

MIMICKING NATURE TO REMOVE PHOSPHORUS IN LEACH FIELDS

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Abstract

Iron-rich ‘B-horizon’ soil is formed naturally by precipitation of oxides of iron leached from the overlying ‘A-horizon’ soil. Reactive phosphorus dissolved in septic tank effluent passing through B-horizon soil adsorbs onto and binds chemically to surfaces of iron oxides and hydroxides. These Fe-P mixtures transform into stable iron-phosphate minerals such as vivianite and strengite, which have very low solubilities in aerobic and anoxic environments. Total phosphorus (TP) is thus removed from the hydrologic cycle, out of groundwater and adjacent surface water bodies.

In cases where soil, sand, or synthetic filtration media are used to treat septic tank effluent, but which have low to no iron content, iron can be added to the system to function as an iron-rich B-horizon soil. A novel method of mimicking iron-rich B-horizon soil formation has been developed since 2010 to remove TP in domestic leach fields that are otherwise poor in iron and therefore otherwise poor in¹ phosphorus attenuation and removal.

Ferrous iron is dissolved into sewage at a controlled rate that is dependent on hydraulic flow, expected concentration of TP, and targeted TP effluent limit. Additional reactive iron may be added to achieve higher percent removals or to deal with higher-than-expected influent TP concentrations. The technology is abiotic and therefore temperature independent. It is not dependent on the salinity of the sewage and has no effect on pH in the system.

The majority of Fe-P particulates formed is removed by biological-physical filtration and mineral precipitation in the downstream sand filter, synthetic biological filter, or soil leach field component, and is not sequestered and concentrated in the septic tank. The volume of mineral precipitate accumulating in the upper 0.3 – 0.5 m of soil is small, estimated at 1 – 2 % and 0.2 – 0.4% of pore space in sandy loam and clay soils respectively, over 20 years of operation at peak flow. For 1.0 m depth of synthetic filtration media, less than 5% of available porosity will be used in a 20-year period.

As well as theory and prototype testing, this paper documents actual field studies where the limits and performance of the technology have been tested:

Generic Recirculating Sand Filter;

- TP = 1.1 mg/L at lesser iron dissolution rate (82% removal) and
- TP = 0.51 mg/L at greater iron dissolution (92% removal) in the first study, and
- TP = 0.58 mg/L (91% removal) in a second study.

Conventional Soil Leach Field;

- TP = 0.11 mg/L after 12” of sandy loam soil (98% removal),
- TP = 0.05 mg/L after 24” of sandy loam soil (99% removal), and

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- TP = 0.02 mg/L after 36" of sandy loam soil (>99% removal).

Residential Waterloo Biofilter;

- TP = 0.61 mg/L (96% removal).

Public School Waterloo;

- TP = 0.56 mg/L (92% removal).

Energy consumption is not substantial and the Fe-P unit was retrofitted easily into systems not otherwise configured for TP removal. This energy efficiency and flexibility has significant advantages for broad use of the system in existing conventional soil leach fields in P-sensitive areas.

Introduction

Where attenuation of the nutrient total phosphorus (TP) in decentralized septic systems is required, such as around fresh water lakes and rivers, ocean reefs, and potable water source protection zones, receiving soils must be iron-rich, preferably with high aluminum or calcium contents, to adsorb and mineralize phosphorus from the wastewater (e.g., Brandes 1975; Anderson et al. 1989; Robertson et al. 1989; Barber 2002).

In certain jurisdictions in Ontario, natural B-horizon soils rich in iron are mined and brought in as imported soil fill below septic leach fields to carry out this function. As well as having to be extracted and transported long distances, the weak link in this method is that TP and Fe are separated in space; TP is in the sewage whereas Fe is in the soil. In order to precipitate insoluble minerals and remove TP from the groundwater, the Fe and TP must get close to each other to react and precipitate. There is no guarantee that phosphorus will be thoroughly removed, though, as preferential flow pathways can form in the larger pores of the soil, possibly overloading the adsorptive capacity of the limited amount of soil in contact with the phosphorus. Phosphorus would therefore by-pass much of the iron-rich soil and discharge to water bodies.

Other methods to remove TP include adding alum to the septic tank (Brandes 1976) to form a flocculent and physically separate TP from the sewage. Alternatively, sewage is passed through iron-rich slag and other reactive or adsorptive materials: many of these efforts are detailed in Hutchinson & Jowett (1997) and Heufelder & Mroczka (2006). Many adsorptive materials have a limited life span and require frequent replacement. Slag effluent is so caustic at pH = 10 – 12 that the leach field soil soon becomes plugged with calcium carbonate cements. Final replacement and disposal of the used slag or other used media is problematic.

A new technique has been developed where iron is dissolved into the sewage itself to react with the TP in the sewage and precipitate out in a filtration component. This paper details field research carried out since 2010 at field sites where the limits and performance of the technology have been tested, including a truck stop, residential, a school, and at the MASSTC (Buzzards Bay) test facility. In all cases, the Fe-P unit was retrofitted easily into an existing system that was otherwise not configured for TP removal: this adaptability has significant advantages for broad use of the system in existing leach fields in P-sensitive areas. It can also be installed in new systems or to replace chemical dosing methods in existing systems.

Natural 'B-Horizon' Soil Formation

B-horizon soil is formed when degrading iron silicates release Fe^{2+} ions into solution in the upper A-horizon soil, aided by decomposing organic matter (Figure 1, Table 1). The dissolved iron percolates downwards, and precipitates, primarily as oxidized ferric iron oxides and hydroxides, in the underlying B-horizon soil. Reactive phosphorus dissolved in water passing through the B-horizon soil binds chemically to iron oxides to ultimately form iron-phosphate minerals, and these reactions can be very quick (e.g., Schulte & Kelling 1996; Barber 2002). Because Fe-P minerals have very low solubility constants under both aerobic and anoxic conditions (Hansen & Poulsen 1999; Barber 2002), phosphorus below septic system leach fields is thus removed from the hydrologic cycle and kept out of groundwater and adjacent surface water bodies (e.g., Robertson 1995).

