1995 (Light Commercial) NATURAL WETLAND, PRE-TREATMENT BASINS, RAINFALL 45% OF INPUT, RETENTION 60% OF TOTAL INPUT INC. RAIN.
- d Cunningham 1993 (Experimental Pond - Deep (9 feet)) SIMULATED STORM EVENTS
- e Cunningham 1993 (Experimental Pond - Shallow (3 feet)) SIMULATED STORM EVENTS
- f Cullum 1984 (Low Density Residential) PRE-TREATMENT BY GRASSED SWALES
- g Harper and Herr 1993 (Commercial) RESIDENCE TIME 7 DAYS.
- h Harper and Herr 1993 (Residential) RESIDENCE TIME 14 DAYS.

This Study

1990 RESIDENCE TIME 2.5 DAYS
1993 RESIDENCE TIME 5 DAYS. RESULTS GREATLY INFLUENCED BY ONE RAIN EVENT.
1994 RESIDENCE TIME 14 DAYS.
* Non-volatile suspended solids

Table 22 also shows that no system achieved the 80 percent reduction goal for all constituents and some fail to achieve it for any pollutants. The purpose of this section is to investigate conditions that lead to greater removal efficiencies. First, some of the best efficiencies in most systems were seen for lead, nitrate+nitrite, and total suspended solids. Poorest removal occurred for organic nitrogen and possibly total phosphorus and total copper. As observed by Harper (1995), organic nitrogen is not readily available for removal through biological or chemical processes, and there are relatively few mechanisms for removal of this species in a wet detention system. In contrast, both nitrate and ammonia are readily taken up in biological processes which accounts for the relatively good removal efficiencies achieved for these species in wet ponds.

Other factors which improve pollution removal include: 1) Residence times, with longer residence times in a permanent pool giving better treatment; 2) Retention of stormwater on site, which gives 100 percent efficiency for the retained stormwater; and 3) Pre-treatment by ditches, sediment sumps and swales, which reduces the amount of some pollutants to levels low enough to make further efficiency difficult. Each of these systems demonstrates at least one of these processes at work.

Residence Time - As has already been discussed in this report, one of the major differences between years in this study was increasing the residence time, and efficiencies using average annual concentrations showed a steady improvement with longer residence times (see Figure 8). Residence time also appeared to be the most common factor for greater pollution removal in the comparison sites. For example, poorest efficiencies were observed at site "a" which had the shortest residence time. Dye studies were conducted by Martin (1989) to determine the short-circuiting and mixing characteristics at site "a". He determined that the median time for 50 percent of the dye recovery from the inflow to the outflow ranged between 47 and 95 minutes for most runs and only 20 minutes for one run. The estimated time to recover 75 percent of the injected dye ranged between 69 and 282 minutes. It is obvious that not much time for treatment took place, but it does indicate that even small sedimentation basins reduce some pollutants and are effective for pre-treatment. Another example using these studies was the improved efficiency (by at least 20%) at site "h" (14 days HRT) compared to site "g" (7 day HRT) except for suspended solids (Harper and Herr 1993). Another observation from the data are the two experimental ponds, "d" (deep pond) and "e" (shallow pond), which showed essentially no differences between the two ponds with the possible exceptions of slightly better removal of organic nitrogen and suspended solids in the deep pond and ortho-phosphorus in the shallow pond (Cunningham 1993).

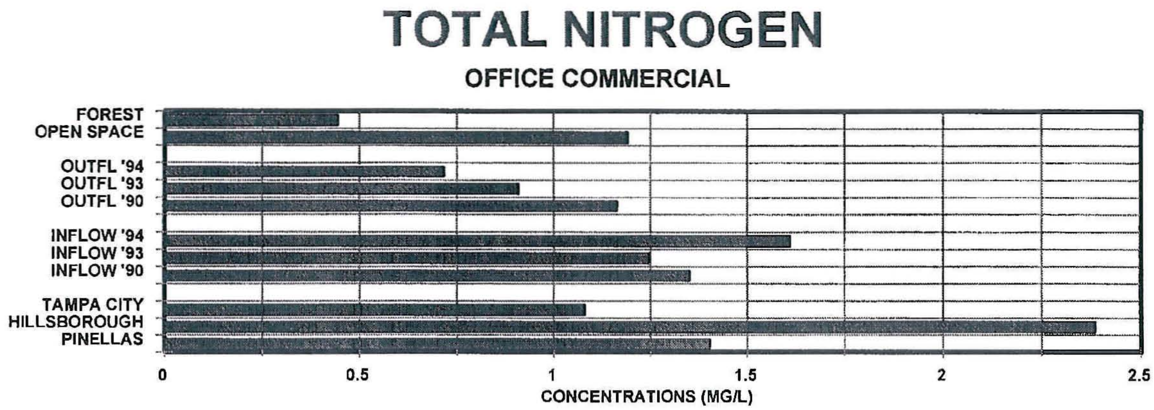
Retention on site - Site "b" retained an estimated 80-90 percent of all stormwater runoff within the system which gives the best removal efficiencies of all sites since water retained on site provides 100 percent load efficiency. Retaining water on site is one of the best strategies for stormwater management since it also provides opportunities to recharge the aquifer. A natural herbaceous marsh used for stormwater treatment, site "c", retained 60 percent of all water entering the system, and also shows good removal efficiencies. It was not effective at removing iron or organic nitrogen which is not surprising since it was a wetland with high levels of these constituents already in the marsh (Carr and Rushton 1995).

