Is "Green" Infrastructure Loaded by Urban Drainage, Sustainable?

Ruben Kertesz, Kerrilynn Maccarone, Saurabh Raje, Karl Seltzer,
Michele Siminari, Peter Simms, Brandon Wood, John Sansalone

Gator Engineering UNIVERSITY OF FLORIDA

UF | UNIVERSITY of FLORIDA

Outline

1. Background and Rationale

2. Design Concepts and Criteria

3. Model Simulations

4. Data Collection and Analysis

5. Design Option Results

6. Cost Analyses and Extensibility

7. Conclusions and Recommendations


A common impervious asphalt: existing condition (circa January 2009)

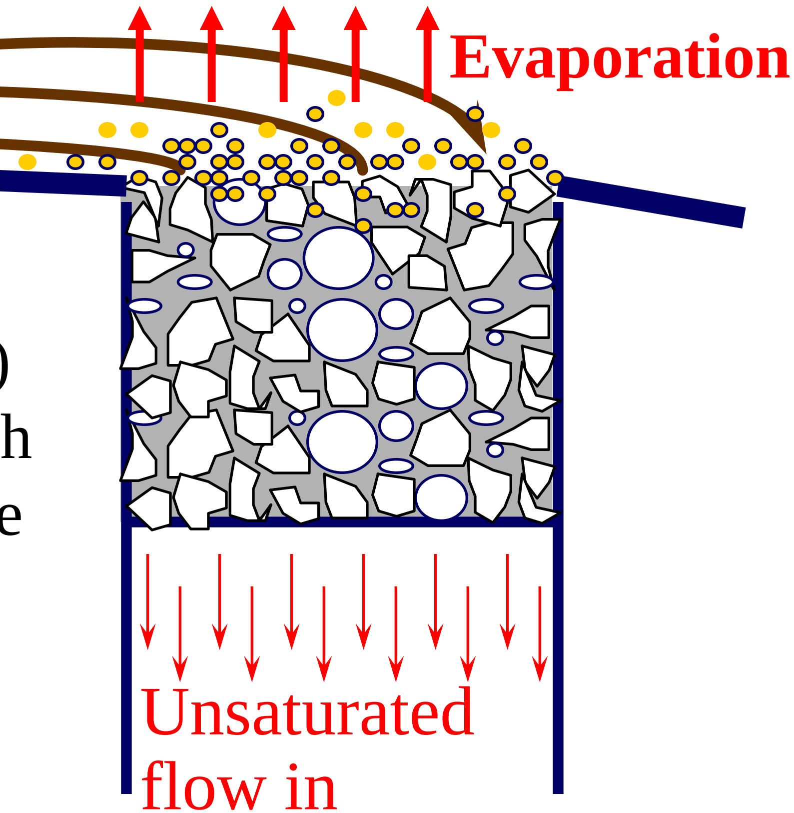
Problem Statement

Urban design elements (for example: roadways, parking) and materials (for example: pavement materials) associated with the motor vehicle; and of vehicular transportation have helped contribute to urban drainage pollutant loads at levels similar to untreated wastewater.

Can we design our way back to urban drainage sustainability or is sustainability purely hydro-fantasy?

Cementitious permeable pavement (CPP), as an in-situ material with behavior that can be measured/modeled

Lateral Sheet Flow, q_{sf}



<u>CPP adsorptive-filter design:</u>

• 11 - 15 kN/m^3	Unit weight
• 0.1- 0.005 cm/s	$K_{saturated}$ (clean bed)
• 25,000 – 30,000 Kpa	Unconfined strength
• 20 - 50 L/min-m^2	Surface loading rate

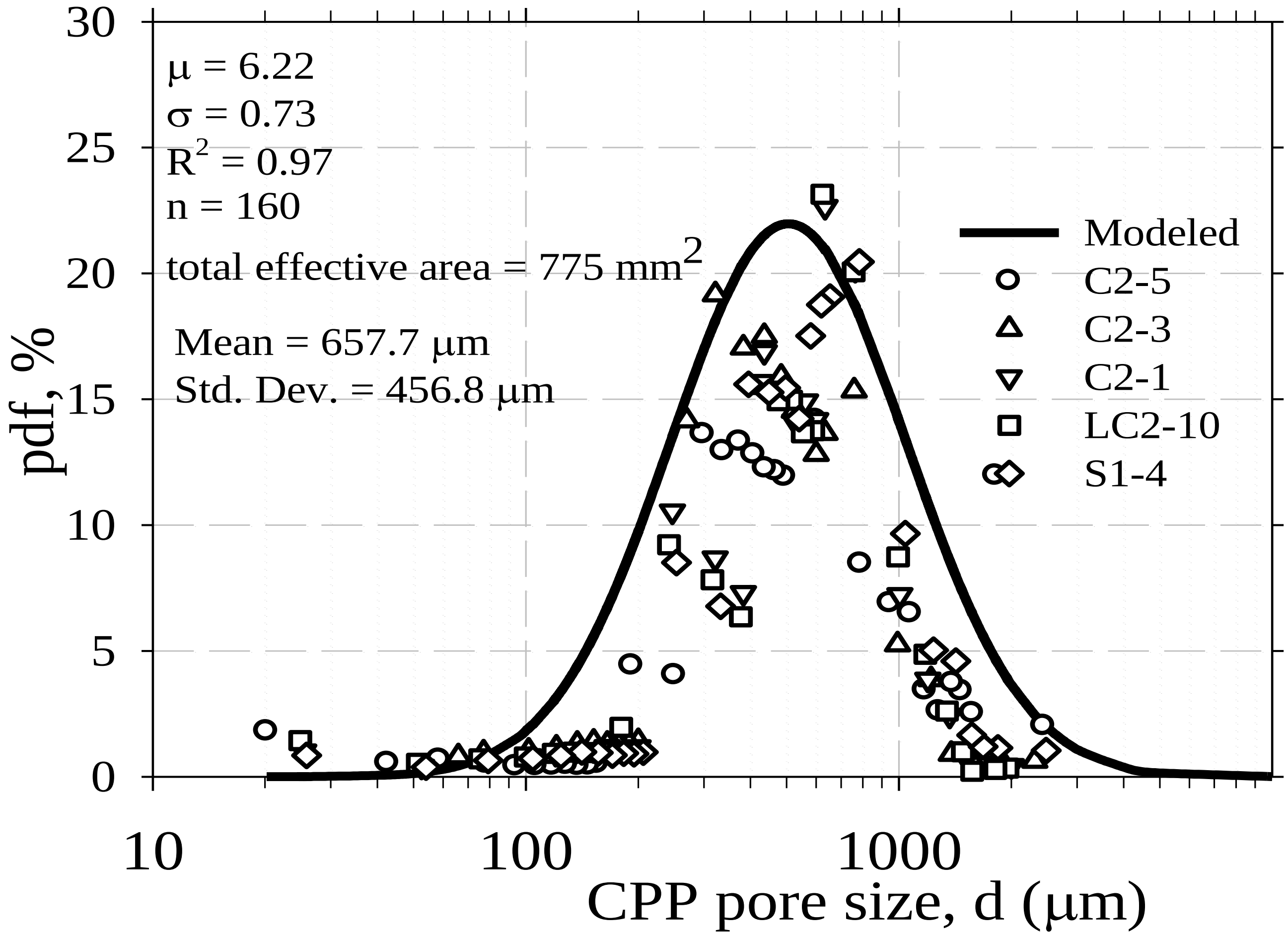
<u>Mix Design Proportions:</u>

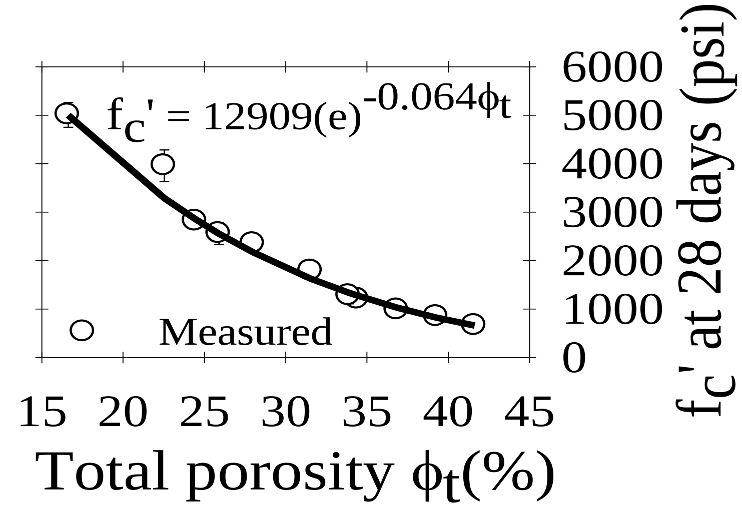
• varies	Type II Cement
• 380 kg	Sand
• 380 kg	Pea Gravel
• varies	Water
• 10 – 30 %	Total porosity
• varies	Amphoteric admixture

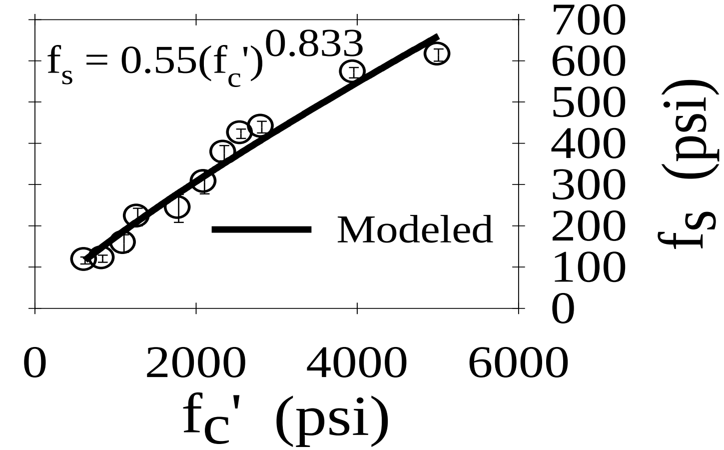
$K_{sat.}$ for media: 0.01 cm/s

Solids & particulates

CPP Pore and Structural Properties (function of mix design)







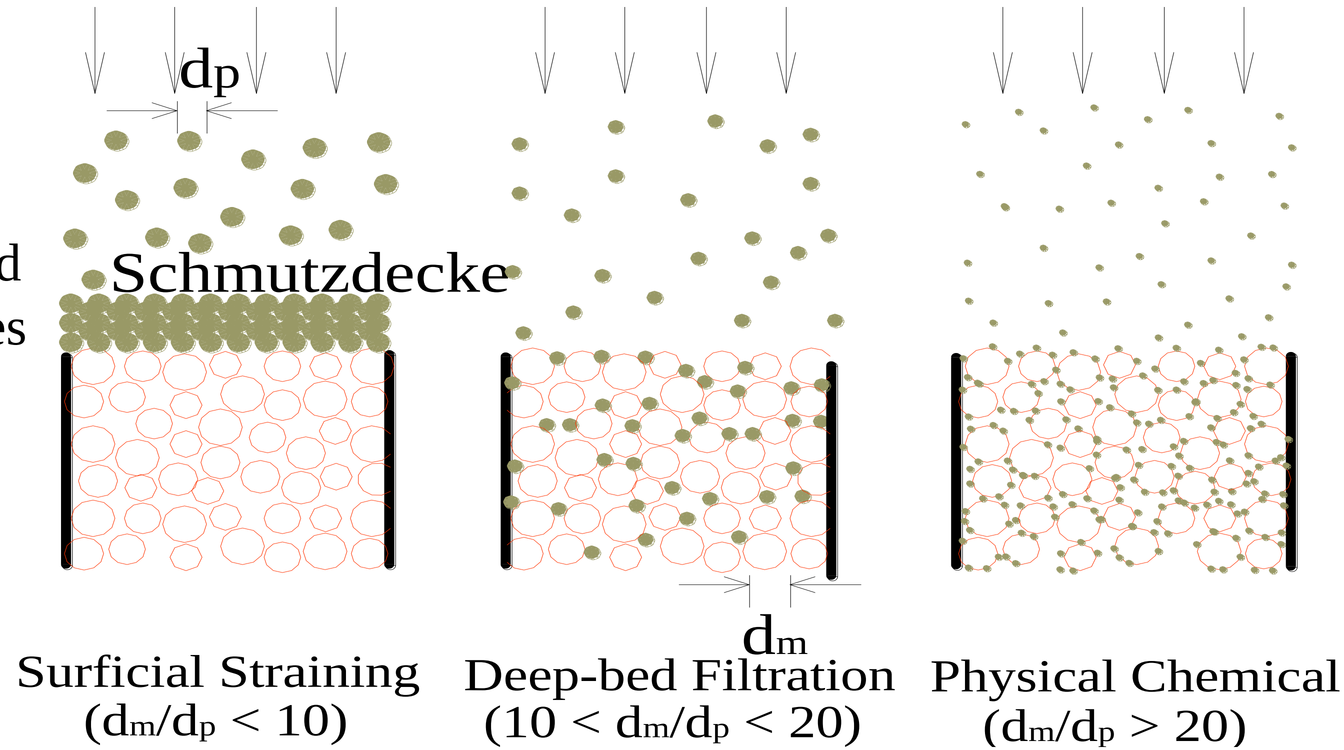
f_c’: unconfined compressive strength

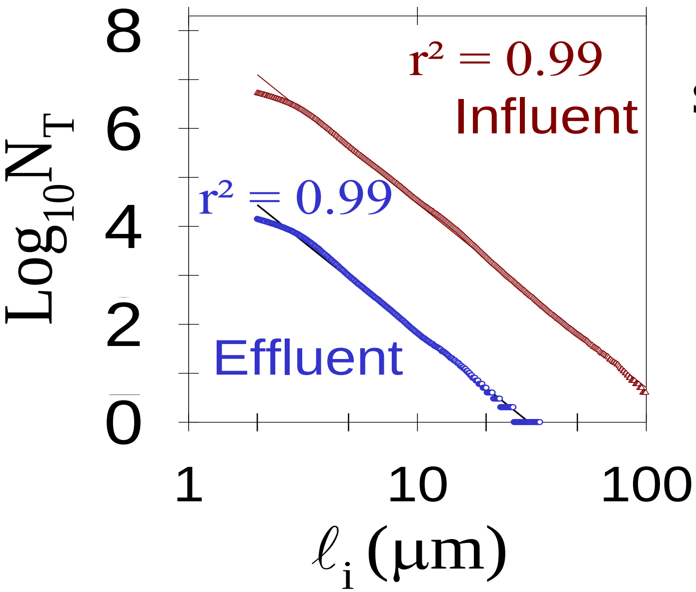
f_s: splitting tensile strength

Filtration mechanisms of CPP
(a pre- or primary unit operation that can be maintained)

