Appendix F – BMP Research Summary Tables

List of Practices:

GREEN ROOFS LITERATURE SUMMARY

Study	Description	Pollutant Reductions	Runoff Reductions	Implications for Design
Banting et al, 2005 CitedRefs: Thompson, 1998 Liesecke, 1998 Zinco Roof Gardens, 1997			Thompson, 1998: 60-80%, depending on substrate depth Liesecke, 1998: 40-45% for 2-4cm of media 60% for 10 cm of media Zinco, 1997: 70-90% Summer 40-50% Winter	
Denardo et al, 2005	7 rainfall events monitored on GR's with a media depth of 89 mm, 8% slope in State College, PA (PSU).		Avg Runoff reduction: 45% (range 19-98%). Rainfall 3.7-13.6mm (2 mo. period in Fall) Tp delay: 1-3hrs Peak Flow reduction: 56%	Runoff reduction was higher during smaller rainfall events. RR is not an annual average, but rather a two month average during Fall months. Expected RR would be higher during summer period.
DeNardo et al, 2005 CitedRefs: Miller (1998) and Scholz (2001)	3" media depth		38-45% 38-54%	

Emilisson et al, 2007	Investigated nutrient runoff, storage, and plant uptake after fertilization of vegetated roof systems during simulated rainfalls over a 6 mo. Period in Sweden. Three levels of fertilizers were applied as either controlled release fertilizer (CRF), or combo CRF and conventional fertilizer. Conventional fertilizers yielded the highest runoff nutrient concentrations. Runoff concentrations decreased over time, but remained higher than CRF runoff conc. Nutrient leaching from established vegetation mats was lower than that from newly established surfaces.			Green roofs applied with low dose fertilizers exported less nutrients than those with conventional fertilizers. Conventional fertilizers should be avoided, or runoff water should be recycled or reused on the roofs or other vegetated surfaces, particularly during the first weeks following fertilization.
Farzaneh et al, 2005	89 mm thick media in beds were tested in a control greenhouse at Pennsylvania State University. The greenhouse temperatures were adjusted to simulate four seasonal climatic conditions, which correlated to the ambient season. 4 different models were used to calculate ET.			ET rates from vegetated beds averaged 0.61 mm/d (winter) and 1.12 mm/d (spring/fall) Vegetated beds lost 28% and 57% more water than unplanted beds in winter and spring, respectively.
Getter et al, 2007	Examined RR for GRs constructed on 2, 7, 15, and 25% slopes at MSU. All roofs		Avg: 80.8% For Light (<2mm),	Green roofs constructed with lower slopes have the potential to retain more water

	contained a 6 cm media layer and 0.75 cm of a moisture retention fabric. Mean retention was least on the 25% slope (76.4%) and greatest at the 2% slope (85.6%). Overall average retention was 80.8% (P<40mm, 62 events) CN for all roofs ranged from 84 (2% slope) to 90 (25% slope), for all rainfall events		Med (2-10mm) and Heavy (>10mm) rainfall events on the 2% slope: 93.3, 92.2, 71.4 (mean 85.6) 62 rain events 0<P<40mm	
Hutchinson et al, 2003	A GR in Portland Ore with a 4-5" media depth was monitored for hydrologic and water quality data.	TP export conc. was high, but showed a decreasing trend over course of 1 yr study. Pollutant load reductions were possible due to the large reduction in runoff vol.	69% average Rainfall over 15 mo. Period. Summer:92% Winter: 59% During dry season, removal approached 100%	
Liptan and Strecker, 2003	A GR in Portland, OR was monitored for hydrologic data. The roof was designed with 2-3" of topsoil and compost mix and planted with seven species of sedum. The roof slope was		Monthly retention ranged from <10% for an 11 in. rainfall, to 100% in dry season months. Over a two year study,	

	~7%.		average annual retention was 28%.	
Long et al, 2007	Columns were filled with 4” of different GR mineral media: two grades of expanded shale, two expanded clays (one with nutrient additives), and an expanded slate. Rainfall was simulated using synthetic rainwater. The study is still ongoing, but preliminary conclusions indicate GR media can effectively buffer rainfall pH and remove heavy metals. The finer graded expanded shale was most effective in pH buffering and metal removal.			The authors forecast that the engineering of a green roof media for water quality improvement is possible. It is recommended that expanded shale be used in green roof media mixes, due to the increase pollutant removal capabilities of this mix. To allow for proper drainage in the media, the fines should be mixed with medium grade materials. The mix ratio is still being studied.
Moran et al, 2005	Location: Kinston, Goldsboro, NC. Media depths and slope were 75mm (3 in) and ~0% for Goldsboro, and 100 mm (4 in) and 7% for Raleigh. Rainfall monitored over 6 month pd.	Green roof drainage exhibited and increase in N and P conc. from rainfall	Average 63% (Goldsboro) and 55% (Raleigh) For P>1.5”, C=0.50 Tp delay 2-4.5 hrs	Results of a related laboratory test showed that soil media with a lower compost content will leach less N and P from the GR runoff. Further, the amount of nutrient leached over time should decrease.
MSU Research 2001-2004	3 year study of plant survival and drought tolerance in Michigan. Sedum and native species were planted and evaluated. The roof was irrigated regularly during the first year; irrigation was reduced and then eliminated in the 2nd and 3rd years. Upon			All tested (9) varieties of *Sedum* and *A. cernuum, C. lanceolata*, and *T. ohiensis* were the most suitable for unirrigated roofs in the Upper Midwest. Species of native plants could be used in GR applications so long as irrigation occurred regularly.

	cessation of irrigation, most native plants died. Only Sedum species survived on natural rainfall.			
MSU Research 2001-2004	9 species of Sedum were planted at depths of 4.0, 7.0, and 10.0 cm on green roof platforms in autumn and spring			Spring plantings had better survival rates (81%) compared to autumn (23%).
MSU Research 2001-2004	Chlorophyll fluorescence (F_v/F_m) measurements were taken on plant leaves to monitor plant stress. Chlorophyll fluorescence can indicate plant photosynthetic potential.			Water was required at least once every 14 days and 28 days to support growth in green roof substrates with 2 cm and 6 cm media depths respectively. Sedum vegetation was still viable after 88 days of drought
Teemusk and Mander, 2007	A study in Tartu, Estonia, compared runoff and WQ from a vegetated GR to a reference bituminous roof. Three rainfall events and two snow melt events were observed. The GR contained 100mm of media and 80 mm or rock wool (for additional water retention). The media layer consisted of a lightweight arrogate (LWA) (66%), humus (30%) and clay (4%). The rainfall was characterized by low intensity.	TP: 12-65% TN: 7-19% First number is avg during heavy storms (P<12.1mm) and second number is avg during small storms (P<2.5mm)	For P<2.5mm, 86% For P>12.5 mm, 0% During snow melt, pollutant concentrations were greater on the greenroof. Greenroof runoff had higher sulphates and Ca–Mg salts conc., due to leaching from the LWA-material.	The quality of the runoff water varied based on rainfall amt, and the amt of pollutants accumulated on the roof. GR effluent conc. of TN and TP were much lower than observed by Moran et al. (2003) or Liptan and Strecker (2003), because the Estonian greenroof did not contain compost The composition of the media layer should be taken into consideration in selecting the soil mix. P and N effluent concentration increased during heavy rainfall events; however, concentrations were still lower than those from the reference roof.
TRCA, 2005	Runoff from a GR was compared to control roof runoff in York, Toronto. Both roofs	Calculated Removal (GR compared to	RR: 54-76%	Fertilizers in the GR media were the primary source of phosphorus.

	were constructed on 10% slopes. The GR was planted with wildflowers and contained 140 mm of growing media consisting of crushed volcanic rock, compost, blonde peat, cooked clay and washed sand.	control roof): TSS: 69% TP: negative TKN: negative Cu: 66% Zn: 18% EColi: negative Al: 18% PAHs: 83-89%		GR phosphorus concentrations decreased more than 50% over two consecutive monitoring years, likely a result of leaching out from the media. Clearing of debris and bird feces from the GR should be done regularly to prevent clogging and decrease pollution export.
VanWoert et al, 2005	Compared RR of three roofs: gravel ballast (2 cm), extensive green roof without vegetation (2.5 cm media), and extensive green roof with vegetation (2.5 cm media) in East Lansing, MI (MSU)		Avg RR: Veg: 60.6% Media: 50.4% Gravel: 27.2% 0.08<P< 53.59 mm (83 events)	GRs with lower slopes and deeper media depth retained more rainfall RR depended on rainfall depth. Overall, vegetated roofs were most effective in retaining rainfall For Light (<2mm), Medium (2-6mm) and Heavy (>6mm) storms, % retention, respectively: Veg: 96.2, 82.9, 52.4 Media: 99.3, 82.3, 38.9 Gravel: 79.9, 33.9, 22.2
Schueler and Brown, 2004 Appendix B, Manual 3				Not included

REFERENCES:

Banting, D., Doshi, H., Li, J., and Missious, P. 2005. Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto. Prepared for City of Toronto and Ontario Centres of Excellence – Earth and Environmental Technologies. October, 2005.

DeNardo, J.C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J., Berghage, R.D. 2005. Stormwater mitigation and surface temperature reduction by green roofs. Trans. ASAE 48 (4), 1491–1496.

Emilsson, T., Berndtsson, J.C., Mattsson, J.E., and Rolf, K. 2007. Effect of using conventional and controlled release fertilizer on nutrient runoff from various vegetated roof systems. *Ecological Engineering* 29, 260-271.

Farzaneh, R., Jarrett, A.R, Berghage, R.D., and Beattie, D.J. 2005. Evapotranspiration rates from extensive green roof plant species. 2—5 ASAE Annual International Meeting, Tampa, Fl. 17 July 2005

Getter, K.L, Rowe, B.D., and Andresen, J.A. 2007. Quantifying the effect of slope on extensive green roof stormwater retenetion. *Ecological Engineering.* 31, 225-231.

Hutchinson, D., P. Abrams, R. Retzlaff, and T. Liptan. 2003. Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA. In *Proc. Greening Rooftops for Sustainable Communities: Chicago 2003*: May 29-30, 2003; Chicago, Illinois.

Liptan, T. and Strecker, E. 2003. EcoRoofs (greenroofs) – A more sustainable Infrastructure. National Conference on Urban Stormwater: Enhancing Programs at the Local Level. February, 2003.

Long, B., Clark, S.E., Bakers, K.H., and Berghage, R. 2007. Selecting a green roof medium for water quality benefits. ASCE World Environmental and Water Resources Congress.

Moran, A. and Hunt, B. 2005. Green roof hydrologic and water quality performance in North Carolina. 2005 ASAE Annual International Meeting, Tampa, Fl. 17 July 2005

MSU. 2004. The green roof research program at Michigan State University. Available at: www.hrt.msu.edu/greenroof/.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD.

VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Fernandez, R.T., Xiao, L., 2005. Green roof stormwater retention: effects of roof surface, slope, and media depth. *J. Environ. Qual*. 34 (3), 1036–1044.

VEGETATED FILTER STRIP LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Abu-Zreig et al, 2003	20 filters with varying length (2 to 15 m), slope (2.3 and 5%), and vegetation cover, were evaluated for phosphorus removal efficiency. Runoff was produced by rainfall simulators. The average P trapping efficiency of vegetated filters was 61%, ranging from 31% in a 2-m filter to 89% in a 15-m filter. Filter length was found to be the largest factor in removal; inflow rate, vegetation type, and density vegetative coverage had secondary influences.	MASS REMOVAL: The average phosphorus trapping efficiencies of the 2, 5, 10, and 15-m-long strips were 32, 54, 67, and 79%, respectively		Short filters (2 and 5 m), which are somewhat effective in sediment removal, are much less effective in P removal. For sediment trapping, increasing filter length beyond 15 m is not at all effective in increasing sediment removal but it is expected to further increase P removal.
Abu-Zreig et al, 2004	20 filters with varying length (2 to 15 m), slope (2.3 and 5%), and vegetation cover, were evaluated for sediment removal efficiency. Runoff was produced by rainfall simulators. TSS removal increased with increasing flowpath	For inflow rates of 0.3, 0.65 and 1.0 L/s TSS mass removal rates were 90%, 82% and 82%, respectively.	Water retention was related to filter length. WR ranged from 20% for the 2m filters to 62% in the 10m filters.	Greater vegetation cover increased TSS removal. Optimum filter length for TSS removal was approximately 10m.

	length up until 10m. Average TSS removal was 84%, ranging from 68% for a 2m filter to 98% for a 15m filter. No difference between the 10 m and 15m filters was observed.			
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques			Vegetation coverage is important for pollutant removal. Little relationship between pollutant removal and vegetation height or type exists.
Barrett et al, 1998	Measured the efficiency of two highway runoff VFS in Austin, TX. Walnut creek and US 183 filters, respectively, had a centerline lengths of 1055 and 356 m, filter lengths of 7.8-8.1 and 7.5-8.8 m, 9.4% and 12.1% side slopes, 1.7% and 0.73% centerline slopes, 104,600 and 13.000 m2 drainage areas, and 38% and 52% paved CDA.	US 183: TSS: 87% FC: neg COD: 61% TOC: 51% Nitrate: 50% TKN: 33% TP: 44% Zn: 91% Pb: 41% Fe: 79% Walnut Creek: TSS: 85% FC: neg COD: 63% TOC: 53% Nitrate: 23% TKN: 44% TP: 34% Zn: 75%	P avg = 25mm (median = 16mm) 8.4 mm	Highway medians with a length of at least 8m, full vegetation, and slopes less than 12% are viable alternatives to structural controls to reduce highway pollutants and loads. Removal efficiencies of the two strips were similar, despite geometric and vegetative differences. Most pollutant removal occurred on the sides of the median, so a V-shaped median is recommended over a trapezoidal shape.

		Pb: 17% Fe: 75% Load reductions were slightly higher		
CALTRANS, 2004	Filter strips were sited, constructed, and monitored at three sites as a part of this study. CDA had I=100% for all locations.	TSS: 69% TP: neg TN: neg Total Cu: 85% Total Pb: 88% Total Zn: 72% Load reductions were higher due to RR from infiltration	RR: 30% (range 14-80%)	Check that the specified vegetation provides a dense enough surface in the climate to stabilize the swale bottom provide effective pollutant removal. Site in areas where sheet flow predominates.
CWP, 2007 NPRPD v.3	See table for WQ Swale			
Garabaghi et al, 2001	An experiment in Guelph, Ontario compared runoff treatment performance of perennial rye grass (*Lolium perenne* L.) VFS under different flow and pollution load conditions. Effects of flowpath length and flow rate on performance was evaluated. The plots were 1.2 m wide, and parallel to each other with a slope of 5.1% to 7.2%.			About 50% of sediments were removed within the first 2.5 m of the filter. An additional 25% to 45% of sediments (depending on flow rate) were removed within the next 2.5 m of the filter. Almost all of the aggregates larger that forty microns in diameter can be captured within the first five meters of the filter strip.
Goel et al, 2004	12 filter strips of 1.2 m width, 3% slope, different lengths (5, 10, 15 m), and different vegetation covers were studied.	Avg EMC removal for all filter strips: NO3-N: 21% PO4: 49% TP: 88%		Generally, denser vegetation and longer filter strips were more efficient in trapping different pollutants.