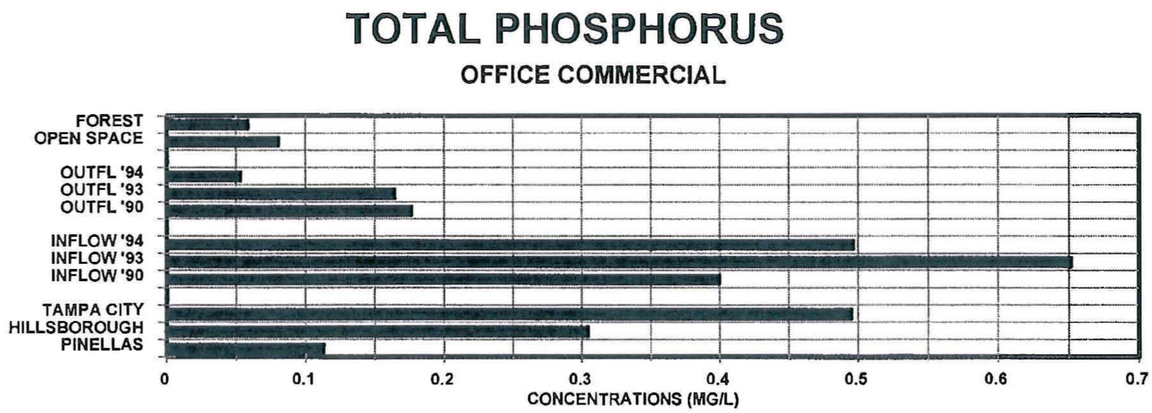
Comparison to Local NPDES Data

The purpose of comparing the data we collected during this study to the data collected by local governments for their NPDES permits was to determine if our untreated stormwater from an office\commercial site was representative of other stormwater from the same type of land use; and also to compare constituent concentrations measured at the outfall of our study to runoff from natural forests and open spaces such as parks. The National Pollutant Discharge Elimination System (NPDES) stormwater permit application is an Environmental Protection Agency (EPA) program authorized by Chapter 40 CFR 122.26(d)(2)(iii)(A). This section of Chapter 40 requires that local governments collect data from five to ten sites for three representative storm events.

When the NPDES data collected from the City of Tampa, Hillsborough County and Pinellas County were compared to the data in this study, there was considerable variability between sites but the overall trends indicate the untreated stormwater concentrations (inflow data) measured in this study were within the same range as urban stormwater measured at commercial sites in the region, except for Pinellas county where low concentrations indicate samples may have been collected downstream of a stormwater treatment BMP (Figure 24). Also when the concentrations measured at the outflow in our study are compared to those from forests and open spaces they were usually in the same range as those measured for open spaces. Especially the concentrations measured during the last year of our study (1994) using the Conservation Wet Detention design. These data indicate that pollutant concentrations can be reduced to levels comparable to forests and open spaces. However, as population increases so will urban pollution because of the increased volume of runoff caused by development. For example, about 65 percent of rain falling on office/commercial sites runs off while only 10 to 15 percent of rain falling on natural forests does (Figure 25).

To reduce nonpoint source pollution, stormwater systems must also reduce the volume of runoff. Unfortunately urban development increases impervious surfaces such as streets, parking lots and rooftops that retard infiltration and increase runoff volume. These "improvements" also increase pollution. Every opportunity to retain and infiltrate runoff within the watershed must be utilized. Forested areas, depression storage, swales and reuse are some mechanisms which can reduce runoff in urban areas.





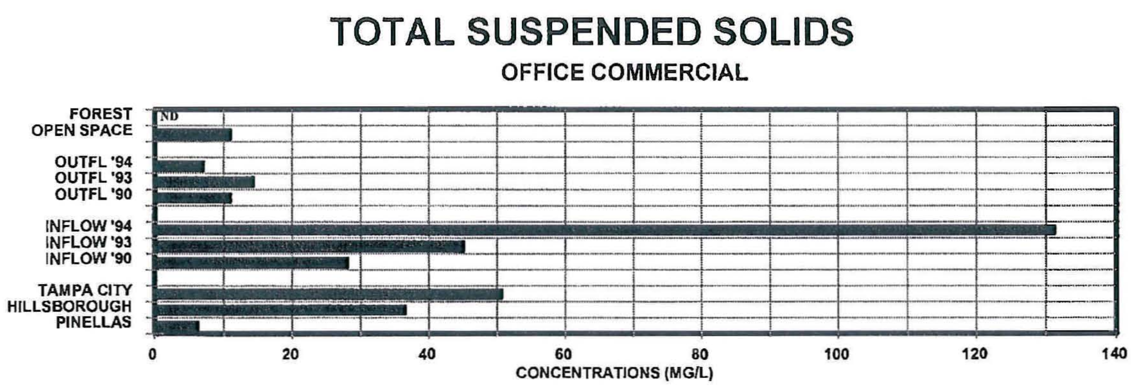


Figure 24. Concentrations (mg/l) of pollutants measured in untreated stormwater during the NPDES program (Pinellas County, Hillsborough County and the City of Tampa) compared to untreated stormwater measured at the inflow in this study. Data at the outflow were compared to runoff from forests and open spaces in the NPDES program.

