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Reducing Phosphorus Loads to Lake Erie: Best Management Practices Literature Review

Reducing Phosphorus Loads to Lake Erie: Best Management Practices Literature Review

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Overview

Strong correlations exist between phosphorus (P) loads discharged into Lake Erie and phytoplankton production (Anderson et al. 2002). Based on concerns over harmful algal blooms and other ecological impacts, the International Joint Commission requested a review of best management practices (BMPs) used to reduce P loading to surface waters. This review provides an overview of BMPs that are employed to reduce P loads, BMPs that are likely to be considered for implementation within the Lake Erie basin to reduce P discharges in stormwater. The review is divided into two sections, urban and rural BMPs. Individual BMPs are often designed to reduce an array of pollutant loads, most commonly they are designed to reduce peak flow and total suspended solids – particularly in urban environments. This review specifically focuses on BMPs that have been evaluated using scientific methods for P reduction. A secondary focus was to highlight BMPs that have been implemented within the Lake Erie watershed, or at least in the Great Lake region.

Review of over 240 primary sources has resulted in the following findings: (1) very few studies have quantified P load reductions by urban or agricultural BMPs within the Lake Erie watershed; (2) it is not possible to determine BMP cost-effectiveness due to costs rarely being reported; (3) BMP effectiveness, both urban and agricultural, vary greatly and are often contradictory; (4) most methods commonly used to quantify BMP performance are ineffective; (5) there is a need to move beyond total P measurements as the only metric used to quantify P, assessing speciation is necessary to advance BMP performance; (6) improved models are required to accurately predict treatment efficiency of BMPs under a variety of conditions and climates; and (7) while some databases exist, a central data repository is critically needed to synthesize data collected and improve understanding of BMP effectiveness.

1. BEST MANAGEMENT PRACTICES IN URBAN ENVIRONMENTS

1.1. Urban Loads

When considering phosphorus (P) loads to aquatic environments urban sources are often underappreciated. The Lake Champlain watershed offers an illustrative example of the importance of urban non-point sources. Despite only constituting only 3% of the land cover within the Lake Champlain watershed, urban sources have been estimated to contribute 18% of the estimated P load (Meals and Budd 1998). In a mixed agricultural and urban watershed located in Canada at the western end of Lake Ontario the total P loading to Hamilton Harbor from 1996 to 2007 are estimated to average 346±45 kg/day, approximately 0.3 tons per year, from all urban sources (Hamilton Harbour RAP Technical Team 2010; Wellen et al. 2012). Approximately 0.57 lb of P/acre/year of dissolved reactive P and 0.98 lb of P/acre/year of total P has been estimated to be derived from urban land cover to Lake Wingra in Madison, Wisconsin (Kluesener 1971). The largest source of P from urban areas is associated with construction activities, which can temporarily generate even larger P loads per area than agricultural row crops (Burton and Pitt 2001). Due to the multitude of land uses within urban watersheds it is often difficult to pinpoint P loads from specific urban land cover.

Given the significant loading from urban environments, there is a clear need to also consider urban sources of P if surface waters are to be managed appropriately. Unfortunately, in order to mitigate the diffuse urban inputs, equally disperse BMPs will likely have to be implemented. For example, in one southern Ontario study by Winter and Duthie (2000), it was determined that P removal would have to be applied to all water entering the watershed from urban areas in order to have an appreciable reduction in stream P concentrations.

1.2. Regulatory Framework

Discharges of P from urban source in the U.S. are primarily controlled by Phase I and II of the U.S. Environmental Protection Agency's (EPA) stormwater program. Phase I rules were promulgated in 1990 under the Clean Water Act and utilizes the National Pollutant Discharge Elimination System (NPDES). Phase I NPDES permits cover (USEPA 2005):

1) "medium" and "large" municipal separate storm sewer systems (MS4s) generally serving populations of 100,000 or greater,
2) construction activity disturbing 5 acres of land or greater, and
3) 10 categories of industrial activity.

Phase II requires MS4s and operators of small construction sites to implement programs and practices (e.g. BMPs) to reduce pollutant loads in stormwater runoff. The Phase II program again utilizes NPDES permits. In Ohio alone, there are 703 NPDES permits within the Lake Erie watershed accounting for 1,076 million gallons per day (MGD) (Ohio EPA 2010). Approximately two-thirds of these permits are issued to small plants discharging less than 50,000 gallons per day. However, the majority of P loadings are associated with 12 (1.7%) WWTPs that discharge more than 15 MGD. It should be noted, that loads generated from WWTPs do not include discharges from CSO facilities.

Michigan has twice enacted legislation limiting the amount of P in cleaning agents, first in 1971 limiting the amount by weight to 8.7% and again in 1977 restricting the amount of P in household laundry detergents to no greater than 0.5% by weight (USEPA 2009). This legislation, as well as improvements to the Detroit Water and Sewerage Department (DWSD) Wastewater Treatment Plant (WWTP) have generally resulted in effluent total P concentrations below 1 mg/L since the early 1980's.

1.3. Selection of Urban BMPs

The selection of urban BMPs for P removal is often conducted based on general classifications of perceived BMP utility, some which may be based on empirical evidence, as demonstrated in the screening matrix proposed by Gibb et al. (1999) (Figure 1). Rarely is the selection of BMPs based on mechanistic models that can accurately describe P reductions. Some empirical relationships describing pollutant removal have been proposed. For example Young et al. (1996) found the amount of P removal in dentition basins was proposal to their detention time:

$$R = 31.4 \cdot t_d^{0.12} \qquad \text{(eq. 1)}$$

where R is the percent removal efficiency and t_d is the detention time in hours. Unfortunately, models capable describing the fate and transport of P in systems similar to some structural BMPs are not effective at modeling the P removal (Roy-Poirier et al. 2010). Export coefficients for P loads at the watershed scale have also been developed (Winter and Duthie 2000). Regardless of the empirical approach used to select BMPs or quantify P loads, whether it is qualitative or quantitative, more effective controls are desired. In order to increase BMP effectiveness across large regions and a variety of urban flow conditions it is necessary to base future BMP designs on and the selection of BMPs on mechanistic understanding.

Type of BMP	Best Management Practice	Sediment	Nitrogen and Phosphorus	Metals and Trace Elements	Oil & Grease, Harmful Organics	Oxygen Demand	Bacteria & Viruses	Floatable Material
Non-Structural	Buffer Zones/Preservation of Natural Areas & Drainage	❸	❸	❸	❸	❸	❸	❸
	Impervious Area Reduction/Restriction/Disconnection	❸	❸	❸	❸	❸	❸	❸
	Construction Design/Review/Inspection Enforcement	❸	❸	❸	❸	❸	❷	❸
	Consultant and Contractor Education	❸	❸	❸	❸	❸	❸	❸
	Education and Training of Municipal Employees	❸	❸	❸	❸	❸	❸	❸
	Commercial/Industrial Education	❸	❸	❸	❸	❸	❸	❸
	Public Education and Participation	❸	❸	❸	❸	❸	❸	❸
Structural	Coalescing Plate Separator	❶	❷	❷	❸	❸	❶	❸
	Water Quality Inlet	❷	❷	❷	❷	❷	❷	❷
	Manhole Sediment Trap, Trapped Catch Basin	❷	❷	❷	❷	❷	❷	❷
	Conventional Dry Detention Pond & Vault	❶	❶	❶	❶	❶	❶	❶
	Extended Detention Dry Pond & Vault, Wet Vault	❷	❷	❷	❷	❷	❷	❷
	Wet Pond	❸	❸	❸	❸	❸	❸	❸
	Wet Vault	❶	❷	❷	❷	❷	❷	❷
	Engineered Wetlands	❸	❸	❸	❸	❸	❸	❸
	Vegetated Swale/Grassed Channel	❸	❶	❸	❸	❷	❶	❸
	Vegetated Filter Strip	❸	❶	❸	❸	❷	❶	❷
	Off-line Infiltration Basin	❸	❸	❸	❸	❸	❸	❸
	Roof Downspout System	❷	❷	❷	❷	❷	❷	❷
	Porous Pavement, Concrete Grid & Modular Pavers	❸	❸	❸	❸	❸	❸	❸
	Bioretention, Dry Swale with Underdrains	❸	❶	❸	❸	❷	❷	❸
	Sand Filter	❸	❷	❸	❸	❸	❷	❸
	Catch Basin Filter	❷	❶	❷	❷	❷	❷	❷
	Organic Filter	❸	❶	❸	❸	❸	❷	❸
	Multi-Chambered Treatment Train	❸	❸	❸	❸	❸	❸	❸
Operational and Maintenance	Maintenance of Structural BMPs	❸	❸	❸	❸	❸	❸	❸
	Detection/Removal/Prevention of Illicit Connections	❷	❸	❸	❸	❸	❸	❸
	Spill and Complaint Reporting and Response	❸	❸	❸	❸	❸	❸	❸
	Street Cleaning	❷	❷	❷	❷	❷	❷	❷
	Maintenance of Runoff Conveyance Systems and Hillslopes	❷	❷	❶	❶	❷	❶	❶
	Catch Basin Cleaning	❷	❷	❷	❷	❷	❷	❷
	Roadway and Bridge Maintenance	❷	❷	❷	❷	❷	❶	❷

❸ High Positive Impact ❷ Moderate Positive Impact ❶ Little or Unknown Impact

Figure 1. Perceived utility of BMPs to mitigate pollutant loads (from Gibb et al. (1999))

1.4. Urban BMPs

1.4.1. Non-structural (Alternative Behavior/Management) BMPs

The results of educational campaigns focused on changing residents' behavior have been found to result in only modest changes in conduct, with some BMP practices being adopted more readily than others. A common non-structural BMP often considered by communities facing P related problems in surface waters is reducing P loads due to lawn fertilizers. Phosphorus loadings are found to be reduced considerably if fertilizing is based on soil tests rather than routine maintenance practice (Erickson et al. 2005; Hipp et al. 1993). Alternatively, composted dairy manure has been used as a source of slow release P and this reduces total P loadings to urban streams when compared to conventional commercial turf-grass sod imported and maintained with inorganic P fertilizer (Richards et al. 2008). Significant reductions in total P and *a* trend of reduction in dissolved P following the implementation of a municipal ordinance limiting the application of lawn fertilizers containing P in Ann Arbor MI (Lehman et al. 2008). Another study by Dietz et al. (2004) found 82% of residents began to leave lawn clippings in place but only 11% applied fertilizer after soil tests. Unfortunately, these changes were not found to result in a significant change in P loadings.

Other non-structural changes include better management of leaves, pet waste, street sweeping and the use of native plants. Leaves from deciduous trees (e.g. oak, poplar) are reported to leach 54-230µg P/g, approximately 85% of which is reactive (Cowen and Lee 1973). Additionally, nearly 3 times as much P was released when leaves were cut, as would occur during mulching. Pet waste was found to be responsible for 84% of P inputs in the Minneapolis-Saint Paul, Minnesota metropolitan area (Fissore et al. 2012). Regular street sweeping is reported to result in 40-70% removal of total P (NVPDC and ESI 1992). However, a much lower amount of removal has been reported by Hurley and Forman (2011) in the Charles River where only an 11-14% reduction in total P, as a percentage of the total non-CSO load entering the lower Charles River, was found to be achieved through combined street sweeping and structural BMPs. While the reductions in stormwater loads to the lower Charles River from the control practices examined appear to be minor, Hurley and Forman (2011) suggest these water-quality benefits are likely to enhance water quality during those times when waters are most impaired – during and immediately after storms. Finally, the use of low maintenance plants that are indigenous to the eco-region are expected to reduce the transport of P via stormwater runoff (Hipp et al. 1993).

Based on these findings, the following non-structural BMPs are suggested:

- Remove leaves immediately (Cowen and Lee 1973)
  Removal of pet waste immediately(Fissore et al. 2012)
- Fertilizing based on soil tests rather than routine maintenance practice (Erickson et al. 2005; Hipp et al. 1993)
- Utilize native plants (Hipp et al. 1993)

1.4.2. Non-Point Source Structural or Engineered BMPs

Traditionally, stormwater infrastructure was designed to mitigate flooding and move water as rapidly as possible to nearby water bodies. When riparian areas became severely degraded due to the large and powerful flows generated during runoff events the design of systems then involved with the aim of reducing peak flows, sediment loads, and turbidity. Unfortunately, these objectives ignore other biochemical factors, such as nutrient loads, that play a more significant role in causing water quality impairments (EPA 2009). As a result, new BMPs are evolving to be more holistic and sustainable with the aim of reducing pollutant loads (Batroney et al. 2010).

Urban structural BMPs are best thought of as a spectrum of approaches rather than specific types (Figure 2). Structural BMPs (engineered systems) typically employ filtration, detention – which allows for settling of sorbed material – or a combination of both. Likewise they can be designed as completely artificial systems or to utilize, or at least mimic, natural processes. Many BMPs overlap in the type of technologies they employ for the removal of pollutants.

For this review, we will start by considering more artificial, filtration based BMPs move through more natural forms of filtration, then evaluate BMPs that primarily utilize detention for P removal. Removal efficiencies reported in the literature will be presented for each type of urban structural BMP. This will be followed by an evaluation of the treatment efficiency based on current (as of January 2013) data collected from the International Stormwater BMP Database (www.bmpdatabase.org).

