Myths, Modeling and Monitoring of Rainfall-Runoff Controls

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Gainesville, FL
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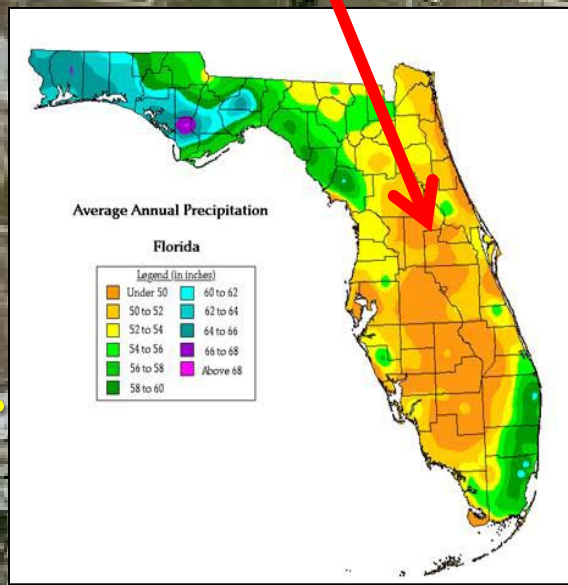
PROBLEM STATEMENT:

The Urban Interface Profoundly Modifies the Coupled Hydrologic, Particulate, Chemical and Thermal Cycles

Orlando Executive Airport, ORL



As a result, monitoring, modeling and control are complex with spatial scales from watershed to molecular; temporal scales from seconds to years. An overview and case study are presented.

The “first-flush” misconception

- *The pollutant first-flush or water quality volume (WQV) for urban watersheds is challenged by a complex reality*
- *As smaller source area catchments of differing times of concentration combine into more complex and larger urban watersheds, a pollutant first-flush is greatly diminished to non-existent*

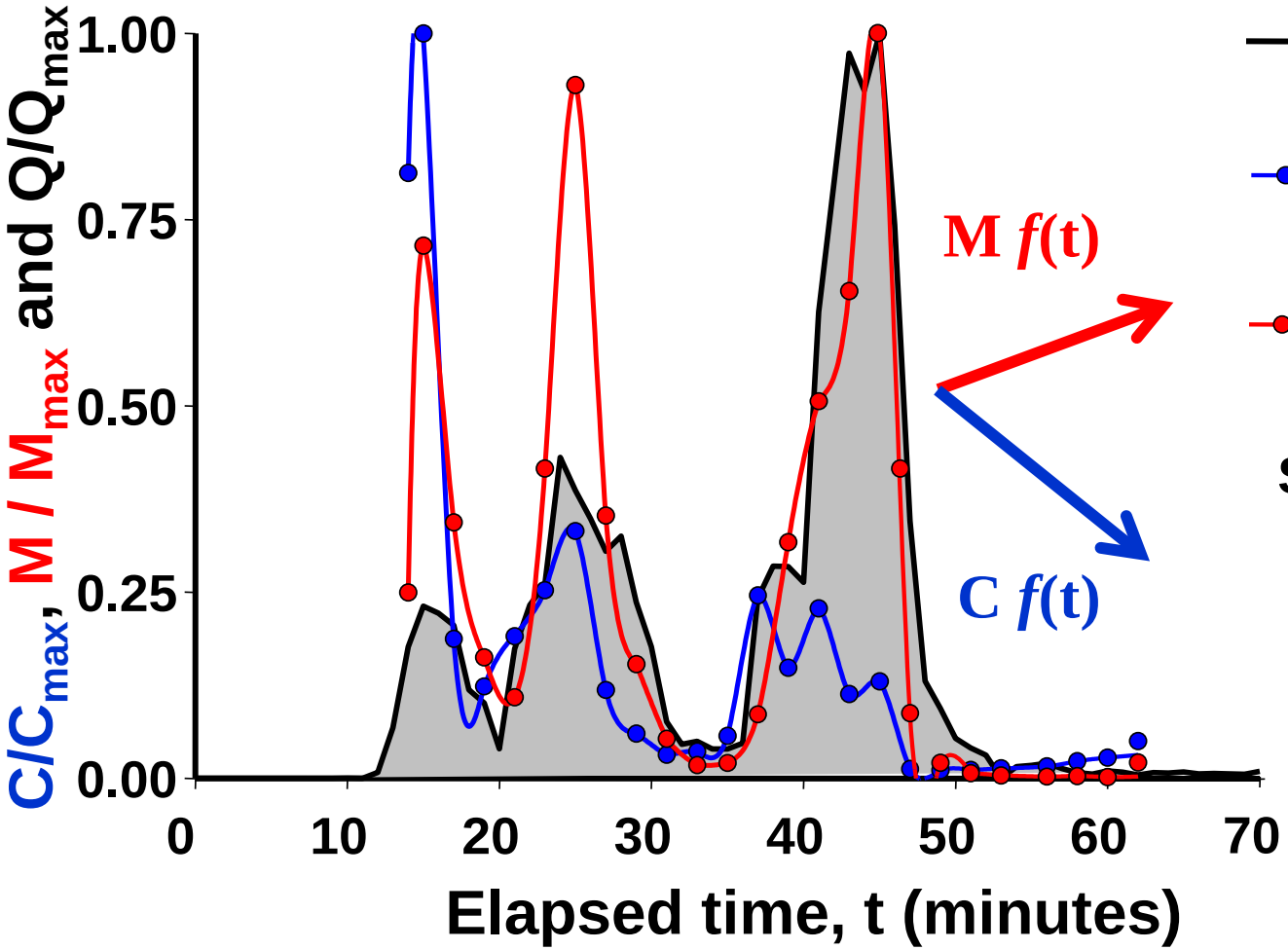
First Flush: Intuitive Misconception vs. Reality

Concept: **A "first flush" is a disproportionate delivery of a constituent during initial portion of a runoff event that may be used to estimate a treatment capture volume or water quality volume, WQV.** ***(Urban runoff to sea in Sorrento, Italia, 2004)***

Reality: ***"First-flush" delivery can be proportionate delivery (flow-limited), may not be initial, and is dependent on: method of measurement, the goal, the constituent phase, the geometry of the watershed, location in the watershed; and is never known a-priori.*** **WITH WASTEWATER REUSE, FIRST FLUSH REGULATIONS ARE DATED**

Hydrologic Delivery of Concentration and Mass

(1) *Does a "first-flush" exist* ? (2) *What volume would you capture/treat* ? (3) *Is this behavior known a-priori* ?



— (Q): Flow
Q_{max} = 244 L/minute

[C]: Concentration (SSC)
C_{max} = 689 mg/L

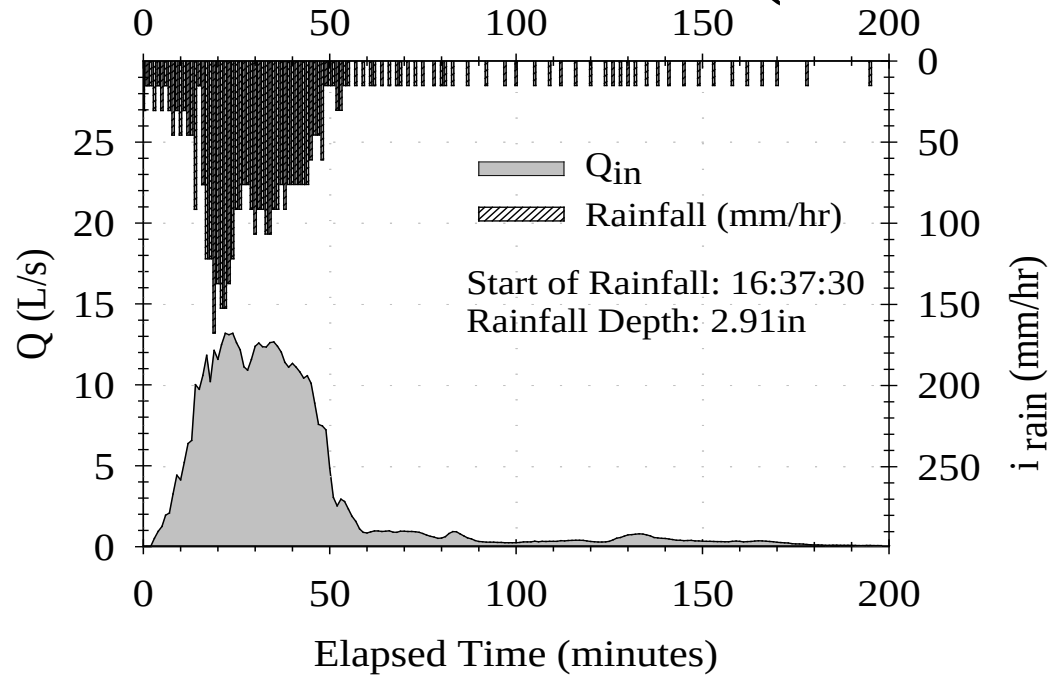
(M): Mass (SSC)
M_{max} = 41,460 mg

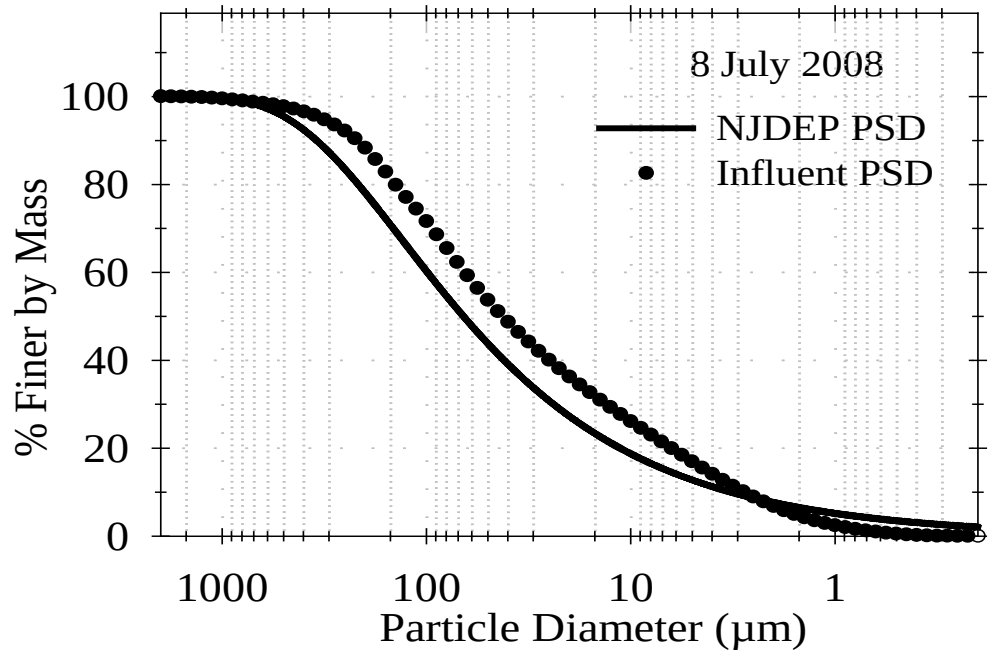
SSC: suspended sediment concentration

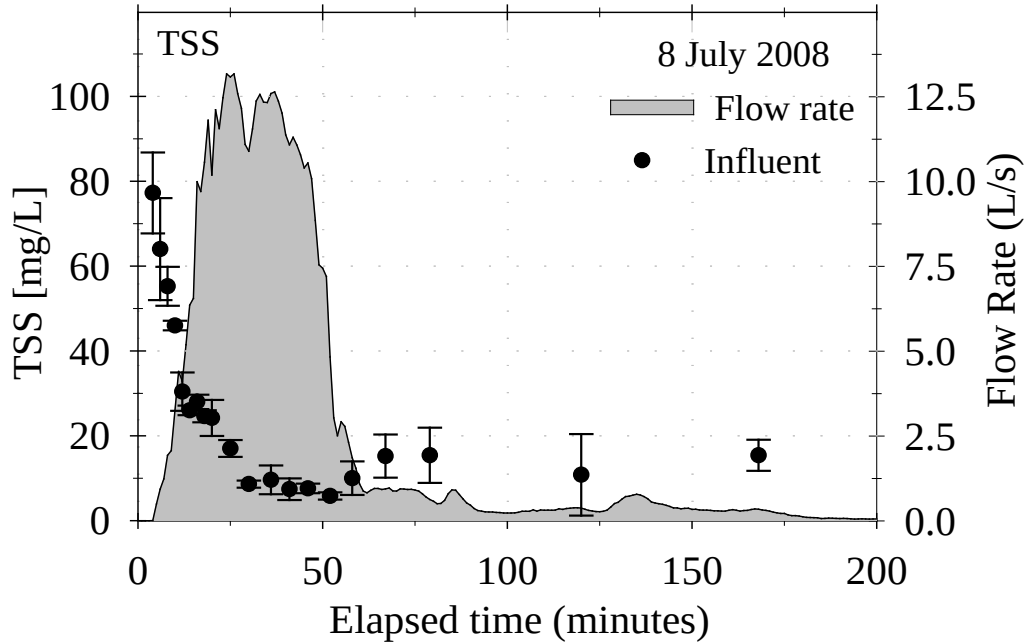
- 300 m^2 paved source area urban catchment

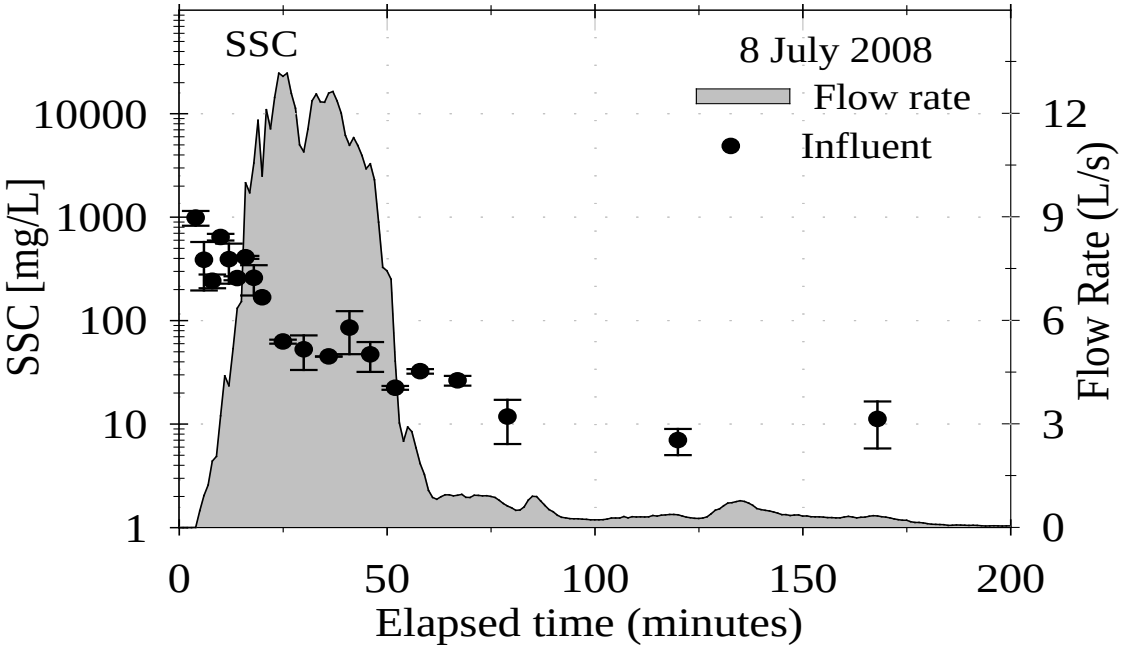
- *In part, acute toxicity is associated with concentration and time; chronic toxicity with mass and time*

8 JULY 2008 (University of Florida Catchment)









Mass Transport Patterns: Differentiation Criteria

First-order mass depletion Mass-limited, ML

$$\frac{dM}{dt} = -KM \quad \longrightarrow \quad \Delta M_t = M_0(1 - e^{-k_1 V_t})$$

$$K = k_1 Q$$

Zero-order mass depletion Flow-limited, FL

$$\frac{dM}{dt} = -K \quad \longrightarrow \quad \Delta M_t = k_0 V_t$$

$$K = k_0 Q$$

ΔM_t : cumulative mass delivered [M];

V_t : cumulative volume [L^3];

M_0 : constituent mass on the surface at the beginning of the rainfall-runoff event [M]; (difficult to measure, now can be estimated)

k_1 : ***first-order*** coefficient [L^{-3}].

k_0 : ***zero-order*** coefficient [ML^{-3}];

M : instantaneous mass remaining on the watershed surface (M);

K : transport rate coefficient.

Motivation : High correlation between ΔM_t and V_t .

Assumption : Mass depletion = Mass delivered.

- PM mass depletion is generally first-order but with k-values that are a function of PM size
- Dissolved mass depletion is generally zero-order but depends on partitioning kinetics with PM

The “automated sampling” misconception

- *Representative monitoring is once of the most challenging aspects of stormwater science*
- *The complex reality of stochastic storm arrival times, highly unsteady flows and complex, heterogeneous-heterodisperse pollutant transport and fate results in a very challenging condition for representative sampling*

The Need and Challenge of Representative Sampling

Automatic (Automated) Sampling:

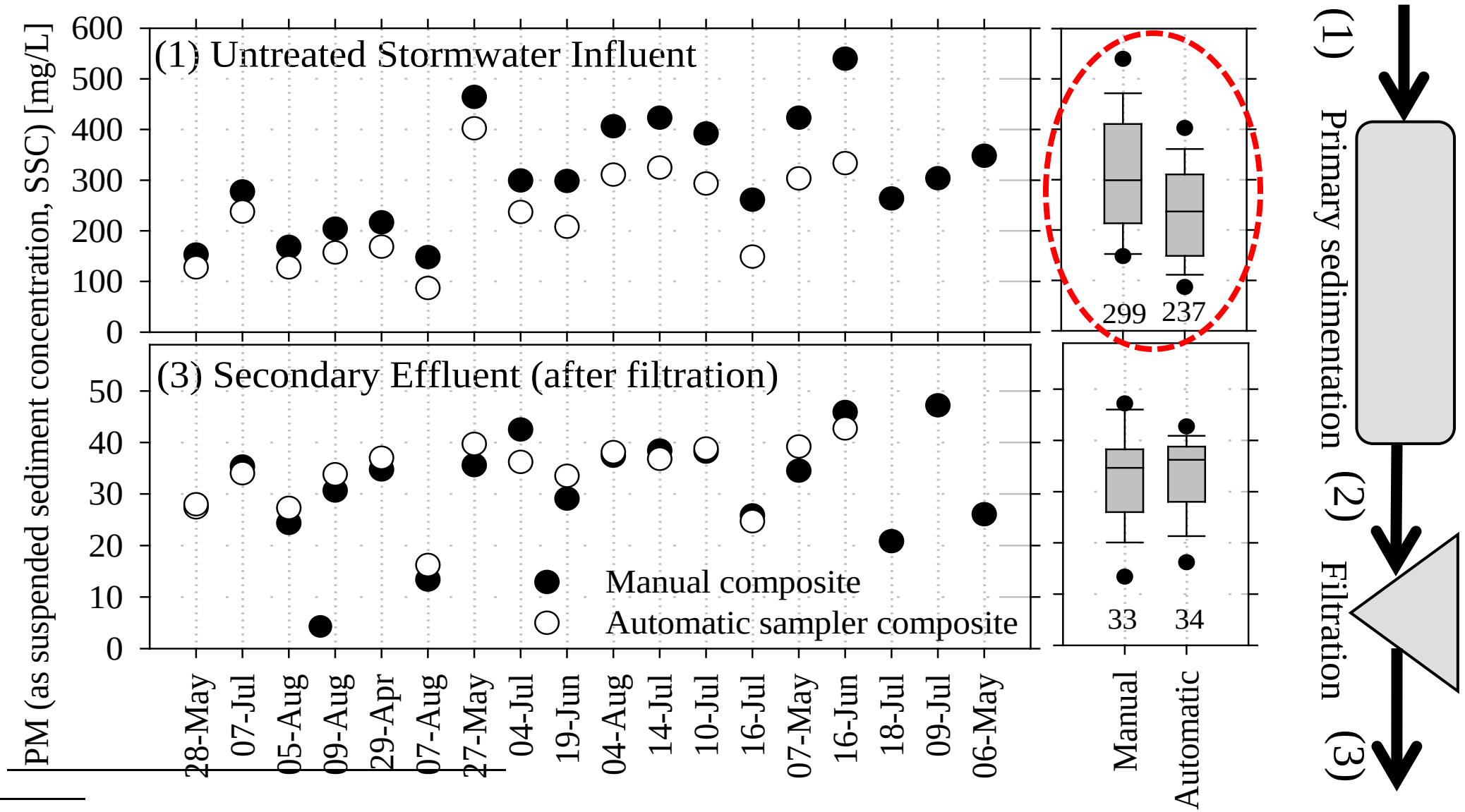
- Standard North American practice for stormwater EMCs
- Adopted from wastewater sampling without modification to account for significant storm and wastewater differences
- Inaccurate and non-representative for stormwater loads !!!
- Reduces labor and decision-making; equipment costly
- Compromised by lack of real-time intelligence to balance sample timing and #, while capturing entire storm duration!