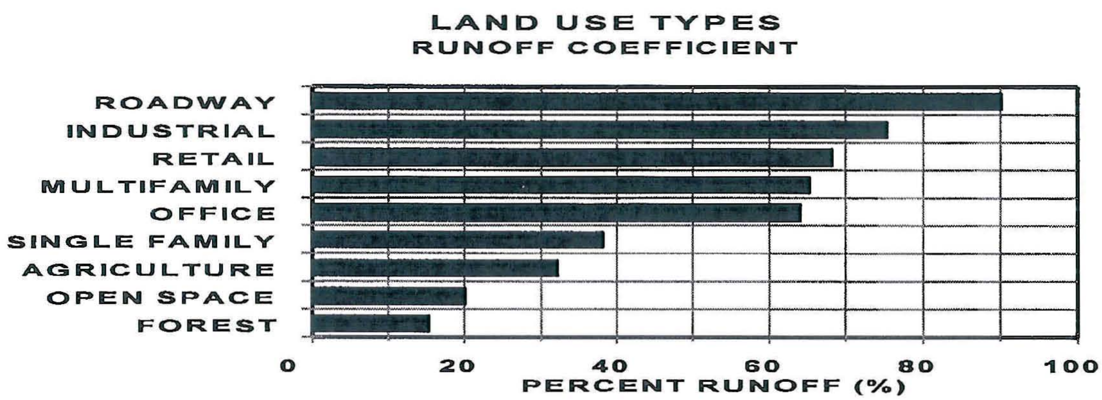


Figure 25. A comparison of different runoff coefficients for various land uses.

CONCLUSIONS

The Conservation Wet Detention criteria, which include a 14-day residence time, not only are superior for removing pollutants, but also provide additional benefits compared to traditional stormwater management design criteria. Projects using the new criteria benefit from reduced development costs, higher quality surface water discharges, and more desirable habitat conditions for aquatic biota.

Florida has little topographic relief and the water table is often near the surface, making flood control a concern of project designers and home builders. Stormwater management facilities are often designed with multiple objectives, combining water quality treatment with flood control. Previous design criteria gave no treatment credit for residence time in the permanent pool, but required detention of stormwater runoff in a fluctuating pool above the seasonal high water table, while slowly releasing this volume in no less than 120 hours. Because of this extended detention time, the storage volume of the fluctuating pool is often not available for flood storage, and flood volumes are stored above the fluctuating pool. This stacking of flood volume on top of "treatment volume" often required minimum floor elevations for buildings to be raised several feet above natural grade. This design required substantial amounts of fill to elevate buildings above flood elevations, a costly component of development in Florida. To generate this amount of fill, stormwater ponds were often excavated to excessive depths, creating anoxic hypolimnetic zones and reducing pollutant removal efficiencies.

Conservation Wet Detention criteria allow treatment credit for residence time below the seasonal high water table in the permanent pool and reduce the flood elevations which resulted from stacking the flood volume on top of the treatment volume. Reducing the flood stage in the pond allows lower minimum floor elevations for buildings and other structures so less fill was required. Reduced fill requirements resulted in less excavation in ponds. Shallower ponds generally have higher dissolved oxygen concentrations, providing better pollutant removal efficiencies and more desirable aquatic habitat.

Previous design criteria allowed a greater range of fluctuation (18") in the fluctuating pool, which had a detrimental effect on the littoral community and promoted the growth of cattails, a species which can be a nuisance in Florida. Reducing the allowed fluctuation range to 10" created more stable littoral conditions and promoted the establishment of a diverse assemblage of more desirable native aquatic vegetation Reducing the allowable range of fluctuation from 18" to 10", coupled with reducing the required detention storage in the fluctuating pool from 1" to ½" of runoff, reduced the land area required for stormwater treatment ponds from nearly 6 percent to about 5 percent, creating additional economic benefit for developers.

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APPENDIX A

Conservation Wet Detention Criteria
Technical Procedure TP/SWP-022 (Alternative 3)

SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT
RESOURCE REGULATION
TECHNICAL PROCEDURE FOR CONSERVATION WET DETENTION

The design guidelines for the Conservation Wet Detention criteria (14-day residence time) are included here for the convenience of anyone wishing to use them. They include the wet detention design pool guidelines that provided the best water quality treatment during this study. The following section is adapted from the original technical procedure developed by SWFWMD's Technical Services Staff in August 1990. The original draft included three alternatives, but only the third alternative, the conservation wet detention design, is included here since those guidelines were the ones used to construct the pond during the third year of this study (1994). Examples for making calculations for the conservation wet detention design are also provided.

This procedure provides interim guidelines regarding concepts and methods for determining design pool[1] requirements and alternatives for wet detention systems used for stormwater quality treatment..

BACKGROUND: Sections 2.0, 3.2.2, 3.2.3 and 3.2.4 in the Basis of Review (BOR) for the managment and storage of surface water (MSSW)(Reference 1), contain guidelines for wet detention systems to provide water quality treatment using a design pool in association with water tolerant vegetation. If adequate residence time is provided, pollutants can be removed through settling, adsorption to soils and uptake by aquatic biota.