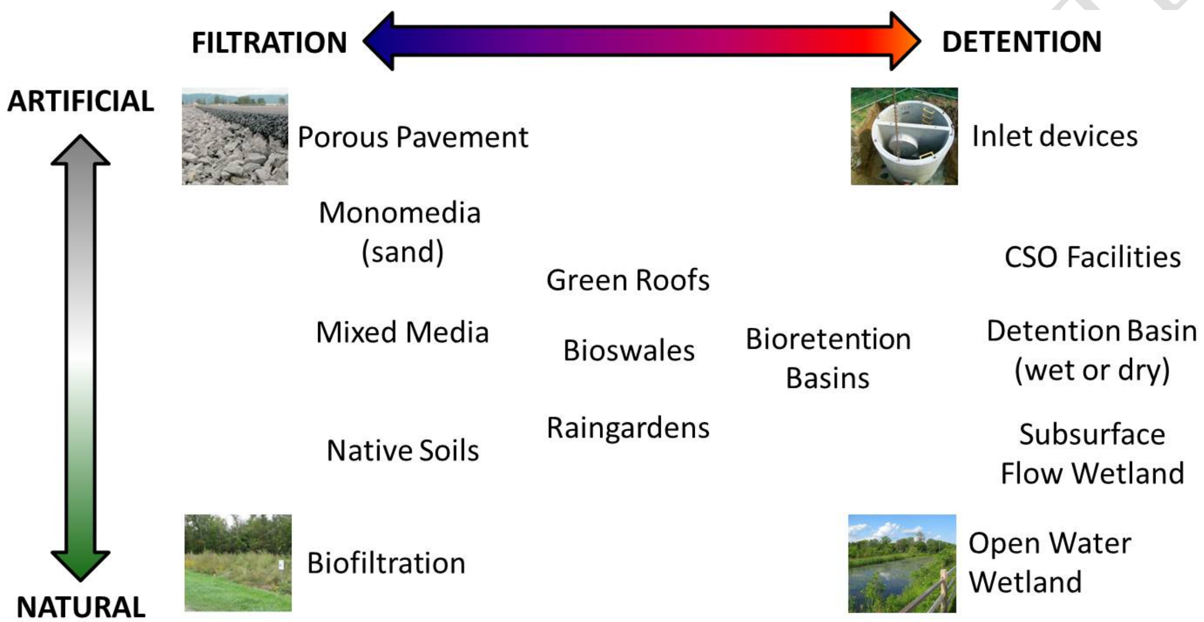

Figure 2. Spectrum of urban structural BMPs

1.4.2.1. ***Porous Pavements***

Total P removal rates of 60-71% have been reported through the use of porous pavements (Hogland et al. 1987; MWCOG 1983; Young et al. 1996). However, statistically significant differences were not observed when comparing total P concentrations in stormwater inflow versus outflow in a study conducted by Leisenring et al. (2010) on data submitted to the International Stormwater BMP Database.

1.4.2.2. ***Media Filters***

Engineered filtration systems appear to be a promising BMP to reduce P loads in stormwater runoff. Subsurface sand filters are reported to remove 43-70% of total P (Bell et al. 1995; Horner and Horner 1995; Young et al. 1996). Similar removal rates are found for subsurface sand filters (City of Austin 1990; Welborn and Veenhuis 1987). Some have suggested that increasing the amount of organic content in filter media would enhance removal (e.g. Leisenring et al. (2010)). Unfortunately, studies investigating the removal of total P by organic medial filters report similar (49%) removal (Claytor and Schueler 1996; Management 1994; Stewart 1992). Winter and Duthie (2000) also P load reductions of 50% in southern Ontario (where sandy soils dominate) using infiltration ponds. Higher removal efficiencies were observed in Korea where approximately 82% of total P was found to be removed across 25 infiltration trenches evaluated over roughly a 2 year period (22 rainfall events) (Maniquiz et al. 2010). These results are similar to results observed in data submitted to the International Stormwater BMP Database, where statistically significant decreases in the concentration of total and ortho- P were observed in stormwater exiting media filters versus concentrations entering (Leisenring et al. 2010).

1.4.2.3. ***Filter Strips/Bioswales***

When carefully designed and constructed, level-spreader-grassed filter strips (LSGFS) along highways appear to result in significant reductions in P loadings in stormwater runoff (48%) (Horner et al., 1994; MMS, 1992; and Reeves, 1994). The length of level spreader-vegetative filter strip_is critical in determining P removal, with longer flow paths having greater removal efficiencies (Winston et al. 2011). When the majority of total P in stormwater is particulate bound, level-spreaders perform about as well as retention basins and permeable pavements (Winston et al. 2011).

Total P removal efficiencies of 45% (range: 19%-74%) for 30m long swales and 29% (range: <0%-58%) for 60m long swales were observed over 6 storms in a set of swales installed in the Pacific NW (Horner et al., 1994; MMS, 1992; and Reeves, 1994). Total P removal efficiencies of 30-85% for vegetated swales have been reported by others (City of Austin 1995 ; Claytor and Schueler 1996; Khan et al. 1992; Yousef et al. 1995; Yu et al. 1993; Yu and Kaighn 1995; Yu et al. 1994). Based on the event mean concentration (EMC), swales removed 25%-70% total P loads (Zhang et al. 2009). However, data reported to the International Stormwater BMP Database (19 studies, 293 outflow datapoints) indicated bioswales were found to produce a statistical significant *increase* in the median total, ortho- and dissolved P concentration in stormwater runoff (Leisenring et al. 2010). Particulate resuspension and nutrient leaching from soils, which may have been treated with P fertilizers, were suggested as possible causes of the increased P concentrations.

1.4.2.4. ***Green Roofs and Filter Boxes***

Green roofs have many positive attributes, such as reduce the peak flow generated from urban roof tops, providing added insulation, etc.; however they may actually contribute more P than they absorb, at least initially. In a study by Hathaway et al. (2008) two green roofs were found to contribute more total P than rainfall alone (an increase of 1 mg/L) and this effect was found to be greater (an increase of 0.8 mg/L) than a control roof, the increase was found to be statistically significant for both contrasts ($p < 0.05$). This increase in P loading was attributed to the leaching of material used to construct the green roof. Relatively few green roof systems have been adequately studied. However, the limited data suggests differences in performance in the short- versus long-term suggesting a need to conduct more rigorous long-term monitoring (Berndtsson 2010).

1.4.2.5. ***Bioretention Basins***

Bioretention basins include rain gardens, filter boxes and all other vegetative basins designed to increase infiltration and evapotranspiration. The removal efficiencies of P by bioretention basins have been reported to be as high as 97.2±2.1 and 76.9±10 depending on the composition of soils used to construct bioretention cells (Carpenter and Hallam 2010). Others have reported lower (50% for total P) removal efficiencies (Prince George's County 1993).

The importance of selecting the appropriate material is exemplified in studies where media high in P have resulted in increased P loads being discharged from BMP structures (e.g. bioretention, Hunt et al. (2006); bioswales and green roofs, Leisenring et al. (2010)). Total P removal rates for planter boxes are reported to be 30%-70% based on the EMC (Zhang et al. 2009).

1.4.2.6. ***Detention and Retention Basins***

Treatment efficiencies of detention basins are found variety vary considerably, ranging from 20% to 90% removal, depending on their design (City of Austin 1990; City of Austin 1995 ; Gain 1996; Harper and Herr 1993; Martin and Smoot 1986; Young et al. 1996; Yu et al. 1993; Yu and Benelmouffok 1988; Yu et al. 1994). Detention basins that are designed to empty completely between storms (typically for storms with 5 or 10 year return periods) are considered *dry* detention basins (Gibb et al. 1999). Detention basins designed to store runoff from more frequent storms (typically storing runoff from storms with return periods of 2 years or less for up to 72 hours) are considered *extended* dentation basins (Gibb et al. 1999). While contaminant removal by conventional dry detention basins is negligible (Gibb et al. 1999), total P removal by extended detention is approximately 20-40% (Horner et al. 1994).

Retention basins, also commonly called “wet ponds”, are a type of basin that is designed to never drain completely. These types of basins are found to remove approximately 47% of total P and 51% of the soluble P – based on the performance observed during 30 different monitoring case studies (Schueler, 1997). The maximum removal of soluble P by wet ponds is estimated to be 60% (Horner et al. 1994).

Indirect evidence, buildup of P in soils and sediment within a stormwater detention basin, suggest that detention basins designed with more natural features (longer flow paths, the use of native wetland plants, etc.) increases the amount of P retained (Hogan and Walbridge 2007). However, there is an insufficient data available to properly characterize the mechanisms responsible for P removal in these systems (Roy-Poirier et al. 2010). Mechanisms of removal include vegetative uptake, mineralization and immobilization. To increase P retention, material with high cation exchange capacity (CEC) (e.g. hemic peat) are recommended (Leisenring et al. 2010). As a result, some of the material known to adsorb P – zeolites, iron, aluminum oxide-coated sand, and similar filtration media – have been found to promote P removal (WERF 2005). Some have even investigated methods of recovering the stored P and regenerating sorption capacity to improve the sustainability of BMP systems. Unfortunately, desorption processes appear to be “much slower than initial sequestration” (Rosenquist et al. 2011).

1.4.2.7. ***Wetlands***

Removal efficiencies of constructed wetlands, which can be classified as surface flow or subsurface flow wetlands, have varied widely (Schueler 1997; Shaver and Maxted 1994). Combined approaches appear to be promising and treatment volumes are likely a significant determinant in performance. Based on measurements of EMCs, treatment wetlands have been found to remove between 30% and 70% of total P loads (Zhang et al. 2009). Leisenring et al. (2010) also found wetland basins to reduce the median total, ortho- and dissolved P concentrations in stormwater; only total P was found experience a statistically significant reduction due to wetland channels. However, based on the performance observed in 35 monitoring studies, the median P removal efficiencies for wetlands were 51% for total P and

39% for soluble P (Schueler 1997). The USEPA (1993) reports an even lower removal efficiency of only 25% for total P.

Removal conditions present in both subsurface flow and open surface wetlands are hampered by reducing conditions that can result in the release of previously sequestered P (Van de Moortel et al. 2009). Ultimately, a better understanding of the dynamic geochemical processes within wetland systems is required.

1.4.2.8. ***Commercial Devices***

Oil and grit separators have been found to be relatively ineffective (<10% removal efficiency) in reducing total P loads (Young et al. 1996). Another type of commercial device, a type of subterranean concrete detention basin designed to remove settled solids, similar to septic systems (i.e. Stormvault^{TM}), was found to remove approximately 50% of the P loads (Zhang et al. 2010).

1.4.3. Evaluation of Structural BMPs Treatment Efficiency

To independently evaluate the treatment efficiency of structural BMPs data was collected from the International Stormwater BMP Database (www.bmpdatabase.org). Over 6,000 records describing the event mean concentration (EMC) of P in runoff entering and exiting structural BMPs were used for this analysis. While measuring treatment based on inflow and outflow concentration alone is flawed (McNett et al. 2011), this is unfortunately the most common approach typically employed. For this analysis we relied on the EMCs, which are found to be one of the most accurate means for estimating pollutant loads. Of the records used for the analysis, ~83% were flow-weighted EMCs, ~2% were time-weighted EMCs, and ~12% were calculated or undefined EMCs. Inflow and outflow were paired based on individual events. From paired EMCs the treatment efficiency (β) was quantified by comparing the concentration of P being discharged from the BMP structure (C_{out}) relative to the concentration entering the structure (C_{in}):

$$\beta = \frac{C_{out}}{C_{in}} \qquad \text{(eq. 2)}$$

When the concentration of P leaving the BMP structure is less than the concentration entering, the treatment efficiency is less than 1 and the structure is removing P (i.e. the BMP is effective). When the concentration of P leaving the BMP structure is greater than the concentration entering the treatment efficiency is greater than 1 and the structure is adding P (i.e. the BMP contributes to P loading). For the purposes of this analysis, the general BMP classifications used by the International Stormwater BMP Database were used. Detention basins that were open or closed (e.g. underground vault), grass or concrete lined were lumped together. Retention ponds are similar to detention basins except they include a permanent pool of water. All media filters – sand, peat, geotextile, carbon, mixed, etc. – were lumped together. All types of porous pavement – asphalt, concrete, modular block, etc. – were lumped together. Bioretention basins include raingardens, tree box filters and other vegetative swales designed to result in ponding of stormwater until it evaporated or infiltrated. Wetlands with and without open water were also lumped together. The results of this analysis are presented in Figure 3.