Manual Sampling:

- Accurate and representative, allows for material balances
- Labor and intelligence intensive, not convenient or common
- Provides real-time flexibility and decision-making throughout the entire storm to balance sample timing and #
- Coupled with real-time radar imagery and geo-referencing to match sampling with spatial and temporal storm scales
- Allows significantly reduced sample holding times- critical!

Example: Automatic Sampler Liability on Storm Basis

Liability for treatment evaluations, load assessment, maintenance



Parameters for Uncontrolled (Field) Physical and Numerical Modeling of a Control Strategy

1. Watershed: cover, slope, geometry, anthropogenic/biogenic activities …
2. Matching unit operation hydraulic/volumetric capacity to watershed loads
3. Granulometric: PSDs, ρ_s, [C], …
4. Rainfall: frequency distributions (embrace variability !!)
5. Hydrodynamics: Q, RTD, regimes, transience, …
6. Sufficient event monitoring for statistical or probabilistic evaluation of unit operations (20 to 25+); examine wrt historical continuous simulations
7. Representative sampling and material balances required (challenging !!)
8. Quantitative impact of O&M (or lack thereof) during campaign
9. Parameter integration for unit operation mathematical modeling
10. A standard regional/national rigorous physical modeling field protocol

Urban Particulate Matter (PM)

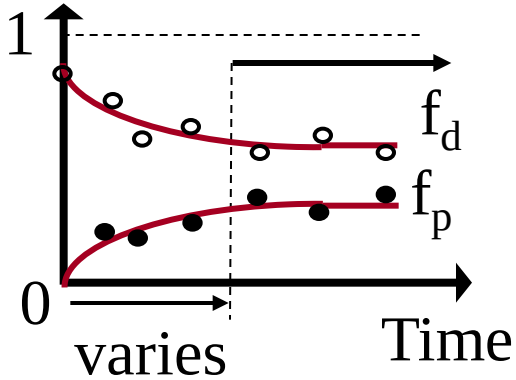
- *PM is the predominate urban sink and source of chemicals*
- *Myths regarding PM as only TSS, are historical and inertial*
- *Myth perpetuation is a function of how we sample and analyze:*
  - *samplers are designed for steady wastewater flows and organic PM*
  - *analysis based on sub-aliquot methods (TSS) without particle size data*
- *Representative sampling/analysis is difficult*
- *Particle size distributions (PSD) required for:*
  - *modeling PM, solute and microbiological fate*
  - *load inventories of PM and chemicals*
  - *urban water cycle and reclaimed water benefits*

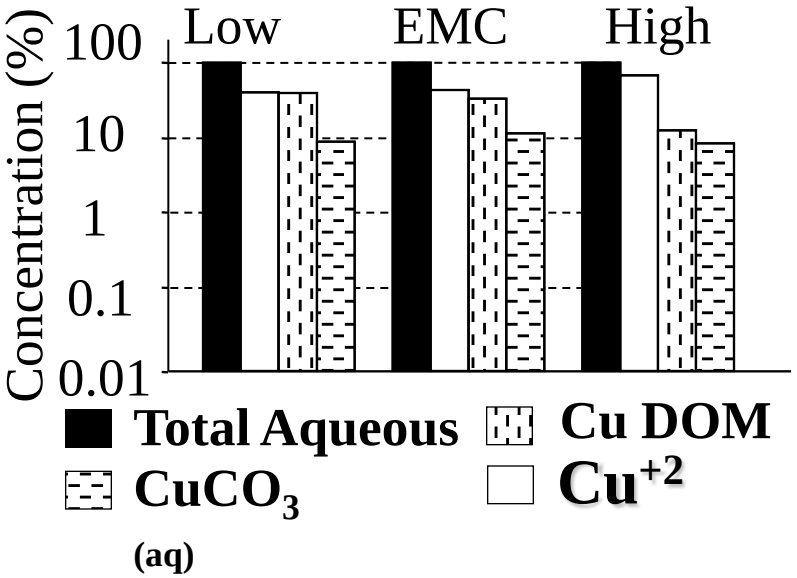
Partitioning and distribution of mass (example – Cu)

Inorganic or organic mass

Dissolved (aqueous) f_d

- Ionic
- Complexed



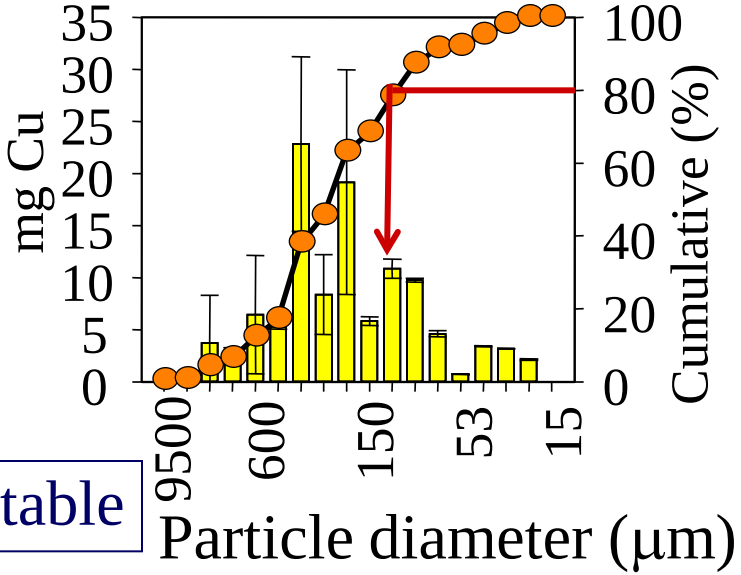


Adsorbed (Particulate-Bound) f_p

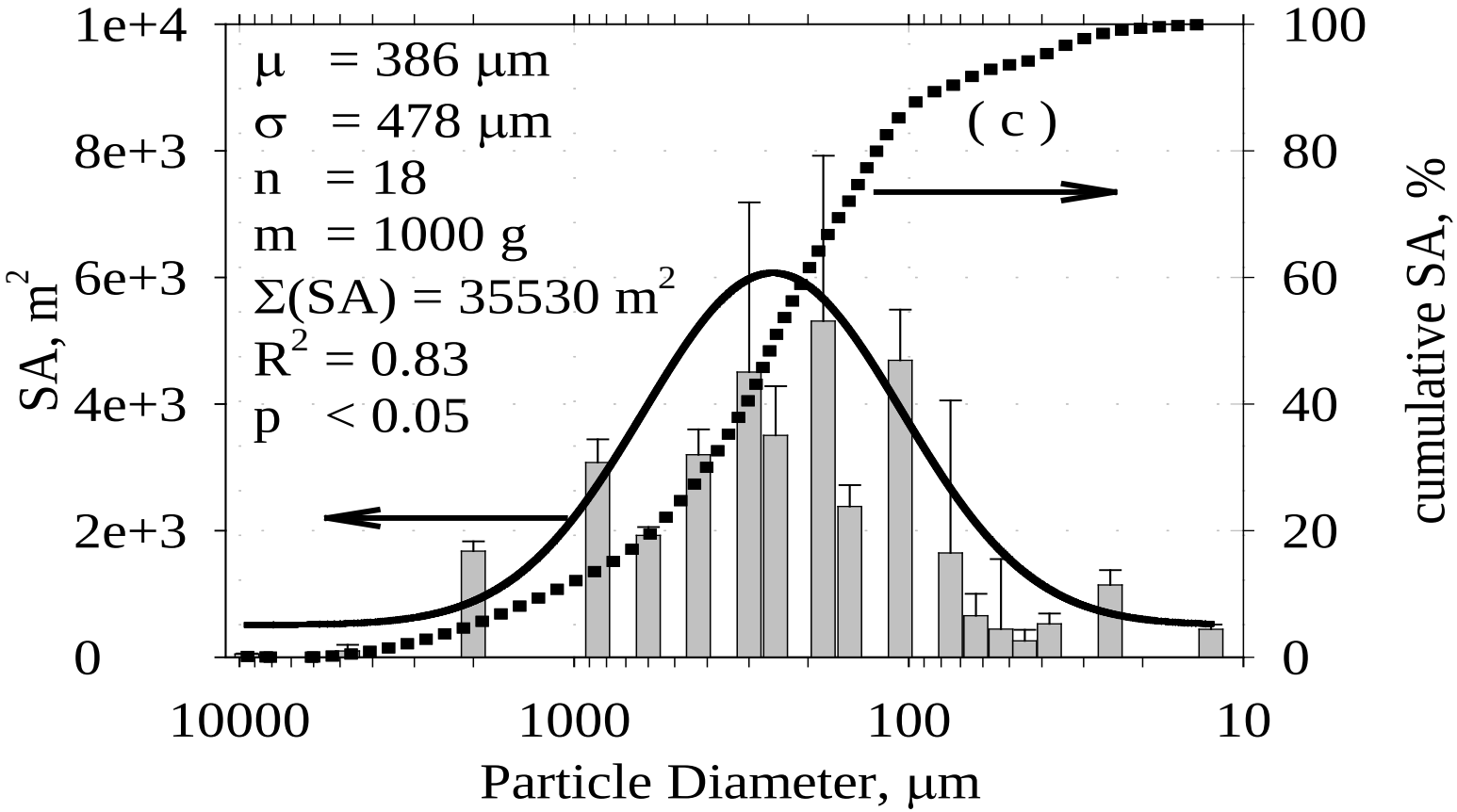
z/m

- Colloidal
- Suspended
- Settleable
- Sediment - Floatable

Poorly sampled and often ignored



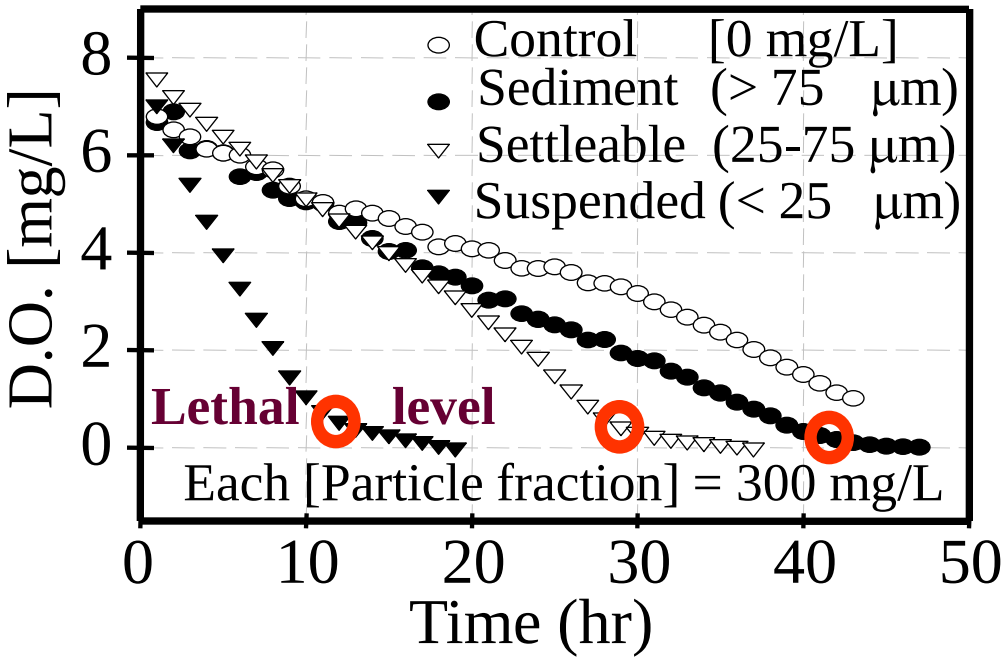
Total surface area (SSA) of urban PM



<u>Log normal distribution function</u>

$$SA = SA_0 + r \cdot e^{[-0.5 \cdot (\frac{\ln(d) - \ln(d_0)}{t})^2]} = 1187 + 12895 \cdot e^{[-0.5 \cdot (\frac{\ln(d) - \ln(255)}{0.39})^2]}$$

Lethality of PM Fractions on Fathead Minnows



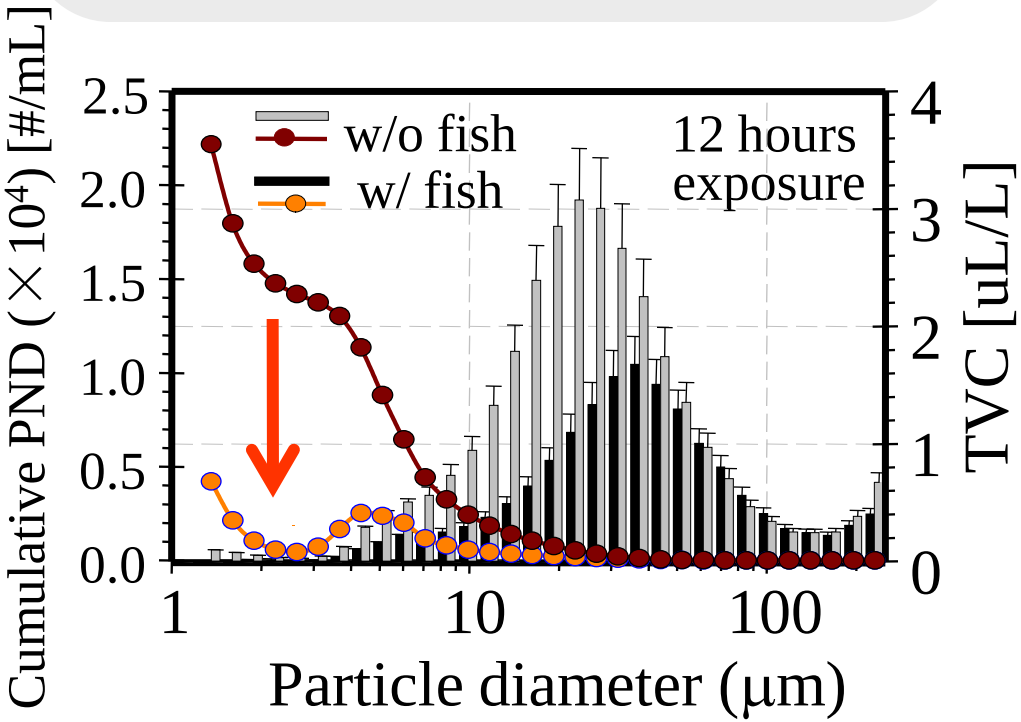
Oxygen consumption rate: mg/(g-hr)

- Amount of dissolved oxygen (D.O.) consumed in 1 hour based on the unit weight of the organism
- Sub-lethal test (gill function)

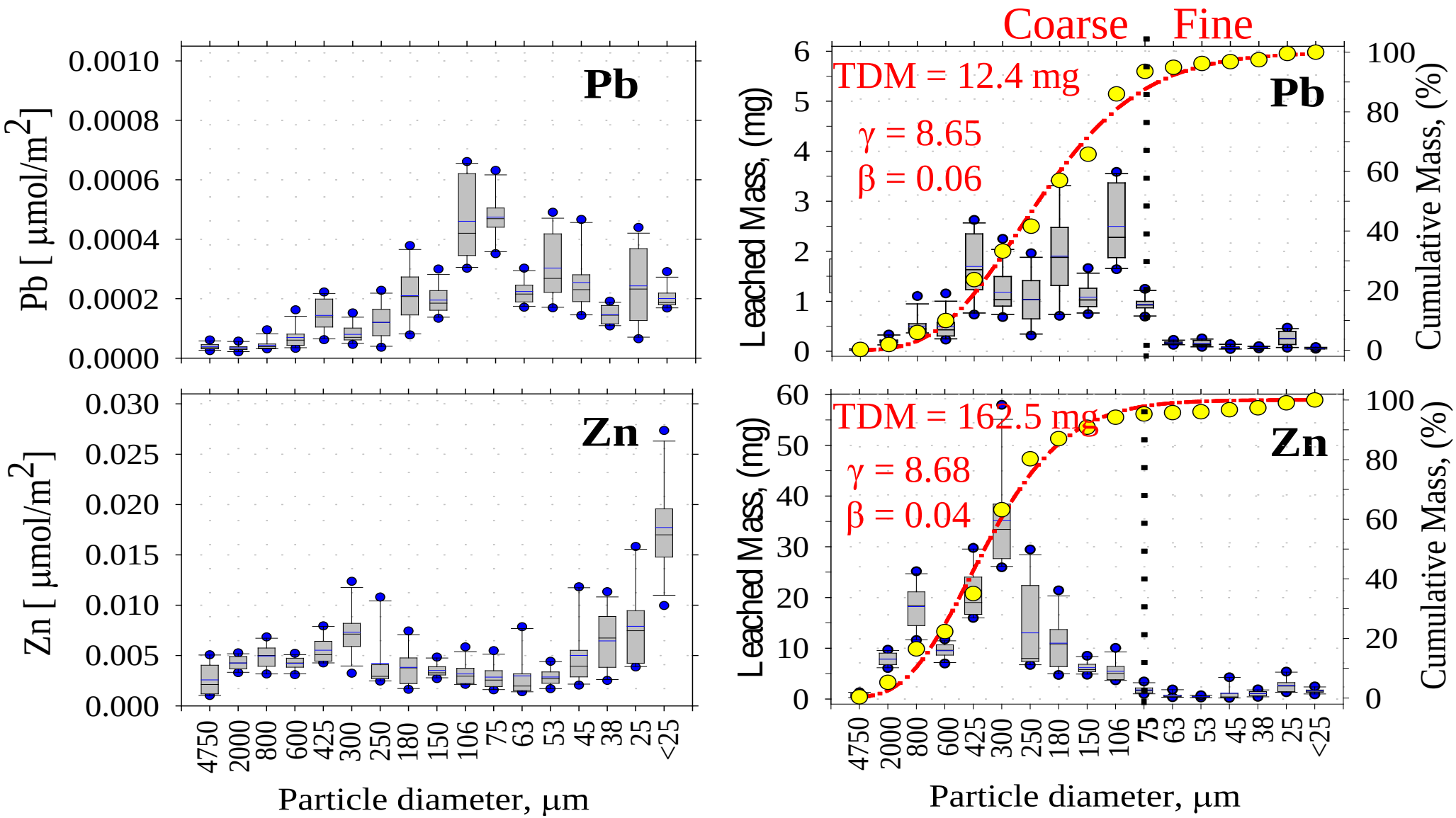
Lethal level:

- D.O. level at which gill pumping stops

- Suspended particles trapped by gill tissue
- Settleable and sediment particles have a significantly lower effect on gill function
- Level of lethality indicated on time axis at the inflection point of each D.O.- time curve. The control generated no lethality.

