Progress on Phase 7 Nutrient Inputs and Sensitivities

Joseph Delesantro, ORISE CBPO

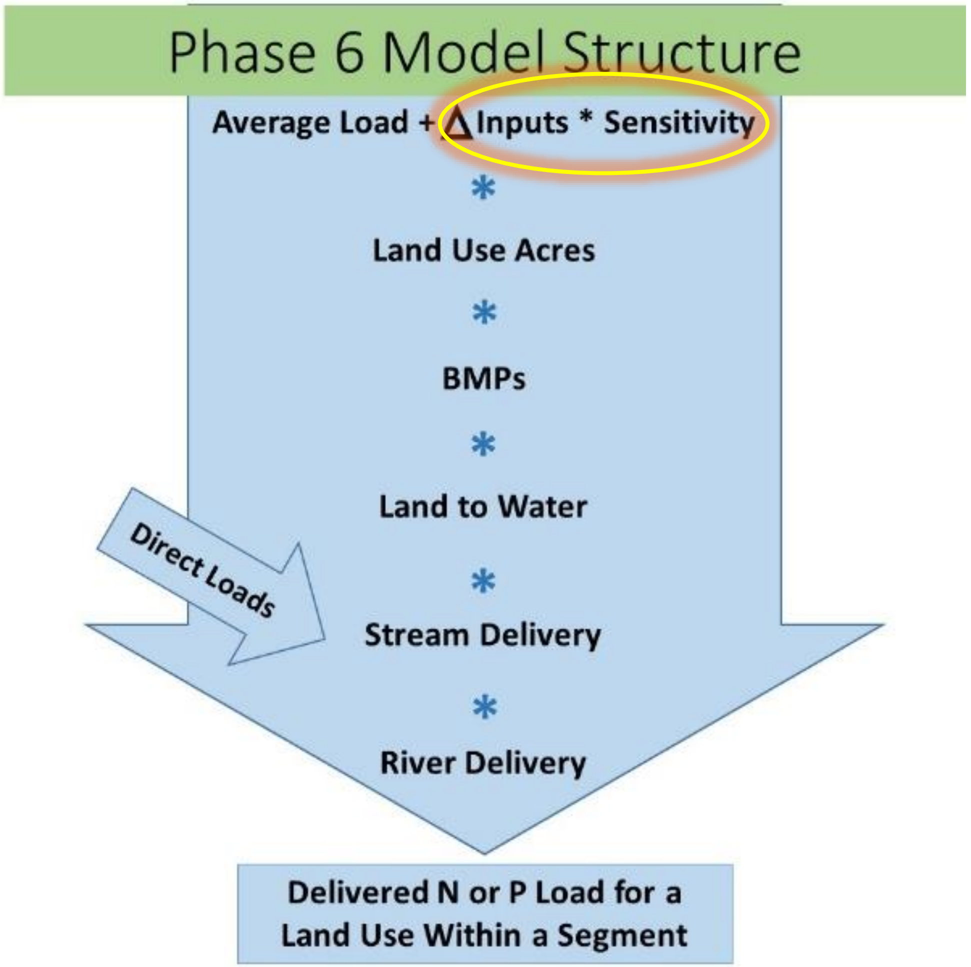
Conor Keitzer and Rosh Nair-Gonzalez, UMCES

CAST Load Sensitivity to Inputs

Sensitivity (S) is defined as the change in export load per change in input load. If inputs change by Δ, the export will change by S*Δ (S=Δ Export/Δ Input). Δ is defined relative to the mean input.

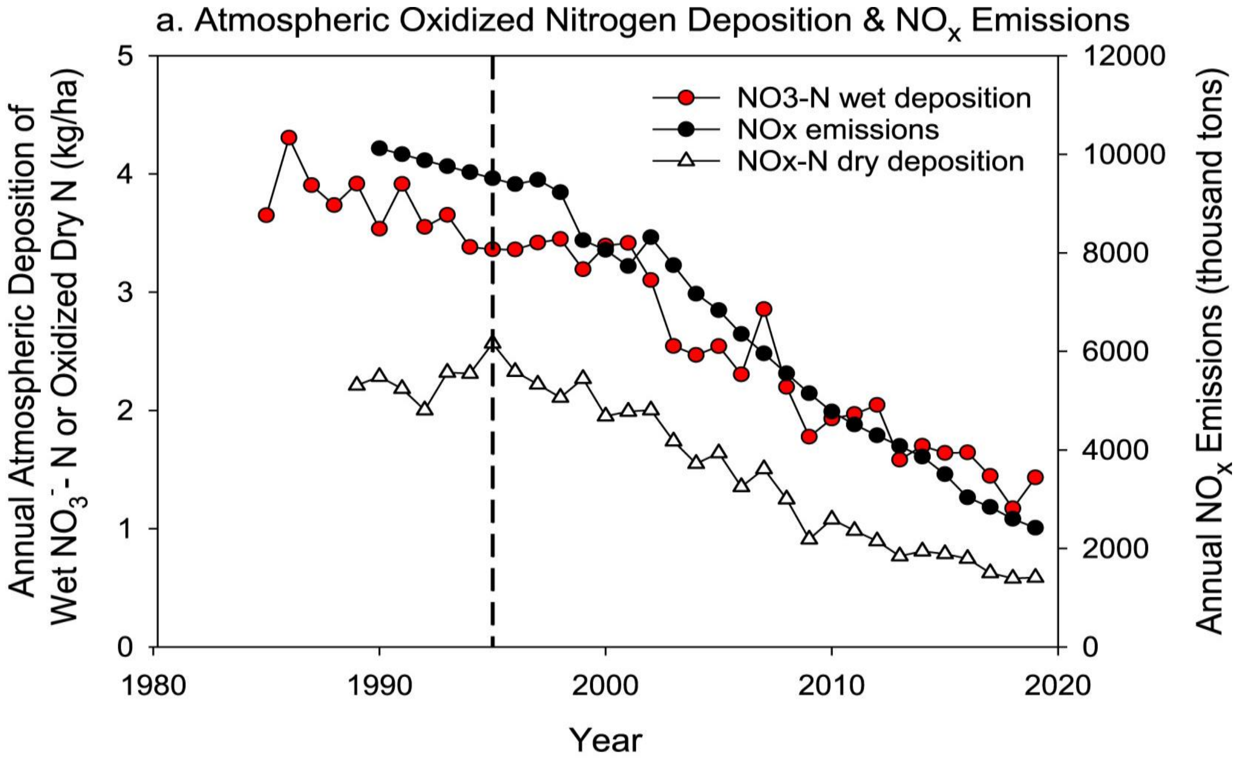
In other words:

- When added to the land use average load we identify the load, by source (land use and input), which is available for export (edge of field or stream load).
- Sensitivities account for the spatial and temporal variation in the load available for export.
- A lower sensitivity value will result in a more muted loading response to changes in inputs.
    - If there is no sensitivity (0), then the load available for export is constant in space and time for that land use defined by the loading rate.



