Using Fly Ash in Bioretention Cells to Remove Phosphorous from Stormwater

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Bioretention Cells (BRC)

- Stormwater runoff from urban areas transports a wide range of pollutants including phosphorus (P) and heavy metals to receiving water bodies.
- BRC have been developed to treat runoff before it reaches receiving bodies.
- P removal in BRC has been reported to be highly variable, and in some cases, the cells have been a P source.

Grand Lake

- Grand Lake, OK, like many waters in the U.S. suffers due to phosphorus over-enrichment.
- Under EPA 319h funding through the Oklahoma Conservation Commission (2005-2008), eight BRC were built in Grove, OK in the Grand Lake basin with the specific goal of reducing P inflow to the lake.
- Under EPA 319h funding through the Oklahoma Office of the Secretary of the Environment (2012-2015) , we have gone back and sampled the cells to quantify their performance.

11 Years of Work in 3 Phases

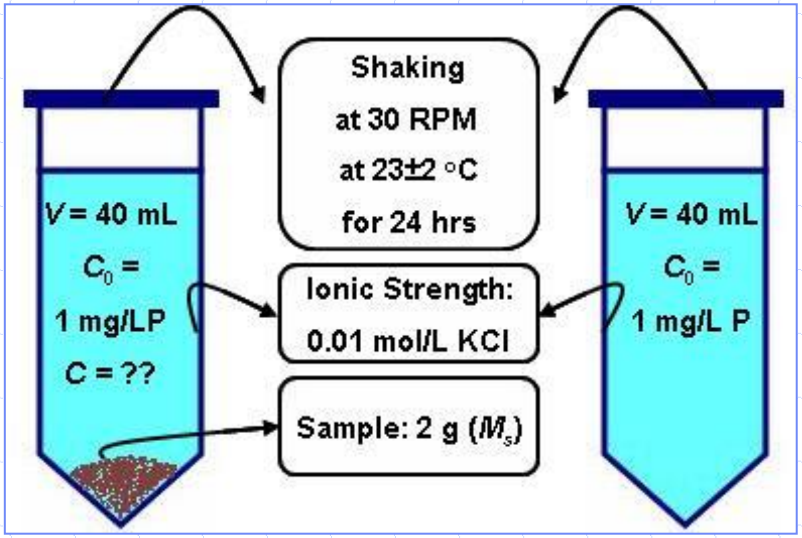
- I: Find an inexpensive filter media with high P and metal retention.
  - Lab screening
  - 1-D modeling
- II: Construct the Grove BRC
  - Standardize design and document construction
  - Quantify filter media during construction
  - Perform detailed 3-D modeling of "As-Built"
- III: Sample filter media and water to evaluate BRC performance after running for seven years.

Phase I: Filter Media Section

- Literature review of materials
- Lab testing of many candidates
- Numerical prediction of BRC performance

Filter Media Section: Lab testing

- Batch P sorption and desorption screening for K_d for several materials.
- Lab Column experiments simulated leaching within the cell and results fitted to find transport parameters.

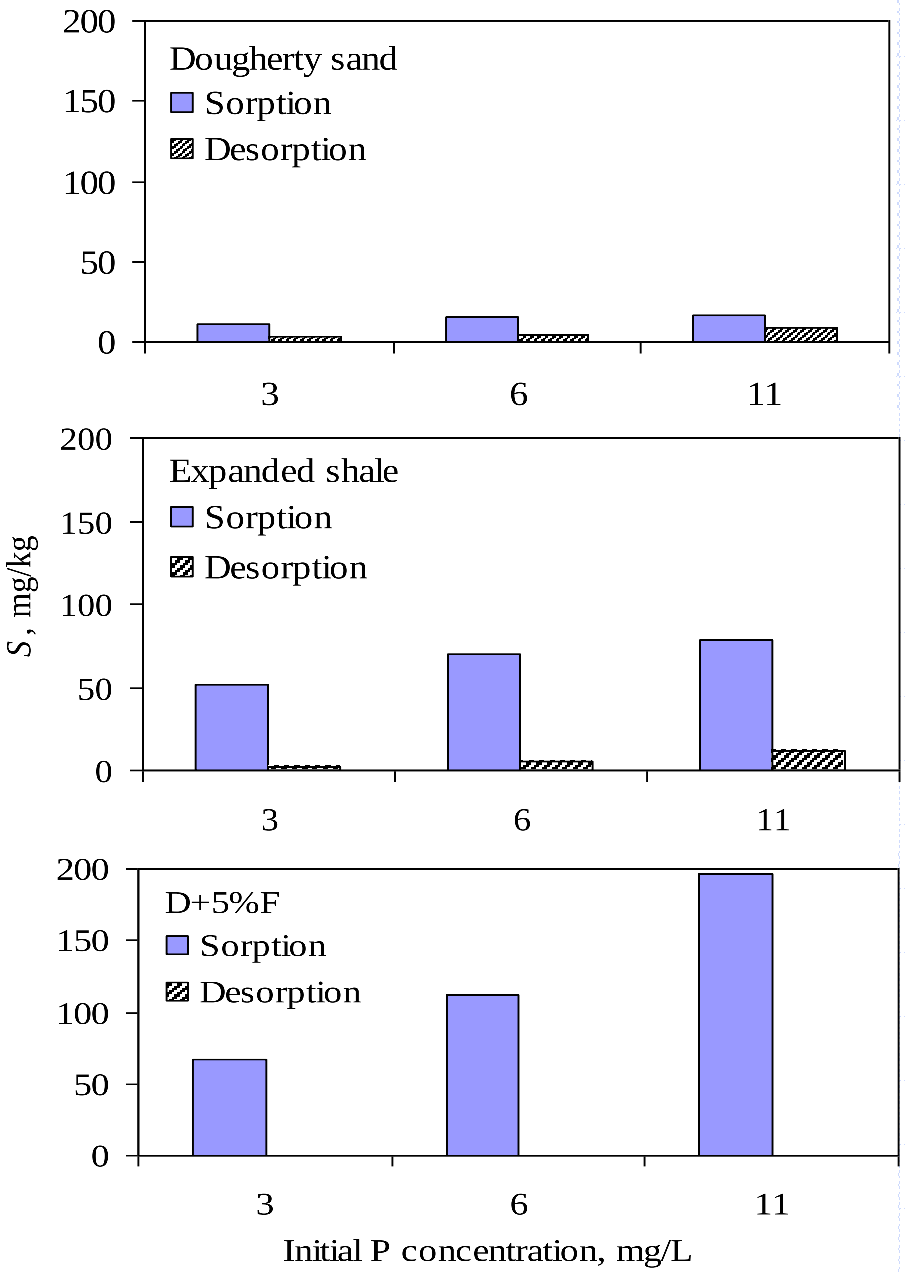


Batch Adsorption - Kd

	P (mL/g)	Zn (mL/g)	Cu (mL/g)	Pb(ml/g)
Peat moss	-5.8			
Teller loam	0.41	351	1650	557
Dougherty sand	2.1	20.6	155	>1,220
Expanded shale, MO	1.2			
Limestone	12			
Expanded shale, KS	280			
Class C fly ash	**2,180**	**4,010**	**8,410**	**3,050**
Sand with 5% fly ash	**300**	**843**	**239**	**>1,200**

Desorption

- Dougherty sand desorbed average 42% of initially sorbed P, expanded shale 7%, and sand and 5% fly ash negligible amounts.
- We selected sand with 5% fly ash as BRC filter media.