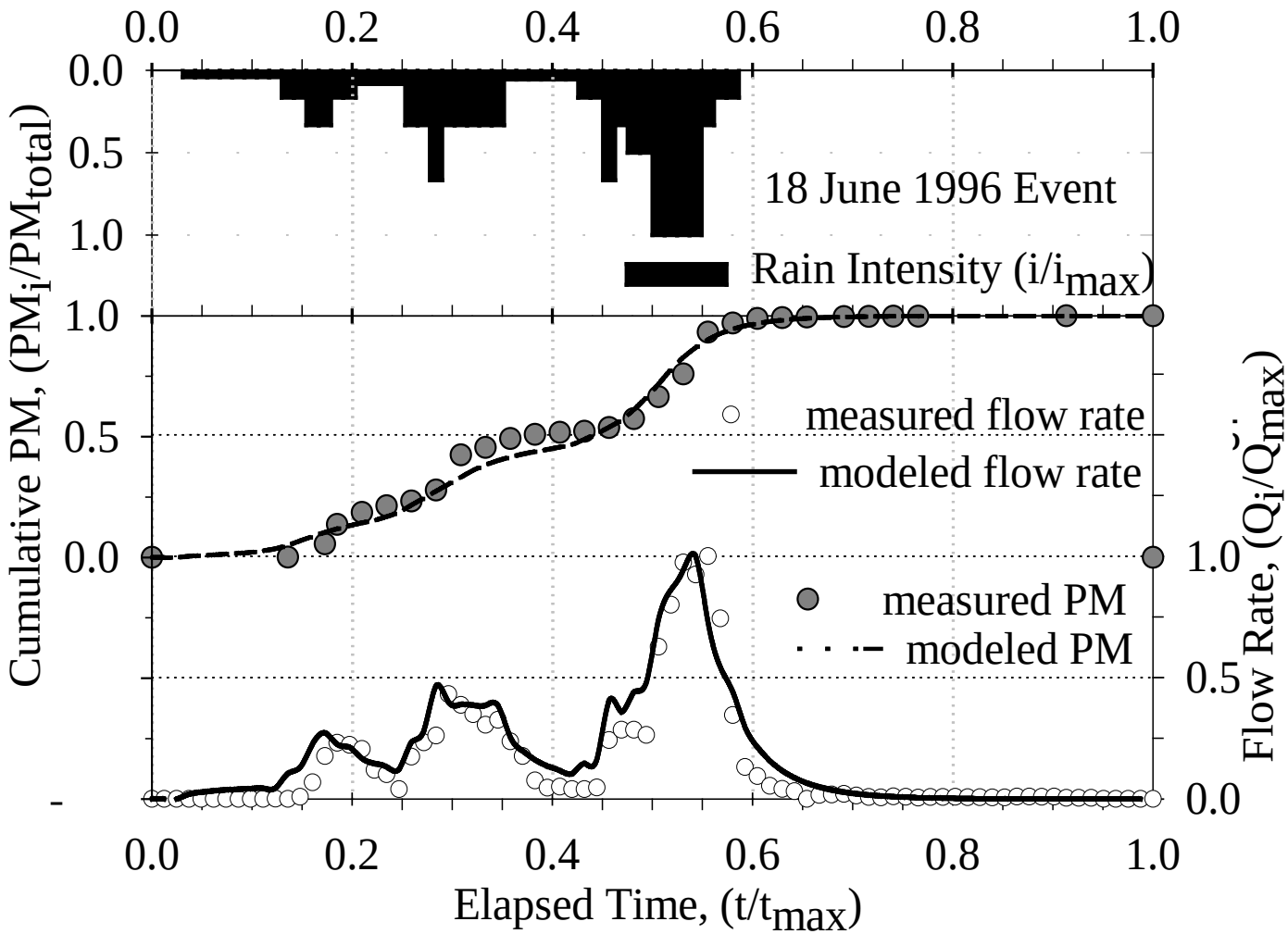


Distribution of Pb and Zn Leached from PM Separated by "BMPs"



Modeling watershed & unit processes as building blocks

(i.e.: Unit hydrograph and pollutograph for hydrologic functional units)



Site, Event Parameters:

- Paved, 2% slope
- Traffic loadings
- Q_p = 244 L/min.
- $t_{max.}$ = 68 min.
- V = 2794 L
- PM = .258 kg

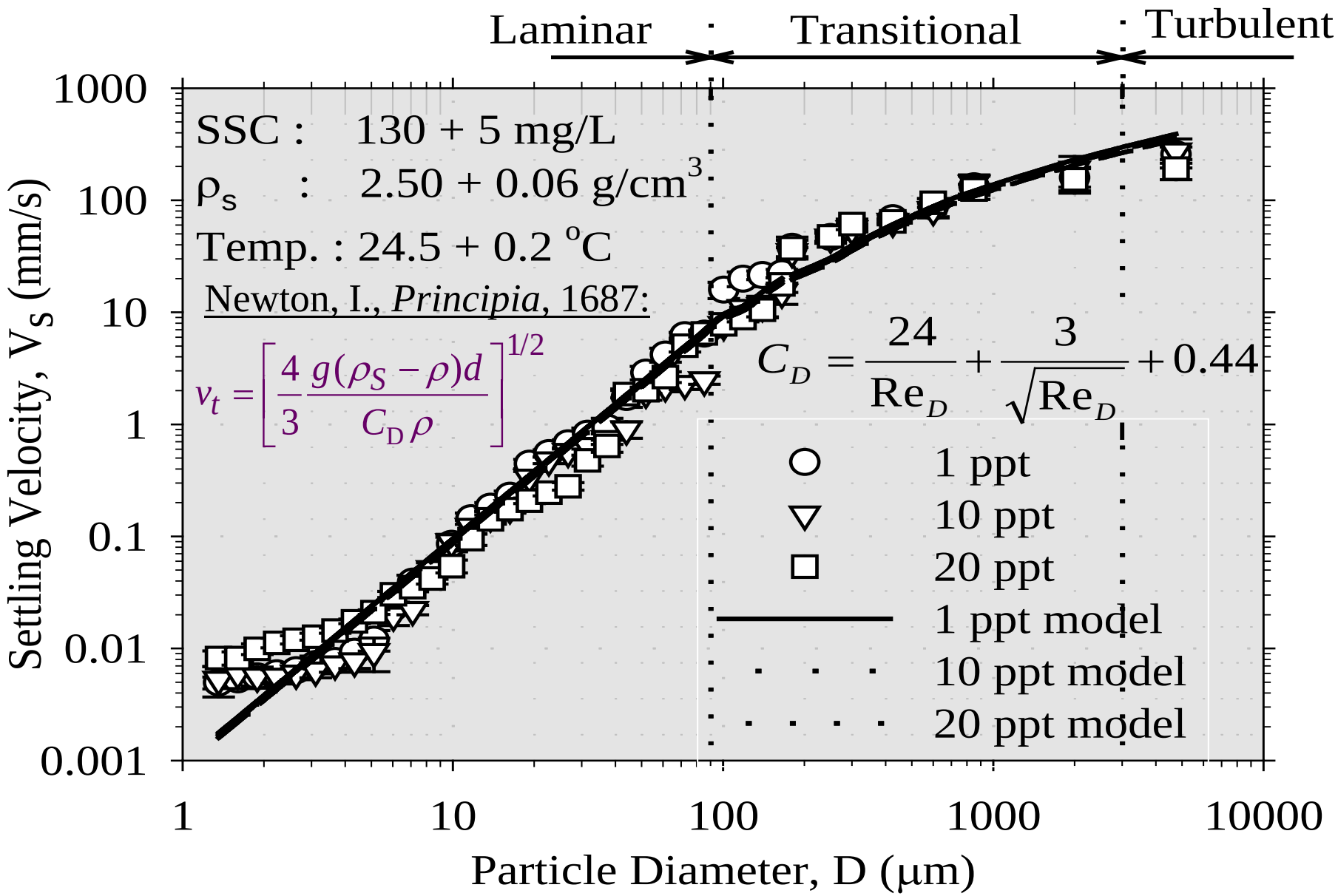
Calibrated Site IUH:

- k = 4.02, n = 0.66

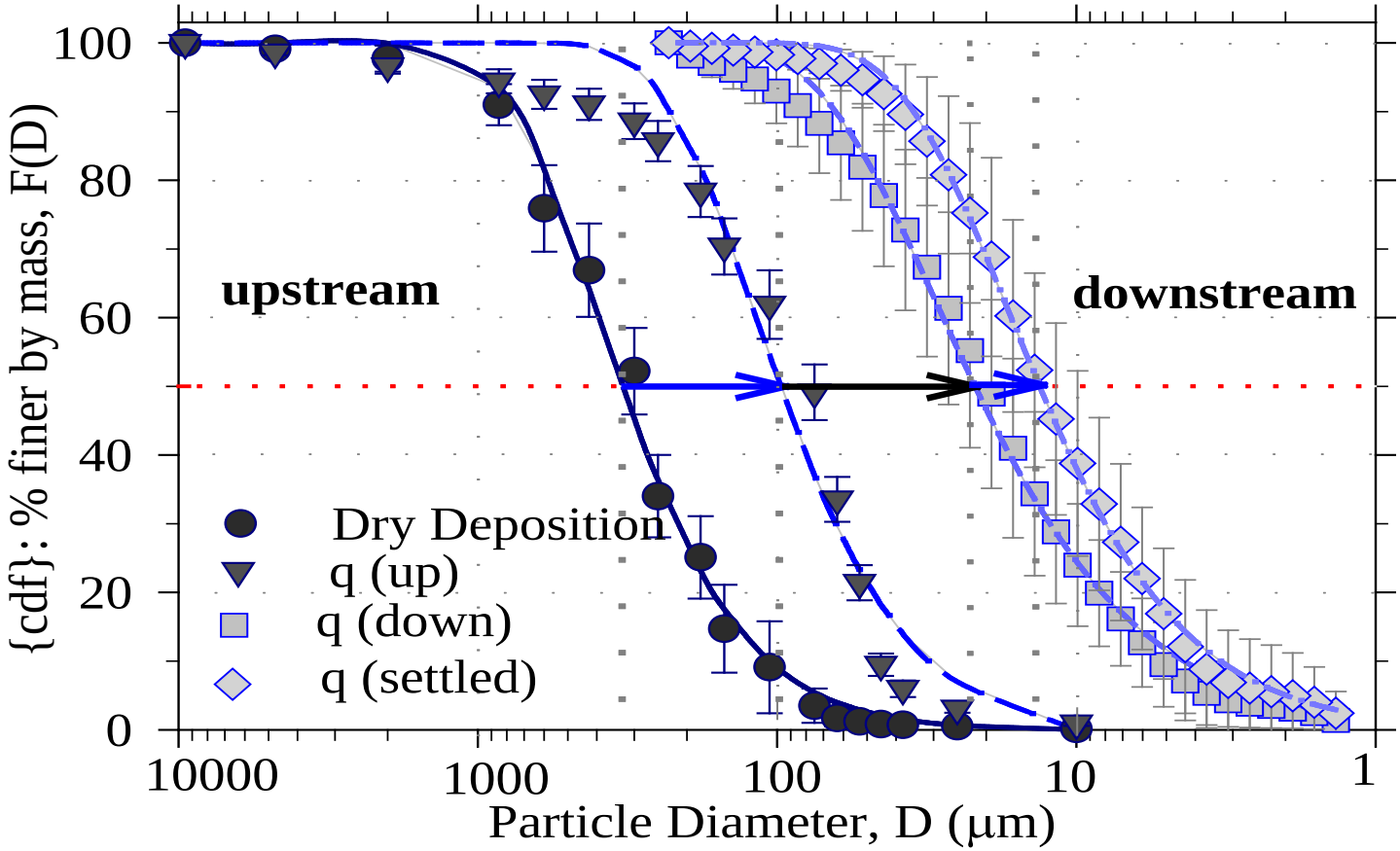
Calibrated Site IUP (PM)

- B = 0.29 min^{-1}
- (NS) R^2 = 0.93

Median Settling Velocities of Particles (Type I: Discrete Settling)



Particle Size Modification by Urban Conveyance System: Choice and location of a unit operation will influence treatment behavior



PSD gamma model

$$f(D) = \frac{(D/\beta)^{\gamma-1} e^{(-D/\beta)}}{\beta \cdot \Gamma(\gamma)}$$

$$F(D) = \Gamma_D(\gamma) / \Gamma(\gamma)$$

$$\Gamma(\gamma) = \int_0^\infty x^{\gamma-1} e^{(-x)} dx$$

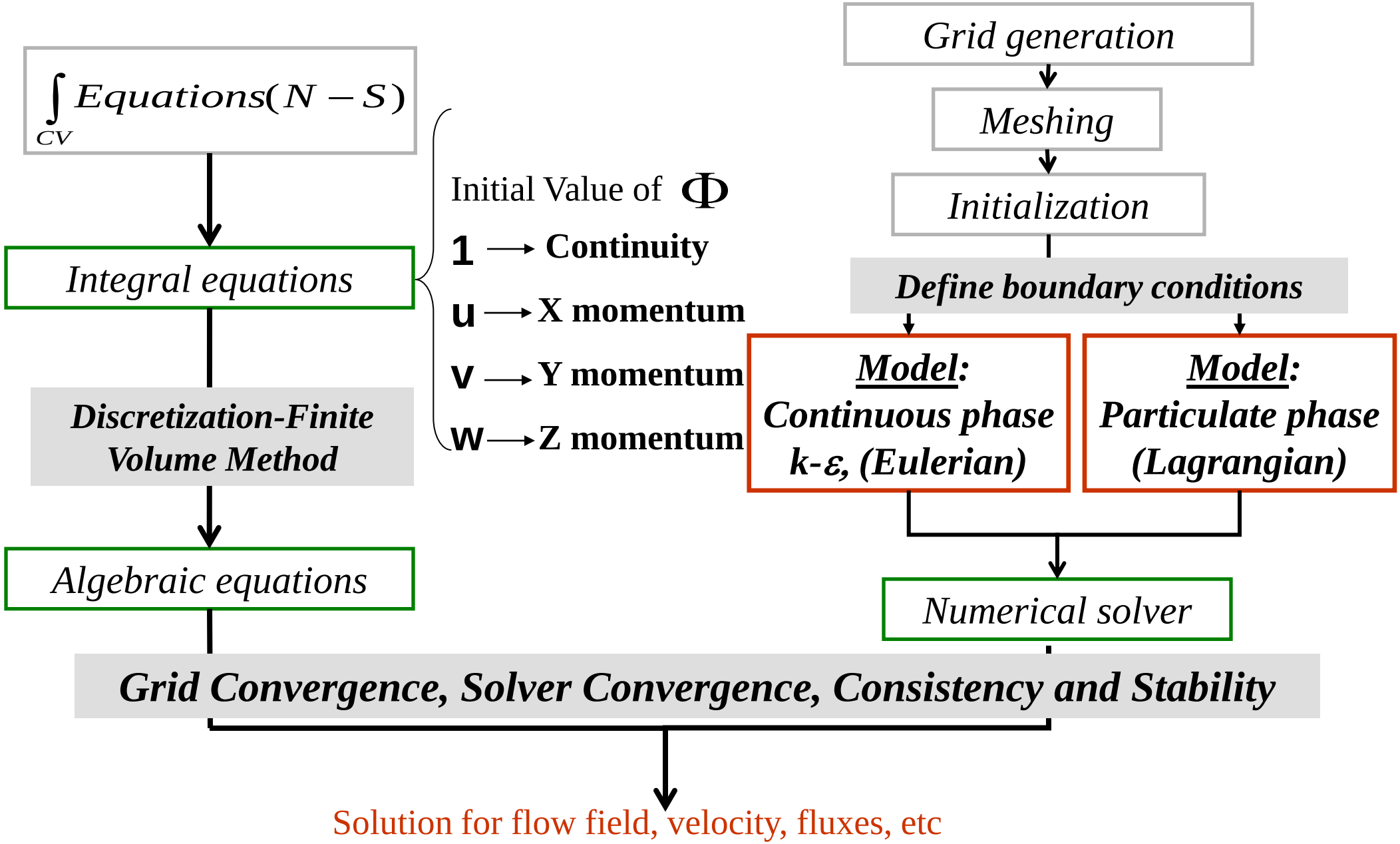
$$\Gamma_D(\gamma) = \int_0^D x^{\gamma-1} e^{(-x)} dx$$

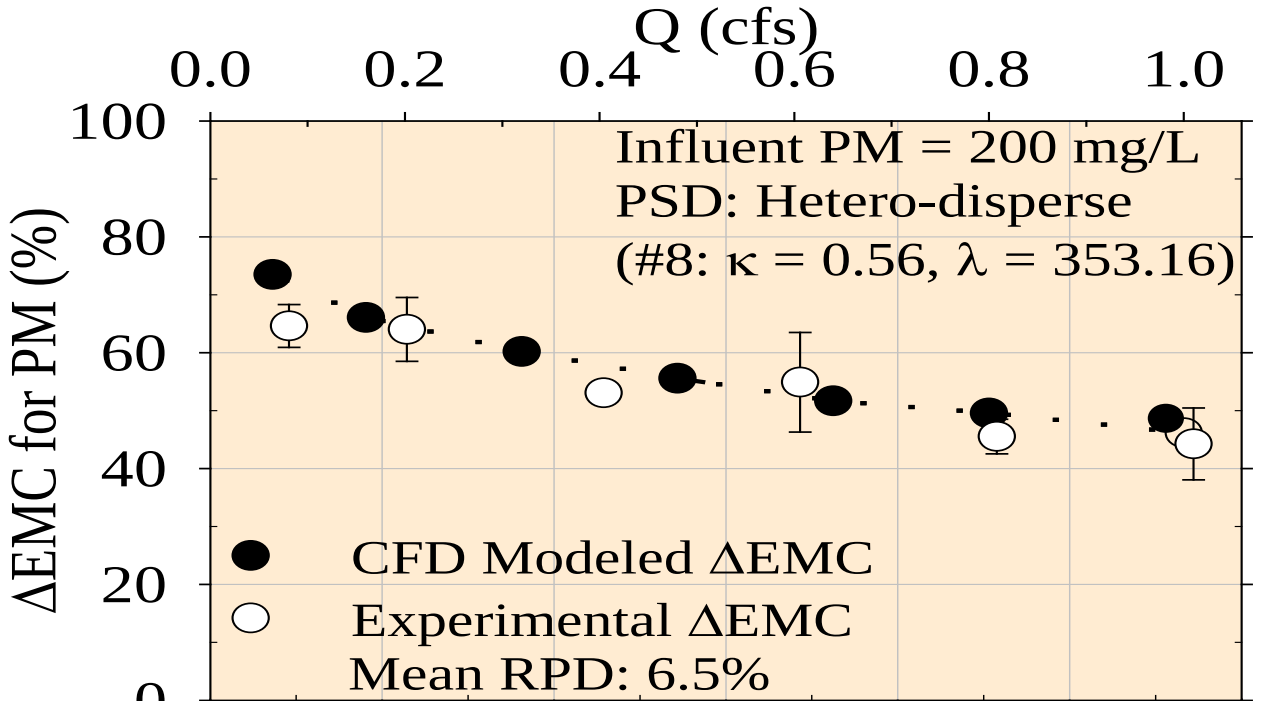
Location	(γ, β)
DD	(2.06, 187.7)
q (up)	(1.90, 61.9)
q (down)	(1.23, 23.6)
q (settled)	(1.51, 11.1)

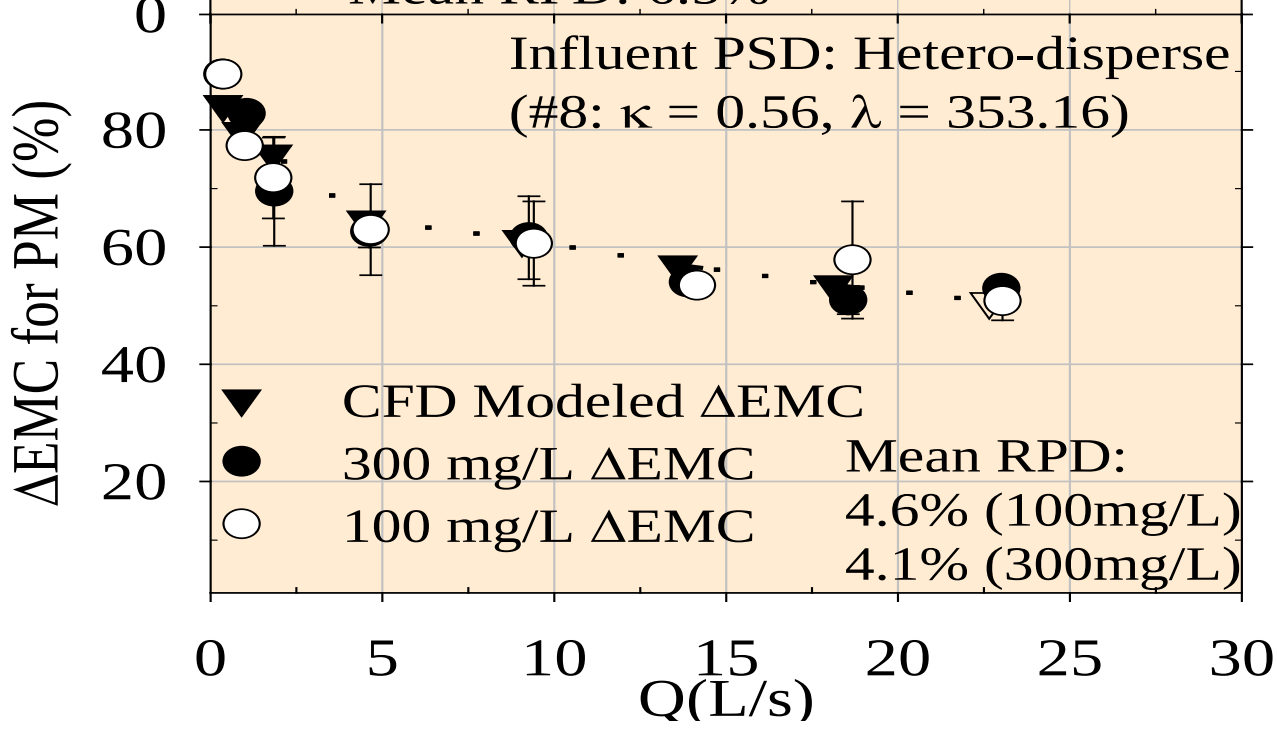
	DD Dry Deposition	q (up) Upstream Runoff	q (down) Downstream Runoff	q (settled) Settled (1 hour) Runoff
D_{50m}, μm	330.7	98.6	22.6	13.7

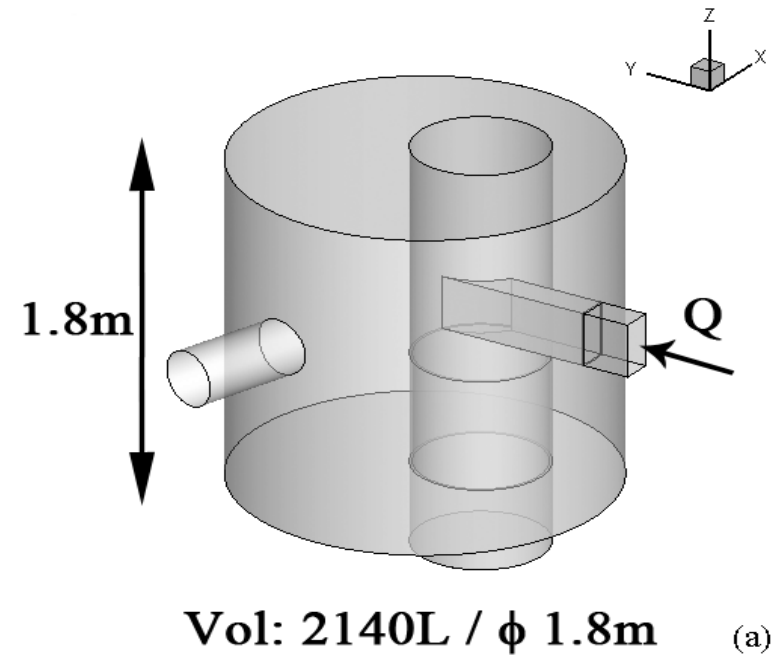
Che cosa è CFD ?

