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RESEARCH LETTER

Introduction to P-TRAP software for designing phosphorus removal structures

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Abstract

Phosphorus (P) removal structures are a new best management practice for filtering dissolved P in non-point drainage from legacy P soils through use of P sorption materials (PSMs). Structures must be designed according to characteristics of the site (hydrology and constraints) and PSMs to be utilized, as well as user-defined goals (P removal, lifetime, and flow rate), making it a cumbersome process. A freely available P Transport Reduction App (P-TRAP) allows users to quickly produce a custom design or evaluate a hypothetical or existing structure. The software includes a library of P removal flow-through curves for many different PSMs conducted under various conditions of inflow P concentration and retention time. Design output includes the necessary PSM mass and orientation, pipe requirement, and a table of annual P removal. The software enables conservationists and engineers to quickly compare cost and efficiency among possible designs.

1 | INTRODUCTION

Phosphorus (P) removal structures are a best management practice (BMP) aimed at reducing dissolved P losses to surface waters. These are landscape-scale filters containing media with a high affinity for P and placed in hydrologically active areas that produce flow with appreciable dissolved P concentrations (Figure 1). Various filter media, known as P sorption materials (PSMs), as well as different forms and applications of this BMP have been demonstrated in a variety of situations for treating non-point drainage (Erickson et al., 2018; Gonzalez et al., 2020; Groenenberg et al., 2013; Mendes & Renato, 2020; Penn et al., 2012, 2014, 2020; Shedekar et al., 2020; Vandermoere et al., 2018). While diverse in appearance, P removal structures possess several core similarities (Penn & Bowen, 2017): (a) sufficient mass of PSM for removing an appreciable amount of dissolved P load for the site, (b) ability to conduct an appreciable portion of the peak flow rate while allowing water to flow through the PSM at a sufficient retention time (RT), and (c) ability to contain the PSM and prevent it from being flushed out so that it may be replaced or regenerated when necessary.

Due to variability in site characteristics (hydrology and dissolved P concentrations), PSM properties (chemical and physical), and P removal goals (desired flow rate, P removal, and lifetime), each P removal structure must be custom designed. Consequently, P-TRAP (Phosphorus Transport Reduction App) was developed to allow users to quickly design P removal structures and compare several different scenarios. Such comparisons are useful when weighing feasibility and cost with P removal. While appreciable literature discusses how P removal structures work and perform, the purpose of this paper is to describe the P-TRAP design software.

Abbreviations: BMP, best management practice; PSM, phosphorus sorption material; P-TRAP, Phosphorus Transport Reduction App; RT, retention time.

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2 | PURPOSE AND DESCRIPTION OF P-TRAP

The P-TRAP software is a tool based on the model presented in Penn et al. (2016) and an updated version of its predecessor, Phrog (Phosphorus Removal Online Guidance). A series of help windows are found for each input and output variable, and several tutorial videos will be made available. With P-TRAP, users input information (Table 1) about their site of interest, PSM characteristics, and desired performance goals. The software outputs design specifications regarding size, area, depth, and PSM mass required for meeting user defined goals, plus expected annual P removal. The software can also be used to estimate P removal and lifetime for an existing or hypothetical structure. The user can choose between two main categories of P removal structure: "bed" and "ditch." A bed structure is any deployment of the PSM contained as a single symmetrical layer, regardless if it is above- or belowground. A ditch structure is distinguished from a bed structure since the PSM is placed directly into a ditch and therefore has additional hydrological restrictions (see below). Users can choose to design for a bottom-up or top-down flow regime through the PSMs. While P-TRAP delivers a design based on meeting dissolved P removal goals, it can also estimate particulate and total P removal as a consequence of the final design; this is an optional feature that requires additional inputs. The core of P-TRAP is the P removal design curve, which is a quantitative description of P removal under given conditions, expressed as a function of dissolved P loading per unit mass of PSM (Figure 1 inset).

Core Ideas

- P-TRAP can be used to evaluate existing or custom design a new P removal structure.
- Free online use: https://www.ars.usda.gov/nserl/ptrap.
- Design is based on meeting dissolved P removal and flow rate goals with site constraints.
- P-TRAP provides access to ∼800 P removal flow-through curves for various P sorption materials.
- P-TRAP allows users to quickly compare cost and efficiency among possible designs.