The explanation of a wet detention system in section 2.25 of the BOR includes a requirement that, "...The bottom elevation of the pond must be at least one foot below the control elevation." The intent of this requirement is to maintain a <u>permanent wet pool</u> which supports residual aquatic biota, dilutes influent stormwater runoff and extends the residence time of water passing through the system.

Design guidelines for wet detention systems in section 3.2.2.2 require that wet detention pond discharge structures normally be designed with a gravity drawdown control device (bleeder). The bleeder allows no more than one-half of the detained treatment volume, stored between the overflow elevation down to seasonal high water level (SHWL) or control elevation, to discharge within the first 60 hours. The Conservation Wet Detention criteria changes this "bleeddown" time to 24 hours. Pool volume below the control elevation that intermixes with the SHWL is the permanent wet pool.

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[1] Design pool = treatment volume + permanent wet pool volume.

CONSERVATION WET DETENTION: The following criteria provide acceptable alternative methods of achieving design pool and gravity discharge configuration when it is justified to provide all or part of the treatment volume below SHWL or control elevation, without design pool bleed down[2]. If all other criteria are in compliance with the BOR, monitoring will normally not be required.

a) In the interest of water conservation, discharge devices below SHWL shall be avoided; and

b) Design pool volume below the control elevation[3] to eight feet depth must be equal to one inch of runoff plus the calculated volume based on average residence time of 14 days and average total rainfall during the wet season (122 days, June through September); and

c) The minimum design pool volume below the control elevation to eight feet depth must be no less than 1.667 inches of runoff from the contributing area; and

d) Systems discharging directly into Outstanding Florida Waters (OFW) shall provide treatment and permanent wet pool volume 50 percent more than required for systems discharging to other receiving waters; and

e) The gravity overflow weir shall be multi-stage, first having a "v"-notch[4] or other equivalent drawdown control device sized to discharge one-half inch of detention runoff from the contributing area in 24 hours with ten inches maximum head (refer to Figure 1); and having a broad crested weir for higher discharges, including the 25 year, 24 hour event; and

f) The control elevation ("v"-notch invert) shall be above SHWL in the pond and above wet season tailwater in the receiving water, but no higher than two feet above SHWL; and

g) For gravity discharge systems with treatment volume below SHWL, credit for water quantity (discharge attenuation) storage may be allowed above control elevation and SHWL, if the "v"-notch meets the requirements of 3) e) and BOR Section 3.2.4.2; and

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[2] Please refer to Clarification Memo No. SWP - 51 for further discussion of circumstances when wet detention systems may justify not using a bleeder.

[3] Longer residence time associated with the design pool for a wet detention system without a bleeder is presumed to offset the benefits of extended detention drawdown of treatment volume by a bleeder.

[4] The "v"-notch weir sized as stated creates a minimum pond area and fluctuation to enhance surface aeration, circulation and mixing in the design pool. The minimum pond area is equivalent to five percent of the contributing area, as recommended by reference 2.

h) At least 35 percent of the pond bottom, based on area at control elevation, must extend below SHWL to help sustain the required littoral area; and the 35 percent littoral area shall extend two feet maximum below the control elevation; and

i) Wet detention systems shall be specifically designed to maximize circulation, mixing and residence time of inflow within the design pool by means such as: maximum separation of inflow and outflow points, locating inflow inverts below the control elevation, use of multi-cell ponds or flow baffles and other locally effective means to avoid "dead" storage areas.

AGRICULTURAL EXAMPLE
CALCULATION OF WET DETENTION DESIGN POOL VOLUME

Given: A citrus grove project near Arcadia, Florida; Project area = drainage area = 320 Acres; Composite Rational runoff coefficient = 0.30; Discharge to Class III waters from a wet detention system.

Required: 1. Calculate the treatment volume; and

2. Calculate the permanent wet pool volume to be retained below the control elevation to eight feet depth. It must be the greater of: a) the volume calculated to provide an average residence time of 14 days based on average total wet season rainfall of 31.04 inches; or, b) the volume produced by 0.667 inches of runoff from the contributing area; and

3. Calculate the average minimum pond area.

1. Calculate the treatment volume (Q) as one inch of runoff -

$$\begin{aligned}(Q) &= (320 \text{ Ac.})\,(1 \text{ inch})\,(1 \text{ ft.}/12 \text{ in.}) \\ &= 26.67 \text{ Ac. - ft. (AF)}\end{aligned}$$

2. Calculate the permanent wet pool volume (V_R) -

a) Based on 14 day residence volume (V_R) -

$$(V_{R}) = (A)\,(C)\,(P)\,(R)\,(1 \text{ ft.}/12 \text{ in.})$$

Where, (A) = Project area = drainage area = 320 Ac
(C) = Composite Rational runoff coefficient = 0.30
(P) = Historic average wet season rainfall rate for
(R) = Residence time = 14 days

(V_R) = (320) (0.30) (31.04/122) (14) (1/12)
= 28.50AF

NOTE: Refer to Figure 2 for graphic solution of 14 day residence volumes for various project types and sizes.

b) As 0.667 inches of runoff (V_{min}) -

(V_{min}) = (320 Ac.) (0.667 inch) (1 ft./12 in.)
= 17.78 AF

Since (V_R) is more than (V_{min}), 28.50 AF is correct for permanent wet pool volume (V_B) in this case.