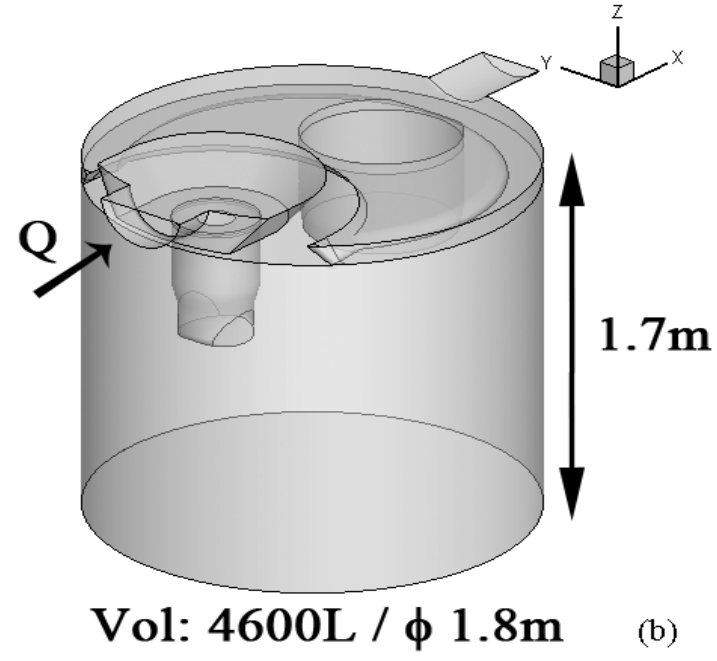
CFD Processes (in this case, Navier-Stokes (N-S) Equations applied)



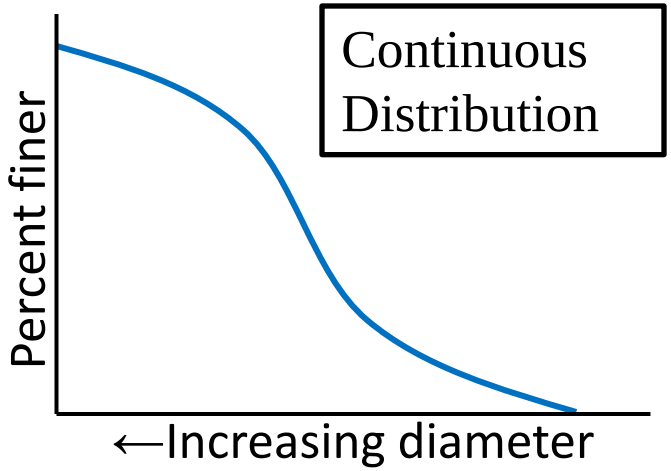

Q (cfs)
0.0
0.2
0.4
0.6
0.8
1.0
100
80
60
40
20
0
ΔEMC for PM (%)
Influent PM = 200 mg/L
PSD: Hetero-disperse
(#8: κ = 0.56, λ = 353.16)
CFD Modeled ΔEMC
Experimental ΔEMC
Mean RPD: 6.5%

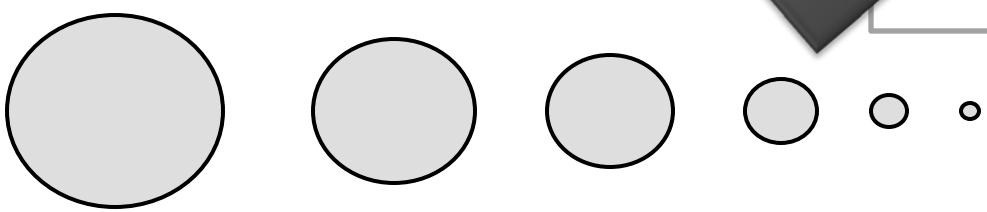

80
60
40
20
ΔEMC for PM (%)
Influent PSD: Hetero-disperse
(#8: κ = 0.56, λ = 353.16)
CFD Modeled ΔEMC
300 mg/L ΔEMC
100 mg/L ΔEMC
Mean RPD:
4.6% (100mg/L)
4.1% (300mg/L)
0
5
10
15
20
25
30
Q(L/s)


1.8m
Q
Vol: 2140L / ϕ 1.8m
(a)


Q
1.7m
Vol: 4600L / ϕ 1.8m
(b)

The Problem of Discretization (the DPM)





Discrete Representative Particles

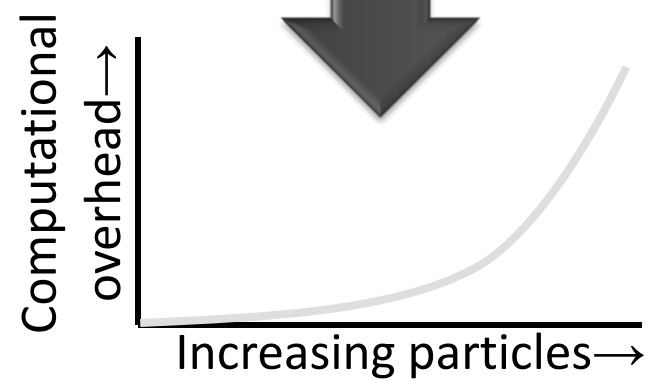
DPM CFD Model

$$\frac{dv_{p\_i}}{dt} = F_{D\_i}(v_i - v_{p\_i}) + \frac{g_i(\rho_p - \rho)}{\rho_p} + F_i$$

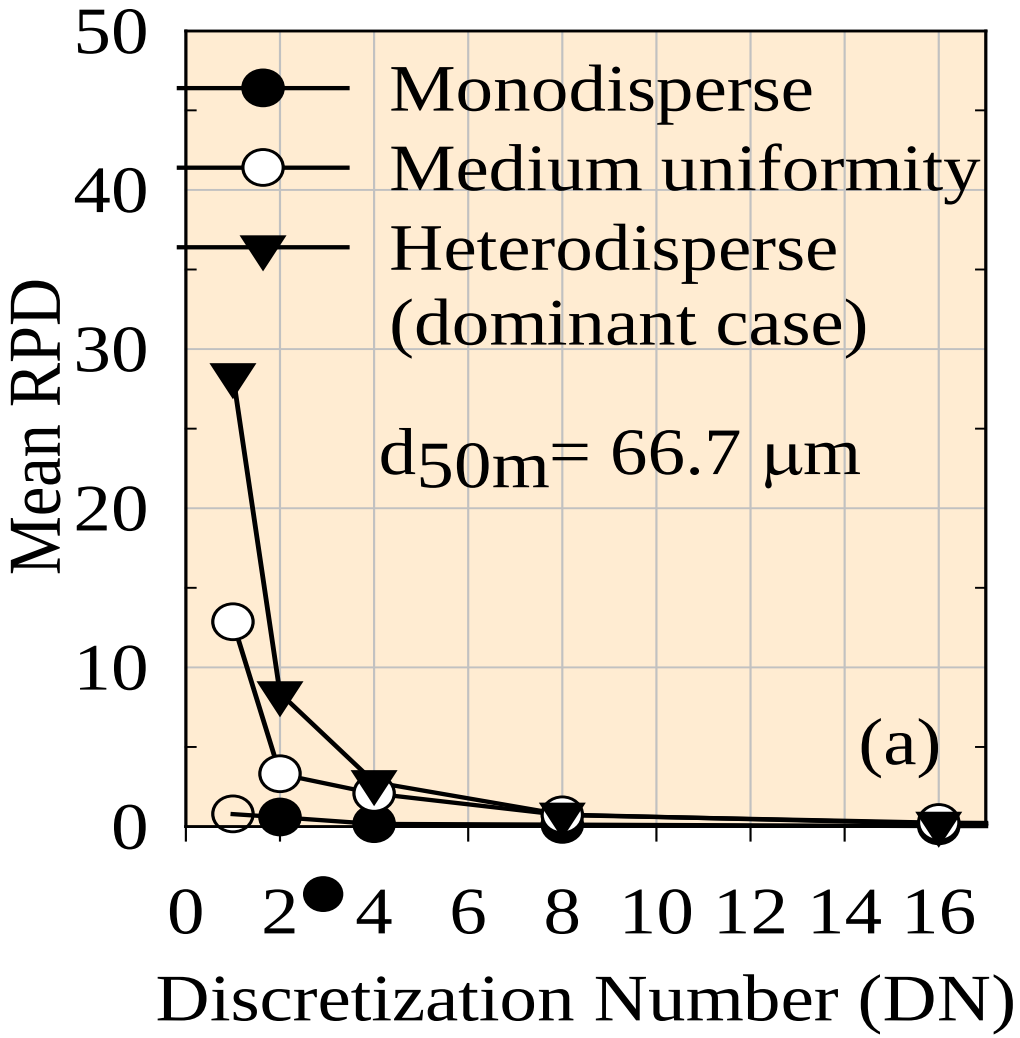
$$F_{D\_i} = \frac{18\mu}{\rho_p d_p^2}\frac{C_{D\_i}\mathrm{Re_i}}{24}$$

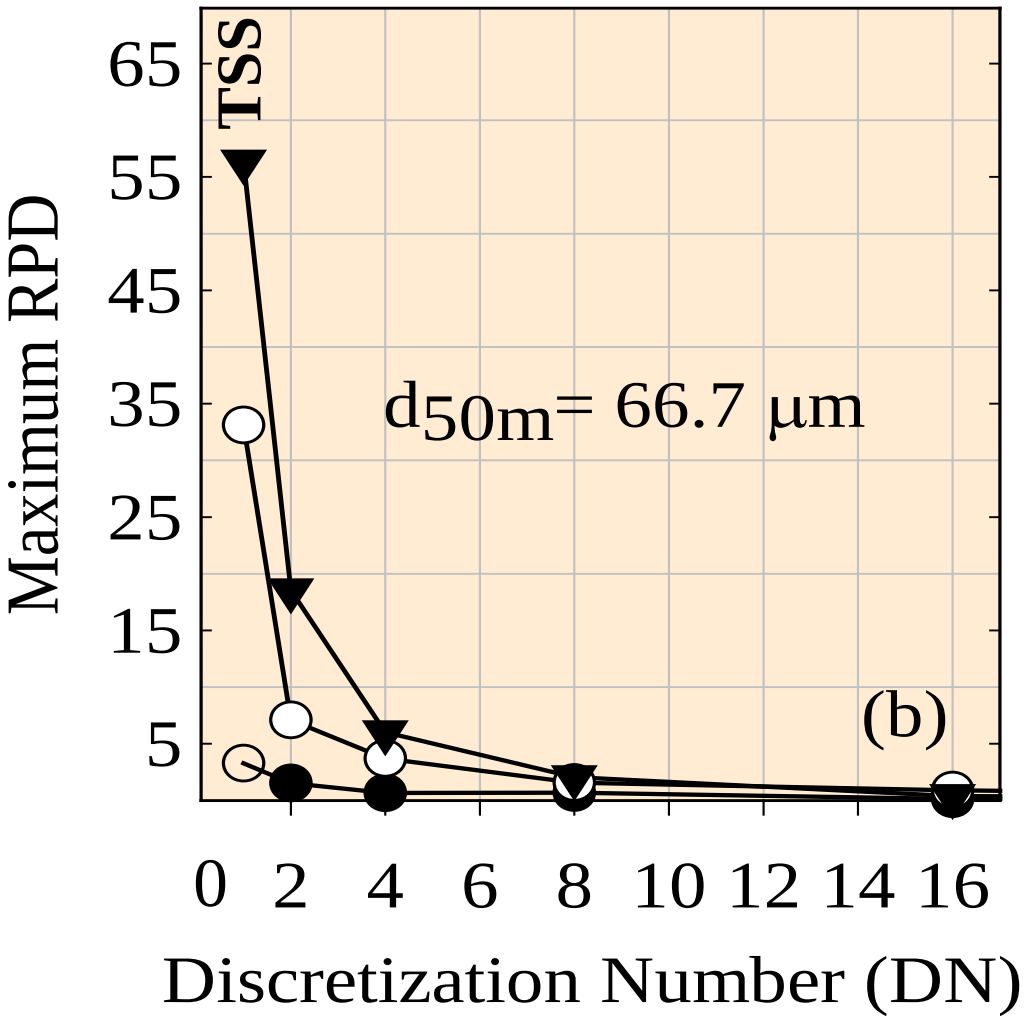
$$\mathrm{Re_i} \stackrel{\text{def}}{=} \frac{\rho d_p |v_{p\_i} - v_i|}{\mu}$$

$$C_{D\_i} = \frac{K_1}{\mathrm{Re_i}} + \frac{K_2}{\mathrm{Re_i}^2} + K_3$$

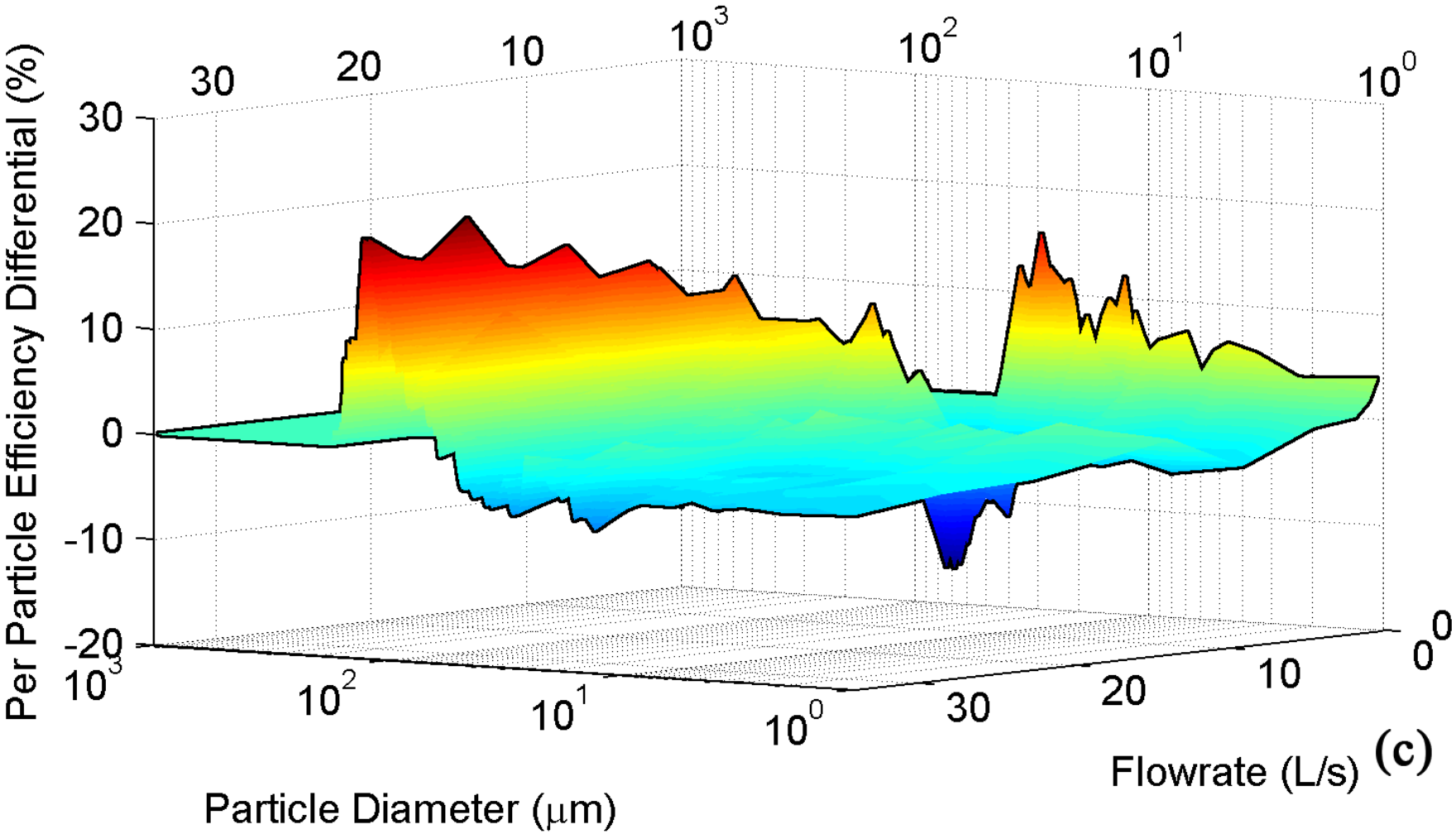


Error reduction (as RPD) as f (DN) for settling unit loaded by a PSD w/d_{50m} = 67μm. TSS introduces large errors



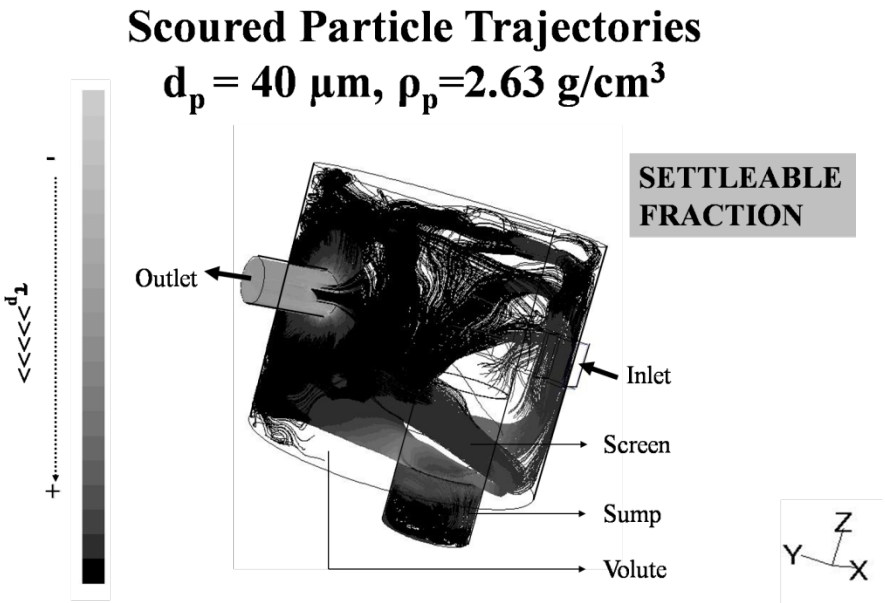


Differential HS Behavior in PSD-Q Space



Maintenance and pollutant inventories: The "Achilles Heel" of Control Strategies, LID and stormwater conveyance components

- The photo is a clogged stormwater catch basin inlet grate on steep slope of NW 22nd Street (Gainesville, FL)
- The challenge of microbiological vectors, long-term contaminant legacy, leaching, scour and clogging. How does MS4 monitor viability and maintenance of hundreds of such BMPs in an MS4 or County ?