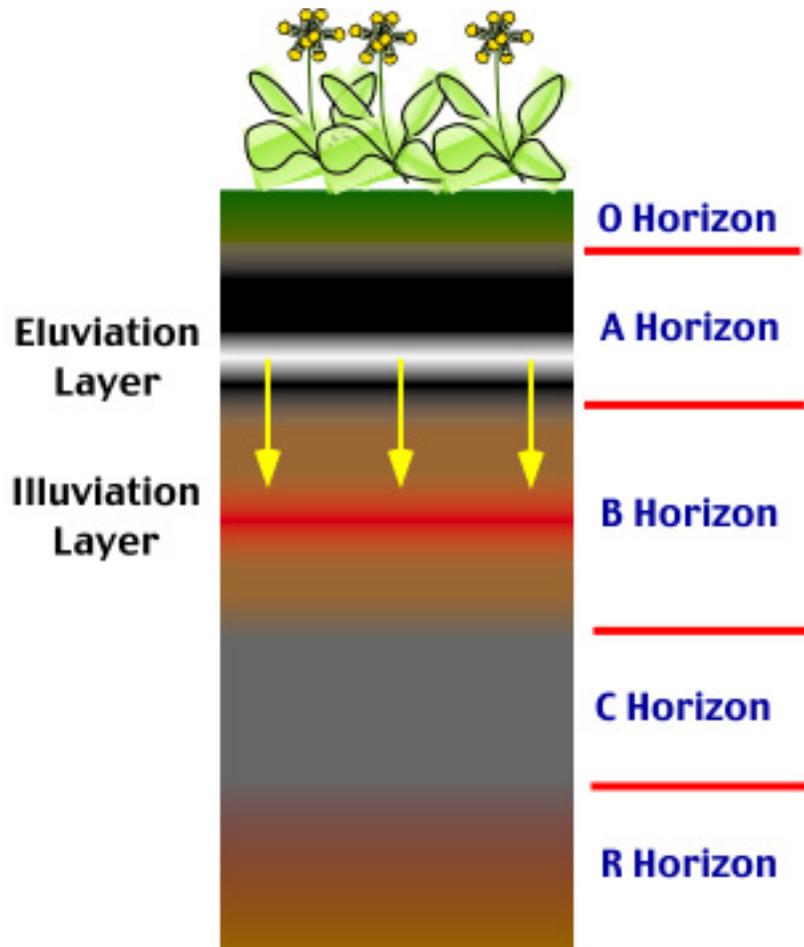


Figure 1. Soil Horizons showing Movement of Soluble Fe^{2+} from A-Horizon Soil to B-Horizon Soil (www.physicalgeography.net).

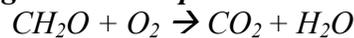
The general chemical processes of B-horizon soil formation are depicted in Table 1. Soil organics in A-horizon soil degrade to form CO_2 and thus carbonic acid ($\text{H}_2\text{CO}_3 = \text{H}^+ + \text{HCO}_3^-$), whose protons (H^+) help degrade Fe-rich silicate minerals, releasing ferrous ions (Fe^{2+}) into

solution. A light-coloured E-horizon layer can form where silicates are left but darker materials are ‘eluviated’ or removed, and are deposited or ‘illuviated’ in the soils below. In the more oxidizing B-horizon soil, ferrous ion is generally oxidized to ferric ion (Fe^{3+}), which is more readily precipitated as the characteristically coloured yellow, red, and brown hydroxides.

Stable, insoluble Fe-P minerals form in both aerobic and anoxic conditions, as e.g., strengite $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ in oxidizing, ferric Fe^{3+} conditions, and as vivianite $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ in reducing, ferrous Fe^{2+} conditions. Strengite has a solubility product constant $K_{\text{sp}} \approx 10^{-22}$ and vivianite has $K_{\text{sp}} \approx 10^{-36}$. These K_{sp} values are very low (compare to e.g., calcium carbonate with $K_{\text{sp}} \approx 10^{-9}$), indicating high stability of these Fe-P minerals once they precipitate (see Schulte & Kelling 1996; Barber 2002).

Table 1. General chemical processes in forming iron-rich B-horizon soil. Note that iron-phosphate minerals occur in both oxidizing (ferric Fe^{3+}) and reducing (ferrous Fe^{2+}) conditions.

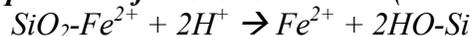
Soil organics decomposition



Generate protons or acidity



Decomposition of iron-rich silicates (biotite, pyroxene, etc.)



Oxidation ferrous to ferric iron



Reduction ferric to ferrous iron



Reduced Fe^{2+} species are more soluble & mobile

- *Ferrous Fe^{2+} iron leaches from topsoil leaving whitish layer with no iron*
- *Ferric Fe^{3+} iron precipitates below in B horizon*

Ferric minerals:

Goethite $\alpha\text{-FeOOH}$ – yellowish brown

Hematite $\alpha\text{-Fe}_2\text{O}_3$ – bright red

Lepidocrocite $\gamma\text{-FeOOH}$ – bright orange

Maghemite $\gamma\text{-Fe}_2\text{O}_3$ – red to brown

Ferrihydrite $5\text{Fe}_2\text{O}_3 \cdot 9\text{H}_2\text{O}$ – reddish brown

Strengite $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$

Ferrous minerals:

Siderite FeCO_3

Vivianite $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$

Pyrite FeS_2

Mimicking B-Horizon Soil Formation

A new method of mimicking iron-rich B-horizon soil formation has been developed since 2010 to remove TP in domestic leach fields and filtration treatment systems. It is intended to be used with soil, sand, etc. that are poor in iron and therefore poor in phosphorus attenuation and removal. The advantage of this method is that both the TP and the Fe have already chemically

bonded in fine particulate form before they enter the soil leach field. They migrate together to the filtration component and all they need to do is precipitate onto soil or sand surfaces, or onto synthetic filtration media like foam. Some iron-phosphate minerals may be contained in part as septic tank solids, but the majority of Fe-P particulates are removed by biological-physical filtration in the downstream biological filters or soil leach field component.

