PM and Nutrient Load Recovery, Credits and Costs for MS4 Maintenance Activities

University of Florida
Engineering School of Sustainable Infrastructure and Environment (ESSIE)
John Sansalone (jsansal@ufl.edu)

Project Objectives and Outcomes

The primary project objective is a ***Florida-based*** "yardstick" or metrics allowing an MS4 to quantify nutrient (N and P) loads through ***separation*** then ***recovery*** of ***particulate matter*** (PM) for common urban hydrologic functional units (HFUs):

1. Pavement systems cleaning (pavement street sweeping),

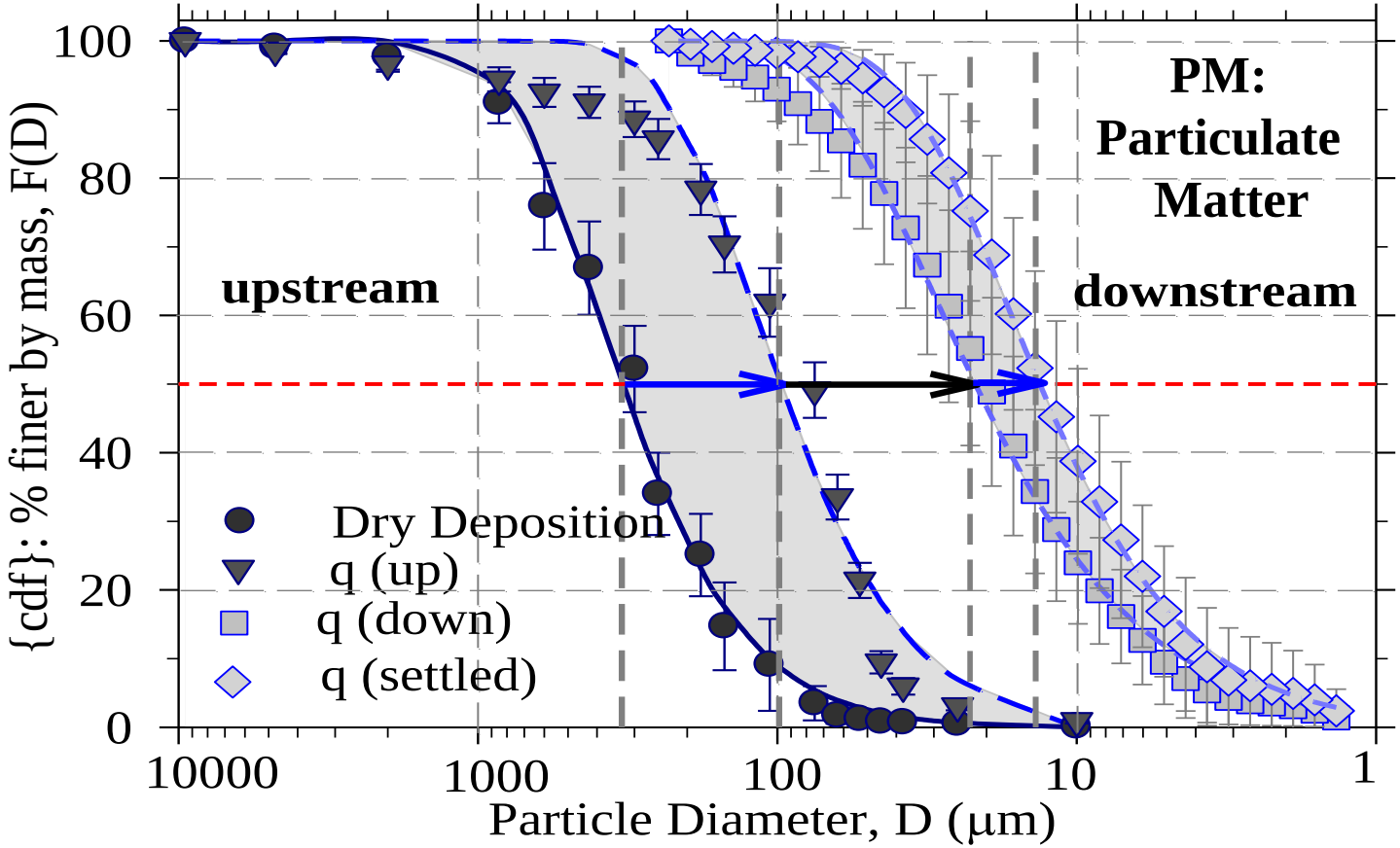
2. Catch basins (inlets),

3. "BMP " (the most utilized and cleaned BMPs for an MS4)

- Outcomes are Florida-based metrics (a statistic of the resulting probability distributions: i.e. median) based on 14 MS4s
- Outcomes allow ***dry-equiv.*** load of PM ***separated*** (i.e. a BMP) and then ***recovered*** by maintenance to be converted to N, P loads
- Outcomes quantified by land use or independent of land use
- Outcomes quantified outside or inside wastewater reuse areas

This study focuses on PM-phase N and P loads

(PM-phase N and P control directly impacts aqueous phase N and P)



PSD gamma model

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

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

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

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

BMP: Clarifier with 1 hr. of quiescent settling

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)

PSD of PM	DD Pavement ***Deposition***	q (up) CB or inlet ***Runoff***	q (down) BMP influent ***Runoff***	q (settled) BMP effluent ***Runoff***
D_{50m}	331 μm	99 μm	23 μm	14 μm

Review of Project Methodology

Participating Florida MS4s

1. Gainesville (GNV) ***[IN + OUT]***
2. Hillsborough County (HC)
3. Jacksonville (JAX)
4. Lee County (LC)
5. Miami-Dade County (MDC)
6. Orange County (OC)
7. Orlando (MCO)
8. Pensacola/Escambia County (PEC)
9. Sarasota County (SAC) ***[IN + OUT]***
10. Seminole County (SEC)
11. St. Petersburg/Pinellas County (SPP)
12. Stuart (ST)
13. Tallahassee (TAL)
14. Tampa (TPH) ***[IN + OUT]***

MCO-CB-R-OUT-2

TPH-BMP-C-OUT-1

HC-CB-R-OUT-2

MDC-BMP-C-OUT-9

JAX-SS-R-OUT-1

ST-BMP-C-OUT-1

Project Process Flow

Sampling Process → **UF Lab Analysis** → **Future Application**

1. The objective is to develop a ‘yardstick’ to quantify the nutrient load recovered through regular maintenance of BMPs, CBs and pavements (street sweeping or cleaning).
2. 14 MS4s, each collected 27 samples with detailed field information for every sample.
3. 3 locations each, in 3 land uses – commercial, highway and residential; for the 3 maintenance practices.
4. 3 MS4s also collected 27 samples from within areas with reclaimed wastewater usage, to compare nutrient loads.

Project sampled a diversity of "BMPs"

(Diversity provided a robust FL-based metric and valuable debate)

BMP Classification	IN	OUT
Pond (Basin)	10	11
Baffle Box	1	27
Swale, Ditch or Sediment Accumulation	11	35
Manufactured BMP (i.e. hydrodynamic separators)	5	28
Drainage or Sump Box (i.e. "French drains")	0	23
Total	**27**	**124**

Cleaning, Sampling, Packing, Shipping, Receiving

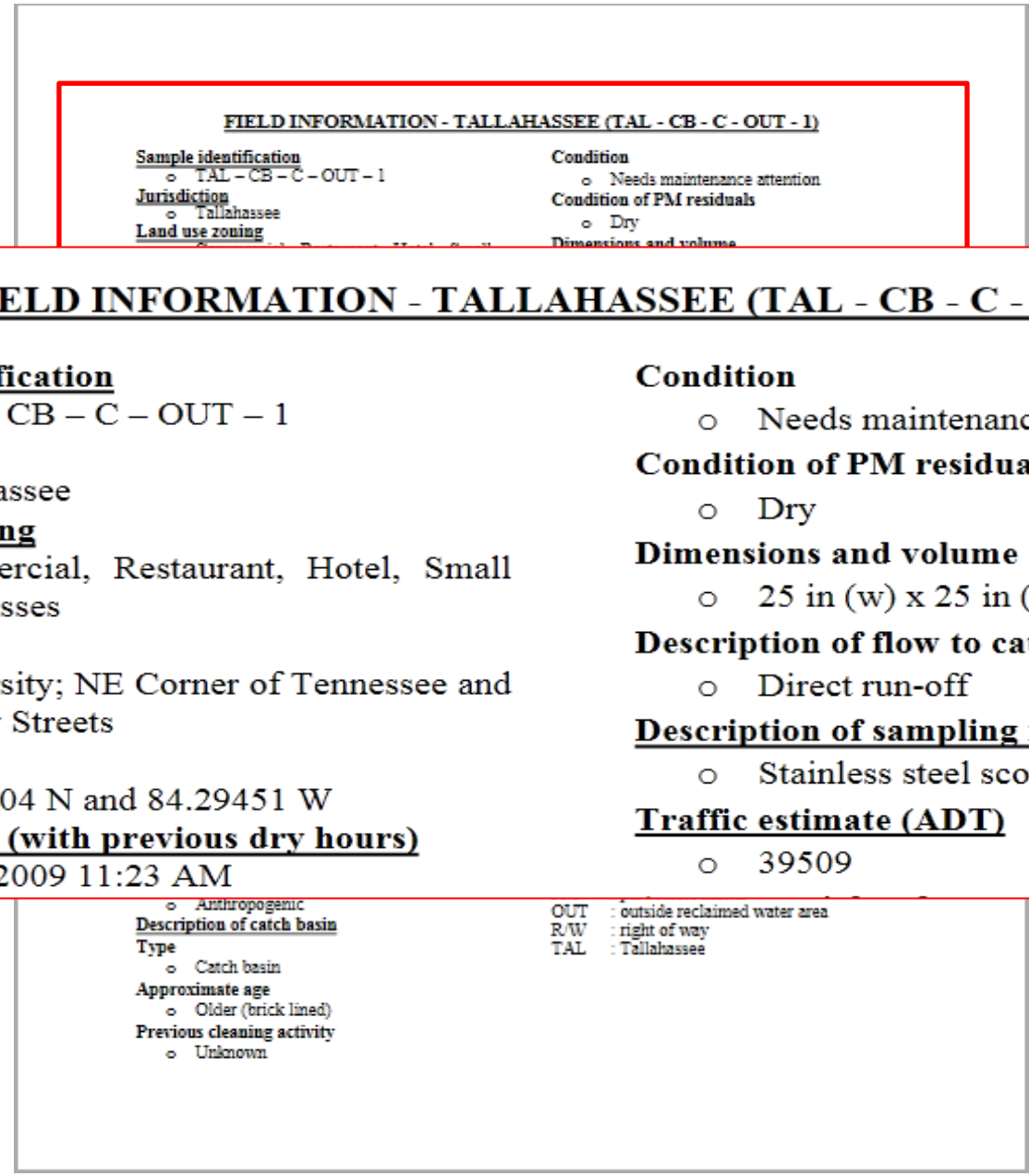
1. QAPP specifies sampling, site information needed
2. Cleaning of equipment is very important to prevent cross contamination
3. Samples have to be collected in 2 L bottles
4. Samples have to be stored on ice immediately after collection and delivered or shipped to UF within 24 hours along with detailed chain of custody (COC)
5. Samples need to have considerable amount of particulate matter (PM)
6. Study utilized dry/moist samples ***(representative moisture content (MC) is a simple and critical requirement for credits)***