		TN: 90% E.Coli: 13% FC: 54% TSS: 88%		
Lim et al, 1998	Tested the effects VFS length on runoff concentrations from cattle-manure treated plots. Runoff was produced by rainfall simulators.	MASS REMOVAL: 6.1 m TKN: 78% PO4: 74.5% TP: 76.1% TSS: 70% TS:23.6% FC: 100% 12.2 m TKN: 89.5% PO4: 87.8% TP: 90.1% TSS: 89.5% TS: 40.8% FC: 100% 18.3 m TKN: 95.3% PO4: 93% TP: 93.6% TSS: 97.6% TS: 69.8% FC: 100%	Runoff Reduction (from simulated rainfall): 98%	75% of TKN, TP, OPO4, and TSS, and 100% of fecal coliform, were removed in first 6.1m of the VFS.
Schueler and Holland, 2000 (Practice) Article 118 Yu et al, 1992	A study on the pollutant removal capacity of a level spreader/grass filter strip designed to capture approximately 0.4 watershed-inches of runoff from a 10-acre shopping center. Eight storms were monitored at distances of 75 and 150	MASS REMOVAL: 75 ft. Filter Strip TSS: 54% NOx: -27% TP: -25% Extractable Pb: -16% Extractable Zn: 47% 150 ft. Filter Strip TSS: 84%		Sparse vegetation and gulley erosion was cited as reasons for poor removal rates in the first 75 feet of the strip. The authors recommend an optimal filter strip length of 80 to 100 feet with the level spreader.

	feet. Removal of particulates increased greatly after 150 feet of treatment but removal of nitrate and total phosphorus was modest.	Nitrate+Nitrite: 20% TP: 40% Extractable Pb: 50% Extractable Zn: 55%		
Strecker et al, 2004	Review of 32 grassed swales and vegetated filter strip studies found in the International Stormwater BMP database	Mass Removal: TSS: 45-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	40% Runoff Reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

References

Abu-Zreig, M., Rudra, R.P., Whiteley, H.R., Lalonde, M.N., Kaushik, N.K. 2003. Phosphorus removal in vegetated filter strips. *Journal of Environmental Quality*. 32: 613-619.

Abu-Zreig, M., Rudra, R.P., Lalonde, M.N., Whiteley, H.R., Kaushik, N.K. 2004. Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. *Hydrological Processes*. 18: 2029-2037.

Barrett, M.E., Walsh, P.M., Malina, J.F., Charbeneau, R.J. 1998. Performance of vegetative controls for treating highway runoff. *Journal of Environmental Engineering*. 124 (11): 1121-1128.

Barrett, M.E. 2005. BMP performance comparisons: examples from the International Stormwater BMP Database. ASCE EWRI.

CALTRANS, 2004. California Department of Transportation, Division of Environmental Analysis. BMP retrofit pilot program. Final Report CTSW-RT-01-050. January, 2004.

Goel, P.K., Rudra, R.P., Gharabaghi, B., Das, S., Gupta, N. 2004. Pollutants removal by vegetative filter strips planted with different grasses. ASAE International Meeting, Ottawa, Canada, 1-4 August 2004: 2521-2535

Gharabaghi, B., Rudra, R.P., Whiteley, H.R., Dickinson, W.T. 2001. Performance testing of vegetative filter strips. ASCE World Water and Environmental Congress Meeting, 2001.

Lim, T.T., Edwards, D.R., Workman, S.R., Larson, B.T., Dunn, L. 1998. Vegetated filter strip removal of cattle manure constituents in runoff. Transactions of the ASAE. 41 (5): 1375-1381.

Schueler, T.R. and Holland, H.K. 2000. The Practice of Watershed Protection. Center for Watershed Protection: Ellicott City, MD

PERMEABLE PAVEMENT LITERATURE SUMMARY

Study	**Description**	**Pollutant Removal** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Andersen *et al.*, 1999;	Performed a **laboratory** study (simulated rainfall) to evaluate permeable pavement hydrological response. For PICP with a base course depth ranging from 30-70cm, a substantial portion of rainfall was retained under both dry and wet initial conditions.		Avg Rainfall Retention: Dry: 55% Wet: 30% (for a 15mm/hr, one hour duration storm)	Evaporation, drainage and retention in the structures were found to be a function of the particle size distribution of the bedding material and water retention in the surface blocks Pavements with smaller grain-sized substrate retained more water and increased attenuation. Evaporation rates were greatest from pavements with the highest retention of water. Pavement systems constructed over subbase materials had higher evaporation rates than systems with no subbase.
Balades et al, 1995	Field study on the clogging rates and effective maintenance of permeable pavements. Found that surface infiltration rates could be decreased by 50% after 2-3 years of use. Clogging was prevented by routine suction sweeping.			Clogging of permeable pavements occurs in the surface open void spaces, due to accumulating material that is retained on the permeable pavement surface. Clogging was effectively prevented through suction sweeping. In cases where severe clogging had occurred, high infiltration rates could be restored via use of a costly high-pressure water jet.
Bean et al, 2007a	Surface infiltration rates of 40 permeable pavement sites in NC, MD, VA, and DE were measured. PICP and PC in close proximity to disturbed soil sites had significantly lower surface infiltration rates than permeable pavements in			To sustain higher surface infiltration rates of CGP with sand, maintenance using a vacuum sweeper, should be performed at regular intervals. The top 13–18 mm of material accumulated within void spaces should be removed and replaced. The location of permeable pavement sites plays an important role in surface clogging rates. PICP and PC

	stable watersheds. Study concluded that the location of permeable pavements away from fines and disturbed sites, as well as maintenance of pavements, were critical to maintaining high surface infiltration rates.			sites should not be located adjacent to areas with disturbed soils
Bean, 2005, 2007b (in NPRPD)	In Goldsboro, NC, nutrient concentrations from PICP subsurface drainage were compared to those in adjacent asphalt runoff. In Cary, NC, PICP subsurface drainage was compared to rainfall. At both sites, NO3-N in the subsurface drainage was higher than the asphalt runoff and rainfall and NH4-N was lower. TP removal varied. In Swansboro, NC, a site was constructed and instrumented to monitor runoff flow and rainfall rates and collect exfiltrate and runoff samples from the permeable pavement lot; however, no site runoff resulted during the study period.	Calculated Removal: Goldsboro: TP: 65% OPO4: 50% TN: 36% NH4: 86% TKN: 55% NO3: -47% TSS: 72% Cu: 63% Zn: 88% Cary: TP: -54% OPO4: -100% TN: -2.2% NH4: 90.6% TKN: 52.4% NO3: -100%	Cary: 66% Swansboro: 100% (complete infiltration)	Increased concentrations of NO3-N in the PICP subsurface drainage were attributed to the probability that aerobic conditions occurred throughout the pavement that nitrified NH4-N to NO3-N. At Cary site, the addition of TP was attributed to atmospheric deposition (dry).
Booth and Brattebo, 2003 (in NPRPD)	Examined long term effectiveness of 4 types of pervious pavement and asphalt with respect to hydrology, water quality, and structural	Calculated Removal: Gravelpave: Zn: 91.6% Cu: 88.8% Grasspave:	Runoff Reduction: 97-100% Study	Permeable pavements can exhibit long term (5 yr) runoff and pollutant reductions Hardness and conductivity levels were significantly higher in permeable pavement subsurface drainage

	durability. All pavements endured structurally. PP drainage, as compared to asphalt, had significantly lower concentrations of Zn, Cu, and motor oil. Conversely, hardness and conductivity levels were significantly higher in pervious pavement drainage.	Zn: 38.9% Turfstone: Zn: 64.4% Cu: 83.3% Uni-Ecostone: Zn: 68.5% Cu: 89.2%	characterized by low rainfall intensities (avg intensity was less than 5mm/hr)	than asphalt runoff. Metals and motor oil concentrations were higher in asphalt runoff. Among the permeable sections, hardness and conductivity were significantly higher in the concrete systems (PICP and CGP) than the plastic grid systems.
Collins, 2008a	Compared 4 types of permeable pavement (PC, PICP1 (12.9% voids), CGP, and PICP2 (8.5% voids)) and standard asphalt in clayey subsoils. PICP1 and CGP cells had the highest volume and peak flow reductions. CGP also had the highest volume of surface runoff. The response of the PICP1 cell was attributed to an increased subsurface storage volume resulting from an elevated outlet pipe; whereas, the CGP cell response was attributed to the properties of sand fill media		Runoff Reductions: 94 - 98% Volume reductions: 32.1, 43.9, 66.3, 63.6, and 37.7% of rainfall volumes for asphalt, PC, PICP1, CGP, and PICP2, respectively. 56 monitored events, 3.1<P<88.9 mm Mean= 20.6 mm Median = 14.7 mm	Hydrologic differences among the permeable pavements, with respect to runoff reduction and peak flow mitigation, did exist mainly due to the properties of sand versus aggregate fill materials; however, they were small in comparison to the overall substantial improvements from asphalt. Among permeable pavements evaluated, CGP generated the greatest runoff volumes, attributed to the lower hydraulic conductivity of the sand fill media, and the resulting lower surface infiltration rate of this section. For the PICP sections, paver geometry seemed to influence surface runoff generation more than percent of open surface void space The sand fill media in CGP likely retained the most runoff, and was most effective in mitigating peak rainfall intensities. Sand fill, which is often seen as a detriment because of increased surface runoff, appears to have the benefit of holding additional water, which then slowly leaks or evaporates. If the installation of underdrains is recommended or

				necessary, design of the subbase can be altered to increase detention time within the pavement subbase by raising the perforated underdrain pipe elevations to create an internal storage zone. Further, an ISZ may decrease total outflow volumes and delay time to peak for small-medium rainfall events
Collins, 2008b	Compared 4 types of permeable and standard asphalt in clayey subsoils. Permeable pavement drainage had higher NO3-N concentrations, and no difference in TP or TSS concentrations were observed. Permeable pavement drainage had lower NH4 and TKN concentrations.	PC, which provided influent water the greatest contact time with cementitious materials, had the highest drainage pH values. For CGP, TN removal: 25%	20 storm events 3.1<P<88.9 mm Mean= 22.1 mm Median = 14.0 mm	The PC cell was most effective in buffering rainfall pH, because it provided influent water the greatest contact time with cementitious materials. Permeable pavement pH values were such that the leaching of metals through the pavements would not be expected. Authors suggest that permeable pavements with sand fill or bedding material may act similarly to a sand filter, and be efficient in TN removal. TP was likely leached from underlying high P-index soils into underdrains. No liner separated the permeable pavements' subbase from the in-situ soils. TSS (and TP) may be reduced by installing a permeable geo-fabric or raising the drainage pipe several inches above the underlying soils, encasing it in a washed aggregate layer.
Day *et al.*, 1981	**Laboratory** experiment (simulated rainfall) on three types of grid pavements and asphalt. Compared to asphalt, surface runoff was much lower from all three CGP systems. High removal rates of TP, organic phosphorus, and heavy metals were observed in CGP	For Monoslab, Grasscrete, Turfstone, respectively (overlying 1-2" gravel and 10-12" soil layer) TP: 70, 60, 59% OPO4: 40, 35, -285%	Runoff Reduction >99% for all CGP types. 10 simulated events: 0.9-3.5 in/hr, return pd <10	CGP systems dramatically reduce stormwater runoff. High phosphorus removal rates in the CGP systems was attributed to P adsorption to the aggregate and soils in the subbase layers Nitrate-nitrite removal rates were minimal; high leaching rates through the pavements were observed.

	subsurface drainage	Org-P: 76, 86, 68% NOx: -928, -777, -593% NH4: 44, 34, 32% ON: 76, 57, 39% TOC: 45, 26, -50% Pb: 92, 94, 93% Zn: 77, 92, 93% Cr: 77, 80, 26%	year storm.	
Dierkes *et al.* 2002	Field Study: Investigation of clogging materials and their distribution in permeable pavement surface. Found that metal conc. in PP decrease rapidly with depth. Most heavy metals were captured in the top 2 cm of the void space fill media. **Lab Study**: Evaluated heavy metal reduction efficiencies of four pavements: solid concrete block pavers with open infiltration joints, concrete block pavers with greened joints (topsoil fill with planted grass), pervious concrete pavers, and pervious concrete pavers with greened joints. All four pavements retained some amount of Cd, Cu, Pb, and Zn.	**Lab results:** Specific removal values were not published by the authors of the study		Field Study: Since metals are captured in top layers of the pervious pavement, through regular maintenance, where the top layer of fill media is removed and then refilled with new material, permeable pavements have the potential to remove heavy metals over long periods of time. **Lab Study:** Systems with pervious concrete or greened joints demonstrated higher pollution retention capacities than those without. The permeable concrete pavers with greened joints had the highest pollutant trapping efficiency.
Dreelin et al,	Compared performance of	For 7 of 9 sampled	RR: 93%	The majority of RR was attributed to infiltration into

2006	plastic grid grass pavers with a conventional asphalt in Athens, GA. The in-situ soils had a relatively high clay content (35-60%). During the 2 of 9 storms when metal and nutrient concentrations could be detected, pollutants were higher at the asphalt, except for TN. Overall pollutant loadings were low due to minimal parking lot use.	rain events, metal and nutrient conc. were below the detection limit at both lots Calculated Removal: Ca: 17% Zn: 80% Si: 50% TP:11% TN: negative	when compared to asphalt lot 0.03<P<1.83 cm	the clay soils. The permeable pavements sited in clay soils effectively to reduce runoff during small storm events It is likely that larger or intense storms would have decreased the pavement runoff reduction. The permeable pavement gravel subbase base storage capacity would be exceeded, and runoff from the practice would increase.
Fach and Geiger, 2005	**Laboratory** experiment to examine pollution removal rates of Cd, Zn, Pb, Cu for pervious concrete pavers, as well as for three variations of solid concrete block pavers; one with wide infiltration joints (29mm), another with narrow infiltration joints (3mm), and a third with narrow joints filled with crushed brick substrate. When set over a 4 cm crushed basalt or brick substrate roadbed and a 40 cm limestone base course, average pollution removal rates for all pavements and substructures were higher, ranging from 96 to 99.8% for all metals analyzed.	Calculated avg. heavy metal removal rate (Zn, Cu, Pb): solid concrete block pavers with brick substrate infill: 93, 92, 94% narrow joint spaces 59, 58, 79% wide joints spaces: 73, 77, 93% PC: 96, 96, 97%		No significant differences for pollution removal between the narrow and wide joint spacing were observed. PC had the highest pollutant removal rates, followed by the block pavers with substrate infill.
Gilbert and Clausen,	22 month study evaluated runoff EMC from three types of	PP runoff: Calculated removal:	Runoff Reduction:	Pollutant concentrations of permeable pavement runoff were significantly lower than asphalt runoff for