P6 N Atm. Dep. sensitivity values

- True Forest: 0.023
- Harvested Forest: 0.161
- Construction: 0.2
- Ag. Open: 0.22
- Road: 0.6247



Burns, D. A., Bhatt, G., Linker, L. C., Bash, J. O., Capel, P. D., & Shenk, G. W. (2021). Atmospheric nitrogen deposition in the Chesapeake Bay watershed: A history of change. *Atmospheric Environment*, *251*, 118277.

Literature review to revise P7 sensitivity values: Forest

- Rosh Nair-Gonzalez and Conor Keitzer - UMCES
- Focused on “true forest” catchments or watershed scale models where harvested forest is assumed to be a small percent.
- 43 papers were reviewed
- Data was compiled from 6 field studies and 5 watershed models

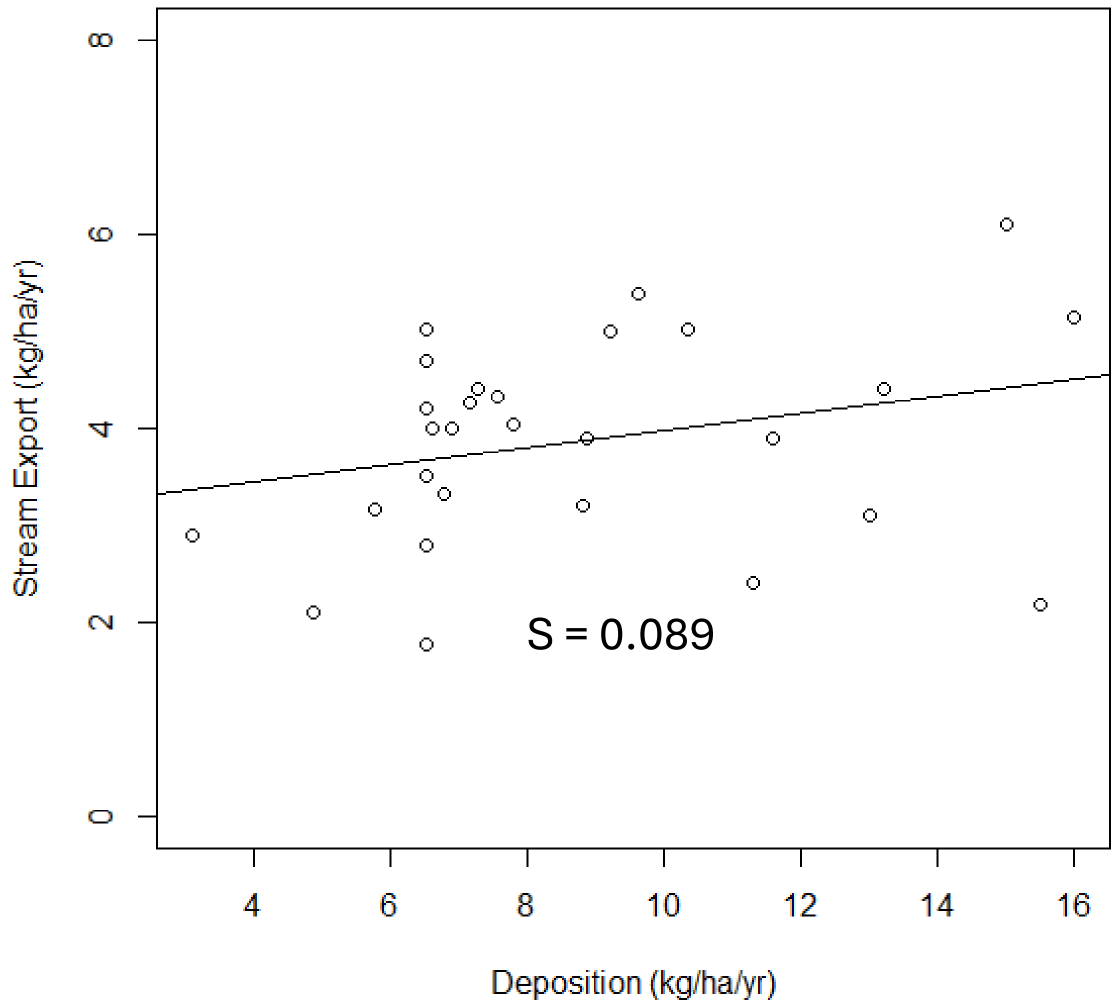
Conor Keitzer - UMCES

Rosh Nair-Gonzalez - UMCES

Forest load sensitivity to N dep., field studies

Outliers were removed based on:

- land use (>20% ag. or >15% urban)
- Export outside 2 std from CAST '23 forest export.