Sample Identification:

City/County Code – HFU – Land use – In/Out of reclaimed water usage area – Dry/Moist/Wet – Sample Location number

i.e. GNV – SS – H – IN – D – 1

Collection of Field Information: 1 Tallahassee Sample



FIELD INFORMATION - TALLAHASSEE (TAL - CB - C - OUT - 1)

Sample identification
- TAL – CB – C – OUT – 1

Jurisdiction
- Tallahassee

Land use zoning
- Commercial, Restaurant, Hotel, Small Businesses

Location
- University; NE Corner of Tennessee and Dewey Streets

Co-ordinates
- 30.44504 N and 84.29451 W

Date and time (with previous dry hours)
- 06/15/2009 11:23 AM

Condition
- Needs maintenance attention

Condition of PM residuals
- Dry

Dimensions and volume
- 25 in (w) x 25 in (d) x 40 in (l)

Description of flow to catch basin
- Direct run-off

Description of sampling method
- Stainless steel scoop

Traffic estimate (ADT)
- 39509

FIELD INFORMATION - TALLAHASSEE (TAL - CB - C - OUT - 1)

Sample identification
- TAL – CB – C – OUT – 1

Jurisdiction
- Tallahassee

Land use zoning

Condition
- Needs maintenance attention

Condition of PM residuals
- Dry

- Anthropogenic

Description of catch basin

Type
- Catch basin

Approximate age
- Older (brick lined)

Previous cleaning activity
- Unknown

OUT : outside reclaimed water area
R/W : right of way
TAL : Tallahassee

Initial Sampling Process

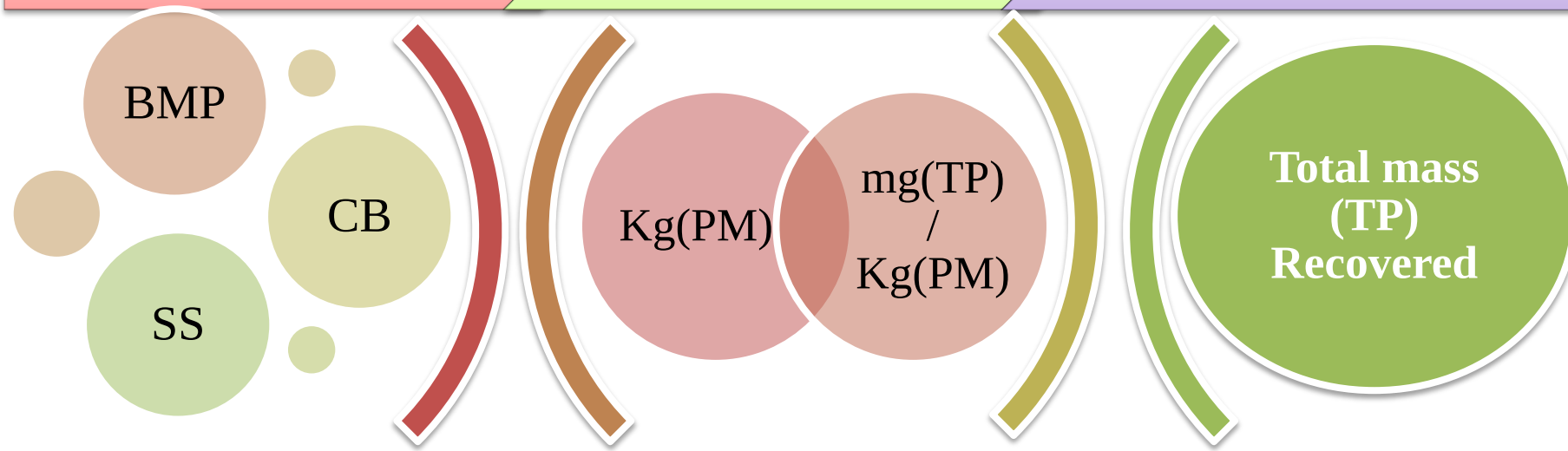
UF Lab Analysis

Future Application

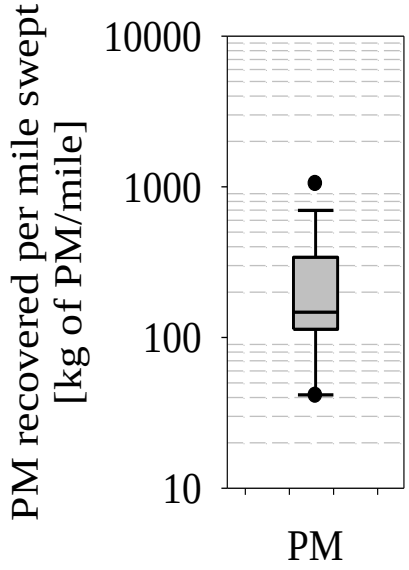
1. U. of Florida analyzed samples for N (as TN) and P (as TP) in NELAC certified labs.
2. TP, TN, and extractable P, moisture content and particle size distribution (PSD) analyses were performed.
3. Based on results, probability distributions (and statistical indices) generated for N, P.
4. Distributions and indices generated on Florida-basis with/without land use, HFU or reclaimed wastewater.

For example, these distribution statistics are in Table 8 of report (and land use results are lumped)

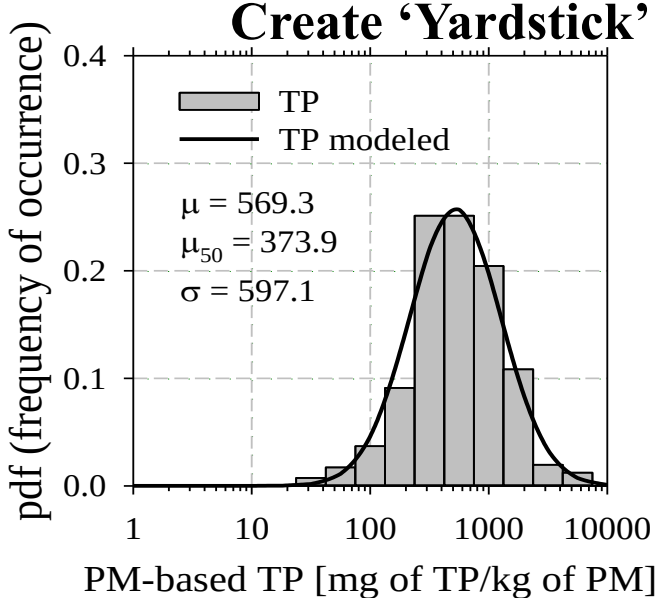
Initial Sampling Process → **UF Lab Analysis** → **Future (NOW) Application**



Measure PM



Create 'Yardstick'



Nutrient (N, P) Credit

Documentation and validation reqr. for dry-equivalent PM recovery

Sample Analysis Flow Chart: MC, dry PM, N, P

40 ~ 60 g
PM analysis

10 g
Moisture content (MC)