2006	driveways: asphalt, crushed stone, and permeable pavement. Permeable pavement driveways had significantly lower concentrations of TP, TN, NO_3-N, NH_3-N, TKN, TSS, Cu, Pb, and Zn than runoff from asphalt driveways. Runoff from the crushed stone driveways was similar to that of asphalt.	TSS: 67% NO3: 50% NH4: 72% TKN: 91% TP: 34% Cu: 65% Pb: 67% Zn: 71%	72% 104 events. Median rainfall = 9mm/h, 3.5 hr duration. 90% of storms < 29mm/h , 10.75 hr duration.	all constituents evaluated.
Hunt et al, 2002	Study of CGP application in permeable soils. The authors conclude that if CGP is properly maintained, nearly all events less than one inch will not produce runoff.		For P>12.7 mm, runoff coefficients ranged from 0.15 - 0.30	Surface runoff from the CGP lot was dependent on rainfall intensity rather than volume. The suggested required maintenance for this application was a street sweeper pass, about once every 9-12 months.
James and Gerritts, 2003	Studied clogging on an 8-year old installation of PICP in Canada.			Infiltration of water through permeable pavements decreased with increasing traffic loads, and also with increasing organic and fine matter in the open void spaces. In low to medium traffic areas, removing the top 15-20 mm of permeable pavement fill material significantly improved the surface infiltration rate. In areas of higher traffic, infiltration rate improved when 20-25mm of the fill material was removed.
James and Shahin, 1998	**Laboratory** study that compared the quantity and quality of runoff from PICP and rectangular concrete pavers to	PICP drainage reduced the concentrations of heavy metals, oils,		The increase in NO3-N and a decrease in TKN was attributed to oxidation within the pavement subbase The low concentrations of heavy metal, oils, grease,

	runoff from a standard asphalt block. Compared to applied rain water concentrations, PICP subsurface drainage exhibited an overall increase in pH and NO3, and a decrease heavy metals, oils, grease, and TSS. No change in TP was observed.	grease, and TSS. An increase in NO3 and pH was observed. Specific removal rates were not provided by the authors		and TSS, in the PICP drainage was likely due to adsorption or filtering by PICP open-graded aggregate base materials. Total void size (not joint size) in the surfaces of permeable pavements was a controlling factor in the amount of surface runoff generated. Pavements with sand and sand/gravel joint fills generated more runoff than those with gravel fill. Water drained faster through subgrades of gravel material compared to sand or a gravel/sand mixture subgrades. Permeable pavements were effective at buffering acidic rainfall pH. The pH of permeable pavement drainage was such that leaching of metals would not be expected.
Jefferies, 2004	Monitoring summary of several SUDS practices in Scotland. Includes runoff reduction data on 2 permeable pavement applications, one having an impermeable liner.		RR (compared to rainfall): 78% with no underdrains, 53% for lined system	RR (compared to conventional surface): 50% with no underdrains, 5% for lined system
Karasawa *et al*., 2006	Temperature study on PICP and standard asphalt.	Compared to asphalt, 15 PICP test stalls suppressed the temperature rise by 7.2 - 16.6ºC the day after rain and at 33.8ºC air temperature.		Generally, pavements having higher evaporation rates had lower road surface temperature. Pavements with higher water content had a lower road surface temperature. The lower temperatures were attributed to the removal of heat by the evaporation of moisture retained in

				pavement blocks
Kresin *et al.*, 1996	Evaluated PICP installations of various ages for infiltration capacities			The effective surface infiltration rate of PICP decreases with increasing age and compaction. By removing the top material of the block paver fill, surface infiltration rates can be improved.
Legret and Colandini, 1999	Compared porous asphalt (PA) drainage to conventional stormwater drainage. PA drainage had lower concentrations of TSS and heavy metals.	Concentrations of SS, Pb, Zn, and Cd were lower in permeable pavement drainage. Calculated removal: TSS: 65% Pb: 83% Cu: 0% Cd: 80% Zn: 73%	Runoff Red = 98-100% 12.7<P<52.1 mm	Samples taken from PA structure and underlying soils indicated that metals are retained in PA and that leaching to the underlying soils is low, even after 8 years of use. Metal pollution concentrations were highest in the pavement surface clogging materials
Pagotto et al, 2000	In Nantes, France, a section of asphalt highway was monitored for 1 year, which was then replaced with PA and monitored for another year. PA runoff yielded lower concentrations of TSS, TKN, hydrocarbons and heavy metals.	PA runoff: TSS: 81% COD: 0.3% TKN: 43% Hydro: 92% Pb: 78% Cu: 35% Cd: 69% Zn: 66% NO3: 69% Cl: 77% SO4: 23% NH4: 74%	Individual storm data not included (only annual summary)	Hydrocarbon and particulate metal removal were attributed to the filtration of fine particulates on the porous asphalt surface. Dissolved metal removal was due to possible adsorption to pavement materials.
Pratt *et al.* 1989	4 pervious pavement stalls were fitted with underdrains and impermeable liners. The stalls		Total Vol. Reduction: 25-45% of	Pavements with subbase materials containing the greatest surface area were able to retain higher amounts of runoff.

	consisted of various subbase materials: pea gravel, blast furnace slag, granite, and carboniferous limestone. All stalls retained some portion of rainfall. Peak flow reductions and time to peak delays were also observed.		rainfall retained (3 events: 19.5<P<34.8 mm) Note: For P < 5 mm, retention = 100%	In areas of low soil permeability, the installation of underdrains in pervious pavement subsurface can still yield reductions in outflow volume and peak flow rate, and delay the time to peak flow.
Rushton, 2001	In Tampa, FL, three parking lot paving surfaces were compared, along with basins with and without swales. Pervious paving with a swale reduced runoff volumes and pollutant loads of metals and suspended solids.		RR: 50% for pervious paving with a swale. RR attributed to permeable paving alone was 32%	Increases in P were attributed to landscaping practices on the grassed swales. Pervious pavement with swales was most effective in reducing runoff during small storms.
Schueler and Brown, 2004. Appendix B, Manual 3				Not included (assumed under infiltration practices)
Traver (2006)	A porous concrete (PC) demonstration walkway site was sampled from 2003-2006 at the Villanova campus in PA. The main traffic on the walkway is pedestrian. As such, pollutant loadings were low. The PC drainage had low loadings of nutrients and metals; however, chloride	MASS REMOVAL: TSS: 99.9% TN: 95% TP: 97% Cl: negative	RR: 94%	Some P leached out of the soil as runoff infiltrated, but this is predicted to decrease as the soil washes out.

	loadings were high.			
Valavala et al, 2006	Rainfall events up to the 100 year frequency were simulated on unclogged PC pavement slabs ranging from 0-10% slopes. The slabs were 17 cm thick and underlain by a 15 cm thick sand bedding layer. Study determined that for unclogged PC with 16-27% porosity overlying a sand bedding layer, little to no runoff results from typical rainfall intensities.		Only during extremely high intensity events (21-47 cm/h) was runoff observed from the slabs with 10% slopes. For the same high rainfall intensities, no runoff resulted from the 2% sloped slabs	Unclogged PC can effectively reduce runoff volumes. Runoff from high intensity storms was generated on steeply sloped slabs; the same intensities did not produce runoff from low sloping slabs.
Van Seters et al, 2006	In King City, Ontario, long term performance of permeable pavers and bioretention were monitored. Virtually no surface runoff left the permeable pavement surface. Initial monitoring data indicates that water infiltrating into pervious pavements has lower pollutants than runoff from conventional pavement.	TP: 33% TKN: 26% Cu: neg Zn: 55% Oil/Grease: 64% (preliminary results from 8 storm events)		
UNH, 2007	Summary of 2 year pollutant removal data for various LID practices, including a porous	% Removal: TSS:99 TP: 38%		

	asphalt parking lot.	Zn: 96% TPH: 99%		

REFERENCES:

Andersen, C.T, Foster, I.D.L., and Pratt, C.J. 1999. Role of urban surfaces (permeable pavements) in regulating drainage and evaporation: Development of a laboratory simulation experiment. *Hydrological Processes* 13(4): 597

Balades, J.D., Legret, M; and Madiec, H. 1995. Permeable pavements: pollution management tools. *Water Science and Technology*. 32(1): 49-56

Bean, E. Z. 2005. A field study to evaluate permeable pavement surface infiltrations rates, runoff quantity, runoff quality, and exfiltrate quality. MS thesis. Raleigh, N.C. North Carolina State University, Department of Biological and Agricultural Engineering.

Bean, E. Z., Hunt, W.F., and Bidelspach, D.A. 2007a. Field survey of permeable pavement surface infiltration rates*. Journal of Irrigation and Drainage Engineering*. 133 (3): 247-255.

Bean, E.Z., Hunt, W.F., and Bidelspach, D.A. 2007b. Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts. *Journal of Irrigation and Drainage Engineering*, 133 (6):583-592.

Brattebo, B. O., and Booth, D. B. 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research* 37(18): 4369-4376.

Collins, K.A., Hunt, W.F., and Hathaway, J.M. 2008a. Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina.. *Journal of Hydrologic Engineering*. (accepted).

Collins, K.A., Hunt, W.F., and Hathaway, J.M. 2008b. Nutrient and TSS removal comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. (*under review*).

Day, G.E., Smith, D.R., and Bowers J. 1981. Runoff and pollution abatement characteristics of concrete grid pavements. Bulletin 135, Virginia Polytechnic Institute and State University.

Dierkes, C., Kuhlmann, L., Kandasamy, J., and Angelis, G. 2002. Pollution retention capability and maintenance of permeable pavements. Proc. 9th Int. Conf. on Urban Drainage, Global Solutions for Urban Drainage. ASCE, Portland, Oregon, USA.

Dreelin E.A., Fowler, L. Carroll, R.C. 2006. A test of porous pavement effectiveness on clay soils during natural storm events. *Water Research.* 40: 799-805.

Fach, S., and Geiger, W. 2005. Effective pollutant retention capacity of permeable pavements for infiltrated road runoffs determined by laboratory tests. *Water Science and Technology*. 51(2): 37-45.

Gilbert, J.K. and Clausen, J.C. 2006. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. *Water Research*. 40: 826-832

Hunt, B., Stevens, S., and Mayes, D. 2002. Permeable pavement use and research at two sites in Eastern North Carolina. Proc. *9th* Int. Conf. on Urban Drainage, G*lobal Solutions for Urban Drainage*. ASCE, Portland, Oregon, USA.

James, W. and Gerrits, C. 2003. Ch 21: Maintenance of Infiltration in Modular Interlocking Concrete Pavers with External Drainage Cells. In *Practical Modeling of Urban Water Systems, Mono, 11*. 417-435 W. James, ed. Guelph, Canada: CHI.

James, W. and Shahin, R. 1998 Ch 17: Pollutants Leached from Pavements by Acid Rain. In *Advances in Modeling the Management of Stormwater Impacts, Vol. 6.* 321-349. W. James, ed. Guelph, Canada: CHI.

Jefferies, C. 2004. SUDS in Scotland – the monitoring programme. Final Report SR (02)51. March 2004.

Karasawa, A., Toriiminami, K., Ezumi, N., and Kamaya, K. (2006). Evaluation of performance of water-retentive concrete block pavements. Proc. 8th Int. Conf. on Concrete Block Paving, *Sustainable Paving for Our Future.* ICPI, San Francisco, CA, USA.

Kresin, C., James, W. and Elrick, D.E. 1996. Observations of infiltration through clogged porous concrete block pavers. In *Advances in Modeling the Management of Stormwater Impacst*, *Vol 5*. 191-205. W. James, ed. Guelph, Canada: CHI.

Legret, M. and Colandini, V. 1999. Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of metals. *Water Science and Technology*. 39(2): 111-117.

Pagotto, C, Legret, M. and Le Cloirec, P. 2000. Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Water Research*. 34(18): 4446-4454.

Pratt, C. J.; Mantle, J.D.G.; and Schofield, P.A. 1989. Urban stormwater reduction and quality improvement through the use of permeable pavements. *Water Science and Technology*. 21(8): 769-778.

Rushton, B.T. 2002. Low-impact parking lot design reduces runoff and pollutant loads. *Journal of Water Resources Planning and Management.* 127 (3): 172-179.

Traver, 2006. Project Overview – Villanova Stormwater Partnership. Philadelphia, PA.

UNH. 2007. University of New Hampshire Stormwater Center. 2007 Annual Report. Durham, NH.

Valavala, S., Montes, F., and Haselbach, L.M. 2006. Area-Rated Rational Coefficients for Portland Cement Pervious Concrete Pavement. *Journal of Hydrologic Engineering*., 11(3): 257-260.

Van Seters, T., D. Smith and G. MacMillan. 2006. Performance Evaluation of Permeable Pavement and a Bioretention Swale. 8th International Conference on Concrete Block Paving. San Francisco, CA. November, 2006.

(NPRPD) CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD.

(Practice) Schueler, T.R. and Holland, H.K. 2000 *The Practice of Watershed Protection*. Center for Watershed Protection: Ellicott City, MD.

(Manual 3) Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD.

DRAINAGE SWALE LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques	TSS: 50% Nutrient reductions were not observed.	RR: approaches 50% in a semi-arid climate with permeable soils or low initial moisture content.	Removal of mowed grass clippings may result in nutrient reductions. Vegetation coverage is important for pollutant removal. Little relationship between pollutant removal and vegetation height or type exists.
CALTRANS, 2004	Six swales were sited, constructed and monitored for this study. Each of the swales treated runoff from highways and had CDA I=0.9-0.95.	TSS: 49% TN: 30% TP: negative Total Cu: 63% Total Pb: 68% Total Zn: 77% Higher load reductions were observed due to high RR though infiltration.	RR: avg 50% (range 33-80%)	Proposed sites should receive sufficient sunlight to support vegetation growth. Check that the specified vegetation provides a dense enough surface in the climate to stabilize the swale bottom provide effective pollutant removal.
Liptan, and Murase, 2000	This study compared the pollutant removal performance between a grass turf and native grass swale. Each swale was identical in geometric shape and soil type. The turf swale was mowed regularly and the native grass swale was allowed to grow naturally. Identical flow volumes were pumped into both from a 50-acre urban area. A total of six events over	MASS BASED: Turf Native Grass TSS: 69% 81% TP: 38% 50% Nitrate–N 8% 16% TKN: 40% 54% O-Phosphate-Phosphorus, diss -45% -75% Cu: 53% 65% Pb: 62% 72% Zn: 63% 76% Cu diss: 38% 52% Pb diss:	Native grass swale runoff attenuation: 41% Grass turf swale runoff attenuation: 27%	There is larger runoff attenuation in native grass swale compared to grass turf swale, presumably from a better infiltration rate from more organic material and robust root systems. Native grass performed better overall except for phosphorus, authors attributed this to accumulation of organic matter in the swale. Pollutant removal efficiency better in warm seasons.

	two years were sampled.	36% 53% Zn diss: 48% 64%		
Schueler and Brown, 2004 Appendix B, Manual 3				Swale should exceed WQv by more than 25%-50% Use dry or wet swale designs Longitudinal swale slope should be between 0.5 to 2.0% Velocity within swale <1 fps during WQv storm Soil infiltration rates should exceed 1.0 in/hr Provide multiple cells with pretreatment Provide off-line design w/ storm bypass
Schueler and Holland, 2000 (Practice) Article 113 Harper, 1988	This study compares surface and groundwater quality as runoff from an interstate highway flows through a vegetated wet and dry swale. Both had the same length (200 feet) but the wet swale had groundwater at the surface, wetland plants and zero infiltration. The dry swale had groundwater two feet below surface, sparse grass cover and high infiltration rate.	Wet Swale TSS: 81% BOD (5 day): 48% TN: 40% TP: 17% Nitrate-N: 52% Organic Nitrogen: 39% NH4: -11% Ortho-phosphorus: -30% Cd: 42% Cu: 56% Cr: 37% Pb: 50% Nickel: 32% Zn: 69% Dry Swale	Dry Swale: 80% of runoff infiltrated before it reached outlet	The dry swale performed better based on the gentle slope and the fact that most of the runoff was infiltrated. The major pollutant removal process appeared to be infiltration and sedimentation. The wet swale outperformed the dry swale in runoff that reached the outlet. The major pollutant removal process appeared to be settling and vegetative filtering. Long swales are effective in treating urban stormwater and groundwater plays an important role when designing them in sandy, low-relief environment.

	Dry swale runoff that did reach the outlet had a higher pollutant load than the wet swale. Trace metals were trapped in surface soils. Dissolved metals were not removed as well as particulate – the sandy soils may not have provided enough binding sites to capture soluble metals. Soluble nutrients migrated into groundwater, especially from dry swale but overall had a modest impact on groundwater quality.	TSS: 87% BOD (5 day): 69% TN: 84% TP: 83% Nitrate-N: 80% Organic Nitrogen: 86% NH4: 78% Ortho-phosphorus: 70% Cd: 89% Cu: 89% Cr: 88% Pb: 90% Nickel: 88% Zn: 90%		
Schueler and Holland, 2000 (Practice) Article 114 Dorman et al, 1989	Pollutant removal performance of highway swales in Florida, Maryland and Virginia. Three swales of similar length (approx. 200 feet) but different slope, cover and soils. Florida - flat with sandy soils and high grass – had the best pollutant removal. Maryland - slope was moderate (3.2%) with short grass, experienced erosion, was a sediment exporter and had low pollutant removal rates.	MASS REMOVAL: Florida (#storms sampled: 8) Sediment: 98% Organic Carbon: 64% TKN: 48% Nitrate: 45% TP: 18% Cd: 29%– 45% Cr: 51%– 61% Cu: 62%– 67% Pb: 67%– 94% Zn: 81% Maryland (#storms sampled: 4) Sediment: -85%	During small storms, no measurable flow detected in VA swale (infiltration of runoff)	Important factors for pollutant removal are higher and better grass cover, flat slope and soils with high infiltration rates. Since slope, soil type and cover can't always be controlled, designs should incorporate features such as sand layers, check dams, underdrains and diversions to off-line swales or pocket wetlands.