Annualized Cost ($)/Pound for Pollutant Load Recovery (compared to pollutant separation by "BMPs")

Separation or Recovery Method	Cost ($/lb)		
	TN	TP	PM (as TSS)
Separation: BMP Treatment Train[a]	743	25,900	45
Separation: FL Database for BMPs[b]	1,900	10,500	41
Separation: Cementitious Permeable Pavement (CPP)	327	9,550	10
Recovery: Street Sweeping	pending	pending	4
Recovery: Catch Basin Cleaning	pending	pending	19

[a]Wet basin sedimentation followed by filtration

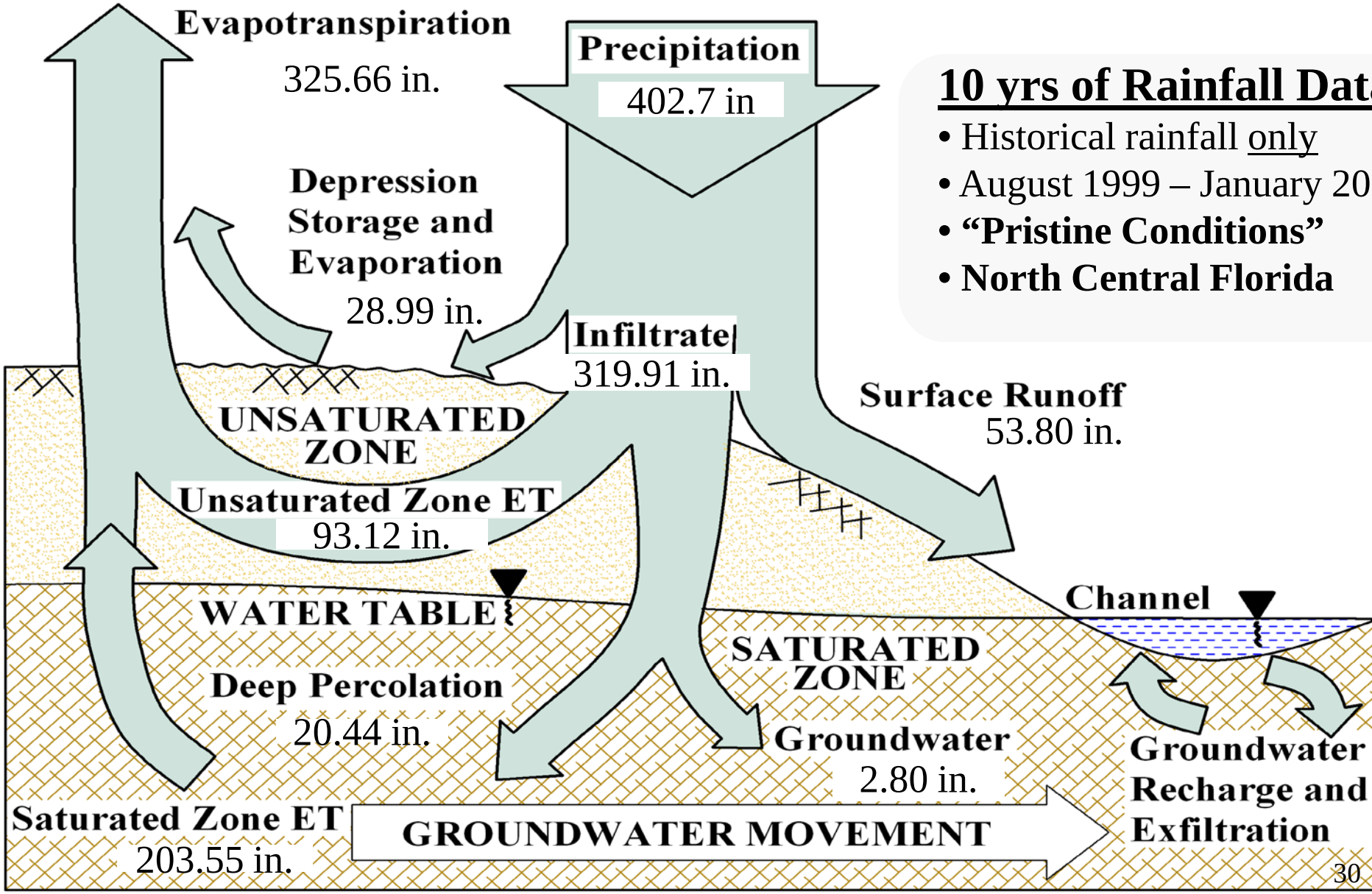
[b]TMDL database for FL Best Management Practices, 2009

The conclusion is that maintenance practices can be significantly more economical than "BMPs". However, such maintenance addresses only constituent load recovery and not hydrologic restoration, unless maintenance is combined with <u>quantitative</u> SUD/LID materials and models

Infiltration, Filtration, Biofiltration: Indirect Reuse

- ***All systems and media are not created equal, in fact systems and media can behave very differently but we have the tools to evaluate and create the building blocks for models, monitoring and maintenance***

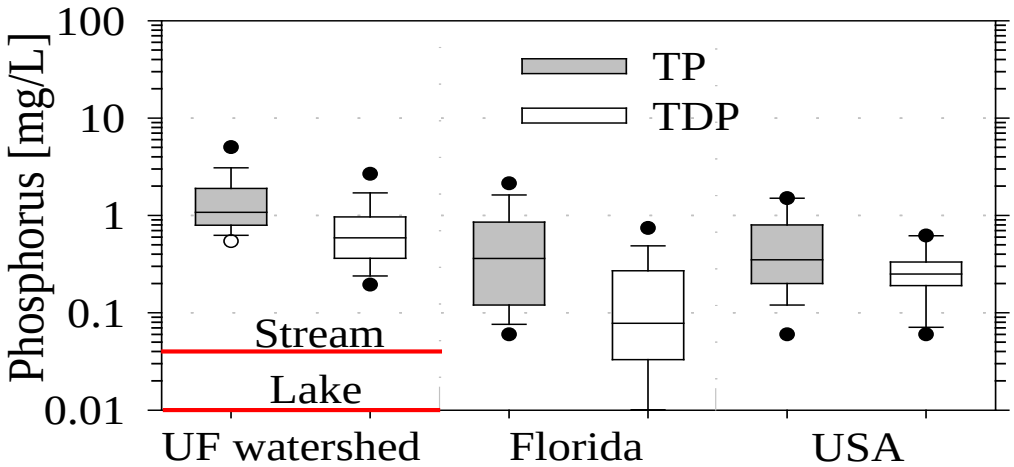
Watershed Pre-Development Hydrologic Cycle

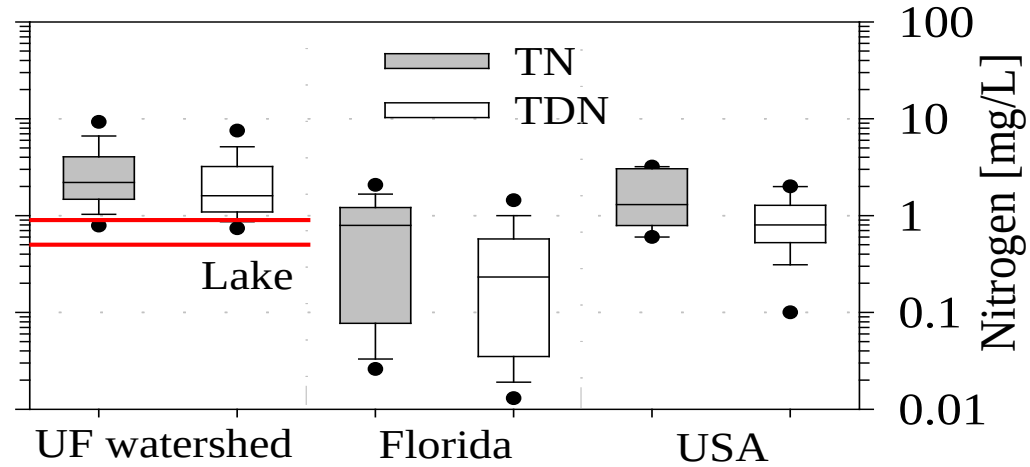


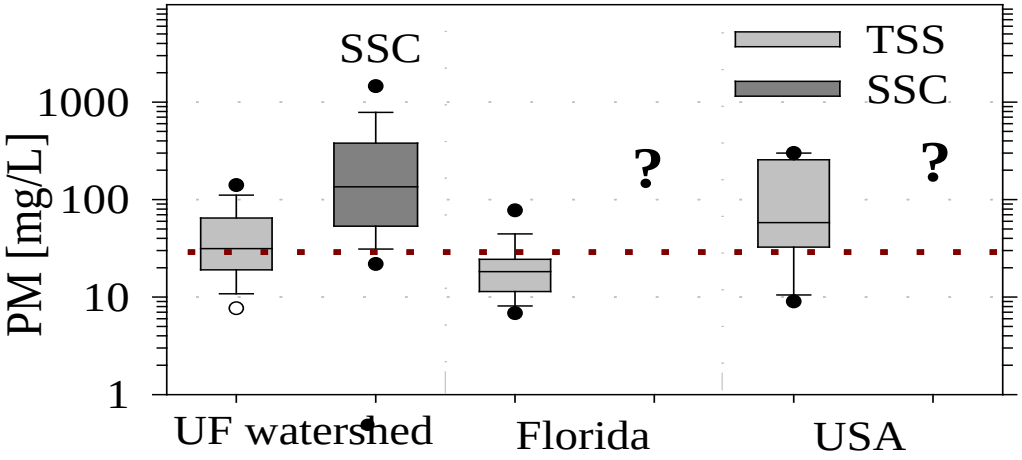
10 yrs of Rainfall Data:

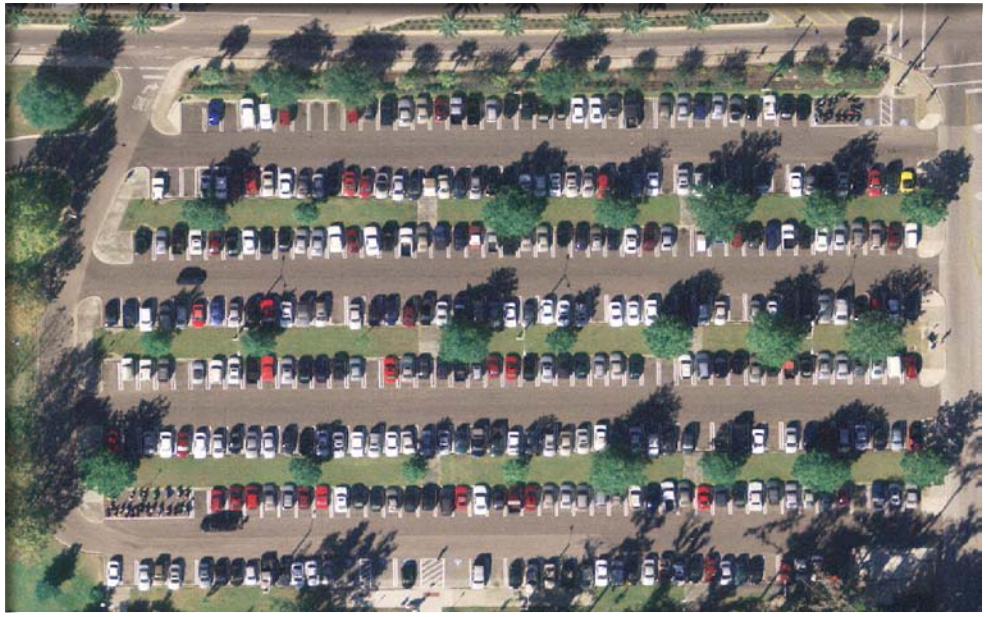
- Historical rainfall only
- August 1999 – January 2009
- **"Pristine Conditions"**
- **North Central Florida**

P, N and PM comparison between watershed studies with surface parking cover conditions (Gainesville, FL watershed)



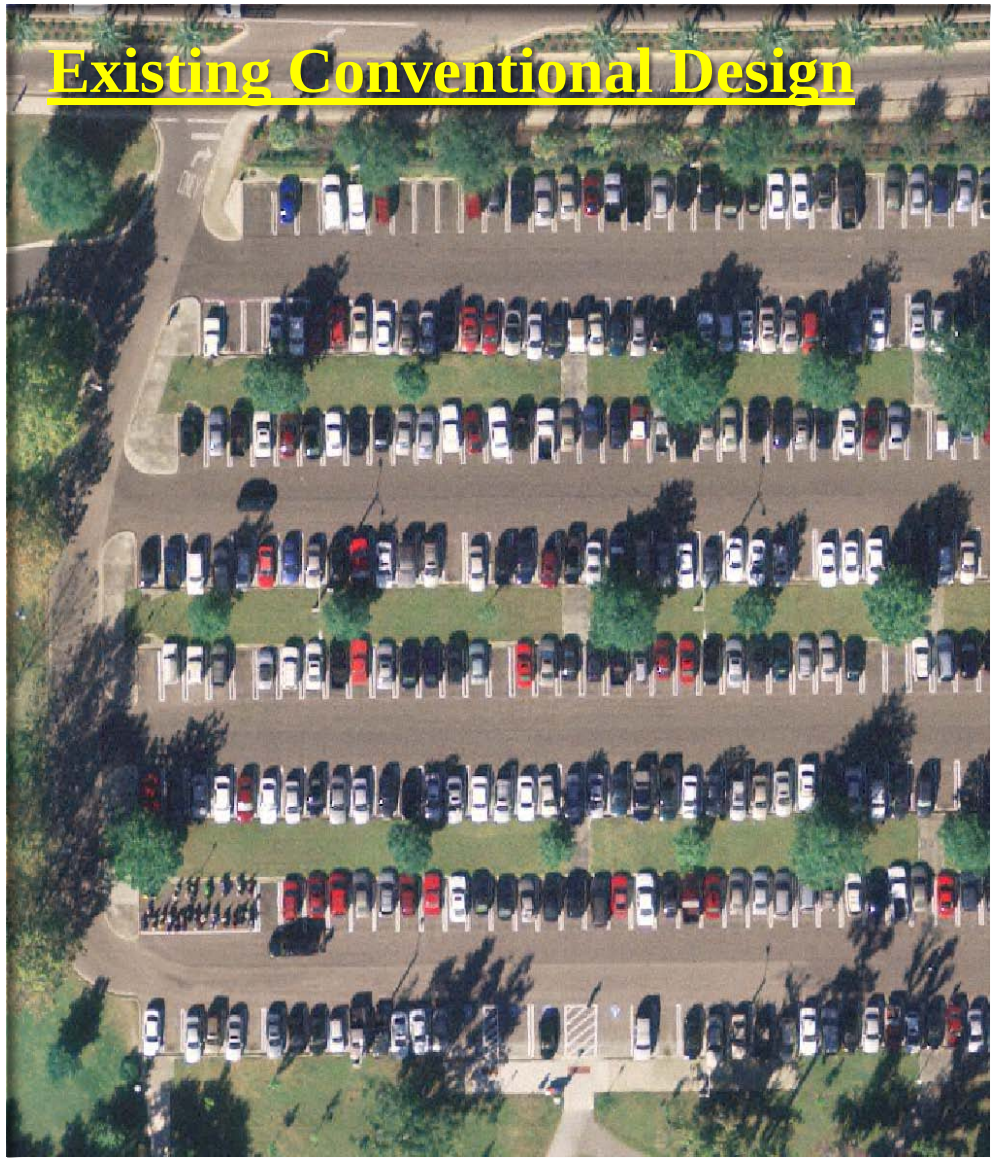






FDEP Numeric Nutrient Criteria Plan, 2009
Nutrient Ecoregion XII Southern Coastal Plain

Existing Catchment Conditions (Post-Development)

