

Editorial

The Past, Present, and Future of Phosphorus Removal Structures

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The purpose of this special issue is to explore current challenges and develop a better understanding of the processes that control dissolved phosphorus (P) removal among P removal structures. By exploring limitations and grasping the details of P removal processes by P sorption materials (PSMs) at a large scale we can begin to develop solutions and create more feasible, effective, and economical P removal structures. The most difficult challenges at the field scale are issues associated with flow rate; specifically, premature clogging, the need to operate at flow rates high enough to treat large flow events that deliver the majority of the dissolved P, and achieving such flow rates while also ensuring proper retention time (RT) for dissolved P removal.

The pre-cursor to the P removal structure was treatment wetlands that incorporated some sort of a PSM, such as steel slag, limestone, and drinking water treatment residuals for treating wastewater [1–3]. Although effective for the high P and low flow rates common for wastewater, these units utilized a long RT, and therefore a large area requirement, neither of which were feasible for treating non-point drainage that has much lower dissolved P concentrations and higher flow rates [4]. After these PSM-enhanced wetlands, the first generation of P removal structures were developed. These initial units contained highly sorptive PSMs, but were not deployed in a manner that allowed for high flow rates to move through the PSM with sufficient contact due to insufficient volume and low hydraulic conductivity of PSM [5,6]. For example, Penn et al. [6] were able to remove 99% of the dissolved P from ditch-water that flowed into a P removal structure containing Fe oxide-rich mine drainage residuals, but the structure was only able to treat 13% of the total flow. The second generation of P removal structures sought to correct this problem by compromising P sorption ability for hydraulic conductivity to permit a greater treatment volume. Most of the second generation structures were constructed using >7 mm diameter steel slag or flu-gas gypsum that were able to convey high flow rates, but due to the chemistry of the PSM were not able to sorb as much P per unit mass of PSM compared to PSMs of first generation structures [7,8]. Currently, the third generation of P removal structures are being developed, which aim to produce a “happy medium” between hydraulic conductivity and P sorption ability. Another issue has been the lack of design guidance for implementation beyond research.

Since the initiation of this special issue, a new software tool for designing site and goal-specific P removal structures was created and released by the USDA Agriculture Research Service [9]. The P-Trap (Phosphorus Transport Reduction App) software is freely available at <https://www.ars.usda.gov/nserrl/ptrap> (accessed on 11 March 2021) and allows conservationists with no engineering background to design a P removal structure for their particular site to reach a desired P removal goal and lifetime, while accounting for the physical and chemical characteristics of the PSMs available to them.

One of the most important highlights of this special issue is the demonstration of field and pilot-scale P removal structures for extended time periods. Several of these projects utilized some sort of steel slag [10–12] that sought to correct the second generation structures by allowing for a greater percentage of the highly-sorptive fine particles than



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before, as well as coating the large size fraction slag with aluminum (Al) to provide additional P sorption capacity. Of the four field-scale slag P removal structures presented in three papers, three were able to treat 100% of the peak flow events while the fourth was able to convey 12 L s^{-1} and treat nearly all flow. This is especially important since >90% of dissolved P was typically delivered in less than 10% of the flow events, which were the largest. Three of four field structures treated tile drainage, which is more challenging than surface water. Shedekar [10] removed 27% and 50% of dissolved and total P, respectively, while treating 100% of the flow from a tile drain with a bed of Al-treated slag contained in a ditch. Penn et al. [11] removed 55% (19.2 kg) of the dissolved P with a buried tile drain structure that conveyed flow at 12 L s^{-1} , and another structure treated 100% of the inflow water with 37% dissolved P removal through use of a surface ditch. Their buried tile drain structure was unique due to the fact that it overcame conditions of little hydraulic head by constructing it with a bottom-up flow regime. Gonzalez et al. [12] illustrated how blind inlets can easily and inexpensively be made into P removal structures to treat surface water by replacing gravel with a PSM such as slag, treating 100% of flow (11.5 L s^{-1}). In their paper >45% of dissolved P was removed over a period of three years, plus >70% of glyphosate. Complementing these field-scale units, Wang et al. [13] studied details of Ca-phosphate precipitation of slag using a segmented-sampling pilot unit. Their results highlighted the greater efficiency of dissolved P removal under longer RT and higher inflow P concentrations, but also illustrated how P is removed in a moving front as Ca^{2+} and slag pH buffer capacity are consumed; such details are important to proper site selection and design of structures that utilize slag and other Ca-rich PSMs. Claveau-Mallet et al. [14] and Claveau-Mallet and Comeau [15] contributed to our understanding of one of the biggest problems with P removal structures that utilize slag: clogging. The authors presented a model for predicting clogging and also demonstrated how clogging can be reduced through recirculation of effluent within the slag bed. In addition, the authors found that the slag filters for wastewater behaved as net CO_2 sinks by consuming the CO_2 that was produced from decomposition of organic carbon.