	Virginia had steepest slope (4.7%), better grass cover, minor erosion and moderate removal rates.	Organic Carbon: 23% TKN: 9% Nitrate: -143% TP: 12% Cd: 85%-91% Cr: 22%-72% Cu: 14% Pb: 18%-92% Zn: 47% Virginia (#storms sampled: 9) Sediment: 65% Organic Carbon: 76% TKN: 17% Nitrate: 11% TP: 41% Cd: 12%-98% Cr:12%-16% Cu: 28% Pb: 41%-55% Zn: 49% Pollutant removal rates as % long term mass reduction.		
Strecker et al, 2004	Review of 32 grassed swales and vegetated filter strip studies found in the International Stormwater BMP database	Mass Removal: TSS: 45-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	40% Runoff Reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.
Yu et al, 2001	Field tests were conducted in Taiwan and Virginia on the pollutant	MASS REMOVAL: 14 to 99% for TSS, COD, TN, and TP.		Grassed swales can be an effective storm-water BMP, particularly for areas subject to low intensity storms.

	removal rates of grassed swales. Virginia experiments tested a highway median swale (274.5 m length, 3% slope), while the Taiwan experiments tested an agricultural swale. (30m length, 1% slope)			Swales should be at least 75 m in long with a minimum longitudinal slope of 3%. Check dams can improve swale performance.

References

Barrett, M.E. 2005. BMP performance comparisons: examples from the International Stormwater BMP Database. ASCE EWRI.

CALTRANS, 2004. California Department of Transportation, Division of Environmental Analysis. BMP retrofit pilot program. Final Report CTSW-RT-01-050. January, 2004.

Liptan, Thomas and Robert K. Murase, "Watergardens as Stormwater Infrastructure in Portland, Oregon." Working Paper, Harvard Design School, Boston, MA, 2000.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD

Schueler, T.R. and Holland, H.K. 2000. The Practice of Watershed Protection. Center for Watershed Protection: Ellicott City, MD

Strecker, E., Quigley, M., Urbonas, B., and Jones, J. 2004. Stormwater management: State-of-the-art in comprehensive approaches to stormwater. *The Water Report.* Issue #6. Envirotech Publishers Inc., Eugene, OR.

Yu, S.L., Kuo, J.T., Fassman, E.A., and Pan, H. 2001. Field test of grassed-swale performance in removing runoff pollution. *Journal of Water Resources Planning and Management.* 127 (3): 168-171

BIORETENTION LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reductions**	**Implications for Design**
CWP, 2007 NPRPD v.3	Summary of performance for 10 bioretention practices	Removal Efficiency: Q1-Q3 (median) TSS: 15-74% (59) TP: -76-30 (5) SolP: -9-49% (-9) TN: 40-55% (46) NOx: 16-67% (43) Cu: 37-97% (81) Zn: 37-95% (79) Bacteria: N/A		Bioretention practices had relatively high TN, heavy metal removal rates
Davis et al., 2001	A detailed study on the removal of heavy metals (copper, lead, and zinc) and nutrients (phosphorus, total kjeldahl nitrogen, ammonium, and nitrate) from synthetic stormwater runoff. Batch, column and pilot-scale experiments found that bioretention areas provide significant reduction of heavy metals, moderate reduction of TP, TKN and NH_3 and poor reduction of NO_3 (in many cases, nitrate production was noted).	Cu: 92% ± 3% Pb: > 98% Zn: > 98% TP: 81% ± 4% TKN: 68% ± 27% NH_3-N: 79% ± 11% NO_3-N: 24% ± 102% Higher mass removal was provided due to water retention within the bioretention areas.		The depth of bioretention areas was found to play a key role in providing phosphorus removal; soil adsorption was cited as the primary phosphorus removal mechanism. Soil adsorption, through ion exchange, was cited as mechanisms that provided NH_3 removal. Organic matter (e.g. peat) is thought to increase removal of ammonia. Confirms that the transformation of organic nitrogen (through mineralization and nitrification) and ammonia (through nitrification) occurs in bioretention areas, especially near the surface. Some denitrification (nitrogen removal) was found to occur toward the bottom of the bioretention areas. The mulch layer was found to play a key role in metal removal; significant accumulation of heavy metals was found

				within the mulch layer, while no heavy metal accumulation was observed within the soil.
Davis et al., 2003	An investigation using pilot-scale bioretention systems and two existing bioretention areas (one in Greenbelt, MD and one in Largo, MD). The study documents the effectiveness of bioretention areas in removing low levels of lead, copper and zinc from synthetic stormwater runoff. The laboratory results of Davis et al. (2001) are presented.	Laboratory Cu: 92% ± 3% Pb: > 98% Zn: > 98% Field Greenbelt, MD: Cu: 97% ± 2% Pb: > 95% Zn: > 95% Largo, MD: Cu: 43% ± 11% Pb: 70% ± 23% Zn: 64% ± 42% Higher mass removal was provided due to water retention within the bioretention areas.	Laboratory Avg. RR: 63% (range 19-99%) Attributed to ET loss	As with the laboratory results presented in Davis et al. (2001) the mulch layer of field bioretention areas was found to play a key role in metal removal; significant accumulation of heavy metals was found at the top of the bioretention areas, especially within the mulch layers. Increased flow rates were not found to significantly affect the amount of heavy metal removal provided by the bioretention areas, unless mass removal is considered (due to overflow). The differences between the Greenbelt, MD and Largo, MD bioretention areas were explained by the differences in the filter bed media. The facility at Largo, MD was built with a filter bed consisting mainly of sand, while the facility at Greenbelt, MD was built with a higher percentage of topsoil and fines.
Davis et al., 2006	This work provides an in-depth analysis of the ability of bioretention areas to remove nutrients from synthetic stormwater runoff. The study involves pilot-scale bioretention systems and two existing bioretention areas (one in Greenbelt, MD and one in Largo, MD). The laboratory results of	Laboratory TP: 81% ± 4% TKN: 68% ± 27% NO_3-N: 24% ± 102% TN: 60% ± 31% Field Greenbelt, MD: TP: 65% ± 8% TKN: 52% ± 7%		Increased flow rates were not found to significantly affect the amount of nutrient removal provided by the bioretention areas, unless mass removal is considered (due to overflow). The authors expected to find better nutrient removal at the Greenbelt, MD facility because the filter bed had a higher percentage of topsoil and fines, but this

	Davis et al. (2001) are presented.	NO_3-N: 16% ± 6% TN: 49% ± 6% Largo, MD: TP: 87% ± 2% TKN: 67% ± 9% NO_3-N: 15% ± 12% TN: 59% ± 6% Higher mass removal was provided due to water retention within the bioretention areas.		was not found. The engineered media at the Largo, MD facility provided better nutrient removal. The depth of bioretention areas was not found to play as significant a role in the removal of TKN, with much of the removal occurring at the top of the bioretention areas within the mulch layer. TN removal was dominated by TKN removal, and little NO_3 removal was provided by the bioretention areas, except at the bottom, where the conditions necessary for dentrification may exist.
Davis, 2008	In College Park, MD, 2 bioretention areas, each $28m^2$ in size, were built to treat runoff from a 0.24 ha section of parking lot. One cell (B) was 0.9m deep with conventional drainage, and the other cell (A) was 1.2m deep and contained an anoxic zone to encourage denitrification. Both cells were lined and fitted **underdrains** for monitoring purposes. Hydrologic analyses found that both cells reduced runoff volumes and peak flow rates. Delays in peak flow were also observed.		(49 rainfall events) Cell A: RR: median 77%, mean 52% Peak flow reduction: 63% Cell B; median 82%, mean 65% Peak flow reduction: 44%	
Dietz and Clausen, 2005	A study on the pollutant removal capacity of two rain gardens constructed in Haddam, CT designed to capture the first inch of runoff from shingled rooftops.	Mass Based Removal: TP: -111% NH_3-N: 85% NO_3-N: 36% TKN: 31%		The mechanisms responsible for NH_3 were nitrification and soil adsorption.

	The rain gardens were found to be effective in providing peak flow rate reduction and in removing NH_3, NO_3, TKN and TN from rooftop runoff.	TN: 32%		
Dietz and Clausen, 2006 (in NPRPD)	A study on the pollutant removal capacity of two rain gardens (**with underdrains**) constructed in Haddam, CT designed to capture the first inch of runoff from shingled rooftops. The rain gardens were effective in reducing the concentrations of NH_3, NO_3, and TN in the rooftop runoff. However, TP concentrations were significantly increased by both of the rain gardens.	Mass Based Removal: TP: -108% NH_3-N: 82% NO_3-N: 67% TKN: 26% TN: 51%	Runoff Reduction: 99.2% Total Volume Reduction: 3.7% (assumed to be ET) 12 month P= 172.8cm	Mulch was found to play a significant role in the removal of TN and TP, as the concentrations of these pollutants increased over time. The rain garden soils were found to be a source of TN and TP, as the concentrations of these pollutants decreased over time. No significant changes in NO_3-N concentrations occurred as a result of raising the underdrain to create a saturated zone at the bottom of one of the rain gardens in an attempt to increase denitrification. The mulch layer was also found to play a key role in metal removal, as the concentrations of these pollutants increased over time.
Dougherty et al, 2007	A rain garden in Auburn, AL, was monitored for nutrient removal data. The garden was 1.2m deep and was filled with native soils mixed with shredded pine bark mulch to improve cell infiltration and the organic content. The cell was lined and	TP and SolP reductions from the bioretention cell were observed under both drainage configurations. TN removal. NH4 was reduced significantly towards the end of the		Peak outflow rates gradually decreased over the entire study period, a probable result of media settlement and consolidation after construction.

	fitted with an **underdrain**. Conventional drainage occurred for the first 2 months (8 runoff events) of monitoring, and then modifications were made to create an IWS zone in the cell (monitoring for 9 subsequent runoff events).	study for the configuration with an IWS zone.		
Ermilio, 2005 (in NPRPD)	A thesis completed at Villanova University and based on the bioretention traffic island built at Villanova University's BMP demonstration park. Water quality results show a significant reduction in many common stormwater pollutants as a result of capturing and treating the first flush runoff of rainfall events.	TSS: 92% TDS: 38% Cu: 47% Pb: 55% Cr: 62% Zn: 17% TN: 48% TP: 1% Higher mass removal was provided due to water retention within the bioretention areas.	Runoff Reduction: 86% 30 rain events 0.23<P<7.1in Mean=1.55 in	Although the bioretention area is designed to infiltrate stormwater runoff, it does not appear the quality of groundwater beneath the basin is being significantly affected. TN and TP are retained during periods of increased plant activity in the summer and fall months and are released during periods of low plant activity in the winter and spring months.
Glass and Bissouma, 2005 (in NPRPD)	In this study, the ability of a bioretention area (**with underdrain**) to remove nutrients and heavy metals was evaluated over a period of 15 rain events. The results indicate that bioretention facilities can be moderately to very effective in removing heavy metals and nutrients from stormwater runoff.	Zn: 79% Cu: 81% Pb: 75% Cd: 66% Fe: 53% Cr: 53% Al: 17% As: 11% Higher mass removal was provided due to water retention within the bioretention areas.		Organic matter and plants were believed to be the dominant mechanisms that provided the removal of heavy metals within the bioretention area. Lack of regular maintenance on the mulch layer of the bioretention area was cited as a reason for lower heavy metal removals than those found by Davis.

		Mass Based Removal: TSS: 98% Zn: 80% Cu: 75% Pb: 71% Cd: 70% Fe: 51% Cr: 42% Al: 17% NH_3-N: 65% NO_3-N: 27% PO_4-P: 3%		
Hsieh and Davis, 2005a	In this study, a bioretention test column was set up and subjected to regular testing once a week for 12 weeks to investigate the ability of bioretention areas to treat frequent storm events. All 12 tests demonstrated that improvements in stormwater quality and excellent removal efficiencies for TSS, oil/grease, and lead were found.	Mass Based Removal: TSS: 91% Pb: > 98% TP: 63% NH_3-N: 13% NO_3-N: -16% Oil/Grease: > 97%		Most of the TSS in the stormwater runoff was removed by the top (mulch) layer of the bioretention test column. This helped prevent clogging within the rest of the test column. Organic matter and Ca content of the filter bed was found to increase during testing. This may have increased the ability of the bioretention test column to remove phosphorus through precipitation and adsorption (ion exchange).
Hsieh and Davis, 2005b	The objective of this study was to provide insight on the filter media characteristics that define the pollutant removal performance of bioretention areas. Eighteen bioretention test columns and six existing bioretention facilities were evaluated using synthetic stormwater runoff. In the laboratory studies, two types of sand and three types of soil with	Mass Based Removal: Field TSS: 72% - 99% Pb: 80% - 98% TP: 37% - 99%		Removal of metals, TSS, and oil/grease were not affected by the chemical properties of the filter bed media. This is not surprising given that these pollutants are removed through filtration, which is a physical, not chemical or biological, process. Permeable sands were found to provide the best overall removal of these pollutants, although all fill media performed well. Although TP removal was expected to

	various physical and chemical properties were used. The field experiments were conducted in Maryland (one in Greenbelt, MD, two in Hyattsville, MD, and three in Landover, MD).			correlate with the chemical properties of the filter bed media (e.g. P content, organic matter, and CEC), based on the laboratory results these characteristics were not found to have a significant statistical correlation with TP removal. In the field, however, a good correlation between TP removal and filter bed depth and organic matter content were found. Filter bed media with higher levels of fines and organic matter were found to provide greater removal of TN. A filter bed media with a coarse sand/sandy soil mixture appears to provide the best overall pollutant removal performance within bioretention areas.
Hunt and White, 2001	This profile sheets contains a good description of the pollutant removal mechanisms at work within bioretention areas and offers guidance on the sizing and design of bioretention areas, with variations for clayey and sandy soils. Contains no performance data, but does provide cost data.			Bioretention areas installed in clayey soils need to be provided with an underdrain and provided with engineered filter bed media. Bioretention areas installed in sandy soils do not need an underdrain do not require the use of an underdrain, provided that the infiltration rate of the native soils is greater than 1.0 in/hr.
Hunt, 2003	Provides a summary of bioretention research conducted at the University of Maryland, Pennsylvania State University and in North Carolina. Summarizes pollutant removal			If a bioretention area is being designed for metals removal, a deep filter bed may not be needed because of the significance of the mulch layer to remove heavy metals. Anaerobic zones appear to develop within

	data presented by Davis et al. (2001) and Davis et al. (2003).			bioretention areas regardless of the drainage configuration of the design cell (although they may be dependent upon the filter bed media) and there does not appear to be a need for the use of engineered saturated zones to increase NO_3 removal.
Hunt et al., 2006 (in NPRPD)	The pollutant removal and runoff reduction abilities of three bioretention areas in North Carolina (Two in Greensboro, NC and one in Chapel Hill, NC) were examined. Sufficient flow data and water quality samples were only collected for two of the bioretention areas (one in Greensboro and one in Chapel Hill). Both bioretention areas were designed with conventional **underdrains**. The field studies found high heavy metals and total nitrogen removal rates in the two conventional bioretention area (e.g. without engineered saturated zones). High TP removal for the cell with a low P-index was observed.	Mass Based Removal Greensboro (G2): P-Index 86-100 (high) TSS: -170% Zn: 98% Cu: 99% Pb: 81% TN: 40% NH_3-N: -1% NO_3-N: 75% TKN: -5% TP: -240% PO_4-P: -9% Mass Based Removal Chapel Hill: P-index 4-12 (low) TN: 40% NH_3-N: 86% NO_3-N: 13% TKN: 45% TP: 65% PO_4-P: 69%	RR: 52-56% (personal communication)	Small saturated, anaerobic zones were found within the Greensboro cell, perhaps created by the presence of clay soils within the fill media. These isolated zones were though to provide the conditions necessary for dentrification, which would explain the high level of NO_3 removal. Similar conditions were not found in the Chapel Hill bioretention cell. The P-index of the fill media used in the Greensboro cell was very high (86 to 100), indicating that the media was saturated with phosphorus. Comparatively, the P-index of the fill media used in the Chapel Hill cell was low (4 to 12), indicating that the media could accept more phosphorus. A lower P-index, along with high amount of cation exchange sites (provided by organic matter), enhances the removal of phosphrous through adsorption. The impact of drainage configuration on TN removal was not statistically significant (e.g. Cell G1 was designed with a saturated zone), which suggests that engineered saturated zones are not needed to increase NO_3 removal. Fill soil content may play a more important role in