Iron is dissolved into septic tank effluent at a controlled rate dependent on the hydraulic flow, expected concentration of TP, and targeted TP effluent limit. The reactive Fe^{2+} ions can be increased to achieve higher percent removals or to deal with higher-than-expected influent TP concentrations, or decreased if lower-than-expected influent TP is encountered. The technology is abiotic, thus temperature independent, is largely independent of water characteristics, and has no effect on pH of the sewage or final effluent.

Several configurations of the technology were first tested at an Ontario truck stop where abundant Waterloo Biofilter effluent was available. Flow rates, dissolution rates, materials, and configurations were examined using prototypes and this resulted in defining the actual systems to be field-tested.

Mineral Volumes Produced

To estimate the volume of Fe-P minerals precipitated in a soil leach field, an Ontario example is used of a 4-person residence with ~ 2.628 kg TP loading per year (www.sciencedirect.com). Assuming that all P is removed in the oxidizing leach field as strengite $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ (with 16.6% P and density of 2840 kg/m^3) and none in the anoxic septic tank, this technology will crystallize out 15.85 kg strengite per year or $15.85 \div 2840 = 0.00558 \text{ m}^3$ of Fe-P minerals. Field experience shows that the iron staining on sand grains penetrates to a $0.3 - 0.5$ m depth in sandy soil and assumed somewhat less in clay-rich soils. In 100 m of 0.6 -m wide trench in sandy loam soil of assumed 30% porosity, this technology will occlude 0.00558 m^3 or $1 - 2\%$ of the available 7.2 m^3 pore space in the upper $0.3 - 0.5$ m of leach field over a period of 20 years. In 500 m trench in clay-rich soil, only $0.2 - 0.4\%$ of the available 30% porosity will be occluded. For 1.0 m depth of synthetic filtration media such as peat, foam or textile, Fe-P minerals will occupy less than 5% of available porosity over a 20-year period at peak flow rates.

Predicting TP Removal

At the truck stop, the technologies removed dissolved TP from a few cubic metres of Waterloo effluent each day, and discharged the Fe-P rich effluent to the septic tank to be re-delivered to the Waterloo. As Fe-P minerals precipitated in the Waterloo, its effluent became weaker in TP with time, from the initial TP $\approx 19 \text{ mg/L}$ and to TP $\approx 12 \text{ mg/L}$ near the end of the testing (Figure 2), even though only a small percentage of the total flow was being treated.

Knowing the details of the whole sewage treatment system at this facility introduced an opportunity to test another theory: that of predicting TP removal using standard laws of physics and chemistry, as outlined in Xu (2010). If the test analytical data conform to calculation using known physics and chemistry theory, the technology gains greater confidence and more general acceptance. The simulation uses actual hydraulic flow rates of influent sewage, of re-used water (this facility uses Waterloo effluent for toilets & urinals), and of water passing through the experimental systems. These data are combined with concentrations of TP in the three water

types, and by using physical relationships of Fe-P chemical bonding the TP concentration in the Waterloo effluent is calculated and compared to the actual laboratory analyses (Figure 2).

In Figure 2 the energy input (solid red line) increases from the starting date of September 27 2010 to Day 112, and TP in Waterloo effluent (black dots) is thereby depleted at a rate conforming to that predicted by theory (solid purple line). This conformity confirms that known physical-chemical theory does apply, that the technology is designed and operated appropriately, and that the mass of TP removed can be predicted to a large degree.

After Day 112, the energy input (solid red line) is decreased and the predicted concentration of TP (solid purple line) increases as expected along with the actual concentration (black dots) until the end at March 7 2011. (The fluctuations seen in the solid purple line around Day 112 are due to anomalously low flows followed by a 7-fold increase in sewage volume from the facility.)

After the experiments were discontinued and energy to the system shut off on March 7 2011, the TP in the Waterloo effluent had returned to normal values of 18 – 20 mg/L by July – August 2011. The simulated theory predicted these concentrations as well, based on the flow rates and zero energy input to the TP removal system.