Filtration mechanism

d_m/d_p ratio using mass based d_{50} of media and particulates

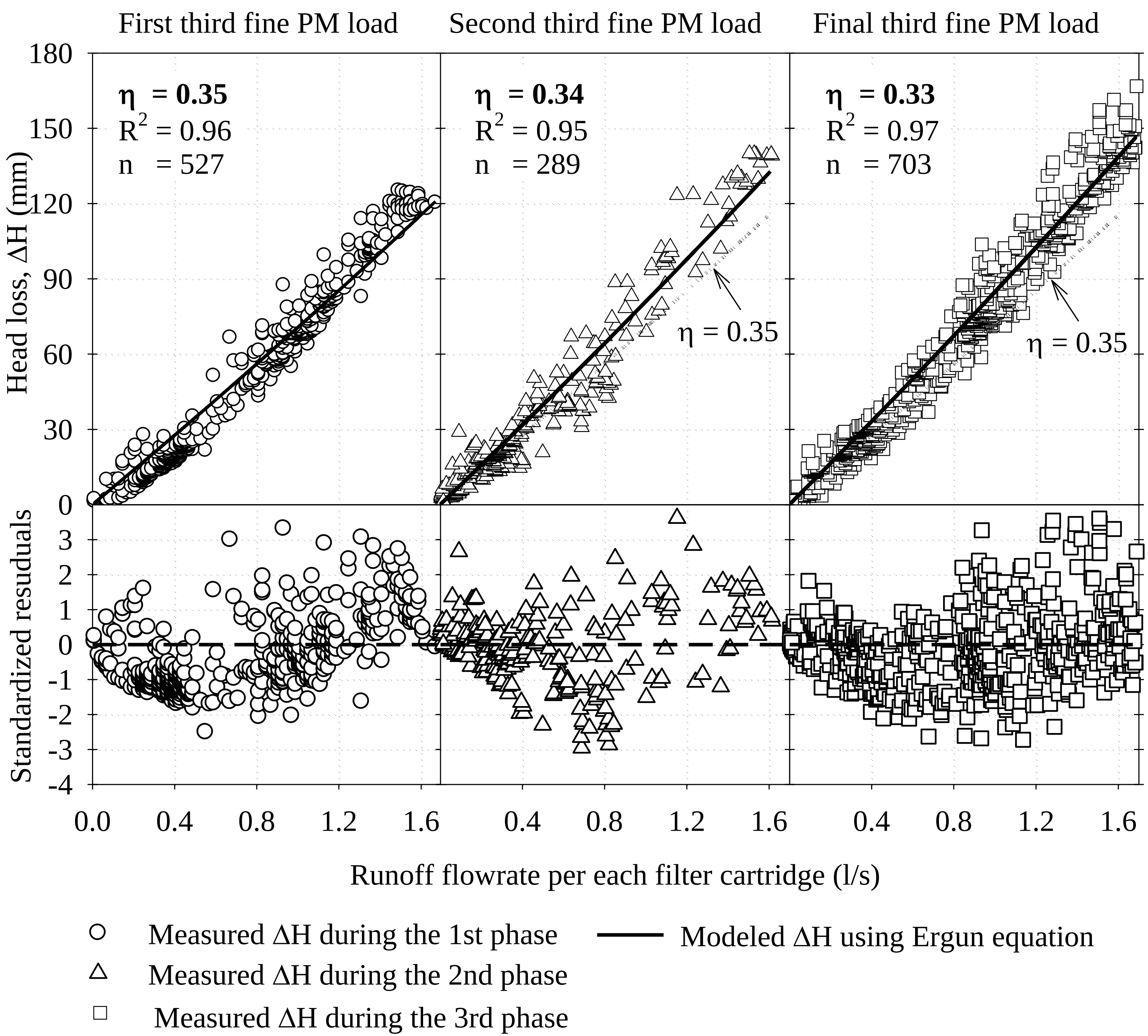




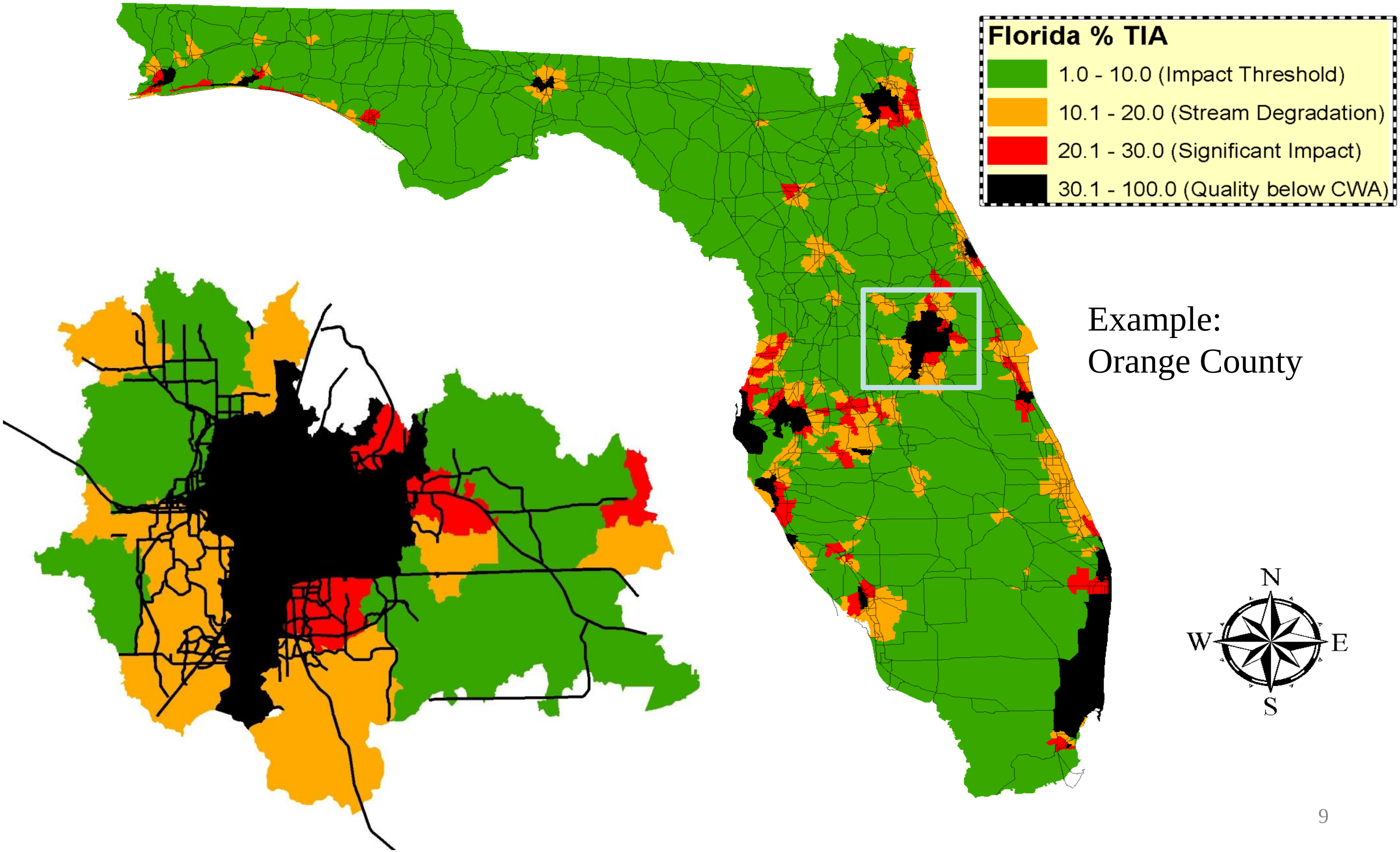
The power law function uses cumulative particle number density (PND) of all particles larger than the reference value R (i.e. 1 μm).

$$N_T = \alpha\left(\frac{l_i}{R}\right)^{-\beta}$$

Loading of urban PM to an in-situ granular filter after sedimentation
(initial porosity = 0.35, n = 19 events)

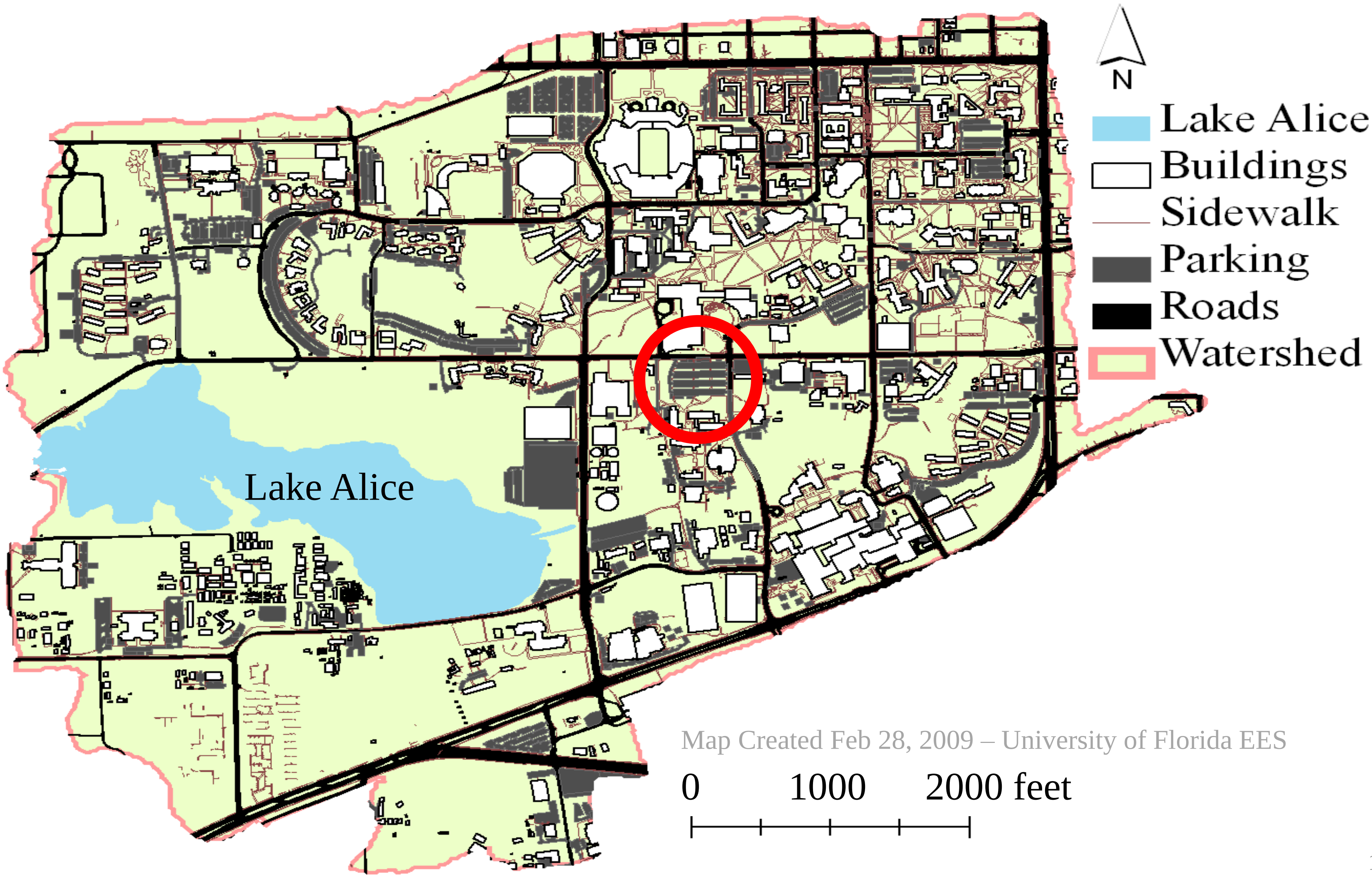


Total Impervious Area (TIA): Florida



Example:
Orange County

Site Vicinity Map: UF Campus in Gainesville

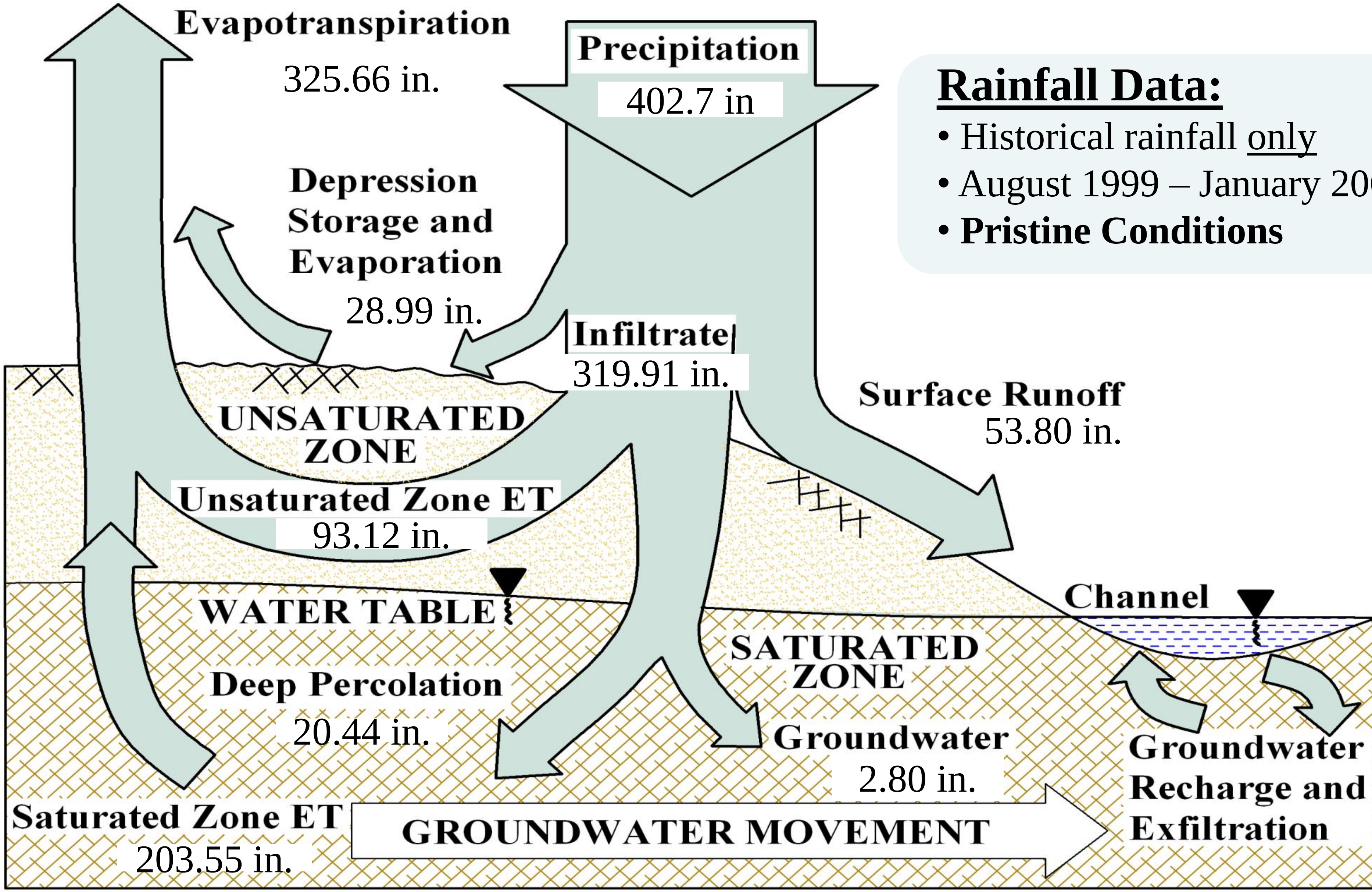


Existing Site Conditions (Post-Development)

Watershed Area	3.23 acres
Total % Pavement	75.61%
Total % Island	24.39%

The current design has raised vegetated islands that drain to impervious asphalt pavement.

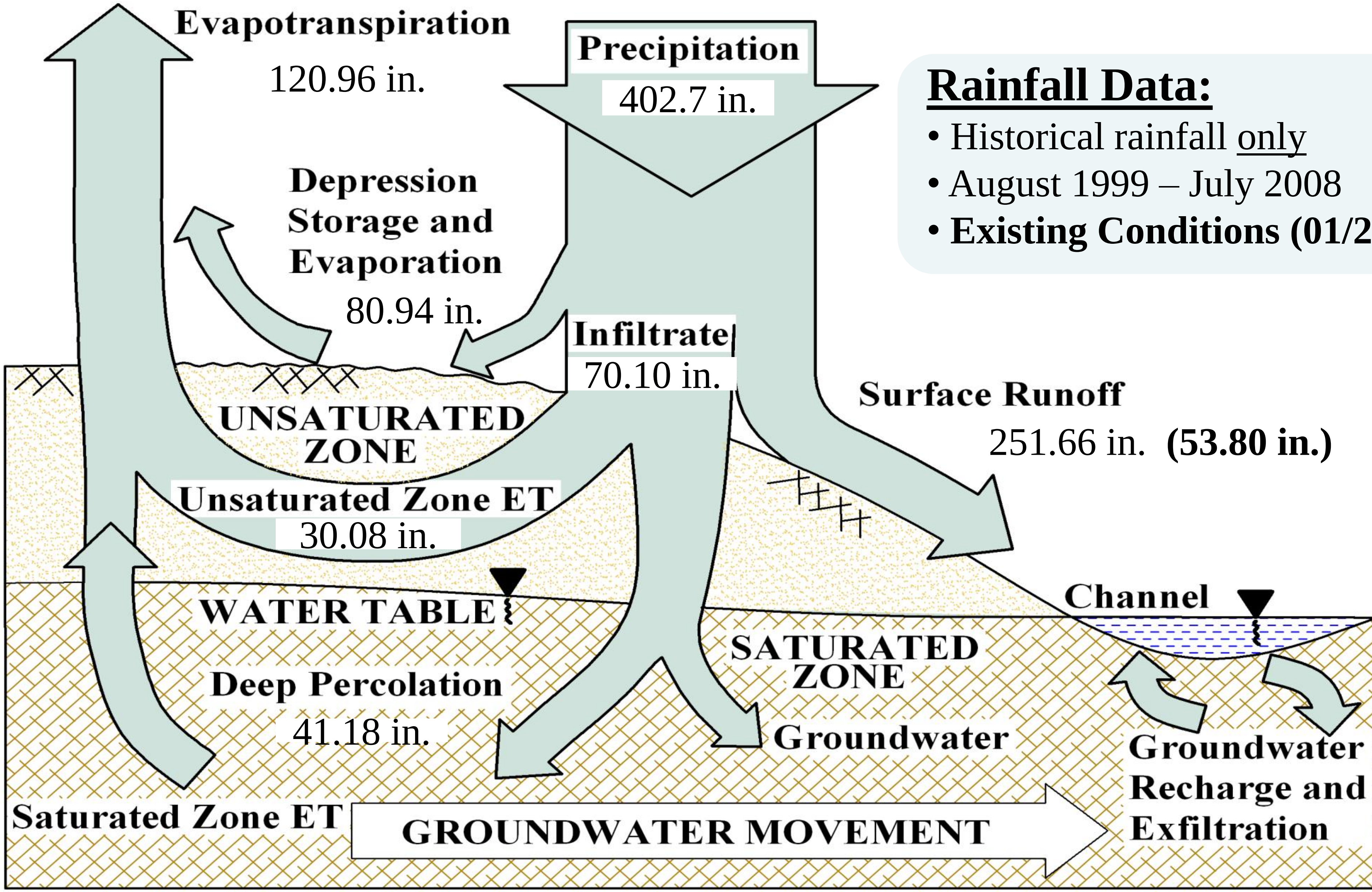
Subject Site Pre-Development Hydrologic Cycle



Rainfall Data:

- Historical rainfall only
- August 1999 – January 2009
- **Pristine Conditions**

Subject Site Post-Development Hydrologic Cycle



Rainfall Data:

- Historical rainfall only
- August 1999 – July 2008
- **Existing Conditions (01/2009)**

Mean Site Discharge Concentration and Hydrology Data

Development Condition	TSS[a] [mg/L]	TP [mg/L]	TN [mg/L]
Pre-Development (**FDEP "Pristine"**)	≈ 7.8[b]	≈ 0.074	≈ 1.15
Post-Development (**Existing Condition**)	346[a]	1.27	4.72
Percent Increase	4400%	1700%	410%

- **Pre-Development Conditions**
  - Based on FDEP pre-developed EMC values and SWMM simulations
  - Table 4.16 of FDEP Stormwater Treatment Report (FAC 62-25 § 4.1.14)
  - Undeveloped rangeland/forest
- **Post-Development Conditions**
  - 9 years of historical rainfall data (Gainesville Regional Airport, NCDC)[c] and ET data
  - Runoff loads for 15 storms at site under existing conditions

a. TSS = ∑ Suspended + Settleable + Sediment
b. Harper, H. and Baker, D. (2003) and as required by FDEP in recent load matching (FDOT, 2007)
c. http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20004544

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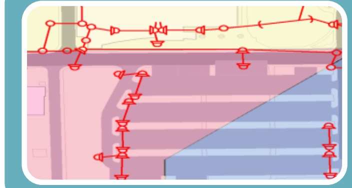
Within the existing site constraints site, can we envision green infrastructure and LID design options?