				providing the conditions necessary for denitrification.
Hunt et al, 2008	Bioretention cell with underdrain	TN: 38% TP: 32%		
Hunt and Lord, 2006	This profile sheet presents information on the performance of bioretention cells installed in Greensboro, NC, Chapel Hill, NC, Louisburg, NC, and Charlotte, NC. The bioretention cells were found to provide moderate to high removal of nutrients and other stormwater pollutants. Summarizes the pollutant removal data presented by Hunt et al. (2006) and includes some additional data. Pollutant specific design guidance, guidelines for selecting fill soil and vegetation, and information about maintenance are also provided within the profile sheet.	Mass Based Removal Greensboro (G1) (**underdrain**): TN: 33% - 40% TP: -39% - (-240%) Soil P-Index: 86 - 100 Cu: 65% - 99% Zn: 65% - 99% Mass Based Removal Greensboro (G2) (IWS): TN: 43% TP: 9% Soil P-Index: 35 - 50 Cu: 56% - 86% Zn: 56% - 86% Mass Based Removal: Chapel Hill (**underdrain**): TN: 40% TP: 65% Soil P-Index: 4 - 12 Mass Based Removal: Louisburg (L1) (**underdrain**): TN: 64% TP: 66% Soil P-Index: 1 - 2 Mass Based Removal:	Runoff Reduction: 33% - 50% Attributed to exfiltration and ET.	Phosphorus removal can be enhanced with proper fill soil selection. As the pollutant removal rates show, using low P-Index soils increases TP removal, while high P-Index soils decrease performance. The recommended P-Index for fill soils is between 10 - 30. Fill soils with a relatively high cation exchange capacity (CEC) are recommended to increase TP removal. While a minimum CEC is not provided, soils with CECs exceeding 10 are expected to provide better pollutant removal. Deeper bioretention cells (36 inches or more) and fill soils with lower infiltration rates are recommended to enhance TN removal and reduce runoff temperature. The addition of fines to the fill soil will help reduce infiltration rates and may promote the formation of small anaerobic zones within the fill soil to remove NO_3. Bioretention cell surfaces should be planted with less vegetation to allow promote bacteria removal through exposure to sunlight. Cleaner stormwater runoff appears to decrease pollutant removal efficiency. Of

		Louisburg (L2) (**underdrain**): TN: 68% TP: 22% Soil P-Index: 1 - 2 Mass Based Removal Charlotte (**underdrain**): TN: 65% TP: 68% Bacteria: >90% Soil P-Index: 7 – 14		the cells that had low P-Index soils, bioretention cell L2, which treated stormwater runoff with the lowest TP concentrations, provided the lowest TP removal. Addition of an IWS zone may reduce effluent temperature and reduce TN concentrations. Tests for TN reduction in these systems did not produce statistically significant results.
Kim et al., 2003	This study systematically evaluated a reengineered concept of a bioretention area designed to promote nitrogen removal via microbial denitrification. An engineered saturated zone was built into bioretention test columns. Inorganic and organic substrates, as electron donors, were mixed with sand and used to fill continuously submerged **anaerobic zones** at the bottom of the bioretention columns. Overdrains were provided to ensure that the anaerobic zones remained saturated. The test columns demonstrated good removal of NO_3.	Mass Based Removal: NO_3-N: 70% - 80%		A saturated, anaerobic zone provided at the bottom of the bioretention cell may help improve nitrogen removal. An electron donor (organic or inorganic substrate) is needed to drive the denitrification process. Denitrifying bacteria (*nitrosomonas* and *nitrobacter*) require both an electron donor substrate and a carbon source as they synthesize by converting NH_3 to N_2. This study found newspaper to be the most effective electron donor, but wood chips and small sulfur particles were also identified as potentially viable substrates.
McCuen and Okunola, 2002	This research extends the widely used Natural Resources Conservation Service TR-55 design procedures for use on microwatersheds. Specifically,		Runoff Reduction: **underdrains**: 19% Infiltration:	Based on the methods presented within this study, bioretention areas able to fully contain all of the runoff from a given design storm (e.g. infiltration-based bioretention) provide a runoff reduction of

	the graphical peak discharge estimation method is extended so that it can be used for catchments with times of concentration as small as 0.02 h. The kinematic-wave time of concentration estimation method is made applicable for multiple-section sheet flow, and a new pond-and-swamp adjustment procedure enables the design and evaluation of small on-site bioretention areas. Estimates of the hydrologic benefits of bioretention areas are provided.		38%	about 38%, while those only able to partially contain the runoff (e.g. underdrained bioretention) provide a runoff reduction of about 19%.
Passeport et al, 2008	Evaluated 2 grassed bioretention areas in NC (depths = 0.75 and 1.05m), both having an expanded slate fill media and internal storage zones. The system efficiently reduced nutrients loads and EMCs. Removal was highest during warmer months.	TKN: 49, 59 NH4: 70, 84 NO3: 33, - TN: 54, 54 TP: 63, 58 OPO4: 78, 74 FC: 95, 85	RR: 20-50%	The deeper media depth did not increase nutrient EMC removal. The grass vegetated bioretention cells performed favorably to conventionally vegetated (trees, shrubs and mulch) bioretention cells studied in North Carolina.
Perez-Pedini et al., 2005	A distributed hydrologic model of an urban watershed was developed and combined with an algorithm to determine the optimal location of infiltration-based BMPs. Model results show that optimal location of infiltration-based BMPs can provide a significant reduction of runoff.		Runoff Reduction: 30%	

Schueler and Brown, 2004 Manual 3 (Appendix B)				Pollutant removal can be increased by designing the filter to treat a larger WQv . Filter media should be tested and have a P Index less than 30. If possible, bioretention areas should be placed in permeable soils, eliminating the need for an underdrain. If underdrain is necessary, putting an upflow pipe can help remove more pollutants. The filter bed should be deeper than 30 inches for additional pollutant removal. A two cell design with pretreatment is recommended. Bioretention cell SA should be more than 5% of CDA.
Sharkey, 2006	Evaluated 2 field sites in NC and performed a laboratory simulation to evaluate nutrient removal and hydrologic response of bioretention cells. The laboratory results showed that a 91% sandy soil was unable to reduce phosphorus concentrations at all P-Index levels.	TN: 62% TP: 66%	RR: 20-29%	The P-Index for bioretention fill soil should be no greater than 40 and contain between 75% and 85% sand.
Smith and Hunt, 2006 (in NPRPD)	This study evaluated the performance of two bioretention cells, vegetated with bermuda grass and containing IWS zones, in removing nitrogen, phosphorus, metals and sediment. The two cells that were tested	Calculated Removal: Graham (N): TSS: 63% Cu: 9% Zn: 37% TN: 61% TKN: 65%	Graham (N): Runoff Reduction: 40% Graham (S): Runoff	Higher pollutant removal efficiency was associated with the cell that had deeper filter media and well-drained (S) underlying soils.

	(both located in Graham, NC) had filter beds with different depths. Sufficient flow data and water quality samples were only collected for one of the bioretention cells (N). The other cell (S) did not produce any measurable outflow on many occasions.	NH_3-N: 79% NO_3-N: 43% TP: 8% PO_4-P: -127% Bacteria: 97% Higher mass removal was provided due to water retention within the bioretention areas. Mass Based Removal: TN: 70-80% TP: 35-50% FC: 97%	Reduction: 60% 12 events 0.19<P<1.88in	
UNHSC, 2005	The performance of a bioretention cell in Durham, NH was evaluated.	Mass Based Removal: TSS: 97% Zn: 99% NO_3-N: 44% TPH-D: 99%	Peak Flow Red'n: 85%	Design of the bioretention cell was based upon the guidance provided in the New York State Stormwater Management Design Manual.
Van Seters et al., 2006	The performance of a bioretention area (located in King City, ON) was evaluated. The bioretention area showed that it was effective in reducing peak flows and in improving water quality from parking lot runoff. Three equal-sized parking lot sections were monitored. The first consisted of porous pavement, the second was conventional asphalt (control section), while the third was conventional asphalt but was treated by a bioretention area.		Runoff Reduction: 40%	

	The porous pavement and bioretention sections were effective at infiltrating stormwater runoff and reducing peak flow.			
Yu and Stopinski, 2001 (in NPRPD)	This study monitored the field performance of four ultra-urban stormwater BMPs: three oil and grit separators (Isoilater, Stormceptor™, and Vortechs Stormwater Treatment System™) and a bioretention area located in Charlottesville, VA. Storm sampling data for each site were analyzed to calculate the removal efficiency for each constituent monitored.	TSS: 53% TP: 13% Oil/Grease: 66%		TSS removal in the bioretention area was found to be affected by rainfall depth. Small-to-medium storms yielded positive removal efficiencies, while large storms yielded negative removal efficiencies.

References

CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD

Davis, A.P., M. Shokouhian, H. Sharma and C. Minami. 2001. Laboratory Study of Biological Retention for Urban Stormwater Management. *Water Environment Research.* 73(5): 5-14.

Davis, A.P., M. Shokouhian, H. Sharma, C. Minami and D. Winogradoff. 2003. Water Quality Improvement Through Bioretention: Lead, Copper, and Zinc Removal. *Water Environment Research.* 75(1): 73-82.

Davis, A.P., M. Shokouhian, H. Sharma and C. Minami. 2006. Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal. *Water Environment Research.* 78(3): 284-293.

Davis, A.P. 2008. Field performance of Bioretention: Hydrology Impacts. *Journal of Hydrologic Engineering.* 13 (2): 90-95.

Dietz, M.E. and J.C. Clausen. 2005. A Field Evaluation of Rain Garden Flow and Pollutant Treatment. *Water, Air & Soil Pollution*. 167: 123-138.

Dietz, M.E. and J.C. Clausen. 2006. Saturation to Improve Pollutant Retention in a Rain Garden. *Environmental Science &Technology*. 40(4): 1335-1340.

Dougherty, M., LeBleu. C., Brantley, E., Francis, C. 2007. Evaluation of bioretention nutrient removal in a a rain garden with an internal water storage (IWS) layer. *ASABE Annual International Meeting*. Minneapolis, MN. 17-20 June 2007.

Ermilio, J.R. 2005. Characterization Study of a Bio-Infiltration Stormwater BMP. M.S. Thesis. Villanova University. Department of Civil and Environmental Engineering. Philadelphia, PA.

Glass, C. and S. Bissouma. No Date. Evaluation of a Parking Lot Bioretention Cell for Removal of Stormwater Pollutants. Howard University. Department of Civil Engineering. Washington, DC.

Hunt, W.F. III. 2003. Bioretention Use and Research in North Carolina and other Mid-Atlantic States. *North Carolina State University Water Quality Group Newsletter*. NWQEP Notes. 109. North Carolina State University. Raleigh, NC.

Hunt, W.F. III, A.R. Jarrett, J.T. Smith, and L.J. Sharkey. 2006. Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *ASCE Journal of Irrigation and Drainage Engineering.* 132(6): 600-608.

Hunt, W.F., J.T. Smith, S.J. Jadlocki, J.M. Hathaway, P.R. Eubanks. 2008. Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, NC. *ASCE Journal of Environmental Engineering* (in press)

Hunt, W.F. III and W.G. Lord. 2006. Bioretention Performance, Design, Construction, and Maintenance. *North Carolina Cooperative Extension Service Bulletin.* Urban Waterways Series. AG-588-5. North Carolina State University. Raleigh, NC.

Hsieh, C.-H. and A.P. Davis. 2005. Multiple-Event Study of Bioretention for Treatment of Urban Storm Water Runoff. *Water Science and Technology*. 51(3-4): 177-181.

Hsieh, C.-H. and A.P. Davis. 2005. Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff. *ASCE Journal of Environmental Engineering.* 131(11): 1521-1531.

Kim, H., E.A. Seagren and A.P. Davis. 2003. Engineered Bioretention for Removal of Nitrate From Stormwater Runoff. *Water Environment Research*. 75(4): 355-367.

McCuen, R.H. and O. Okunola. Extension of TR-55 for Microwatersheds. 2002. *Journal of Hydrologic Engineering*. 7(4): 319-325.

Passeport, E., Hunt, W.F., Line, D.E., and Smith, R.A. 2008. Effectiveness of two grassed bioretention cells at reducing stormwater pollution. *(under review).*

Perez-Pedini, C., J.F. Limbrunner and R.M. Vogel. 2005. Optimal Location of Infiltration-Based Best Management Practices for Stormwater Management. *ASCE Journal of Water Resources Planning and Management*. 131(6): 441-448.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD.

Sharkey, Lucas J. 2006. The Performance of Bioretention Areas in North Carolina: A Study of Water Quality, Water Quantity, and Soil Media. M.S thesis. North Carolina State University. Department of Biological and Agricultural Engineering. Raleigh, NC.

Smith, R.A. and W.F. Hunt. 2006. Pollutant Removal in Bioretention Cells with Grass Cover. North Carolina State University. Raleigh, NC.

University of New Hampshire Stormwater Center (UNHSC). 2005. 2005 Data Report. University of New Hampshire Stormwater Center. Durham, NH.

Traver, 2006. Project Overview – Villanova Stormwater Partnership. Philadelphia, PA.

Van Seters, T., D. Smith and G. MacMillan. 2006. Performance Evaluation of Permeable Pavement and a Bioretention Swale. 8th International Conference on Concrete Block Paving. San Francisco, CA. November, 2006.

Yu, S.L. and M.D. Stopinski. 2001. Testing of Ultra-Urban Stormwater Best Management Practices. VTRC 01-R7. Virginia Transportation Research Council. Charlottesville, VA.

