



Evaluation of a universal flow-through model for predicting and designing phosphorus removal structures



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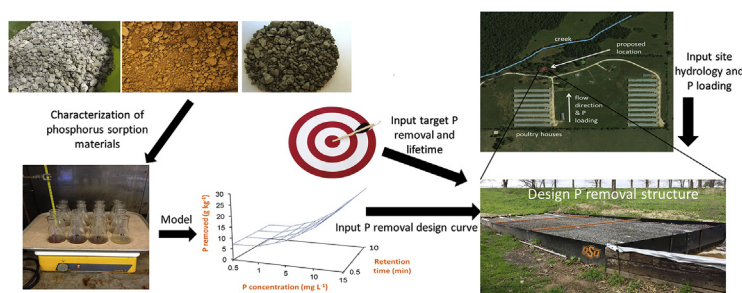
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HIGHLIGHTS

- Evaluated flow-through model for predicting phosphorus (P) removal by materials.
- Model considered material characteristics, retention time, and P concentration.
- P removal predictions were successful from lab to field-scale P removal structures.
- Model can be used to design P removal structures or predict performance.
- Model incorporated into design software, “Phrog”.

GRAPHICAL ABSTRACT



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ABSTRACT

Phosphorus (P) removal structures have been shown to decrease dissolved P loss from agricultural and urban areas which may reduce the threat of eutrophication. In order to design or quantify performance of these structures, the relationship between discrete and cumulative removal with cumulative P loading must be determined, either by individual flow-through experiments or model prediction. A model was previously developed for predicting P removal with P sorption materials (PSMs) under flow-through conditions, as a function of inflow P concentration, retention time (RT), and PSM characteristics. The objective of this study was to compare model results to measured P removal data from several PSM under a range of conditions (P concentrations and RT) and scales ranging from laboratory to field. Materials tested included acid mine drainage residuals (AMDRs), treated and non-treated electric arc furnace (EAF) steel slag at different size fractions, and flue gas desulfurization (FGD) gypsum. Equations for P removal curves and cumulative P removed were not significantly different between predicted and actual values for any of the 23 scenarios examined. However, the model did tend to slightly over-predict cumulative P removal for calcium-based PSMs. The ability of the model to predict P removal for various

Abbreviations: P, phosphorus; PSM, phosphorus sorption material; RT, retention time; DP_{rem}, discrete phosphorus removed; CP_{rem}, cumulative phosphorus removed; CP_{add}, cumulative phosphorus added; PL_{annual}, annual phosphorus load; DL, desired lifetime; RG, removal goal; FGD, flue gas desulfurization; EAF, electric arc furnace; BMP, best management practice; TMDL, total maximum daily load; AMDR, acid mine drainage residual.

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materials, RTs, and P concentrations in both controlled settings and field structures validate its use in design and quantification of these structures. This ability to predict P removal without constant monitoring is vital to widespread adoption of P removal structures, especially for meeting discharge regulations and nutrient trading programs.

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1. Introduction

Eutrophication reduces the ability of surface water bodies to provide drinking water, serve as a means of recreation, and sustain a diverse group of organisms (Carpenter et al., 1998). While both nitrogen (N) and phosphorus (P) are required for algae growth, P cannot be fixed from the atmosphere, so P is typically the limiting nutrient for eutrophication (Schindler et al., 2008). Phosphorus sources to surface waters include effluent from wastewater treatment plants, runoff and subsurface drainage from agricultural land and urban areas, and domestic septic systems which release both dissolved and particulate P. Agriculture has been identified as a major contributor of P due to over application of chemical fertilizer or manure, allowing soil P levels to accumulate beyond plant needs. Soils with high P levels will release small amounts of dissolved P in runoff for years or even decades providing a “legacy” of P that will continue even after adoption of BMPs and cessation of P additions (Haygarth et al., 2014; Sharpley et al., 2013). The released dissolved P is relatively low in concentration (King et al., 2015; Smith et al., 2015), yet 100% bioavailable upon reaching an aquatic ecosystem.