Green Infrastructure, LID, Source Control Design



Conventional Stormwater Treatment (Existing)

- Standard curb and gutter design

***Design*: Street Sweeping**

- Particulate Matter (PM), TN and TP Removal
- Monthly maintenance as source control, restores conductivity

***Design*: Cementitious Permeable Pavement (CPP)**

- This Linear Infiltration Reactor (LIR) allows PM & TP Filtration
- Dissolved Phosphorus Adsorption through Al-oxide Admixture

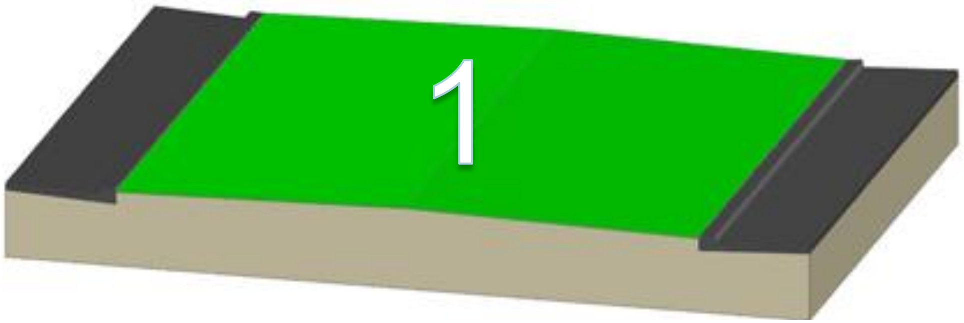
***Design*: Biofiltration Area Reactor (BAR)**

- Storage, Sedimentation, Phyto-pumping with vegetative design
- Evapotranspiration, Infiltration, Biogenic source of organic C

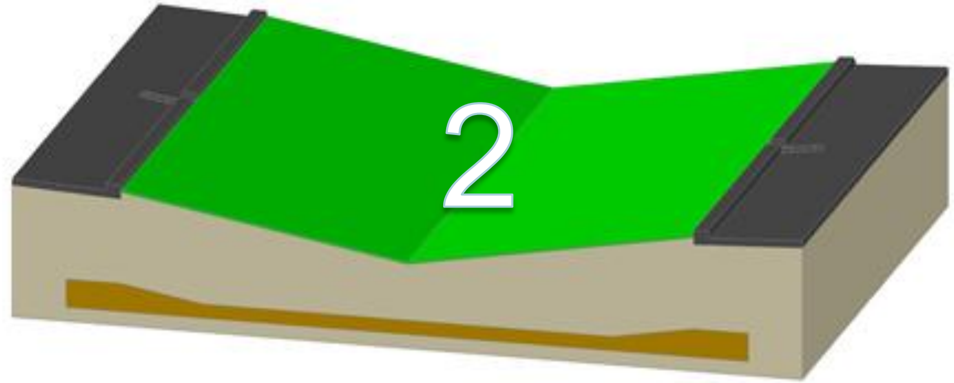
***Design*: Clay Bounding Layer of Sub-surface Biofilter**

- Nitrate utilized as electron acceptor in sub-surface biofilter: to allow denitrification through water table management

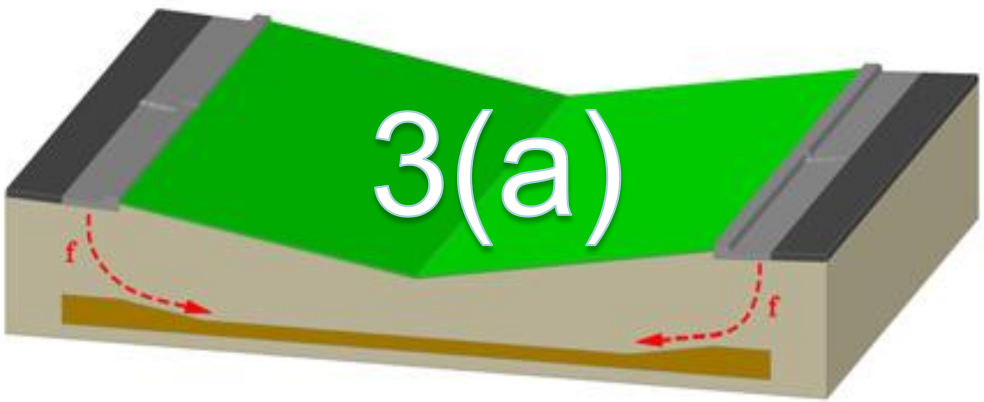
Design Options



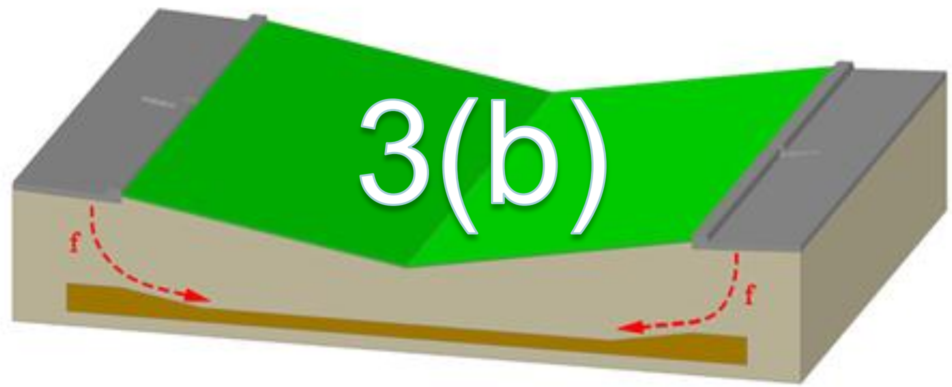
Existing Condition



BAR only

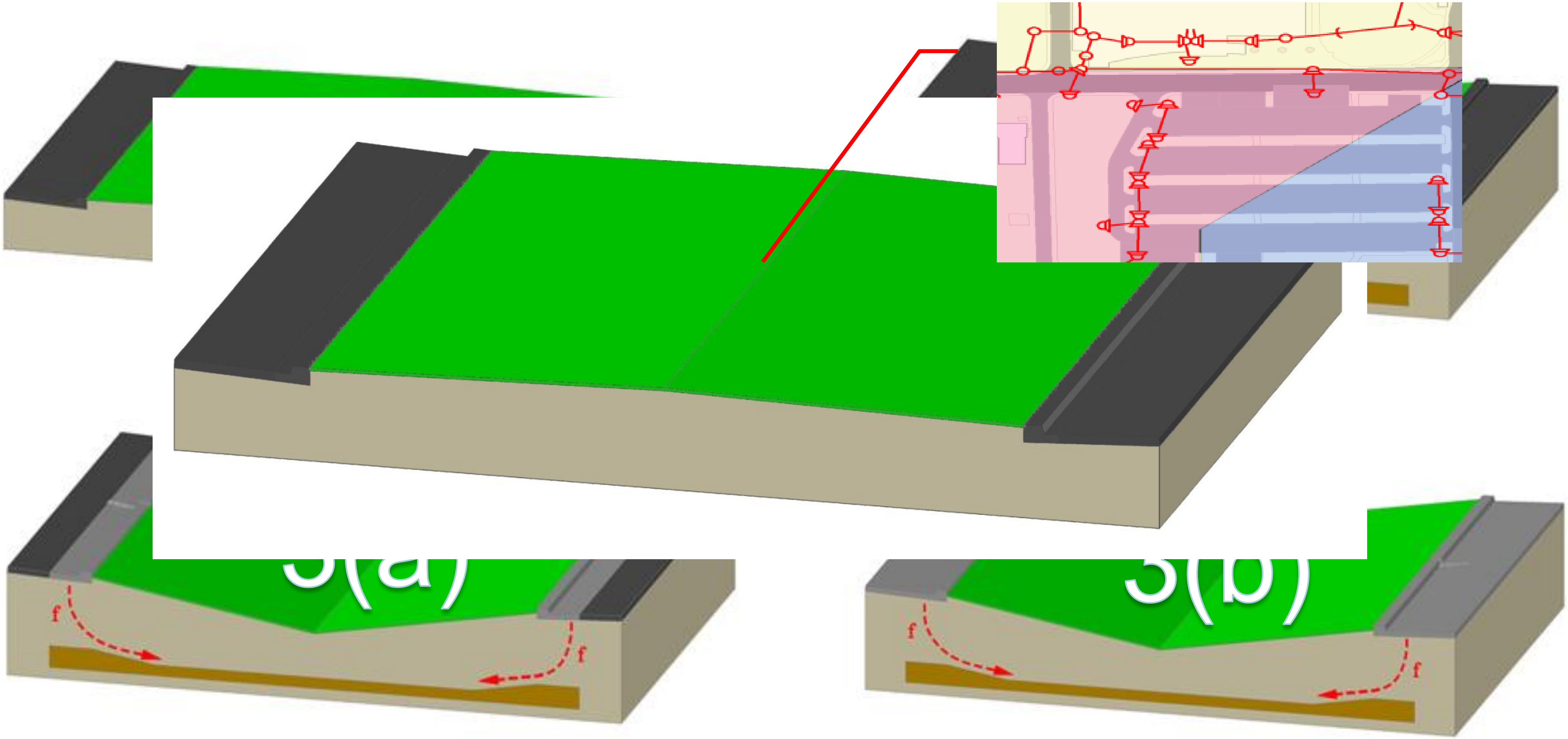


Varying width LIR (with CPP) and BAR

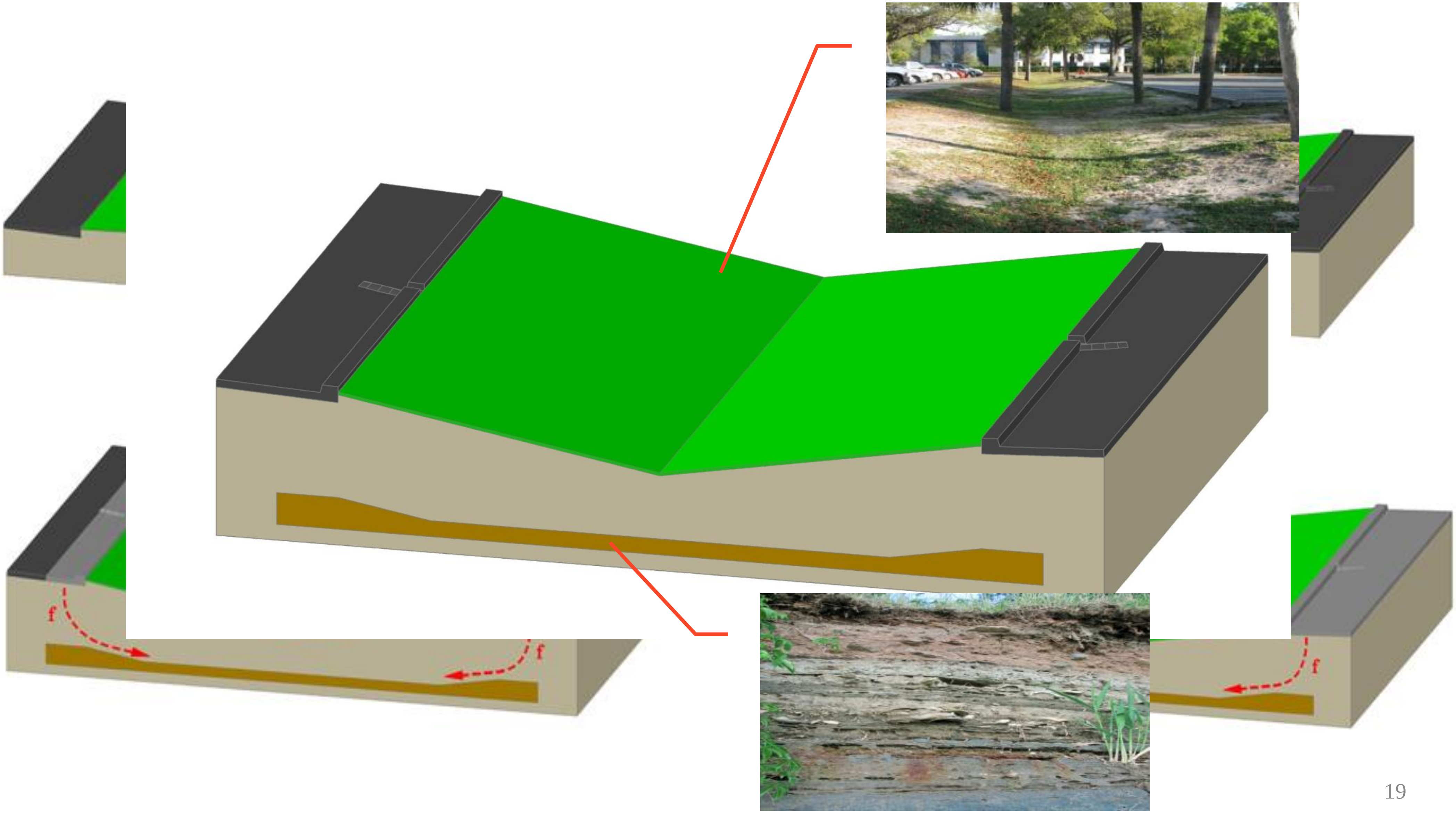


All CPP and BAR

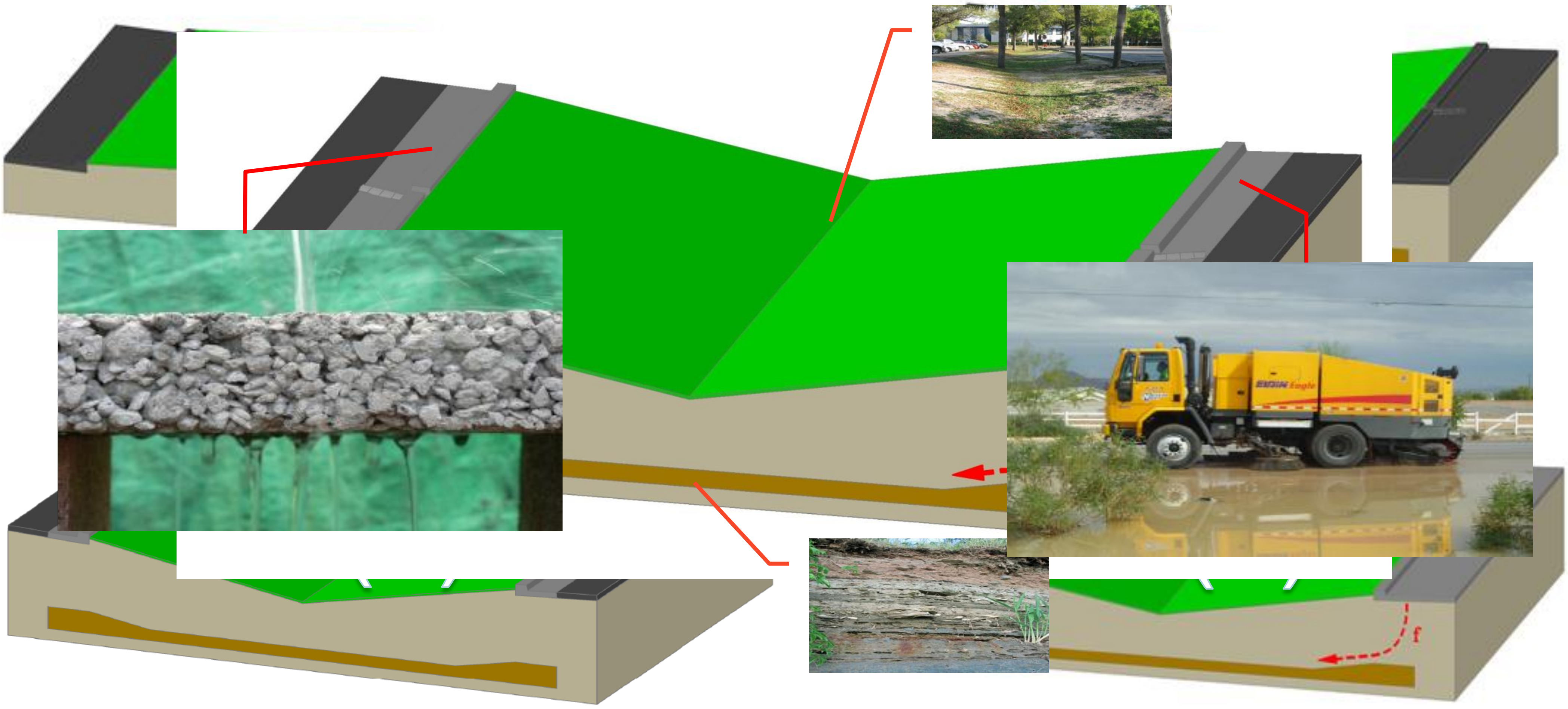
Design Option 1 (Post-Development Existing Condition)



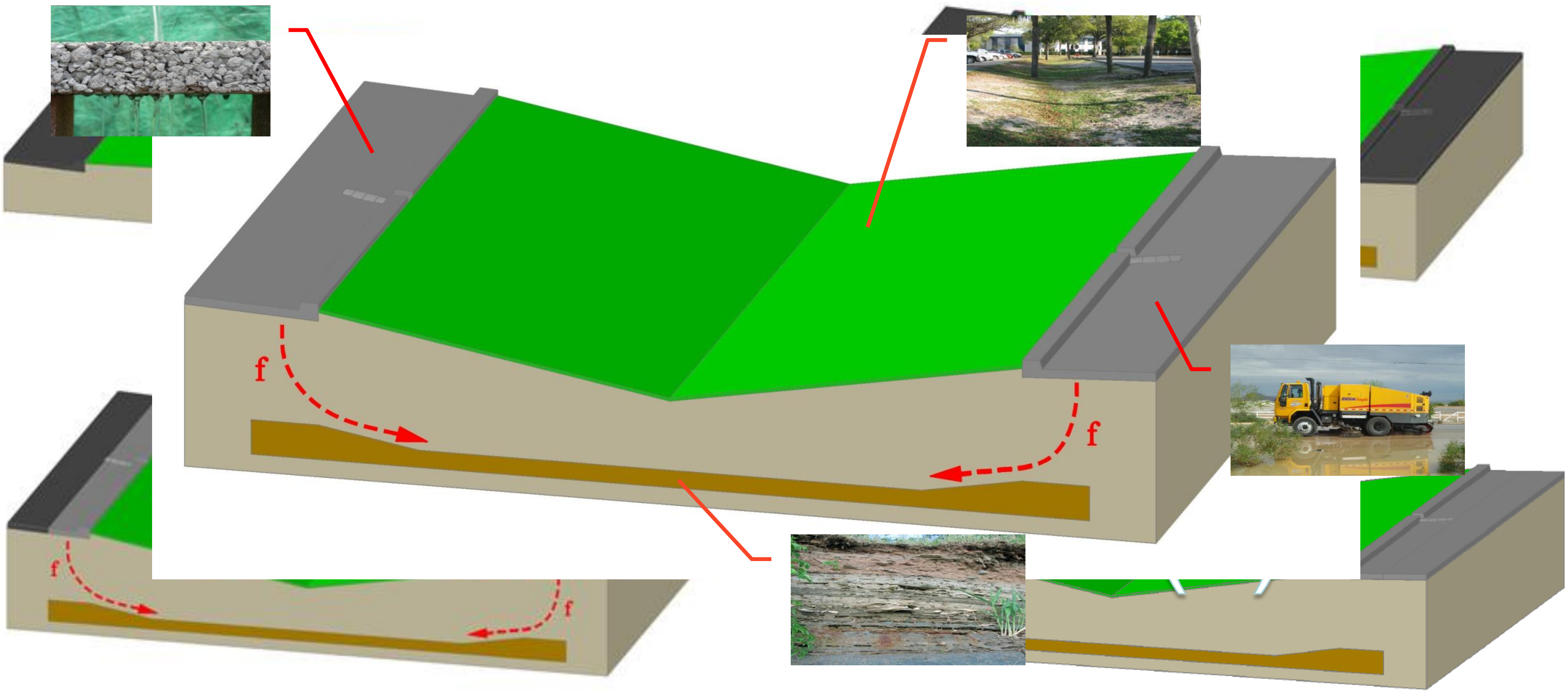
Design Option 2 (Biofiltration Area Reactor, BAR only)