Scott et al. [16] tested three Fe oxide materials and found that two of them had a tremendous P removal capacity under flow-through conditions that utilized a RT < 30 s, which is a great benefit when smaller field units with high flow rates are necessary. The authors additionally developed a technique for regenerating Fe oxide PSMs in a manner that will be feasible when scaled up to the field. While the cost of the field-scale P removal structures varied, overall costs were as low as 1500 USD for the blind inlet, and up to 10,000 USD for the ditch structure described in Shedekar et al. [10]. Considering the cost of P removal on a per mass basis, three of the four structures were within the range of wastewater treatment (100 to 1500 USD per kg P removed). However, the P removal and regeneration technique for Fe oxides developed by Scott et al. [16] has the potential for realistic P removal costs on the lower end of this range at ~400 USD per kg P removed.

Several potential pitfalls are also highlighted in this special issue. One of the most important is the problem of bicarbonate and dissolved CO_2 found in tile drainage and wastewater which was shown to not only consume soluble Ca and reduce pH in slag which reduces its ability to remove P, but also cause clogging through precipitation of carbonates. Thus, the buried tile drain filter shown in Penn et al. [11] greatly under-performed compared to expectations and prematurely failed after about one year. Claveau-Mallet and Comeau [15] provided insight into this particular clogging mechanism. Therefore, for non-point subsurface tile drainage, it is recommended that Ca-rich PSMs such as normal (not Al-coated) slag should not be used. Meanwhile, Gonzalez et al [12] illustrated how normal slag is well-suited for treating surface water. Wang et al. [13] highlighted how PSMs require evaluation under flow-through conditions, not batch, as well as utilizing realistic inflow P concentrations that are sufficiently low and at a RT that is not excessively long. Use of high inflow P concentrations and long RT will highly overestimate P removal of a field-scale unit that does not employ the same conditions.

Moving forward, while the research presented in the special issue provides several improvements toward the proper design and implementation of P removal structures into the third generation, it also points towards further challenges with buried tile drainage P filters, which have been tested far less at the field scale compared to surface structures. Unlike surface treatment wetlands [17] and urban bioretention cells [18], the tile drainage P removal structures cannot afford the luxury of a PSM bed with a very large surface area, relatively low flow rates and annual flow volumes, or possess surface water storage for hydraulic buffering during large flow events. That said, Penn et al. [11] was able to utilize a water table control structure for partly buffering the hydraulic load into their buried filter; this allowed the soil to temporarily store water while it was being treated. Such water storage must be minimized, or else serious crop damage or flooding may occur. More spatially-efficient tile drain filters can also be realized in the future through the use of highly conductive PSMs that also possess high capacity for P removal under short RT. For this reason, future research should additionally focus on Fe and Al oxide-based PSMs. Another advantage of the Al and Fe oxide PSMs is their potential to be recharged, as demonstrated by Scott et al. [16]; this process must be tested at the field-scale. Last, it is anticipated that if the goal of creating more efficient (spatially, chemically, economically) P removal structures is achieved as expected, an additional need will arise to develop processes to back-wash such small units to maintain optimal flow performance, i.e., a smaller and more efficient filter will receive more water and particulates on a per PSM mass basis compared to larger filters, and therefore be likely to clog faster.

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