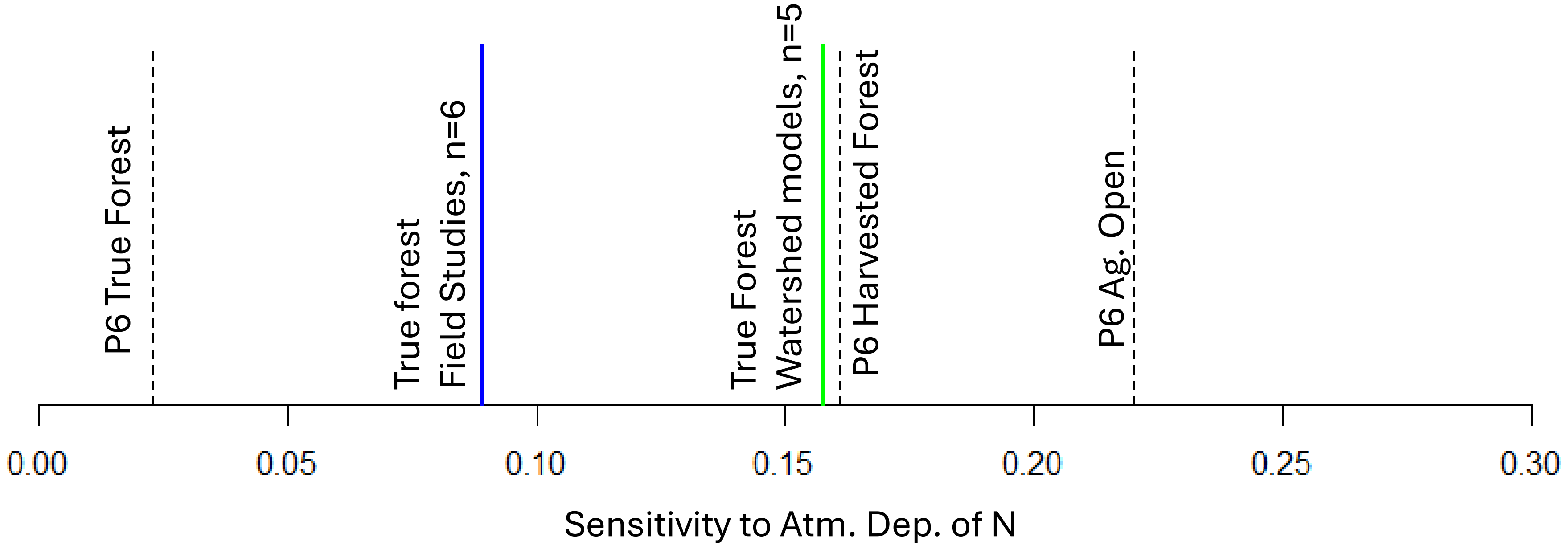


Forest load sensitivity to N dep., SPARROW

- Watershed models include non forested land use which is accounted for using the associated P6 load source sensitivity values.
- Mean value is 0.158 (0.07 – 0.22)

Forest load sensitivity to N dep. literature

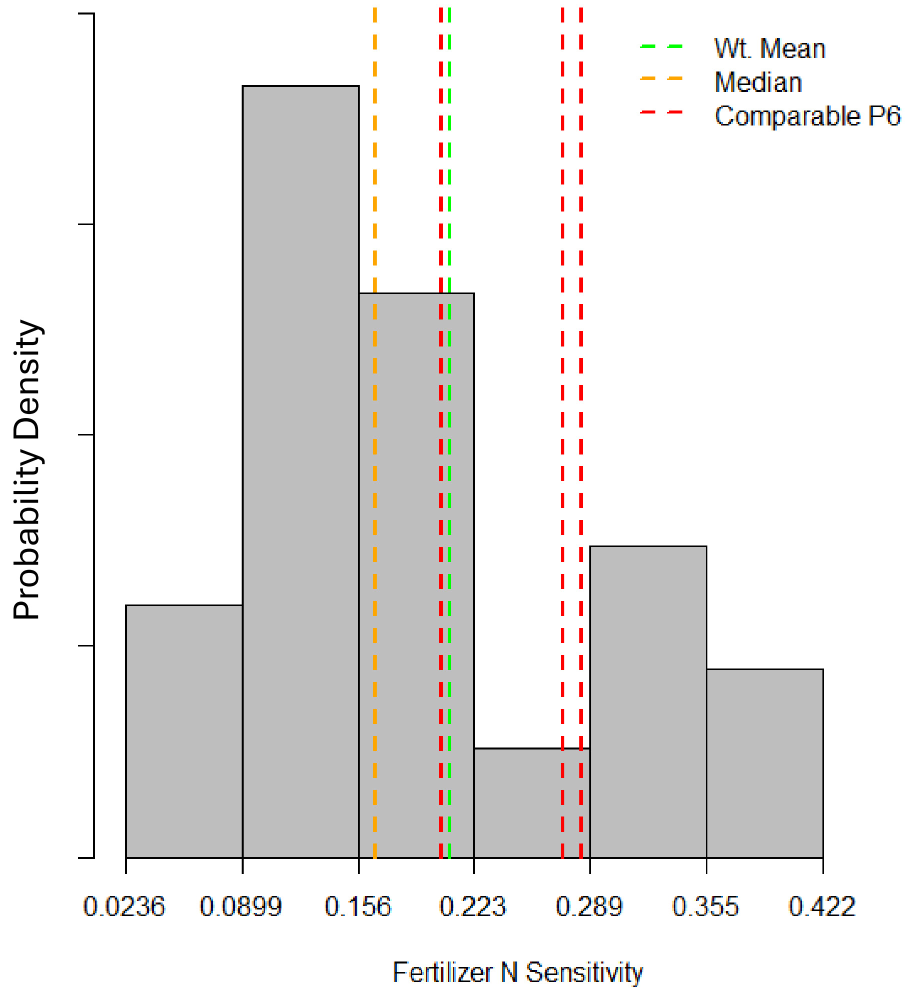
- Literature values are less than harvested forest
- While forests are very retentive, most atm. deposition is coincident with rainfall and high flows, elevating sensitivity
- Final sensitivity value may be calibrated within the literature range, or assigned via the central tendency
- Small group is being set up to evaluate if and how Harvested Forest and other natural load source sensitivities should change given the True Forest findings
- The mean loading rate form literature was 3.32 lbs./ac/yr vs P6 value of 1.68
- We will need to assess the stability of the model with new values given that forest load sets the model unit minimum



Fertilizer N literature values

Value	TN
Weighted Literature Mean	0.19
Literature Median	0.14
P6 Grain w/ Manure	0.26
P6 Specialty Crop High	0.25
P6 Grain w/o Manure	0.18