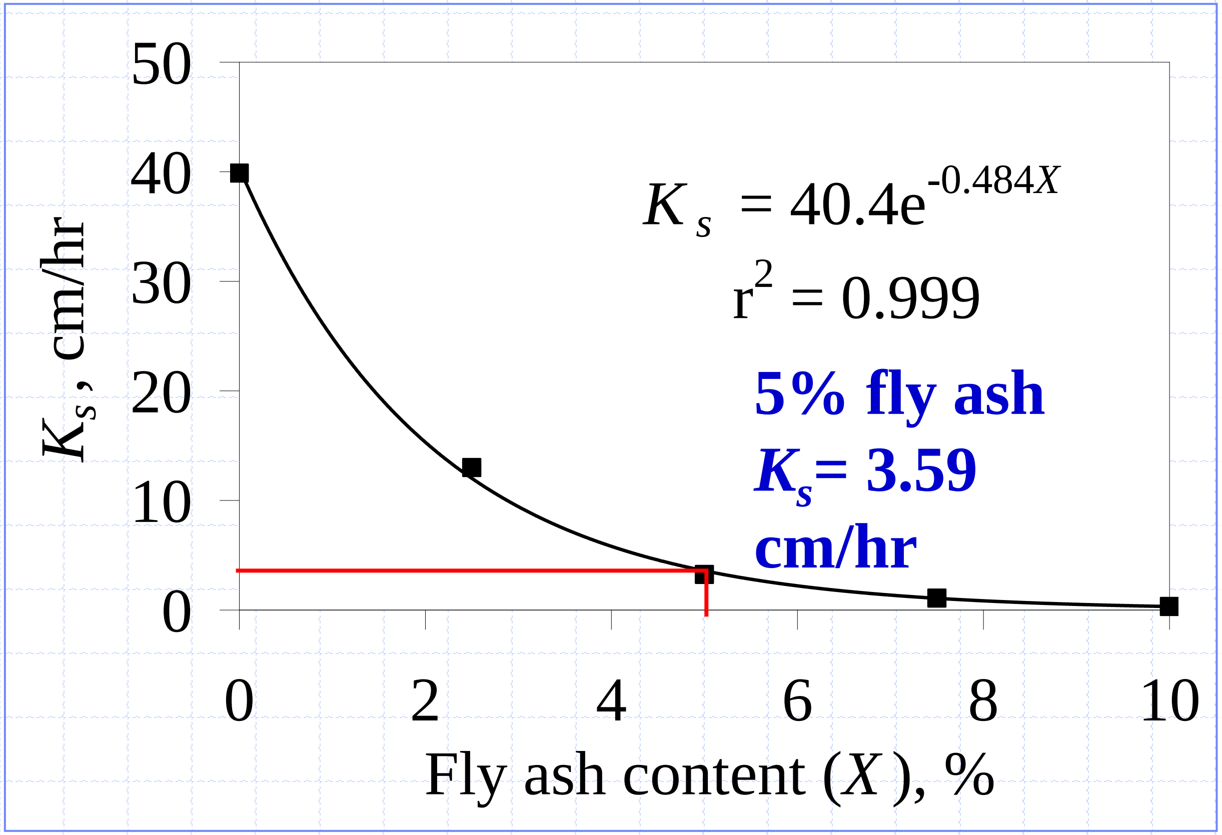
Fly Ash

- Class C fly ash, a byproduct of coal fueled electrical power plants, contains the metal oxides CaO, MgO, Al_2O_3 and Fe_2O_4 (23, 5, 18, and 6% respectively in our samples).
- Those oxides will react with phosphorous and heavy metals to form relativity insoluble minerals.
- The fly ash used “passed” RCRA testing.

Metal	Concentration in leachate, mg/L: Acetic acid solution	Concentration in leachate, mg/L: De-ionized water	Regulatory level, mg/L
As	0.07	0.02	5.0
Cd	0.00	0.00	1.0
Pb	0.00	0.00	5.0
Cr	0.33	0.03	5.0
Se	0.28	0.02	1.0

One big concern - Hydraulic conductivity

- Fly ash greatly reducing permeability of sand.

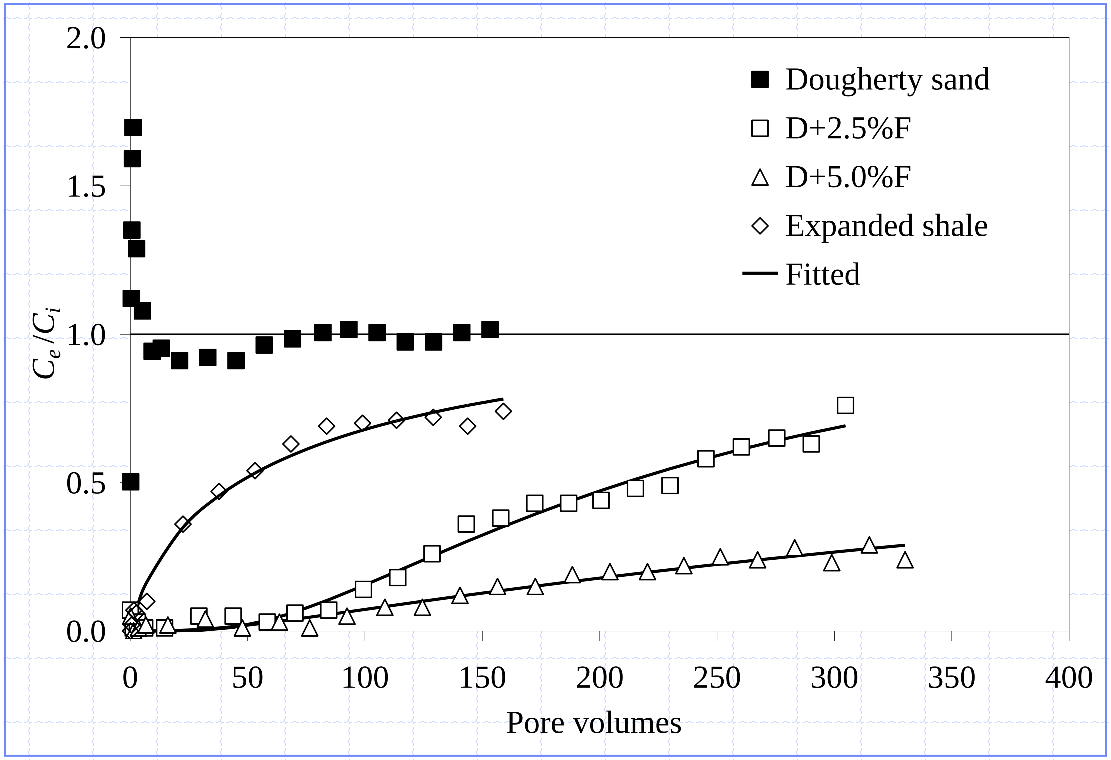


Column Experiments

- Column: 14.4 cm I.D., 14.3 cm long.
- Influent: P, Pb, Cu & Zn, 1 mg/L @ 0.5 L/hr, for up to 350 pore volumes.
- Evaluate P sorption from break through curve.
- Little of the metals leached. Transport was evaluated by minimum transport theory and core sectioning.

1-D Phosphorus Transport Modeling

- One dimensional linear equilibrium adsorption convection-dispersion transport model in CXTFIT 2.1 in the STANMOD software package developed by the U.S. Salinity Laboratory.
- Fit observed breakthrough curves by the model to estimate hydrodynamic dispersion and sorption K_d.
- Column K_d only ¼ of batch estimate.



1-D Model Estimated Lifetime

- Filter media: sand & 5% fly ash
- Depth: 1 m
- Inflow P: 1 mg/L
- Outflow P limit: 0.037 mg/L
- Fifty years daily precipitation data were used to estimate the runoff loading.

