

Phosphorus removal structures: A management option for legacy phosphorus

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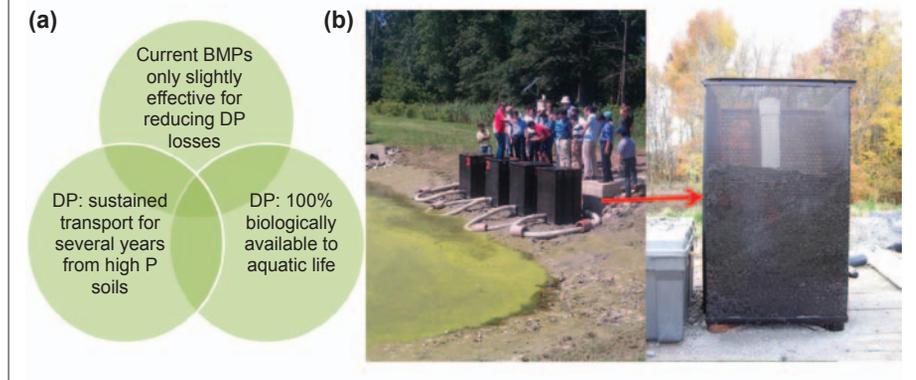
Phosphorus (P) loading is considered a primary contributor to surface water eutrophication (Daroub et al. 2009). Phosphorus moves from soil to surface water as dissolved or particulate P. Particulate P is typically not 100% bioavailable, having to enter solution (through dissolution or desorption) before being available for uptake. On the other hand, transported dissolved P is immediately 100% bioavailable to aquatic biota. In addition, dissolved P can be released over very long periods of time from high P source areas on the landscape even when practices are used to control particulate losses. Therefore, dissolved P is generally considered more problematic for water quality, both due to its immediate impact on the ecosystem and difficulties in controlling its movement.

The term “legacy P” is often used to refer to accumulated P that can serve as a long-term source of P to surface waters. Terrestrial P legacies result from past management decisions that lead to high soil P concentrations (Sharpley et al. 2013). Soil P dynamics are such that once soil P concentrations are elevated it can take many years for them to decrease below levels of environmental concern. These high-testing soils are able to release dissolved P for many years, even after all P applications have ceased. Most examples of the slow recovery of terrestrial legacy P is for agricultural settings; however, it is important to note that legacy P can be found anywhere soil P has accumulated, including horticultural, residential, and golf course settings. For example, Sharpley et al. (2009) showed that soil Mehlich-3 concentrations only decreased 4.6 mg kg⁻¹ yr⁻¹ (9.2 lb ac⁻¹ yr⁻¹) after eliminating

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Figure 1

(a) Justification for the cost and construction of a dissolved phosphorus (DP) removal structure best management practice (BMP), and (b) example of a P removal structure in Maryland designed to treat runoff water from a poultry farm as the water drains from a retention pond into a ditch through the filtration material (steel slag).



P applications while growing continuous corn (*Zea mays* L.). Multiple examples of long-term soil P draw down are provided by Sharpley et al. (2013). As long as soils remain high in soil P concentrations, they can act a source of P to surface waters if there is hydraulic connectivity.

Although current best management practices (BMPs) are effective at reducing the transport of particulate P or direct transfer of applied P, they tend to be mostly ineffective for dissolved P loss from the terrestrial legacy P pools. This is due to the fact that most BMPs are focused on reducing erosion or placement of fertilizer P below the surface. For example, vegetated buffer strips are a viable BMP for trapping sediment (and therefore particulate P), but those accumulated sediments can potentially increase dissolved P release (Deng et al. 2011). Penn et al. (2012) monitored a 61 ha (150 ac) watershed dominated by a residential neighborhood and found that there was little to no particulate P, while dissolved P concentrations ranged from 0.3 to 1.5 mg L⁻¹ (0.3 to 1.5 ppm). Similarly, if subsurface flow to tile drainage or ditches is the dominant hydrologic process that transports P, then conventional BMPs will do little to reduce dissolved P losses in the short term (Vadas et al. 2007). Other BMPs, such as manure transport programs, P draw down by crops, and nutrient management, can reduce or

prevent soil P from increasing, but as previously mentioned, such BMPs require appreciable time for soil P concentrations to decrease. During that time period, significant amounts of dissolved P can be lost.