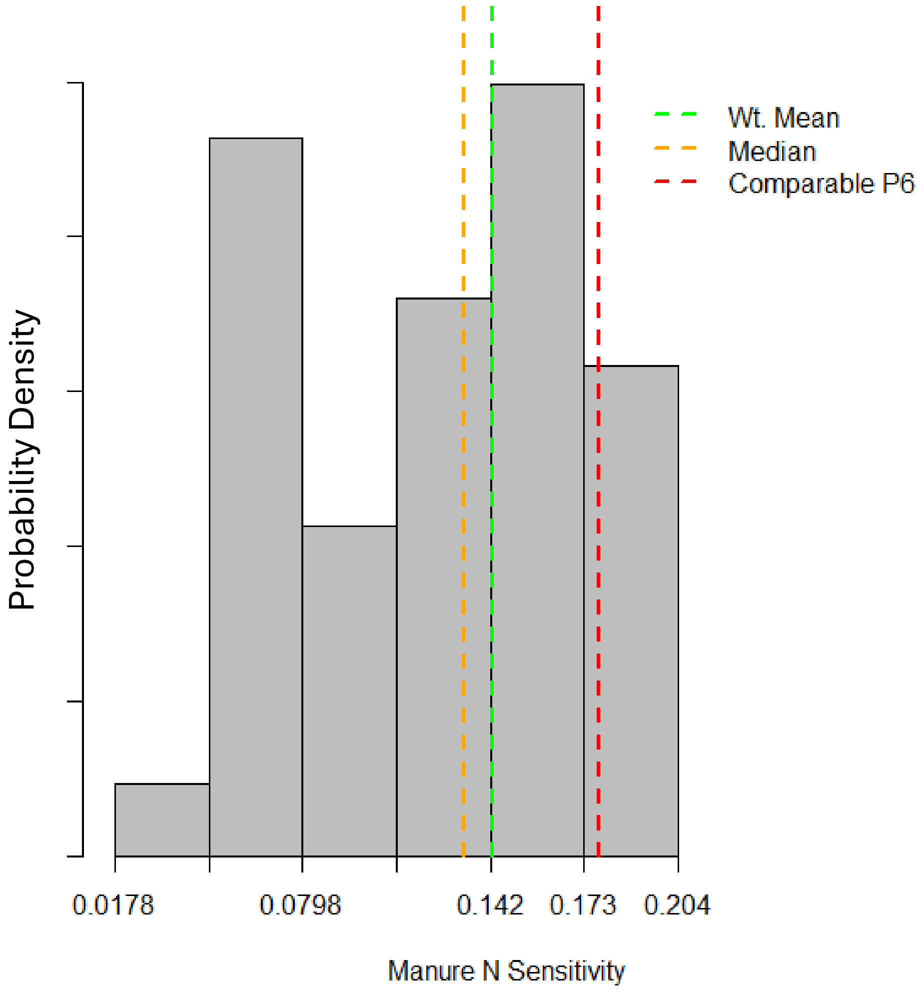
- n=24
- Literature values are normalized by % intensive ag. land area in the study to account for major differences in land use.
- Values have been weighted by the quality of the study using fit criteria and sample count.



Manure N literature values

Value	TN
Weighted Literature Mean	0.122
Literature Median	0.115
P6 Grain w/ Manure	0.16
P6 Specialty Crop High	0.16

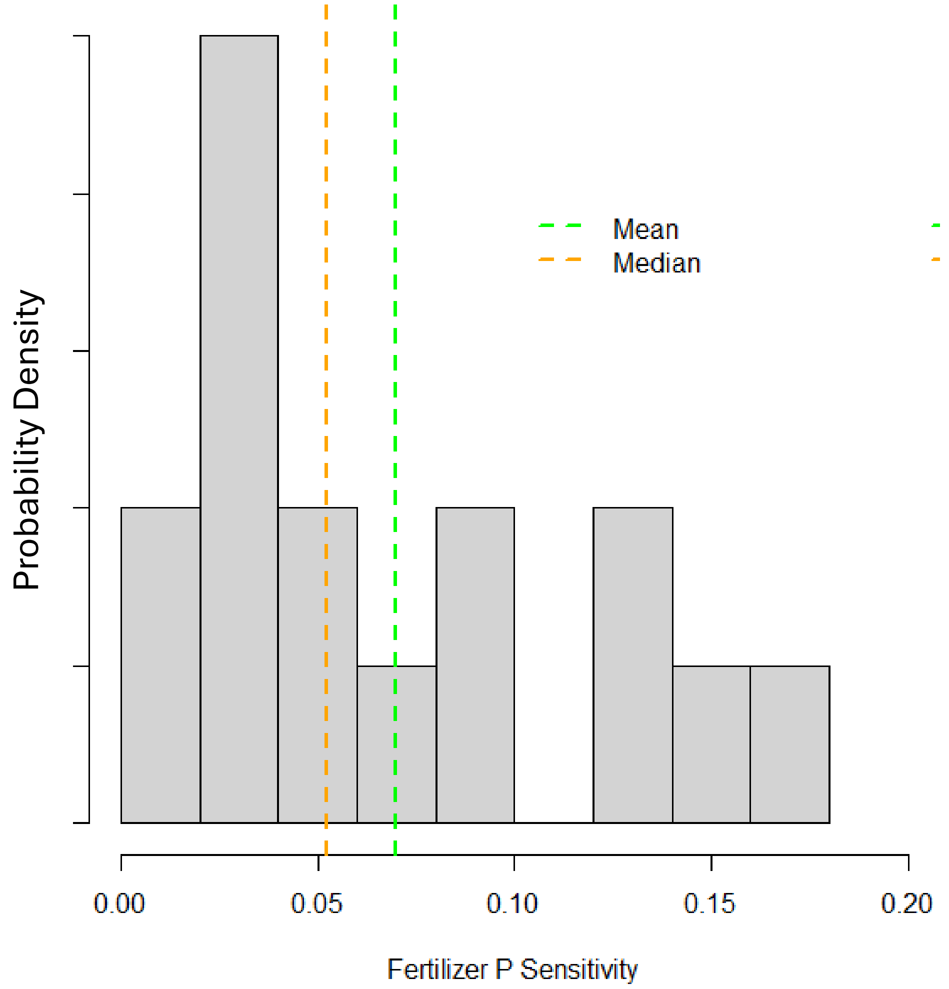
- n = 22
- Literature values are normalized by % intensive ag. land area in the study to account for major differences in land use.
- Values have been weighted by the quality of the study using fit criteria and sample count.