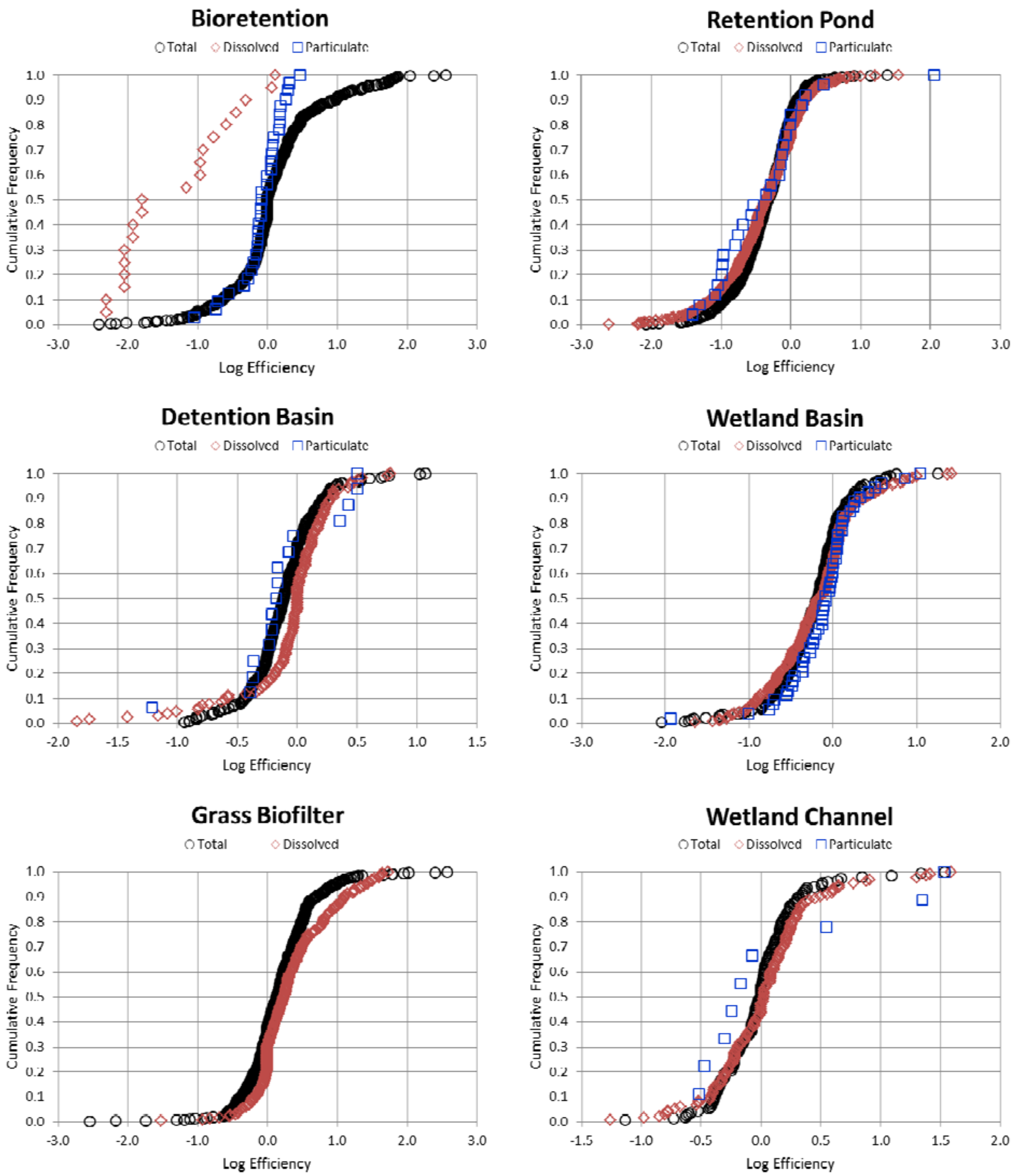

Figure3. Treatment efficiency for 6 classes of urban structural BMPs based on data collected in the International Stormwater Best Management Practices Database.

Based on this analysis, bioretention ponds and wetland basins appear to be the most reliable types of urban BMPs for the removal of P. Approximately 82% and 75% of the paired total P EMCs from bioretention basins and wetland basins showed some removal. Alternatively, grass biofilters (e.g. bioswales) were generally found to be ineffective at removing P. Based on total P EMCs only 43% of the samples were found to demonstrate P removal.

Results of this analysis also highlight the importance of understanding the different forms of P. Consider the results observed for detention basins (Figure 3). For these systems total P removal was observed in approximately 66% of all samples. However, only 45% of
the dissolved P samples demonstrated removal. Detention basins, biofilters and wetland channels were all found to have clearly different removal efficiencies for total versus dissolved P. As can be seen in Figure 3, the removal of different forms of P by structural BMPs tended to follow the order particulate > total > dissolved. It is important to note that the EMC for each form of P are often not equal. For instance, the average EMC for total P entering detention basins reported was 0.48 mgP/L while the average EMC for dissolved P was only 0.17 mgP/L. Therefore, from a loading perspective, detention basins are likely to still reduced overall P loads.

1.4.3.1. ***Cost of Structural BMPs***

Little reliable data is available regarding the cost of structural urban BMPs. Again data was collected from the International Stormwater BMP Database to provide cost estimates of structural BMPs. These costs were broken down into total facility costs (Figure 4) – which generally include the cost of design, construction, excavation, landscaping, etc. – and maintenance costs (Figure 5).

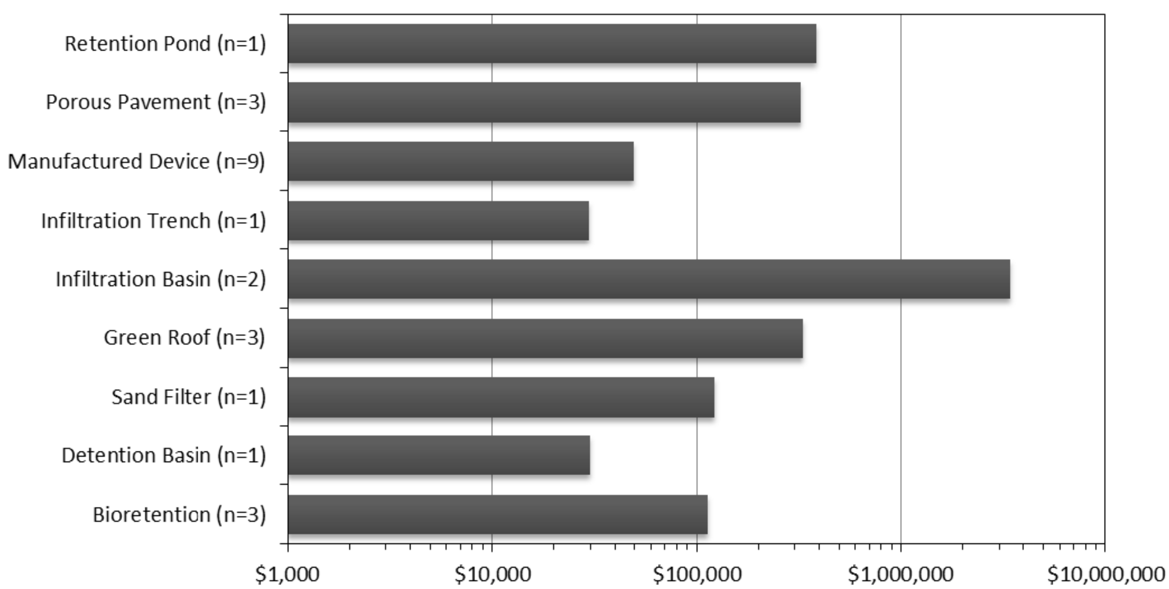

Figure 4. Average total facility costs in 2012 US/Canadian Dollars (note log scale).

While the amount of cost data available in the International Stormwater BMP Database is not conclusive, it does provide a general indication of the system costs. Based on the data available, engineered infiltration basins are clearly the most expensive type of structural BMPs. Detention basins and infiltration trenches appear to be the cheapest facility. Caution must be used when considering these costs due to the (1) small sample size, (2) diversity of specific BMPs that are included within broad categories, and (3) the size of watersheds and facilities is not taken into account. For example, rain gardens are one type of bioretention basin. The cost of installing a rain garden is generally \$3 to \$5 per square foot or roughly \$10 to \$12 per square foot if installed by a professional landscaper. It is difficult to assess this cost with other types of larger retention basins that may be built to manage stormwater from large developments.

Significant differences between structural BMPs were also observed between the average annual maintenance costs (Figure 5). The single infiltration trenches that reported cost data to the database not only had the lowest total facility cost but also the lowest estimated cost for annual maintenance. Retention basins appeared to have the greatest annual maintenance cost, likely due to regular cleanings that typically are required to remove trash and other debris from the structure. While other systems undoubtedly retain these items, removal from dry systems between storms is typically easier and less costly.

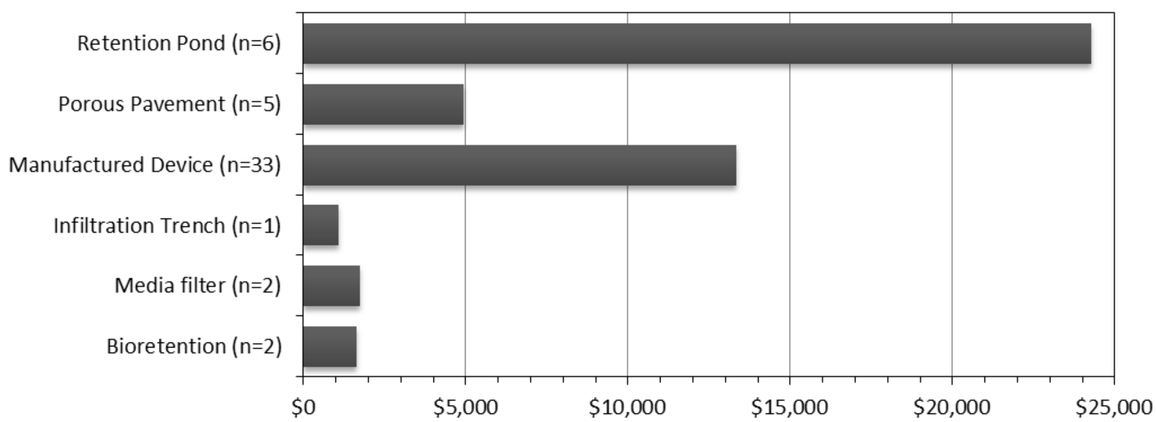

Figure 5. Estimated average annual maintenance cost (US/Canadian Dollars)

Ultimately, it would be extremely useful for enough cost data to be available to evaluate which systems are the most cost effective for given situations. While this data does not appear to be currently available, others have conducted studies to directly address this question. Based on the amount of total P removed as well as the construction and annual operating and maintenance (O&M) cost over a 20yr life, constructed wetlands appear to be more cost effective than other common BMPs – dry extended detention basins, wet basins, sand filters, bioretention filters, and infiltration trenches (Weiss et al. 2007). However, comparison of BMPs by Weiss et al. (2007) neglected the cost of land acquisition. Because wetlands tend to require larger land area than other BMPs, other BMPs may be preferred in densely urban areas where land is expensive. Clearly, much more work needs to be done in this area and greater data synthesis would be extremely helpful in order to properly evaluate BMP cost effectiveness.

1.4.4. Urban Point Sources

Structural and non-structural BMPs also exist for point sources and are largely responsible for large reductions in P loads to Lake Erie. While not the focus of this review a few illustrative examples are warranted. For example, the 1972 Great Lakes Water Quality Agreement limited discharges from major municipal sewage treatment plants to 1 mg/L total P. While Lake Erie receives the largest municipal load of P of any of the Great Lakes, large scale wastewater treatment plants have been nearly 100% compliant since the 1990s (Dolan 1993). One of the remaining sources of point source loadings of P to Lake Erie, and the Great Lakes in general, remains combined sewer overflows. Combined sewer overflow (CSO) facilities are estimated to be responsible for 90.4 metric tons of total P being delivered to Lake Erie annually from Ohio alone (Ohio EPA 2010). This is highlighted by Gomberg (2007), who cites 19 CSO outfall that discharge untreated sewage directly into Lake Erie and 107 other CSO outfalls to receiving waters that terminate in Lake Erie. These receiving waters include Mill Creek, the Cuyahoga River, Rocky River, and Big Creek. Finally, rather than reducing the amount of P being discharged from wastewater and CSO outfalls, reducing P loads before they enter sewer systems is likely to be cost effective. Therefore, if reducing P loads is desired, efforts should be made to identify sources of P loadings that could be eliminated. For example, one potential source of P loads to urban systems that are not typically considered and would contribute to the point source load that was identified by the work group responsible for this review is the addition of P to drinking water systems for corrosion prevention.