WATER QUALITY SWALE LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Barrett et al, 1997	In Austin, TX, a swale was constructed with an underdrain. Influent runoff EMCs were compared to infiltrated runoff EMCs from the swale underdrain.	TSS: 74% BOD:46% COD: 35% NO3: 59% TP: 31% Oil and Grease: 88% Cu: 49% Fe: 79% Pb: 35% Zn: 74% Reductions in pollutant load were even higher due to a large volume of infiltrated runoff.	RR: 90%	
CWP, 2007 NPRPD v.3	Summary of the performance of 17 open channel practices, including 3 grass channels, 12 dry swales, and 2 wet swales.	Removal Efficiency: Q1-Q4 (median) TSS: 69-87% (81) TP: (-15-46% (34) SolP: -94-26% (-38) TN: 40-76% (56) NOx: 14-65% (39) Cu: 45-79% (65) Zn: 58-77% (71) Bacteria:-63 to -25% (-25)		Bacteria removal rates were negative, while removal rates for metals, and TSS tended high.
Horner et al, 2003				
Fletcher et al, 2002	In Brisbane, Austrailia, pollutant removal rates of a residential swale (65m long, 1.6% longitudinal slope, 1:13 side slopes,	TSS: 83 (73-94)% TP: 65 (58-72)% TN: 52 (44-57)%		TSS removal decreased with increasing flow rate, reflecting the importance of physical processes (sedimentation and filtration) in TSS removal.

	and catchment area of 1.03ha, triangular cross section, 67% vegetative cover). Synthetic rainwater was tested. High concentration reductions were observed for TSS, TP, and TN.			TN and TP removal were less dependent on flow, reflecting more importance of chemical processes (e.g. soil sorption). TSS removal also increased with increasing swale length. TP and TN concentrations decreased rapidly in the first quarter of the swale length
Jefferies, 2004	Monitoring summary of several SUDS practices in Scotland. Includes runoff reduction data on 2 swales compared to runoff from a car taramac. The runoff reduction values are for surface runoff only, and do not include flow through the underlying pipes		RR (compared to conventional surface): 85%	
Schueler and Brown, 2004 Appendix B, Manual 3				Should exceed target WQv by more than 50% Use dry or wet swale design Should exceed target WQv by more than 25% Longitudinal swale slope between 0.5 to 2.0% Velocity within swale < 1 fps during WQ storm Measured soil infiltration rates should exceed 1.0 in/hr Use multiple cells with pretreatment Use off-line design w/ storm bypass
Schueler and	The purpose of this study	200-foot		Authors suggest the following design criteria

Holland, 2000 (Practice) Article 112 Seattle Metro, 1992	was to determine the pollutant removal capability of a 200-foot long, trapezoidal biofilter and test the performance after its length was reduced to 100 feet. Six storm events were monitored for both lengths. The study took place in the Pacific Northwest.	TSS: 83% TPH: 75% Total Zinc: 63% Diss Zn: 30% Total Pb: 67% Total Aluminum: 63% Total Cu: 46% TP: 29% Nitrate-N: negative 100-foot TSS: 60% TPH: 49% Total Zn: 16% Diss Zn: negative Total Pb: 15% Total Aluminum: 16% Total Cu: 2% TP: 45% Nitrate-N: negative		based on both monitoring and field experience. One additional improvement would be to place more biofilters off-line to treat the water quality design storm. Key Biofilter design criteria: • geometry (gentle slopes, parabolic or trapezoidal shape, sideslopes no greater than 3:1) • longitudinal slope (2 to 4%, check dams should be installed if slopes exceed 4% and underdrains installed if slopes are less than 2%) • swale width (no more than 8 feet unless structural measures are used to ensure uniform spread of flow) • maximum residence time (hydraulic residence time for the 6 month 24 hour storm of about 9 or 10 minutes) • maximum runoff velocity (no more then 0.9 fps for 6 month, 24 hour storm, and no more than 1.5 fps for 2 year storm event) • mannings n value (use 0.20 for design) • mowing (routine mowing to keep grass in active growth phase and maintain dense cover) • grass height (should be at least two inches above design flow depth) • biofilter soils (sandy loam topsoil layer, with an organic matter content of 10 to 20%, and no more than 20% clay.) • water table (if seasonal groundwater table is within a foot of the bottom of the biofilter, then select wetland species.) • plant selection (grass species that produce a uniform cover of fine-hardy vegetation that

				can withstand the prevailing moisture condition. *Juncus* and *Scirpus* may be used if drainage is poor.) • landscaping (other plant material can be integrated into biofilter; but care should be taken to prevent shading or leaffall into swale. • Construction (use of manure mulching or high fertilizer hydroseeding to establish ground cover should be avoided during construction, as these can result in nutrient export.)
Schueler and Holland, 2000 (Practice) Article 116	Sixteen historical performance monitoring studies of grass swales were reanalyzed based on the open channel classification (drainage channel, grass channel, dry swale and wet swale).	(includes a summary of pollutant removal capabilities of 10 drainage channels and 6 water quality channels)		Open channels should be designed to increase the volume of runoff that is retained or infiltrated within the channel. Designs should be based on water quality volume not flow. Key design criteria for dry swale: • Design to retain full water quality volume over entire length • Pretreatment is required. For pipe inlets, 0.1 inch per contributing acre should be temporarily stored behind a checkdam. For lateral flows, gentle slopes or a pea gravel diaphragm can be used. • Modify soils to improve infiltration rate. Use 30-inch filter bed composed of 50% sand and 50% silt loam. • Filter beds are drained by perforated pipes to keep swale dry after storm events • Parabolic or trapezoidal shapes with gentle side slopes (3:1 or less), and bottom widths ranging from 2 – 8 feet.

				• Determine location of water table. If water table is within 2 feet of proposed swale bottom , a dry swale is not feasible.
Schueler and Holland, 2000 (Practice) Article 117 Goldberg, 1993	Two studies of biofilters in Seattle: one was a biofilter retrofit (Dayton Ave.) and one was designed as a conveyance channel but was constructed with dimensions similar to a wet biofilter (Uplands). Eight storm events were sampled for Dayton Ave. and 17 events for the Uplands.	Dayton Ave. TSS: 68% TP: 4.5% Soluble Reactive Phosphorus: 35% Bio-Active Phosphorus: 32% Nitrate-Nitrogen: 31% Total Pb: 62% Total Cu: 42% Diss Cu: 21% FC: -264 Oil/Grease: not detected Uplands TSS: 67% TP: 39% Soluble Reactive Phosphorus: -45% Bio-Active Phosphorus: -31% Nitrate-Nitrogen: 9% Total Pb: 6% Total Cu: -35% Total Pb: 6% Total Zn: -3%	Dayton Ave.: 30 – 80% of runoff infiltrated into soil	Pets and beavers were cited as source of bacteria in the Dayton Ave. biofilter. Poor design, construction and maintenance are cited as reasons for reduced pollutant removal Require performance bonds for biofilters to make sure they are correctly installed, vegetated and protected from construction sediment. Key design criteria: • Require pretreatment at upper end of bioflter • Limit longitudinal slopes to 1% or greater, unless it is intentionally designed as a wet biofilter. • Develop more specific design criteria for wet biofilters that govern ponding, wetland stabilization, check dams and other criteria. • Require stringent geo-technical testing prior to design and construction. • Train public works crews on the best techniques for maintaining the long-term performance of biofilters.
Stagge, 2006	Evaluated highway grass swales with a grass filter strip pretreatment area in Maryland.	EMC removal: TSS: 41-52% NO3: 56-66% Zn: 30-40% Pb: 3-11%	RR: 46-54% of total volume 22 rainfall events over 1.5 years	

		Cu: 6-28% Swales exported Chloride, and did not significantly effect nutrient concentrations		
Strecker et al, 2004	Review of 32 grassed swales and vegetated filter strip studies found in the International Stormwater BMP database	Mass Removal: TSS: 45-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	40% Runoff Reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

References

Barrett, M.E. 2005. BMP performance comparisons: examples from the International Stormwater BMP Database. ASCE EWRI.

Barrett, M.E., Smith, P., Malina, J.F. 1997. Performance of permanent runoff controls. ASCE Proceedings of the 24th Annual Water Resources Planning and Management Conference.

CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD

Fletcher, T.D., Peljo, L., Fielding, J., Wong, T.H.F., and Weber, T. 2002. The performance of vegetated swales for urban stormwater pollution control. *ACSE 9th International Conference on Urban Drainage*. Portland, Oregon, Sept 8-13, 2002.

Horner, R., H. Lim and S. Burges. 2003. Hydrologic monitoring of the Seattle ultra-urban stormwater management project. University of Washington. Department of Civil and Environmental Engineering. Water Resources Series. Technical Report 170.

Schueler, T.R. and Holland, H.K. 2000. The Practice of Watershed Protection. Center for Watershed Protection: Ellicott City, MD

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD

Stagge, J. 2006. Field evaluation of hydrologic and water quality benefits of grass swales for managing highway runoff. M.S. Thesis, University of Maryland, Department of Civil and Environmental Engineering. College Park, MD.

Strecker, E., Quigley, M., Urbonas, B., and Jones, J. 2004. Stormwater management: State-of-the-art in comprehensive approaches to stormwater. *The Water Report.* Issue #6. Envirotech Publishers Inc., Eugene, OR.

INFILTRATION LITERATURE SUMMARY

(include applications of pervious pavement that demonstrate complete infiltration of runoff (no underdrains))

Study	**Description**	**Pollutant Reductions (PR)** (conc. based unless noted)	**Runoff Reduction (RR)**	**Implications for Design**
Barraud *et al.*,1999	Examined subsoil pollution concentrations from a newly installed infiltration basin and a 30 year old basin in a similar catchment area.	MASS BASED: Newer application: Zn: 54-88% Pb: 98% Older Application: Zn: 31% Cd: 29.5%		Over time there is a slight spread of pollution downward through underlying soils Older basin had detectable pollutant concentrations up to depths of 1m.
Bright, T 2007	Two field dune infiltration systems were installed in Kure Beach, NC to capture ocean outfall runoff from up to 1.3 cm of rainfall. Data was collected from 25 storms (rainfall 4-105mm). Runoff samples were compared to groundwater samples underneath DIS.	Calculated PR: FC: 99.3-100% E.Coli: 87-100% Note: For 23% of storms GW samples exceeded State bacteria standards. Lab Study: lower infiltration rates decreased E.coli conc. in effluent	Site L: 100% Site M: 95.9% (over entire study period)	For effective FC treatment, DIS system should be designed to treat runoff from smaller watersheds (<16 ac) and lower intensity storms
CWP, 2007 NPRPD v.3	Summary of the performance of 12 infiltration practices, including 3 infiltration trenches and 9 pervious pavement studies	Removal Efficiency: Q1-Q3 (median) TSS: 62-96% (89) TP: 50-96% (65) SolP: 55-100% (85) TN: 2-65% (42) NOX: -100 -82% (0) Cu: 62-89% (86) Zn: 63-83% (66%)		Infiltration removal efficiencies are high, mainly due to the large amounts of runoff reduction provided by these practices

		Bacteria: N/A		
Schueler and Brown, T.E. (2004). Appendix B, Manual 3				Pollutant removal can be increased by designing the filter to treat a larger WQv . Ideal tested infiltration rates for infiltration practices should be between 1.0 and 4.0 in/hr. Pretreatment practices, preferably two, prior to runoff infiltration is recommended. CDA should be nearly 100% impervious (with few fines or disturbed areas) and less than 1.0 acre in size. Design should be off-line and include cleanout pipes. When possible, underdrains or filter fabric on trench bottom should be avoided.
Schueler and Holland, 2000 (Practice) Article 101 Galli, 1993	A field survey on the performance of over 60 infiltration trenches and basins in MD.			Regular maintenance is important and should be performed regularly (particularly sump cleanout) Adequate pretreatment helps reduce clogging of trenches Setting a maximum ponding depth can reduce basin compaction Geotechnical and groundwater investigations for good soils and low water tables may increase infiltration performance.
Schueler and Holland, 2000	Survey of 23 infiltration basins in Puget Sound Basin of the Pacific Northwest. Basin soils had high infiltration rates and			Pretreat runoff to reduce sediment clogging in infiltration basins. Avoid installing basins in areas with a high water

(Practice) Article 102 Gaus, 1993	low clay contents. Most sites had experienced regular maintenance and inspections.			table. Basins located in coarse, gravelly soils demonstrated subsoil metal migration, potentially a source of GW contamination
Schueler and Holland, 2000 (Practice) Article 104 Pitt et al, 1994	Three year study of infiltration basins to evaluate potential GW contamination risks.			Pretreatment may lower GW contamination potential for several stormwater pollutants, particularly heavy metals, pesticides, and other organic coumpounds. Due to potential for GW contamination, runoff from CSOs, impervious area snowmelt, manufacturing and construction sites should be directed away from infiltration practices. Runoff from gas stations, vehicle maintenance operations, and large parking lots should be adequately pretreated prior to being infiltrated
UNH, 2007	Summary of 2 year pollutant removal data for various LID practices, including an ADS water quality and infiltration unit	% Removal: TSS: 99% TP: 81% Zn: 99% TPH: 99%		

REFERENCES

Barraud, S., Gautier, A., Bardin, J.P., and Riou, V. 1999. The impact of intentional stormwater infiltration on soil and groundwater. *Water Science and Technology*. 39(2): 185-192

Bright, T.M. 2007. M.S. Thesis. Raleigh, N.C. North Carolina State University, Department of Biological and Agricultural Engineering.

CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD.

Schueler, T.R. and Holland, H.K. 2000. *The Practice of Watershed Protection*. Center for Watershed Protection: Ellicott City, MD.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD.

UNH. 2007. University of New Hampshire Stormwater Center. 2007 Annual Report. Durham, NH.

EXTENDED DETENTION LITERATURE SUMMARY

Study	Description	Pollutant Reductions (conc. based unless noted)	Runoff Reductions	Implications for Design
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques			No relationship between basin depth and TSS removal was observed in the data set. Total metals removal was high. Little effect on bacteria and nutrient removal was observed. Percent reductions (if observed) were highly dependent on influent concentrations.
CALTRANS, 2004	Five extended detention basins were sited as part of this study, 4 unlined earthen and 1 lined concrete basin. All sites were located within the highway right-of-way and collected runoff exclusively from the highway.	Unlined only: TSS: 72% TN: 14% Particulate P: 39% TP: 39% Total Cu: 58% Total Pb: 72% Total Zn: 73% Percent removal in unlined basins was higher on a load basis due to RR through infiltration. Lined: TSS: 40% (ns) TN: 14% (ns) TP: 15% (ns)	40 % in unlined ED basins	Contributing watershed area should be at least 2 ha to reduce fixed costs and minimize clogging small orifices. Due to lower initial cost and better pollutant removal, use earthen (unlined) basins where possible and groundwater conditions allow.
CWP, 2007 NPRPD v3	Summary of the performance of 10 dry Ponds, including 3 quality control ponds and 7 dry ED ponds	Removal Efficiency Q1-Q3 (median) TSS: 18-71% (49) TP: 15-25% (20)		Dry ponds appear to be efficient at removing bacteria and TSS.

		Sol P: -8-8% (-3) TN: 5-31% (24) NOx: -2-36% (9) Cu: 22-42% (29) Zn: 1-59% (29) Bacteria: 83-92% (88)		
Hathaway et al, 2007a,b.	Two dry detention basins were monitored in Charlotte, NC. The basins treated runoff from commercial office parks, parking lots, and landscaped areas. The University basin had 5.9 ac CDA and I = 0.7. The Morehead basin had 3.8 ac CDA and I = 0.7	University: BOD: 22% COD: neg NH4: 29% NOx: 31% TKN: 2% TN: 13% TP: neg TSS: 39% Cu: 11% Zn: 32% Morehead: BOD: 18% COD: 33% NH4: 14% NOx: -11% TKN: 20% TN: 10% TP: -13% TSS; 65% Cu: 17% Fe: 68% Mn: 56% Zn: 34%		Pollutant removal efficiency was high for TSS, but lower for nutrients. Low TP removal was attributed to clean inflow. Based on these results, ED is recommended for TSS removal credit, but not nutrient removal credit in NC. Sedimentation is considered the dominant pollutant removal mechanism
Harper et al., 1999	Monitoring study of a dry ED pond with CDA=23.86 ac and	TN: neg% TP: 34%	9% ET. 71% infiltrated.	Migration through the filter system provided little additional removal for most parameters, with the

(NPRPD v3)	single-family residential land use (I=37%) in DeBary, FL. Pond contained a small filter system near the outfall structure. Concentration pollutant removal efficiencies of the pond measured 30-90% except for dissolved organic nitrogen, particulate nitrogen, total nitrogen, and BOD. Load removals were higher due to volume seepage to GW. The filter system reduced concentrations of ON and Particulate N, but increased concentrations of NH4-N, NO3-N, TP, OPO4, and Particulate P. TN concentrations were reduced 37% within the filter system.	TSS: 90% FC: 97% Metals: 33-76% Mass removal: TN:86% TP: 84% TSS: 99% BOD: 82% Heavy metals: 88-96% Large mass removal efficiencies were attributed to high runoff reduction through pond bottom seepage.	Individual rainfall events ranged from 0.03-4.70 cm (0.01-1.85 in), with avg of 0.9 cm (0.36 in) per rain event. 35 storm events monitored.	exception of TN.
Middleton and Barrett, 2006	In Austin, TX, the outlet of an existing detention basin was modified to allow for batch treatment of runoff and control over the hydraulic residence time. Significant reductions for TSS, total metals, COD, nitrate and nitrite, and TKN were observed, while an increase in dissolved copper and dissolved phosphate occurred.	Total Cu: 46% Total Pb:63% Total Zn:48% COD: 23% NOx: 70% DP:-12% TP: 7% TKN: 28% TSS: 91%	Sampled 5 storm events 2.3<P<10.5mm	
Schueler and Brown, 2004 Manual 3				Design should be a Wet ED or contain multiple cells. Pollutant removal can be increased by designing