Volatile PM
Fraction

50 g
Sub-sample

50 g
Sub-sample

50 g
Sub-sample

5.0 g
TN

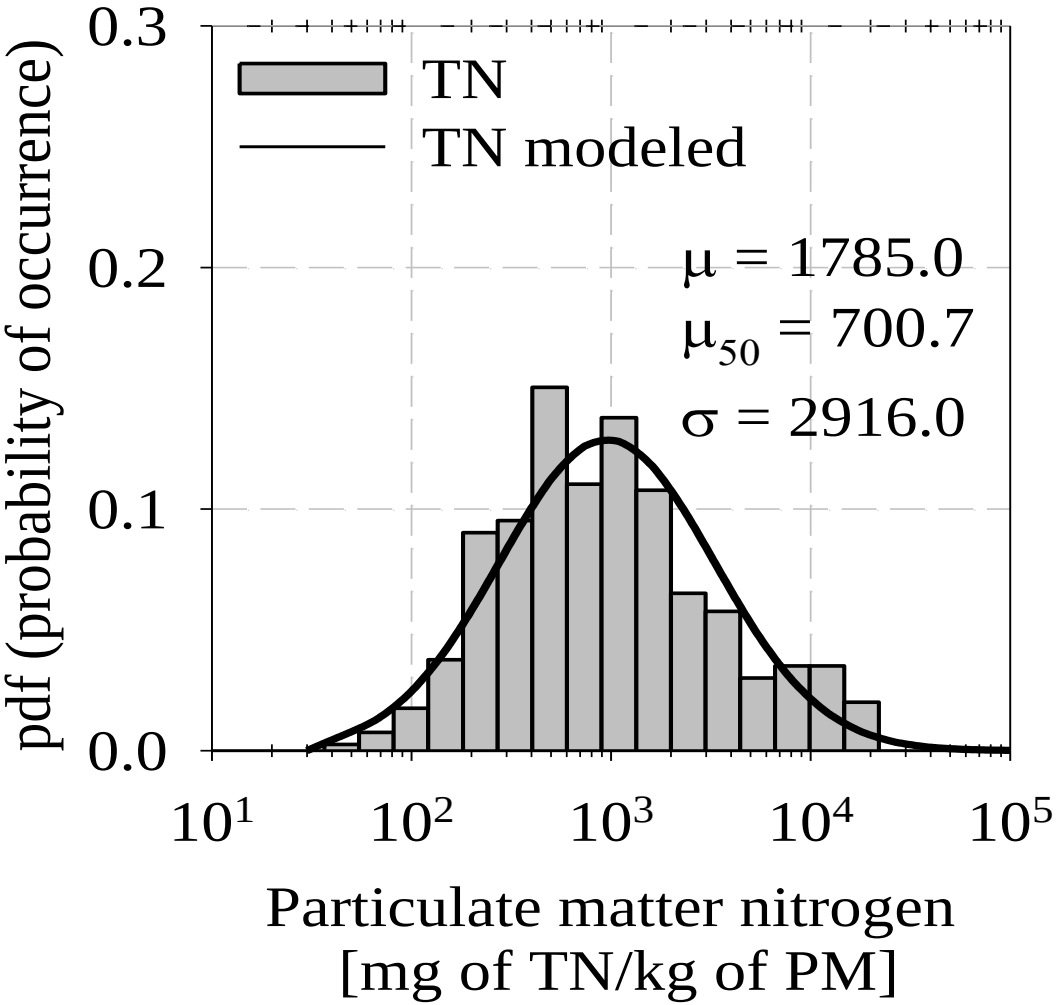
2.5 g
Extractable P

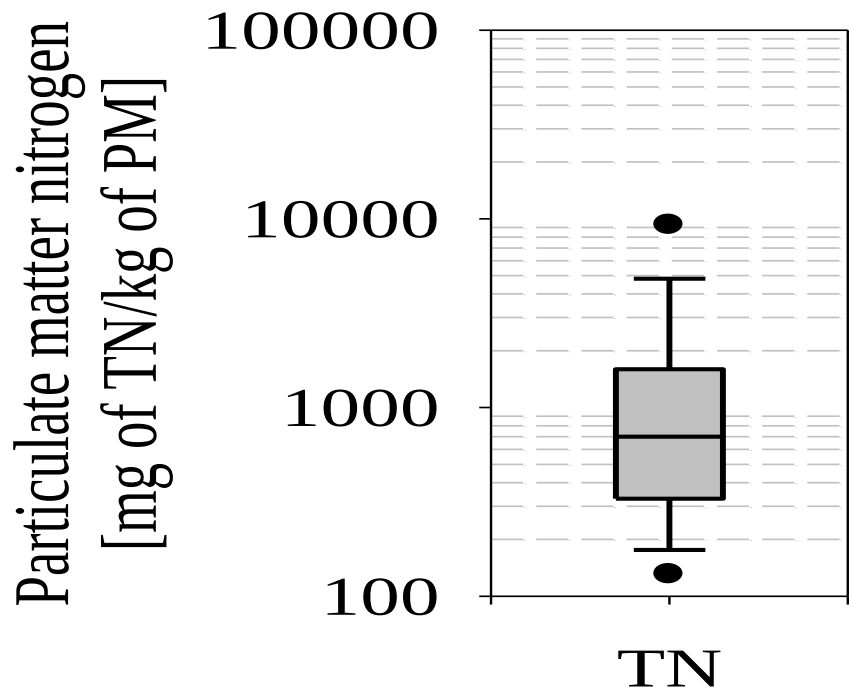
1.0 g
Total P

Review of Primary Project Results

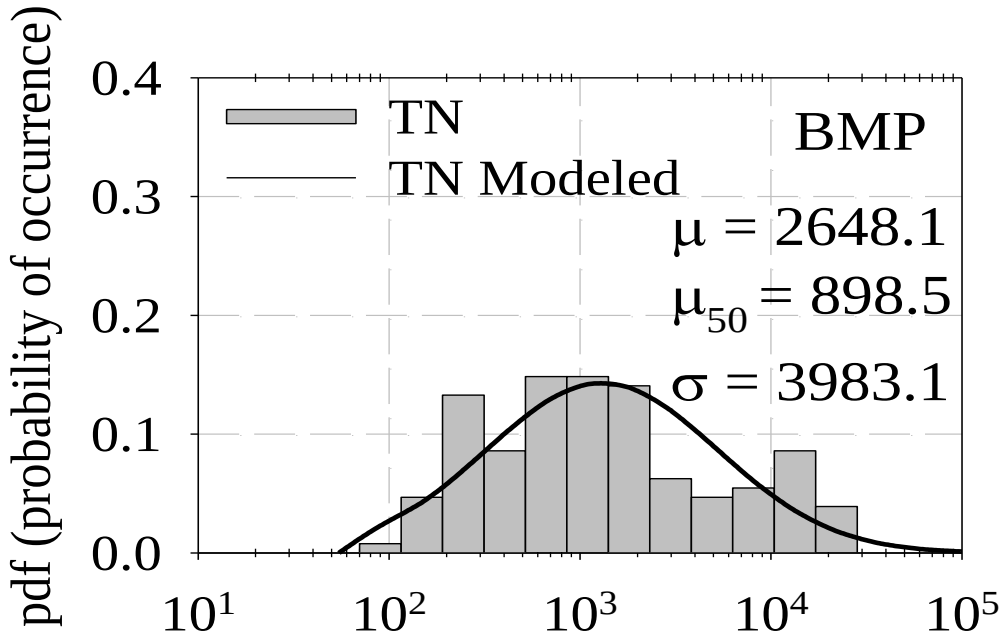
1. Results presented are from outside (OUT) reclaimed wastewater areas, unless inside (IN) reclaimed area results are specifically identified.
2. Results are either composited by combining separate land use results or combining separate HFU results or both, OR results are delineated as a function of land use and HFU
3. Land uses:
   - "Highway" (H) {major transportation R/W}
   - Residential (R)
   - Commercial (C)

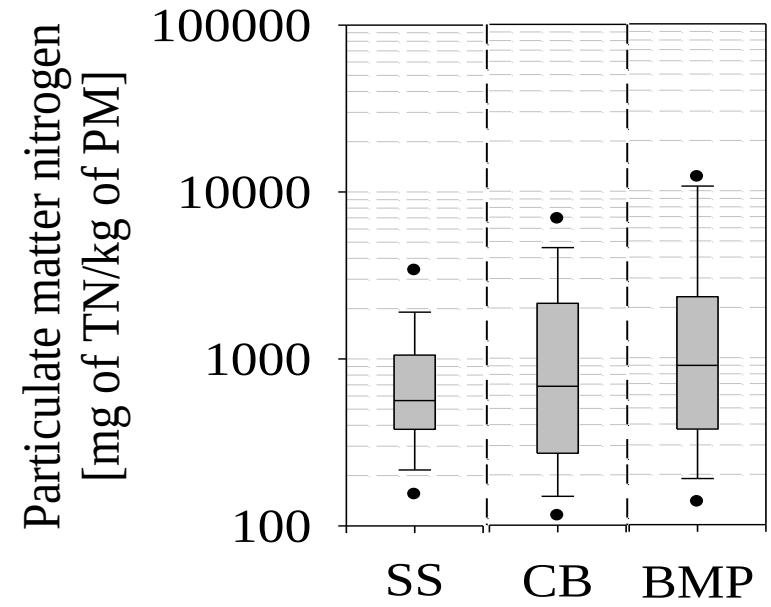
Florida-Based Distribution of N (as TN) (Land Uses Composited and HFUs Composited)