1.5. Monitoring of Urban BMPs

There is a general lack of coordination in evaluating urban, as well as rural, BMPs in the Lake Erie basin. The same could probably be said for the Great Lakes region as a whole. However, examples do exist within the Great Lakes where urban BMPs have been implemented, some specifically to reduce P loads to surface waters. Some examples systems include:

- Multiple BMPs – Laurel Creek, in the Grand River in Southern Ontario
- Bioretention - Detroit's storm-sewer-shed, Southfield, Michigan (Carpenter and Hallam 2010)
- Openwater Wetland – Swift Run Wetland, Huron River Watershed Ann Arbor, MI
- Detention Basin – Traver Creek Detention Basin, Huron River Watershed Ann Arbor, MI
- Retention Basin – Pittsfield Retention Basin, Huron River Watershed, Ann Arbor, MI
- Bioretention Basins and surface wetlands – Lake St. Clair Metropark, Mt. Clements, MI (expected to be completed 2013)

Two large scale efforts to evaluate the urban BMP performance within the Great Lake Watershed include those undertaken by Western Michigan University and the City of Columbus. Western Michigan University in Kalamazoo, Michigan has implemented 14 stormwater BMPs including using native plants and repairing erosion caused by urban runoff (Boyer and Kieser 2012). The City of Columbus, Ohio has also recently started monitoring total and dissolved P from a subset of representative watersheds (3 residential, 1 commercial and 1 industrial) (Ohio EPA 2010).
Despite these two locations, monitoring of BMP effectiveness is largely inadequate, even monitoring and reporting of P discharges is lacking (Gomberg 2007). Many urban BMPs simply to do not have enough data to fully evaluate their effectiveness (Strecker et al. 2001).

Two databases contain invaluable information regarding the performance of BMPs:

- ***International Stormwater Best Management Practices (BMP) Database –*** This database contains data on more than 30 types of BMPs from 531 sites (as of January 4, 2013). Users of the website can perform custom queries or download technical papers summarizing performance results. Unfortunately, less than 5% of these sites are within states or providences (Michigan, Ohio, Pennsylvania, New York, Ontario) adjacent to Lake Erie and most of these sites lie outside the Lake Erie watershed.

- ***National Pollutant Removal Performance Database –*** This technical brief by the Center for Watershed Protection summarizes the results of more than 150 pollutant removal studies.

1.6. Urban BMPs Performance Metrics

BMP performance can vary dramatically depending on the metric used (Lenhart and Hunt 2011). Recent research provides valuable direction to developing better metrics. Articles by Strecker et al. (2001) and Urbonas (1995) are required reading for determining stormwater BMP effectiveness. Numerous studies strongly discourage evaluating BMPs based on concentrations alone because performance varies during and between stormwater runoff events (Lenhart and Hunt 2011; Park et al. 2010). Particularly problematic is the simple percent removal metric because it is dependent on the initial concentration of pollutant (e.g Zhang et al. (2010)).

The "removal efficiency metric is flawed because it does not account for background water quality, eco-region differentiation, and background, or "irreducible," concentrations. Additionally, the removal efficiency metric inherently assumes a definite association exists between influent and effluent pollutant concentrations" (McNett et al. 2011). This is particularly apparent when evaluating the effectiveness of total P removal in bioretention systems where a statistically significant relationship could not found between influent and effluent total P concentrations for 11 bioretention cells in the mid-Atlantic United States (McNett et al. 2011).

Regardless of the type of BMP, there are only a handful of mechanisms responsible for the removal of P in stormwater: biouptake, sorption and precipitation. Ultimately P is retained via physical processes, either by attaching to material within BMPs (e.g. sorption to wetland plants) or by settling out - directly as a precipitate or indirectly while associated with biological material or suspended solids. Of these mechanisms, sorption reactions are the most common mechanism employed by most BMPs. On average, ~ 70% of P in stormwater is removed by the elimination of particles greater than 20μm in diameter; 90% P is associated with dissolved particles (>0.45 μm) (WERF 2003). However, because P partitioning between particulate and soluble forms can vary widely depending on amount and type of solids present and chemical species can convert rapidly, improving BMP performance "*will also likely need to address dissolved P in order to achieve high and/or consistent pollutant removal"* (Leisenring et al. 2010). This need for more advanced analysis of phosphorus is a common theme throughout urban and agricultural BMPs.

Additionally, stormwater runoff events are not independent of each other and therefore all storm volumes and their chemical composition cannot be considered equal (Strecker et al. 2001). Consider wetlands or detention basins with permanent pools where runoff from one storm event inevitably mixes with water retained from previous storm events. Even in "dry" systems previous runoff events can influence current or future runoff events. For example, sediments deposited previously during relatively low flow runoff events may be resuspended later during high flow, more intense runoff events. Sorption reactions may be reversed due to changes in chemical conditions resulting in an increased dissolution of P previously retained on soil, sediment or other material. Both of these processes, resupsension and desorption, are cited as resulting in ***increased*** P loadings from physical structures installed as BMPs (e.g. Leisenring et al. (2010)). Due impart to the aforementioned processes, Strecker et al. (2001) suggests effluent quality appears to be a much better estimate of BMP effectiveness than percent removal.

Furthermore, sampling schemes must take into account the variability inherent to these dynamic systems. For instance, rarely if ever would grab sampling be effective in assessing water quality. Flow weighted event mean concentrations are the preferred measurement technique for estimating loadings. If systems are large enough or contain sufficient amount of natural vegetation (e.g. constructed wetlands) sampling will likely also need to account for diurnal and seasonal variation (e.g. Burniston et al. (2009)). Overall much more rigorous sampling analysis protocols are needed to assess the effectiveness of urban BMPs.

1.7. Summary of Findings and Research Needs: Urban BMPs

1. Very few studies have been conducted on quantifying non-point source loads of P, let alone the treatment efficiency of urban BMPs, within the Lake Erie watershed

2. Urban BMP treatment efficiency varies greatly and some BMPs actually increase P loadings.

3. There is a need to develop better models to assess and predict treatment efficiency of urban BMPs

4. Mechanistic understanding of desorption processes and methods for regenerating sorption capacity must be achieved so that systems can become more sustainable (Rosenquist et al. 2011)

5. The majority of monitoring conducted on urban BMPs measures only total P. While this may provide an estimate loads, it is not sufficient to assessing processes for BMP functions that are required to enhance the design of structural BMPs.

6. Assessing the effectiveness of a single BMP is complicated and difficult since most BMPs are in combination with at least another BMP.

7. Most monitoring is conducted for short periods of time (1 year is common). Long-term monitoring is required to accurately describe the effectiveness of urban BMPs as well as their sustainability.

8. Central data repository is required to monitor BMPs (e.g. www.bmpdatabase.org/)

9. Effect of extreme weather and climate change need to be taken into account to better understand the long-term sustainability of urban systems.

2. BEST MANAGEMENT PRACTICES IN AGRICULTURAL AND RURAL ENVIRONMENTS

2.1. Agricultural BMPs

Agriculture has been targeted as a major source of nonpoint pollution, such as phosphorus (P), nitrogen (N) and sediments. Carpenter et al. (1998) reported that: (1) over-enrichment of rivers, lakes, estuaries, and coastal oceans with P and N has resulted in widespread eutrophication; (2) nonpoint pollution from agriculture and urban activity is a major source of P and N to surface waters of the United States; (3) in the United States and many other nations, inputs of P and N (e.g., fertilizers) exceed agricultural outputs in produce; (4) nutrient flows to aquatic ecosystems are correlated with animal stocking densities, and manure production in high livestock densities exceeds crops' needs to which manure is applied; (5) excess fertilization and manure production cause soil P accumulation and can be transported to aquatic ecosystems. Agricultural systems have evolved from net P sinks, where crop production is P-limited, to sources where there is net P excess in the farms. Sharpley et. al. (2006) suggested that the control of agricultural P losses should be directed towards the long-term goal of increasing farm P-use efficiency. This goal is achieved by practices that balance P inputs and outputs within a watershed and improve the management of soil, manure, and mineral fertilizer at the farm, watershed, or regional scales.

The effectiveness of agricultural best management practices (BMPs) is better understood by identifying the phosphorus forms in the soil, their transformations, transport, and pathways (i.e., the phosphorus cycle). The P in the soil occurs in organic or inorganic (mineral) form (Figure 6).

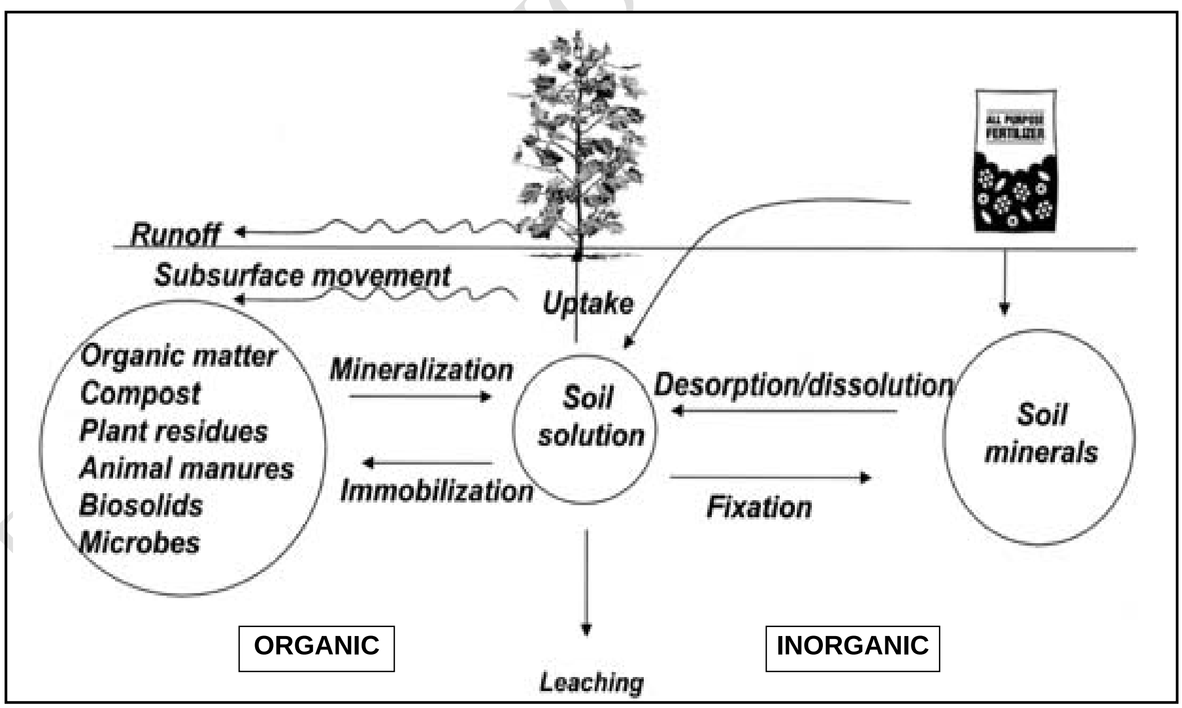

Figure 6. Simplified phosphorus cycle in the soil (adapted from Espinoza et al., 2005).

Organic P associated with plant residues, organic matter, microbial biomass, etc., makes up a large portion of phosphorus in the soil. Until the organic materials are mineralized and the subsequent release of phosphorus, organic P is highly stable and is not available for plant uptake. Inorganic P (as orthophosphate, PO_4^-) is usually sorbed in aluminum, iron, or calcium compounds, depending on the soil pH. Inorganic P in the soil solution at any given time is very small, amounting to less than 1.1 kg/ha in Arkansas soils (Espinoza et al. 2005). During storm events, particulate P (PP, both organic and inorganic soil-bound P) and dissolved P (both organic and inorganic) are transported by runoff water. Studies have shown that the amount of P in runoff water is directly correlated with the available P in the soil (McDowell and Sharpley 2001; Schroeder et al. 2004; Sharpley 1985; Sharpley 2003; Sims 1998; Torbert et al. 2002). Dissolved P maybe leached with the downward vertical water movement through the soil profile. Leaching of dissolved-P is an issue in soils nearly or at P-saturation and where there is macropore and bypass flow to tile drains (Sharpley et al. 2006).

Gentry et al. (2007) indicated that tile drains are a source of phosphorus to streams and showed a considerable increase in DRP and PP concentrations in tile-drains with increasing discharge. A recent study in Canada showed that PP contributed to as much as 80% of the total P loss through the tile-drainage system (Tan and Zhang 2011).

The BMPs can be divided according to source and transport of different forms of phosphorus. In the United States, most of these BMPs are established according to the United States Department of Agriculture's National Resources Conservation Service (USDA-NRCS) standards. These standards and their description are listed in the following URL (accessed on December 10, 2012: http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/nra/nri/?&cid=nrcs143_026849). Source BMPs are generally the management approaches that minimize the potential of P as a pollution at the origin, i.e., before P is transported from the soil by water movement. Transport BMPs are mostly structures and methods that reduce the transport of P with water and sediments (Agouridis et al. 2005; Herendeen and Glazier 2009).

In the succeeding sections, agricultural BMPs recommended by the Ohio Lake Erie Phosphorus Task Force (OH-LEPFT) for reducing phosphorus, nitrogen and sediment exports to Lake Erie are presented (OH-EPA 2010). There were several literature reviews about BMP effectiveness and the latest was by (Kroger et al. 2012). Most of the materials gathered evaluated a suite of BMPs implemented simultaneously together. The most comprehensive one was by (Bishop et al. 2005) where they evaluated 16 BMPs, both management and structural practices, at field and watershed scales in a paired watershed study. These studies were done or focused outside of Lake Erie watersheds, but some these BMPs maybe already implemented or are applicable in the Lake Erie watersheds. BMP effectiveness is very site-specific and depends on local topography, climate, cropping systems, maintenance, selection, and installation (Alfera and Weismiller 2002). The BMP effectiveness tool (available online, (Gitau 2013)) created by Merriman et al. (2009) with the addition of recent references were used to tabulate the effectiveness of the BMPs discussed. Current challenges and research needs are also discussed.