Therefore, the wet detention system design pool volume
= (Q) 26.67 AF + (V_B) 28.50 AF = 55.17 AF.

3. Calculate the average minimum pond area (A_S) -

Based on treatment volume below control elevation of "v"-notch weir, ½ inch runoff and 10 in. maximum head or based on design pool volume at maximum depth -

1) Based on 10 in. maximum head on the "v"-notch:

(V_W) = (320 Ac.) (0.50 inch) (1 ft./12 in.)
= 13.33 AF

(A_S) = (13.33 AF/0.833 ft.) = 16.00 Ac.

2) Based on design pool volume [(Q) + (V_B) = 55.17 AF] at maximum depths:

55.17 AF = [(0.35) (2 ft.) (A_S)] + [(0.65) (8 ft.) (A_S)]

(A_S) = (55.17 AF) / (5.9)
= 9.35 Ac.

Check Max. head (H) = (V_W) / (A_S),

(V_W)	=	13.33 AF; (A_S) = 9.35 Ac.

(H)	=	(13.33/9.35) = 1.425 Ft. = 17.1 in. > 10 in.

Therefore, the correct minimum pond area is 16.00 Ac.

COMMERCIAL EXAMPLE
CALCULATION OF WET DETENTION DESIGN POOL VOLUME

Given: A shopping plaza project near Oneco, Florida; Project area = 16 Acres; Drainage area = 18 Acres; Composite Rational runoff coefficients: project site = 0.90; offsite = 0.45; drainage area = 0.85; Discharge occurs to Class III waters from a wet detention system.

Required: 1. Calculate the treatment volume; and

2. Calculate the permanent wet pool volume to be retained below the control elevation to eight feet depth. It must be the greater of: a) the volume calculated to provide an average residence time of 14 days based on average total wet season rainfall of 31.04 inches; or, b) the volume produced by 0.667 inches of runoff from the contributing area; and

3. Calculate the average minimum pond area.

1. Calculate the treatment volume (Q)

a) For project site, as 1 inch of runoff (Q_P) -

(Q_P)	=	(16 Ac.) (1 inch) (1 ft./12 in.)
	=	1.33 Ac. -ft. (AF)

b) For offsite, as runoff from first inch of rainfall (Q_O) -

(Q_O)	=	(2 Ac.) (1 inch) (0.45) (1 ft./12 in.)
	=	0.08 AF

Therefore, (Q) = (Q_P) 1.33 AF + (Q_O) 0.08 AF = 1.41 AF

2. Calculate the permanent wet pool volume (V_B) -

   a) Based on 14 day residence volume (V_R) -

$$(V_R) = (A)\ (C)\ (P)\ (R)\ (1\ \text{ft.}/12\ \text{in.})$$

Where,
(A) = Project site + offsite = drainage area = 18 Ac.
(C) = Composite Rational runoff coefficient = 0.85
(P) = Historic average wet season rainfall rate for Arcadia, Bradenton, Brooksville, Lakeland and Ocala gauging stations = (31.04 in./122 days)
(R) = Residence time = 14 days

$$(V_R) = (18)\ (0.85)\ (31.04/122)\ (14)\ (1/12)$$
$$= 4.54\ \text{AF}$$

NOTE: Refer to Figure 2 for graphic solution of 14 day residence volumes for various project types and sizes.

   b) As 0.667 inches of runoff (V_{min}) -

$$(V_{min}) = (18\ \text{Ac.})\ (0.667\ \text{inch})\ (1\ \text{ft.}/12\ \text{in.})$$
$$= 1.00\ \text{AF}$$

Since (V_R) is more than (V_{min}), 4.54 AF is correct for permanent wet pool volume (V_B) in this case.

Therefore, the wet detention system design pool volume
= (Q) 1.41 AF + (V_B) 4.54 AF = 5.95 AF.

3. Calculate the average minimum pond area (A_S) -

Based on treatment volume below control elevation of "v"-notch weir, ½ inch runoff and 10 in. maximum head or based on design pool volume at maximum depth -

   1) Based on 10 in. maximum head on the "v"-notch:

$$(V_W) = (18\ \text{Ac.})\ (0.50\ \text{inch})\ (1\ \text{ft.}/12\ \text{in.})$$
$$= 0.75\ \text{AF}$$

$$(A_S) = (0.75\ \text{AF}/0.833\ \text{ft.}) = 0.90\ \text{Ac.}$$

2) Based on design pool volume [(Q) + (V_B) = 5.95 AF] at maximum depths (i.e., 35% @ 2' and 65% @ 8' depth):

$$5.95\text{ AF} = [(0.35)(2\text{ ft.})(A_S)] + [(0.65)(8\text{ ft.})(A_S)]$$

$$(A_S) = (5.95\text{ AF}) / (5.9) = 1.01\text{ Ac.}$$

Check Max. head (H) = (V_W) / (A_S),

$$(V_W) = 0.75\text{ AF};\ (A_S) = 1.01\text{ Ac.}$$

$$(H) = (0.75/1.01) = 0.743\text{ Ft.} = 8.9\text{ in.} < 10\text{ in.}$$

Therefore, the correct minimum pond area is 1.01 Ac.