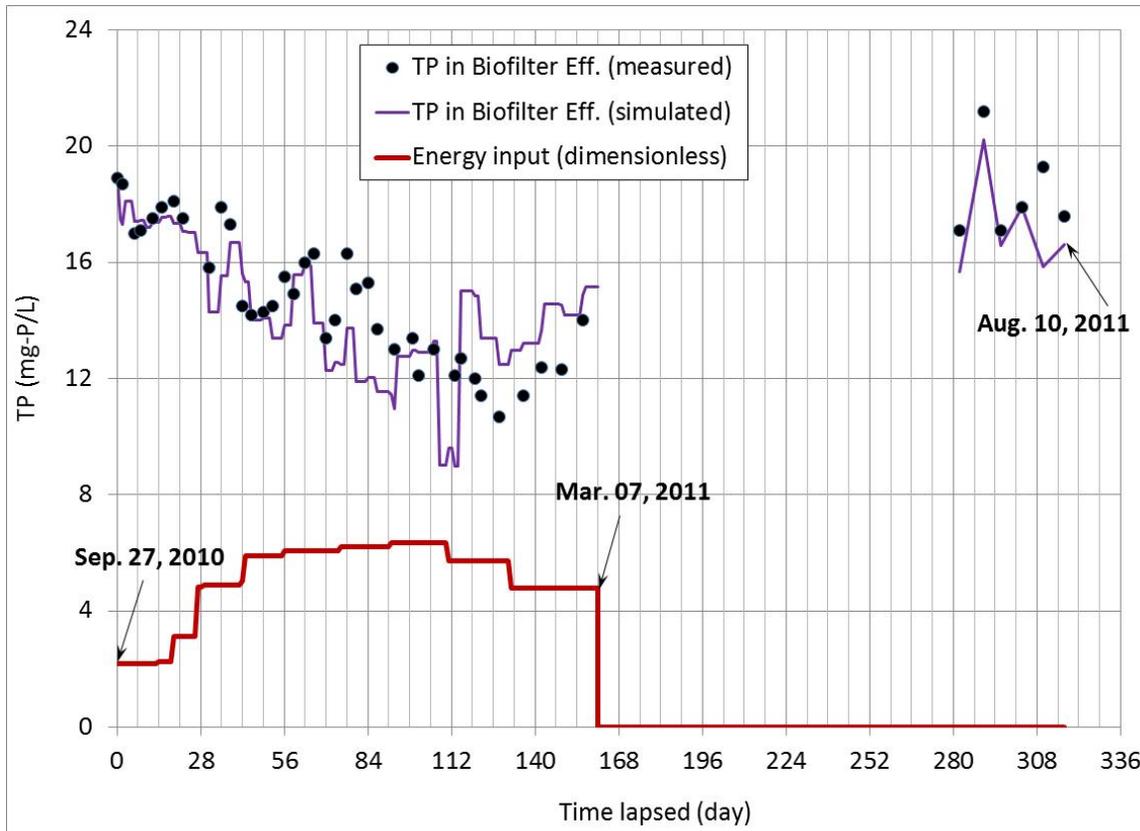


Figure 2. Theory of Predictability of TP Removal Applied in Bench-Scale Testing.

ETI Recirculating Sand Filter

In a generic recirculating sand (pea gravel) filter (RSF) at the MASSTC in MA (Figure 3), TP at ~6 mg/L in the prior RSF effluent is taken down to ~1 mg/L and then to ~0.5 mg/L after

installation of the unit for Study 1. Red iron oxides coating the pea gravel are readily visible (Figure 4). After the unit was removed at Day 180, there was a residual ‘grace period’ effect over several months when additional TP was removed, presumably due to surplus Fe having accumulated in the sand filter.

In Study 3, phosphorus was successfully removed to average TP = 0.5 mg/L concentrations in the coarse sand within 4 weeks of start-up (92% removal), with average total Fe = 0.3 mg/L, lower than the influent sewage value of 1.1 mg/L.

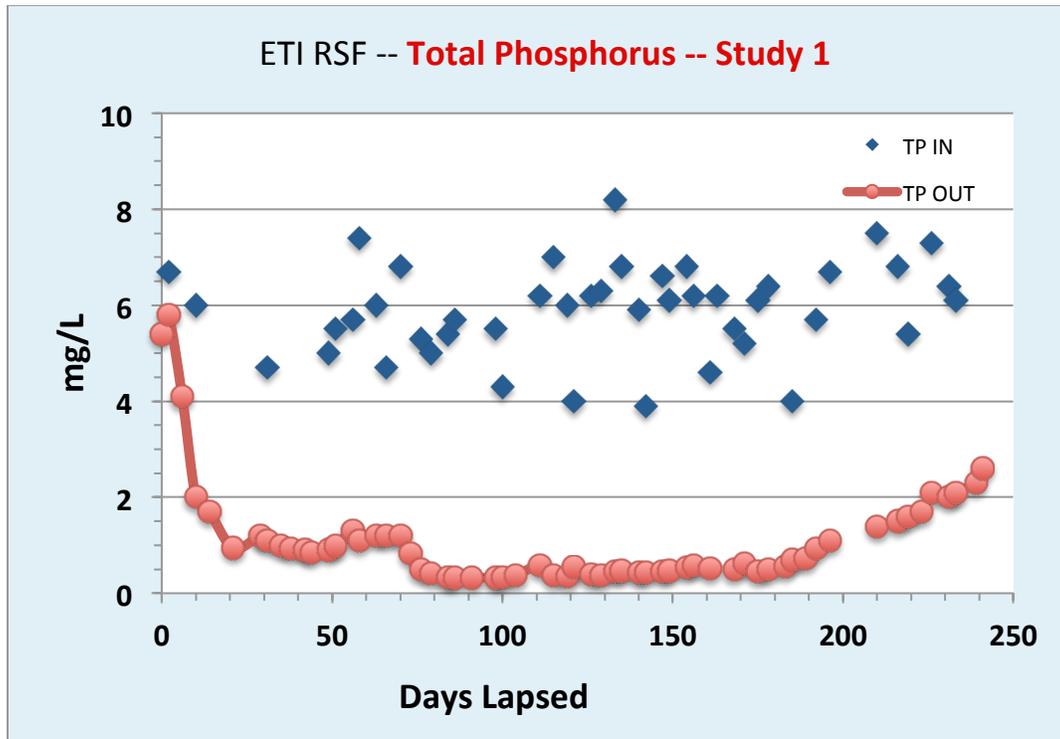


Figure 3. TP Removal in ETI Re-Circulating Sand Filter testing, MASSTC



Figure 4. Iron Oxide Coating on Pipes and Pea Gravel in the ETI RSF

Residence with Waterloo Biofilter

Figure 5 demonstrates removal of TP at an Ontario residence with high-strength sewage due to water conservation measures in the house. Levels were lowered from ~ 18 mg/L TP in the sewage, to 2 – 8 mg/L in the septic tank, and to 0.5 – 1.0 mg/L in the Waterloo Biofilter effluent. TP in Waterloo effluent averages TP = 0.61 mg/L ($\sim 96\%$ removal). As an experiment, iron dissolution was increased by 35%, which caused much Fe and some TP to pass through the system. After the unit was removed at Day 250, there was a residual effect of continued P removal, with septic tank effluent climbing back to its original levels, but with Waterloo effluent still below 1 – 2 mg/L.