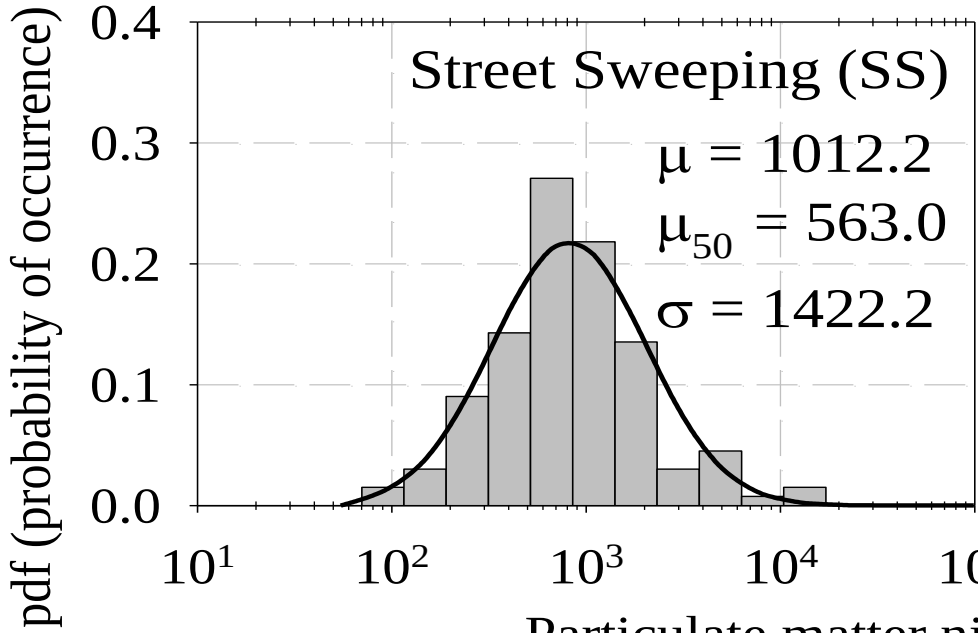


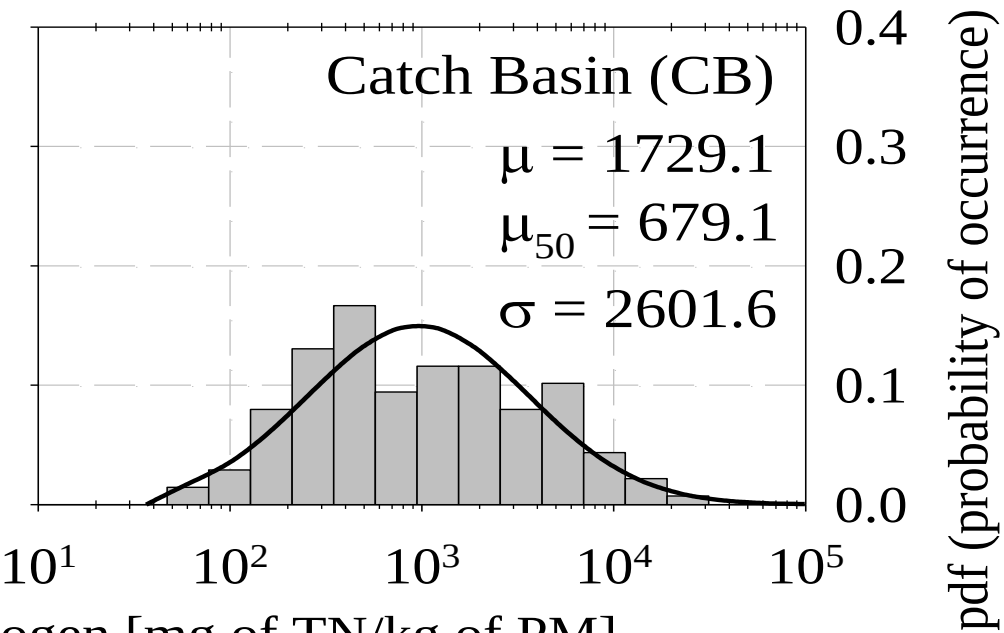


TN Results – Distribution by HFUs



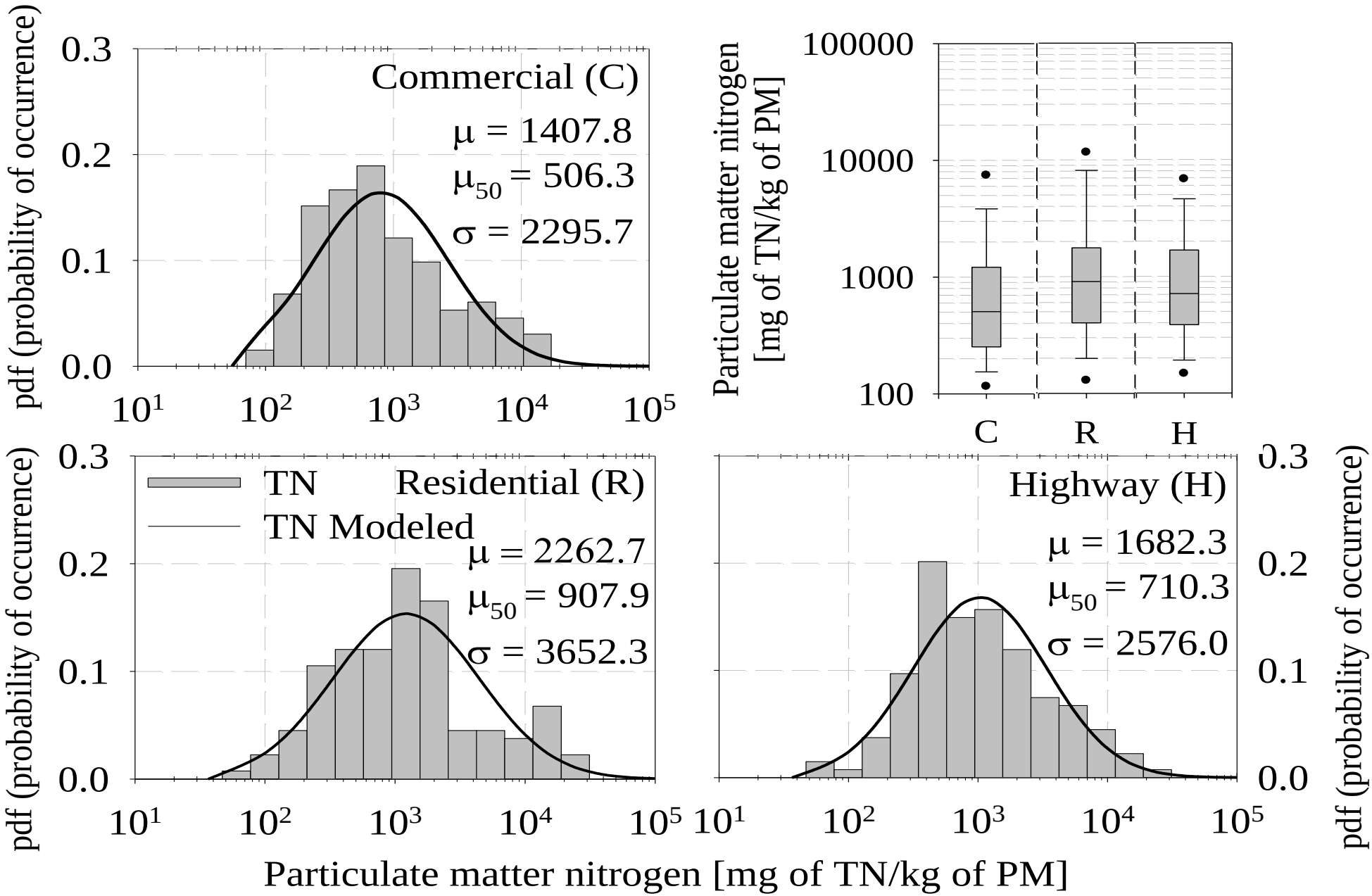




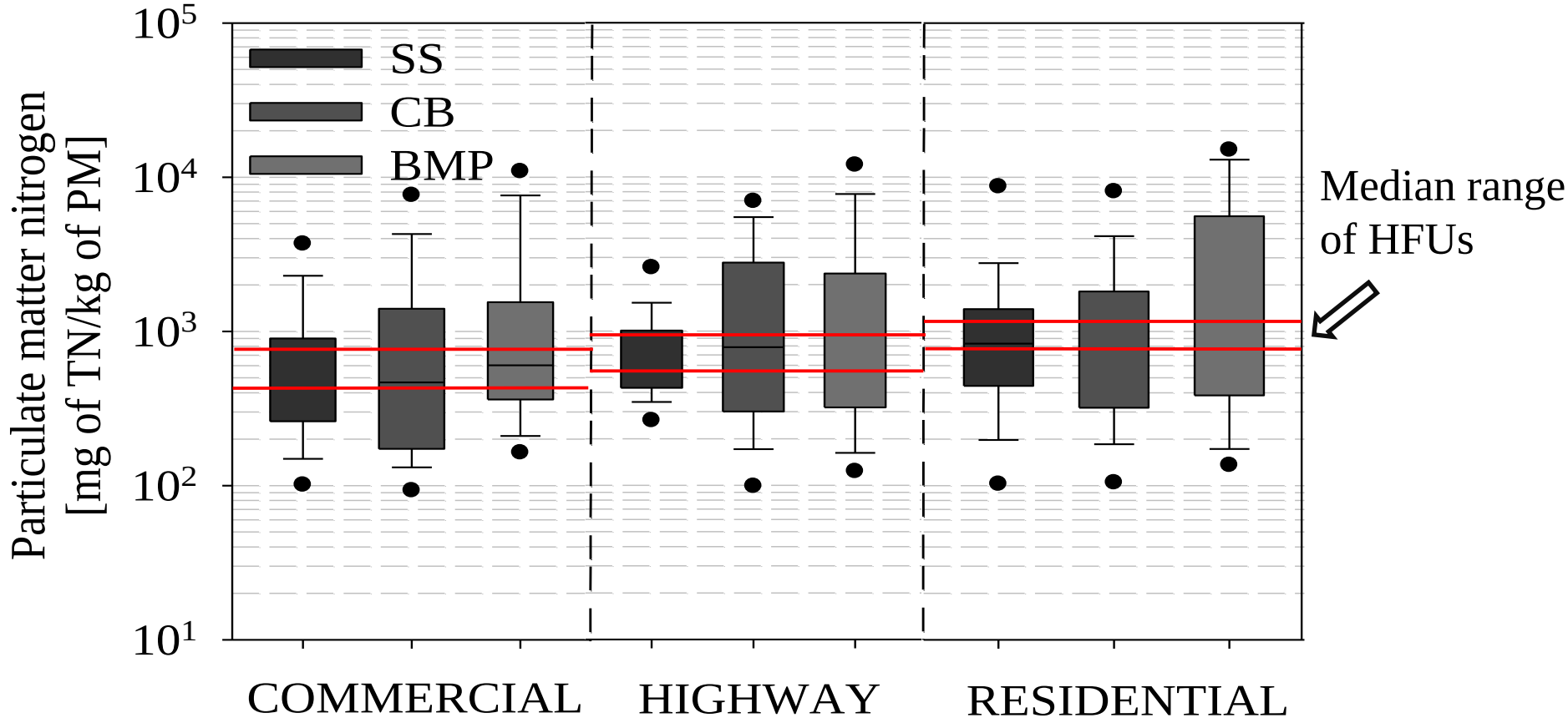


Particulate matter nitrogen [mg of TN/kg of PM]

TN Results – Distribution by Land Use



TN Results by Land Use and HFU (Table 6 or S1)