REFERENCES:

1. "Permit Information Manual, Management and Storage of Surface Waters," March 1988 (Revised), SWFWMD, Brooksville, Florida.

2. "The Florida Development Manual: A Guide to Sound Land and Water Management," June 1988, FDER.

3. "Design of Urban Runoff Quality Controls," Proceedings of an Engineering Foundation Conference held in July 1988, American Society of Civil Engineers, 1989.

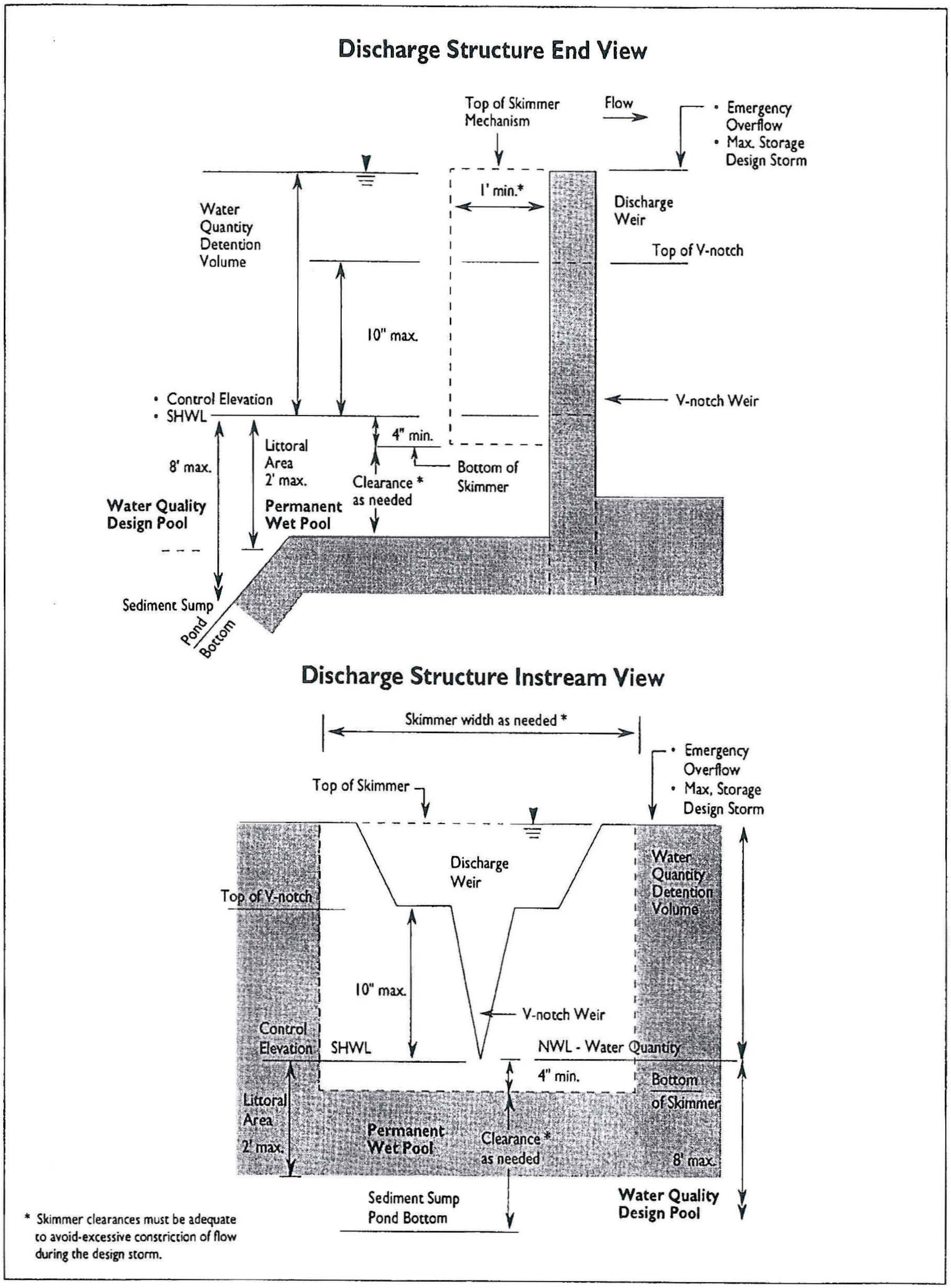
4. "Wet Detention Systems," A paper by Peter J. Singhofen, David W. Hamstra and Martin W. Pawlitkowski; 1990 Stormwater Management: A Designer's Course, the Florida Engineering Society, February 1990.

5. "Management and Storage of Surface Waters, Permit Information Manual, Volume IV," June 1987 (Revised), SFWMD, West Palm Beach, Florida.

6. Clarification Memo No. CM/SWP-51, "Wet Detention Systems - Use of Gravity Bleeddown Orifices" (SWFWMD).

ATTACHMENTS:

Figure 1.	Discharge Structure End View and Discharge Structure Instream View.
Figure 2	14-Day Residence Volume in Acre-Feet Per Acre of Contributing Area - DISTRICT-WIDE.
Figure 3	Discharge and Central Angle for a "V"-Notch Weir.
Table A-1	Wet Detention Treatment, Conservation Design Pool Below SHWL Without Discharge.