(appendix B)				the ED pond to treat a larger WQv. Design should be off-line and not intersect with groundwater. Design should contain a sediment forbay and include constructed wetland elements. The flow path should be greater than 1.5:1(not less than 1:1). The pond SA/CDA ratio should be greater than 2%
Schueler and Holland, 2000 (Practice) Article 76 Borden et al, 1997	Monitoring study of pollutant removal performance for 2 wet ED ponds in NC piedmont: one in a rural watershed (Davis), and one in an industrial watershed with 2x the impervious cover (Peidmont). Each CDA~ 2 sq.mi. Monitored storm and baseflow inflow/outflow for TSS, nutrients, TC, COD, bacteria and metals. Residence time of the Davis pond ~ 60 hrs and Piedmont pond ~ 8hrs	MASS REMOVAL: Davis: TSS: 60% TOC: 22% TP: 46% OPO4: 58% TN: 16% NO3: 18% FC: 48% Cu: 15% Pb: 51% Zn: 39% Piedmont TSS: 20% TOC: 27% TP: 40% OPO4: 15% TN: 30% NO3: 66% FC: neg		Davis pond (rural watershed) had higher algal production, which allowed for more nutrient uptake during the summer months, but then exported nutrients in the winter months. The longer residence time in this basin allowed for greater removal of TSS. The Piedmont basin had stormwater pretreatment

Schueler and Holland, 2000 (Practice) Article 77 Stanley, 1994	A dry ED basin was monitored in NC coastal plain. 200 ac CDA (I=0.29). Designed to treat 0.5" of runoff. The basin demonstrated high removal rates of particulate nutrients, but low removal rates of soluble nutrients.	(0.5"<P<2") TSS: 71% TN: 17% TP: 23% Cd: 0% Cr: 60% Cu: 35% Pb: 63% Zn: 40%	30% from a 9.8" event.	Pollutant removal during the large event was still positive, despite the large volume of overflow. This suggests that treating the first 0.5" of runoff is still effective, even during large events. Dry ED ponds can effectively remove particulate pollutants, but not soluble pollutants.
Strecker et al, 2004	Review of 24 detention basins found in the International Stormwater BMP database	Mass based: TSS: 55-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	RR:30%	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

REFERENCES:

Barrett, M.E. 2005. BMP performance comparisons: examples from the International Stormwater BMP Database. ASCE EWRI.

CALTRANS, 2004. California Department of Transportation, Division of Environmental Analysis. BMP retrofit pilot program. Final Report CTSW-RT-01-050. January, 2004.

CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD.

Harper, H., J. Herr, D. Baker, and E. Livingston. 1999. Performance Evaluation of Dry Detention Stormwater Management Systems. Sixth Biennial Stormwater Research & Watershed Management Conference September, 1999.

Hathaway, J.M., W.F. Hunt, and A. Johnson. 2007. Morehead Dry Detention Final Report – Stormwater Treatment Capabilities. Report from North Carolina State University Department of Biological and Agricultural Engineering to City of Charlotte Stormwater Services.

Hathaway, J.M., W.F. Hunt, and A. Johnson. 2007. University Executive Park Dry Detention Basin, Final Report – Stormwater Treatment Capabilities. Report from North Carolina State University Department of Biological and Agricultural Engineering to City of Charlotte Stormwater Services.

Middleton, J.R. and Barrett, M.E. 2006. Improved extended detention basin performance through better residence time control. Proceedings of the ASCE World Environmental and Water Resources Congress. May 21-25, 2006, Omaha, NE.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD

Schueler, T.R. and Holland, H.K. 2000. *The Practice of Watershed Protection*. Center for Watershed Protection: Ellicott City, MD

Strecker, E., Quigley, M., Urbonas, B., and Jones, J. 2004. Stormwater management: State-of-the-art in comprehensive approaches to stormwater. *The Water Report.* Issue #6. Envirotech Publishers Inc., Eugene, OR.

FILTRATION LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reductions**	**Implications for Design**
Aulenbach and Chan (1988)	Laboratory experiment that examined sand filtration removal rates of TOC, TP, and heavy metals from applied wastewater. (3.8 d x 100 cm long sand packed glass column). Phosphorous removal rates were very high. For trails where 2.0<pH<11.0, releases of metals from the filters were observed.	TOC: 20% TP: 99% Cd: 15% Cu: 25% Pb: 35% Zn: 45% Addition of CaCo3 increased pollutant removal to ~50% (excluding Zn)		Mechanism responsible for P removal is primarily chemical precipitation. Sand filters should not be used to treat acid or base spills, due to the potential for metal leaching.
Barrett, 2003	Evaluated performance of 5 retrofitted Austin sand filters in southern CA in small watersheds (<1.1ac) with high impervious cover (56-100% I). Flow weighted composite samples were collected for storm events (no characterization of storms included in ref). Using linear regression techniques, effluent EMC was found to be *independent* of the influent EMC.	TSS: 90% NO3: -74% TN: 22% TP: 39% Cu: 50% Pb: 87% Zn : 80% *TPH: 25-30% *FC: 65% * grab sample, not EMC		Percent removal may not be an accurate characterization of sand filter performance, particularly for runoff with high influent pollutant concentrations. Author suggests it may be better to characterize performance by an “expected effluent concentration.”
CWP, 2007 NPRPD v.3	Summary of performance for 18 filtration practices: 7 organic filters and 11 sand	Removal Efficiency Q1-Q3 (median) TSS:80-92% (86)		Filters are very effective at reducing TSS and heavy metals, but do tend to export nitrates (although not TN).

	filters.	TP: 41-66% (59) solP: -11-63% (3) TN: 30-47% (32) NOx: -70-21% (-14) Cu: 33-67% (37) Zn: 71-91% (87) Bacteria: 36-70% (37)		
Nielsen *et al*., 1993	A laboratory study that evaluated pollution removal in sand filter columns.	30-45% nitrogen removal and 40-60% phosphorous sequestration. 70-90% phosphorous sequestration rates were achieved by sands containing natural iron compounds		Removal of P was determined to be the result of chemical precipitation.
Schueler and Brown, 2004. Appendix B, Manual 3				Pollutant removal can be increased by designing the filter to treat a larger WQv. Filters can be used to treat severe pollution sites or hotspots. For additional pollutant removal (not N/P), an organic media can be used in filter bed. A wet pretreatment practice (for at least 25% WQv) is recommended. Filter bed should be exposed to sunlight and sized as >2.5% CDA. Design should be off-line and include storm bypass and an easy maintenance access.

				Designs should be above ground (except MCTT).
Schueler and Holland, 2000 (Practice) Article 105 City of Austin, 1990	Performance review of various types of sand filters.	High removal rates (> 75%) of TSS, TOC, Pb, Zn, and ON, and variable removal rates (20-75%) of FC, NH4, OPO4, and Cu have been documented TP: 19-80% TN: 31-71%		Pollutant removal can be improved by adding an organic layer to the filter bed. Designing an anaerobic zone in the bottom of a filter bed may promote denitrification, and potentially increase nitrate removal. Sand filters must be regularly maintained to prevent clogging and failure.
Schueler and Holland, 2000 (Practice) Article 106 COA, 1997 LCRA, 1997 Leif, 1999 Davis et al, 1998	Review of peat sand and organic sand filters.	Basic sand filter removal rates (no peat or compost) TSS: 80% TP: 40% Metals: 60% Barton Creek sediment/sand system TSS: 89% TN: 17% TP: 59% 2 peat systems: TSS: 88, 84% TN: 51, 30% TP: 47, 48% NO3: negative Compost Filter: TSS: 43% TP: neg Soil/Mulch filter (MASS BASED): TP: 65%		Organic filter media can effectively reduce hydrocarbons and metals, and should be considered for treatment of hotspot runoff. Decomposition of this layer can export NO3 and OPO4. TP removal can be boosted to 60-70% removal by using soil filtration. Peat filters can potentially remove up to 50% of TP. Vertical sand filters should be avoided, due to rapid clogging rates.

		TN: 49%		
Schueler and Holland, 2000 (Practice) Article 107 Horner, 1995 Bell et al, 1995	Assessment of a DE sand filter performance.	Concentration removal for 2 Seattle filters: TSS: 83, 8% Oil and Grease: 84, 69% Hydro: 84%, 55% TP: 41, 20% Zn: 33, 69% Cu:22, 31% Mass removal rates: for a filter in Alexandria, VA TSS: 79% TOC: 66% TP: 63% OPO4: 63% TN: 47% NOx: -53% TKN:71% Zn: 91% Cu:25%		A relationship exists between pollutant removal efficiency and inflow pollutant concentrations. The sand layer in a filter system should be designed with positive drainage to prevent areas from becoming anaerobic and releasing previously captured phosphorus. If runoff contains TOC, increased N removal may be possible by designing a layer of flooded gravel below the sand filter. When possible, sand filters should treat runoff from 100% IC watersheds, to reduce possibility of failure due to clogging.
Schueler and Holland, 2000 (Practice) Article 109 Stewart, 1992	Performance review of an organic leaf compost filter.	TSS: 95 TDS: -37% COD: 67% TP: 41% OPO4: negative ON: 56% NO3: -34% Zn: 88% Hydro: 87% Cr: 61%		Higher pollutant removal rates may be attained by increasing SA or storage volume of filter. Compost should be removed and replaced annually.

		Cu: 67% Pb, Cd: no difference		
Schueler and Holland, 2000 (Practice) Article 111 Pitt, 1996	MCTT design utilizes screening, settling, and filtering in underground chambers to effectively treat pollutants in hotspot runoff.	Mass Based: TSS: 85-98% TP:50-84% Zn: 71-93% Cu: 43-89%		MCTT can be used to treat runoff in areas where there is limited space for surface filters. Tests have shown high removal rates of TSS, nutrients, metals, and hydrocarbons. The screening process does not remove pollutants, but rather captures larger materials to reduce maintenance concerns.
Strecker et al, 2004	Review of 30 media filter studies found in the International Stormwater BMP database	Mass Based: TSS: 80-90% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	No runoff reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

REFERENCES:

Aulenbach, D.B, and Chan, Y. 1988. Heavy metals removal in a rapid infiltration sand column. *Particulate Science and Technology*. 6: 467-48.

CALTRANS, 2004. California Department of Transportation, Division of Environmental Analysis. BMP retrofit pilot program. Final Report CTSW-RT-01-050. January, 2004.

CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD.

Barrett, M. E. 2003. Performance, Cost and Maintenance Requirements of Austin sand filters. *Journal of Water Resources Planning and Management*. 129(3): 234-242.

Nielsen, J; Lynggaard-Jensen, A., and Hasling, A. 1994. Purification efficiency of Danish biological sand filter systems. *Water Science and Technology*. 28 (10): 89-97.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD.

Schueler, T.R. and Holland, H.K. 2000 *The Practice of Watershed Protection*. Center for Watershed Protection: Ellicott City, MD.

Strecker, E., Quigley, M., Urbonas, B., and Jones, J. 2004. Stormwater management: State-of-the-art in comprehensive approaches to stormwater. *The Water Report.* Issue #6. Envirotech Publishers Inc., Eugene, OR.

STORMWATER WETLANDS LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
CWP, 2007 NPRPD v.3	Evaluation of 40 wetland studies, including 24 shallow marshes, 4 ED wetlands, 10 pond/wetland systems, and 2 submerged gravel wetlands	Removal Efficiency: Q1-Q3 (median) TSS: 46-86% (72) TP: 16-76% (48) SolP: 6-53% (25) TN: 0-55% (24) NOx: (22-80% (67) Cu: 18-63% (47) Zn: 31-68% (42) Bacteria: 67-88% (78)		
Hathaway et al, 2007a	A 0.32 ac stormwater wetland was analyzed for pollutant removal performance in Charlotte, NC. CDA was 15.8 ac, I=0.6	FC: 70% Oil and Grease: 15% NH4: 55% NOx: 20% TKN: 35% TN: 35% TP: 45% TSS: 55% Cu:5% Zn: 55%	RR: Negative	Overland flow may have contributed to additional pollutant loadings to wetland. The pollutant removal rates represent the best estimates. TSS removal ranged between 50 and 66%, with an estimated reduction of 55%, well below the state standard of 85% TSS removal. According to authors, 85% TSS removal is a likely an overestimation of what *any* BMP can reliably remove.
Hathaway et al, 2007b.	A 0.5 ac wetland with an avg depth of 1.5 ft in Charlotte, NC, was monitored for pollutant removal performance. The drainage watershed Mainly consisted of single family homes.	FC: 99% E-coli: 92% BOD: 82% COD: 63% NH4: 62% NOx: 62% TKN: 41% TN: 45% TP: 45% TSS: 15%	RR: negligible	The observed 45% TN and 45% TP removal was at or above the NC State standard for these nutrients.

		Cu: 57% Fe: neg Zn: 71% Pb: 32%		
Li et al, 2007	A laboratory study investigated the TSS removal in 4 wetland cells: three having different densities of well-established vegetation, and one without any vegetation. All cells contained a 0.4 m thick sandy loam layer. A simple non-linear two-parameter regression model is defined for prediction of TSS trapping efficiency in constructed stormwater wetlands.			Confirmed that sediment concentration decreases exponentially with distance travelled. TSS removal was not dependent on vegetation density, flow turbulence, or shear flow velocity. Particle diameter, and flow characteristics (flow rate and velocity) had the greatest influence on TSS removal.
Schueler and Brown, 2004 Appendix B, Manual 3				Use pond-wetland or multiple cell design Should exceed target WQv by more than 50% Use complex wetland micro-topography Should exceed target WQv by more than 25% Flow path should be greater than 1.5 to 1 Wooded wetland design is a benefit Off-line designs preferred
Schueler and Holland, 2000 (Practice)	A study comparing the pollutant removal performance between two stormwater wetlands in the coastal plain of	MASS BASED: TSS: 65.0% OPO4: 68.7% Total Diss Phosphorus:		Authors expected better overall removal rates and attributed it to the fact that the sand substrate did not contain enough organic matter to trap pollutants.

Article 89 Athanas and Stevenson, 1991	Maryland – one site had been planted with wetland vegetation and the other had volunteer colonization.	44.3% Total OP: -5.7% TPP: 7.2% TP: 39.1% NOx: 54.5% NH4: 55.8% Total ON: -5.4% Total Particulate Nitrogen: -5.0% TN: 22.8% Numbers are from the planted site only. Percent mass reduced for both storm and baseflow events over 23 months		The planted species survived well but invasive species did appear. The volunteer site was completely dominated by cattail and phragmites. It appears that intentional planting has value.
Schueler and Holland, 2000 (Practice) Article 90 OWML and GMU, 1990	A study on the performance of a small stormwater wetland (created within an existing detention basin) over a 2-year period. Storm event and baseflow monitoring were performed and biomass was examined for nutrient dynamics.	MASS BASED: Small Storms: OPO4: 59% Total Soluble Phosphorus: 66% TP: 76% NH4: 68% TSS: 93% TKN: 81% NOx: 68% TN: 76% All Storms: OPO4: -5.5% Total Soluble Phosphorus: -8.2% TP: 8.3% NH4: -3.4% TSS: 62.0%		The wetland was found to be effective in removing nutrients and sediment during small storm events (runoff volumes < 0.1watershed inches of storage provided by the wetland) but ineffective during larger storms. Stormwater wetlands need an appropriately sized treatment volume to remove pollutants from larger storm events. Sediment forebays help to prevent sediment deposition and resuspension. A wide range of depth zones promotes rapid establishment of diverse wetland species.