	Lifetime, yr	
	Pavements	Lawns
Transport K_d	4	11
Batch K_d	12	34

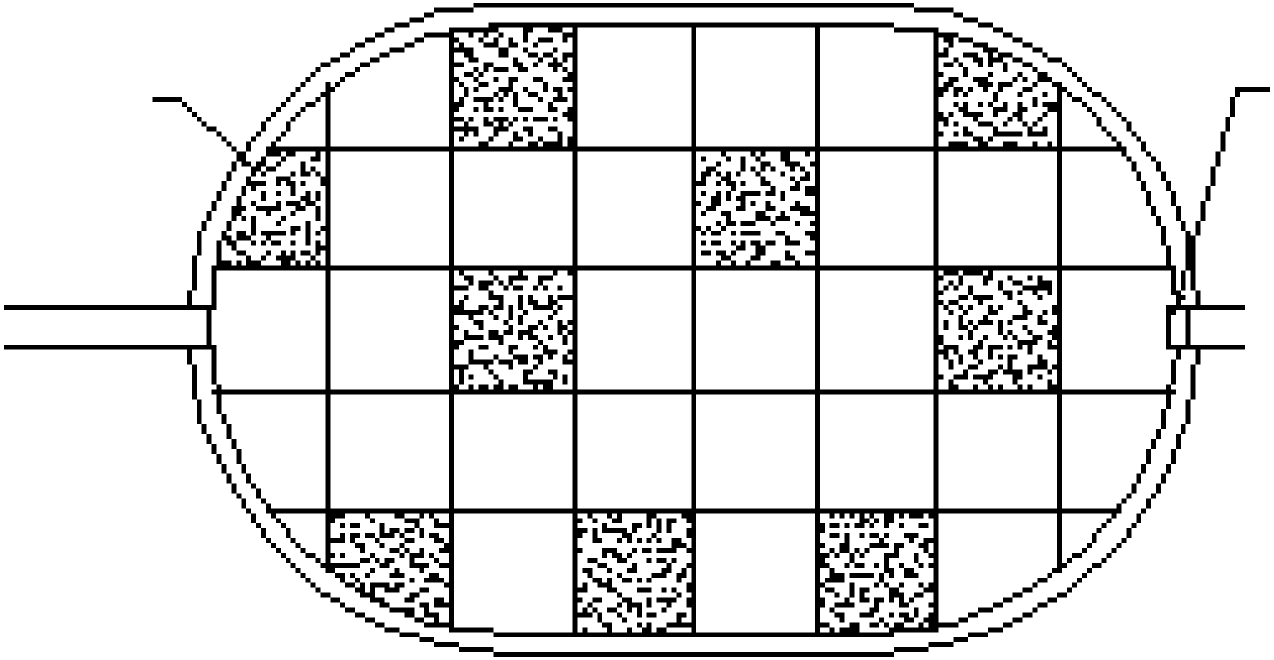
Phase II: Construction & Evaluation

- Conceptual Design
- Construction
- Evaluation of BRC
  - Fly-ash distribution
  - 3-D modeling of flow and transport

Conceptual Design

- 3% to 5% of area.
- Sized for runoff:
  - ½” in pool
  - ½” in filter
- 1’ topsoil.
- Filter media a blend of sand and 5% fly ash.
- Bottom drain to atmosphere.
- Sand plugs on 25% of surface for infiltration.

Sand Plugs for Infiltration

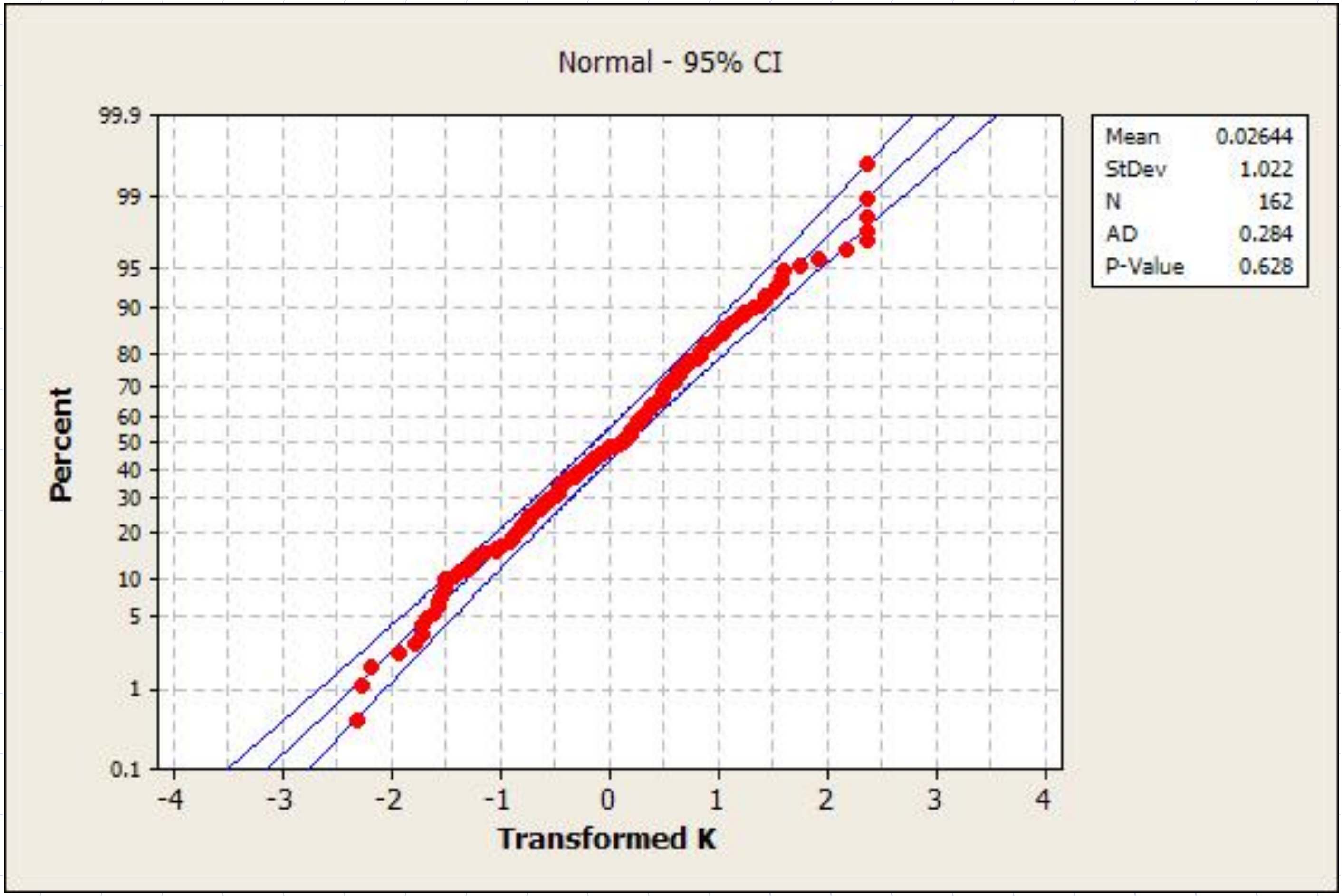


Construction

Construction

Mixing Fly Ash on Site Proved Difficult

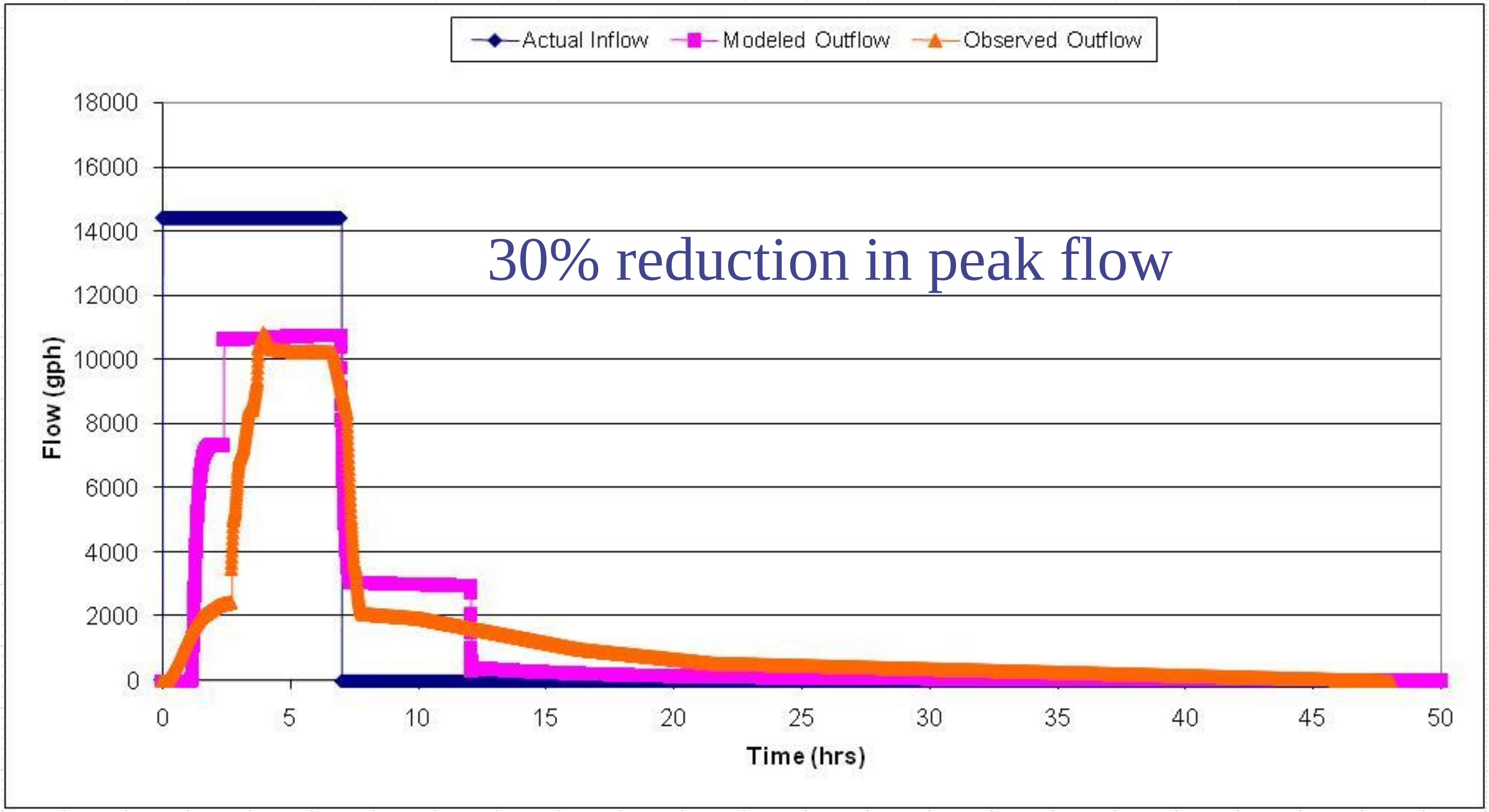
Evaluation: As built fly-ash distribution