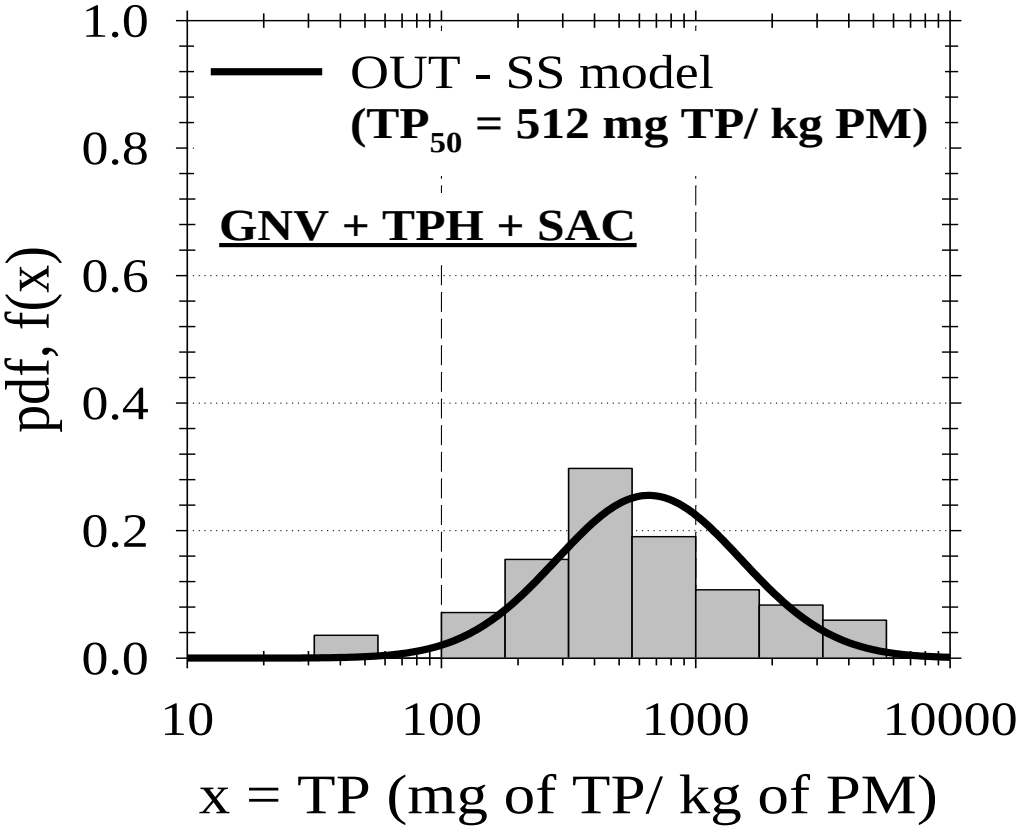


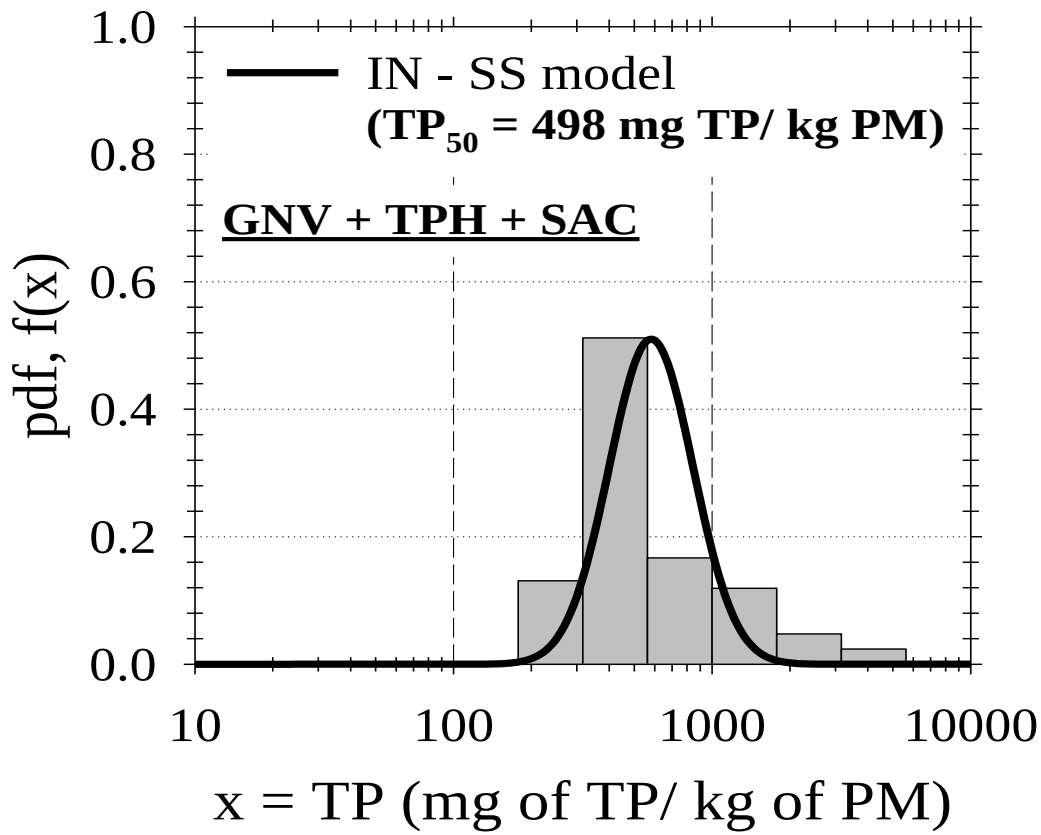
TN [mg/kg]	Street Sweeping (SS)			Catch Basin (CB)			BMP		
	Mean	Median	St. Dev.	Mean	Median	St. Dev.	Mean	Median	St. Dev.
C	789.1	429.6	944.2	1459.7	467.2	2237.8	1999.0	602.1	3104.1
R	1439.0	832.4	2169.9	1803.9	773.8	2955.8	3587.7	1169.0	4991.9
H	826.6	546.4	654.8	1926.3	785.4	2587.8	2342.4	939.2	3496.6

“In” vs. “Out” numerical offset results: N and P load offsets for MS4 areas that irrigate with reclaimed wastewater

Should there be a numerical offset for loads recovered inside reclaimed wastewater irrigation areas of MS4s? (Results have a physical-chemical basis)

Comparing nutrient loadings inside and outside areas with reclaimed wastewater usage: **TP for SS**

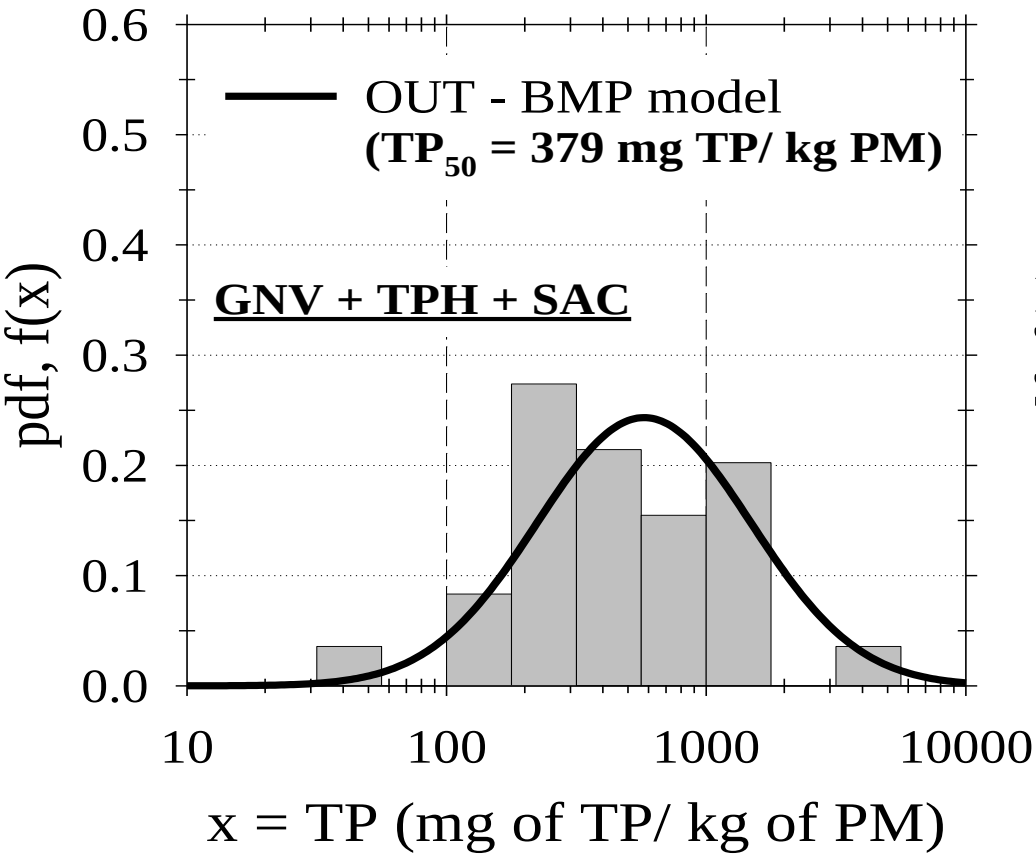


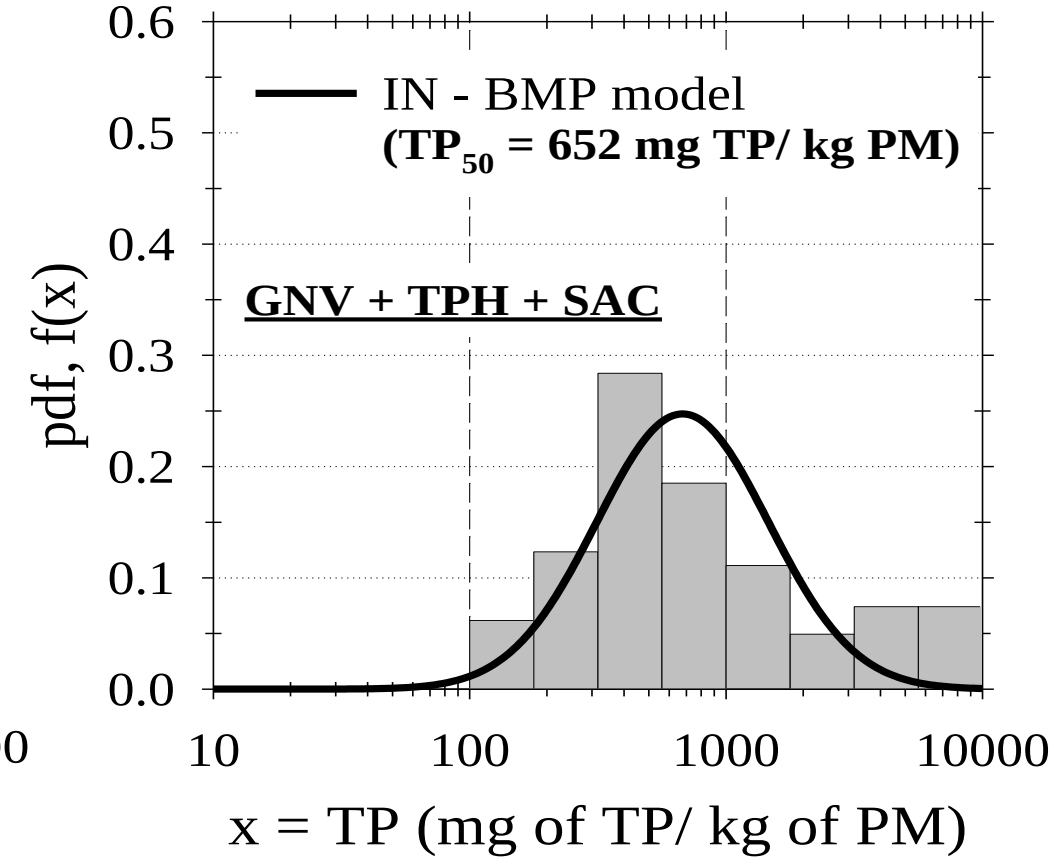


Total Phosphorus (TP) for Street Sweepings (SS)

No statistically significant difference between collected datasets at 95% C.L.

Comparing nutrient loadings inside and outside areas with reclaimed wastewater usage: **TP for BMPs**