The temporal disconnect between water quality goals and the length of time that legacy terrestrial P remains a viable source, the difficulty in controlling dissolved P loss from soil, and the immediate bioavailability of dissolved P justify investment in a new BMP for reducing dissolved P transport to surface waters (figure 1). The P removal structure is a new BMP that can decrease dissolved P loading in the short term until terrestrial legacy P concentrations decrease below levels of environmental concern. Phosphorus removal structures contain P sorbing materials (PSMs) and can be placed in a location to intercept runoff or subsurface drainage with high dissolved P concentrations. As high P water flows through the PSMs, dissolved P is sorbed onto the materials (typically by ligand exchange or precipitation mechanisms), allowing low P water to continue to the outlet. An example of a P removal structure is shown in figure 1. While P removal structures vary in form and appearance, they include three common elements: (1) the use of a filter material that has a high affinity for P, (2) containment of that material,

and (3) the ability to remove that material and replace it after it becomes saturated with P (i.e., when it no longer removes P). Researchers throughout the world have examined various materials that may serve as a PSM in this fashion (Claveau-Mallet et al. 2011; Klimeski et al. 2012; Vohla et al. 2011; Lyngsie et al. 2013). While the operational theory of P removal structures is simple, proper design of a structure for specific site conditions and a given lifetime is more involved. Here we provide a case study example of design and construction of a P removal structure for a poultry farm located in eastern Oklahoma.

ASSESSMENT OF SITE LOCATION

There are three site requirements for construction of a P removal structure:

- Elevated dissolved P concentrations in runoff. For most PSMs, it is generally not worthwhile to construct a P removal structure unless the dissolved P concentrations are greater than 0.2 mg L⁻¹ (0.2 ppm). Most PSMs are unable to sorb appreciable amounts of P from low concentration water for prolonged periods due to the equilibrium law (Le Chatlier's principle), although there are some PSMs capable of this.
- Hydraulic connectivity. The runoff or subsurface drainage produced at the site must have the potential to reach a surface water body.
- Flow convergence. The potential to channel the runoff water into a single point for treatment is necessary to build an effective filter. This is inherent to a site if there is a drainage ditch, culvert, subsurface drainage outlet, or similar convergence point. Otherwise, the flow must be manipulated so that it will converge into a single point for treatment.

The site used in this case study was a 3.6 ha (9 ac) subwatershed with several poultry houses (figure 2). Poultry litter spillage occurred near the entrance to the houses, and the site was hydrologically connected to a nearby creek, located within the Illinois River Watershed. An elevation survey and visual observations during runoff events were used to determine the exact location of the structure (figure 2). Starting in September of 2012, grab samples of runoff were taken and

analyzed for dissolved P, which consistently showed dissolved P concentrations ranging from 1 to 2 mg L⁻¹ (1 to 2 ppm). Therefore, all three site requirements were met for this particular location regarding construction of a P removal structure.

SITE DATA COLLECTION REQUIRED FOR STRUCTURE DESIGN

In addition to estimates of runoff dissolved P concentrations, it was necessary to estimate the peak flow rate, average annual flow volumes and dissolved P load, and hydraulic head. The average annual flow volume and peak flow rate were calculated using site information required for estimating the Natural Resources Conservation Service curve number (CN). This included soil type (used to determine hydrologic soil group), ground cover, greatest length of flow, and slope. Each parameter, except for soil type and flow length, was determined via site visit. The CN was 78 since the cover was mostly pasture. The curve number was used in conjunction with precipitation depth for the design storm in order to estimate peak runoff flow rate. In our case, the structure was designed for a 2-year, 24-hour storm, which produces about 10 cm (4 in) of rainfall as estimated by standard USDA Natural Resources Conservation Service rainfall tables.

The CN method resulted in an estimated runoff depth of 5 cm (2 in) for this watershed (a 2-year, 24-hour storm).