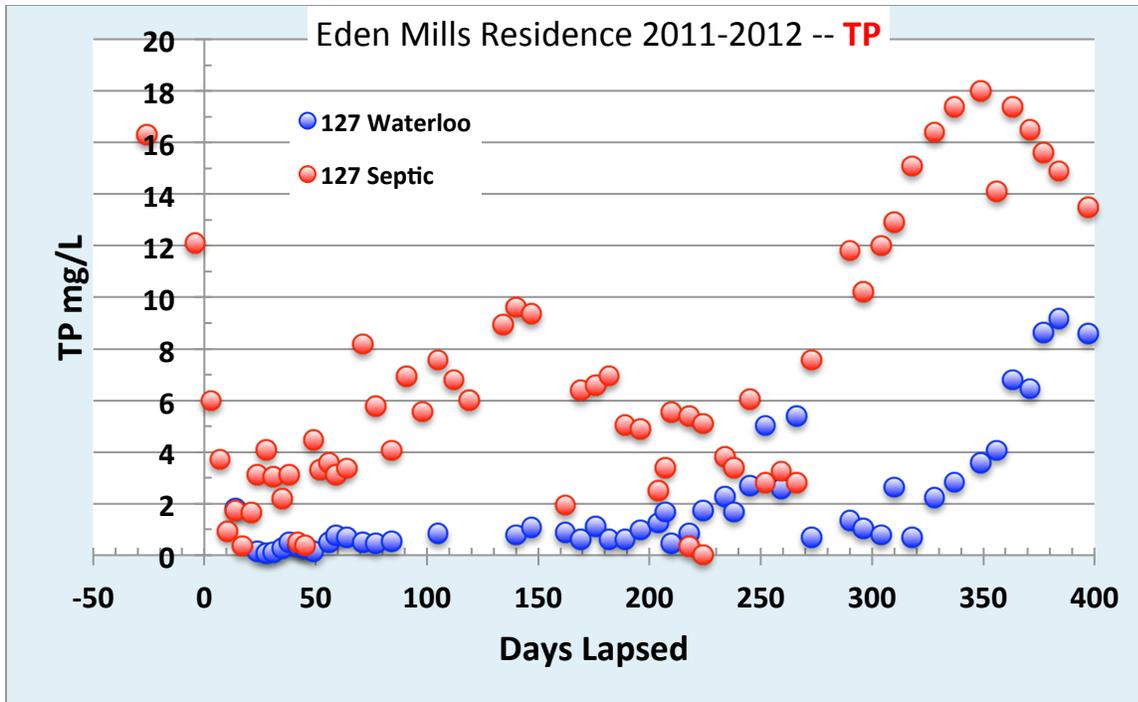


Figure 5. Removal of TP from High-Strength Residential Sewage

School with Waterloo + Fine Sand Dispersal

At an Ontario school with concentrations normally in the TP = 4 – 15 mg/L range, TP is being lowered to 0.1 – 1.0 mg/L in the Waterloo Biofilter effluent as Fe-P minerals precipitate in the foam filtration medium (Figure 6a). The TP unit was retrofitted on Day 365 and removal is effective within a month or so.

The average filtration effluent is TP = 0.56 mg/L or 92% removal from raw sewage. Total iron averages 0.41 mg/L in the effluent compared to 0.64 mg/L in the sewage, and pH averages 7.2, no change from the sewage average of 7.2. There was no flow in summer holidays Days 620 – 690 and thus no samples. This commercial unit has low maintenance with two cleanings in 7 months. Around Day 560, one unit disconnected by accident and the TP rose in the effluent as seen in Figure 6a, after which the unit was repaired and put back into service.

Unusually heavy rains occurred intermittently between Day 500 and Day 700 and groundwater infiltration was noticed in the flow meters and pump activity. Around Days 585 – 605, high groundwater enlarged breaks in the septic tank and the high infiltration affected the TP values in the treatment filters (Figure 6a) and to a lesser degree in the dispersal bed (Figure 6b) until repaired on Day 665. These findings emphasize the need for robust, leak-proof tankage to isolate treatment from groundwater and stormwater infiltration.

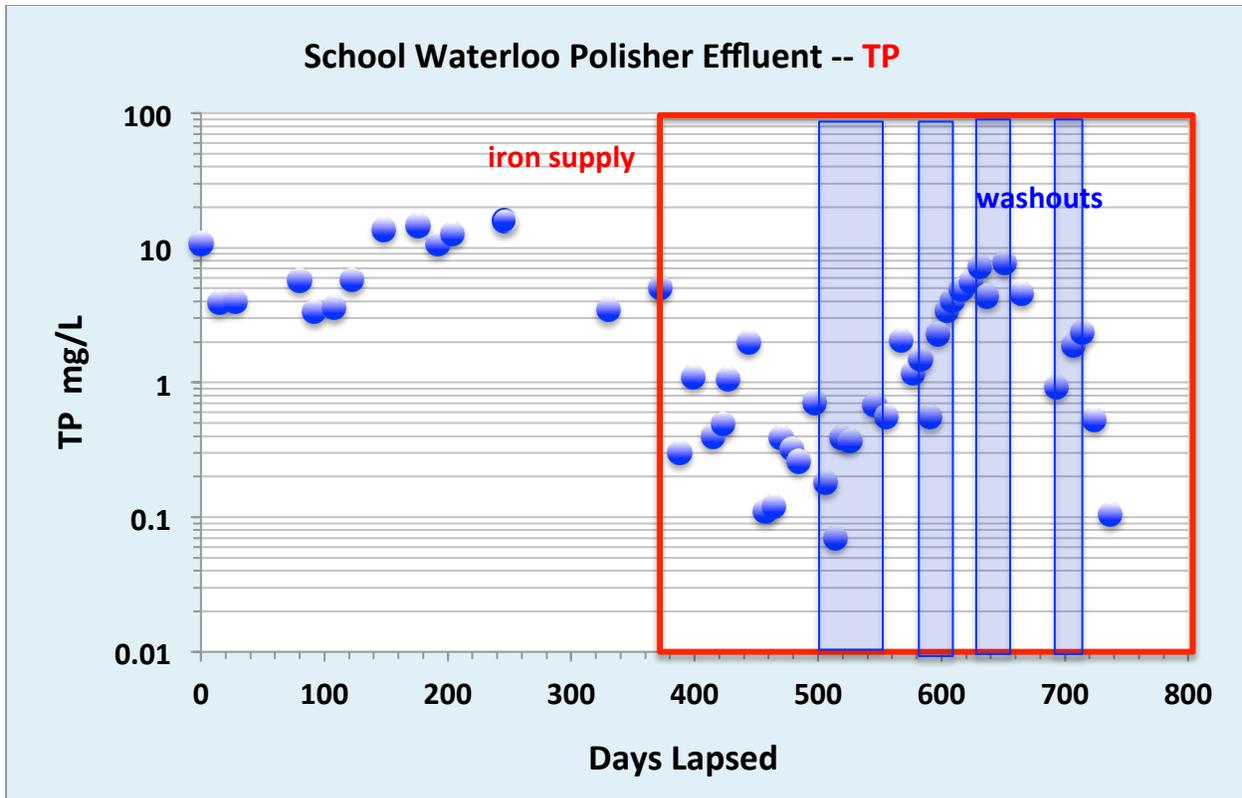


Figure 6a. TP Values in Filtration Effluent with Iron Supply Starting Day 365; Very high Washout Flows Days 585 – 605, recovered by Day 720.

