Phosphorus Remediation

Improving water quality with phosphorus removal structures.

BY CHAD PENN, GREG BELL, JASON WARREN, AND JOSH McGRATH

The USGA continues to examine and support innovative ways to reduce the environmental impact of golf courses. Previous research indicated that phosphorous can be found in runoff and tile drainage water leaving golf course properties. The transport of phosphorus (P) from soils to surface waters is a major cause of eutrophication (i.e., enriched with dissolved nutrients and lacking oxygen). Eutrophication results in algal blooms, excessive aquatic plant growth, low dissolved oxygen levels, and potential fish kills. Phosphorus is more important than nitrogen in this regard because P is the most limiting nutrient for aquatic life.

There are two main forms of P, particulate P and dissolved P, which are transported to surface waters via surface runoff and subsurface flow. Particulate P is sorbed onto soil particles and it is not 100% available after it reaches a water body. Controlling erosion eliminates particulate P transport. Dissolved P is 100% bio-available upon reaching a water body, and erosion control does little for reducing its movement. Controlling dissolved P losses from suburban and urban landscapes is especially challenging when soil P accumulates due to several years of P fertilization beyond plant needs. Even after cessation of P fertilization and implementation of traditional best management practices, dissolved P will continue to leak out of high-P soils for many years.

One potential solution to this problem is through the use of various industrial byproducts that are rich in P-sorbing minerals. These materials (phosphorus sorbing materials, or PSMs) are able to react with dissolved P and remove it from solution, preventing transport (Penn et al., 2011). Some examples of PSMs include acid mine drainage residuals from the coal mining industry, drinking water residuals from

Figure 1. The uncompleted phosphorus removal structure shown during construction.

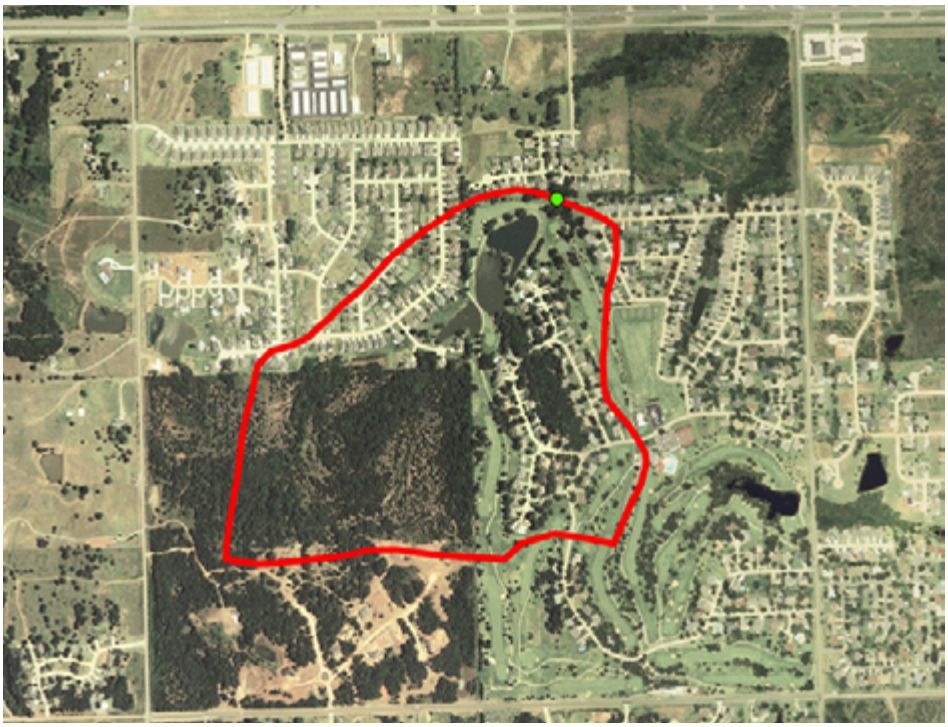

Figure 2. Location of the phosphorus removal structure (green dot) at the outlet of the 150-acre mixed residential and undeveloped watershed (outlined in red) in Stillwater, Oklahoma.

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municipalities, and steel slag from steel production. Specifically, P can be directly removed from runoff and drainage waters through the use of a P removal structure containing a PSM (Penn et al., 2010). These structures can be strategically placed in "hot spots" or drainage ditches where runoff with elevated concentrations of dissolved P is likely. The P removal structure intercepts runoff or subsurface drainage and channels it through contained PSMs. After the PSMs become saturated with P, they can be replaced with new PSMs, thereby effectively removing P from the watershed.

An ideal PSM should be locally available, inexpensive (or free), able to sorb P quickly, have high hydraulic conductivity, and be safe in regards to potential pollutants such as sodium, trace metals, and various organic compounds. Generally, materials that are rich in calcium (Ca), aluminum (Al), and iron (Fe) are potential PSMs. For a Ca-rich PSM to be effective, it needs to be well buffered to a pH above 6 and the Ca must be soluble in water. These conditions are necessary to precipitate Ca phosphates effectively

Figure 3. The completed phosphorus removal structure filled with steel slag, a byproduct of the steel production industry. Close-up of steel slag shown in inset.

and quickly. PSMs containing Al and Fe minerals must not be coated, and the pH must not be excessively high (> 8.5) for them to effectively sorb P by a process known as "ligand exchange."