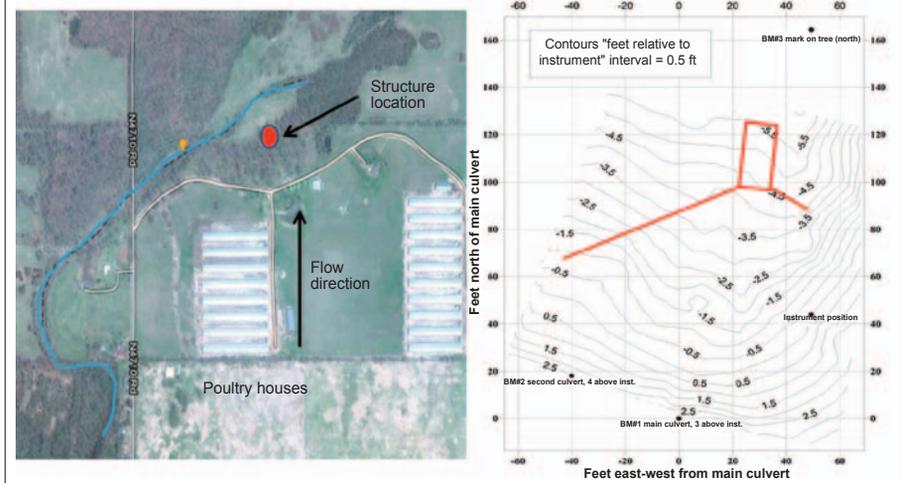
Runoff depth was then used to calculate peak flow rate by the Soil-Cover-Complex method and time of concentration (USDA SCS 1986). The time of concentration was calculated using the CN at 24 minutes, and the greatest length of flow was determined to be 331 m (1,059 ft). Therefore, the predicted peak discharge was calculated as 1.5 m³ min⁻¹ ha • cm⁻¹ (0.9 ft³ s⁻¹ ac • in⁻¹). Based on the size of the watershed, this was equal to about 27 m³ min⁻¹ (16 ft³ s⁻¹). Therefore, our goal was to design a structure that could handle at least this flow rate in order to treat all of the runoff produced from a 2-year, 24-hour storm.

Annual flow volume is necessary in order to estimate annual dissolved P load. This was achieved by the runoff coefficient method, which was simply based on cover, watershed area, and average annual rainfall depth (USDA SCS 1986). For an average annual rainfall depth of 112 cm (44 in), the average annual runoff volume at the site was determined to be 30 cm yr⁻¹ (12 in yr⁻¹) or 1.1 ha • m (9 ac • ft). Using the highest observed dissolved P concentrations for this site (2 mg L⁻¹ [2 ppm]) and average annual runoff volume, the resulting average annual P load was estimated at 22 kg yr⁻¹ (48.5 lb yr⁻¹).

Hydraulic head is necessary to achieve flow through the P removal structure. Hydraulic head is the elevation difference between the entry point of flow into the structure and the elevation of the water

Figure 2

(a) Aerial view of the site described in this paper in which the phosphorus (P) removal structure was constructed, and (b) contour map showing (in red) the structure location and berms used to converge water into the structure.



body receiving the discharged water. While this may seem simple, hydraulic head often has to be manipulated in extremely flat landscapes such as those common to coastal plain regions. The site used for this case study had ample topographic relief necessary to generate the required hydraulic head. In order to estimate flow rates through the structure, hydraulic head was estimated by the elevation survey (figure 2).

-sizing the phosphorus removal structure

Required Mass of Phosphorus Sorbing Materials. The necessary mass of PSM was determined from annual P load, typical dissolved P concentration in runoff (or drainage) water to be treated, P removal goal (i.e., the % of the annual P load that is desired to be removed), and characteristics of the locally available PSM. An annual P load of 22 kg (48.5 lb) was calculated in the previous section based on the highest observed dissolved P concentration of 2 mg L⁻¹ (2 ppm). The structure was

designed to remove ~50% of the load in year one. Proper design requires development of a design curve for the PSM utilized in the structure. A design curve is simply a quantitative description of the relationship between dissolved P loading to the PSM and the percentage of discrete P removal (figure 3). This must be determined in a flow-through setting. A batch P sorption experiment will not suffice. A batch sorption experiment in this context is only useful as an index to compare different PSMs, not to quantify how much P they would remove from a flowing solution. Penn and McGrath (2011) and Stoner et al. (2012) provide examples and discussion of flow-through versus batch P sorption experiments and their utility in determining discrete P removal.