Design Option 3(a) (BAR + Permeable Pavement LIR)



Design Option 3(b) (BAR + All Permeable Pavement)



Design Criteria and Considerations

- Meet pre-development condition pollutant loading
- Provide consistent treatment throughout lifespan using maintenance practices
- Reduce strain on stormwater infrastructure
- Restore hydrologic cycle
- Green infrastructure design
- Maintain existing land use function

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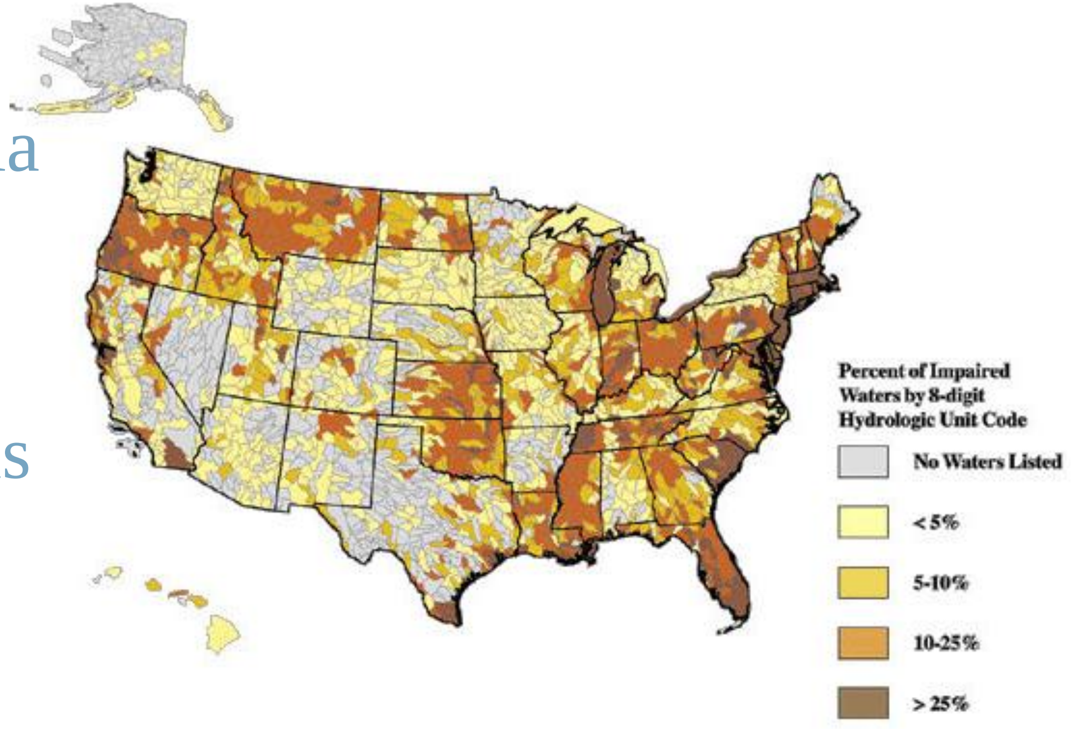


Impaired Waters (USEPA)

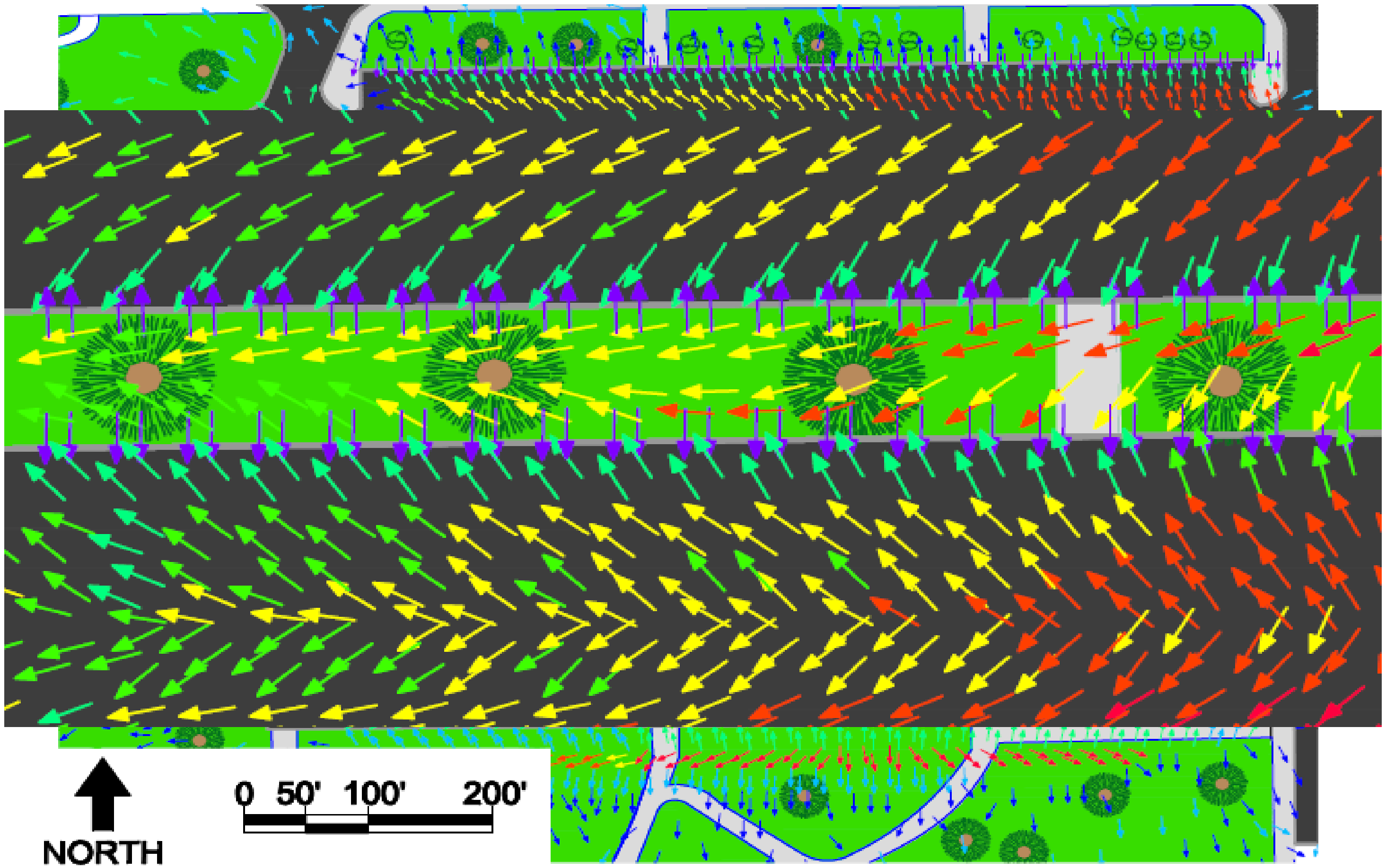
Modeling Process Flow

Surveying → AutoCAD → GIS → SWMM → VS2DTI

Watershed Area	3.23 acres
Surface Area of Islands	0.79 acres
Surface Area of Pavement	2.45 acres
Volume of Pavement	1970 yd^3
Total % Island	24.39%
Total % Pavement	75.61%

Modeling Process Flow

Surveying → AutoCAD → GIS → SWMM → VS2DTI

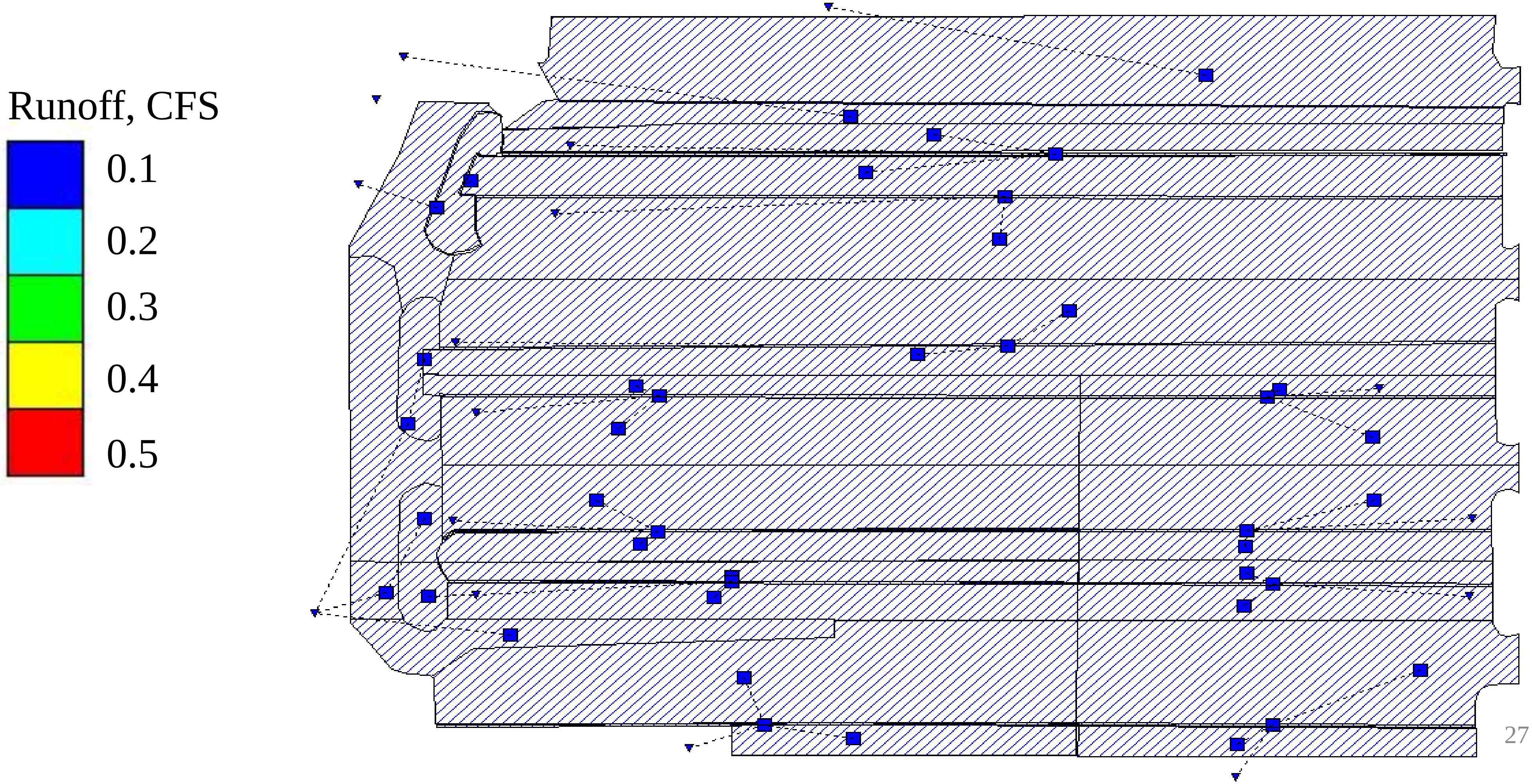


Modeling Process Flow

Surveying → AutoCAD → GIS → SWMM → VS2DTI

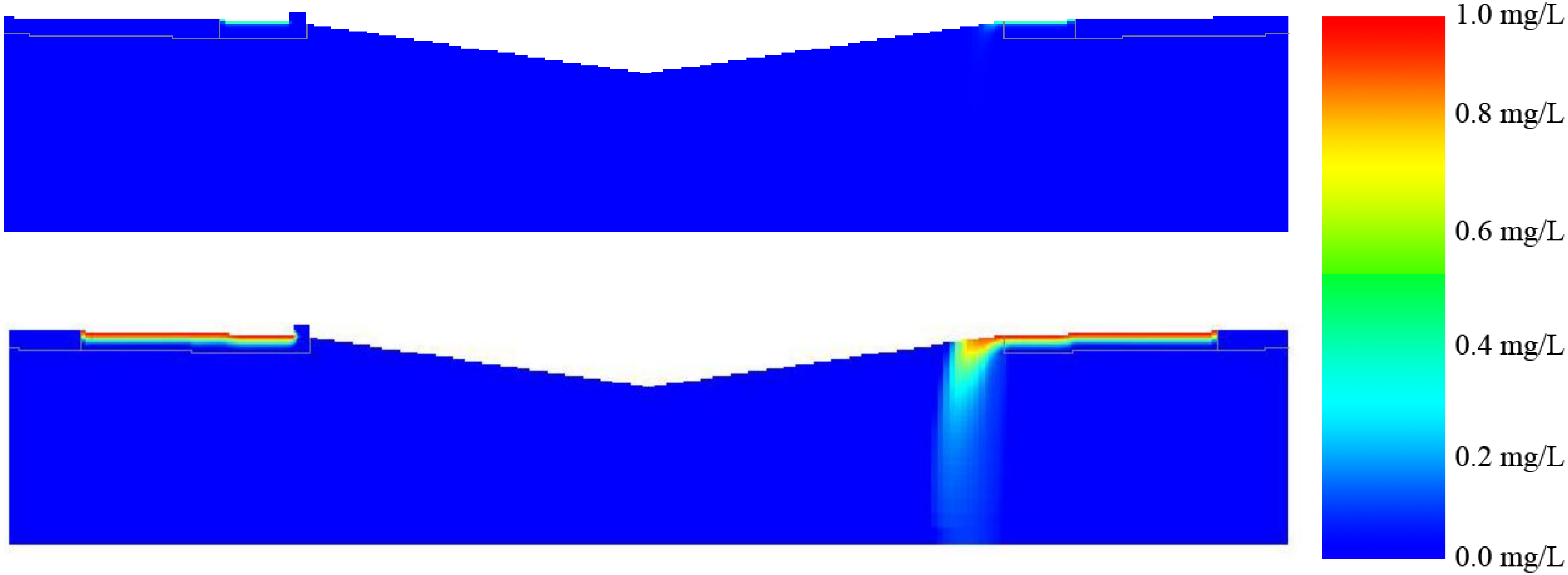
Modeling Process Flow

Surveying → AutoCAD → GIS → SWMM → VS2DTI



Modeling Variably Saturated Groundwater Flow

Surveying → AutoCAD → GIS → SWMM → VS2DTI



Storm Water Management Model (SWMM)

- Open Source
- Quality and Quantity
  - BMP evaluation
  - Flood control
- Continuous simulation
- Eliminates need for peak flow analysis or design storm event
- Porous surface runoff
- Infiltration

VS2DT*I*

- Developed by USGS to solve problems of water flow and predict 2-D subsurface solute transport in variably saturated porous media
- Transport processes: advection, dispersion, first-order decay, equilibrium adsorption as described by Freundlich or Langmuir isotherms, and ion exchange
  - Representation of unsaturated hydrologic characteristics and breakthrough

Richard's Equation: $$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi}{\partial z} + 1\right)\right]$$

K = hydraulic conductivity [L/T]; ψ = pressure head [L]; *z* = elevation above datum [L]; θ = water content [L^3/L^3]; *t* = time [T]