Conventional BMPs focus on reducing particulate P through erosion prevention, but do little to reduce transport of dissolved P and potentially increase losses of dissolved P (Darch et al., 2015; Fox and Penn, 2013; Sharpley and Smith, 1994). Materials with a high affinity for P have been used to reduce solubility of soil P in efforts to reduce dissolved P transport in runoff, tile drainage, and other effluents (Ippolito, 2015; Dunets et al., 2015; Callery et al., 2015; Karczmarczyk and Bus, 2014; Claveau-Mallet et al., 2013; Uusitalo et al., 2012; McDowell et al., 2008; Penn et al., 2011). These P sorbing materials (PSMs) are able to reduce dissolved P concentrations in water, but have a finite ability to sorb P, requiring additional material for continued reductions. In order to facilitate this process, PSMs have been used as a replaceable filter media in large landscape filters, or P removal structures, that are strategically placed in areas receiving drainage water with high concentrations of dissolved P (Ibrahim et al., 2015; Shipitalo et al., 2012; McDowell, 2015; Wang et al., 2014; Penn et al., 2014a; Bryant et al., 2012) as a precision conservation BMP (Delgado et al., 2011). A P removal structure can take the form of a ditch filter (Bryant et al., 2012), confined bed runoff filter (Penn et al., 2012), riparian runoff filter (Kirkkala et al., 2012), surface inlets (Feyereisen et al., 2015), pond filter (Penn and McGrath, 2011), subsurface drainage filter (McDowell et al., 2008), or bio-retention cells (Zhang et al., 2008).

Most PSMs are able to remove P from solution by two main mechanisms: ligand exchange onto Fe and Al materials and precipitation of Ca phosphates (Karczmarczyk and Bus, 2014; Klimeski et al., 2012; Lyngsie et al., 2015; Stoner et al., 2012). These mechanisms are a function of the chemical characteristics of the PSM (Penn et al., 2011), which also provide a means of modelling P removal (Stoner et al., 2012).

Using a series of flow-through experiments, Penn and McGrath (2011) and Lyngsie et al. (2015) developed an approach for individual PSMs to predict P sorption onto steel slag and manufactured PSMs under flow-through conditions as a function cumulative P loading. Briefly, a flow-through experiment consisted of using a

known mass of PSM in a flow-through cell and maintaining a constant head of P solution at a known concentration as the solution was pulled through the PSM using a pump at a constant rate for achieving a desired retention time (RT). Discrete solution samples that passed through the PSM are taken at various time increments and measured for dissolved P concentration in order to determine P removal. Flow-through techniques are superior to batch P sorption tests in the context of P removal structures (Lyngsie et al., 2015; Klimeski et al., 2014; Stoner et al., 2012; Penn and McGrath, 2011). Individual models were later developed for other PSMs (Stoner et al., 2012). Each individual model took the form:

$$DP_{rem} (\%) = be^{m*CP_{add}} \quad (1)$$

Where DP_{rem} is discrete P removed as a function of cumulative P added to the PSM (mg P kg^{-1} PSM), CP_{add} . Coefficients b and m are simply the coefficients of an exponential equation that predicts DP_{rem} with respect to CP_{add} . Next, equation (1) is integrated with respect to CP_{add} to calculate cumulative P removal (CP_{rem} ; mg kg^{-1} PSM) as a function of CP_{add} (mg kg^{-1} PSM); details of this are further described in the Methods section. Stoner et al. (2012), Penn et al. (2012) and Penn and McGrath (2011) expanded this approach by conducting flow-through experiments on materials at different RTs and inflow P concentrations, which enabled prediction of log transformed coefficients m and b from equation (1) as a function of RT and P concentration:

$$\log(-m) = (\alpha RT) + (\beta P) + \chi \quad (2a)$$

$$\log(b) = (\delta RT) + (\varepsilon P) + \mu \quad (2b)$$

After log transformation, coefficients b and m from equation (1) become the y-intercept and slope, respectively, for the relationship between DP_{rem} and CP_{add} . The coefficients, α , β , χ , δ , ε , and μ are specific to each individual PSM. Therefore, each individual model was limited to the specific samples that it was developed for due to the high spatial and temporal variability within PSM types (Wang et al., 2014; Penn et al., 2012). As a result, when an individual model for a specific steel slag sample, for example, was applied to a different steel slag sample collected from the same steel mill, the individual model would fail at predicting P removal performance due to variation in PSM chemical character (Penn et al., 2012). This exposed the need for a universal flow-through model that could be used to predict P removal for any PSM type as a function of PSM properties, in addition to considering RT and inflow P concentration.

As a result, a universal model was developed from over 1000 flow-through P removal experiments conducted on a variety of PSMs at five different RTs and inflow P concentrations (Stoner et al., 2012). The universal model (described in detail in Methods) predicts DP_{rem} and CP_{rem} as a function of cumulative P loading to the PSM (i.e. CP_{add}), based on flow conditions (inflow P concentration and RT) and chemical and physical properties unique to the individual sample. Essentially, the coefficients listed in equations (2a) and (2b) are predicted as a function of PSM properties. This model eliminates the need for time and cost consuming flow-

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