A design curve is specific with regard to the retention time (i.e., contact time) and the inflow P concentration that is moving through the PSM. The design curve in figure 3 is specific to an inflow P concentration of 2 mg L⁻¹ (2 ppm) and a retention time of 30 seconds. In other

words, it takes 30 seconds for the solution to pass through the PSM. The P sorption is initially very high, but with further P loading, the PSM is not able to sorb as much P as it did previously. The shape of the curve varies between PSMs, retention times, and inflow P concentrations. A detailed discussion of design curves is provided by Stoner et al. (2012).

The design curve equation can be solved in the following multiple ways to provide the desired output:

1. Estimate the lifetime of the structure if a given mass of a specific PSM is to be placed in the structure. In this case, “lifetime” is defined as the amount of time until the P removal structure is no longer able to sorb P that flows into it.
2. Upon integration of the design curve, estimate how much P will be removed by the structure during that lifetime.
3. Upon integration of the design curve, estimate how much of the PSM (i.e., mass) will be necessary to remove a desired amount of P under the condition of the design curve.

An example of how to use design curve equations for proper design is found in Penn et al. (2012) and Stoner et al. (2012). At this particular site, we used the design curve to determine the appropriate amount of PSM to achieve the desired P removal (option 3 above). In designing the structure, we considered several locally available PSMs. An annual P load of 22 kg (48.5 lbs), inflow P concentration of 2 mg L⁻¹ (2 ppm), and the design curve for each potential material were used to estimate the mass required of each material (table 1). Other PSMs may be available in different regions.

Because of the difficulty associated with conducting a flow-through P sorption experiment, a model was developed for predicting the equation of a design curve for a specific PSM under a given retention time, inflow P concentration, and selected PSM characteristics (chemical and physical). This model was developed for the following reasons:

- Conducting a flow-through experiment for every single individual PSM sample and every possible flow condition (i.e. inflow P concentration and retention time) is extremely time consuming and expensive.

Figure 3

(a) Example of a phosphorus (P) removal curve as determined by a flow-through P sorption experiment conducted on a P sorbing material, and (b) side cutaway diagram of the P removal structure constructed on a poultry farm.