3 | REQUIRED INPUTS

Proper design requires assessment of P removal under flowing conditions instead of batch (Klimeski et al., 2015; Penn

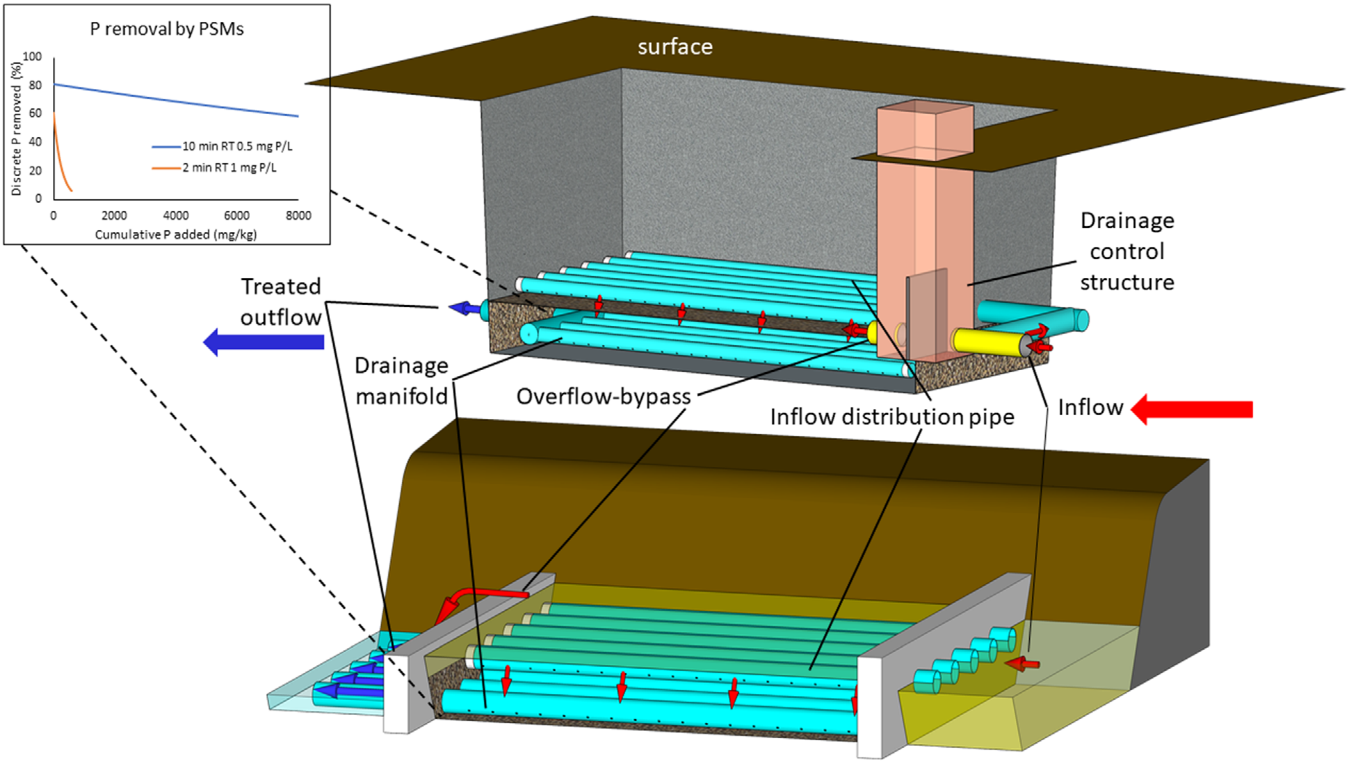

FIGURE 1 Diagram of general components for subsurface bed (upper) and surface ditch (lower) P removal structures with top-down flow regimes. Red and blue arrows indicate untreated inflow water and treated outflow water, respectively. Inset shows an example of P removal design curves for P sorption material (PSMs), which are used to design and evaluate P removal structures. In this example, P removal by steel shavings are shown under different conditions of retention time (RT) and inflow P concentrations

TABLE 1 General inputs and outputs for designing a phosphorus removal structure using P-TRAP software