2.2. Agricultural P-source BMPs

The "front line of action" in minimizing P exports from agricultural lands is the control of P at the source: i.e., reduce the potential of P to be carried away. P-source BMPs are designed to decrease P buildup in the soil but sufficient enough for optimum crop growth. Recommended management approaches are: (a) regulate P at the farm gate, (b) control the quantity of P in manure, and (c) manage the amount of P application (Sharpley et al., 2006). Table 1 summarizes common actions associated with source BMPs.

Table 1. Actions associated with P-source BMPs (Adapted from Sharpley et al., 2006)

1. Balance P inputs with outputs at farm or watershed scale
2. Minimize P in livestock feed
3. Test soil and manure to maximize P management
4. Physically treat manure to separate solids from liquid
5. Chemically treat manure to reduce P solubility (i.e., alum, fly ash, and water treatment residuals)
6. Biologically treat manure (i.e., microbial enhancement)
7. Calibrate fertilizer and manure spreaders
8. Apply proper application rates of P
9. Use proper method for P application (i.e., broadcast, plowed in, injected, subsurface placement, or banding)
10. Carefully time P application to avoid imminent heavy rainfalls
11. Implement remedial management of excess P areas (spray fields and disposal sites)
12. Compost or pelletize manures and waste products to provide alternate use
13. Mine P from high-P soils with certain crops and grasses
14. Manage urban P use (lawns and gardens)

2.2.1. Farm gate regulation

2.2.1.1. ***Fertilizer management***

Economic pressure and extension activities have resulted in efficient fertilizer management; thus, the unnecessary influx and over-application of fertilizers into farms and agricultural soils were generally not considered a major cause of nonpoint source pollution (Sharpley et. al., 2006). In northwest Ohio however, it is not uncommon for the farmers to apply two years' worth of fertilizer at the start of a corn-corn or corn-soybean crop rotation. This practice is now being discouraged and its use is slowly diminishing. Efficient fertilizer management is a component of the "4R" nutrient stewardship principle and is further discussed in the succeeding sections (see Managing P Applications to Soil).

2.2.1.2. ***Animal feed management***

In animal-based agriculture, feed mass balance has become an evolving and important BMP. Animal farms have decreased in numbers but their capacity (herd size and animal densities) have increased. As a consequence, net nutrient influxes and net nutrient excess occurs in most of these farms (Sims, 1977). Studies have shown a direct relationship between dairy cow P-intake and P-excretion (Dou et al. 2002; Wu et al. 2001). According to (Knowlton and Kohn 1999), phosphorus intake beyond the minimum dietary requirements increased feed costs and reduced profitability but did not result in any animal growth or health advantages.

Feed management (NRCS 592 standard) is defined as "manipulating and controlling the quantity and quality of available nutrients, feedstuffs, or additives fed to livestock and poultry" (USDA-NRCS 2011). The objectives of feed management are: 1) Improve feeding efficiency to facilitate and contribute to the conservation of natural resources; 2) Reduce the quantity of nutrients (e.g., N, P, S, salts, etc.) excreted in the manure; 3) Reduce pathogens in manure, and 4) Reduce odor, particulate matter, and greenhouse gas (GHG) emissions production from animal feeding operations (USDA-NRCS 2011).

Effectiveness

McDowell et al. (2008) suggested that decreasing P in feeds is the best method to mitigate P loss from feces. Manure total P reductions with feed management range from 16% to 33% (Cerosaletti et al. 2004; Ghebremichael et al. 2008; Hristov et al. 2006; Wu et al. 2000; Wu et al. 2003). Two studies were found to evaluate feed management effectiveness in reducing nutrient export: 1) Ghebremichael et al. (2008) evaluated land application of dairy manure in a watershed over a 3-year SWAT model simulation period and 2) VanDevender (2003) as cited by (Merriman et al. 2009) evaluated nutrient runoff in field plot study of swine manure application (Table 2).

Table 2. Animal feed management effectiveness in nutrient reduction (%).

Study Method	Study scale	Remarks	TP	DRP	PP	TN	SS	Reference
Field Plot	Field plot	Swine	25	9	-	-	-	Van Devender et al., 2003
Modeling	Small watershed	Dairy Cow	-	13	16	-	-	Ghebremichael et. al., 2008

2.2.2. Manure Management

Manure export from the farm is not a viable management option because the hauling costs generally preclude its transport across long distances and off-farm land application options are generally restricted to the nearest neighbors (Sharpley et. al., 2006). In most areas, waste storage, composting, and land applications are the most viable options for manure management.

2.2.2.1. Animal waste system: waste storage facility (NRCS code 313), treatment lagoon (NRCS code 359), and waste treatment (NRCS code 591).

A waste storage facility is an impoundment made by constructing an embankment and/or excavating a pit or dugout, or by fabricating a structure (USDA-NRCS 2003). Its purpose is "to temporarily store wastes such as manure, wastewater, and contaminated runoff as a storage function component of an agricultural waste management system."

Effectiveness: Table 3 shows the nutrient reduction efficiencies of animal waste system BMPs.

Table 3. Nutrient reduction efficiencies of animal waste system BMPs (%).

Study Method	Study scale	Remarks/State	TP	DRP	PP	TN	SS	Reference
Field studies	Field	Poultry litter alum	70	-	-	-	-	(Lory 1999)
Field Studies	Field	Swine manure alum	-	84	-	-	-	(Smith et al. 2001)
Plot Studies	Plot/rainulator	Poultry litter alum	-	87	-	-	-	(Shreve et al. 1995)
Literature	Small watershed	Poultry litter alum	72	75	-	-	-	(Moore et al. 1999)
Literature	Field	Animal waste system	90	-	-	80	60	(Cestti et al. 2003)
Modeling	Large watershed	Waste Storage Facility	27	-	-	29	-	(Mostaghimi et al. 1997)

Literature	Field	Waste Storage Facility	90	-	-	75	-	(Randall et al. 1987)
Literature	Field	Waste Treatment Lagoon	0-90	-	-	-	-	(Gilliam 1995)
Field	Field	Waste Treatment Lagoon	34	-	-	43	-	(Hubbard et al. 2004)

2.2.2.2. Composting facility (NRCS code 317).
"A structure or device to contain and facilitate the controlled aerobic decomposition of manure or other organic material by micro-organisms into a biologically stable organic material that is suitable for use as a soil amendment." (USDA-NRCS 2003). The goals of a composting are: 1) reduce the pollution potential and improve the handling characteristics of organic waste solids, and 2) produce a soil amendment that adds organic matter and beneficial organisms and provides slow-release plant-available nutrients, and improves soil condition.

Effectiveness: One study directly evaluated a composting facility in reducing phosphorus as a pollutant source. (Bekele et al. 2006) reported that the implementation of a manure composting program reduced runoff SRP concentrations from field sites by 19% to 23%.

2.2.2.3. Vegetative treatment area (VTA, NRCS code 635)
"An area of permanent vegetation used for agricultural wastewater treatment to improve water quality by reducing loading of nutrients, organics, pathogens, and other contaminants associated with livestock, poultry, and other agricultural operations." (USDA-NRCS 2008). There are four kinds of plant-based treatment systems: 1) VFS that matches crop nitrogen uptake with estimated N in runoff and requires sheet flow across the filtering slope, 2) constructed wetlands but their design and management should take account intermittent flow from open lots, 3) discharging or nondischarging infiltration basin systems with berms placed around the vegetative area and the size of the infiltration basin is based on the vegetative area that can allow infiltration design runoff within 30 to 72 h, and 4) overflow and/or cascading terraces that are similar to infiltration basins (Koelsch et al. 2006). In 2008, the USDA-NRCS released updated and specific guidelines and standards for vegetative treatment areas (USDA-NRCS 2008).

Effectiveness: Most of the literatures gathered explicitly identified VTAs as VFS, constructed wetlands, and infiltration/ponding basins or a combination of the three. For brevity, effectiveness of these BMPs is discussed in the later sections.

2.2.3. Managing P Applications to Soil

2.2.3.1. ***Nutrient management***
The USDA-NRCS standards for nutrient (both fertilizer and manure) management (NRCS code 590) entails managing the amount (rate), source, placement (application method), and timing of plant nutrients and soil amendments. Nutrient management is devised to : 1) budget, supply, and conserve nutrients for plant production; 2) minimize agricultural nonpoint source pollution of surface and groundwater resources; 3) properly utilize manure or organic by-products as a plant nutrient source; 4) protect air quality by reducing odors, nitrogen emissions (ammonia, oxides of nitrogen), and the formation of atmospheric particulates; and 5) maintain or improve the physical, chemical, and biological condition of soil (USDA-NRCS 2012).

The "4R" stewardship framework

The updated nutrient management practices are largely based from the “4R” (right source, right rate, right time, and right place) nutrient stewardship framework jointly promoted by The Fertilizer Institute (TFI), International Plant Nutrition Institute (IPNI), the International Fertilizer Industry Association, and the Canadian Fertilizer Institute (CFI). The role of fertilizer distributors, retailers, and certified crop advisors (CCAs) is vital in managing fertilizer at the farm. The “4R” was mostly based from (Roberts 2007):

> *Right Fertilizer Source.* The right source means matching appropriate fertilizer source and product with soil properties and crop needs. Nutrient interactions should be accounted and nitrogen, phosphorus, potassium, and other nutrients should be balanced according to crop needs and soil tests.
>
> *Right Rate.* The right rate means matching application rates with crop requirements. Excessive fertilizer application may lead nutrient loss to the environment with no additional gain crop yield and quality.
>
> *Right Time.* The right time means making the nutrient available when the crops need them. Practices such as pre-plant or split application timing, controlled release technologies, stabilizers, and inhibitors influence the timing of nutrient availability.
>
> *Right Place.* The right place means placing and keeping nutrients where the crop can efficiently use them. The method of fertilizer application is critical for efficient fertilizer use. The most appropriate placement method is determined by the crop, cropping systems, and soil properties. Injection or incorporation is the preferred method but soil disturbance needs to be balanced with erosion-control BMPs. Among these erosion-control BMPs that help keep nutrients in place and increase nutrient efficiency fertilizer use are conservation tillage, buffer strips, cover crops, and irrigation management.

The implementation of nutrient-management related BMPs has environmental as well as economic benefits; off-farm nutrient transport is an investment loss for the farmers (Mullen et al., 2009). Among the specific practices are:

i. Soil, Manure, and Tissue Sampling and Laboratory Analyses. Nutrient planning must be based on recent soil, manure, and tissue tests and the analysis should be according to a land-grant university guidance or a university-recognized industry practice (USDA-NRCS 2010). Soil testing is the most cost effective and environmentally sound practice a producer can implement (Mullen et al., 2009). Fertilizer recommendations are usually available for each state in the U.S. and application rates can be calculated based from the soil tests and the crop demands.

ii. Timing and applications. According to the (USDA-NRCS 2010), the timing and placement of nutrients must correspond with crop demand and account for nutrient source, cropping system limitations, soil properties, weather conditions, drainage system, soil biology, and nutrient risk assessment results. Furthermore, nutrients must not be applied on 1) frozen and/or snow-covered soils, and 2) when the top 2 inches of soil are saturated from rainfall or snow melt.

Effectiveness: Nutrient management and other related practices (e.g., soil and tissue test, fertilizer rates calculation, variable rate application, precision agriculture, etc.) in crop-based agriculture were primarily geared towards efficient agronomic output (Bermudez and Mallarino 2007; Kitchen et al. 1995; Mallarino et al. 1999; Nanni et al. 2011; Wittry and Mallarino 2004; Yang et al. 1999; Yang et al. 2001) but not necessarily for environmental quality. Nutrient management towards better water quality seems to be more prevalent in animal-based agricultural production. It is not surprising that the effectiveness of nutrient management in reducing nutrient loads is not well-studied in purely crop-based production agriculture.

The method of nutrient application is related to tillage methods (Andraski et al. 1985). (Reckhow et al. 2009) further suggested that the fertilizer application rate's effect on phosphorus loss at a farm scale is directly related to application method, the hydrologic soil group, and crop type. Most nutrient management evaluation studies dealt with fertilizer (or manure) application rates in combination with tillage and fertilizer application methods (Hamlett and Epp 1994; Lewis and Makarewicz 2009; Li et al. 2011; Mostaghimi et al. 1991; Sedorovich et al. 2007). The risk of DRP transport and potential loss is reduced with minimum amount of tillage following nutrient application (Kleinman et al. 2002; Mullen et al. 2009). Nutrient management in combination with tillage and erosion practices may reduce total P loads by more than 80% (Figure 7), but in some cases may increase the loads (Cestti et al. 2003). (Lewis and Makarewicz 2009) observed that the concentrations of TP (~50%) and soluble reactive phosphorus (SRP similar to DRP, ~100%) increased in stream water when manure was applied in the winter after 2 years of BMPs (strip cropping, nutrient management, and drainage tiles) implementation. Nonetheless, after 4 years implementation of these BMPs, TP concentration decreased by 69% and SRP by 74%. Table 4 shows the summary of nutrient management effectiveness in reducing pollutant loads.