Discharge Structure End View
Top of Skimmer Mechanism
Flow
• Emergency Overflow
• Max. Storage Design Storm
1' min.*
Discharge Weir
Water Quantity Detention Volume
Top of V-notch
10" max.
• Control Elevation
• SHWL
V-notch Weir
4" min.
Littoral Area 2' max.
8' max.
Clearance * as needed
Bottom of Skimmer
Water Quality Design Pool
Permanent Wet Pool
Sediment Sump
Pond Bottom
Discharge Structure Instream View
Skimmer width as needed *
• Emergency Overflow
• Max. Storage Design Storm
Top of Skimmer
Discharge Weir
Top of V-notch
Water Quantity Detention Volume
10" max.
V-notch Weir
Control Elevation
SHWL
NWL - Water Quantity
4" min.
Bottom of Skimmer
Littoral Area 2' max.
Permanent Wet Pool
Clearance * as needed
8' max.
Sediment Sump
Pond Bottom
Water Quality Design Pool
* Skimmer clearances must be adequate to avoid excessive constriction of flow during the design storm.

Figure 1

Table A-1
Wet Detention Treatment

CONSERVATION DESIGN POOL BELOW SHWL WITHOUT DISCHARGE

MANMADE WET DETENTION DESIGN AND PERFORMANCE STANDARDS	
Treatment Volume/Depth	1" runoff from on-site; runoff from first 1" of rainfall from offsite
Draw Down Time	Not required for treatment volume
Permanent Design Pool Volume	Rainy season 14 day residence volume plus treatment volume; minimum 1.667 inch runoff
Other Criteria for System Design	• 35% littoral zone @ control elevation; concentrated at outfall. • V-notch weir sized to discharge ½ inch runoff in 24 hours, 10" maximum flux. above SHWL/control elevation. • Littoral zone 2' maximum depth below control elevation. • Design pool, 8' maximum depth; 34% minimum pond bottom below SHWL. • Sediment sump and skimmer usually required. • Mulching or planting required if soils are unsuitable. • Side slopes 4H:1V unless safety fenced. • Inflow/outflow points must maximize circulation. • Control elevation not lower than SHWL and tailwater, nor higher than 2' above SHWL.

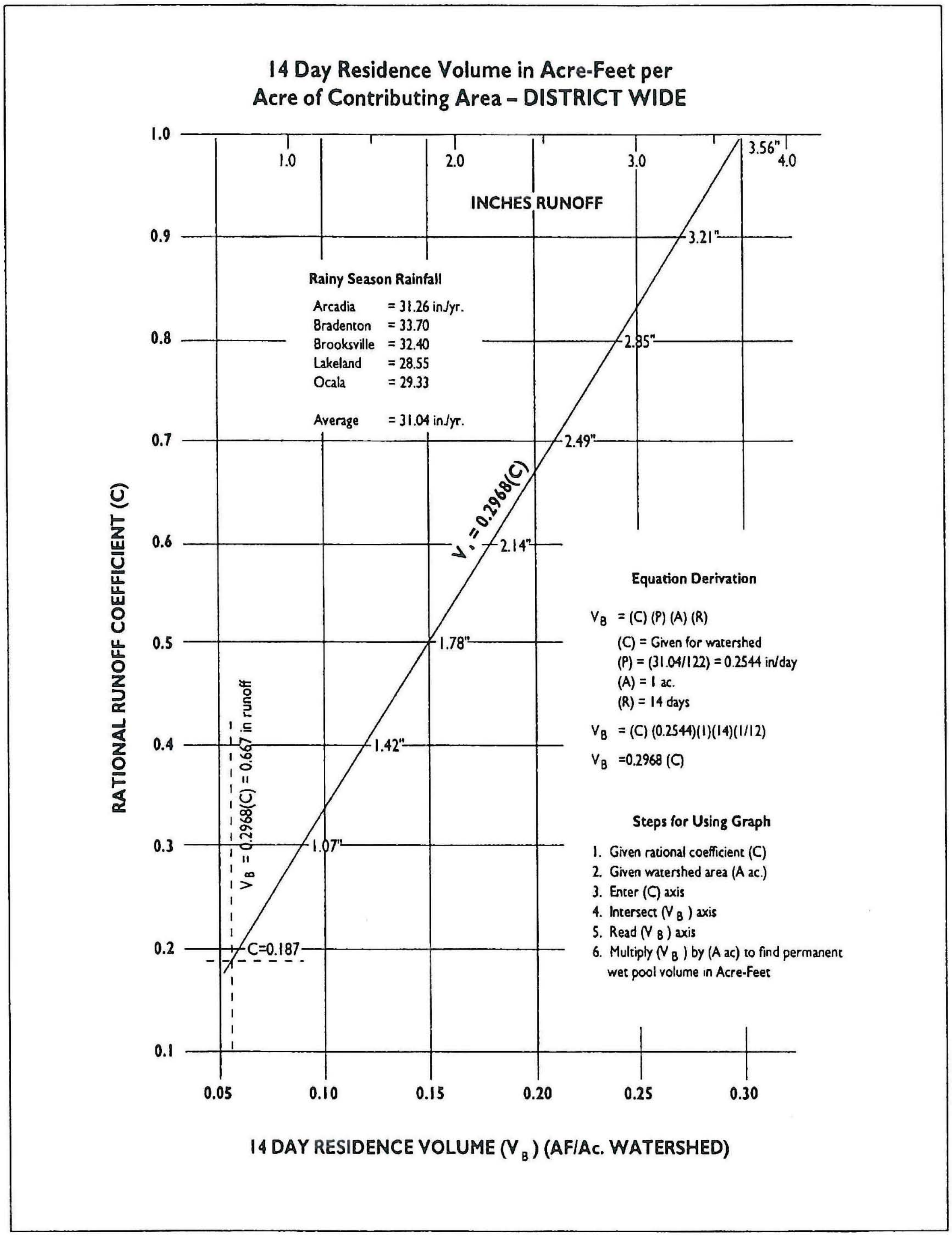
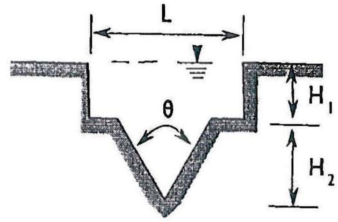