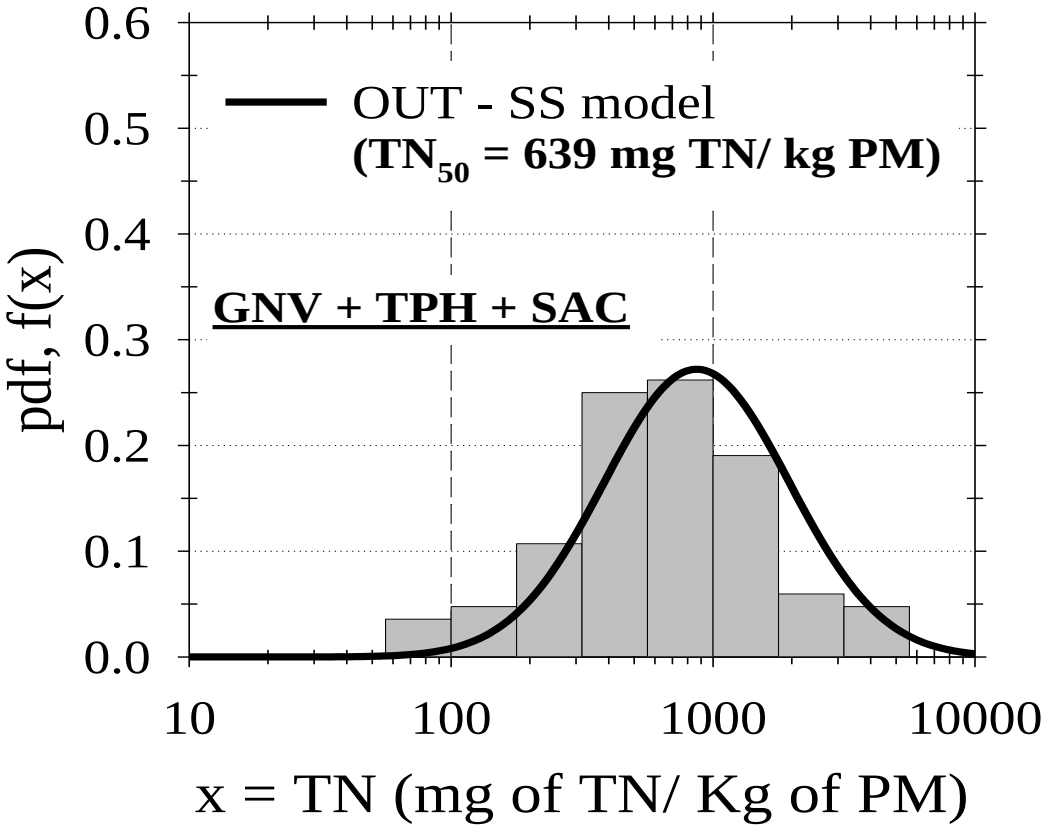


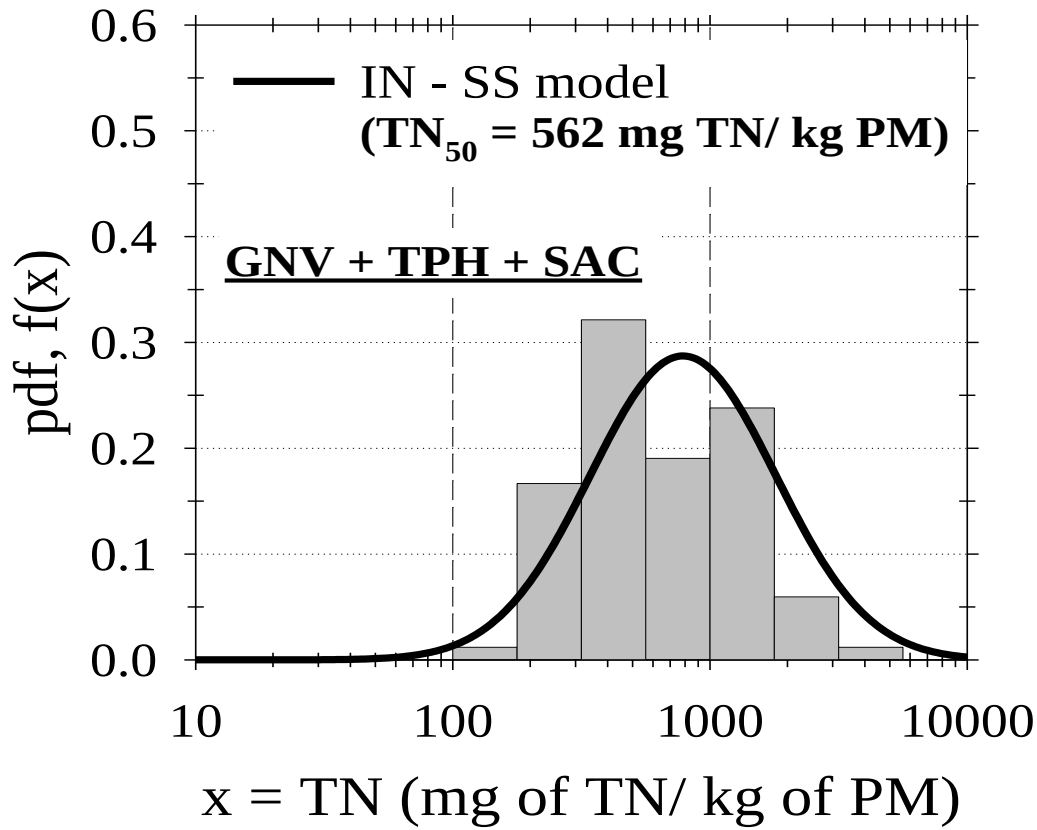


Total Phosphorus (TP) for BMPs

Statistically significant difference between collected datasets at 95% C.L.

Comparing nutrient loadings inside and outside areas with reclaimed wastewater usage: **TN for SS**

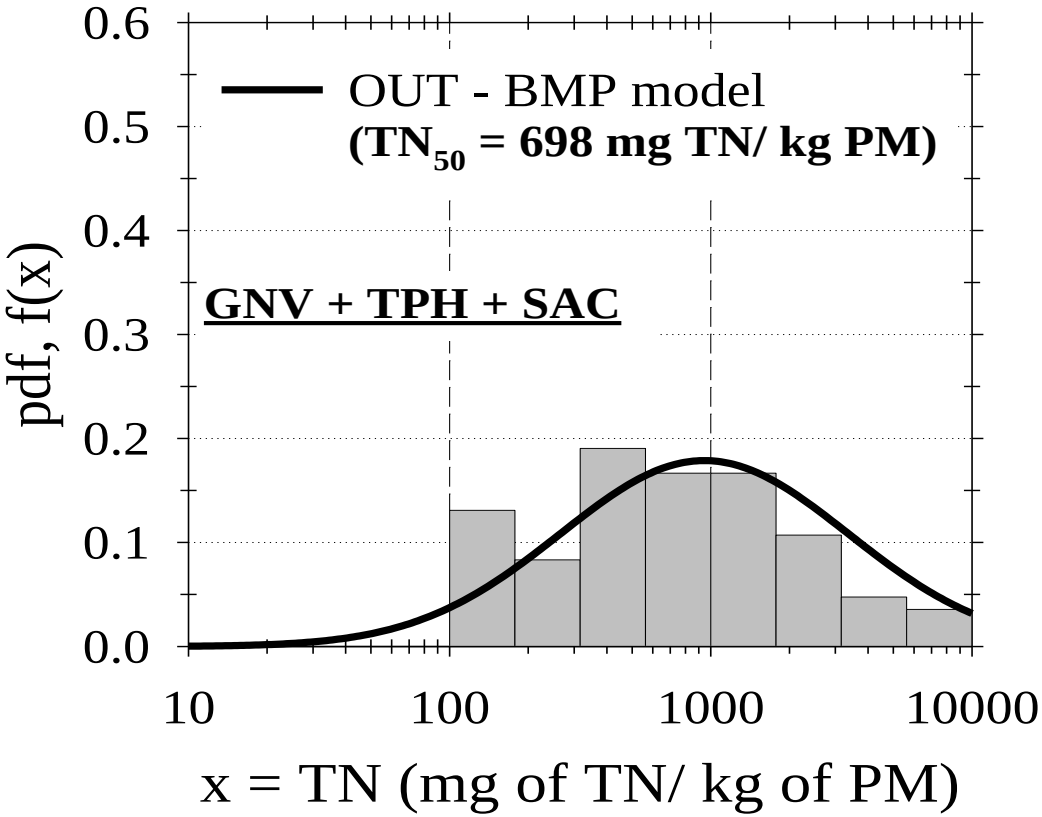


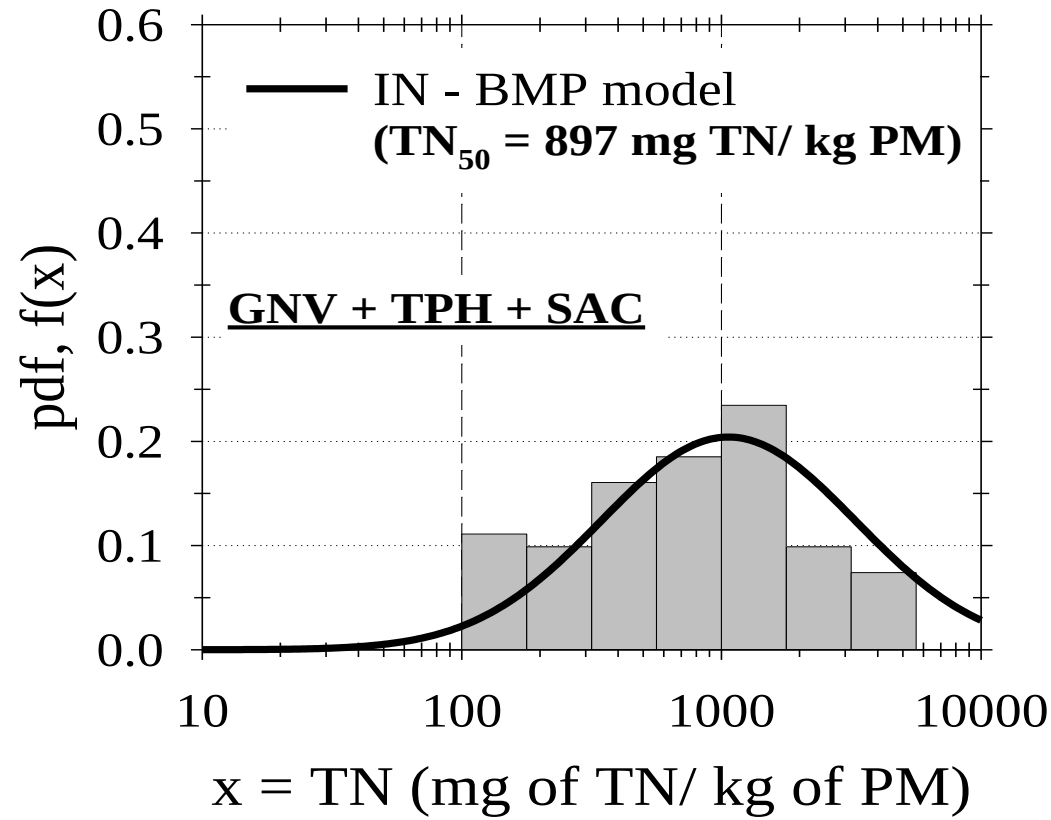


Total Nitrogen (TN) for Street Sweepings (SS)

No statistically significant difference between collected datasets at 95% C.L.

Comparing nutrient loadings inside and outside areas with reclaimed water usage





Total Nitrogen (TN) for BMPs

No statistically significant difference between collected datasets at 95% C.L.

Conclusions: Comparing nutrient loadings inside and outside areas with reclaimed wastewater usage

1. Based on the statistical analyses, no significant difference was observed for street-sweeping between areas inside and outside reclaimed areas, for both nutrients in this study (N and P).

2. An offset factor of 1.0 is recommended for sweepings in reclaimed areas, with respect to results compiled for areas outside the reclaimed areas, to obtain mg (TP or TN)/ kg (PM) from the dry weight of sweepings collected [kg (PM)]

3. This eliminates the issue of changing or monitoring sweeping routes to prevent overlap between areas. There will be no effect on the calculation of mg (TP or TN) for the PM collected by a sweeper whose route passes through areas, both inside and outside reclaimed areas.