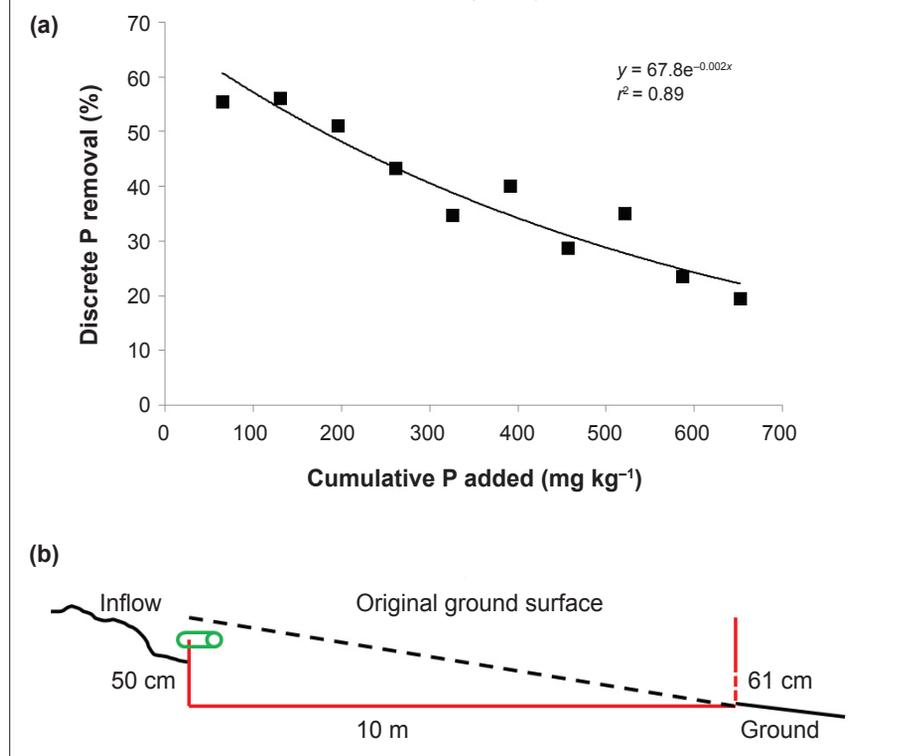


Table 1

Required mass, area, and depth of several phosphorus sorbing materials (PSMs) for removing the indicated percentage of the year 1 P load (22 kg) and treat the peak flow rate for a 2-year, 24-hour storm on a poultry farm located in eastern Oklahoma. Calculations were made based on respective design curves (figure 3) and material and site characteristics. Lifetime indicates the number of years in which the theoretical structure would be able to remove P at this site under current conditions.

PSM	Mass (Mg)	Cumulative first year removal (%)	Lifetime (y)	Hydraulic conductivity (cm s ⁻¹)	Area (m ²)	PSM depth (cm)
WTR	7	37	21	0.01	286	2.3
AMDR	4	50	7	0.009	225	2.2
Fly ash*	3 (plus 95% sand)	50	3.6	0.03 (mixed with 95% sand)	406	13
>6.35 cm slag†	171	21	1.4	1.0	190	50
Treated >6.35 cm slag‡	36	45	3.5	1.0	40	50

Notes: WTR = Water treatment residuals from the AB-Jewel treatment plant located in Tulsa, Oklahoma. AMDR = acid mine drainage residuals from southeast Oklahoma.

* Fly ash from Muskogee, Oklahoma, mixed with 95% sand (60 Mg sand).

† Electric arc furnace steel slag from Ft. Smith, Arkansas (Tube City IMS).

‡ Steel slag treated for increased P sorption.

- There is variation in P sorption behavior between different PSMs and among the same type of PSMs that come from different sources and produced at different times.
- It is easier and less expensive to measure certain chemical and physical characteristics of PSMs and then predict a design curve than it is to conduct many flow-through P sorption experiments.

Data from over 1,000 flow-through experiments conducted on different PSMs under various conditions were used to develop a model to predict the equation for a design curve unique to any unknown material under given flow conditions. It was determined that among practical retention times for treating runoff and subsurface drainage (from seconds up to 20 minutes), retention time usually has little impact on P removal (Stoner et al. 2012). This is true for materials that dominantly remove P via fast kinetics by aluminum (Al) and iron (Fe) sorption (ligand exchange) and for calcium (Ca)-rich materials that have relatively high pH. For example, flue gas gypsum is an example of a Ca-rich material that is not highly buffered with regard to pH, and therefore the retention time does have a dramatic impact on P removal in a flow-through setting. Gypsum is one of the few materials that display this behavior.

While the details of this model for predicting the design curve will not

be discussed here, the design curve is at the heart of the current program being developed, which essentially helps one to design a site-specific P removal structure in the same manner in which this paper describes. The design program can be found at <http://soilchemistry.okstate.edu/phosphorus-removal-structures-1/design-a-structure>.

Orientation of the Phosphorus Sorbing Materials. This part of the design is flexible and somewhat unique to the site. While PSMs can be oriented in different ways, the water must flow through the material in an amount of time (i.e., retention time) that is sufficiently short enough to treat most of the water. For example, one may design the water flow from the bottom of the sorption bed upward, laterally, or from the top downward. An advantage to flow design from the top downward is that it is free draining and avoids saturation with water during nonflow events, avoiding dissolution of P sorbed onto Fe-rich PSMs. Regardless of the water flow direction through the material, flow rate is dependent on hydraulic head, thickness of the PSM layer, and hydraulic conductivity of the PSM. In any of those situations, the standard Darcy Equation can be used to design the structure after you have determined the required mass of PSM, peak design flow rate, and site limitations such as area and slope (i.e., hydraulic head).