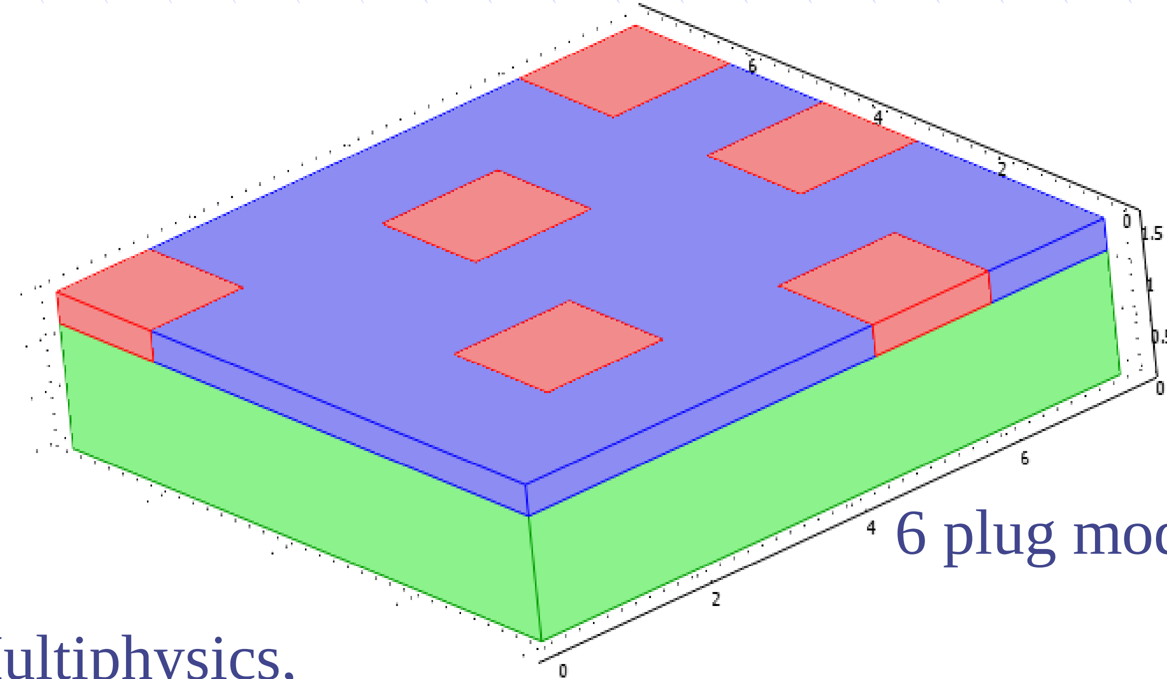
Construction Cost

BRC Location	Area (m^2)	Volume (m^3)	Cost ($)
Elm Creek Plaza	63	128	12,496
Lendonwood Gardens	23	19	8,847
Grove High School	149	161	17,070
Grand Lake Association	172	435	29,172
Cherokee Queen	116	108	13,796
Early Childhood Development Center	48	70	10715
Clark Residence	30	27	7,368

Evaluation: As Built Hydraulics



Evaluation:
3-D Model

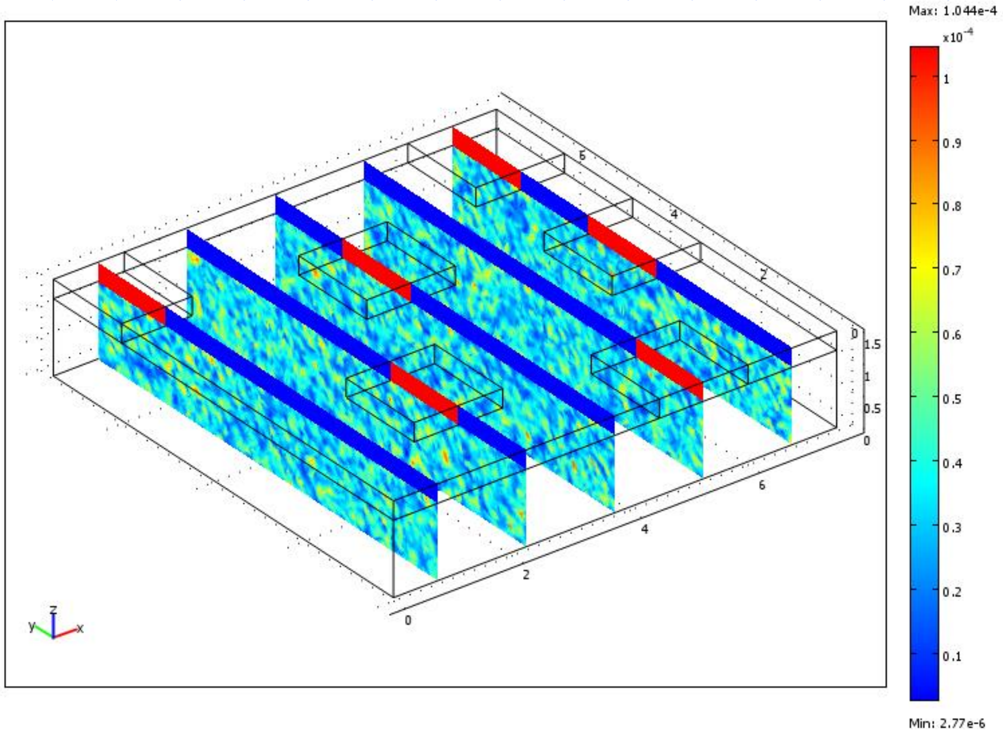


6 plug model

- BRC modeled
  in COMSOL Multiphysics,
  Earth Science Module, with saturated conditions.
- Finite element model, 7.5 x 7.5 x 1.5 m, with 75,088 elements.
- 9 configurations representing different constructions designs and construction quality examined.