Fertilizer P literature values

Value	P
Literature Mean	0.07
Literature Median	0.05

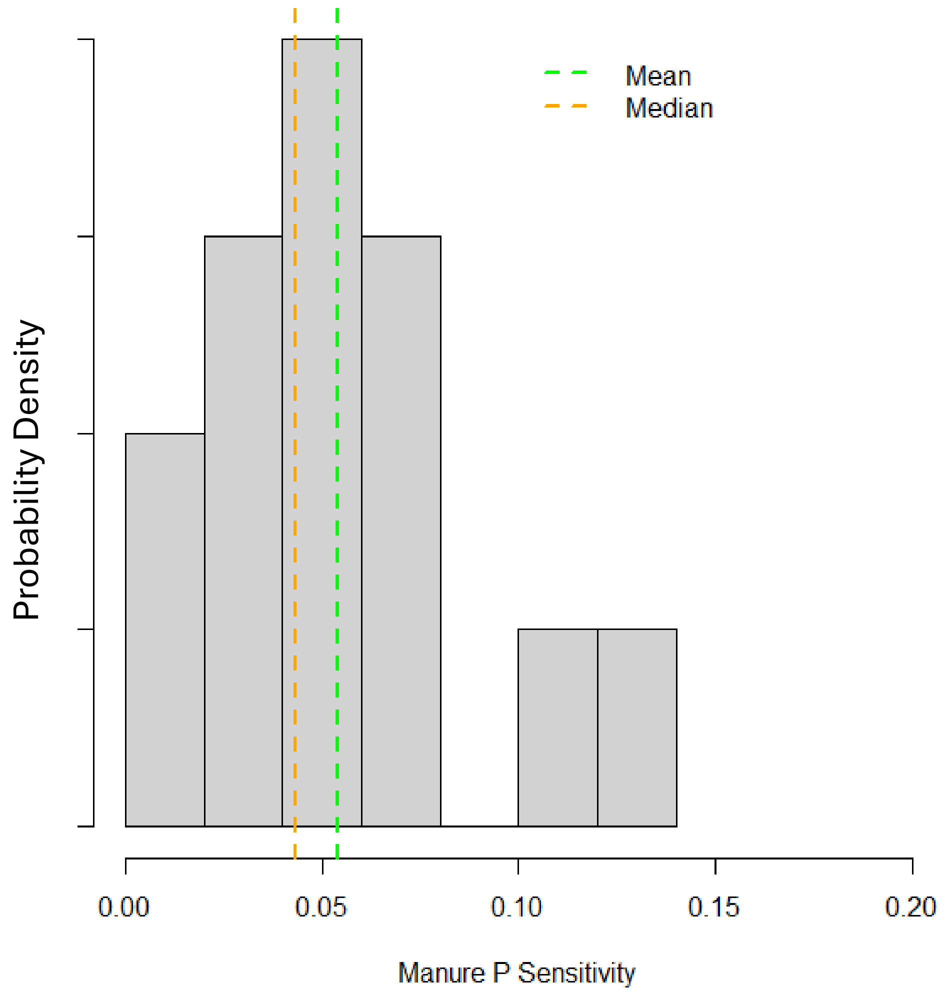
n=17
Values are lower than N sensitivity values validating model assumptions and APLE results



Manure P literature values

Value	P
Literature Mean	0.05
Literature Median	0.04

n=14
Likewise, manure P sensitivity is lower than fertilizer sensitivity validating current assumptions



Ongoing work on additional sensitivities

- Crop Uptake

MANAGE Dataset

“Measured Annual Nutrient loads from AGricultural Environments” (MANAGE)

- developed in 2006 to summarize annual field-scale nitrogen (N) and phosphorus (P) runoff data from agricultural land uses
- presents descriptive data such as land use, tillage, conservation practices, soil type, soil test P, slope, and fertilizer formulation, rate, and application method, along with runoff, precipitation, and soil erosion.

Harmel, R. D., Kleinman, P., Hopkins, A. P., Millhouser, P., Ippolito, J. A., & Sahoo, D. (2022). Updates to the MANAGE database to facilitate regional analyses of nutrient runoff. *Agricultural & Environmental Letters*, *7*(2), e20095.

Potential template for databasing CBP literature reviews and literature informing the model in tabulated format

Land-to-water and river delivery factors for improved P estimation

Major unaccounted for controls on P loading:

- Hydrologic connectivity of landscapes and sources (Land-to-water factors)(work of Michelle Katoski)
    - Inverse Euclidean distance to NHD Medium Resolution Flowline (mean, median, mode, std)
    - Inverse flow distance to Medium Resolution Flowline (mean, median, mode, std)
    - TWI (mean, median, mode, std)
    - SedIC to Medium Resolution Flowline (mean, median, mode, std)
    - Summaries repeated within mask extents of Phase 6 LULC classes
    - Road length and density for Census TIGER/Line 2023 Roads

- Biogeochemical controls on P mobility (Stream/River Delivery)(work with Conor Keitzer)
    - Alkaline desorption
    - Salinity and road salting
    - Increasing temperature
    - Geogenic P