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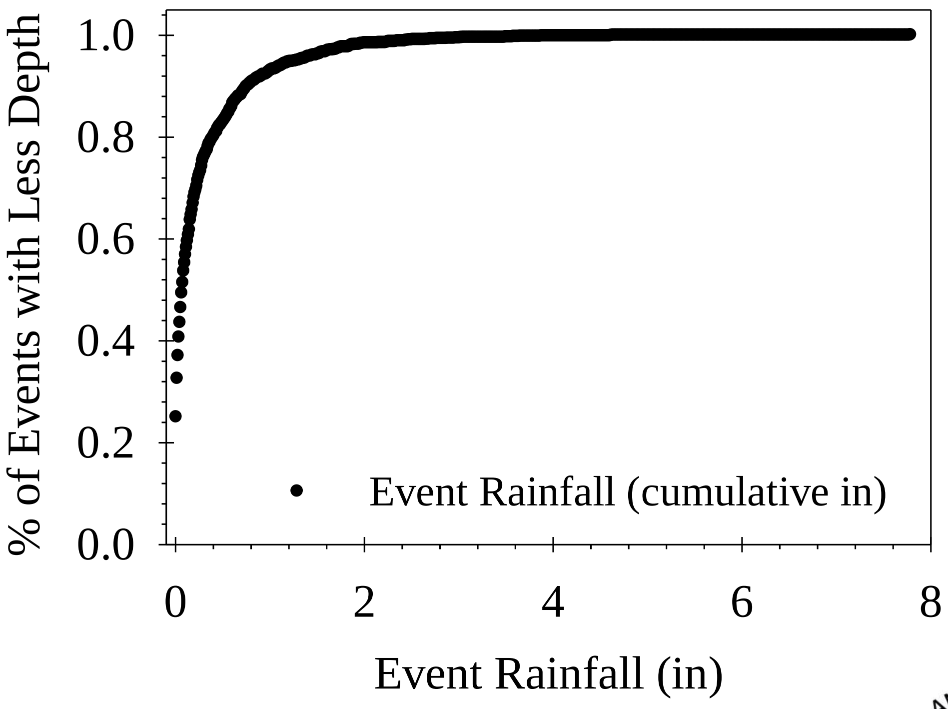
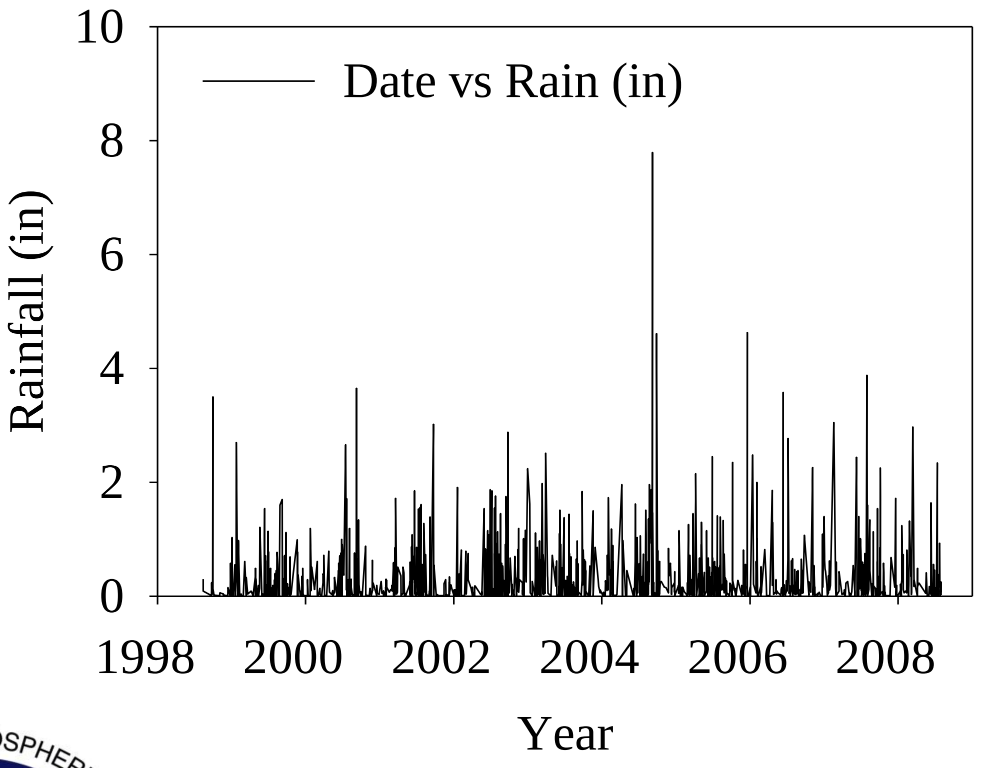
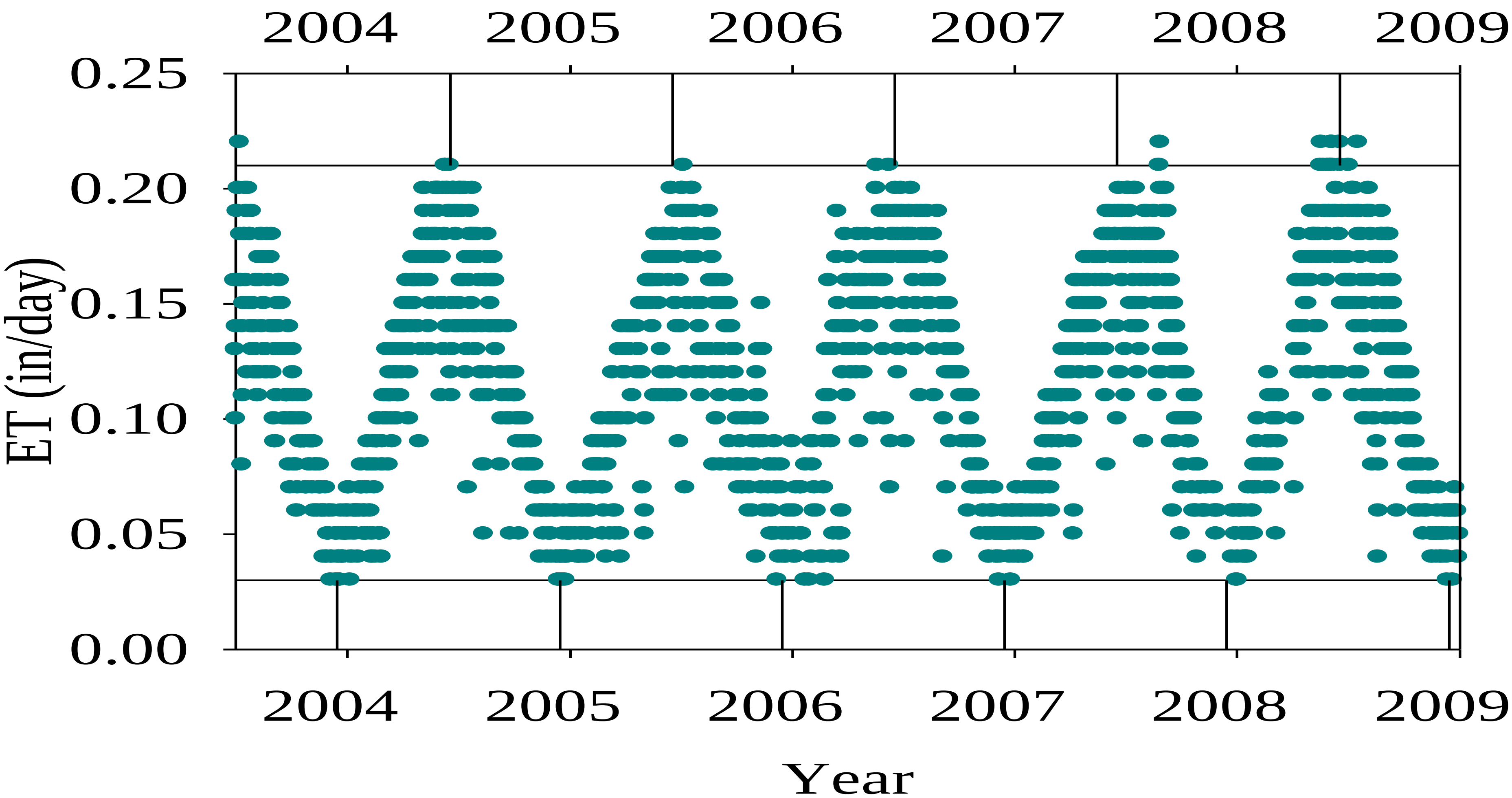
Utilization of Continuous Simulation Data: Historical Rainfall Distribution for Load Assessment





Measured[a] Gainesville Evapotranspiration (ET)



a. Data from Florida Automated Weather Network (FAWN)

ET/E_o Ratios for Selected Plants

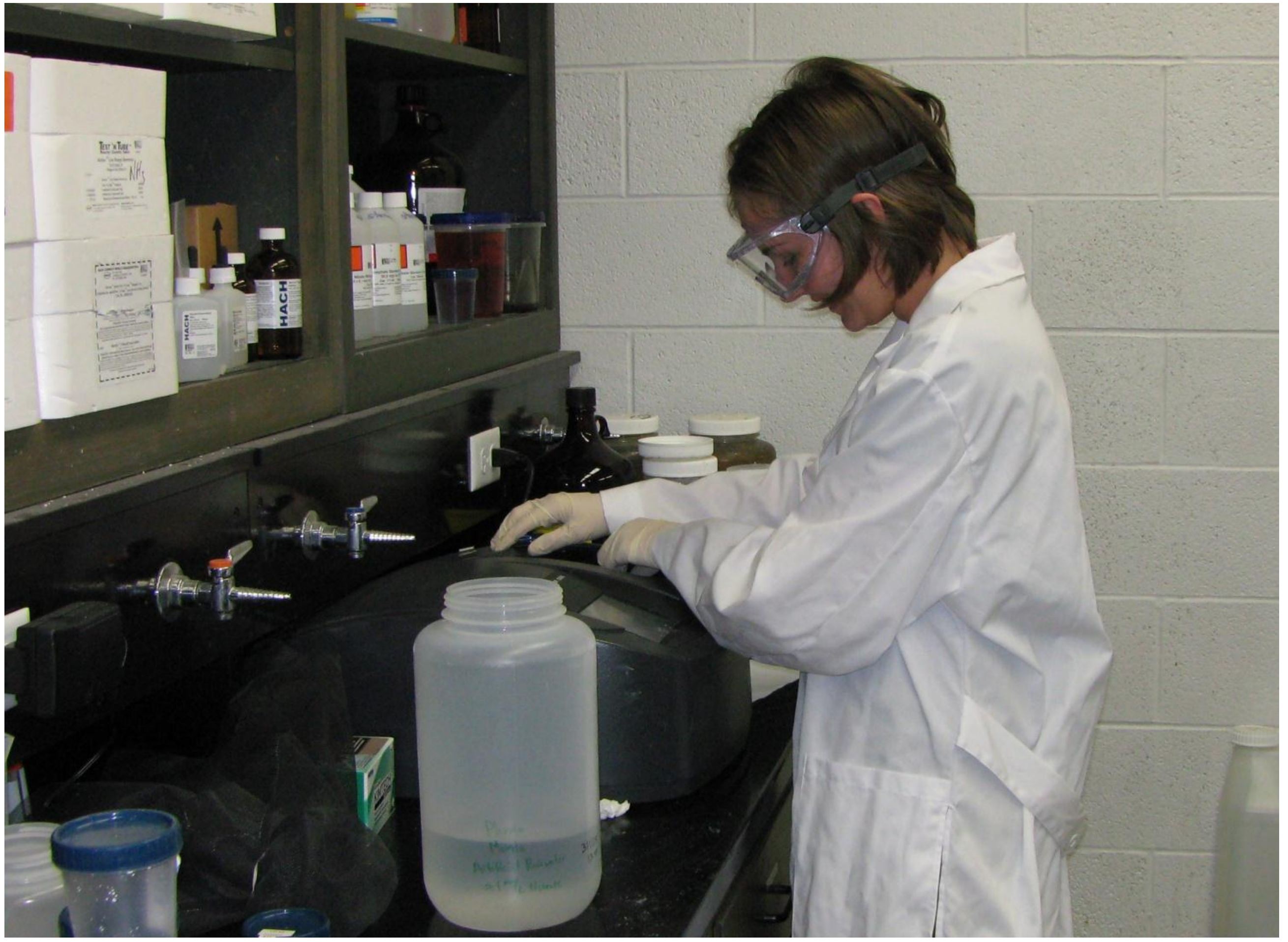
$$E = \frac{\Delta}{\Delta+\gamma} E_r + \frac{\gamma}{\Delta+\gamma} E_a \qquad E_a = B(e_{as} - e_a) \qquad E_r = 0.0353 R_n$$

Plant Species	**E/E_o** [a,b]
Panicum rigidulum	1.58
Juncus effusus	1.52
Alternathera philoxeroides	1.26
Typha latifolia	2.0 (average)
Pontederia cordata	1.2
Scirpus validus	1.9
Grass	0.75

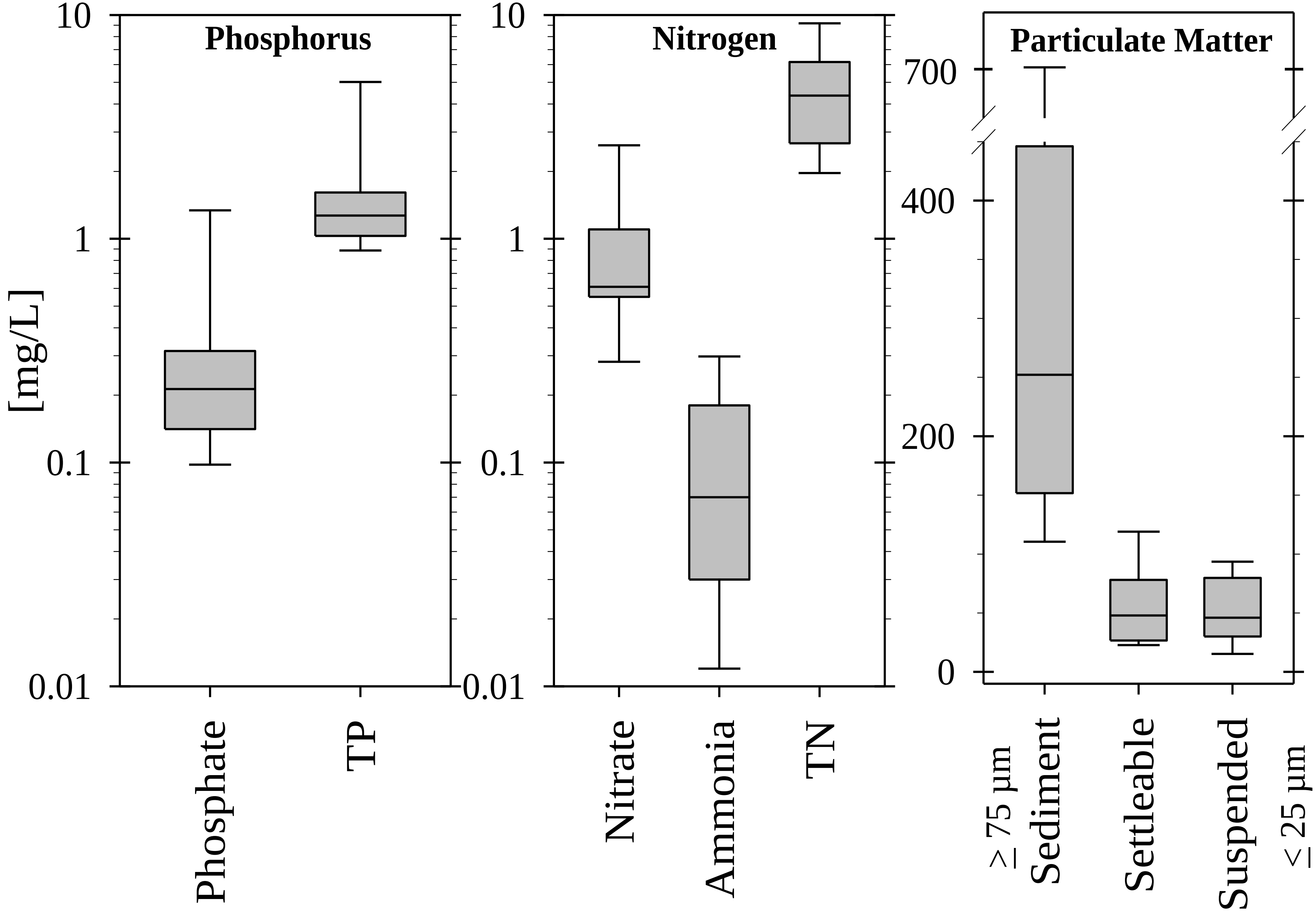
a. Boyd, 1987
b. Ramey, 2004 (http://aquat1.ifas.ufl.edu/guide/evaptran/climatology)

Pollutant Load Characterization for Existing Site Conditions

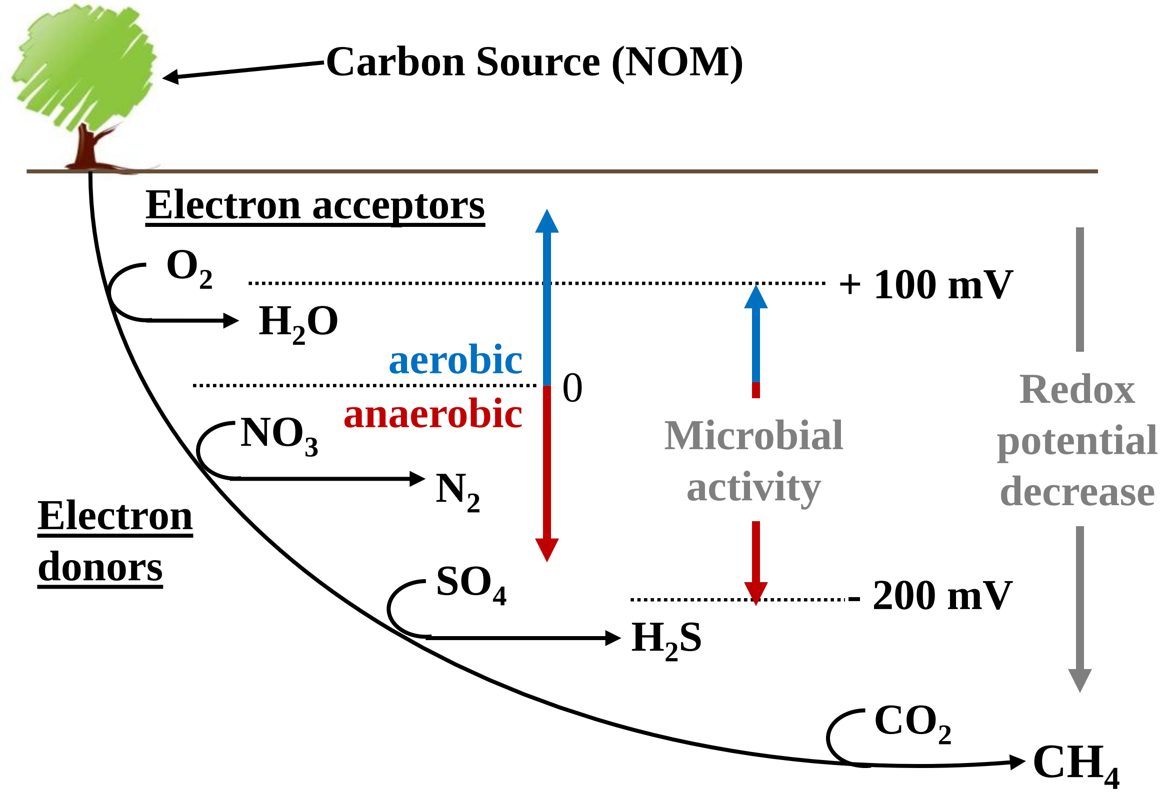
- Pollutant Loading
  - 15 rain events
  - P, N, TSS
- Manually sampled
- In-house analyses
- Chain of Custody