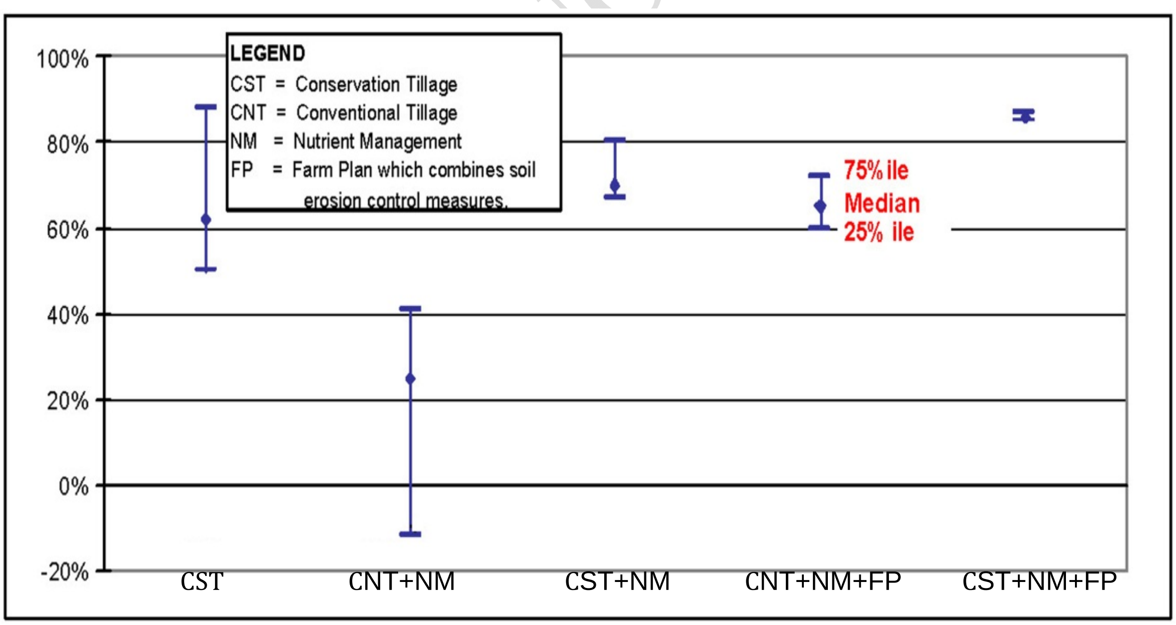

Figure 7. Total phosphorus reduction efficiency of BMPs in cultivated lands (adapted from Cestti, et. al., 2003).

Table 4. Summary of nutrient management (NM) efficiencies (%) in reducing pollutant loss.[a]

Method	Scale	Remarks/Location	TP	DRP	PP	TN	SS	Reference
Plot Studies	Plot/rainulator	Fertilizer and tillage treatments, VA	na[b]	na	na	96	95	(Mostaghimi et al. 1991)
Literature review	Plot, Field, watershed	Modeling and field app. across the US	35	na	na	15	Na	(USEPA 1993)
Literature review	Plot, Field, watershed	NM with a suite of BMPs, Cheasapeake Bay	-10[c] to 88	na	na	-2 to 84	Na	(Cestti et al. 2003)
Modeling	Field/farm	Manure and Tillage systems, PA	46	-62	na	na	56	(Sedorovich et al. 2007)
Field	Small watershed	NM with 4 other BMPs, manure based, NY	69	74	na	70	Na	(Lewis and Makarewicz 2009)
Field	Small watershed	NM with 4 other BMPs, Manitoba, Canada	38	41	42	41	Na	(Li et al. 2011)
Modeling	Small watershed	Manure nutrient management, TX	-5 to 12	na	na	-3 to 11	-22 to 12	(Rossi et al. 2012)

[a] Negative values indicate percent increase in nutrient loss instead of nutrient loss reduction.
[b] na: not applicable; not calculated.
[c] as total dissolved phosphorus (TDP).

2.3. P-Transport BMPs

Traditionally, transport BMPs are aimed for erosion control and total P reduction. Table 5 summarizes the common actions and objectives associated with transport BMPs.

Table 5. Actions associated with transport BMPs (Adapted from Sharpley et al., 2006).

1. Minimize erosion, runoff, and leaching
2. Use cover crops to protect soil surface from erosion
3. Terrace to minimize runoff and erosion
4. Practice strip cropping to minimize runoff and erosion
5. Practice contour farming to minimize runoff and erosion
6. Manage irrigation to minimize runoff and erosion
7. Practice furrow management to minimize runoff and erosion
8. Install filter strips and other conservation buffers to trap eroded P and disperse runoff
9. Manage riparian zones to trap eroded P and disperse runoff
10. Install grass waterways to trap eroded P and disperse runoff
11. Manage wetlands to trap eroded P and disperse runoff
12. Manage drainage ditch to minimize erosion
13. Stabilize streambank to minimize erosion
14. Fence streambank to keep livestock out of water course

15. Protect wellhead to minimize bypass flow to ground water
16. Install and maintain impoundments to trap sediment and P
17. Retain crop residues to minimize erosion and runoff
18. Consider reduced tillage systems to minimize erosion and runoff
19. Manage grazing (pasture and range) to minimize erosion and runoff
20. Restrict animals from certain sites
21. Install and maintain manure handling systems (houses and lagoons)
22. Manage barnyard storm water
23. Install and maintain milk-house waste filtering systems
24. Practice comprehensive nutrient management planning (CNMP)
25. Install and maintain tail-water return flow ponds

2.3.1. Residue and Tillage Management (Conservation Tillage)

These are management practices that leave at least 30% of the soil surface covered with crop residue following tillage and planting to reduce soil erosion (Galloway et al. 1981).

2.3.1.1. Mulch-till (NRCS code 345)

Mulch-till (NRCS code 345) is defined as "managing the amount, orientation and distribution of crop and other plant residue on the soil surface year round while limiting the soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting." Mulch-till is designed to:1) reduce sheet and rill erosion, 2) reduce wind erosion and particulate matter less than 10 micrometers in diameter - PM 10, 3) maintain or improve soil quality, 4) increase plant-available moisture, and 5) reduce energy use (USDA-NRCS 2011).

2.3.1.2. Strip-till and No- till

Strip-till and No- till (NRCS code 329) include "managing the amount, orientation and distribution of crop and other plant residue on the soil surface year round, limiting soil-disturbing activities to those necessary to place nutrients, condition residue and plant crops." They are designed to: 1) reduce sheet/rill erosion, 2) reduce wind erosion and particulate matter less than 10 micrometers in diameter - PM 10, 3) improve soil organic matter content, 4) reduce CO2 losses from the soil 5) reduce energy use, 6) increase plant-available moisture, and 7) provide food and escape cover for wildlife (USDA-NRCS 2011).

2.3.1.3. Ridge-till

Ridge-till (NRCS code 346) is the "managing the amount, orientation, and distribution of crop and other plant residues on the soil surface year-round, while growing crops on pre-formed ridges alternated with furrows protected by crop residue." Ridge-till is implemented to:1) reduce sheet and rill erosion, 2) reduce wind erosion and Particulate matter less than 10 micrometers in diameter - PM 10, 3) maintain or improve soil quality, 4) reduce energy use, 5) manage snow to increase plant-available moisture, 6) modify cool wet site conditions, and 7) provide food and escape cover for wildlife (USDA-NRCS 2011).

Conservation Tillage Effectiveness

Studies have reported that conservation tillage increases infiltration thereby decreases runoff (Baker and Laflen 1983; Blevins et al. 1990; Bosch et al. 2005; Chichester and Hauser 1991; Fawcett and Caruana 2001; Langdale et al. 1979). Nicolaisen et al. (2007) discussed that in no-till systems, the plant residue left on the soil surface reduces runoff volume but the runoff P-concentration is not reduced.

Cestti et al. (2003) reported that in general, conservation tillage reduces TP loads by as much as 60% and more than 80% when in conjunction with nutrient management and a farm plan (Figure 7). Table 6 summarizes the effectiveness of conservation tillage. It is not surprising that most studies evaluated sediment reduction. Conservation tillage was primarily implemented for erosion and total P control. A few studies however evaluated DRP reduction and there was a wide range of efficiency values (-390% to 91%). Nonetheless, Yates et al. (2007) concluded that no-till systems have a positive effect on the stream quality and the practice improved habitat and water quality as well as the benthic macro-invertebrate community.

Table 6. Effectiveness of conservation tillage BMPs in nutrient loss reduction (%).[a]

Method	Scale	Remarks/Location	TP	DRP	PP	TN	SS	Reference
Field Studies	Field plot	Soybeans, 0.01 ha plots., MS	na [b]	na	na	na	86	(Mcgregor et al. 1975)
Field Studies	Small watershed	Soybeans, 91 cm wide rows, tillage systems, GA	na	na	na	na	86	(Langdale et al. 1979)
Field Studies	Field plot	Soybeans, no till vs. conventional tillage, MS	84	na	na	90	99	(Mcdowell and Mcgregor 1980)
Field Studies	Field	Corn, 0.01 ha plots on 5% slope, MS	na	na	na	na	95	(Mcgregor and Greer 1982)
Field Study	Field plot	Soybeans, no-tillage, MS	na	na	na	na	16	(Hairston et al. 1984)
Field Plot Studies	Field plot	Soybeans, 4 m x 22.1 m plots, MS	na	na	na	na	94	(Mutchler and Greer 1984)
Field Plot Studies	Field plot	Corn, tillage systems at 2% off-contour, WI, Great Lakes	59 to 81	27 to 63[c]	na	na		(Andraski et al. 1985)
Field Plot Studies	Field plot	Cotton, no till vs. conventional tillage, MS	na	na	na	na	47	(Mutchler et al. 1985)
Literature review	varied	crop cover or residue left on the soil, Chesapeake Bay	87	na	na	82	97	(Randall et al. 1987)
Field Plot Studies	Field plot	Cotton, 1 m wide rows @ 20 seeds per meter , AL	23	na	na	24	52	(Yoo et al. 1988)
Paired Watersheds	Small watershed	Wheat, 4 sub-watersheds, OK	5	na	na	8	21	(Berg et al. 1988)
Field Studies	Field plot	Grains, VA	97	91	93	na	98	(Mostaghimi et al. 1988)
Field Studies	Field plot	Grains, rainulator, VA	na	na	na	91	95	(Mostaghimi et al. 1991)

Field Studies	Field plot	Rainulator, sludge, VA	66	29	66	91	69	(Mostaghimi et al. 1992)
Modeling	Large watershed	Livestock and related crops, VA	9	na	na	9	14	(Mostaghimi et al. 1997)
Field Studies	Field plot	Rice, LA	na	na	na	na	74	(Feagley et al. 1992)
Field Plot Studies	Field plot	Soybeans, plots 2.3 m x 20m, MS	na	na	na	na	83	(Dabney et al. 1993)
Paired Watersheds	Small watersheds	Soybeans, , MS	59	-390	93	82	98	(Schreiber and Cullum 1998)
Field Studies	Field plot	Soybeans, MS	na	na	na	na	70 to 90	(Meyer et al. 1999)
Modeling	Field size watershed	Cotton and soybeans, AnnAGNPS 2.1, MS	na	na	na	na	50	(Yuan et al. 2002)
Field monitoring	Small watershed	Suite of BMPs in the watershed	17	na	na	na	na	(Bryant et al. 2008)
Field/ Literature	Varied	Estimates for Cheasapeake Bay watershed	22	na	na	8	30	(Simpson and Weammert 2009)
Field/ Literature	Varied	Seasonal evaluation, Europe	10 to 80	na	na	na	70 to 89	(Ulen et al. 2010)
Paired watershed	Small watershed	Cereals & oil seed, Manitoba, Canada	-12	na	na	68	65	(Tiessen et al. 2010)

[a] Negative values indicate percent increase in nutrient loss instead of nutrient loss reduction.
[b] na: not applicable; not calculated.
[c] as algal available P (AAP).

2.3.2. Conservation Cropping

2.3.2.1. *Crop rotation*

Crop rotation (NRCS code 328) is growing crops in a planned sequence on the same field and is applied to 1) reduce sheet-and-rill or wind erosion, 2) improve soil quality, 3) manage the balance of plant nutrients, 4) supply nitrogen through biological nitrogen fixation to, 5) reduce energy use, 6) conserve water, 7) manage saline seeps, 8) manage plant pests (weeds, insects, and diseases), 9) provide feed for domestic livestock, 10) provide annual crops for bioenergy feedstocks, and 11) provide food and cover for wildlife, including pollinator forage, cover, and nesting (USDA-NRCS 2011). (Randall et al. 1987) discussed that crop rotation may reduce phosphorus (30 to 75%) and nitrogen (55 to 80%) runoff losses.

2.3.2.2. *Cover Crops* (NRCS code 340)

Areas that need vegetative cover for natural resource protection and or improvement can be planted with grasses, legumes, and forbs for seasonal cover and other conservation purposes (Nanni et al. 2011) . Cover crops are planted to: 1) reduce wind and water erosion, 2) increase soil organic matter content, 3) capture/recycle/redistribute nutrients in the soil profile, 4) promote biological nitrogen fixation and reduce energy use, 5) increase biodiversity 6) suppress weeds, 6) manage soil moisture, and 7) minimize and reduce soil compaction (Nanni et al. 2011).