Have the data, requires testing

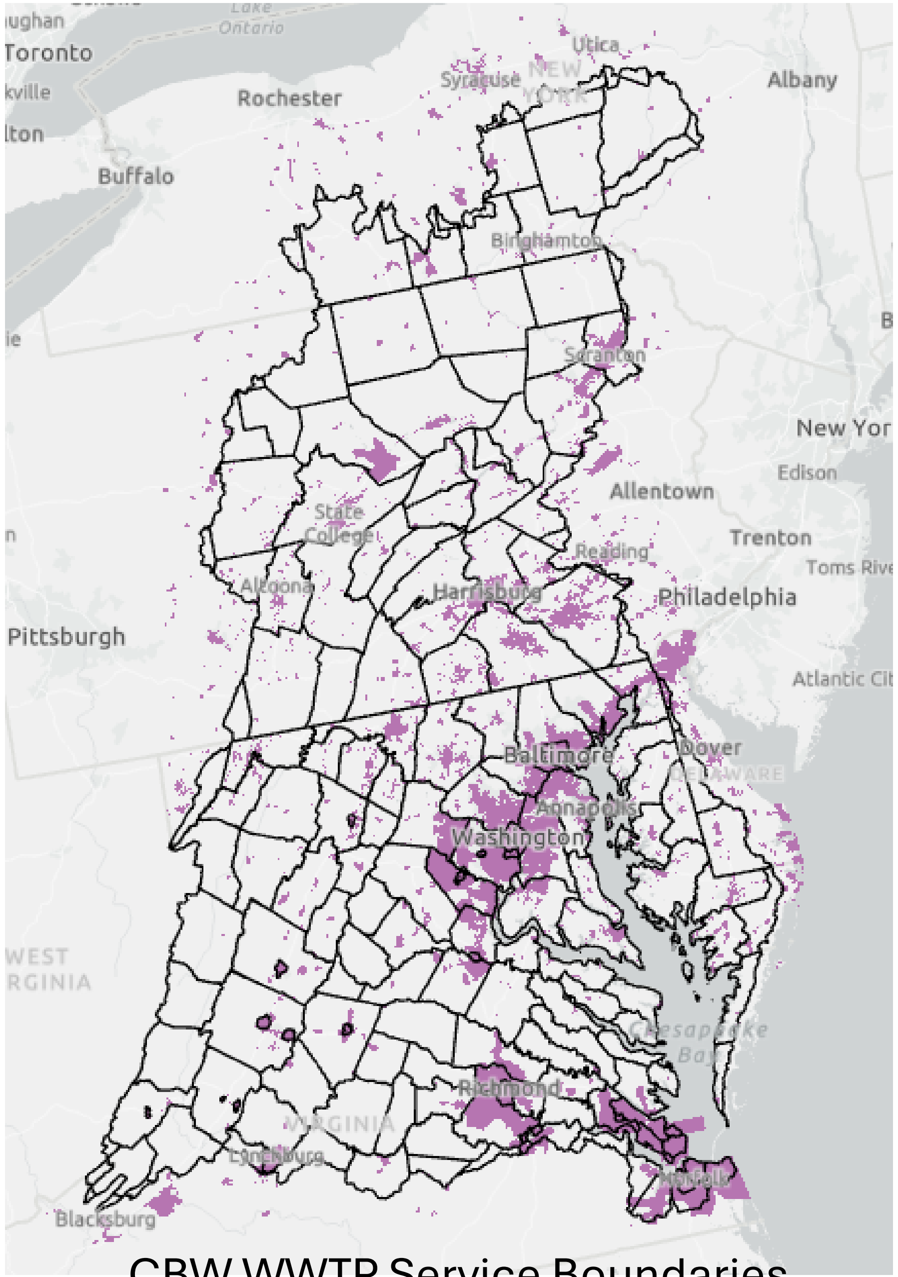
Requires processing

Sanitary Sewer Exfiltration Update

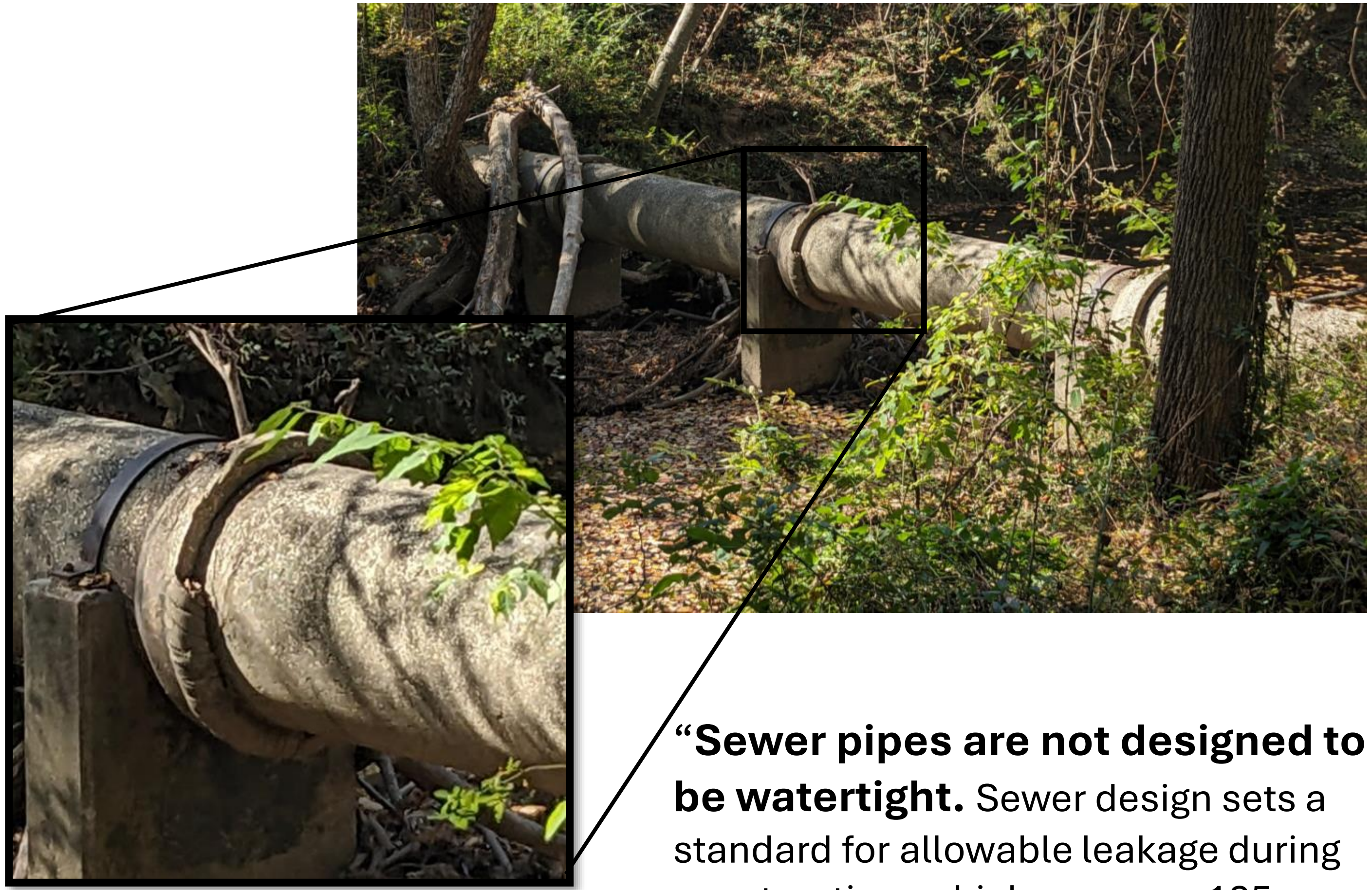
Joseph Delesantro, ORISE Fellow, EPA CBPO

jdelesantro@chesapeakebay.net

DETAILS For reference, but not discussed in presentation



CBW WWTP Service Boundaries



“**Sewer pipes are not designed to be watertight.** Sewer design sets a standard for allowable leakage during construction, which averages 125 gallons per 400 feet of pipe, which is the standard distance between sewer manholes (ASTM, 2009), or about 1,650 gallons per mile of standard sewer pipe.”