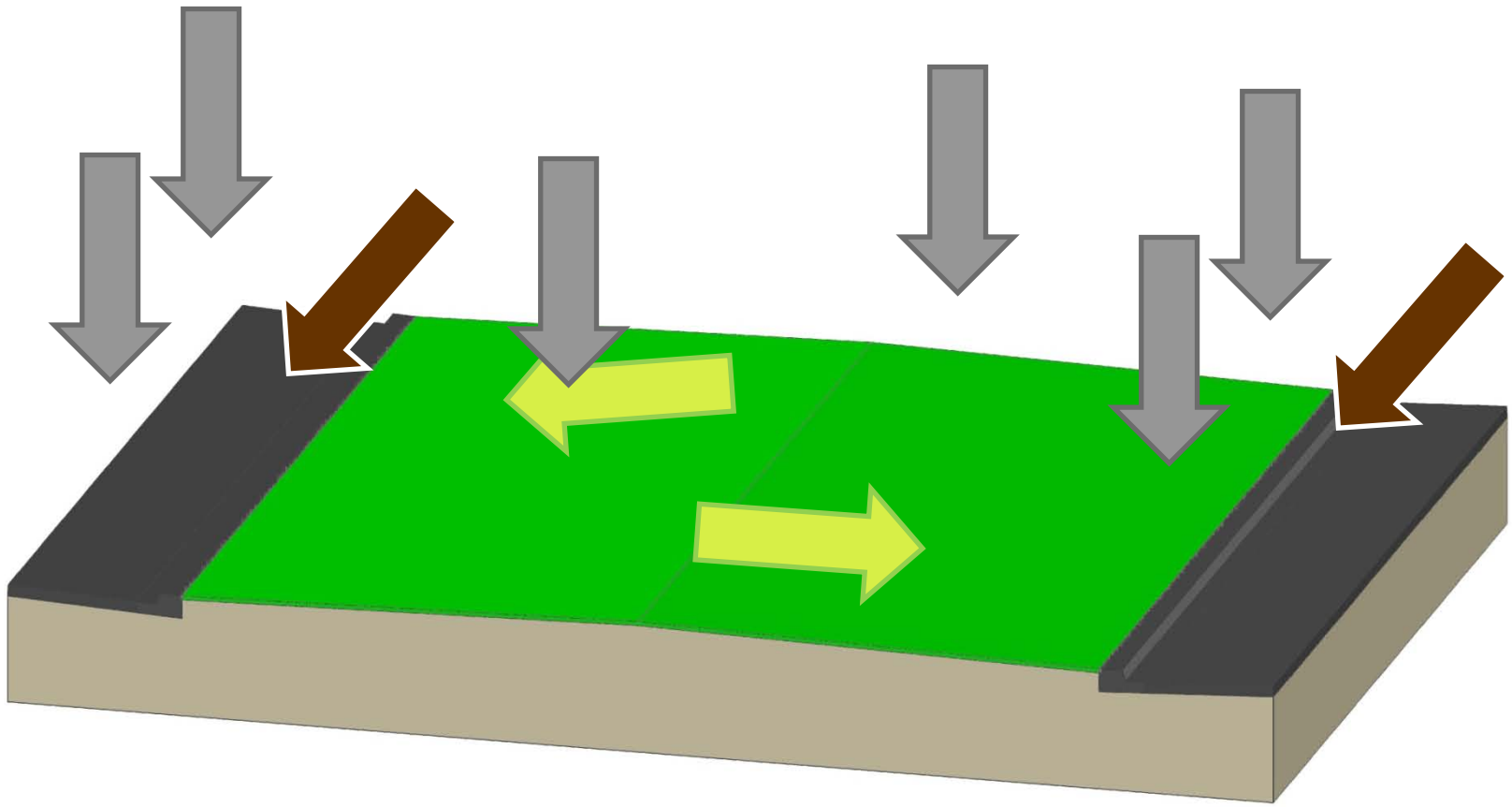


Catchment Area	3.23 acres
Total % Pavement	75.61%
Total % Vegetated	24.39%

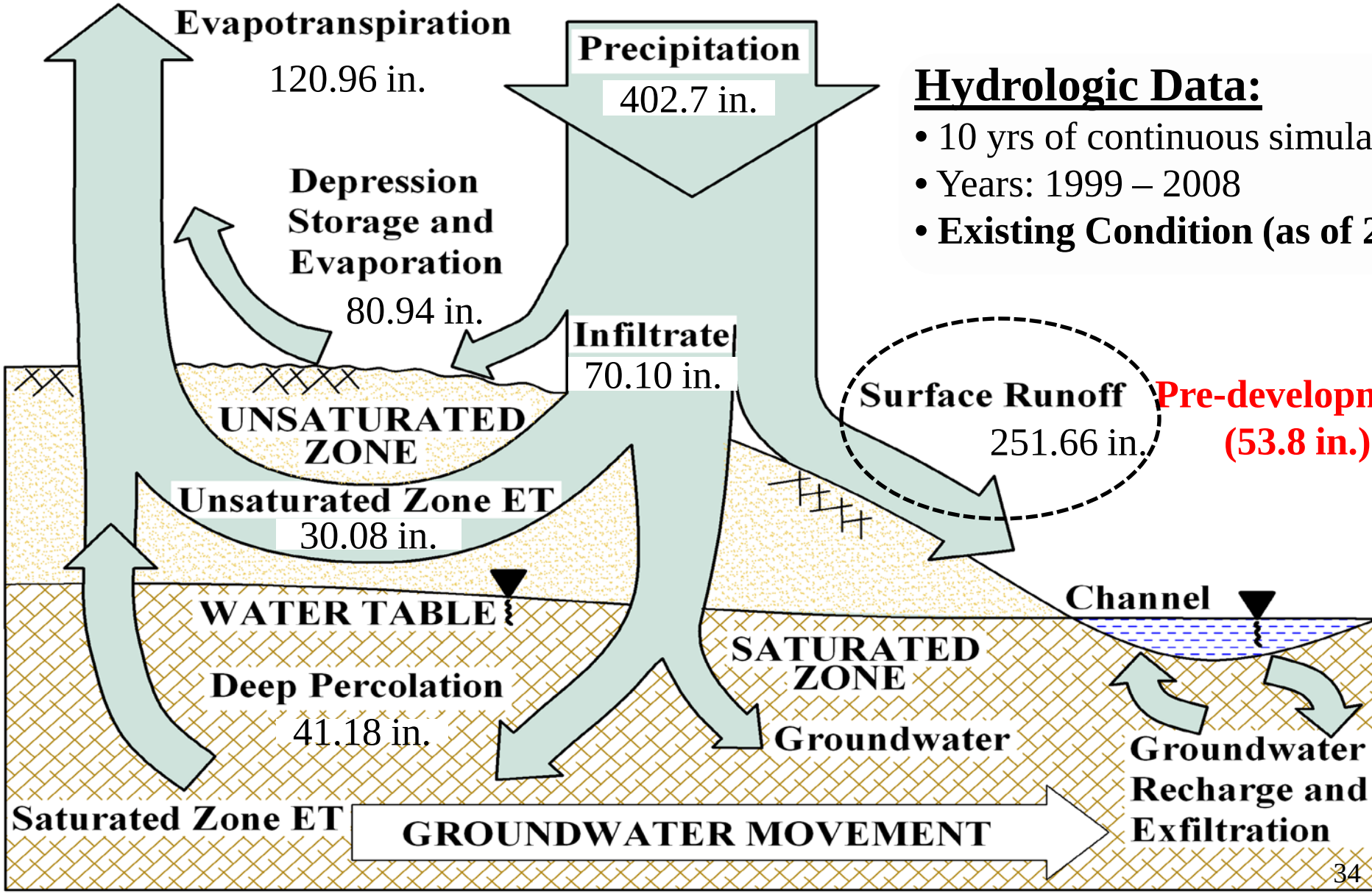
Problem: Existing condition of raised vegetated islands that drain to impervious asphalt

Hypothesis: *For given catchment constraints, we can quantitatively demonstrate PM and solute control with green infrastructure and LID.*

Existing Post-Development Condition



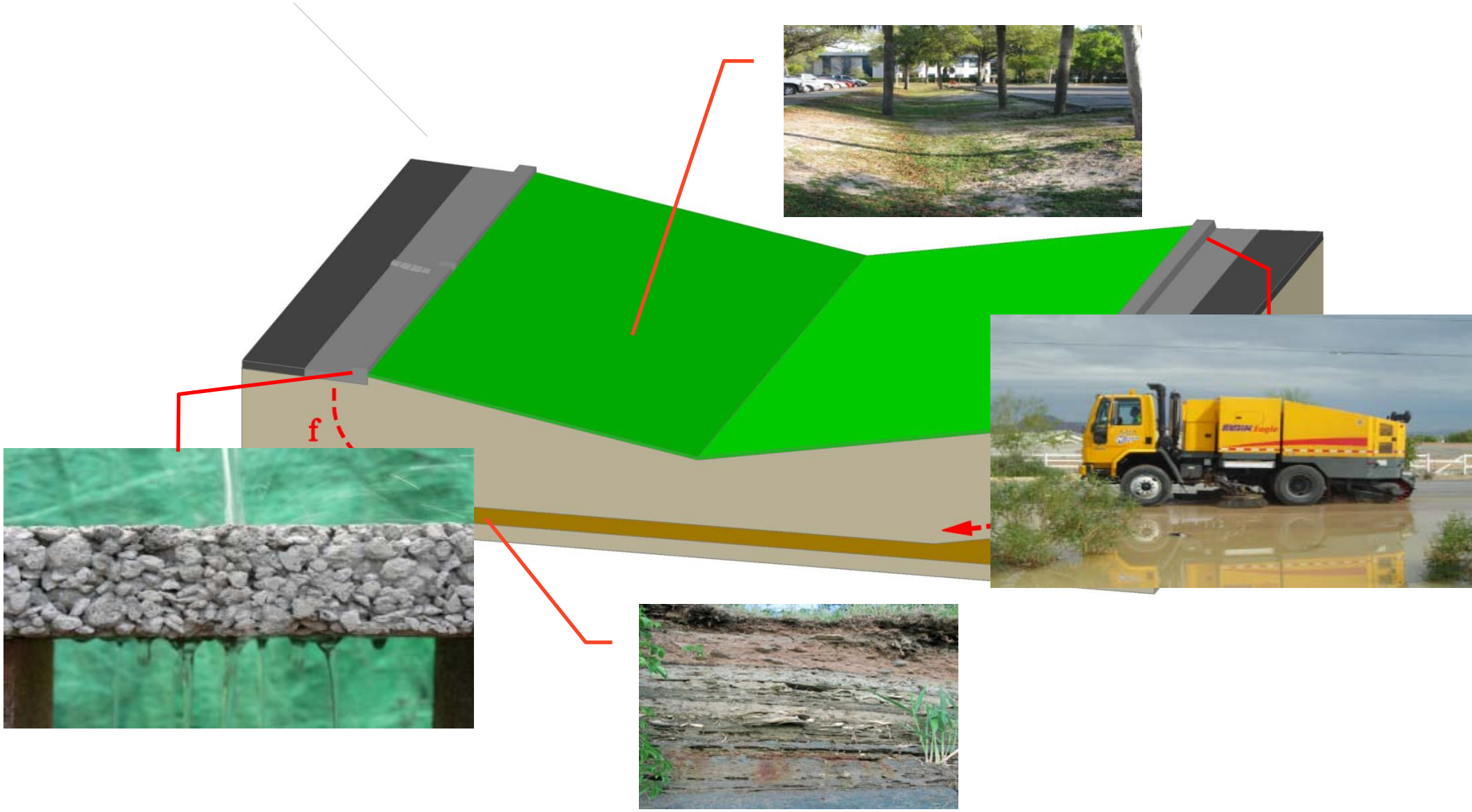
Catchment Post-Development Hydrologic Cycle



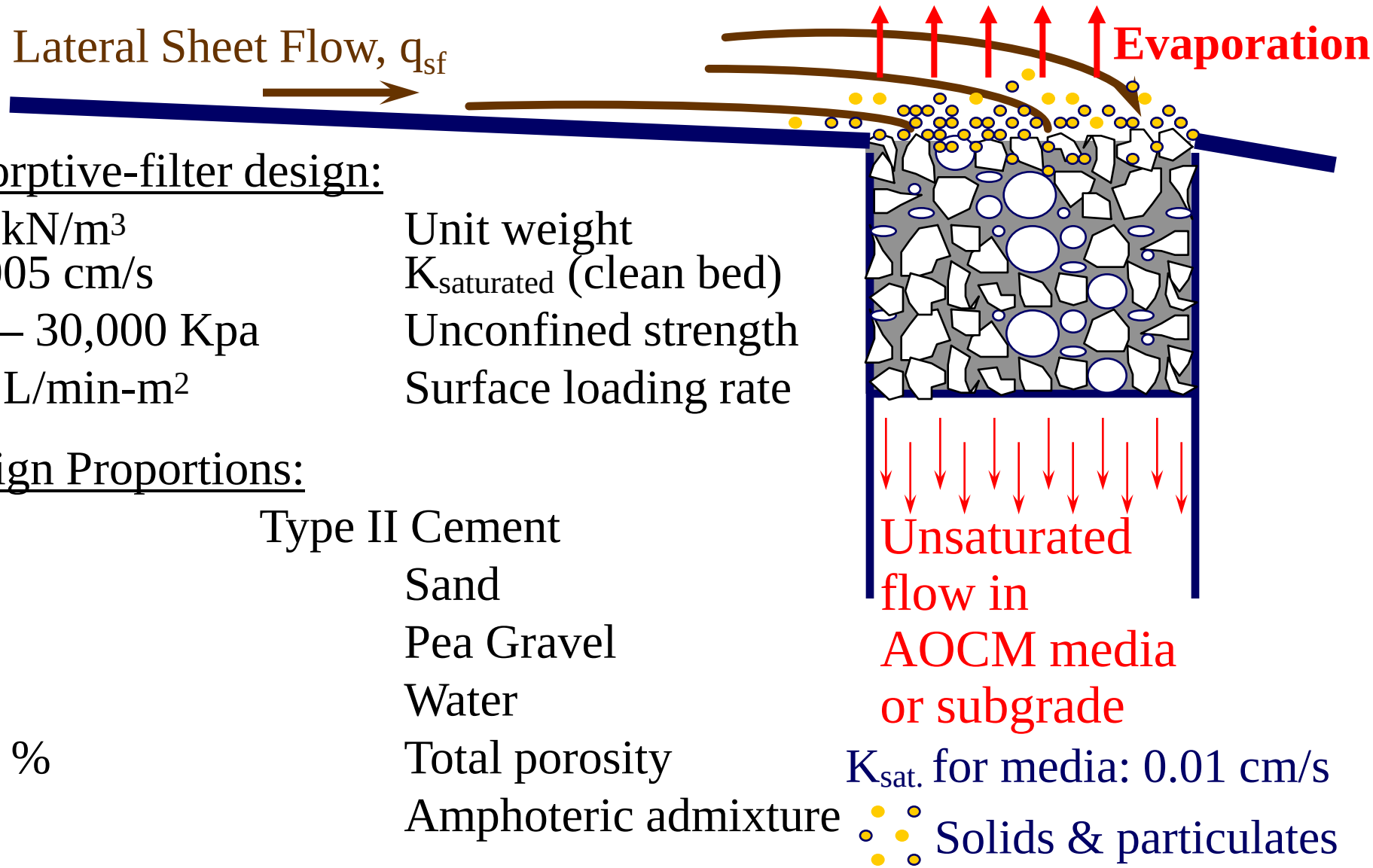
Hydrologic Data:

- 10 yrs of continuous simulation
- Years: 1999 – 2008
- **Existing Condition (as of 2009)**

Green Infrastructure Option (Permeable Pavement + BAR)



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



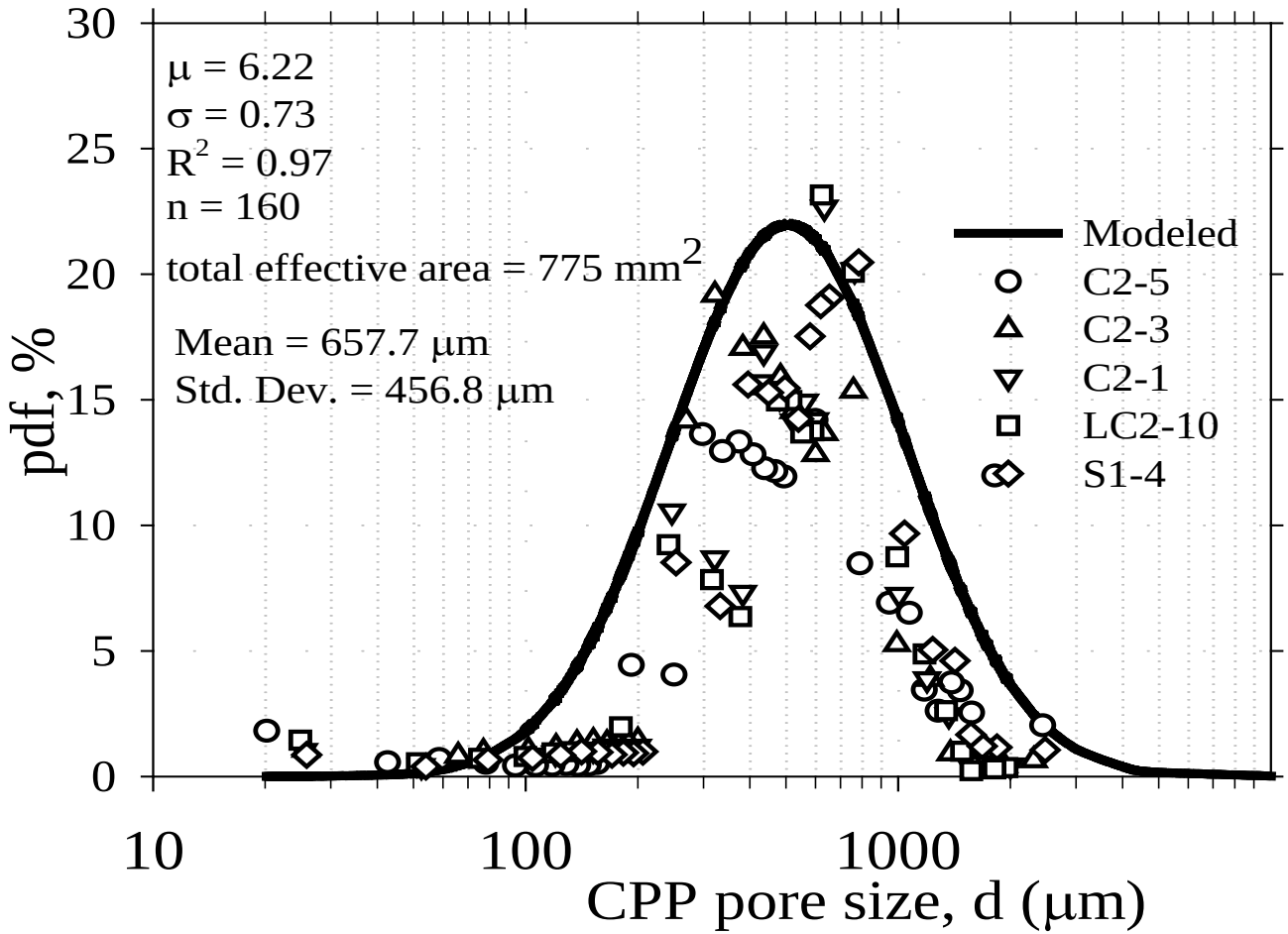
CPP adsorptive-filter design:

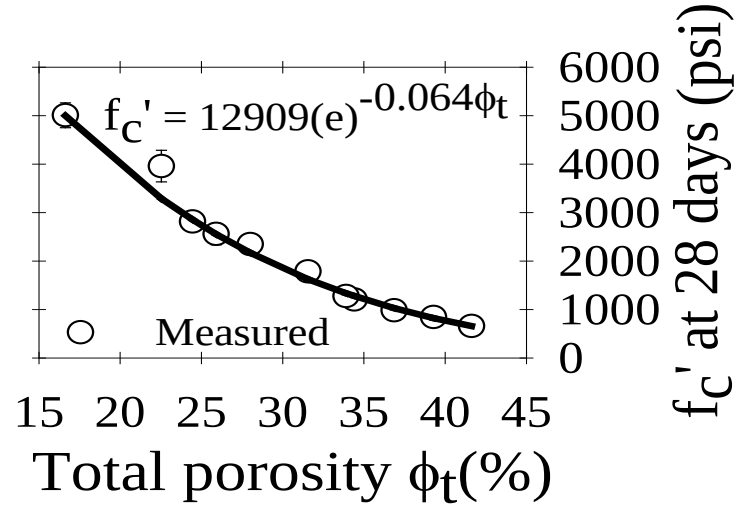
- 11 - 15 kN/m³ — Unit weight
- 0.1- 0.005 cm/s — $K_{saturated}$ (clean bed)
- 25,000 – 30,000 Kpa — Unconfined strength
- 20 - 50 L/min-m² — Surface loading rate

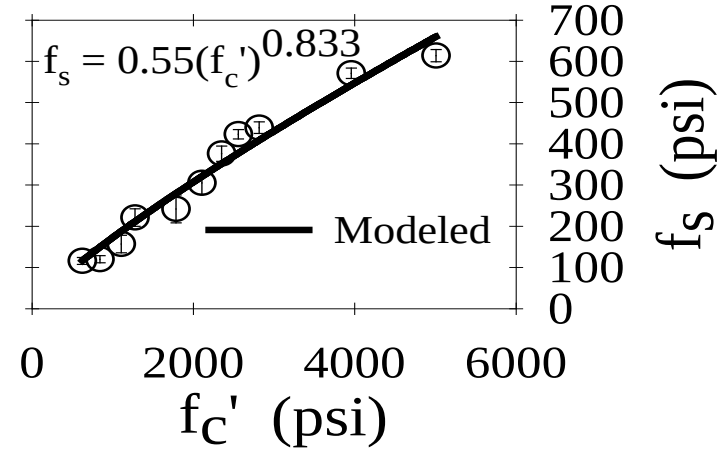
Mix Design Proportions:

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

CPP Pore and Structural Properties (function of mix design)