After studying many PSMs and conducting laboratory and pilot scale experiments, we constructed a P removal structure on the property of Stillwater Country Club, Stillwater, Oklahoma (Superintendent, Jared Wooten). The P removal structure was placed at the outlet of a 150-acre suburban watershed, which consisted of approximately 35%, 50%, and 15% residential, undeveloped area, and golf course, respectively. Two irrigated golf greens were located within 300 to 400 feet from the structure. The greens were regularly irrigated as necessary, and this irrigation sometimes produced runoff that reached the structure.

The structure was located in a drainage ditch immediately on the downstream side of a drainage culvert where all water exited the watershed via a concrete, trapezoidal bar ditch maintained by the City of Stillwater. The bar ditch drained directly into Stillwater Creek. Some runoff entered the structure by flowing along the side of the culvert into the structure inlet. Runoff entered the structure through several 2-inch-diameter pipes connected to buried perforated pipe for evenly distributing the water throughout the PSMs. The water could then infiltrate through the bed of PSMs and drain out through the 4-inch-diameter outlet.

The PSM selected for this 8 foot x 10 foot structure was electric arc furnace steel slag that was sieved to ¼ inch in size in order to ensure a high hydraulic conductivity, thereby treating as much water as possible. Although the finer size fraction of the slag is more effective at sorbing dissolved P, a pilot scale study showed that the non-sieved slag was prone to clogging. However, after observing the system for several months, it is probable that we could have used a smaller size fraction than ¼ inch for improved P sorption without greatly compromising hydraulic conductivity. Three tons of slag was placed in the structure to a depth of 8 to 9 inches.

Table 1
Summary of the suburban phosphorus (P) removal structure performance over the first 5 months of operation

	Rainfall Runoff Events	Irrigation Runoff Events	All Runoff Events
Number of runoff events	20	34	54
Maximum flow rate (L min^{-1})	506	47	506
Weighted average flow rate (L min^{-1})	30.3	11.5	29.8
Weighted average retention time (min)	18.9	50	19.3
Maximum runoff P concentration (mg L^{-1})	1.61	0.97	1.61
Flow weighted runoff P concentration (mg L^{-1})	0.59	0.44	0.50
Total P input to structure (mg kg^{-1})	92.1	10.7	102.8
Total P removed by structure (mg kg^{-1})	19.3	6.6	25.9

Flow rate measurements and samples were collected during runoff events using ISCO automatic samplers at the structure inlet and outlet. Using both P concentration and flow rate data, we were able to calculate the mass of P (P load) entering the structure and the P load removed by the structure. It is important to evaluate P losses as loads rather than concentrations only. After delivery to a water body, the dissolved P concentration in the body will be a function of the total P load in the water/sediments and the volume of water in the body. This concentration can vary annually and with season. Consider that a large volume of runoff water with a low P concentration can potentially deliver a greater P load than a small volume of runoff water with a high P concentration. For this reason, comparing P concentrations can be misleading. Regulating agencies are more interested in P loads, for example, total maximum daily loads (TMDLs).

During the first five months of operation, there were 54 total runoff events, the majority of which were irrigation induced (Table 1). Dissolved P concentrations in irrigation runoff originating from nearby putting greens were typically between 0.3 and 0.5 mg L^{-1}, while rainfall-induced runoff events were normally 0.5 to 1.3 mg L^{-1}. Most of the rainfall-induced runoff was produced from the residential areas outside of the golf course. Rainfall-induced runoff events also delivered the majority of dissolved P loads to the structure, compared to golf course irrigation events (90% of total P load delivered to structure).

After five months, the P removal structure captured 25% of the total P load entering the structure (Table 1). As expected, the removal efficiency of the structure was highest at the beginning (near 100%), then decreased with further P inputs. Phosphorus removal efficiency was greater for the low-flow irrigation-induced runoff events compared to rainfall-induced events. The lower flow rate of the irrigation events resulted in a greater retention time, i.e., the time of contact between runoff water and PSMs, compared to rainfall events (Table 1). Retention time is calculated as the total pore space divided by flow rate. In fact, we found a significant relationship between retention time and P removal efficiency. The P removal efficiency of steel slag increased with increasing retention time. However, this is not true for all materials; some PSMs sorb P so quickly that they do not respond to changes in retention time (Stoner et al., 2012).