		TKN: 15.0% NOx: 1.2% TN: -2.1% Smaller storms had higher mass removal. Larger storms had smaller or negative removal rates.		
Schueler and Holland, 2000 (Practice) Article 91 Hey et al, 1994 Mitsch et al, 1995	Two independent studies were done to analyze the ability of off-line wetlands to remove sediment and nutrient levels from river runoff. Four wetlands were constructed in the floodplain of the Des Plaines River, located near Chicago. Water from the river was pumped into the wetlands and sampling occurred at the inlet and outlet of each wetland. Summarizes pollutant removal data presented by Hey et al., 1994a and Mitsch et al., 1995.	These numbers show the range over two years and represent percent removal efficiency based on mass balance and flux. TSS: 77%-99% Nitrate-N: 39%-99% TP: 53%-99%		In the first two years the pollutant removal efficiency was high. The third year yielded lower phosphorus removal rates prompting the question of whether wetlands have a limited life span for pollutant removal. Need to continue long-term monitoring. The off-line riverine wetlands were found to be beneficial for pollutant removal and wildlife habitat. Consideration must be given to designing these systems so they don't raise local flood elevations. Also, they will require maintenance and power to pump water to and from the river.
Schueler and Holland, 2000 (Practice) Article 97 Egan et al, 1995	In this study, the ability of crushed concrete and granite rock wetland cells to remove pollutants was evaluated for 15 simulated storm events. The cells were part of a larger treatment train, the first components providing some pretreatment. The results indicate that these cells can be an effective enhancement to	MASS REMOVAL: TSS: 81% TOC: 38% TKN: 63% NO3: 75% TN: 63% OPO4: 14% TP: 82% Cd: 80% Cr: 38% Cu: 21%		The rock surfaces were believed to be the key factor in pollutant removal by creating substrate area for epilithic algae and microbes, reducing flow rates and providing more contact surfaces. Recycled crushed concrete cells performed better than granite rock perhaps due to the higher pH promoting greater epilithic algae and bacterial growth. To prevent clogging or sediment deposition, the

	stormwater wetland designs, especially in coastal regions where greater nitrogen removal is desired.	Pb: 73% Zn: 55% FC: 78%		cells should be located off-line and protected by pretreatment cells.
Strecker et al, 2004	Review of 29 wetland basins found in the International Stormwater BMP database	Mass based: TSS: 70-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	RR: 5%	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

References

CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD

Hathaway, J.M., W.F. Hunt, A. Johnson, and J.T. Smith. 2007a. Bruns Ave. Elementary School Wetland, Final Report – Stormwater Treatment Capabilities. Report from North Carolina State University Department of Biological and Agricultural Engineering to City of Charlotte Stormwater Services.

Hathaway, J.M., W.F. Hunt, A. Johnson, and J.T. Smith. 2007b. Edwards Branch Wetland, Final Report – Stormwater Treatment Capabilities. Report from North Carolina State University Department of Biological and Agricultural Engineering to City of Charlotte Stormwater Services.

Li, Y., Deletic, A., Fletcher, T.D. 2007. Modeling wet weather sediment removal by stormwater constructed wetlands: Insights from a laboratory study. Journal of Hydrology. 338: 285-296.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD.

Schueler, T.R. and Holland, H.K. 2000. *The Practice of Watershed Protection*. Center for Watershed Protection: Ellicott City, MD.

Strecker, E., Quigley, M., Urbonas, B., and Jones, J. 2004. Stormwater management: State-of-the-art in comprehensive approaches to stormwater. *The Water Report.* Issue #6. Envirotech Publishers Inc., Eugene, OR.

WET PONDS LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques			Emergent vegetation around the pond perimeter is responsible for a small percentage of overall nutrient and metal removal (<5%). Larger permanent pools (Sized to capture 4-6x the runoff from mean rainfall events) reduce dissolved P, but had little effect on other pollutants. Removal of N and P tends to decline in winter months.
CALTRANS, 2004	One wet basin was sited as part of this study. The site was located within the highway right-of-way and had CDA of 1.7 ha, I=0.47, collected highway runoff.	Storm Reductions: TSS: 94% NO3: 77% TN: 51% TP: 5% (ns) Total Cu: 80% Total Pb: 76% Total Zn: 41% Baseflow Reductions: TSS: 21% (ns) TN:43% TP: 49% (ns) Total Cu: 54% (ns) Total Pb: 62% (ns) Total Zn: 62%		Locate, size, and shape wet basins relative to topography and provide extended flow paths to maximize pollutant removal potential.
CWP, 2007 NPRPD v.3	Summary of 46 wet pond studies, including 12 wet ED ponds, 1 multiple pond system, and 30 wet ponds.	Removal Efficiency: Q1-Q3 (median) TSS: 60-89% (80) TP: 39-76% (52) SolP: 41-74% (64) TN: 16-41% (31)		

		NOx: 24-67% (45) Cu: 45-74% (57) Zn: 40-72% (64) Bacteria: 52-94% (70)		
Guo, 2007	An existing detention basin in NJ was retrofitted to an extended detention basin-surface wetland system, to have flood control and pollutant removal functions. Performance was field monitored, and the system was found to be effective.	TSS: 48% TP: 51% Influent TSS concentrations were low, which resulted in lower TSS removal efficiency.	7 monitored storm events 7.4<P<76.5mm	The extended detention- wetlands system effectively removed TSS and TP from stormwater runoff. The system required no or minimal maintenance over a long period of time.
Hathaway et al, 2007a	Monitoring was performed on a residential pond in Charlotte, NC, estimated to be 50-70 years old. CDA was 120 ac of commercial and residential development. Pond was 1 ac with avg. depth 3-6 ft.	BOD: 45% COD: 42% NOx: 45% TN: 23% TP: 41% TSS: 56% Cu: 40% Mn: negative Zn: 49% Pb: 26%	negligible	The studied pond removed TN and TP with efficiencies of 23% and 41%, respectively. TSS removal was 56%, lower than the state of NC recommended 85%. 85% TSS removal is unlikely for ponds sited in clayey watersheds Aged ponds are able to provide substantial stormwater treatment for various nutrients, sediment, pathogens, and metals. The establishment of a diverse, dense plant community around the perimeter of the pond may increase nutrient removal. This may also discourage water fowl activity, potentially reducing organic nutrient and pathogen inputs.
Hathaway et al, 2007b	In Charlotte, NC, performance of an urban wet pond was studied. The CDA of the pond	NH4: 22% NOx: 74% TKN: negative TN:19%	negligible	Removal efficiencies of TSS, TN, and TP were 63%, 19%, and 15%, respectively. TSS removal was lower than the 85% removal

	was 27.3 ac and consisted of commercial, residential, and transportation land uses. I=0.86. Wet pond was 0.6 ac with an average depth of 3 ft.	TP: 15% TSS: 63% Cu: 63% Fe: 49% Zn: 49% Pb: 18%		credit assigned to wet ponds by the state of NC.
Mallin et al, 2002.	Monitored performance of 3 wet ponds in Wilmington, NC for 29 months. One pond had high pollutant removal. The other two ponds were less effective; one experienced additional overland inflow which short-circuited pollutant contact time, and the other had high pollutant inflow from a golf course in the CDA.	Calculated removal: TN: 40% TP: 57% FC: 86%		A high length-to-width ratio and establishment of a diverse vegetation community is recommended to obtain better pollutant removal by maximizing inflow contact time with vegetation and organic sediments.
Rushton et al, 2002 (NPRPD v3)	Studied pollutant removal and runoff reduction of a wet detention pond in an agricultural basin in Ruskin, FL over a 4-year period. Influent runoff received pretreatment from a roadside ditch. The watershed was 85 ha and the pond was 5.8 ha. Influent and effluent samples were obtained to determine differences for event EMCs.	For 1998, 1999, 2000, and 2001, resp. TP: 37%, 63%, 52%, 46% TN: 28%, neg, 28%, 44% TSS: neg, neg, neg, 85% Load reductions were higher due to runoff reduction in the basin.	25% RR (45% if rainfall is considered as an input) 8% loss due to evaporation, 15% to seepage	Runoff coefficient was 0.4 for storms greater than 2.0 in. TP effluent concentrations, although lower than influent, were still above national standards.
Schueler and				Use wet ED or multiple pond design

Brown, 2004 Appendix B, Manual 3				Should exceed target WQv by more than 50% Should exceed target WQv by more than 25% Use off-line design Flow path should be greater than 1.5 to 1 Use sediment forebay at major outfalls Wetland elements should cover at least 10% of surface area
Schueler and Holland, 2000 (Practice) Article 73 Wu, 1989	In this study, the role of permanent pool volume on pollutant removal performance is examined. Investigators found that the pond with the larger permanent pool volume performed better than the smaller pond with >80% removal of TSS and some metals. However, the performance of the larger pond in removing nutrients was modest, only 10% higher. It was speculated that a large population of geese at the larger pond could have reduced its efficiency. Short-circuiting and low inflow concentrations were also cited as reasons. Dry weather	Mass Removal: Lakeside Pond Drainage area: 65 acre Volume: 38.8 acre-ft Mean Depth: 7.9 ft Equiv. watershed storage: 7.1 inches TSS: 93% TP: 45% TKN: 32% Zn: 80% Fe: 87% Runaway Bay Drainage area: 437 acre Volume: 12.3 acre-ft Mean Depth: 3.8 ft Equiv. watershed storage: 0.33 inches TSS: 62% TP: 36% TKN: 21%		Satisfactory pollutant removal performance could be achieved if wet ponds were sized to be at least 2% of the contributing drainage area, with an average depth of six feet. Treatment volume alone does not guarantee good performance – need to provide good internal geometry and pondscaping to discourage large geese populations.

	sampling yielded higher nutrient levels than during storm events. Eleven storm events were monitored, ranging from 0.5" - 3.6" of rainfall.	Zn: 32% Fe: 52%		
Schueler and Holland, 2000 (Practice) Article 72 Urbonas et al, 1994	A study of the pollutant removal performance of a stormwater pond/wetland system. The watershed draining to the system was 550 acres. Runoff entered the wet pond then exited over a spillway and into a series of six cascading wetland cells. In general the combined system worked effectively with the bulk of the pollutant removal coming from the pond. The wetland cells provided pollutant removal during dry periods where the pond tended to be an exporter. Thirty six storm events were samples over a three year period during the growing season (May to September).	Mass Removal: By Wetpond- TP: 49% Dissolved P: 32% Nitrate-Nitrogen: -85% Organic- Nitrogen: 32% TN: -12% Total Copper: 57% Diss Cu: 53% Total Zn: 51% Diss Zn: 34% TSS: 78% Mass Removal: By Wetland- TP: 3% Diss P: 12% Nitrate-Nitrogen: 5% Organic- Nitrogen: -1% TN: 1% Total Cu: 2% Diss Cu: -1% Total Zn: 31% Diss Zn: -5% TSS: -29% Mass Removal:		Greater pollutant removal rates are achieved by having multiple and redundant treatment systems. Dry weather sampling should not be neglected in pond systems serving large drainage areas.

		By System TP: 51% Diss P: 40% Nitrate-Nitrogen: -76% Organic- Nitrogen: 31% TN: 19% Total Cu: 57% Diss Cu: 58% Total Zn: 66% Diss Zn: 30% TSS: 72%		
Schueler and Holland, 2000 (Practice) Article 70 Leersnyder, 1993	A study on the pollutant removal capacity of a pond/marsh system at an industrial site in New Zealand. The system was found to be very effective in the removal of sediment, nutrients and metals. However it was an exporter of ammonia and ineffective in removing COD. Six storm events were monitored.	Mass Removal: TSS: 78% TP: 79% Sol. Reactive Phosphorus: 75% Nitrate: 62% NH4: -43% COD: 2% Total Cu: 84% Total Pb: 93% Total Zn: 88%		A large treatment volume and good design features (oil trap at inlet, long flow path, submerged berm, shallow marsh zone, micropool at outlet) were cited as the reasons for effective pollutant removal.
Strecker et al, 2004	Review of 33 retention ponds found in the International Stormwater BMP database	Mass based: TSS: 60-95% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	RR: 7%	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.
Taylor et al, 2001	A wet pond in San Diego County, CA, was	TSS: 94% NO3-N: negative		Vegetation in and around the basin provides for enhanced solids, and potentially dissolved

	constructed as a retrofit project to treat highway stormwater runoff from a 4.2 ac CDA. The pond was designed to capture the 1-yr, 24hr rainfall event (1.34 in) and have a 24 hr drawdown time (orifice d=3in). The wet pond demonstrated high removal of TSS and metals, and low nutrient removal, particularly for nitrate. Nitrate and TN concentrations did decrease in the dry flows.	TKN: 44% TN: negative TP: 29% Total Cu: 99% Total Pb: 99% Total Zn: 93% Diss Cu: 27% Diss Pb: 94% Diss Zn: 33% TPH-oil: 21% TPH-diesel: 92% FC: 100%		metal removal. Vegetation re-growth was most rapid after a harvest. The 3 in orifice remained submerged to avoid clogging by floating debris. There were no clogging problems observed during this one-year study.
Teague and Rushton, 2005 (in NPRPD)	A filter pond treated parking garage and throughfare runoff a from 10.4 ac watershed. N and P concentrations were reduced in the system, but effluent concentrations remained above water quality standards.	The effluent filtration system was effective in reducing metals and suspended solid loads, but not successful in reducing soluble nutrients.	negligible	Provide some pre-treatment to further reduce metals, oils, and greases. Clean out the concrete lined sedimentation basin and vacuum out underdrain pipes at least once a year to remove pollutants. Restrict mowing too close to littoral zone vegetation. Use material in the filter system designed to remove nutrients.

References

Barrett, M.E. 2005. BMP performance comparisons: examples from the International Stormwater BMP Database. ASCE EWRI.

CALTRANS, 2004. California Department of Transportation, Division of Environmental Analysis. BMP retrofit pilot program. Final Report CTSW-RT-01-050. January, 2004.

CWP, 2007. National Pollutant Removal Performance Database, Version 3. Center for Watershed Protection. Ellicott City, MD.

Guo, Qizhong. 2007. Performance of retrofitted stormwater extended detention wetlands. Proceedings of the ASCE World Environmental and Water Resources Congress. May 15-19, 2007, Tampa, FL.

Hathaway, J.M., W.F. Hunt, A. Johnson, and J.T. Smith. 2007a. Pierson Pond, Final Report – Stormwater Treatment Capabilities. Report from North Carolina State University Department of Biological and Agricultural Engineering to City of Charlotte Stormwater Services.

Hathaway, J.M., W.F. Hunt, A. Johnson, and J.T. Smith. 2007b. Shade Valley Pond, Final Report – Stormwater Treatment Capabilities. Report from North Carolina State University Department of Biological and Agricultural Engineering to City of Charlotte Stormwater Services.

Mallin, M.A., Ensign, S.H., Wheeler, T.L., and Mayes, D.B. 2002. Pollutant removal efficacy of three wet detention ponds. *Journal of Environmental Quality*. 31: 654-660.

Rushton, B. 2002. Treatment of stormwater runoff from an agricultural basin by a wet-detention pond in Ruskin, Florida. Final Report to the Southwest Florida Water Management District. November, 2002.

Schueler, T.R. and Holland, H.K. 2000. The Practice of Watershed Protection. Center for Watershed Protection: Ellicott City, MD.

Schueler, T.R. and Brown, T.E. 2004. Urban Subwatershed Restoration Manual, No.3: Urban Stormwater Retrofit Practices. Appendix B. Center for Watershed Protection: Ellicott City, MD.

Strecker, E., Quigley, M., Urbonas, B., and Jones, J. 2004. Stormwater management: State-of-the-art in comprehensive approaches to stormwater. *The Water Report.* Issue #6. Envirotech Publishers Inc., Eugene, OR.

Taylor, S., Barrett, M., Borroum, J.S., Currier, B. 2001. Storm water treatment with a wet pond: a case study. Proceedings Proceedings of the 2001 Wetlands Engineering and River Restoration Conference, 2001, 323-332.

Teague, K. and Rushton, B. 2005. Stormwater runoff treatment by a filtration system and wet pond in Tampa, Florida. Final Report to the Southwest Florida Water Management District. February, 2005.