Chesapeake Bay Program, (2014). “Final Expert Panel Report on Removal Rates for the Elimination of Discovered Nutrient Discharges from Grey Infrastructure”

Why does this matter for the model?

- ★ Proper appropriation of loads
- Improved targeting and crediting of management actions
- Scenario analysis (E.g., remediation, pipe ageing, etc.)

This load is in the bay, the load is in the model, but it is currently misappropriated.

The majority of misappropriation is likely to other urban load sources such as stormwater and lawn fertilizers.

WWTWG Considerations

- Acknowledge interest in more accurately attributing the sources of the load.

- Prefer a conservative estimate
  - to capture the impact of small defects and joint leaks, not large structural failures which are more quickly identified and addressed,
  - and to reflect the uncertainty in estimates.

Preliminary model structure

Exfiltration Vol. = Fraction exfiltration * Annual system treatment volume (dry-weather) * Geologic coef. * Fraction gravity line * (Fraction new or rehabbed*Rehabbed coef.)

Exfiltrated nutrient mass = Exfiltration Vol. * concentration in raw WW (33 mg/L TN, 6 mg/L TP)[1]*Soil Treatment*GW Transmission

Workgroup Defined, Required State Provided Input, Optional State Provided Input

[1]Chesapeake Bay Program, (2014). "Final Expert Panel Report on Removal Rates for the Elimination of Discovered Nutrient Discharges from Grey Infrastructure"

- An initial default exfiltration value as a percent of treated volume will be defined by expert judgement and literature
- Spatially exfiltration will be mediated soils, geology, and by optional factors identified as drivers of exfiltration and transmission by expert judgement and literature.
  - Geologic basin as a metric of water table depth driving exfiltration vs infiltration
  - The proportion of the system which is gravity fed
  - The proportion of the system which is new or recently rehabilitated
  - Soil and groundwater transmission attenuation (?)

Literature search to focused on exfiltration as a percent of system volume

Study	% System	Observation	System flow
Nguyen and Venohr, 2021	2%	to groundwater	dry-weather
Delesantro et al., 2022	2.40%	to stream	dry-weather
Steele et al., 2025	0.60%	from pipe	total
Amik et al., 2000	11.40%	from pipe	dry-weather
Ellis et al., 2004	3-5%	from pipe	review, both
Fenz, 2003	1-5%	from pipe	dry-weather
Fens et al., 2005	1%	to groundwater	dry-weather
Karpf and Krebs 2004	2.80%	to groundwater	dry-weather
Giulianelli et al., 2003	0.24-2.96%	from pipe	dry weather
Yang et al., 1999	1-2%	to groundwater	total
CIRIA, 1995	3.00%	from pipe	total (leaky system)

Notes:

- Filtered to remove laboratory analyses which tend to be higher
- Amik et al., and CIRIA 1995 were removed as an outliers from subsequent analyses
- Delesantro et al., 2022: Assuming NO_3^- proportion from WW ~ TN proportion from WW
- Studies estimate exfiltration from pipe, to GW, or to streams
- Studies may estimate treated volume based on total flow or dry-weather flow
- Dry-weather flow is generally analogous to generated wastewater

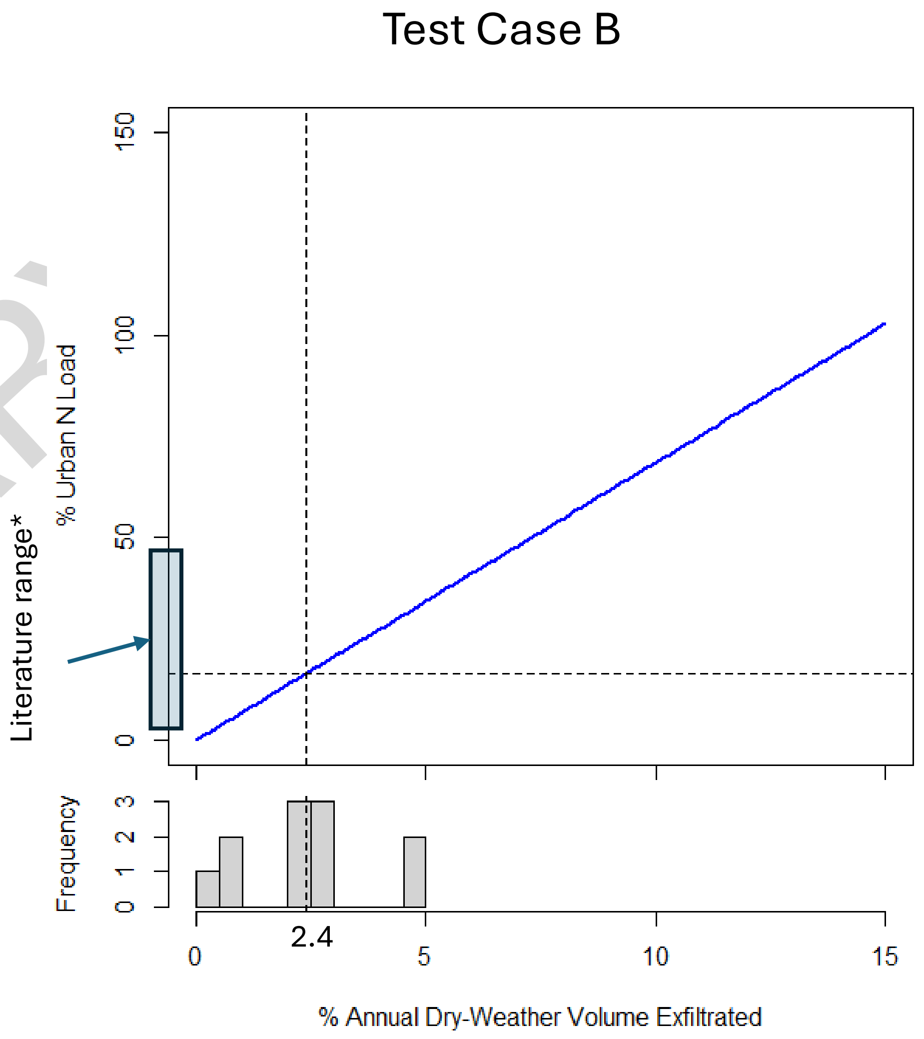
Values are generally in agreement, suggesting reasonable basis for generalization.