3-D Modeling of flow and transport

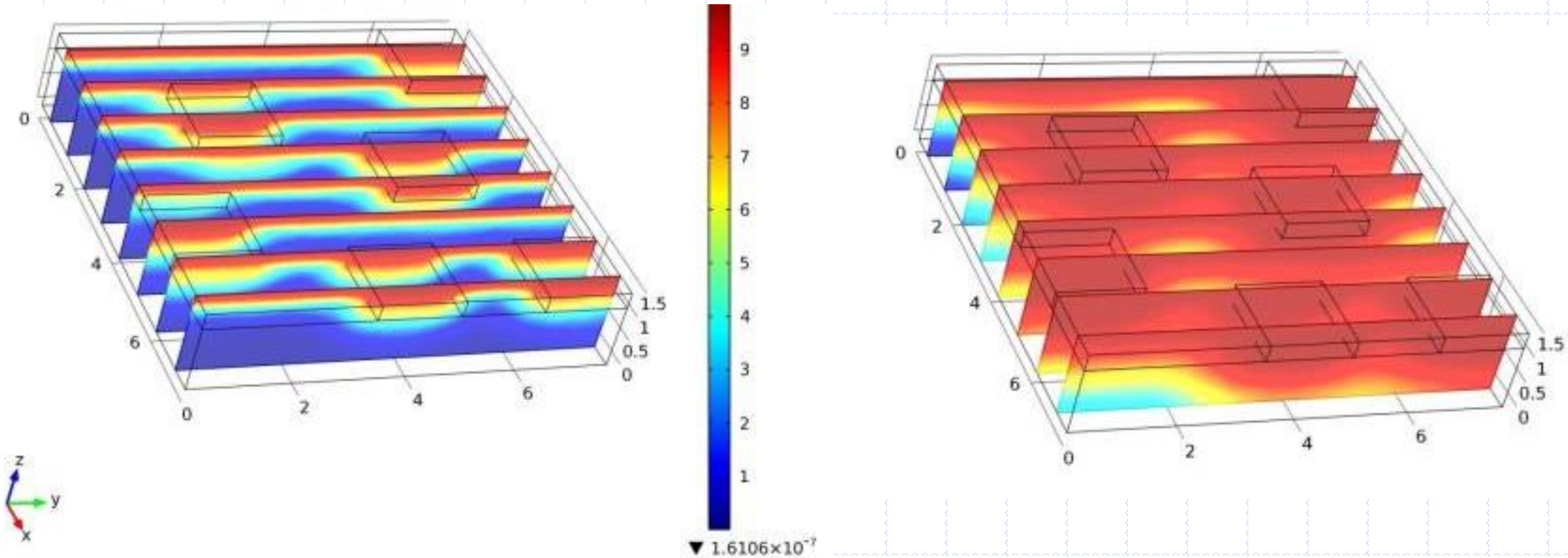
- Filter conductivity and P sorption varied for each 1 liter volume using flay ash distribution measured during construction.
- 20 random realizations for each configuration
- 180 simulations in total.



6 plug model *K* distribution

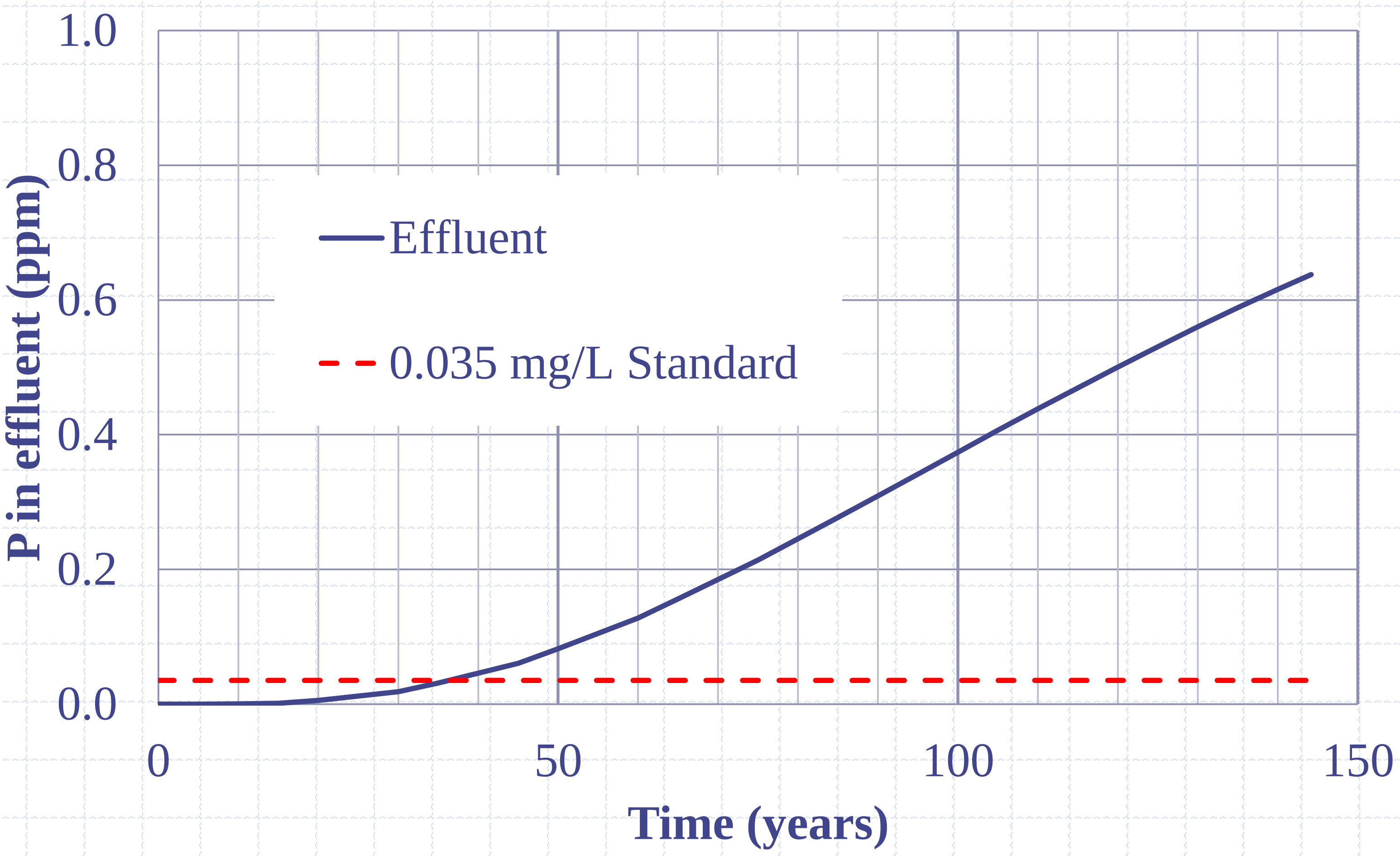
3-D Model Concentration Results

20 years 144 years



- 17 nominal years of complete treatment
- More than 144 years of some P removal

3-D Model Effluent Concentration



Phase III: Sampling of Aged Cells

- Under Office of the Secretary of the Environment / EPA 319-h evaluated how the BRC were working
  - Core sampling
  - Water sampling
  - Load reduction estimations

Aged BRC Studied

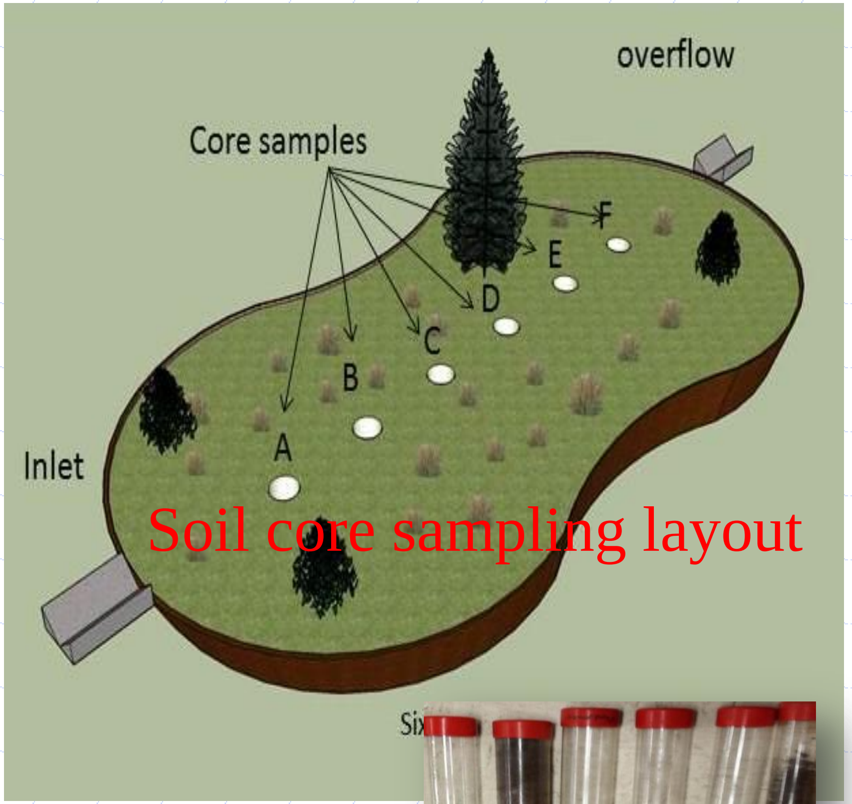
Site	Grand Lake Association (GLA)	Grove High School (GHS)	Elm Creek Plaza (ECP)	Spicer Residence (SR)
Location	36˚36’39” N, 94˚48’14”W	36˚37’19” N, 94˚44’50”W	36˚34’47” N, 94˚46’08”W	36˚38’59” N, 94˚46’08”W
Property Type	Public	Public	Commercial	Residential
Land Cover	36% Impervious	90% Impervious	100% Impervious	13% Impervious
Drainage area(Hectares)	0.76	0.26	0.25	0.15
Cell area (m^2)	172	149	63	101
Surface/drainage area ratio	2.2%	5.7%	2.5%	6.7%
Sampled media depth (m)	0.6	0.6	0.6	0.6

Sampling of Aged Cells

- Cored selected cells in 2014.
- Monitored cell influent and effluent for a year ending in 2015.