Hoorman (2009) reported that cover crops increase mycorrhizal fungus activity that fosters a symbiotic relationship with the plants' roots for water and nutrient uptake. Plants provide the polysaccharides and the mycorrhizal fungus provided the protein to form a glycoprotein called glomalin which promotes soil aggregate stability (more macro-aggregates) and improved soil structure. Sorensen et al. (2005) further reported that cover crops increased the colonization of leek roots by mycorrhizal fungi.

The effects of cover crops on surface water quality can vary as a function of climatic, soil, and crop factors (Sharpley and Smith 1991). Cover crops reduce soil erosion (Mutchler and Mcdowell 1990) but may increase DRP (Simpson and Weammert 2009). Blanco-Canqui et al. (2011) reported that cover crops in no-till systems improved soil physical properties. Franchini et al. (2004) discussed the possibility of P redistribution into the soil under no tillage by using cover crops in rotation with cash crops. Further research is needed to determine the effects of cover crops on phosphorus reduction, especially DRP (Simpson and Weammert 2009).

2.3.2.3. <u>*Conservation Cover*</u>

Conservation cover (NRCS code 327), in contrast to crop cover, involves establishment and maintenance of a permanent vegetative cover. Conservation cover may accomplish one or more of the following: 1) reduce soil erosion and sedimentation, 2) improve water quality, 3) improve air quality, 4) enhance wildlife habitat and pollinator habitat, 5) improve soil quality, and 6) manage plant pests (USDA-NRCS 2011).

2.3.2.4. <u>*Strip Cropping*</u>

Strip cropping (NRCS Code 585) is the rotational growing of row crops, forages, small grains, or fallow of equal width strips arranged systematically across a field. Strip cropping may: 1) reduce water–induced soil-erosion and sediment transport and other contaminants, 2) reduce wind soil-erosion, and 3) protect crops from damage by wind-borne soil particles (Drizo 2009).

<u>Effectiveness:</u> Bosch et al. (2009) observed that post-BMP loading of SRP decreased by 74% and nitrate (NO_3) by 73 to 88%. The implemented BMPs include crop rotations, tillage practices, etc. (Jiao et al. 2011) also reported that double cropping systems reduced runoff volume and losses of total dissolved P (TDP), PP), and TP as compared with a wheat-fallow system. The observed that the wheat-soybean system reduced the 3-year mean runoff volume by 58%, TDP by 81%, PP l by 89%, and TP by 85% compared with wheat-fallow. Table 7 shows the effectiveness of general conservation cropping in reducing phosphorus and sediment loss.

Table 7. Effectiveness of conservation cropping in reducing nutrient and sediment loss (%).

Method	Scale	Remarks/Location	TP	DRP	PP	TN	SS	Reference
Field Studies	Field plot	chickweed as cover crop in soybeans with no-till, MO	na[a]	7 to 63	na	33 to 77[b]	92	(Zhu et al. 1989)
Field Studies	Field plot	Cover crop in cotton, MS	na	na	na	na	72.3	(Mutchler and Mcdowell 1990)
AnnAGNPS Modeling	Small watershed	Cotton and soybeans system, wheat as cover crop, MS.	na	na	na	na	32	(Yuan et al. 2002)
Literature review	varied	Crop rotation, across the USA	30	30 to 75	60 to 70	na	na	(Gitau et al. 2005)
Literature review	varied	Contour strip crop, across the USA	8 to 93	20 to 93	43 to 76	na	na	(Gitau et al. 2005)
Field	Small watershed	crop rotations & tillage practices, NY	na	74	na	73 to 88c	na	(Bosch et al. 2009)
Field/ literature	Varied	Cheasapeake Bay watershed	0 to 15	na	na	9 to 45	0 to 20	(Simpson and Weammert 2009)
Field	Small watershed	double cropping system, NY	85	81	1 to 89	na	na	(Jiao et al. 2011)
Paired Field Study	Small watershed	cover crop (cereal rye), spring manure and chisel plow, WI	26	8	na	21	30	(Jokela and Casler 2011)

[a] na: not applicable; not calculated.
[b] values for NO_3-N and NH_4-N.
[c] nitrate (NO_3) only.

2.3.3. Conservation Buffers

2.3.3.1. ***Contour buffer strips***

Contour buffer strips (NRCS code 332) are narrow strips of permanent, herbaceous vegetative cover established around the hill slope, and alternated down the slope with wider cropped strips that are farmed on the contour (USDA-NRCS 2010). Contour buffer strips are used to 1) reduce sheet and rill erosion, 2) reduce sediment and other water-borne contaminants downslope transport, and 3) increase water infiltration.

2.3.3.2. ***Riparian forest buffers***

Riparian forest buffers (NRCS code 391) are areas dominated by trees or shrubs adjacent to and up-slope of watercourses or water bodies. These buffers are used to: 1) lower or maintain water temperatures to improve habitat for aquatic organisms through shading, 2) create or improve riparian habitat and provide a source of detritus and large woody debris, 3) reduce excess amounts of sediment, organic material, nutrients and pesticides in surface runoff and reduce excess nutrients and other chemicals in shallow ground water flow, 4) Reduce pesticide drift entering the water body, 5) restore riparian plant communities, and 6) increase carbon storage in plant biomass and soils (USDA-NRCS 2010).

2.3.3.3. ***Filter Strips***

Filter strip (NRCS code 393) are strips or areas of herbaceous vegetation that remove contaminants from overland flow. These practice may reduce 1) runoff suspended solids and associated contaminants, 2) runoff dissolved contaminant loadings, 3) irrigation tail-water suspended solids and associated contaminants (USDA-NRCS 2010). Bhattarai et al. (2009) showed that vegetated filter strips reduced nutrient concentrations in surface runoff and can be used for controlling nutrients from feedlot.

Table 8. Effectiveness of conservation buffer in reducing nutrient and sediment loss (%).

Method	Scale	Remarks/Location	TP	DRP	PP	TN	SS	Reference
Field Studies	Field plot	Fescue filter strips, rainulator, MO	na[a]	62 to 87	48 to 92	38 to 86[b]	60 to 91	(Blanco-Canqui et al. 2004)
Literature	Field plot	Chesapeake Bay watershed	75	na	na	70	65	(Cestti et al. 2003)
Field Plot Studies	Field plot	Vegetated filter strip, poultry litter, AR	40 to 91	39 to 90	na	39 to 86	na	(Chaubey et al. 1995)
Field Plot Studies	Field plot	Erosion strip, KY	na	na	na	na	99	(Coyne et al. 1995)
Field Study	Field	grass filer strip, NC	55 to 65	25 to 55	na	40 to 48	53 to 68	(Daniels and Gilliam 1996)
Field Plot Studies	Field plot	Livestock, vegetated filter strip, VA	2 to 80	-108 to 31		1 to 80	31 to 95	(Dillaha et al. 1988)
Field Plot Studies	Field plot	Corn systems, vegetated filter strip, VA	49 to 93	-83 to 69	na	47 to 93	53 to 98	(Dillaha et al. 1989)
Literature	Field plot	Grass buffer strips, worldwide	14 to 85	-83 to 93	na	47 to 96	53 to 93	(Dorioz et al. 2006)
Field Plot Studies	Field plot	mudding-in w/ vegetated filter strip, rice systems, LA	na	na	na	na	78	(Feagley et al. 1992)
Field Plot Studies	Field plot	Multi-species riparian buffers, IA	78	58	na	80	95	(Lee et al. 2003)
Field Study	Farm	Three-zone riparian buffer, GA	56	na	63	37	na	Lowrance and Sheridan, 2005
Field Plot Studies	Field Plot	Grass-shrub riparian buffer,	92	na	na	92	99	(Mankin et al. 2007)
Field Plot Studies	Field plot	grass filters, corn systems VA	na	na	na	56 to 82	82 to 90	(Mendez et al. 1999)
Field Plot Studies	Field plot	4 m grass filter, North Carolina,	50	na	na	50	na	(Parsons et al. 1994)
Field Plot Studies	Field plot	Switchgrass filter strip, beef cattle systems,	47 to 76	na	na	na	na	(Sanderson et al. 2001)
Field Study	Field	Mature forest riparian buffer GA	na	na	na	na	68 to 95	Sheridan et al., 1999
Field Plot Studies	Field plot	Vegetated filter strip treated with poultry, AR	26 to 66	na	na	21 to 67	na	(Srivastava et al. 1996)
Modeling	Field size watershed	AnnAGNPS 2.1, cotton and soybeans systems, MS	na	na	na	na	18	(Yuan et al. 2002)

[a] na: not applicable; not calculated.

[b] values of NO_3-N, NH_4-N, and organic N.

2.3.4. *Wetlands*

Constructed wetlands (NRCS code 656) are artificially-made ecosystem with hydrophytic vegetation. Similar to urban constructed wetlands, they are designed to treat wastewater and runoff primarily from agricultural processing, livestock, and aquaculture facilities (USDA-NRCS 2010). Constructed wetlands are also used to improve storm runoff quality or other water flows lacking specific water quality discharge criteria. Other wetland-related conservation practices include 1) restoration (NRCS code 657), 2) creation (NRCS code 658), and 3) enhancement (NRCS code 659).

Wetland Effectiveness

Fisher and Acreman (2004) reviewed wetland (riparian and marshes) studies across the world and found out that majority of the wetlands reduced nitrogen and phosphorus loading. They also reported that increased nutrient loading resulted in elevated soluble N and P species that was observed in long-term and frequent sampling studies. Yates and Prasher (2009) reported an average decrease in concentration of 52% of total dissolved phosphorus (TDP) between the inlet and outlet of a constructed wetland. Hoffmann et al. (2012) observed a high nitrogen reduction efficiency and a net phosphorus release in two restored riparian wetlands. Rogers et al. (2009) observed that a disturbed wetland exported 50% more sediments and 30% more TP than what has entered the wetland. Table 9 shows the effectiveness of wetlands in reducing nutrient and sediment loads.

Table 9. Effectiveness of wetlands in reducing nutrient and sediment loss (%).

Method	Scale	Remarks/Location	TP	DRP	PP	TN	SS	Reference
Field Study	Field	Wetland restoration, Atlantic Coastal Plain, GA	97	na[a]	na	80 to 85	na	(Luederitz et al. 2001)
Field Study	Field	Wetland restoration, Atlantic Coastal Plain, GA	na	na	74	64	na	(Vellidis et al. 2003)
Field Study	Field	Constructed wetland, Southern Finland	-6 to 67	-33 to 33	na	-7 to 40	-5 to 72	(Koskiaho et al. 2003)
Field/ Literature	Varied	Several kinds of wetland, worldwide	50 to 90	25 to 95[b]	na	70 to 90	na	(Fisher and Acreman 2004)
Pilot Study	Plot/tank	2 soil types, Quebec, Canada	na	40	na	na	na	(Yates and Prasher 2009)
Field Study	Field	Compared retention in dry and wet days, South Korea	57	na	na	6 to 18	na	(Yi et al. 2010)
Field/ Literature	Varied	Efficiencies used in Chesapeake Bay model	12 to 50	na	na	7 to 25	4 to 15%	(National Research Council 2011)
Field Study[c]	Field	Restored riparian wetland, Denmark	26 to -127[c]	na	na	43 to 75	na	(Hoffmann et al. 2012)

[a] na: not applicable; not calculated.
[b] several P species.
[c] negative values indicate percent increase in nutrient loss instead of nutrient loss reduction.

2.3.5. *Grassed waterways*

Grassed waterways (NRCS code 412) are shaped or graded channels established with appropriate vegetation to carry surface water at a non-erosive velocity to a stable outlet. Grassed waterways are designed to 1) convey runoff from terraces, diversions, or other water concentrations without causing erosion or flooding, 2) reduce gully erosion, and 3) protect and improve water quality (USDA-NRCS 2010).

Mishra et al. (2006) studied the effects of percent slope and vegetative cover area of grassed waterways. They observed that under bare soil, the sediment concentration increased by 5 times from a 1% to 5 % bed slope. They suggested that a 25% cover was acceptable in a 1% slope. Dermisis et al. (2010) suggested that sediment yield reduction is a function of peak runoff and slope gradient. Fiener and Auerswald (2006) concluded that grassed waterways, when combined with an intensive soil and water conservation system, has a high potential of reducing runoff and sediment delivery. Table 10 summarizes the effectiveness of grassed waterways from the literature gathered. It is not surprising that all the studies measured sediment yield reduction only since grassed waterways are primarily designed to control erosion.

Table 10. Effectiveness of grassed waterways in reducing nutrient and sediment loss (%).