The school dispersal bed has 10” fine sand for dispersal over soil, and pan lysimeter values are depicted in Figure 6b. Effectively 100% of the TP generated in the school entered the pan lysimeter before the TP-removal system was installed (Days 0 – 365), whereas TP removal was 90% after that. This difference in TP passing through shows that even clean foam filter medium and clean sand can be made to remove TP by mimicking iron rich B-horizon soils. Washouts affecting treatment also affected the dispersal sand bed, to a lesser degree.

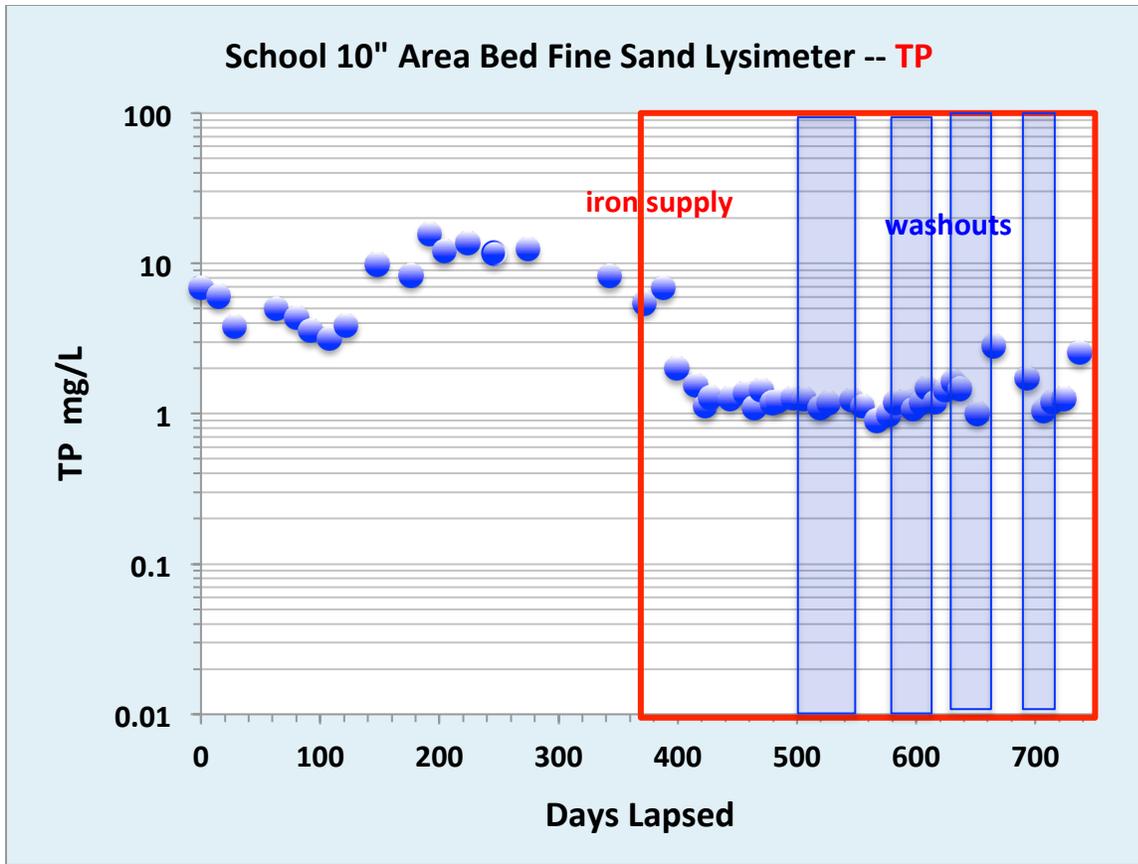


Figure 6b. School Pan Lysimeter Effluent under 10” Fine Sand in Dispersal Bed.

Study of Particulate Sizing

It is useful to understand the size of particulates containing remnant TP and the proportion of particulate to dissolved P. Final Waterloo Polisher effluents were filtered through membranes of pore sizes 8 μm , 2.5 μm , 0.7 μm , 0.45 μm , and 0.2 μm , and the permeate analysed for TP and total Fe (Figures 7a,b). The ‘100 μm ’ value is used for convenience as the actual unfiltered Biofilter effluent. The permeate analyses give a rough estimate of the non-particulate portion of TP that passes through the membranes.

For the Waterloo effluents (i.e., ‘100 μm ’) clustered around 0.3 mg/L TP (Figure 7a) the permeate values decrease quickly to ~ 0.04 mg/L TP. This substantial decrease indicates that most of the phosphorus (87%) is in particulates sized >8 μm , since there is only ~ 0.04 mg/L TP in the non-particulate permeate. The influent for each membrane is Biofilter effluent, and not the effluent from larger membranes. The slight rise in concentration with smaller membrane pore size is considered to be standard error of sampling and analysis.

The January 16 final effluent in Table 7a has a lower, 0.16 mg/L TP initial value and does not change substantially in the filtered permeate. Only about 17% of the TP is in particulates sized >8 μm , and the remainder is as non-particulates in the permeate.