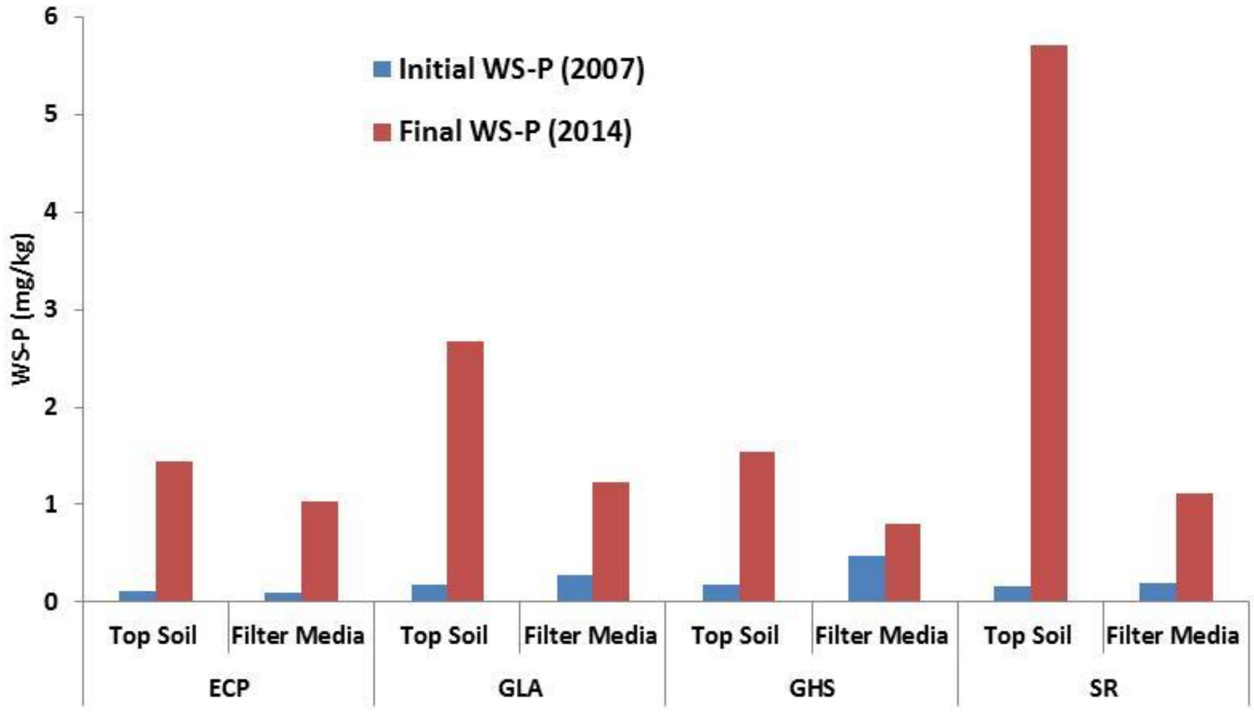
2014 Filter Sampling

- Six core samples from BRC at four sites.
- Analysis
  - WSP extraction (1:10 soil:solution) for soluble P.
  - Mehlich-3 (weak acid) extraction.
  - Total acid digestion (EPA 3050) for total elemental P.