Conclusions: Comparing nutrient loadings inside and outside areas with reclaimed water usage

1. Based on the analyses, a statistically significant difference was observed for BMPs, between areas inside and outside reclaimed areas, for TP.

2. A factor of **1.75** is recommended for residuals recovered from BMPs as compared to BMPs outside the reclaimed areas, to obtain mg (TP)/ kg (PM) from the dry weight of residuals collected [kg (PM)].

3. Based on the analyses, no statistically significant difference was observed for BMPs, between areas inside and outside reclaimed areas, for TN.

4. A factor of 1.0 is recommended for BMP residuals from reclaimed areas as compared to BMPs outside the reclaimed areas, to obtain mg (TN)/ kg (PM) from the dry weight of residuals collected [kg (PM)].

Moisture Content (MC) Requirement

Determining a representative moisture content (MC) associated with collected PM

Moisture content (%)	Range	Max.	Min.	Median	25%	75%
BMP	98.3	98.5	0.24	26.0	16.1	38.1
CB	87.6	87.8	0.25	21.3	14.0	29.7
SS	72.9	73.0	0.06	5.9	2.1	15.8

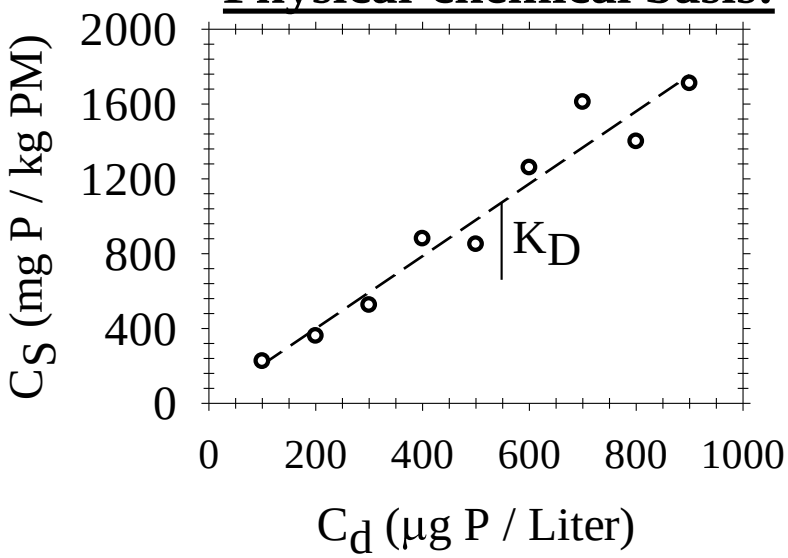
- Representative nutrient load credit requires MC of PM: measured and eventually modeled *(Recall study samples were sampled as "dry" to moist)*
  - BMPs have highest MC: BMPs predominately have wet sumps
  - CBs have an intermediate MC: CBs by design should be free-draining
  - SS have the lowest MC: SS are in equilibrium with atmospheric MC

We strongly recommend that for the first year each MS4 is involved in the load credit process, each MS4 requesting credit generate supporting MC data in a defensible manner as part of their verification process for load credits.

Is it scientific heresy to include Florida basins in the same “population” as other BMPs in this study?

For the metrics of this study are BMPs created equal?

Physical-chemical basis:



- Different BMP classes provide significantly different treatment levels for the aqueous phase. However, in all BMPs an equilibrium is established between aqueous and PM phases that is dependent on influent PM and dissolved concentration [C_d].
- μ_{50} runoff P: f_d is 25 to 35%, K_D: 10^4 to > 10^6 L/kg
- μ_{50} runoff N: f_d is 55 to 65%, K_D: 10^2 to > 10^4 L/kg

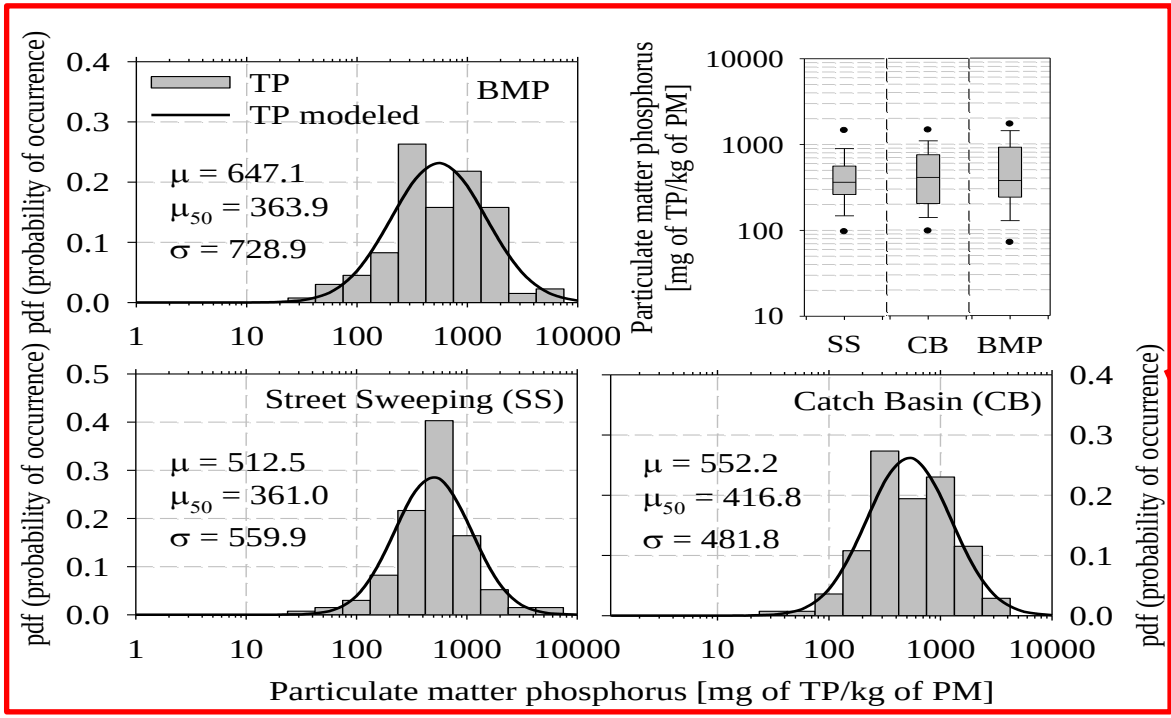
Statistical basis (at 95% C.L.):

FL BMP Population (w/ or w/o basins)	P-value	Median	25%	75%
TP [mg/kg] (all BMPs with basins)	0.69	363.9	239.8	914.4
TP [mg/kg] (BMPs without basins)		382.7	258.9	941.3
TN [mg/kg] (all BMPs with basins)	0.65	898.5	377.1	2283.3
TN [mg/kg] (BMPs without basins)		940.0	405.2	2356.9

- For a given watershed and land use the [mg N,P/kg PM] recovered from BMPs **are not statistically different**. This does not imply that manufactured BMPs are equal to FL basins.

Example

Example: Selection of metric or "yardstick"



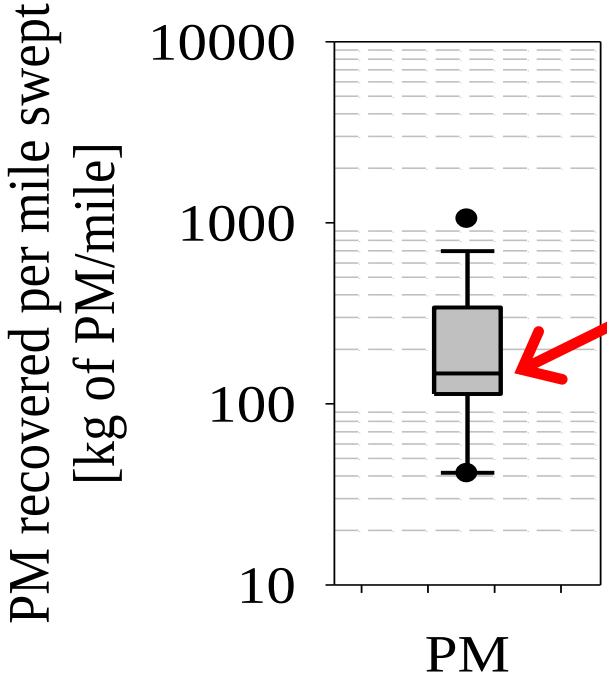
All evaluations **for this example** are performed using:

- **median** concentrations
- Florida-basis (not MS4 specific)
- **Based on different HFUs**
- independent of land use, but can be based on land use

Excerpt from Table 8:

HFU	TP [mg/kg]			TN [mg/kg]		
	Mean	Median	St. Dev.	Mean	Median	St. Dev.
Street Sweeping (SS)	512.5	361.0	599.9	1012.2	563.0	1422.2
Catch Basin (CB)	552.2	416.8	481.8	1729.1	679.1	2601.6
BMP	647.1	363.9	728.9	2648.1	898.5	3983.1

Example: Street Sweeping PM, TP, TN Recovery



10 MS4s have provided 67 discrete values of the amount of PM (mass or volume) swept in regular cleaning procedures.

Median value = 147 dry-equiv. kg PM/mile swept

147 kg PM → 0.12 lb TP and 0.18 lb TN recovered

- To recover 1 pound of TP → 8.5 pavement miles need to be swept (cleaned)
- To recover 1 pound of TN → 5.5 pavement miles need to be swept (cleaned)

Excerpt from Table 8: (Table 8 results are not a function of land use)

HFU (land use independent)	TP [mg/kg]			TN [mg/kg]		
	Mean	Median	St. Dev.	Mean	Median	St. Dev.
Street Sweeping (SS)	512.5	361.0	599.9	1012.2	563.0	1422.2
Catch Basin (CB)	552.2	416.8	481.8	1729.1	679.1	2601.6
BMP	647.1	363.9	728.9	2648.1	898.5	3983.1

Example: Street Sweeping Costs

- Cost of street sweeping is based on utilizing a street sweeping contractor, a common practice in Florida

<u>Street Sweeping Cost:</u> $30.14 per mile (City of Oakland Park, Florida by FDOT)

(Cost range by Florida MS4s = $17.20 – $28.30)

1 pound of TP → 8.5 pavement miles → $257/lb TP

1 pound of TN → 5.5 pavement miles → $165/lb TN

- These costs do not include solid waste landfill disposal (on the order of $80 to $95/ton)
- Note: Recovery costs for maintenance of each HFU or BMP type does not include solid waste landfill costs

Example: BMP Separation and Recovery: PM, TP, TN

- This examples utilizes a common screened **hydrodynamic separator (screened HS)** and monitored data for the performance of a screened HS subject to actual storm events
- HS units and comparison of HS units subject to controlled and uncontrolled loadings (actual events) are well-documented:
- (Kim and Sansalone 2008; Sansalone and Ying 2008; Sansalone and Pathapati 2009; Dickenson and Sansalone 2009, Pathapati and Sansalone 2011).