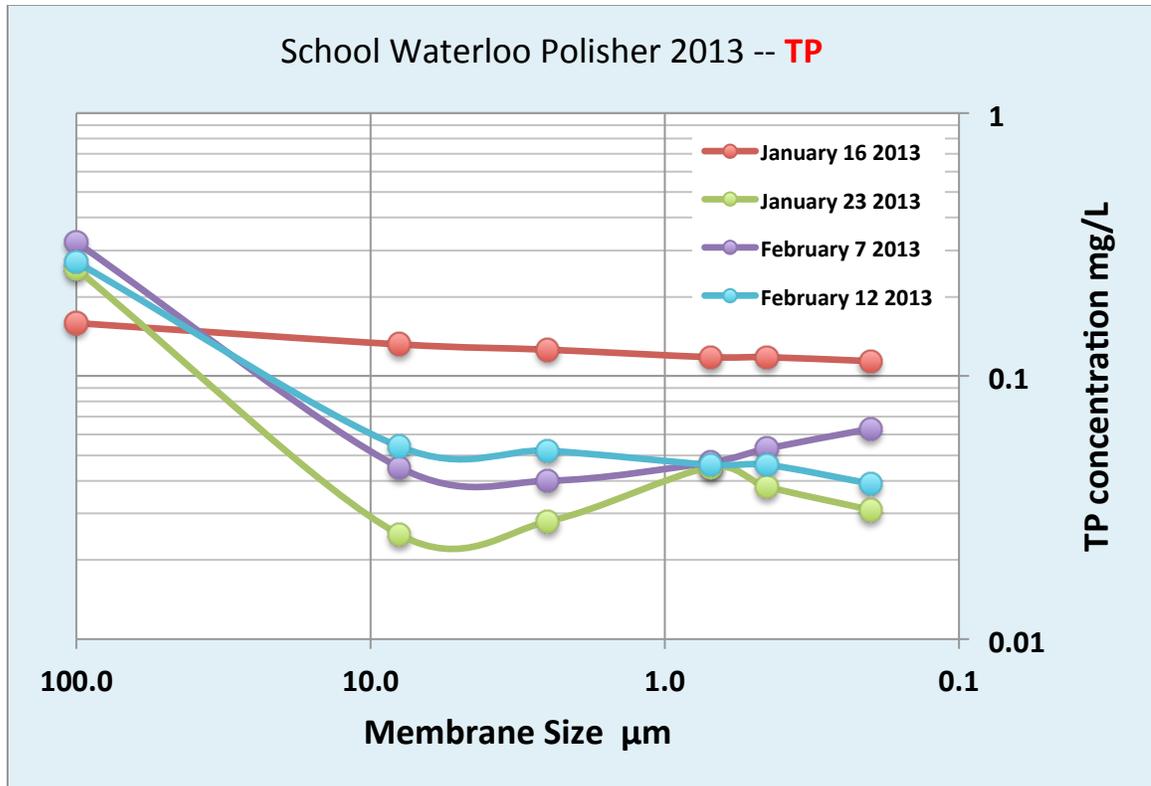


Figure 7a. Membrane Permeate Analyses for Particle Size Distribution of Phosphorus

Total iron in the membrane permeates shows a more regular pattern with most of the iron in particulates sized $>8 \mu\text{m}$ (Figure 7b). Three of the samples at 75 – 80% of the total iron being in particulate form $>8 \mu\text{m}$, whereas the February 7 sample has the highest values and flattest curve, with only 61% of its iron in particulates sized $>8 \mu\text{m}$.

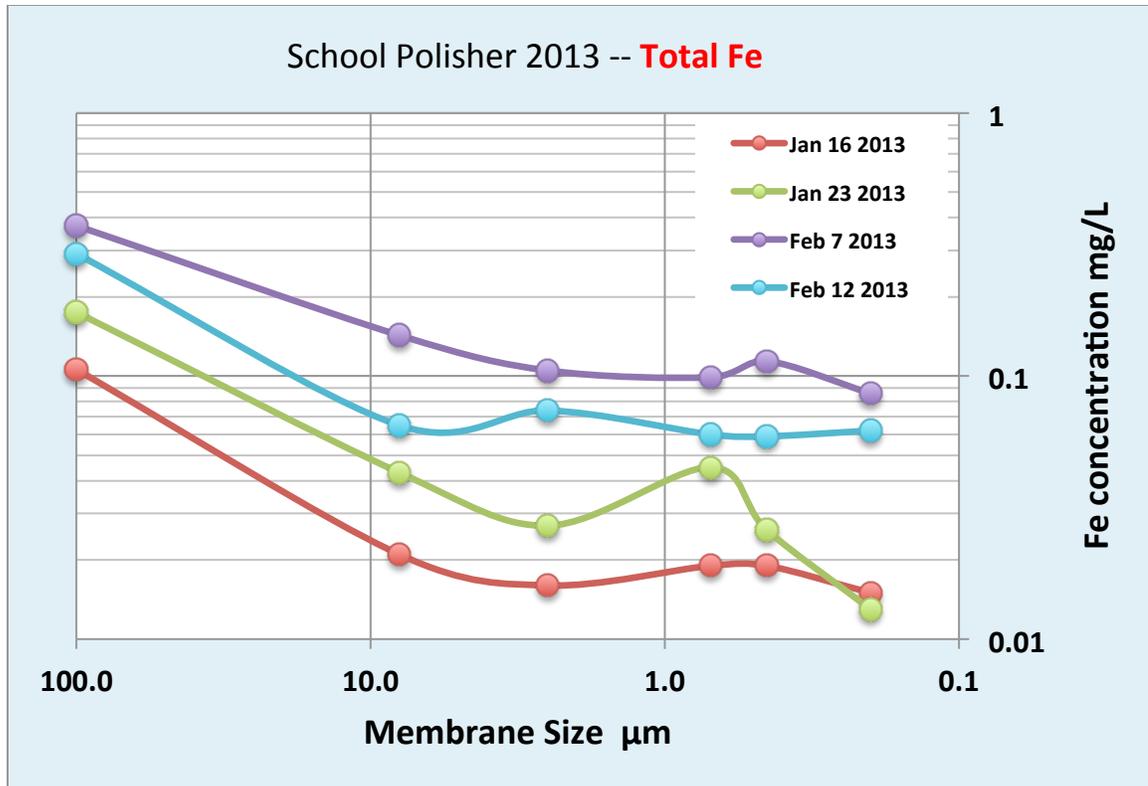


Figure 7b. Membrane Permeate Analyses for Particle Size Distribution of Iron

Soil Leach Field with Septic Tank

To understand how a standard soil leach field would behave with the technology, a unit was retrofitted at MASSTC into an existing septic tank trickling to a soil leach field designed for three bedrooms. The soil was standardized with 60% C33 sand and 40% sandy silt loam. Pan lysimeters were installed within the sandy loam soil at 300, 600, and 900 mm (12", 24", 36") depths. The 300 mm vertical separation is used for highly treated effluent in some jurisdictions, and the 900 mm depth is a common vertical separation to groundwater for septic tank effluent for adequate removal of pathogenic organisms.