Inputs	Outputs
PSM characteristics	**Construction Specifications**
P removal design curve slope and intercept	PSM mass required
Bulk density	Thickness of PSM layer
Hydraulic conductivity	Length and width; for ditches, length required only
Porosity	Number of collection drain pipes needed
Mean particle size (optional)	Size of single orifice (if chosen in inputs)
Site information	**Performance**
Max. depth allowable for PSM	RT at max. flow rate
Hydraulic head	Actual max. flow rate through structure
Average annual flow volume	If RT and flow rate goals not possible: suggested increase in desired lifetime for meeting goals
Average DP concentration	Reduction in ditch flow capacity
Average total P and sediment concentration (optional)	Cumulative annual % DP removal and load until PSM is spent
Average duration and number of flow events per year (optional)	Cumulative annual % particulate and total P removal and load until PSM is spent (only with corresponding inputs)
Max. length and width available for structure	
Max. ditch length available (ditches only)	
Ditch dimensions and slope (ditches only)	
Manning's roughness coefficient (ditches only)	
Performance goals and structure preferences	
Min. peak flow rate	
Max. allowable decrease in ditch flow capacity (ditches only)	
Min. RT	
% Cumulative DP removal goal and lifetime	
Drainage pipe diameter and slope	
Option for use of single orifice for meeting RT	
Choice of top-down or bottom-up flow direction	

Note. DP, dissolved P; PSM, P sorption material; RT, retention time.

& McGrath, 2011; Stoner et al., 2012). Users must input an equation for the P removal design curve, specific to inflow P concentration and RT conditions (RT = total pore volume/flow rate). Not only is there a high degree of variability in P removal between different PSMs (Stoner et al., 2012), but inflow P concentrations and RT can have significant impacts on P removal, even after normalization for P loading and PSM mass (Canga et al., 2016; Klimeski et al., 2012; Penn et al., 2017). For example, Figure 1 inset illustrates drastic differences in P removal with different flow conditions. For most PSMs, increased RT and inflow P concentration will result in increased dissolved P removal when normalized for P loading, although some PSMs possess sufficiently fast P sorption kinetics that RT has minimal impact (Stoner et al., 2012). Details on the flow-through procedure for measuring the P removal design curve are described in Penn and Bowen (2017). Because specialized equipment is needed for flow-through analysis, P-TRAP provides nearly 800 PSM design curves in a database library to allow users to choose a PSM design curve in cases where they have not measured it. The database can be sorted by PSM type, source, RT, and inflow P concentration. Caution should be exercised when using a design curve from the library for PSMs that are by-products, as there may exist appreciable variation in P removal within some by-products, such as drinking water or mine drainage residuals. Important PSM physical characteristics required for input are bulk density, porosity, and hydraulic conductivity. Mean particle size is an optional input used when total and particulate P removal is to be estimated. Porosity and hydraulic conductivity are especially important because they affect flow rate and RT.

Site inputs listed in Table 1 are necessary for sizing the P removal structure: specifically, calculation of annual dissolved P load with flow volume and dissolved P concentration. Flow weighted mean concentration is preferred, although rarely available; in cases where flow data is not available, dissolved P concentrations in flow can be estimated from soil test P concentrations (Duncan et al., 2017; Penn et al., 2006;

Vadas et al., 2018). As a general rule, soils should possess at least 100 mg kg^{-1} Mehlich-3 P for a site to produce sufficient dissolved P concentrations for most PSMs to be effective and efficient. In choosing a flow rate goal for the structure, first estimate peak flow rate for the site, whether it be a ditch, tile drain, or overland flow. The user should design the structure to capture as much of the peak flow rate as possible, such as a 1-yr, 24-h storm, since flow events with the greatest discharge deliver the majority of P loads (King et al., 2017; Pionke et al., 2000; Williams & King, 2020; Williams et al., 2018). A variety of techniques for estimating flow rate and volume for each scenario are listed under the help buttons. Maximum hydraulic head at the site is required to perform a design for meeting flow rate goals. All structures require an input for maximum area available. Users choose pipe diameter and slope when designing a structure, which are necessary for draining and/or uniformly distributing water onto the PSMs. In addition, one can choose to regulate flow rate and RT through a restriction orifice; P-TRAP will then calculate the necessary diameter. Other flexible inputs are the P removal and lifetime goals. Choice of the cumulative percentage dissolved P removal goal and lifetime will have profound impacts on the size and cost of the structure. It is critical that the input RT goal be equal to or greater than the RT used to produce the PSM P removal design curve; construction of a structure with lower RT will likely result in underperformance. Similarly, inflow P concentration used to produce the PSM P removal design curve should be similar to the average dissolved P concentration for the site.