Often, the most limiting factor in structure design is hydraulic conductivity of

the PSM. The dichotomy is that PSMs which have the best P sorption ability tend to have poor hydraulic conductivity, and PSMs with large hydraulic conductivity have low P sorption ability. Using a material with a low hydraulic conductivity translates to designing a structure that has a larger area, since thickness of the sorption bed must be lower in order to achieve a reasonable flow rate.

Determining the layout of the structure for a particular PSM is a function of the following parameters:

- required mass of PSM,
- hydraulic conductivity of PSM,
- porosity of PSM,
- bulk density of PSM,
- target peak flow rate for structure,
- maximum area for structure at site, and
- maximum hydraulic head at site.

Table 1 shows potential layouts for several PSMs local to the site. Each scenario can handle a 2-year, 24-hour storm event (27 m³ min⁻¹ [16 ft³ s⁻¹]).

Table 1 clearly shows that PSMs with lower conductivity (water treatment residuals, acid mine drainage residuals, and fly ash) tend to have a greater P sorption ability and therefore require relatively small amounts of PSM and large area. On the other hand, use of the sieved steel slag also requires a large amount of area, not because of limited hydraulic conductivity, but because of the physical constraint of housing a large mass of material. We utilized treated slag since it was a compromise

between the low hydraulic conductivity, high P sorption materials and the high hydraulic conductivity, low P sorption materials, such as the sieved steel slag. The suitable layout for each PSM in table 1 was estimated using the software developed for designing P removal structures.

SITE PREPARATION FOR CONSTRUCTION OF THE STRUCTURE

Since there was no drainage ditch or subsurface drainage outlet at the site, it was necessary to manipulate flow to converge at a single point. Flow was only somewhat concentrated along the gravel road in front of the poultry houses and on the east-west gravel road. Runoff from the field flowed to the gravel road, which acted as a natural drainage swale. Earthen berms were constructed to direct flow to this swale and then the P removal structure (figure 2). Berms were seeded with tall fescue (*Festuca arundinacea* Schreb.) and covered with an erosion control mat.

The foundation for the structure (figure 2) was excavated, and the material was used for berm construction. We elected to use treated slag screened to greater than 6.35 cm (0.25 in). Using the design curve equation, we found that 36 Mg (40 tn) of slag were required. In order to meet desired flow rate of $27 \text{ m}^3 \text{ min}^{-1}$ ($16 \text{ ft}^3 \text{ s}^{-1}$) the material was arranged to 10 m (33 ft) long by 4 m (13 ft) wide by 0.52 m (20 in) deep. The foundation was made by cutting into the ground on the upslope side, producing a 10 m (33 ft) long flat surface that was 0.52 m (20 in) deep on the upslope side (figure 3).

Hydraulic head is critical to force water through the PSMs, which is a function of the slope of the site. As mentioned previously, some sites have very low topographic relief, such as ditch drained fields in coastal plain regions, and hydraulic head must be manipulated. A proven solution to this problem is incorporating flow control structures into filter design to increase hydraulic head, thereby increasing flow rate through the PSM and maintaining a more buffered and constant flow rate.

CONSTRUCTION AND INSTALLATION OF STRUCTURE

For this site, a simple bed-style structure where water flows through the PSM from

the top into subsurface drainage pipes was utilized. The frame was 6.35 mm (0.25 in) carbon steel, and the structure was constructed in modular form for hand assembly in the field.

Figure 4a shows the structure from the perspective of the downhill (drainage) side looking up toward the uphill (inflow) side. Runoff enters the structure on the uphill side through 10 cm (4 in) diameter pipes connected to perforated pipes located just below the surface for the purpose of distributing runoff throughout the entire bed of PSMs (figures 4b and 4c). Note the expanded metal on the drainage side. The deep perforated pipes will drain treated water to the expanded metal, where the water can then exit the structure. The discharge side of the structure was designed to be removed when the PSMs become saturated with P, providing access for a skid-steer to drive in and remove the material. The completed structure is shown in figure 4d.