Figure 8 shows the results of the on-going study. TP of 6 – 10 mg/L in the sewage is being lowered to 0.5 – 0.05 mg/L with time at 300 mm depth (12") in the soil leach field and to 0.03 – 0.01 mg/L with time at 900 mm depth (36"). The soil filters and precipitates out Fe-P particulates, and the septic water passing through averages 0.15 mg/L TP, 0.05 mg/L TP, and 0.02 mg/L TP with increasing depth of soil. These reflect very high percentage removals of 97.9%, 99.2%, and 99.6% respectively. MASSTC staff measured power consumption to be 0.45 kW-hr per day for this residential size leach field.

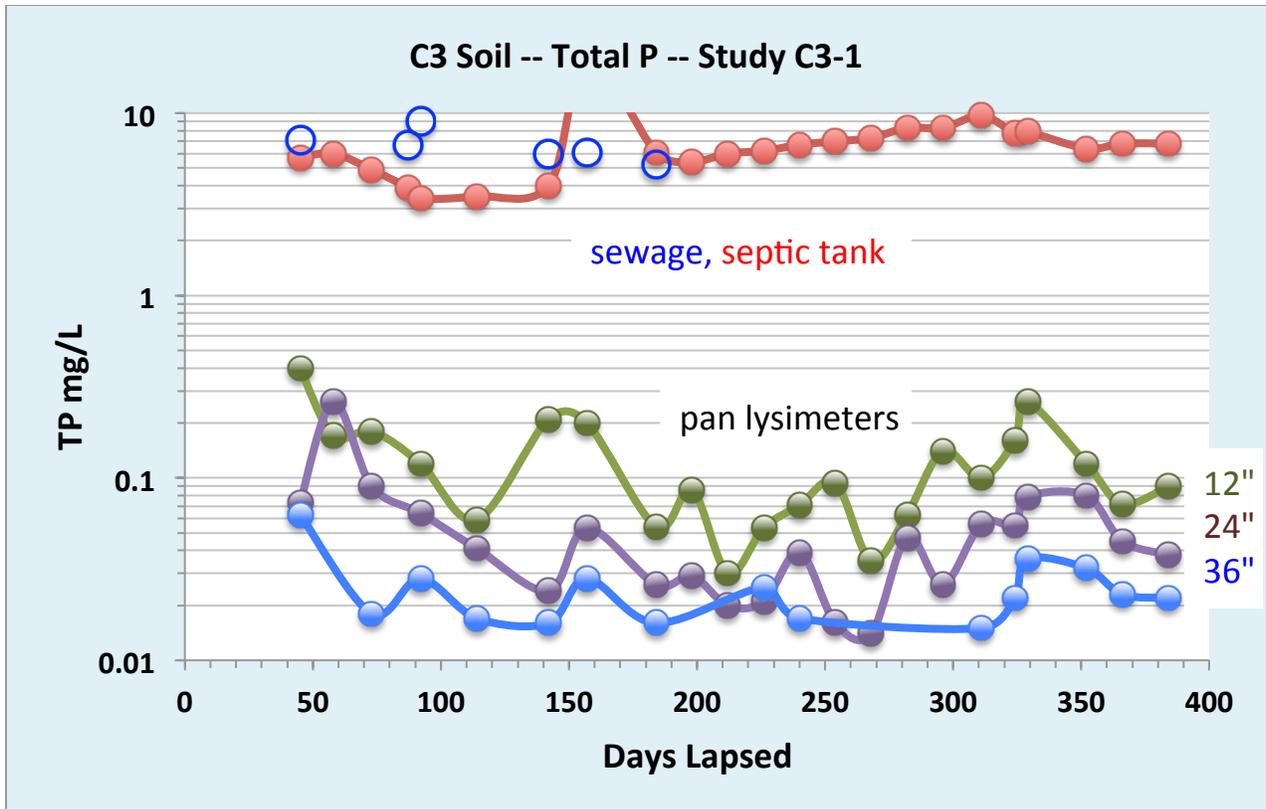


Figure 8. On-Going Soil Leach Field Study at MASSTC

Leach field testing had been carried out in 1999 – 2001 at MASSTC in the 24-month Environmental Technology Verification program, which provides a comparison study to the present study, as well as the school system (Figure 6b) above using foam and fine sand, before and after a TP-removal system was installed. The ETV soil filter used coarser C33 sand and no TP-removal system had been installed. Pan lysimeter samples under the leach field revealed that only 19 – 26% TP was removed, a value possibly typical for conventional residential leach fields without TP removal technology. The present study as depicted in Figures 6b and 8 reinforces the idea that otherwise clean foam and soil filters can be made into dynamic TP-removal systems simply by mimicking the function of iron rich B-horizon soils.

Conclusions

A new technology to remove TP from sewage by mimicking the formation and function of iron-rich B-horizon soil has been successfully tested at a variety of field sites and conditions. The unit is designed to remove TP by forming insoluble Fe-P mineral precipitates in a filtration component following pre-treatment like a septic tank. The filtration component can be clean foam or sand or soil that is otherwise poor in TP removal. The following characteristics are demonstrated: low energy consumption, temperature independence, no effect on pH, and no disposal issues as with concentrated sludge or slag. Retrofitting the unit into existing conventional septic systems means that all residences close to P-sensitive water bodies can improve the TP removal from their sewage.

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