4 | HOW P-TRAP WORKS

The P-TRAP software conducts a design to meet P removal and flow rate goals while minimizing structure area and PSM mass to minimize cost. Dissolved P loading is calculated from annual flow volume, dissolved P concentration, and desired lifetime. These are applied to an integrated version of the P removal design curve equation for determining required PSM mass (Penn & Bowen, 2017). Additionally, annual P removal and the ultimate lifetime of the structure (i.e., point at which inflow P concentration equals outflow P concentration) are also calculated. After PSM mass is calculated, P-TRAP determines proper orientation of the media using the Darcy equation for achieving both minimum peak flow rate and RT goals, without exceeding user constraints (e.g., area and depth). Through this approach, minimum RT will occur only during peak flow rate, with lesser flow rates resulting in greater RT. Balancing RT and flow rate is challenging since they are inversely proportional to each other; therefore, it is always easier to satisfy both when the goals for each are low. Sometimes it is impossible to satisfy both goals at the minimum PSM mass required to meet the P removal goal. If so, P-TRAP will alert the user by indicating such and will provide a suggestion for increasing the P removal lifetime goal so that both RT and flow rate goals can be met. Essentially, this increases PSM mass and therefore, total pore volume that can allow for meeting both constraints. Next, pipe requirements are calculated using Manning's pipe flow equation; P-TRAP uses pipe diameter and pipe slope provided by the user and may limit the number of pipes to not exceed minimum required RT; flow rate "choking" is also achieved with a single restriction orifice, if chosen by the user. For ditches, flow capacity reduction of the ditch is calculated using Manning's open channel equation and uses the user-defined limit; addition of any solid material into a channel will reduce total flow capacity. If optional inputs are included, P-TRAP calculates subsequent particulate and total P removal expected to occur with the final P removal structure design; such estimates are based on predicted sediment removal using the equation for single collector removal efficiency (Ryan & Elimelech, 1996). However, note that P removal structures are not intended to target sediment; much simpler BMPs exist for such an end.

5 | IMPLICATIONS AND EXAMPLE

With proper inputs, P-TRAP is used to quickly design a site-specific P removal structure for achieving load reduction goals and to compare designs for cost and feasibility assessment. For example, consider a 60-ha site that produces 155 million L yr^{-1} overland flow with 0.2 mg dissolved P L^{-1}, with goals of 40% cumulative removal over 7 yr, 52 L s^{-1} minimum peak flow rate, and 10 min minimum RT. In this case, we specify using 10-cm-diameter pipe at 0.5% slope for drainage in a top-down system with 76-cm hydraulic head and maximum PSM depth. Gravel-steel shavings mixture (8% by weight) are specified as the PSM with appropriate design curve and physical properties input. Goals are met with 99 Mg PSM oriented 76 cm deep by 11.3 m by 10 m with 16 drain pipes. Alternatively, attempts to use a 0.5-min RT through use of the corresponding design curve show that achieving the goals are impossible since the steel shavings remove less than 40% under that RT. However, if Actiguard AAFS50 (Axens Solutions), an Fe-coated alumina, is selected and RT goal is changed to 0.5 min with use of corresponding design curve, only 7.9 Mg is required to meet the goals. Although this material is initially expensive (~US$3.2 kg^{-1}), it can be regenerated after P saturation (Scott et al., 2020). Steel shavings, on the other hand, are ~US$0.22 kg^{-1}. Preliminary research suggests that steel shavings may be regenerated.

The P-TRAP software is freely available from its landing page at the National Soil Erosion Research Laboratory (https://www.ars.usda.gov/nserl/ptrap). Further documentation, videos, and publications will be provided at this landing page. This software can potentially transform P removal structures from the demonstration phase to widespread implementation, in combination with inclusion into the Federal Environmental Quality Incentives Program (EQIP; Standard 782).

DATA AVAILABILITY STATEMENT

Data are available at https://www.ars.usda.gov/nserl/ptrap.

AUTHOR CONTRIBUTIONS

Chad J. Penn, Conceptualization, Investigation, Project administration, Writing-original draft, Writing-review & editing; James Frankenberger, Formal analysis, Software; Stanley Livingston, Investigation, Visualization.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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