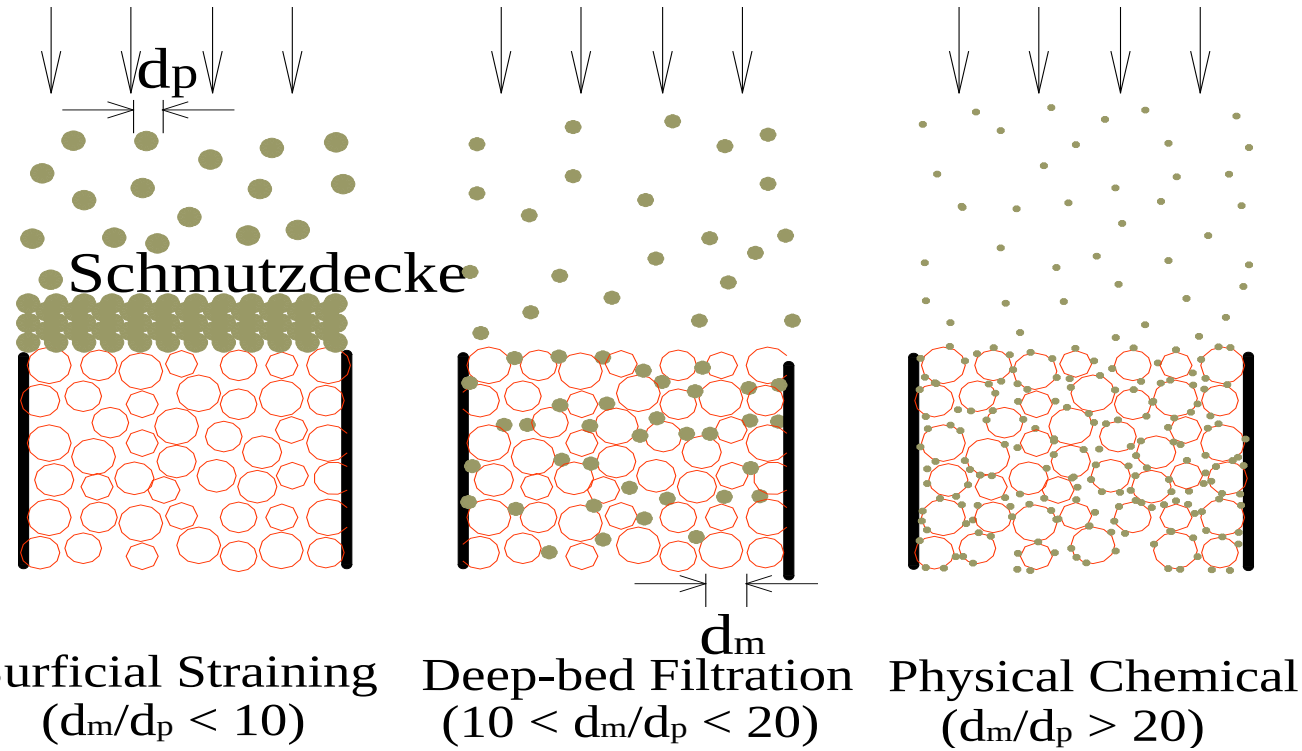
f_c': unconfined compressive strength

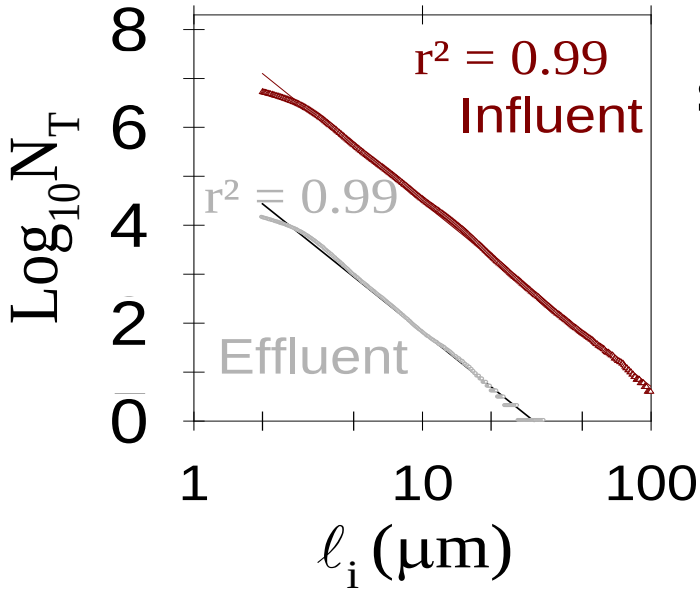
f_s: splitting tensile strength

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

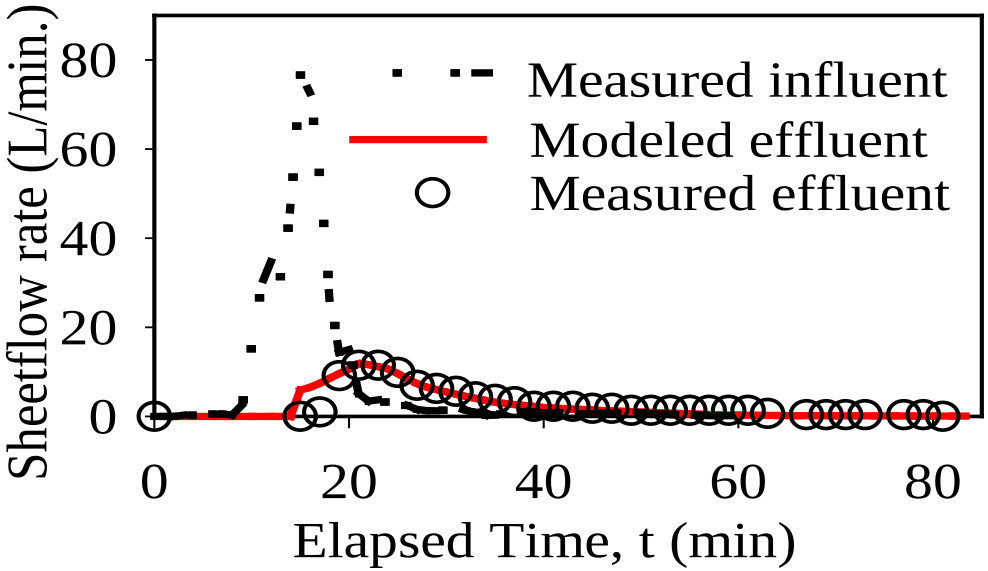


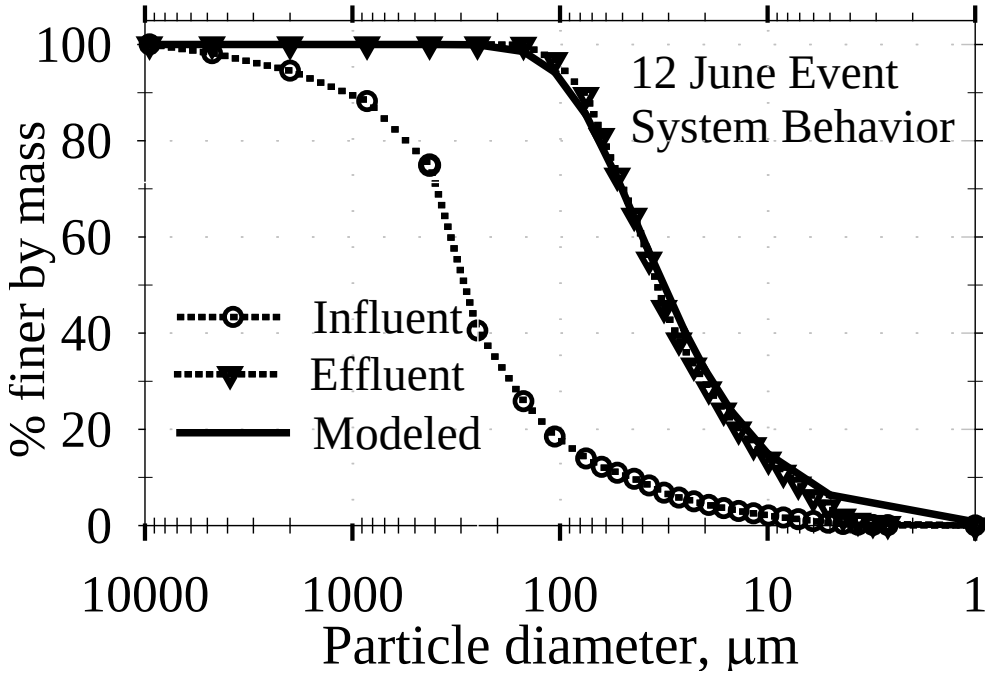


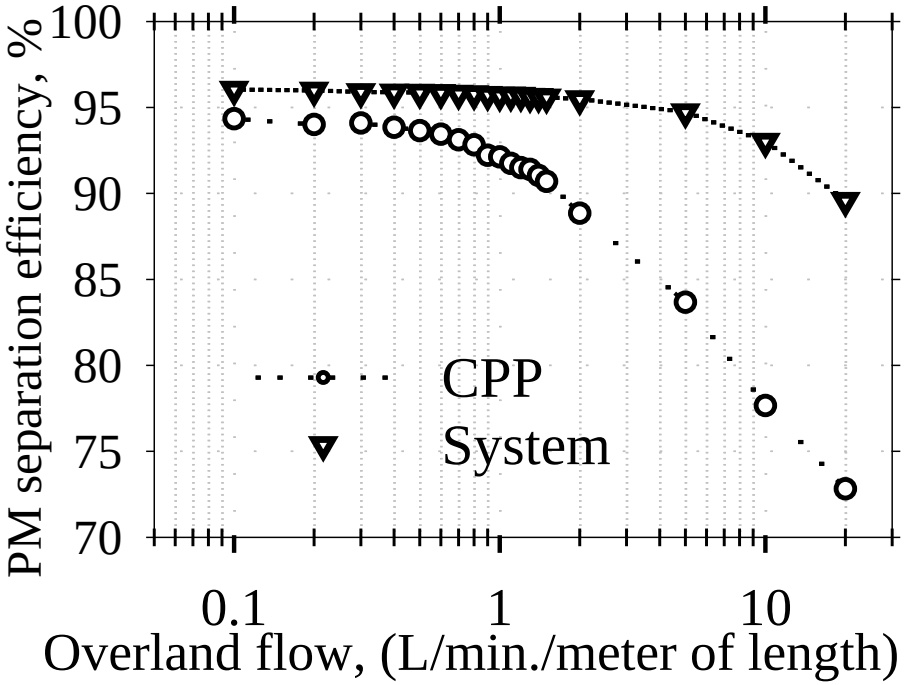
The power law function uses cumulative particle number density (PND) of all particles larger than the reference value R (i.e. 1 μm).

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

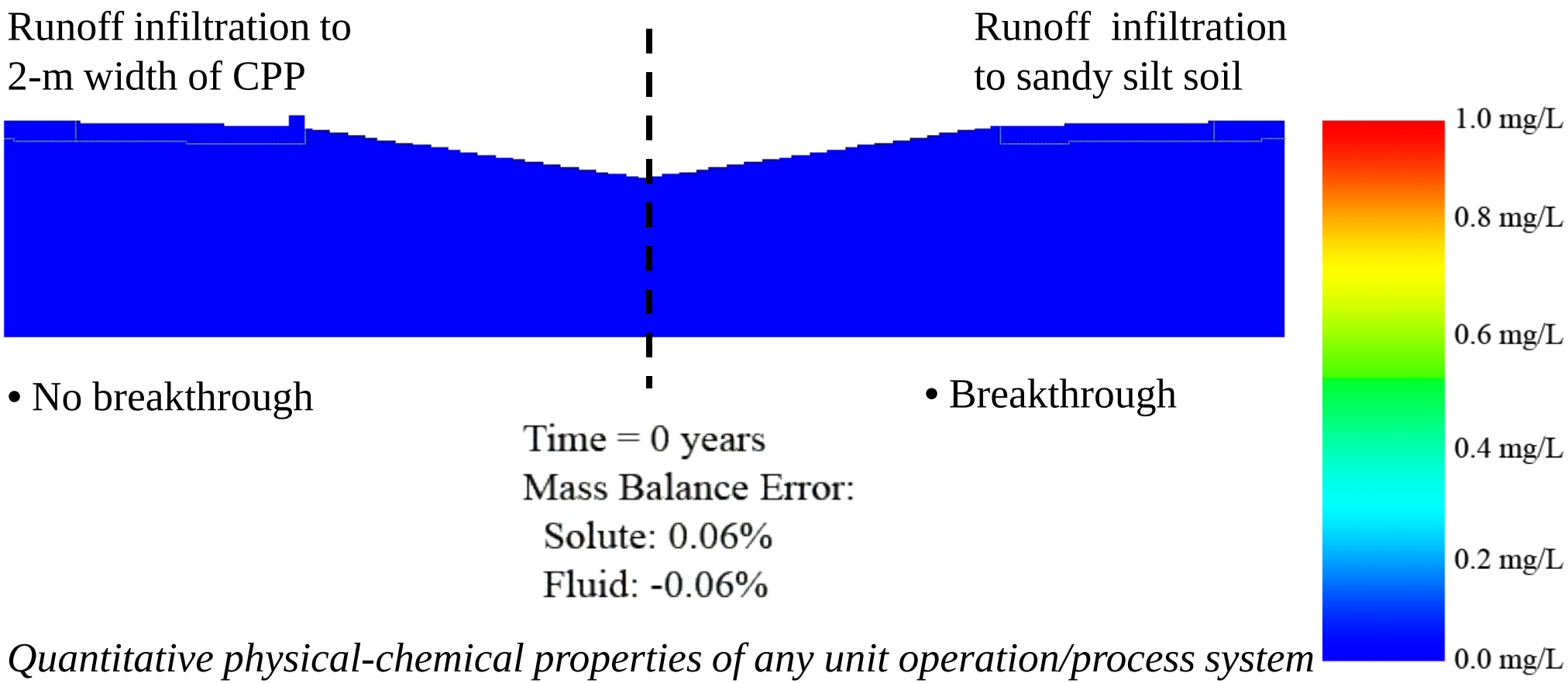
Event- and Flow-based PM Separation by an Engineered Infiltration System: Permeable Pavement with Filtration Media Subgrade





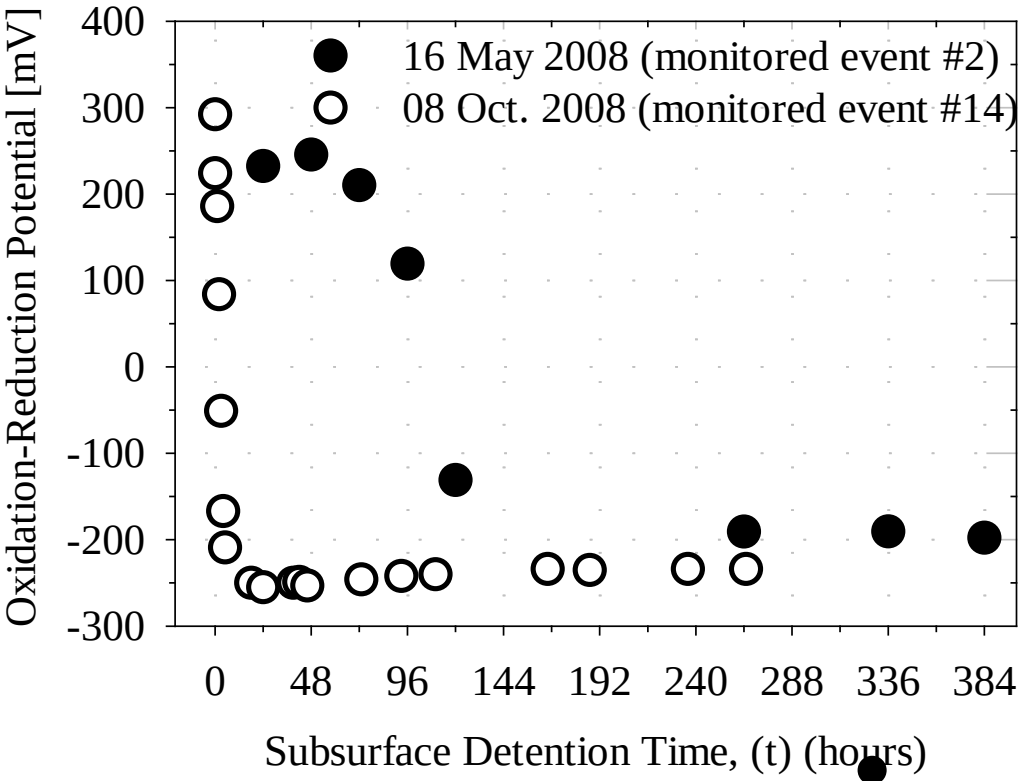


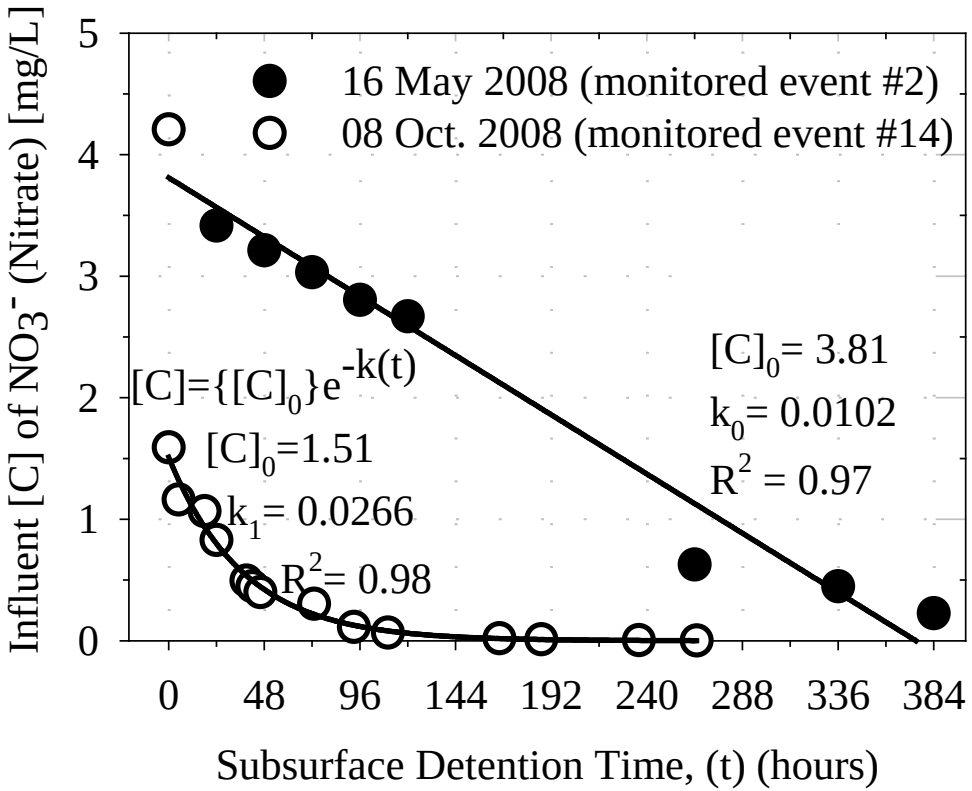
Sustainability: Monitoring, Modeling, Maintenance
(Phosphorus Adsorption Example: CPP vs. sandy silt soil)



- *Quantitative physical-chemical properties of any unit operation/process system (engineered or natural) are required with monitoring, modeling and maintenance.*
- *Qualitative approaches to decentralized controls will not permit sustainability.*

Redox as a f(runoff storage) in below-grade BMP vault/sump
(BMPs contain high microbial activity for electron transfers)





Adsorptive-Filtration Media for Phosphorus (as TDP)

Problem Statement:

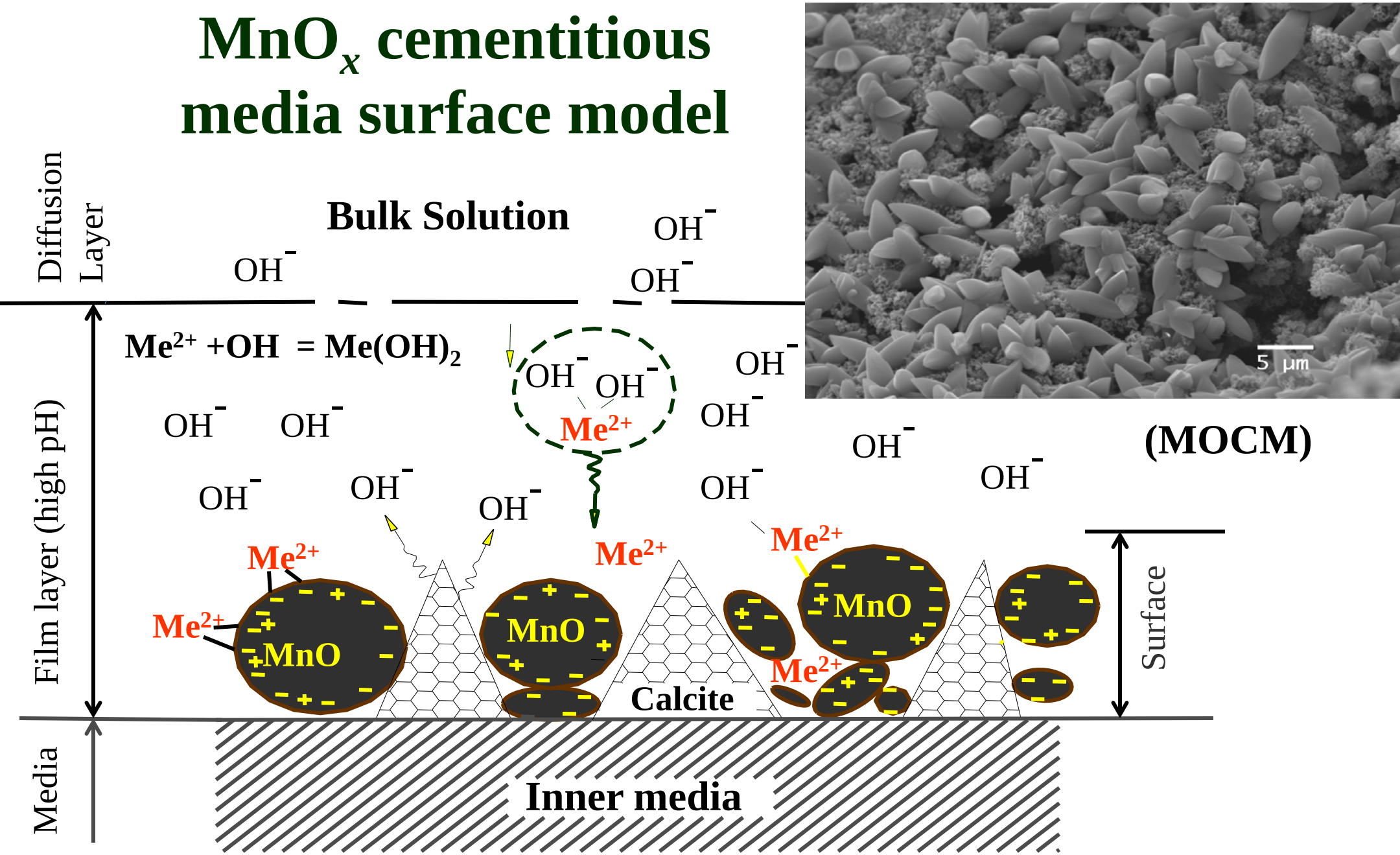
1. Most media currently applied to rainfall-runoff treatment is not engineered (sand, perlite, zeolites, GAC …) for runoff solute mass transfer;
2. Most media evaluations utilize surrogate aqueous matrices in comparison to a rainfall-runoff matrix.