The discharge side is fitted with an H flume for monitoring flow rate. Two automatic samplers were installed to monitor inflow and outflow P concentrations and flow rates. Testing P concentrations alone is not sufficient to completely assess performance of a P removal structure. By also recording flow rates in real time, the cumulative volume of water passing through the structure can be calculated along with the total mass or load of P removed by the structure. Ultimately, load reductions are what are required to benefit water quality. An illustration of this principle is described in Sharpley et al. (2013). Briefly, the authors showed that the portion of the watershed that delivered 72% of the P load to the stream had the lowest runoff P concentration, while the area that had the highest runoff P concentration delivered only about 1% of the load. This also illustrates why the US Environmental Protection Agency regulates P loss through total maximum daily loads.

Figure 4

The frame of the phosphorus (P) removal structure from the perspective of looking from the (a) downhill (drainage) side toward the uphill (inflow) side, (b) side view, (c) structure partly filled with slag showing the attached inflow perforated pipes, and (d) the complete structure from the perspective of looking from the inflow toward the drainage side. Note the H flume for monitoring flow rates.



The site described in this paper is currently being used not only as a research site, but also to demonstrate this new tool for controlling dissolved P losses from terrestrial legacy P sources to stakeholders, including state and federal agencies, nonprofit organizations, producers, and the general public. There are also similar research and demonstration sites located in ditch-drained fields and poultry farms on the Delmarva Peninsula (Maryland, United States). Demonstrations and field-days will be conducted at these sites for several years.

WIDESPREAD IMPLEMENTATION AND FUTURE RESEARCH

Widespread adoption of P removal structures in the United States will depend on economic viability. For this technology to be economically viable, the value of clean water (or conversely the cost of nonpoint P losses) has to be internalized to the end user. To date, even with an increasingly aggressive regulatory approach, the reality is that the cost of nonpoint pollution is external to the market. It may require government investment (e.g., cost-share programs) to initiate widespread implementation of P removal structures. This type of early cost support is typically viewed as a mechanism to offset early adoption risk. There are also entities, such as golf courses, municipalities, or home owners associations, that may be willing to voluntarily bear the cost of P removal structure construction because they place value on reducing P loading, either as a matter of public image or for the intrinsic value of clean water. On the other hand, many agricultural producers are less likely to absorb the cost of P removal structure construction because of the complete absence of economic incentive and because profit margins in agriculture typically do not support investment in the technology purely for intrinsic value.

Beyond initial support from a cost-share program, nutrient trading coupled with regulatory limits could eventually provide the economic incentive for construction of structures. For example, the Chesapeake Bay watershed is under a total maximum daily load limit imposed by the US Environmental Protection Agency, and most Bay states have initiated trading programs. These programs allow nutrient point sources to purchase credits from nonpoint

sources to allow for discharge beyond their cap. The nonpoint sources install BMPs to remove the credited amount of nutrients, plus some efficiency factor to account for uncertainty associated with quantifying nutrient reduction through most nonpoint BMPs. For example, a point source might pay for 10-fold more P credits than they will actually be able to discharge.

Phosphorus filters provide clear advantages over other types of BMPs in such cap and trade systems. First, they provide more certain and verifiable nutrient load reductions than have been typically associated with BMPs in the past. Nutrient trading is often confounded by the simultaneous implementation of other BMPs that also contribute to nutrient loading reductions, making it difficult to determine whether nutrient loadings were reduced by nutrient trading or by other factors. The concept of additionality has emerged to describe the additional quantity of nutrient reduction which results from, and only from, the active presence of nutrient trading. It is now commonly accepted that additionality should be established before projects are implemented. A desirable feature of P removal structures is that additionality is readily established due to their operational features and location. Measurements can be taken at the outlet of the P removal structure to quantify the change in P levels relative to upstream, unfiltered water that might be influenced by other upstream BMPs. It is also expected that the P filtration structure, by providing a transparent accounting of the nutrient reduction, will reduce the risk and uncertainty often associated with the verification of nutrient trading, enabling markets to operate more efficiently.

Future research should focus on examining the economic potential and cost of widespread implementation. While the structure highlighted in this paper utilized a frame made of steel, this is not always necessary and costs could be greatly reduced by using earthen berms or other material. In addition, an assessment of P loading hot spots would permit one to target critical areas in order to maximize efficiency and minimize costs, i.e. "precision conservation" (Delgado et al. 2011). Last, there is also a need to further examine beneficial reuse of the spent PSMs.

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