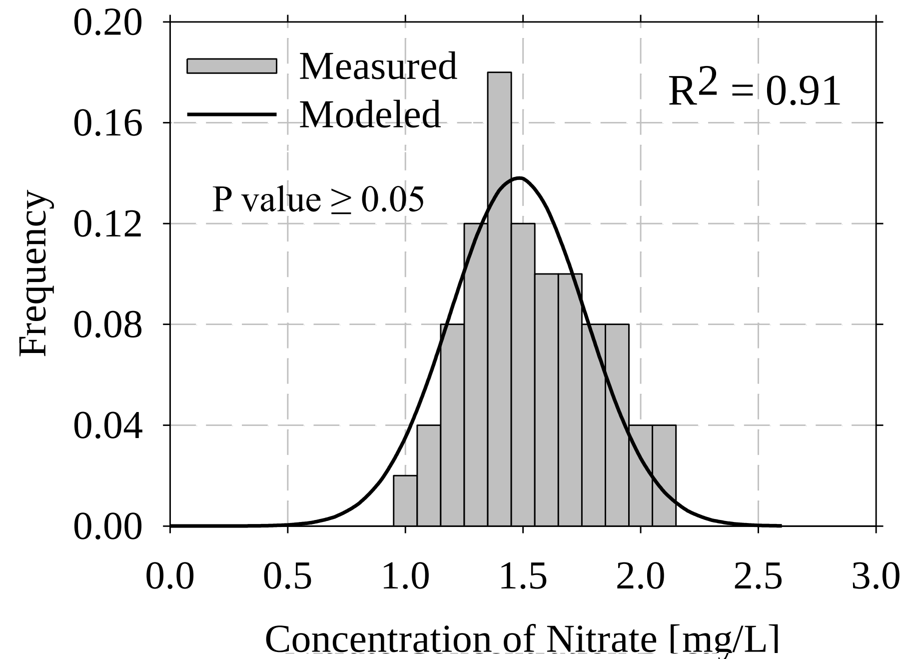


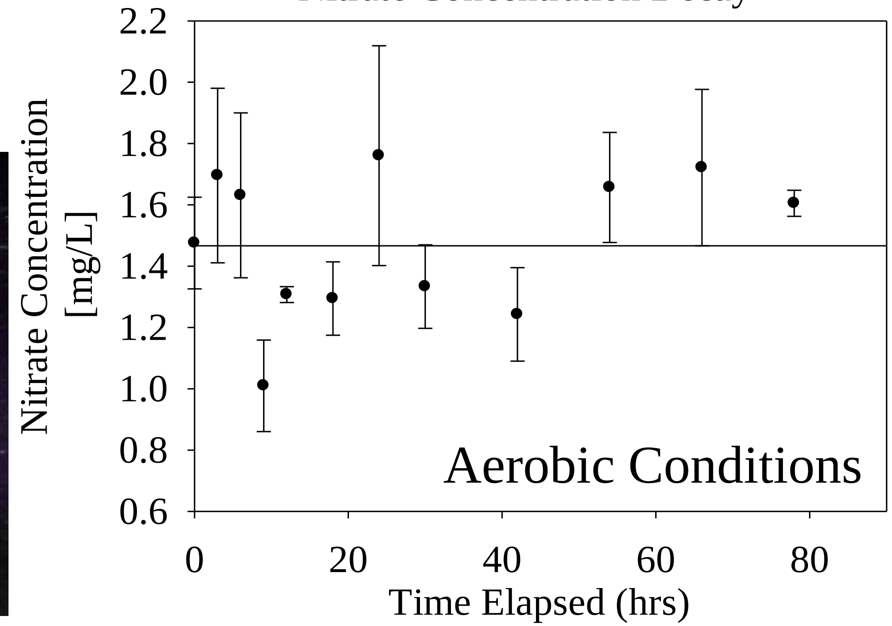
Nutrient (P, N) and Particulate Matter (PM)

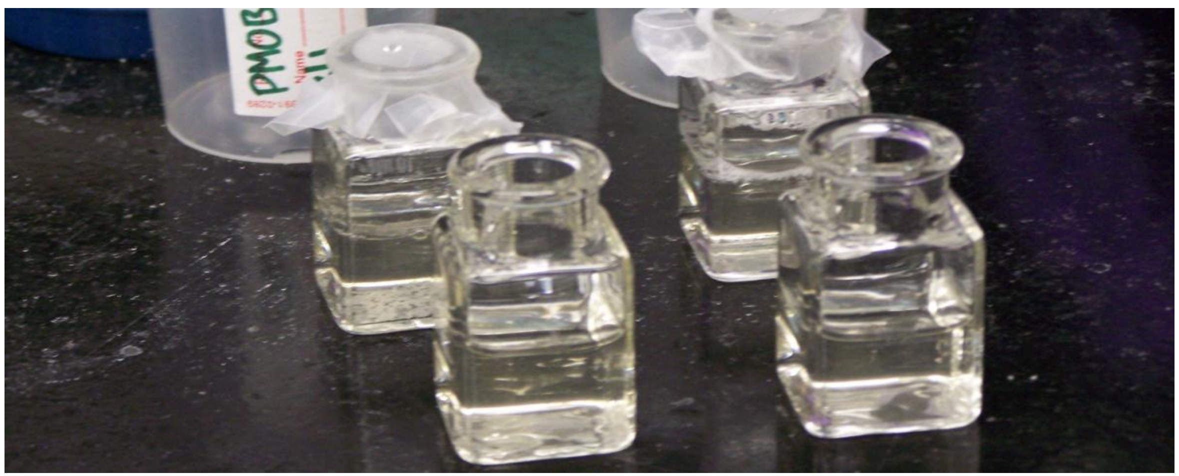


Nitrate Persistence (without denitrification)

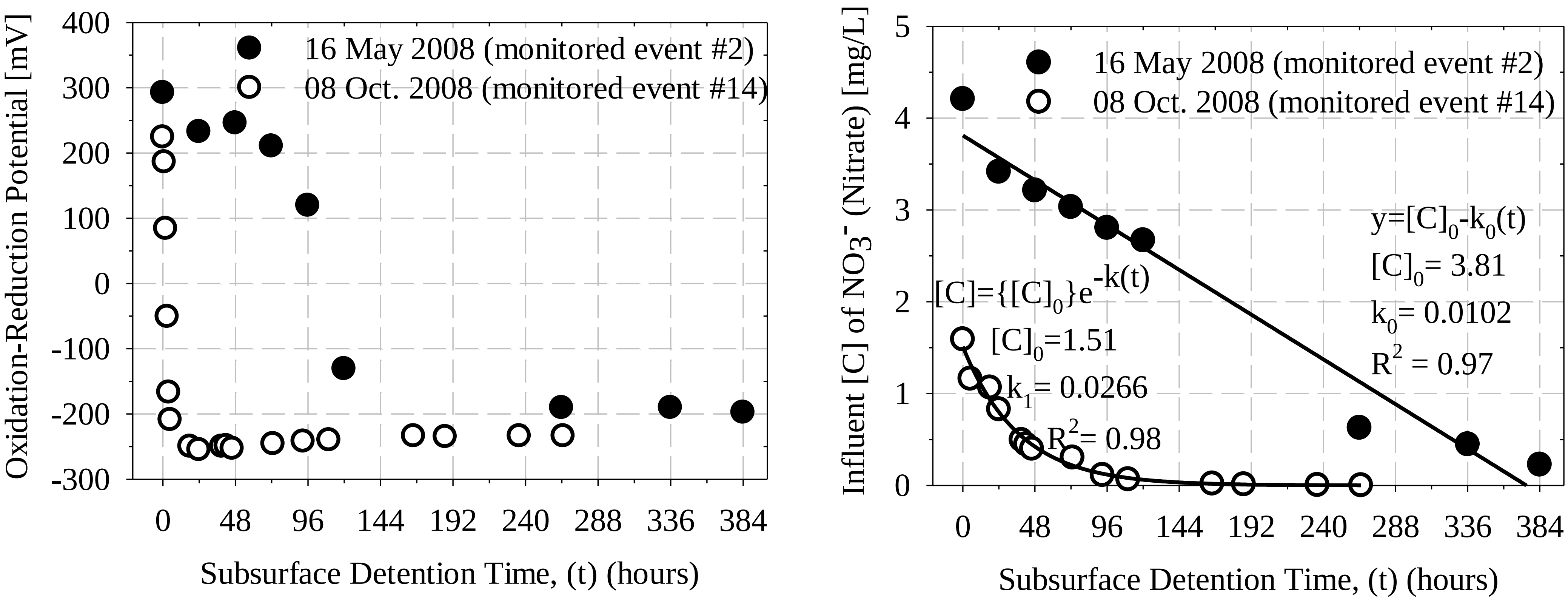








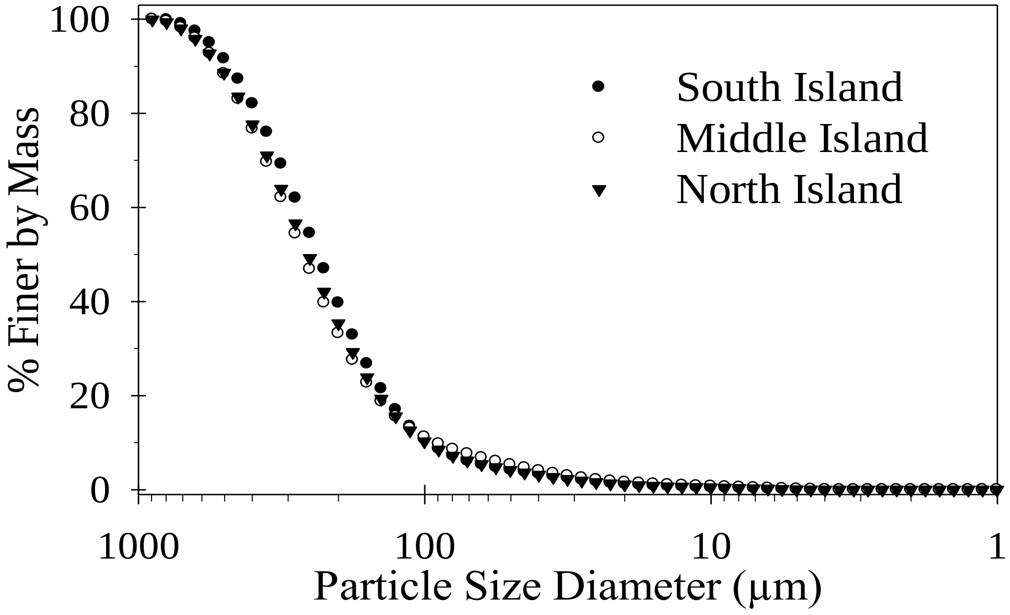
Redox as a function of runoff detention in Subsurface Filtration
(BMPs contain high microbial activity for electron transfers)



Existing Site Soil Parameters

- Sandy soil with silt (USCS)
- K_s: 10.6 – 13.5 cm/h (11.7 cm/h)
- Ψ: -5cm pressure[a]
- n_t: 0.36
- Initial deficit: 0.2 cm

$$f_p = K_{SV} + \frac{K_{SV} M S_f}{F}$$



a. Rawls, Brakensick, Miller (Jan 1983 J. Hydraulic Engineering Volume 109)

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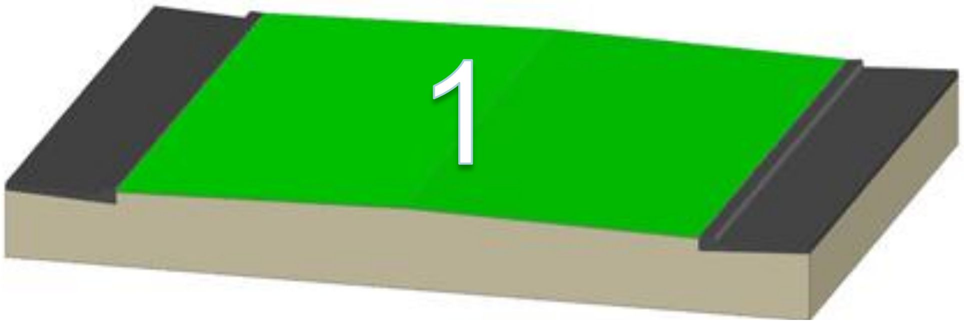
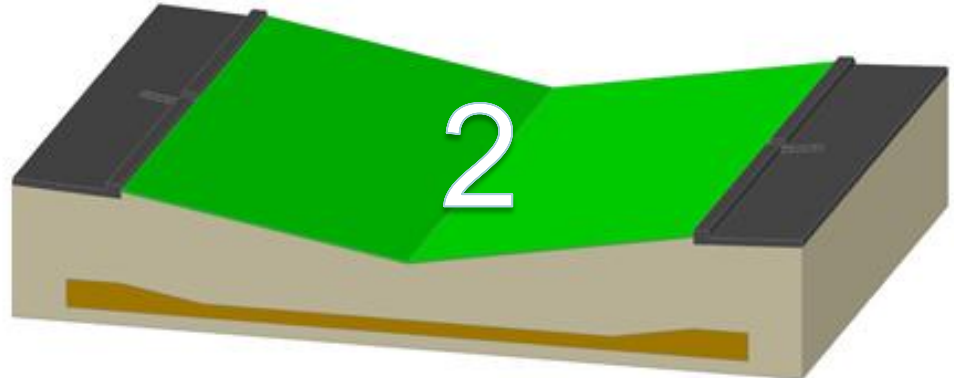
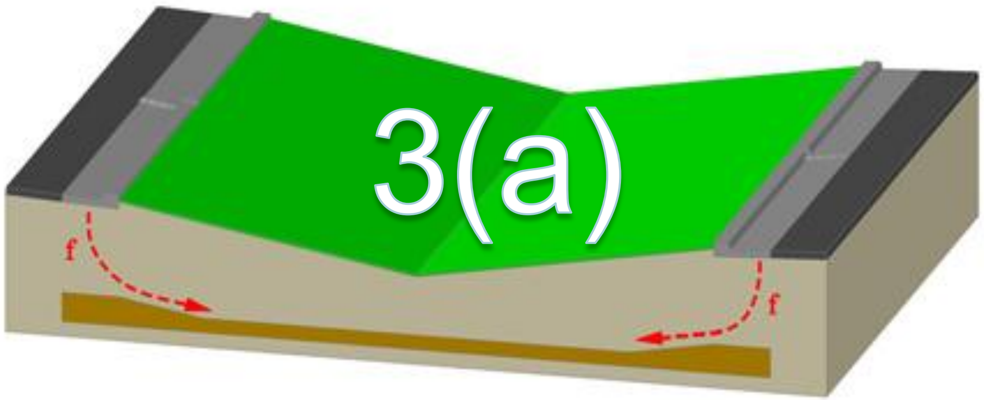