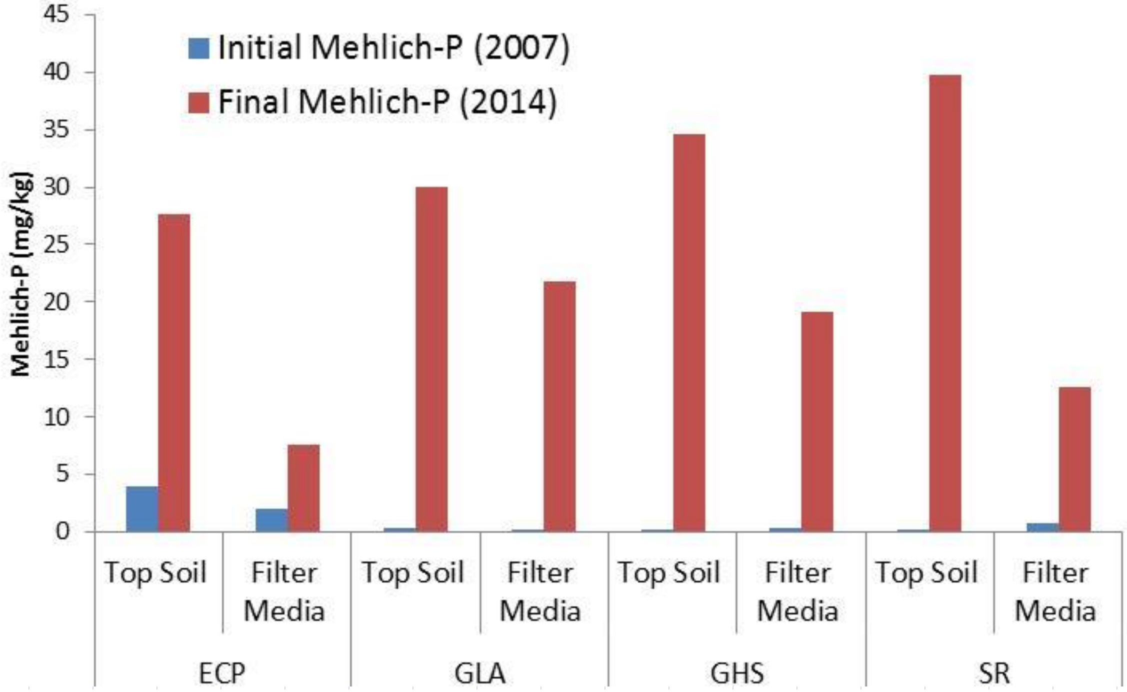


Soil core sampling layout

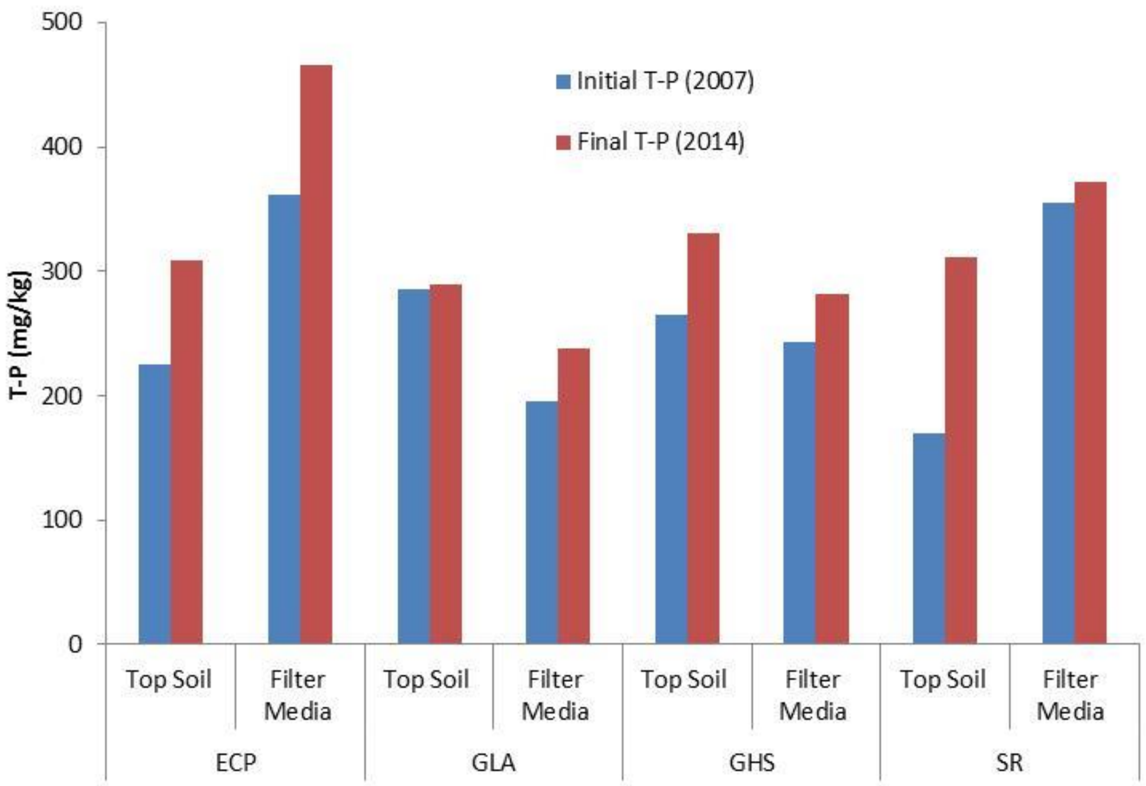
2014 Cores: Filter Water Soluble P



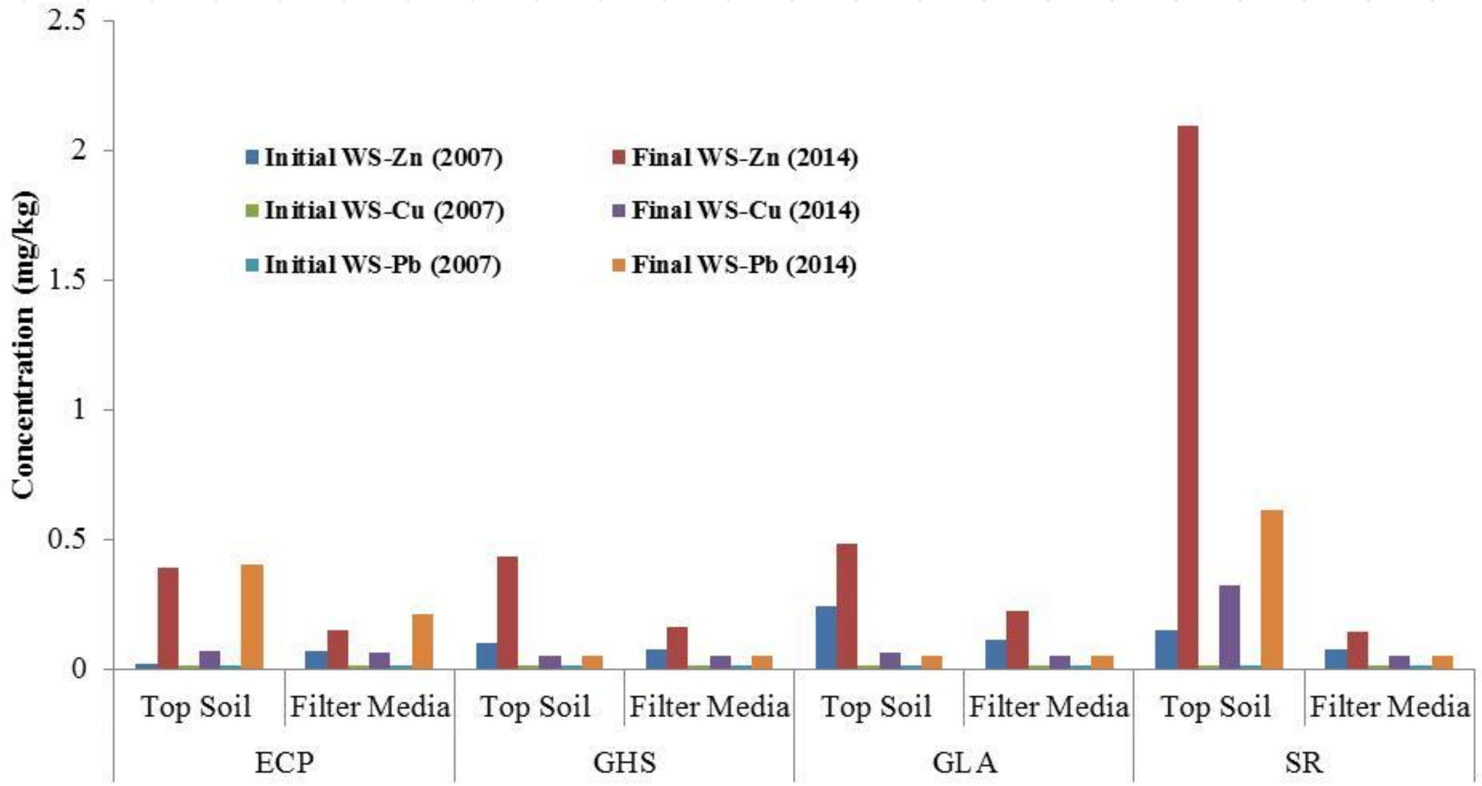
2014 Cores: Filter Media Mehlich-3 P



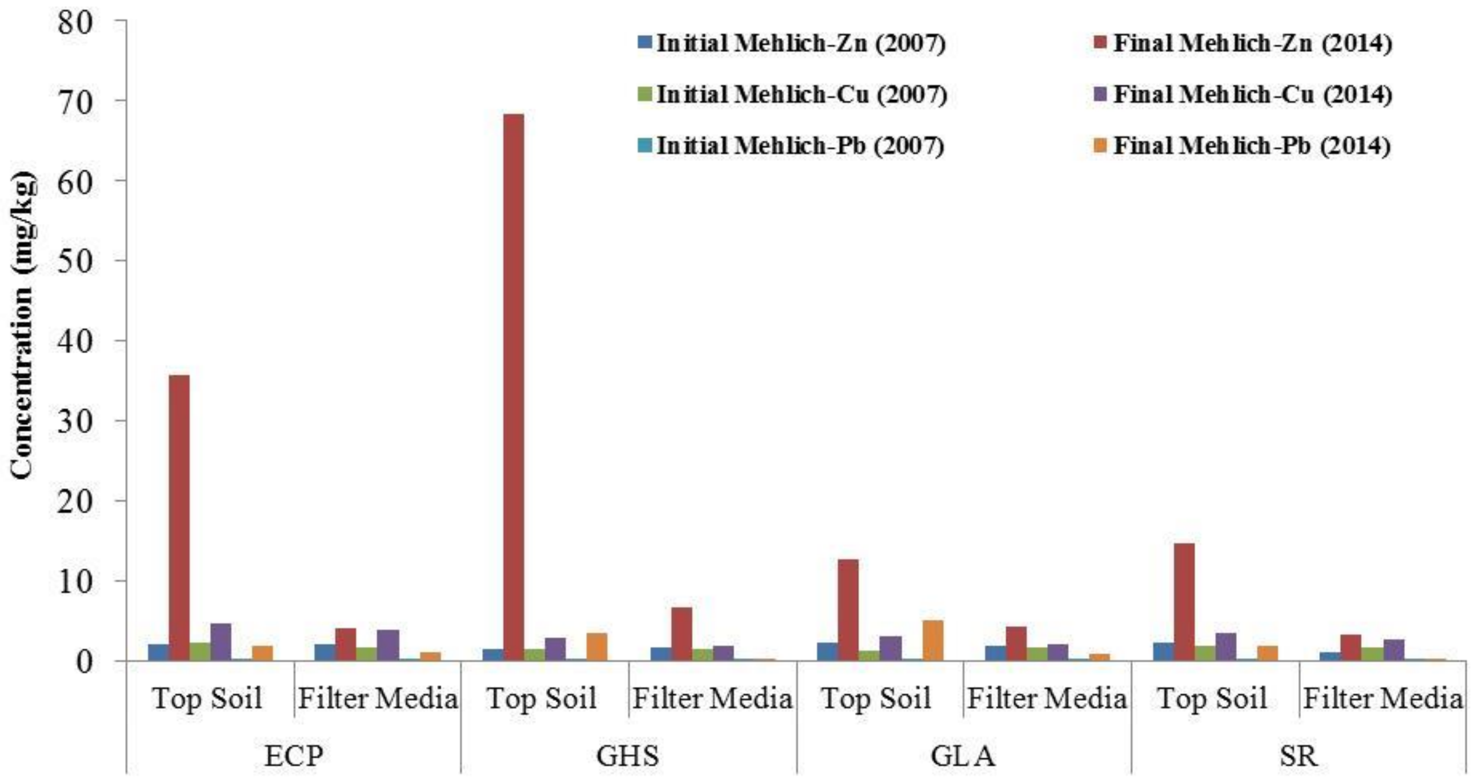
2014 Cores: Filter Media Total-P



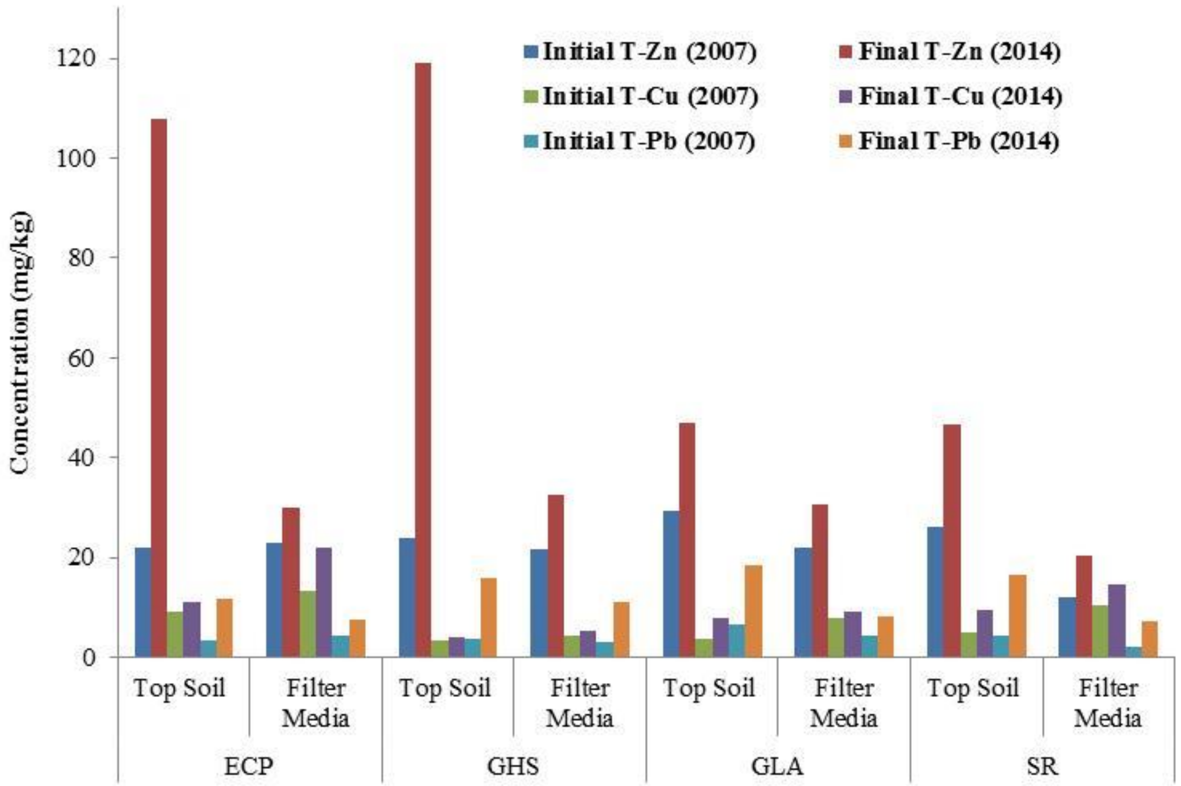
Water Soluble Metals 2007 & 2014



Mehlich-3 Metals 2017 & 2014



Total Metals 2007 & 2014



2014 Cores: P Mineralogy

- Mineralogy of the adsorbed P determined with Bookhaven National Synchrotron Light Source II by X-ray absorption near edge structure analysis (XANES).
- Most P was held as calcium phosphates: brushite, monetite, hydroxyapatite, tricalcium P, and octacalcium P.

2015 Water Sampling

- Automated samplers installed on inflow, drain and overflow of 3 cells, ECP, GHS, & GLA.
- Volume weighted composite samples analyzed for each storm.

2015 Water Sampling: Total P Reduction

		Mean Concentration			Mass Loading		
Cell	**# events**	**Inflow (mg/L)**	**Under drain (mg/L)**	**Reduc -tion**	**Inflow (g)**	**Under drain (g)**	**Reduc -tion**
ECP	20	0.12	0.03	75%	3.25	0.22	93%
GHS	10	0.15	0.05	67%	5.13	0.83	84%
GLA	11	0.21	0.08	64%	13.8	3.22	76%

2015 Water Sampling: Total Zn Reduction

		Mean Concentration			Mass Loading		
Cell	**# events**	**Inflow (mg/L)**	**Under drain (mg/L)**	**Reduc -tion**	**Inflow (g)**	**Under drain (g)**	**Reduc -tion**
ECP	20	0.05	0.02	60%	1.10	0.13	88%
GHS	10	0.07	0.03	57%	3.10	0.72	77%
GLA	11	0.04	0.02	50%	2.46	1.40	43%

Annual Load Reduction: P & Zn

- Annual Load Reduction were estimated by two methods.

1. Cores: Increase in total mass, from 2007 to 2014, over volume of cell and divided by the 7 year age.
2. Water Samples: Apply the USGS model LOADEST (Runkel et al. 2004). LOADEST uses best fit regressions of limited measured data to predict the instantaneous load based on one or more input variables including rainfall, discharge and concentration in collected samples. That model is then applied to the full rainfall hydrographic to predict the total influent and effluent mass loadings.

Annual Load Reduction

	Total P (kg/yr)			Total Zn (kg/yr)		