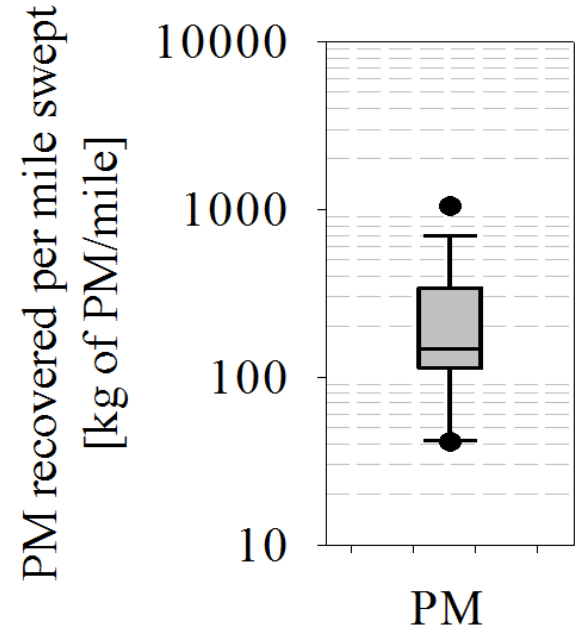
Parameters: (Note: in this case knowledge of runoff loads must be used)

1. Drained urban area of 2000 m^2
2. Annual removal efficiency of 50% for PM
3. No washout and scour from screened HS (Hydro-fantasy !)
4. A yearly rainfall depth of 1270 mm (for GNV, from NOAA)
5. Based on 22 monitored rainfall-runoff events for GNV
6. Watershed-based 400 mg/L PM (suspended + settleable + sediment)
7. Hydrology: Berretta and Sansalone, 2011a; Berretta and Sansalone 2011b

Why measure [kg of PM/mile] and not just miles swept?

A pavement cleaning (street sweeping) metric [kg of PM/mile] depends on:

1. how loaded with PM is the pavement
2. frequency swept
3. inter-event rainfall time
4. previous rainfall frequency/intensity/duration
5. equipment type
6. how the equipment is operated, i.e. speed
7. location on the pavement
8. PSD (particle size distribution): more work is required to differentiate PSDs



However, [mg of N,P/kg of PM] is not dependent on 1 to 7 but dependent on 8
(at this time there is no substitute for load verification based on kg of PM/mile)

Impact of maintenance interval on PM removal efficiency

(Results validated with actual events of return periods at ~ 1 month)

Treatment Train:

- Primary (Type I) settling followed by secondary filtration

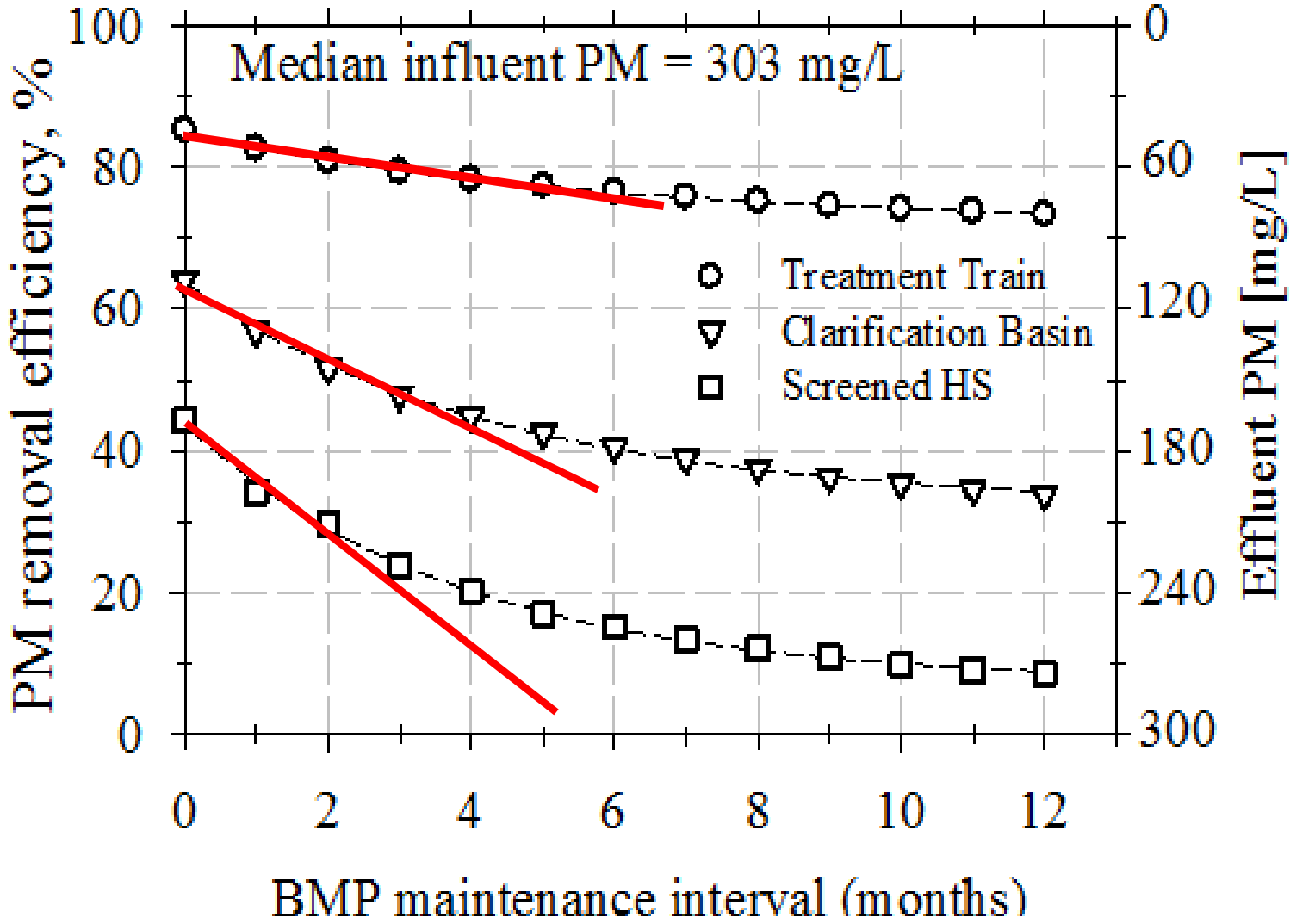
Clarification Basin:

- Primary (Type I) setting

Screened HS:

- Primary (Type I) setting and size exclusion by screen

Screened HS function governed by cleaning interval, whereas treatment train can be governed by head loss



Example: PM, N, P Recovery from BMPs

- Utilizing example parameters and peer-reviewed scientific literature:

627 lb of PM (284 Kg) separated yearly by a screened HS (BMP)

627 lb PM → 0.23 lb TP and 0.56 lb TN separated for one BMP

To recover 1 pound of TP → 4.4 BMPs need to be maintained

To recover 1 pound of TN → 1.8 BMPs need to be maintained

- While example uses annual maintenance frequency, most BMPs need more frequent maintenance to reduce PM washout and changing inter-event sump water chemistry

Excerpt from Table 8:

HFU	TP [mg/kg]			TN [mg/kg]		
	Mean	Median	St. Dev.	Mean	Median	St. Dev.
Street Sweeping (SS)	512.5	361.0	599.9	1012.2	563.0	1422.2
Catch Basin (CB)	552.2	416.8	481.8	1729.1	679.1	2601.6
BMP	647.1	363.9	728.9	2648.1	898.5	3983.1

Example: BMP Costs

1. Catch basin have only a maintenance cost (not designed or intended for PM separation)
2. BMP costs include the capital cost for the BMP (designed and purchased for PM separation) and the cost of maintenance
3. For this example utilizing a screened HS and GNV hydrology:
    - Median capital costs ($25K) (range is $20K to $30K) at 4% interest
    - BMP design life is 25 years ➔ Annualized capital cost ~ $1600
    - With an annual frequency ➔ Annualized maintenance cost ~ $500
4. 1 pound of TP → 4.4 BMPs → $9.2K/pound of TP (3.2K – 36.7K)
5. 1 pound of TN → 1.8 BMPs → $3.7K/pound of TN (1.3K – 14.9K)
6. The bracketed ranges allow for parameter variability of:
    - Annual interest rate from 0 to 6% and capital costs from $20 to 30K
    - PM separation efficiency from 90% to 20%
    - Maintenance frequency of once per year to twice per year

Cost $/Pound: PM, TP, TN Separation or Recovery

Separation or Recovery Method	Cost ($/lb) (excluding SW landfill costs) TN	TP	PM
BMP Treatment Train[a]	935	**32,600**	26
FL Database for BMPs[b]	1,900	10,500	**41**
Screened Hydrodynamic Separator[c]	**3,730 (1,280 - 14,860)**	9,210 (3,170 - 36,680)	4 (1 - 13)
Baffled Hydrodynamic Separator[c]	3,020 (1,280 - 14,860)	7,450 (3,170 - 36,680)	3 (1 - 13)
Street Cleaning (lowest cost)	**165**	**257**	**0.10**
Catch Basin Cleaning[d] (2nd lowest)	1,016	1,656	0.70

[a] Wet basin sedimentation followed by granular media filtration, UF, 2010.

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

[c] Based on 2000 m^2 urban catchment draining to a screened hydrodynamic separator (HS) with 50% PM annual removal efficiency ***based on clean sump conditions***

[d] Based on 100 dry pounds of PM recovery with an annual cleaning frequency

Florida-based MS4 Nutrient Load Credits

1. The consistent log-normality of TN and TP results leads to the recommendation of a median (50^{th} percentile) concentration [mg/kg] from each TN and TP distribution.

2. This result is important for **FDEP allocation of load credits** because the results are not represented by a singular concentration [mg/kg] but by log-normal distributions

3. Through 3 MS4s, results illustrate reclaimed wastewater does enrich urban PM and detritus with P and likely other constituents (not measured herein). Results have physical basis.

4. The cost of load recovery for PM, TP and TN by maintenance practices, in particular for street sweeping, is significantly lower than current manufactured BMPs, even assuming such BMPs are maintained annually and do not scour or washout. (See following $/pound slide)

5. Moisture content (MC) is a critical parameter for load credits. This study recommends that a MS4 measure MC for a year to develop a MC factor as a f(HFU). Avoid bulk densities.

6. For PM-based nutrient concentrations (not loads), basins are statistically equivalent to manufactured BMPs despite far superior aqueous treatment and hydrologic benefits of basins

7. Study results are only valid on a Florida-wide basis and is not intended to compare MS4s