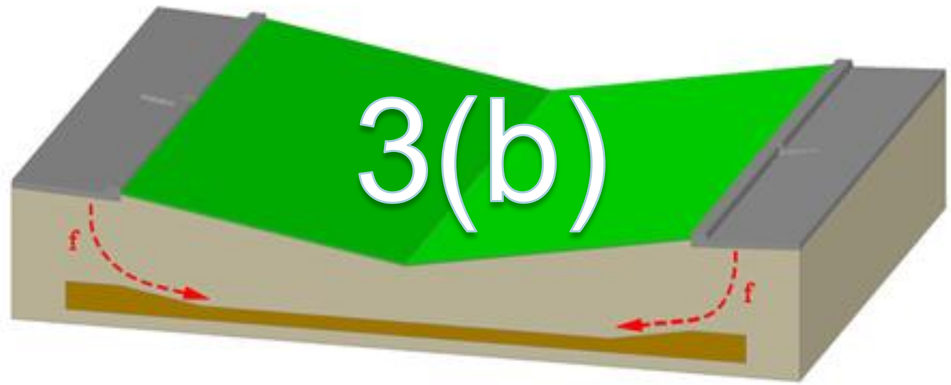
Existing Condition



BAR only

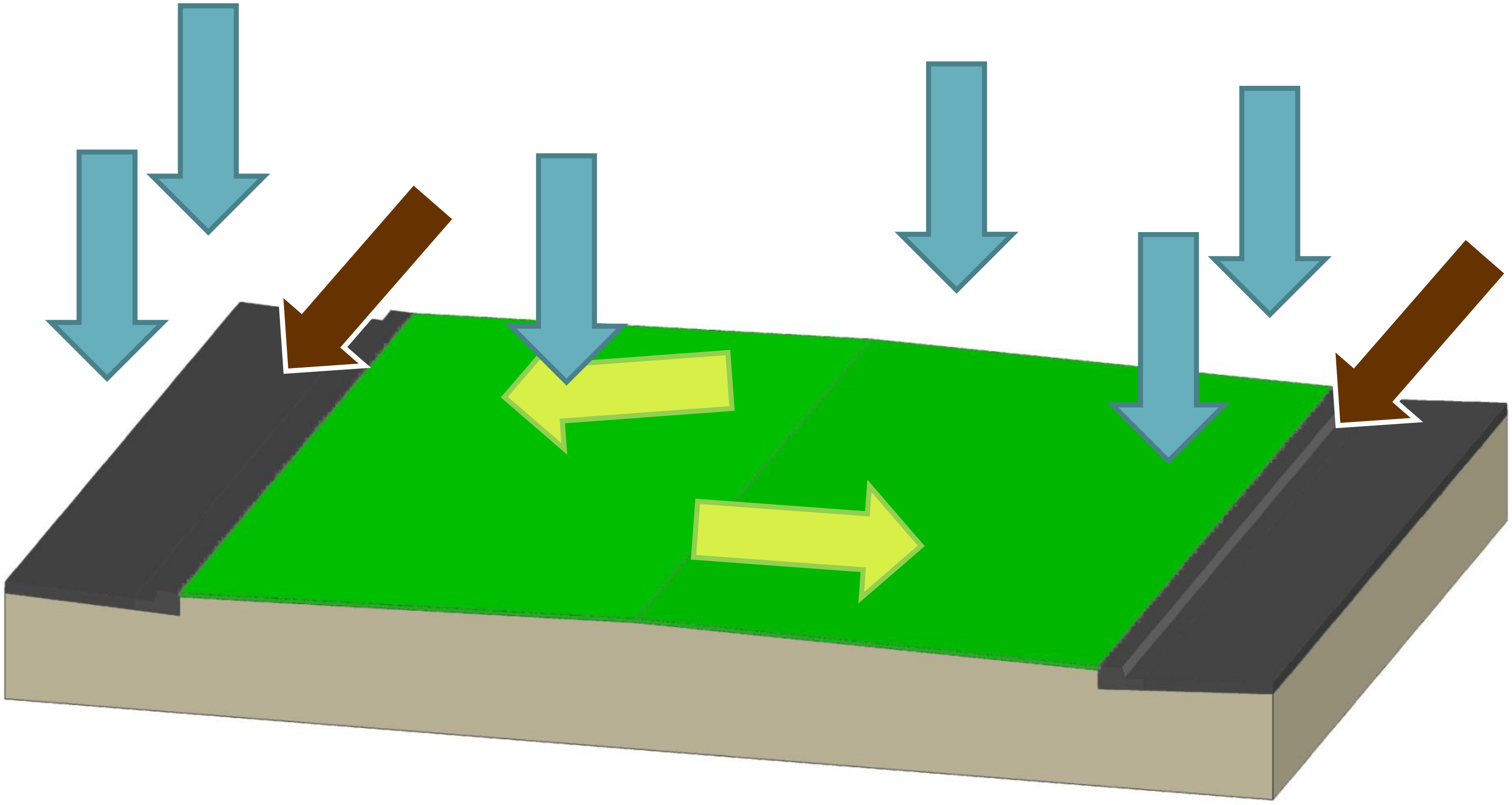


Varying width LIR (with CPP) and BAR



All CPP and BAR

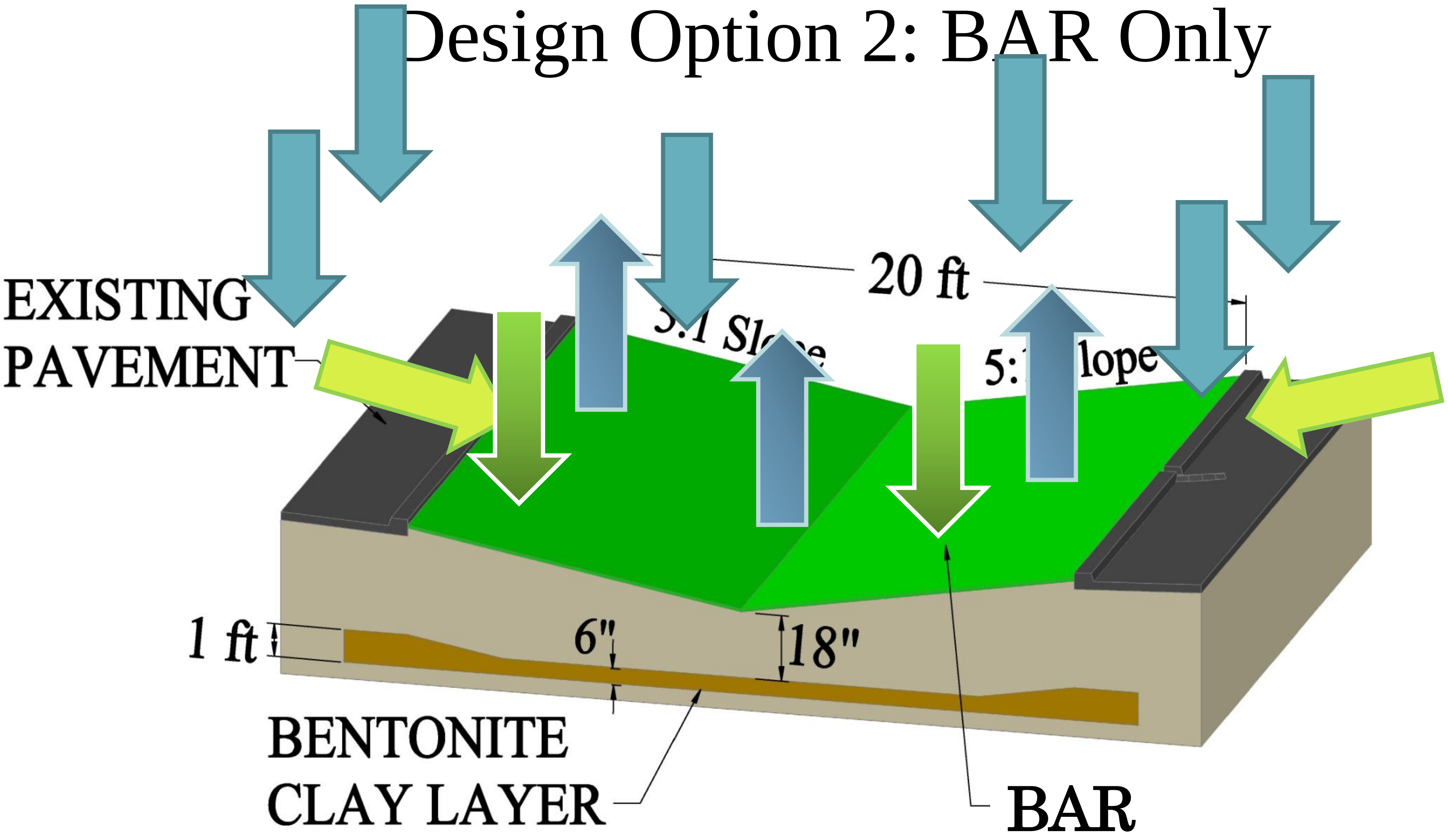
Design Option 1: Existing Conditions



Design Option 1: Water Quantity & Quality

	Design Option	R[illegible]ff ([illegible])	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine		5[illegible]3	7.78	301.61	296.26
Current	**1**	**251.66**	**243.05**	**1065.83**	**61143.81**
BAR	2				
2 ft LIR + BAR	3(a)				
4 ft LIR + BAR	3(a)				
6 ft LIR + BAR	3(a)				
All CPP + BAR	3(b)				

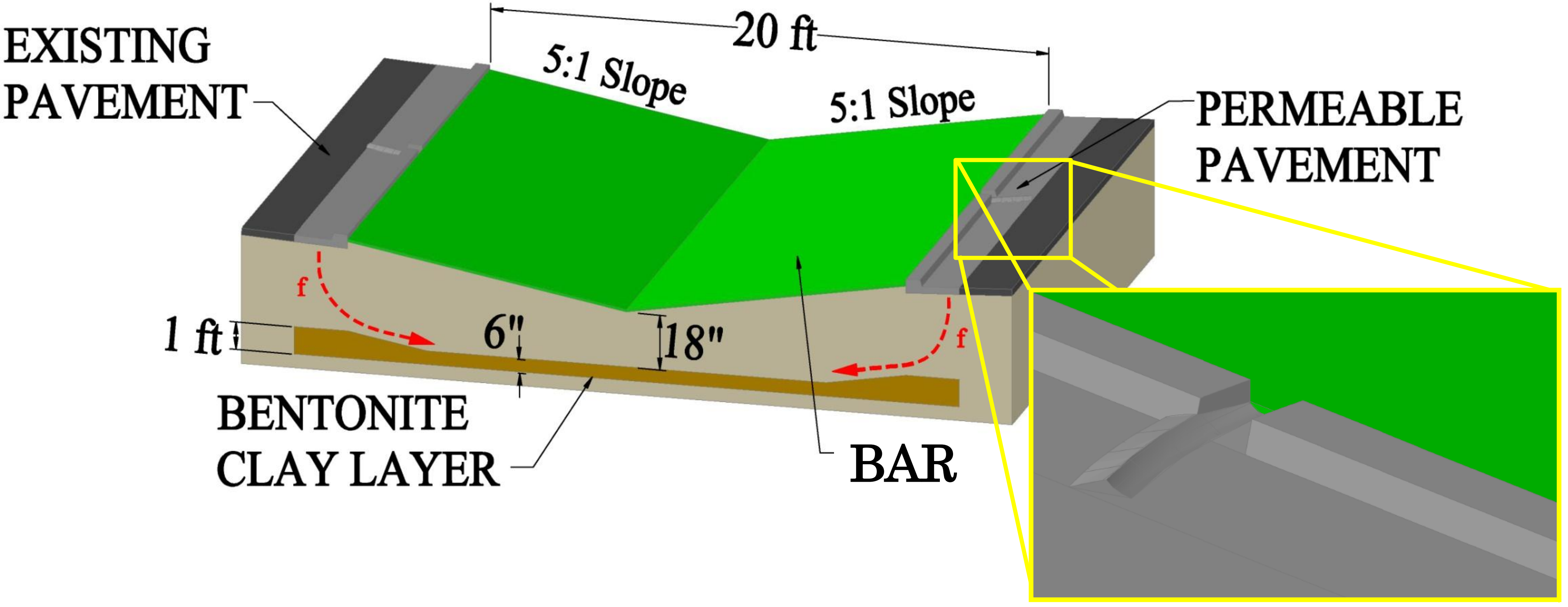
Design Option 2: BAR Only



Design Option 2: Water Quantity & Quality

	Design Option	**Runoff ([illegible])**	**Phosphorus (lb)**	**Nitrogen (lb)**	**TSS (lb)**
Pristine		5[illegible]3	7.78	301.61	296.26
Current	1	2[illegible]6	243.05	1065.83	61143.81
BAR	**2**	**117.21**	**13.48**	**575.83**	**1907.14**
2 ft LIR + BAR	3(a)				
4 ft LIR + BAR	3(a)				
6 ft LIR + BAR	3(a)				
All CPP + BAR	3(b)				

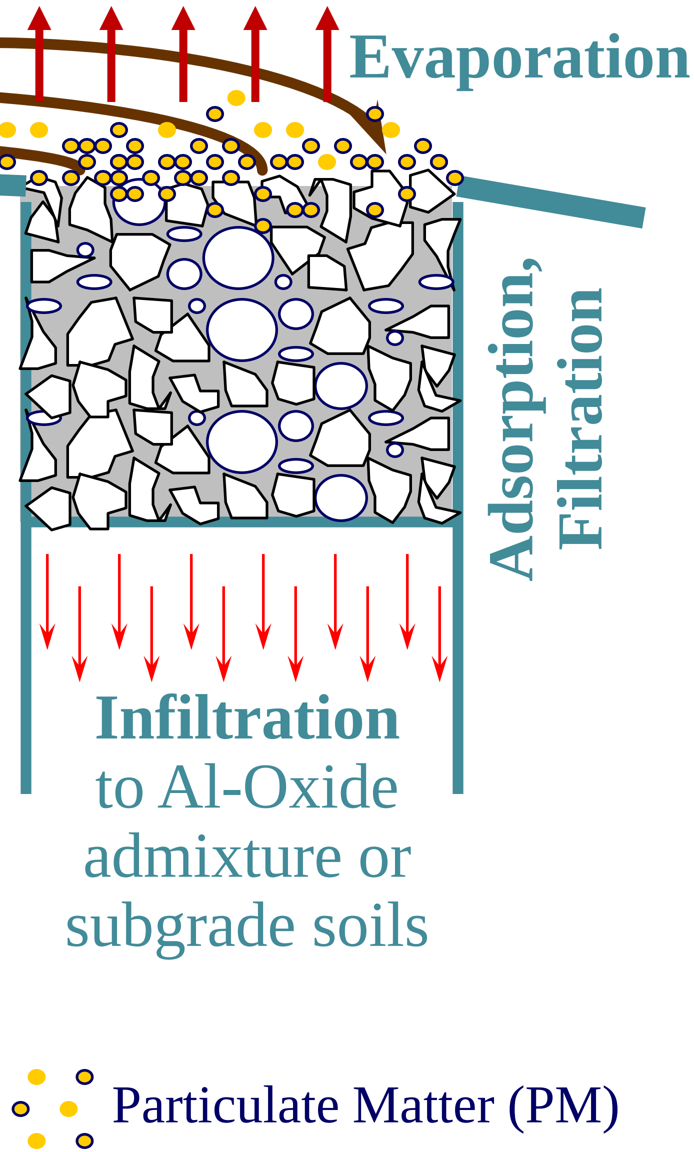
Design Option 3(a):
Linear Infiltration Reactor Design



Design Option 3(b): Water Quantity & Quality

	Design Option	Runoff (in)	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine		53.8	7.78	301.61	296.26
Current	1	251.66	243.05	1065.83	61143.81
BAR	2	117.21	13.48	575.83	1907.14
2 ft LIR + BAR	3(a)	7[illegible]9	5.56	270.57	731.76
4 ft LIR + BAR	3(a)	6[illegible]9	3.95	210.23	489.11
6 ft LIR + BAR	3(a)	5[illegible]3	2.17	133.18	239.85
All CPP + BAR	**3(b)**	**1.16**	**0.001**	**13.95**	**0.18**

Cementitious permeable pavement (CPP), as an LID material with behavior that can be measured/modeled



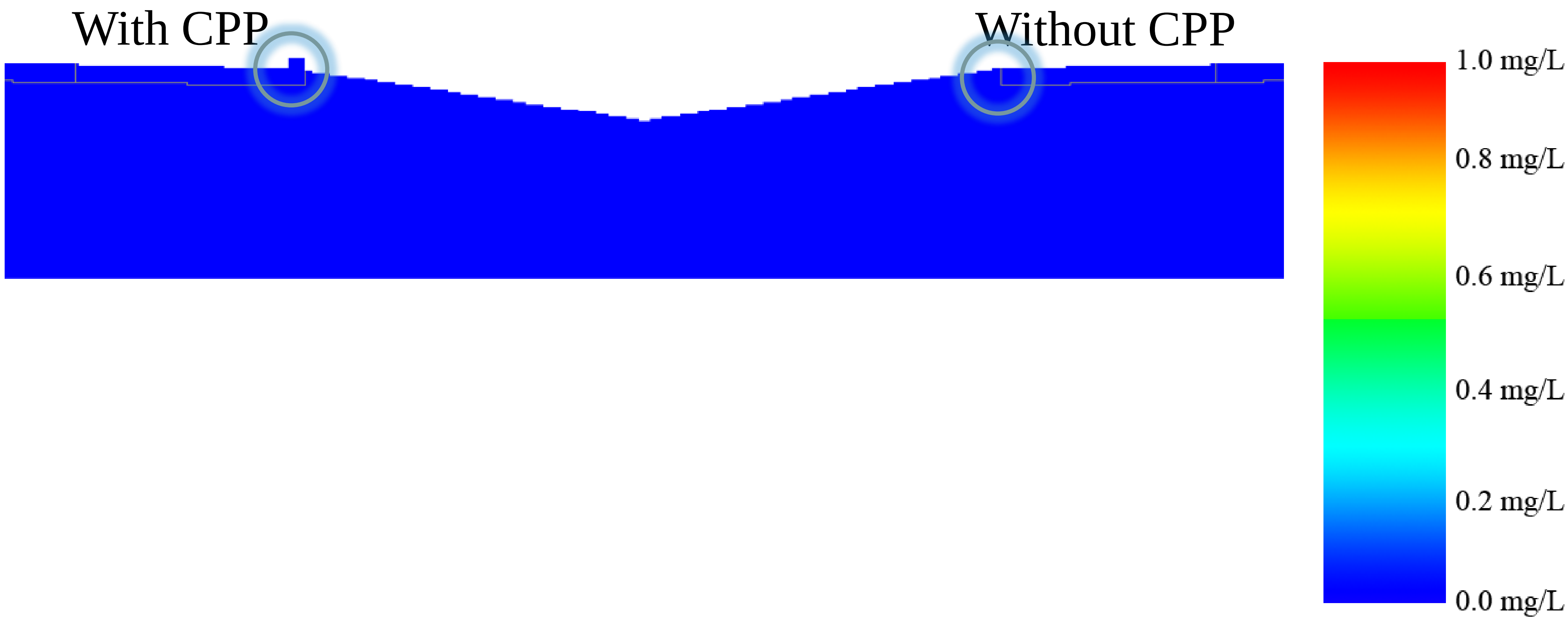
CPP adsorptive-filter design:

- $11 - 15\ kN/m^3$ — Unit weight
- 0.1 – 0.005 cm/s — $K_{saturated}$ (clean sand)
- 25,000 – 30,000 kPa — Unconfined strength
- $20 - 50\ L/min\text{-}m^2$ — Surface loading rate

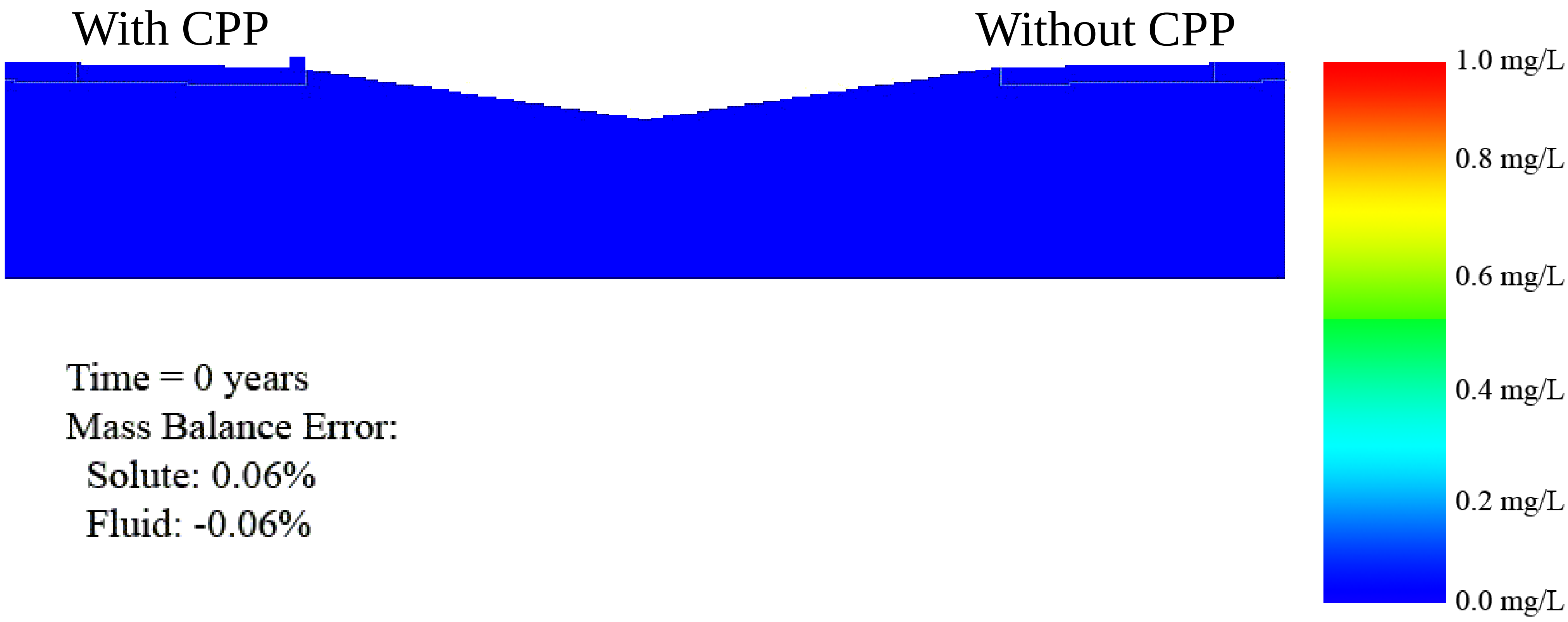
Mix Design Proportions:

- Varies — Type II Cement
- Varies kg — Sand
- Varies kg — Gravel
- Varies — Water (w/c < 0.4)
- 10 – 30 % — Total porosity
- Varies — Amphoterics (Al-Oxide)

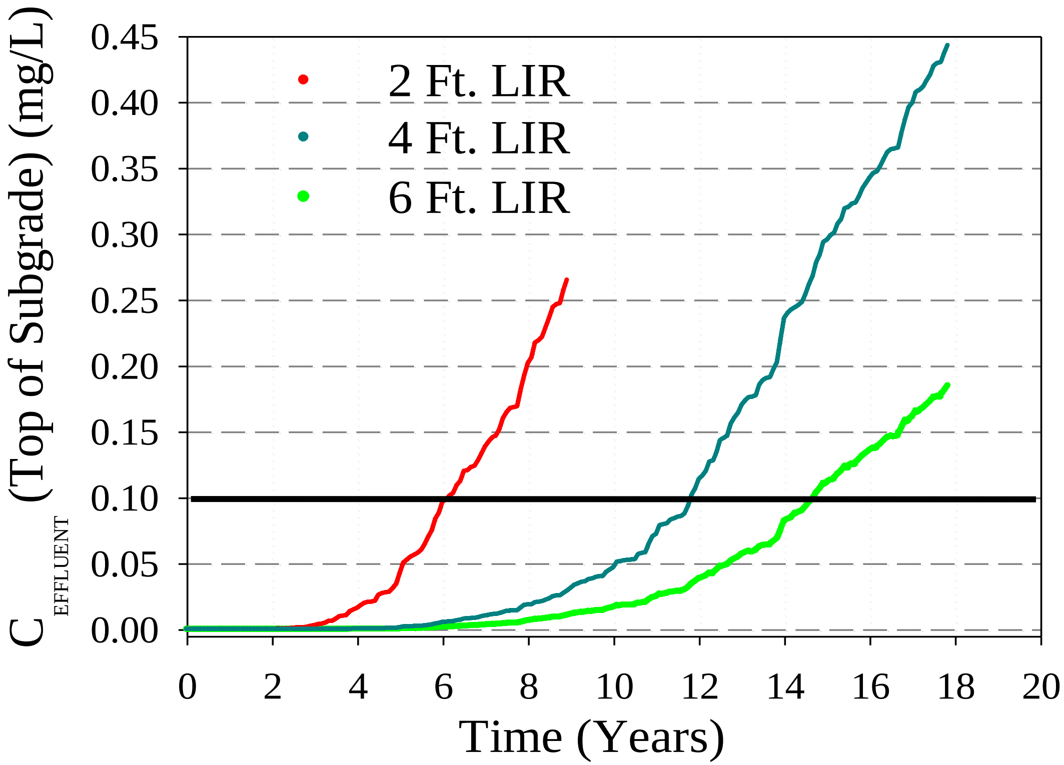
Phosphorus Adsorption over Time – 6 ft. LIR

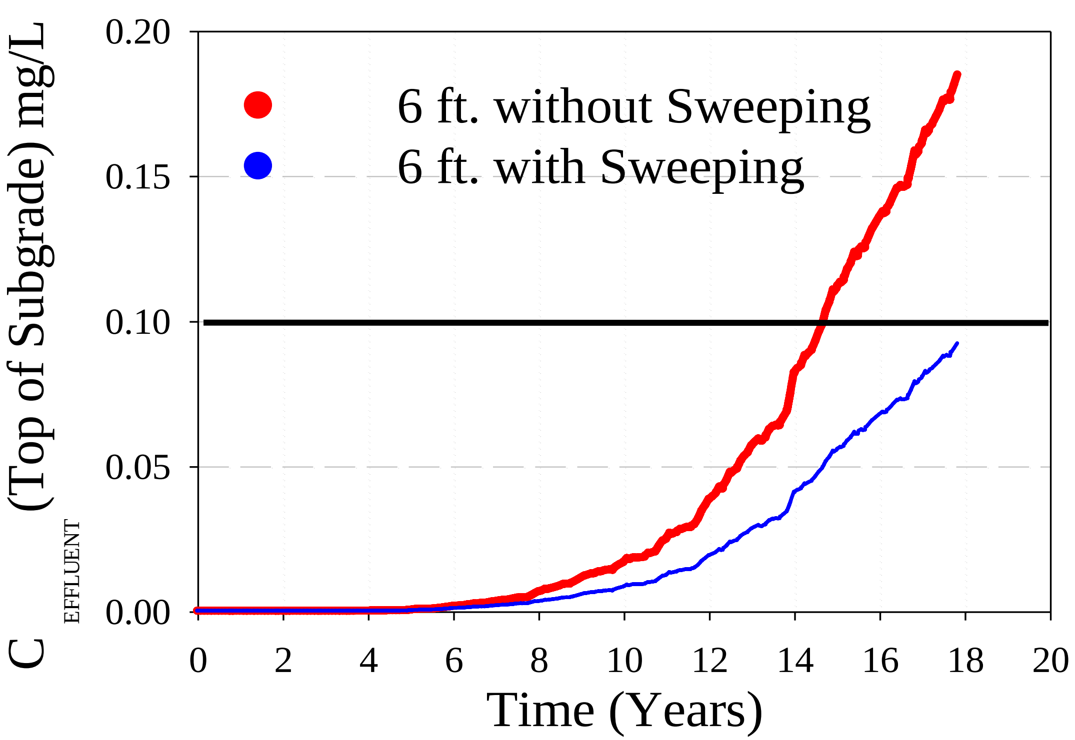


Phosphorus Adsorption over Time – 6 ft. LIR



Breakthrough and Adsorption Results





	Runoff (in)	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine	53.8	7.78	301.61	296.26
Current	251.66	243.05	1065.83	61143.81
BAR	117.21	13.48	575.83	1907.14
2 ft LIR + BAR	74.19	5.56	270.57	731.76
4 ft LIR + BAR	62.79	3.95	210.23	489.11
6 ft LIR + BAR	53.63	2.17	133.18	239.85
All CPP + BAR	1.16	0.001	13.95	0.18

Outline

1. Background and Rationale
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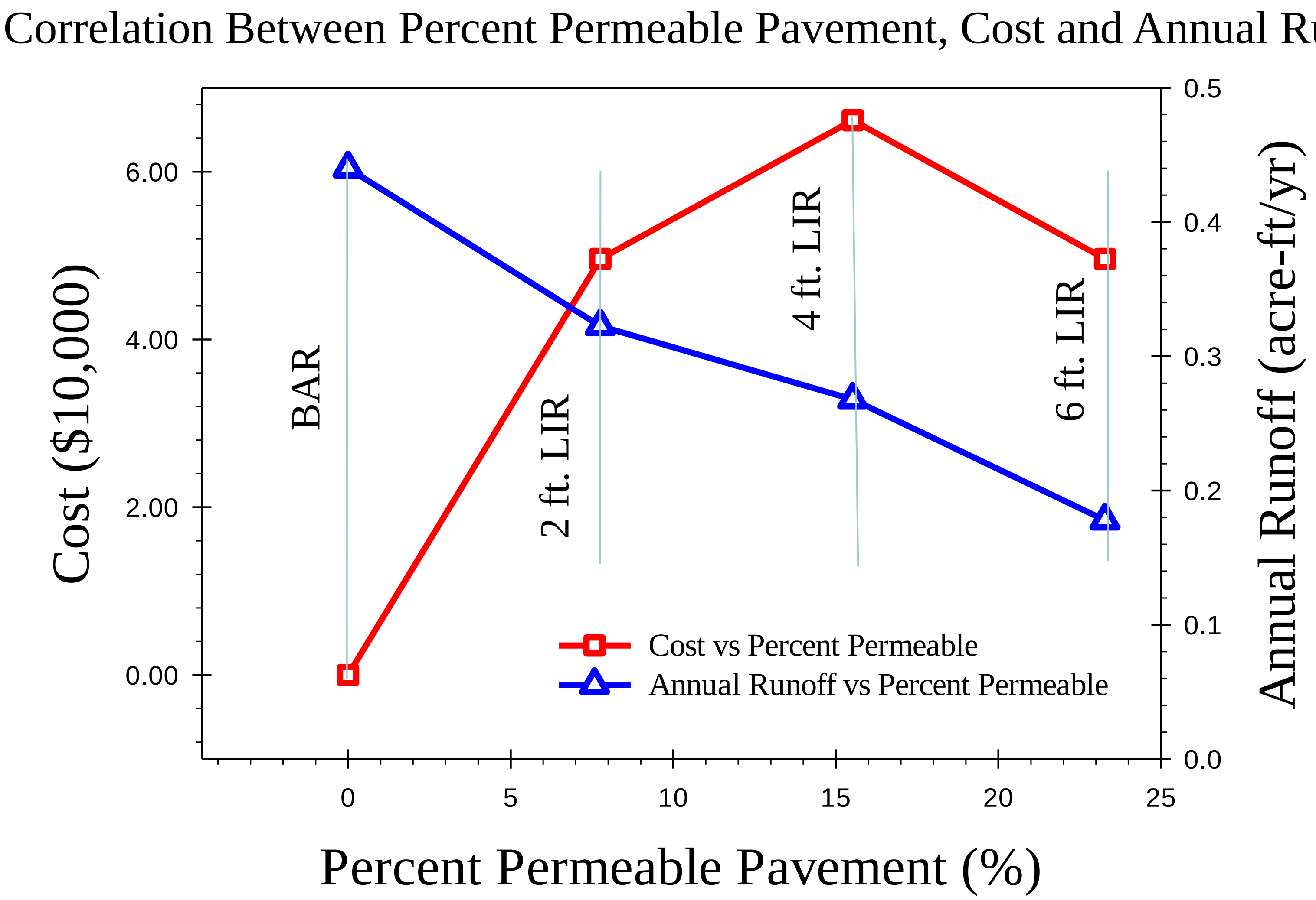
3. Model Simulations
4. Data Collection and Analysis
5. Design Option Results
6. **Cost Analyses and Extensibility**
7. Conclusions and Recommendations

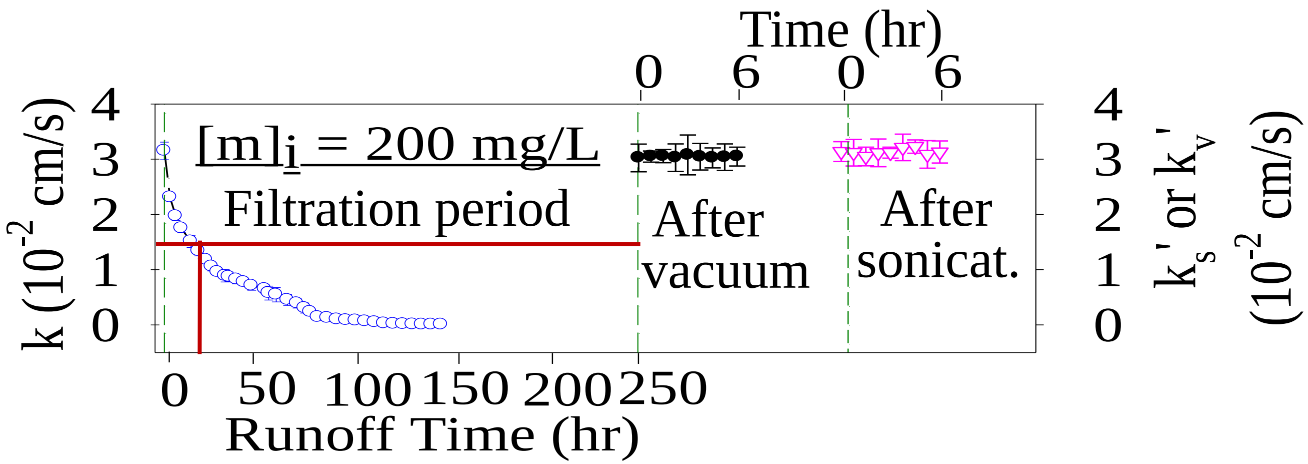
Economics and Cost Analysis



Economics and Cost Analysis of Street Sweepers

Sweeper Type	Purchase Price ($)	O&M Cost ($/curb mile)
Mechanical	75,000	30
Vacuum Assisted	150,000	15

Sweeper Type	Annual O&M Costs ($)	Total O&M Costs	Purchase Costs ($)	Total Costs ($)
Mechanical	4,000	59,500	173,600	233,100
Vacuum Assisted	1,000	15,400	203,200	218,600



Hydraulic Conductivity (k):

After vacuuming

k_v/k_0 = 96.9%

After sonicating

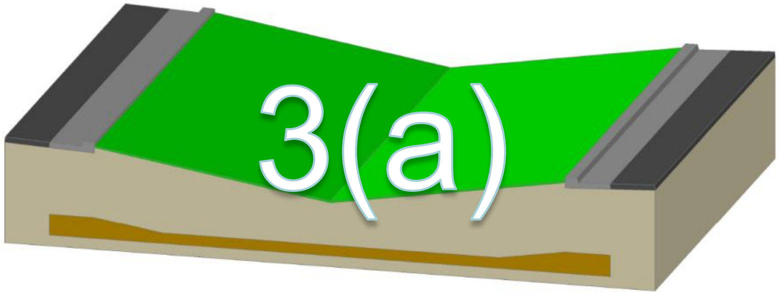
k_s/k_0 = 99.3%

Economics and Cost Analysis

Overall Costs for Option 3(a): 6ft LIR with BAR

Cost Category	LIR	BAR
Capital	$131,000	$70,000
O&M	$5,400	$54,000
Subtotal	$137,000	$124,000
Engineering fee	$13,700	$12,400
Contingency fee	$20,500	$18,600
PV of Cost	$171,000	$155,000

Overall Cost (LIR and BAR)	$325,000



Capital Costs for LIR	
	Cost
Excavation	$9,100
Al-Oxide	$23,000
Pavement	$99,200
Total	$131,000

Outline

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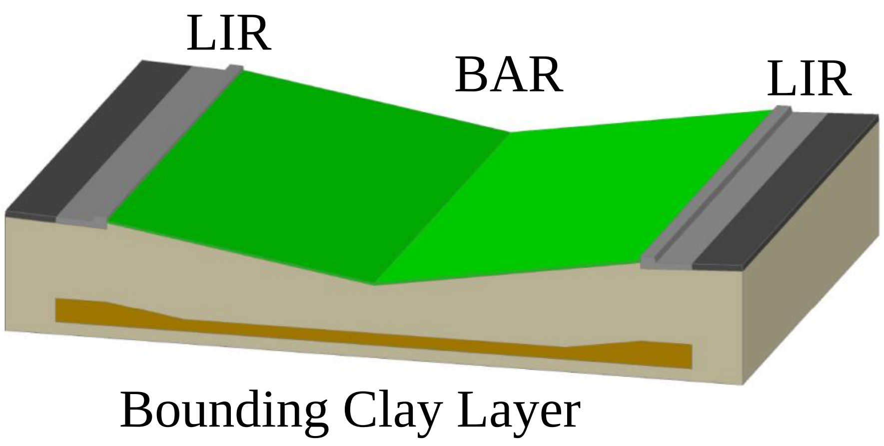
Final Design Recommendation

Design Option 3(a): 6 ft LIR with BAR (based on 9 yrs of loads)

Condition	Design Option	Runoff (inches)	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine		53.8	7.78	301.61	296.26
Current	1	251.66	243.05	1065.83	61143.81
6 ft LIR + BAR	3(a)	53.63	2.17	133.18	239.85

$325,000



Economics and Cost Analysis

Cost Comparison of Option 3(a) with a 6 ft LIR to Mean BMPs in Florida

Nutrient	Mass in runoff from site (lb/yr)	Option 3(a) Design Cost ($/lb/yr)	Mean cost for treatment with FL BMP ($/lb/yr)[a]	Difference ($/lb/yr)	Percent Difference (%)
Nitrogen	100	3,260	3,730	470	13
Phosphorus	26	12,530	14,720	2,190	15

a. (2008) FDEP, "TMDL Costs of Florida BMPs for Nitrogen and Phosphorus"

Extensibility To New Construction Design

Cost of Conventional Construction and BMPs:

Component Cost		Cost
Capital	Piping	$31,300
	Lights	$11,300
	Drains	$16,400
	Excavation	$58,700
	Asphalt	$117,200
	Concrete	$13,700
Total Capital Cost		$248,000
Engineering Fee (10%)		$24,800
Contingency Fee (15%)		$37,200
Total cost to Build Parking Lot		$310,000
Cost of Compliance with Unified Stormwater Rule Using Conventional BMPs:		
Mean Cost of BMP in Florida	(for this watershed)	$383,000
Overall Cost		**$693,000**

Cost using LID through Design Option 3(a):

Cost Category	LIR	BAR
Capital	$283,000	$54,900
O&M	$420	$3,300
Engineering fee	$28,300	$9,700
Contingency fee	$43,300	$14,600
PV of Cost	$361,000	$121,600
Overall Cost		**$482,000**

Questions

Thank You:

- Eric Livingston, FDEP
- Dr. Christian Beretta,
- Hao Zhang, Giuseppina Garofalo, Natalie Magill, and Eban Bean
- Chuck Hogan (UF Physical Plant)
- Ron Osteen and Darrin Vogeli (Financial Information)