Media Matrix:

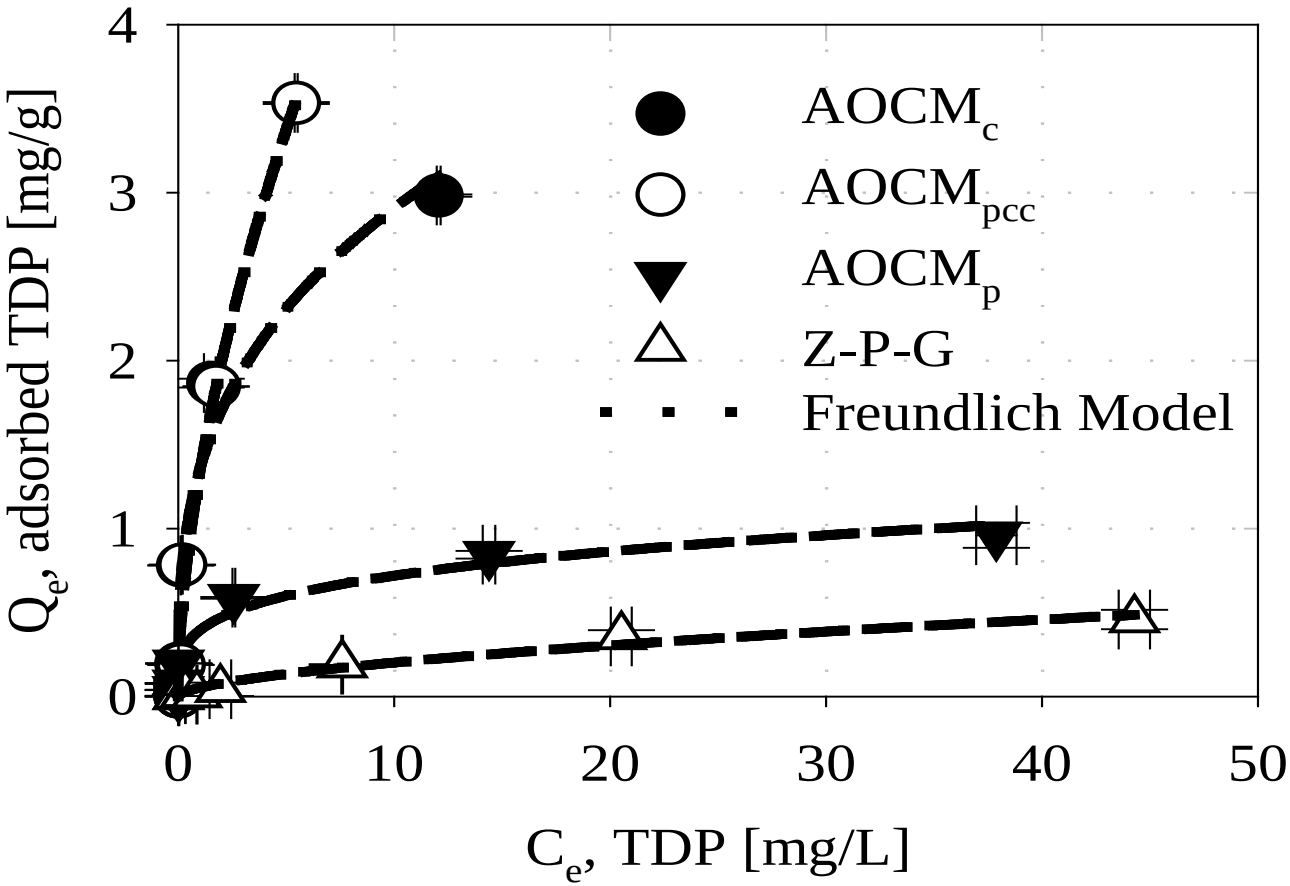
AOCM	Reactive Aluminum Oxide
	$AOCM_c$ (clay substrate)
	$AOCM_p$ (pumice substrate)
	$AOCM_{pcc}$ (concrete substrate)
Z-P-G	mixture of Zeolite, Perlite and GAC

- (1) Equilibria, (2) kinetics, (3) breakthrough parameterization required for models as illustrated in the next several slides

MnO_x cementitious media surface model



TDP Equilibria (Freundlich Isotherm)



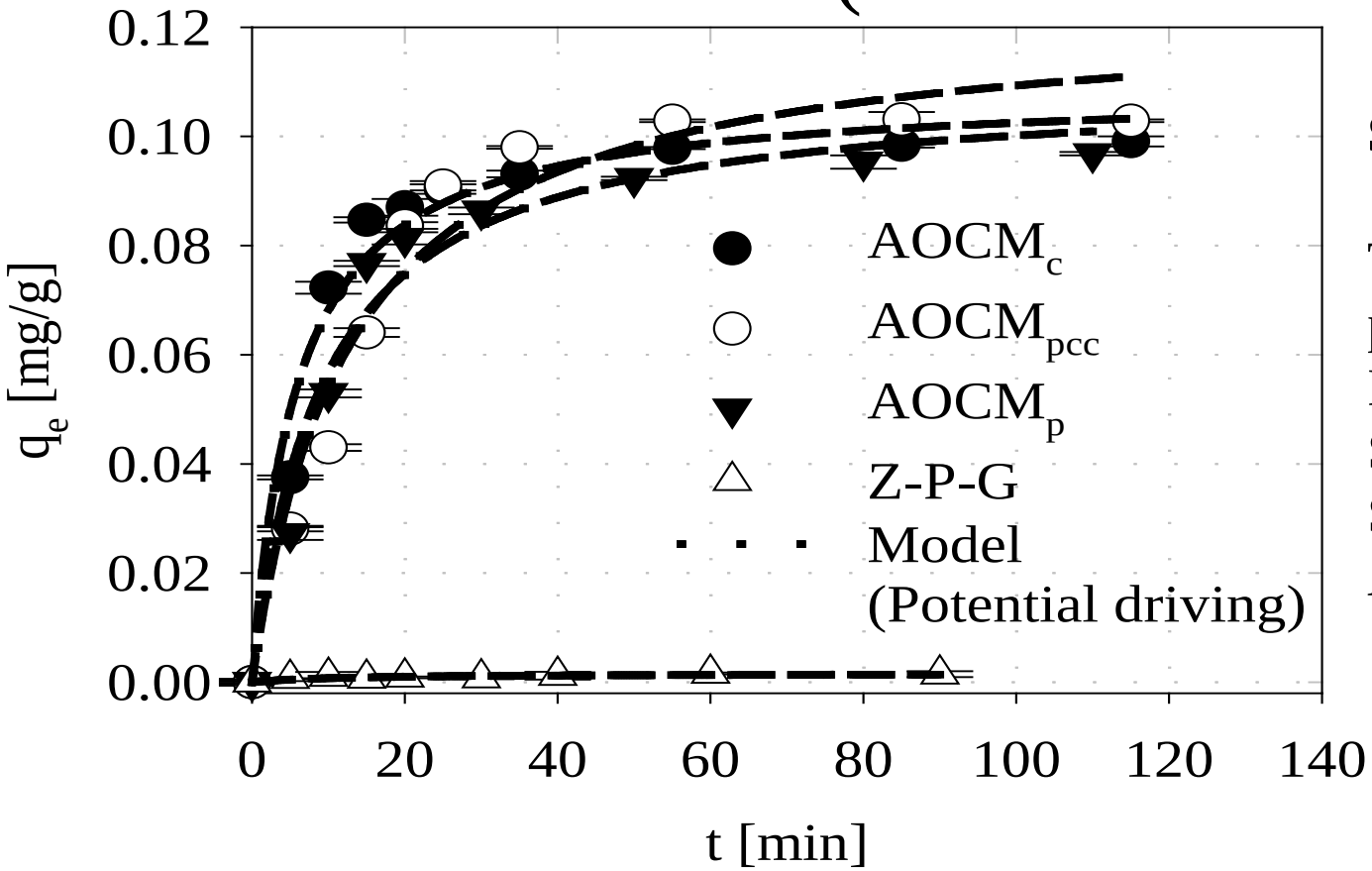
Surrogate Aqueous Matrix:

Temperature: 20 °C;
TDP: 0.05 ~ 50 mg/L (n =7);
pH: 7;
Sorbent/Solution: 0.5 g/ 40 mL;
Ionic strength: 0.01M
Aqueous matrix: D.I.
Equilibria is dependent on concentration illustrating the invalidity of the P-index

$$q = \int_0^\infty \frac{C}{b' + C} N(b') db' \qquad N(b') = A'(b')^{\frac{1}{p}-1}$$

$$q = K_F C^n$$

TDP Kinetics (Potential Driving Model)



Surrogate Aqueous Matrix:

TDP: 1.0 mg/L;
pH: 7;
Ionic strength: 0.01M;
Sorbent/Solution: 20 g/ 2 L;
SLR: 40 L/min·m^2 ;
Aqueous matrix: D.I.

$$\frac{dC_t}{dt} = k(q_e - q_t)(C_t - C_e)$$

$$\frac{t}{C_0 - C_t} = \frac{t}{C_0 - C_e} + \frac{a}{k(C_0 - C_e)^2}$$

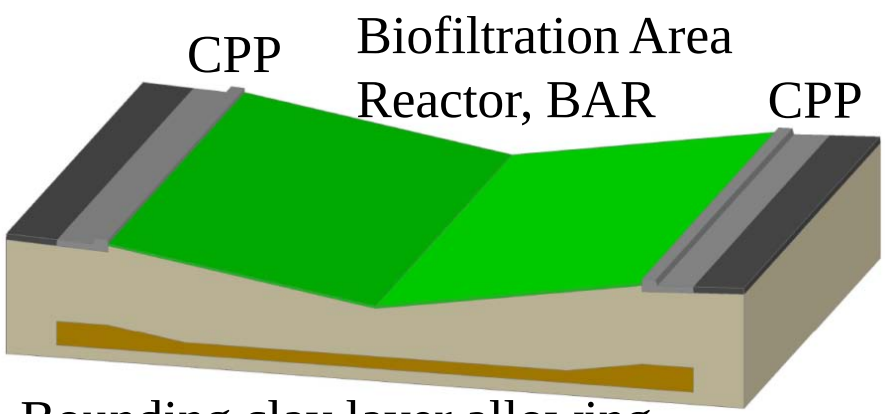
Infrastructure and Design Solution: No Loss of Function

Design: 2 m of CPP (Al admix) with BAR (10 yrs of loads)

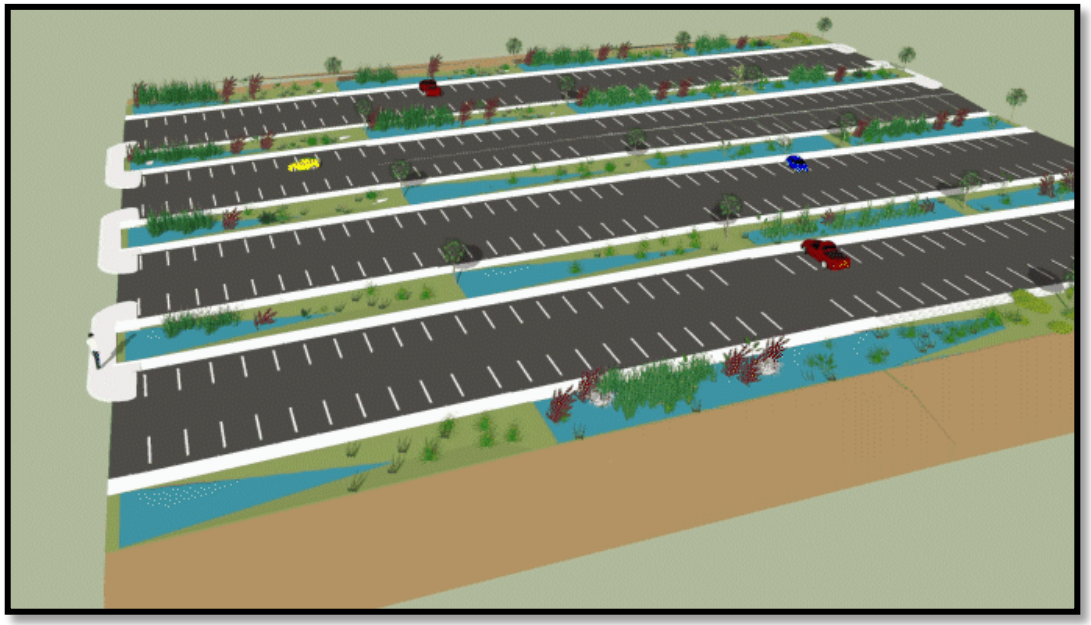
Condition	Design Option	Runoff (inches)	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine		53.8	7.78	301.61	296.26
Current	1	251.66	243.05	1065.83	61143.81
6 ft LIR + BAR	**3(a)**	**53.63**	**2.17**	**133.18**	**239.85**

Compared to conventional Florida BMPs:

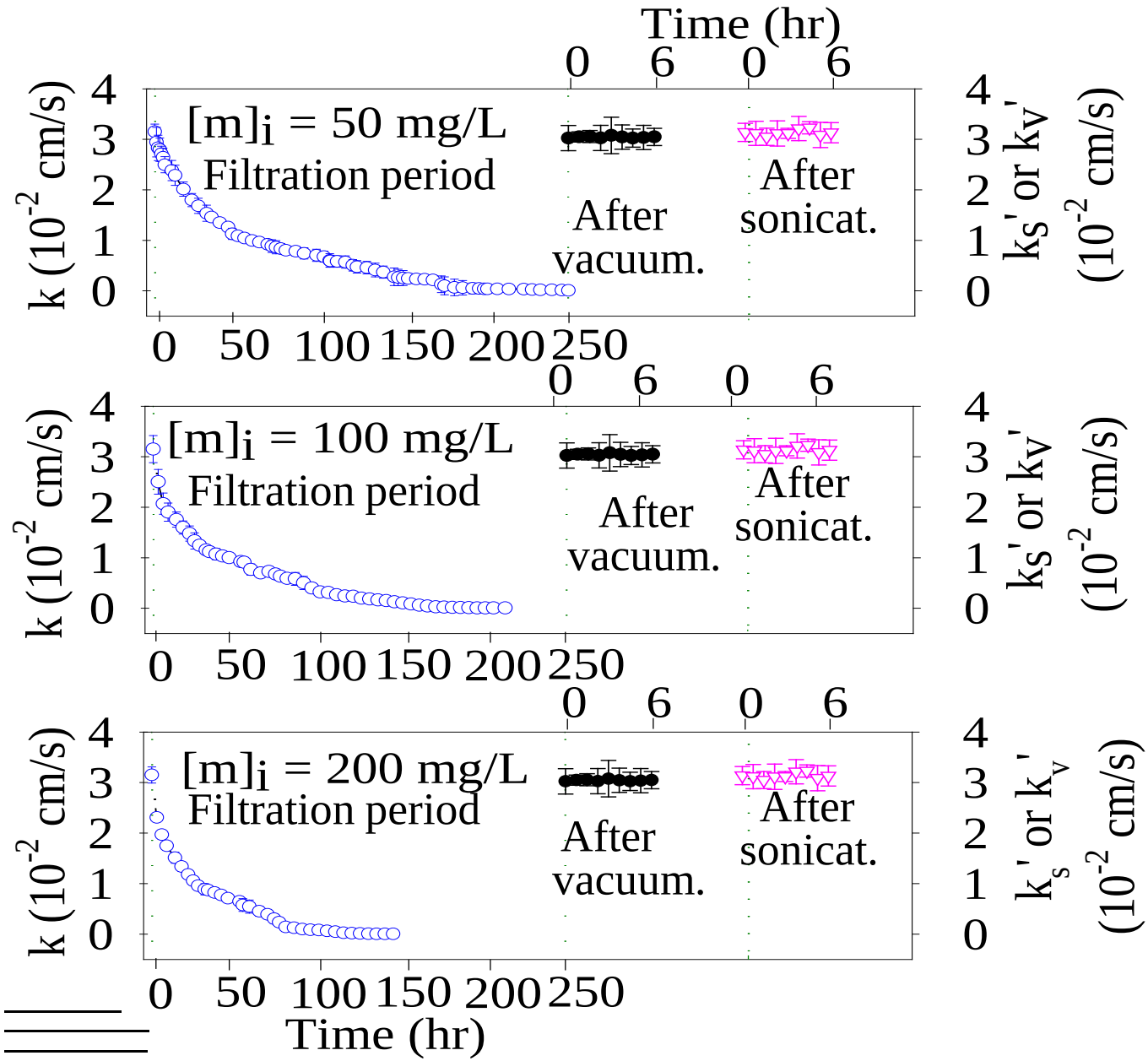
- ***13% more economical for P treatment***
- ***15% more economical for N treatment***



Bounding clay layer allowing storage and denitrification



Restoration of CPP hydraulic conductivity



After vacuuming

k_v/k_0 = 97.3%

After sonicating

k_s/k_0 = 99.6%

After vacuuming

k_v/k_0 = 96.1%

After sonicating

k_s/k_0 = 99.8%

After vacuuming

k_v/k_0 = 96.9%

After sonicating

k_s/k_0 = 99.3%

Pavement Cleaning (Source Area Control)

It is always more economical to recover street sweeping residuals in the dry phase instead of separation of such residuals and pollutants in runoff by structural "BMPs". Source area control critical for LID.

- **Arguably, the most logical and cost-effective pollutant load recovery tool of a municipality**
- HOWEVER, not all pavement cleaners or street sweepers are created equal
- This is significant mis-application of street sweeper types for given conditions
- How (speed, frequency …) a street sweeper is operated is also important
- New generation, high efficiency street sweeper are significantly more effective than older systems

Urban Water Cycle Management Needs

1. The urban water cycle including quantitative control strategies is not sustainable without decentralized hydrologic restoration, source control and frequent maintenance (no different than POTWs)

2. Monitoring, analysis and models that accurately represent urban water complexity for transport, treatment, reuse (especially with wastewater superimposed) and fate of “chemicals” in engineered and natural systems.

3. Models and monitoring for control strategies that incorporate fundamental mechanistic and probabilistic phenomena in contrast to examining controls as “black boxes” using indices, or resorting to modeling hydro-fantasy.

4. Frequent quantitative maintenance for residuals/toxics. Control strategies are short-term repositories at best, the urban water cycle is much longer.

5. Acceptance of new knowledge, methods and rigor – why are we afraid ?

6. Regular operation and maintenance requirements for all control strategies.