We conducted numerous laboratory flow-through P sorption experiments on 14 different PSMs and developed a user-friendly model to aid in designing P removal structures. The result is a "universal model" that can predict P removal and longevity of any PSM as a function of inflow P concentrations, flow volumes, retention time, and

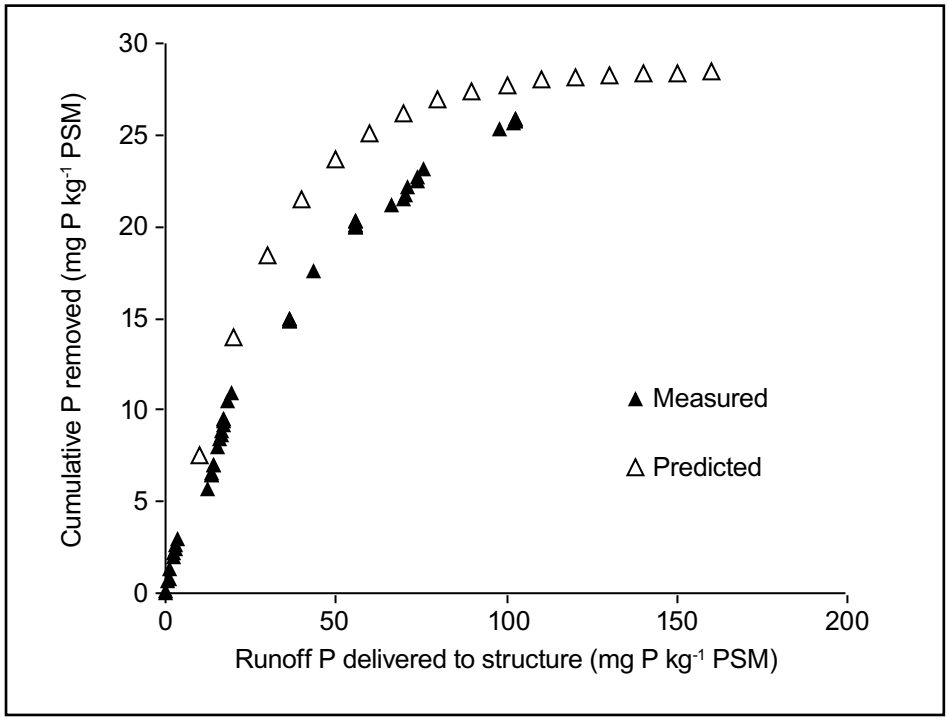

Figure 4. Measured and predicted cumulative phosphorus (P) removal by the P removal structure after five months of operation, as a function of P loading to the P-sorbing materials (PSMs). The PSM utilized for this structure was steel slag sieved to ¼ inch.

characteristics of the PSM. The model was successful at predicting the performance (P load removal and longevity) of the Stillwater structure. In addition, this model can be used to determine how much of a particular PSM is necessary for removing a targeted P load at a particular site.

It is important to keep in mind that the Stillwater structure was a prototype. Using the previously mentioned model, if the goal was to remove 60% of the P load instead of 25%, then the structure could have simply been built to a larger size to accommodate 17 tons of sieved steel slag. On the other hand, based on laboratory experiments with non-sieved slag, only 500 lbs. of material would be necessary to remove 60% of the dissolved P load. However, the non-sieved slag is likely to exhibit poor hydraulic conductivity. Future research is required to determine the steel slag size fraction that achieves the ideal balance between maximum P sorption and hydraulic conductivity.

Phosphorus removal structures should be designed to be free-draining, especially if Fe-rich PSMs are utilized; stagnant water may induce Fe reduction and potential release of previously sorbed P. Also, P removal structures should only be constructed in areas with high dissolved P concentrations only. The reason for this is because many PSMs are less effective when P concentrations in runoff are less than 0.2 mg L^{-1}. Ultimately, structures can have a variety of designs. They do not have to resemble the "box" structure displayed in Figures 1 and 3.

The keys to successfully constructing a P removal structure are use of a suitable amount of effective PSM, water flow through the PSM, and containment of the PSM. Once the PSM is no longer able to remove P, it can be removed from the structure and replaced with fresh material. The "spent" PSM may be suitable as a P fertilizer applied elsewhere, depending on the PSM utilized, or it may simply make a good soil amendment. For the ¼-inch sized slag used in our structure, we intend to test the ability of the material to serve as landscape mulch.

The golfing public needs to be aware that there are a few environmental consequences when providing quality playing surfaces for the game. Through USGA-supported research, scientists have identified potential problems where the management of golf courses can be improved to reduce the environmental impact and still provide an excellent golfing experience. We need to support the efforts of golf course superintendents who identify an environmental problem and then, based on reliable information, provide a management solution such as phosphorous removal structures.

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DR. CHAD PENN, *Associate Professor, Soil and Environmental Chemistry, Department of Plant and Soil Sciences, Oklahoma State University.* DR. GREG BELL, *Huffine Endowed Professor of Turfgrass Science, Department of Horticulture and Landscape Architecture, Oklahoma State University.* DR. JASON WARREN, *Assistant Professor, Soil and Water Conservation, Department of Plant and Soil Sciences, Oklahoma State University.* DR. JOSH McGRATH, *Assistant Professor, Department of Environmental Science & Technology, University of Maryland.*