14 Day Residence Volume in Acre-Feet per
Acre of Contributing Area - DISTRICT WIDE
INCHES RUNOFF
1.0
2.0
3.0
3.56"
4.0
3.21"
2.85"
2.49"
2.14"
1.78"
1.42"
1.07"
C=0.187
V_B = 0.2968(C)
V_B = 0.2968(C) = 0.667 in runoff
Rainy Season Rainfall
Arcadia = 31.26 in./yr.
Bradenton = 33.70
Brooksville = 32.40
Lakeland = 28.55
Ocala = 29.33
Average = 31.04 in./yr.
Equation Derivation
V_B = (C) (P) (A) (R)
(C) = Given for watershed
(P) = (31.04/122) = 0.2544 in/day
(A) = 1 ac.
(R) = 14 days
V_B = (C) (0.2544)(1)(14)(1/12)
V_B =0.2968 (C)
Steps for Using Graph
1. Given rational coefficient (C)
2. Given watershed area (A ac.)
3. Enter (C) axis
4. Intersect (V_B) axis
5. Read (V_B) axis
6. Multiply (V_B) by (A ac) to find permanent wet pool volume in Acre-Feet
RATIONAL RUNOFF COEFFICIENT (C)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.05
0.10
0.15
0.20
0.25
0.30
14 DAY RESIDENCE VOLUME (V_B) (AF/Ac. WATERSHED)

Figure 2

Discharge and Central Angle for a "V" - Notch Weir



The total flow over a rectangular sharp crested weir with a "v" - notch step discharge fluctuation device is approximated by the equation:

$$Q_D = 3.13\,(L)(H_1)^{1.5} + 4.8\,[(H_2)^2\ \mathrm{Tan}\,\theta/2](H_1 + H_2/3)^{0.5}$$

Refer to Reference 1., pp. C-48 through C-50; and Reference 5., pp. C-IV-26 through C-IV-28.

Required V-Notch Size, θ

NOTE: V-Notch Size Required to Bleed-Down 0.5 Inch of Detention Volume in 24 Hours

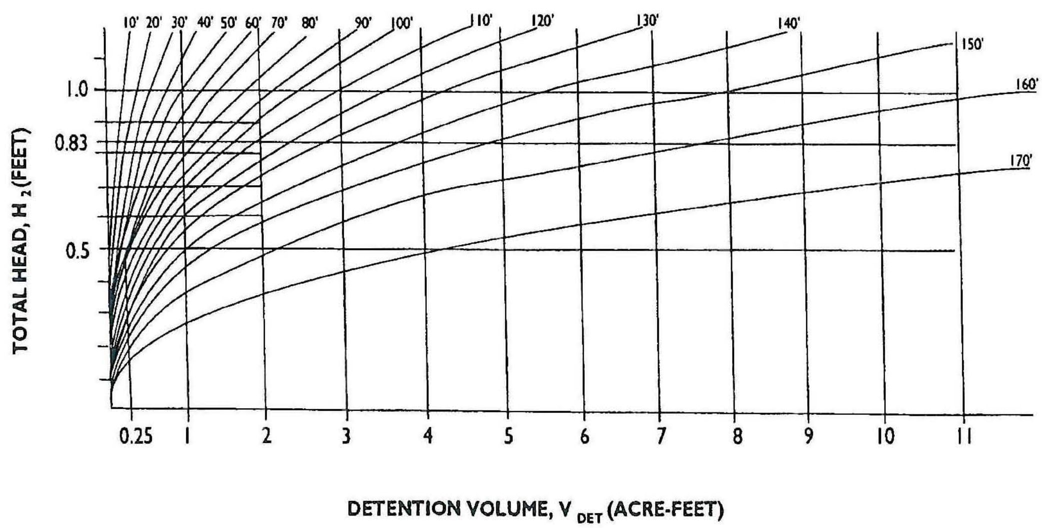


Figure 3