Cell	Core	LOADEST	Average	Core	LOADEST	Average
ECP	0.40	0.27	0.34	0.21	0.06	0.14
GHS	0.33	0.18	0.26	0.63	0.13	0.38
GLA	0.51	0.37	0.44	0.24	0.09	0.17

Other work on these cells includes

- Construction costs
- Construction standards
- Maintenance issues
- Planting
- Plant survival
- Initial water quality
- Initial hydraulics
- Current hydraulics
- Bacteria
- Expected future performance.

Conclusions

- Fly ash amended filter media is effectively removing P and Zn from stormwater in the Grove BRC.
- The BRC are expected to continue to remove P and Zn with decreasing effectiveness for ~20 to 100+ years.
- All lab, modeling and field results justify expanded use of fly ash in stormwater systems where P or metals are a concern.

One concern and a possible solution

- Fly ash's powder particle size is problematic.
  - It is difficult to store on site and mix.
  - At high contents, filter permeability will be unacceptable.
  - Some will move through the sand, and work out the drain.
- Under OSU, Berry's Fellows funding, we are investigating granulizing fly ash such that it can be added at higher rates to the filter, and used as a stand alone media in high pollutant runoff applications.

With thanks to our many students and collaborators…

Students (current position)

- Megan Perry Lasch, BS, (Pinroc Construction, Austin)
- Katie Halgren, BS, (EDSA, Fort Lauderdale)
- Wei Zhang, MS, (Michigan State University)
- Reid Christianson, Ph.D., (Center for Watershed Protection, Urbana)
- Rebecca Chavez, Ph.D., (CP&Y, Austin)
- Sheila Youngblood Johnson, Ph.D., (Cameron University)
- Saroj Kandel, Ph.D.
- Alex McLemore, Ph.D. candidate, (Oklahoma State University)

Collaborators

- Chad Penn, (USDA-ARS, West Lafayette)
- Reid Coffman, (Kent State University)
- Hailin Zhang, (Oklahoma State University)
- Bill Barfield, (Oklahoma State University emeritus)
- Mike Smolen, (Oklahoma State University emeritus)
- Kevin Gustavson, (City of Tulsa)

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Several publications are in preparation and will be submitted soon under the authorship of S. Kandel, S. Youngblood, A. McLemore, J.R. Vogel, and G.O. Brown.