Method	Scale	Remarks/Location	TP	DRP	PP	TN	SS	Reference
Field Study	Field	Central Europe	na[a]	na	na	na	82	(Fiener and Auerswald 2003)
Modeling	Large watershed	Corn and soybean system, GA, MS, OK	na	na	na	na	1 to 35	(Renschler and Lee 2005)
Field Study	Field	Summer crops, with earthen dam, Belgium	na	na	na	na	93	(Evrard et al. 2008)
Field, Modeling	Small watershed	Corn and soybean, WEPP model, IA	na	na	na	na	10 to 80	(Dermisis et al. 2010)

[a] na: not applicable; not calculated.

2.3.6. Drainage Water Management

Drainage water management (NRCS code 554) involves managing the discharge water from surface and/or subsurface agricultural drainage systems. The goals of this conservation practice are: 1) reduce nutrient, pathogen, and/or pesticide loading from drainage systems into downstream receiving waters, 2) improve productivity, health, and vigor of plants, 3) reduce oxidation of organic matter in soils, 4) reduce wind erosion or particulate matter (dust) emissions provide seasonal wildlife habitat (USDA-NRCS 2008). Other practices or structures in drainage water management include: 1) subsurface drains (NRCS code 606) where excess water is collected and conveyed beneath the ground surface (USDA-NRCS 2011), 2) field ditch surface drain (NRCS code 607) where excess water from subsurface drains and surface water (e.g., sheet flow from land surfaces or channel flow from furrows) are intercepted and conveyed to drainage outlets (USDA-NRCS 2011), and 3) main or lateral surface drains (NRCS code 608) that serve as the drainage outlets for agricultural lands and are designed to convey surface and subsurface drainage water from field ditches and subsurface drains (USDA-NRCS 2011).

Effectiveness: According to Madramootoo et al. (2007), drainage and water table management practices may sometimes cause a largely water quality third-party impacts and drainage practices have evolved from water removal in increasing crop productivity to environmental control. Skaggs et al. (2012) discussed drainage water management and reviewed N loss and crop yield effectiveness but none on phosphorus. Adeuya et al. (2012) observed an annual NO_3 load reduction of 15 to 31% attributed to impacts of drainage water management on subsurface drain flow in Indiana. Cooke and Verma (2012) also reported a reduction of annual NO_3 loads by

37% to 97% in a drainage water management in Illinois. They further cited that a combination of BMPs, including drainage water management, results in a 20% reduction of edge-of-field N loss and costs less than a third of reducing fertilizer application by 45% that would result in the same N reduction.

It can be observed that the above studies evaluated N reduction only. This is not surprising since the conventional wisdom was that the majority of P losses occur as particulate P attached to sediments that are transported by surface runoff. As such, P losses in subsurface water are small compared to surface runoff and increasing subsurface drainage volume will lower surface runoff and the potential of P loss Grazhdani et al. (1996). However, Gentry et al. (2007) concluded that tile drains are a source of phosphorus to streams and showed a considerable increase in DRP and PP concentrations in tile-drains with increasing discharge. Reid et al. (2012) discussed tile drainage systems as a significant conduit for P losses to surface water. They specified that dissolved P forms from fertilizer, manure, and other organic P sources maybe transported by: 1) preferential flow to tiles, 2) matrix flow to tiles, and 3) matrix flow to surface drains.

Reid et al. (2012) observed 0.07 to 36.0 kg/ha of P-loss through tiles drains across various soil types. Vidon and Cuadra (2011) reported that SRP transport to tile-drains was a function of macropore flow in large storms (>6cm), where macropore flow is between 43 and 50% of total tile-drain flow. SRP transport was controlled by matrix flow in smaller tile-flow generating precipitation events (<3cm), for which macropore flow only accounted for 11–17% of total tile-drain flow. They further observed SRP (0.006–0.025 mg/L) and TP (0.057–0.176 mg/L) median concentrations varied between storms. Coelho et al. (2012) noted that drainage tile flow had 31, 24 and 16% of the overland + subsurface DRP, TP and sediment loads, respectively. They concluded that P and turbidity in surface water can be controlled by suitable artificial drainage strategy.

Jia et al. (2006) suggested “that irrigation scheduling and proper management were more to water quality than remedial actions such as controlled drainage or vegetative buffers.” Tan et al. (2007) reported that a controlled drainage and sub-irrigation (CDS) system reduced total nitrate loss by 41% compared to traditional tile drainage (DR). The CDS system also reduced TDP losses in tile drainage water 36% relative to the non-irrigated DR system.

2.3.7. Emerging Technologies

Examples of current and emerging technologies that need more research for the reduction of P loadings from agricultural areas include: 1) two-stage ditches (Powell et al. 2007), 2) controlled drainage (Kroger et al. 2011; Nistor and Lowenberg-DeBoer 2007), 3) focus on overall soil quality/health, 4) hydrologic attenuation, 5) nutrient management education as a BMP, 6) treatment of tile outlets with bioreactors, filters, etc. (McDowell et al. 2008). Lastly, more edge of field research and monitoring under real world farming systems and real world climatic events should be done (Steve Davis, personal communication).

2.4. Effects of Extreme Weather

Chaubey et al. (2010) reported that pollutant losses are greater under certain extreme weather conditions than the pollutant reductions caused by BMP implementation in a watershed. The NCWQR data (available at http://www.heidelberg.edu/academiclife/distinctive/ncwqr, unpublished) also showed that the *DRP* loads in the Sandusky and Maumee watersheds for Spring 2012 was less than 3% of the *DRP* loads in the Spring 2011. Spring of 2011 was among the wettest on record, while the spring of 2012 was among the driest. It is noteworthy that BMPs were similar between these two periods. Based from these data, BMP effectiveness threshold limits is confounded by weather patterns. BMP effectiveness therefore should be assessed over a long period of time to account for these uncertainties.

2.5. Focus on management of DRP vs. PP

Traditionally, TP was considered as 23-33% bioavailable (Baker 2010), however, Seo et al. (2005) measured DRP (dissolved PO4-P) as 70% of TP in runoff from a no-tilled and broadcast fertilizer field. Sweeney et al. (2012) also observed that P loss from a field applied with turkey litter was mainly in soluble form and annual losses tend to increase with larger annual flow volumes. The effects of no-till in the Fall on DRP losses are frequently negative, as observed by Ulen et al. (2010) where DRP losses increased four times in a no-till system compared to conventional tillage in field experiments. They further discussed that a high erosion-risk Norwegian field has a runoff DRP that was twice as high as TP after direct drilling compared to plowing. Tiessen et al. (2010) observed that conversion to conservation tillage increased P concentrations and exports with soluble P comprising the majority of the P export, especially during snowmelt.

Kleinman et al. (2011) also discussed the tradeoffs between fertilizer and manure management vs. no-till systems. They showed that TP increased by 12% and PP decreased by 37% in a no-tilled watershed compared with conventional-tilled watershed. The increase in TP was attributed to the increase in dissolved P due to severe soil stratification. BMPs that lower the accumulation of soil-P and plant residue at the soil surface should be considered in areas where dissolved P is a major concern (Tiessen et al. 2010).

Data gathered by the National Center for Water Quality Research (NCWQR), Heidelberg University, show that from the mid-1970's to date, the sediment and PP exports to Lake Erie have been reduced and are still decreasing while TP load remains relatively constant. These trends imply that conservation practices to control sediments and TP were successful (Richards et al. 2010). However, from the mid-1990's the dissolved reactive phosphorus (DRP) load has been rapidly increasing in the monitored tributaries (Figure 8). Daloglu et al. (2012) used the Soil and Water Assessment Tool (SWAT) watershed model to demonstrate that the increasing DRP trend after the mid-1990's was driven by increasing storm events, changes in fertilizer application timing and rate, and management practices that enhanced P-soil stratification. A summary of BMPs (BMP toolbox) focused on controlling DRP was developed as a part of Heidelberg University's project funded by the Great Lakes Protection Fund (GLPF) Grant # 833 (Crumrine 2011).

The recurrence of severe algal blooms in Lake Erie in the mid-1990's coincided with this increase in DRP loads. A combination of several factors may have caused the increase in DRP export from agricultural lands (OH-NRCS 2012):

- Conservation practices (e.g., reduced- and no-till cropping systems) implemented since the early 1990's in the predominantly agricultural northwest Ohio have mainly focused on reduction of sediment and TP; these practices are less useful for controlling dissolved phosphorus.

- Farming equipment has become larger and the producers broadcast fertilizer onto the soil surface, rather than banding it.
- Large-equipment traffic may have caused soil compaction resulting in decreased infiltration and increased runoff.
- Increasingly, fertilizer is applied in the fall instead of spring.
- The application of two years' worth of fertilizer in one year for a corn-corn or corn-soybean crop sequence saves money, time, and labor for the producers but results in higher rates and amounts of fertilizer available for export out of the cropland into the streams.
- The maximization of crop yields through fertilizer application and the use of conservation tillage may have also increased soil phosphorus levels, particularly at the soil surface (soil stratification) over a long period of time.

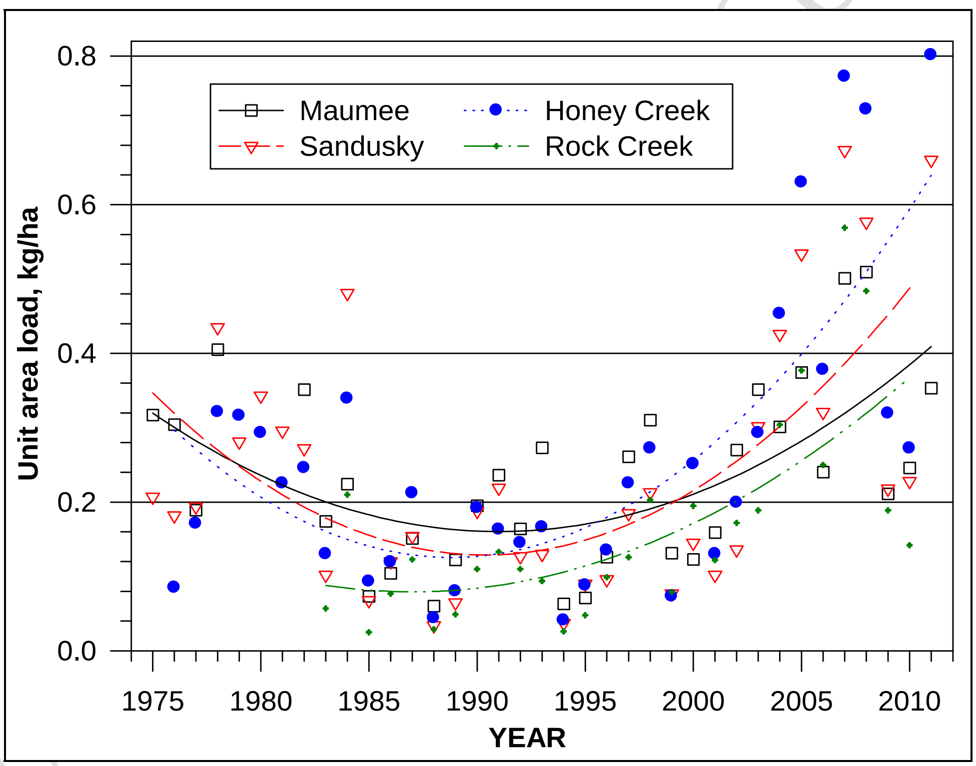

Figure 8. Annual unit area loads of dissolved reactive phosphorus (DRP) at four Lake Erie watersheds. NCWQR, Heidelberg University, unpublished data.

2.6. Summary of Findings and Research Needs: Agricultural BMPs

1. Most studies were done or focused outside of and there was no rigorous assessment of agricultural BMPs specific to the Lake Erie watersheds; some of the BMPs maybe already implemented or are applicable in the Lake Erie watersheds.

2. Most BMP effectiveness assessments were focused on TP and sediment reduction. The traditional idea was that the majority of P losses occur as particulate P attached to sediments.

3. The range of BMP effectiveness greatly varies (Alfera et. al. 2002, Cestti et al., 2003, Gitau, 2005) and results from numerous studies of BMP effectiveness are often conflicting (Merriman et al. 2009).

4. BMP assessments were done at different scales (plot, field, and watershed scales). Methods are either field studies and applications or simulation modeling. Most BMP assessment at watershed scales were done with modeling or assessment of general trend changes in WQ parameters at the watershed outlet. Major issues that need to be addressed are: a) scaling up of BMP effects to watershed scale from plot scale and b) model reliability.

5. Assessing the effectiveness of a single BMP is complicated and difficult since most BMPs are in combination with at least another BMP. Caution should be done in extrapolating effectiveness to other sites and in modeling.

6. There is no silver bullet to solve non-point source pollution, particularly DRP. The use of a suite of BMPs (or toolbox) is currently recommended (Kevin King, personal communication). A major challenge is how to evaluate the synergy of BMP effectiveness.

7. Other challenges include soil-P stratification and the tradeoffs in controlling DRP and sediment/erosion, e.g., no-till vs. conventional-till vs. nutrient management (Kleinman et al. 2011; Tiessen et al. 2010).

8. There is a need of an inventory of implemented agricultural BMPs (a BMP clearing house) in Lake Erie watersheds and in the Great Lakes in general. This inventory is essential in assessing programmatic and the overall effects of BMP implementation.

9. There are a few studies on BMP cost-effectiveness (not discussed in this review) and must be considered in future implementation and studies.

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