Exfiltration as a percent of dry-weather flow

Exfiltration Vol. = Fraction exfiltration * Annual system treatment volume * Fraction gravity line* Geologic coef. * New or rehabbed coef. * Soil atten. factor * GW atten. factor

- This is the default or initial estimate of exfiltration.
- Additional factors will mediate this load.
- Exfiltration as a percent of dry-weather flow (as opposed to total flow) reduces impacts of I/I on exfiltration estimate.
- The median literature value for %DWF was selected
- For Test Case B, 98% of the system is gravity fed
- Compared to urban N load to streams (CAST '23)

Test Case B at this step:
383350.7 lbs. N/yr
18.41% of Developed Load



*3-48%
Divers et al., 2013
Recommendations of the Expert Panel to Define Removal Rates for the Elimination of Discovered Nutrient Discharges from Grey Infrastructure, 2014
Nguyen and Venohr, 2021
Delesantro et al. 2022, 2024
Wakida and Lerner, 2005

DETAILS

Calculating dry-weather flow

- Annual dry weather flow is defined as the lowest monthly flow * 12
- Outlier identification is needed to prevent facility flow transfers from creating anomalously low exfiltration years
  - The % dry-weather flow of total flow is calculated for each year
  - An outlier is defined by a value +/- 2 SD
  - Outlier years are assigned the last years dry-weather flow

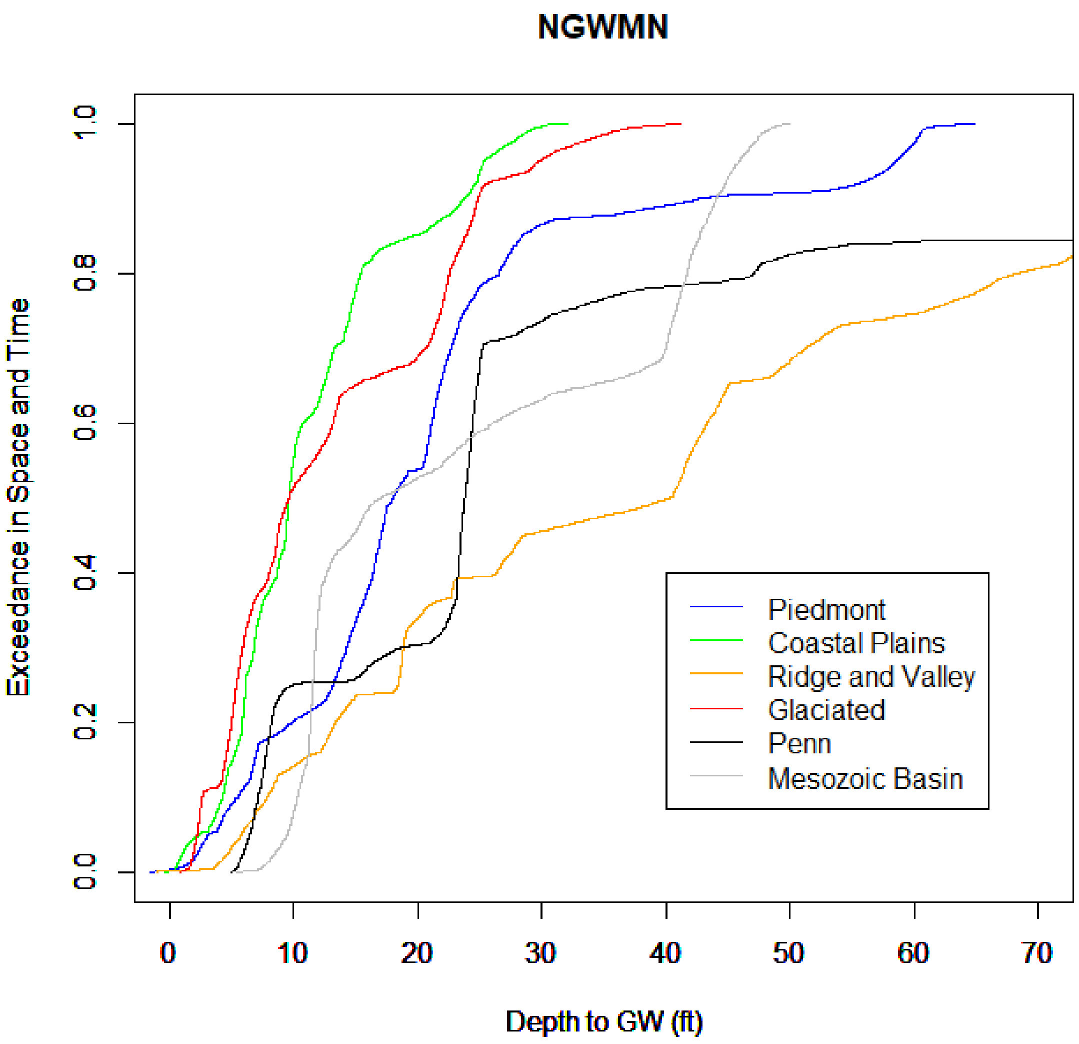
DETAILS

Groundwater Coefficient

Exfiltration Vol. = Fraction exfiltration * Annual system treatment volume * Fraction gravity line* Geologic coef. * New or rehabbed coef. * Soil atten. factor * GW atten. factor

The depth to groundwater fraction exceedance in space and time has been calculated for each hydrogeomorphic basin. This value represents the fraction of time/space that is inundated at a given depth to GW.

- A critical depth of 10 ft was selected to represent a mean invert depth. This value is based on literature and best professional judgement.
- Where service boundaries cross multiple hydrogeomorphic basins the groundwater coefficient value is population weighted.



For the test case region fraction exceedance was 0.36. Coef.=(1-0.36)

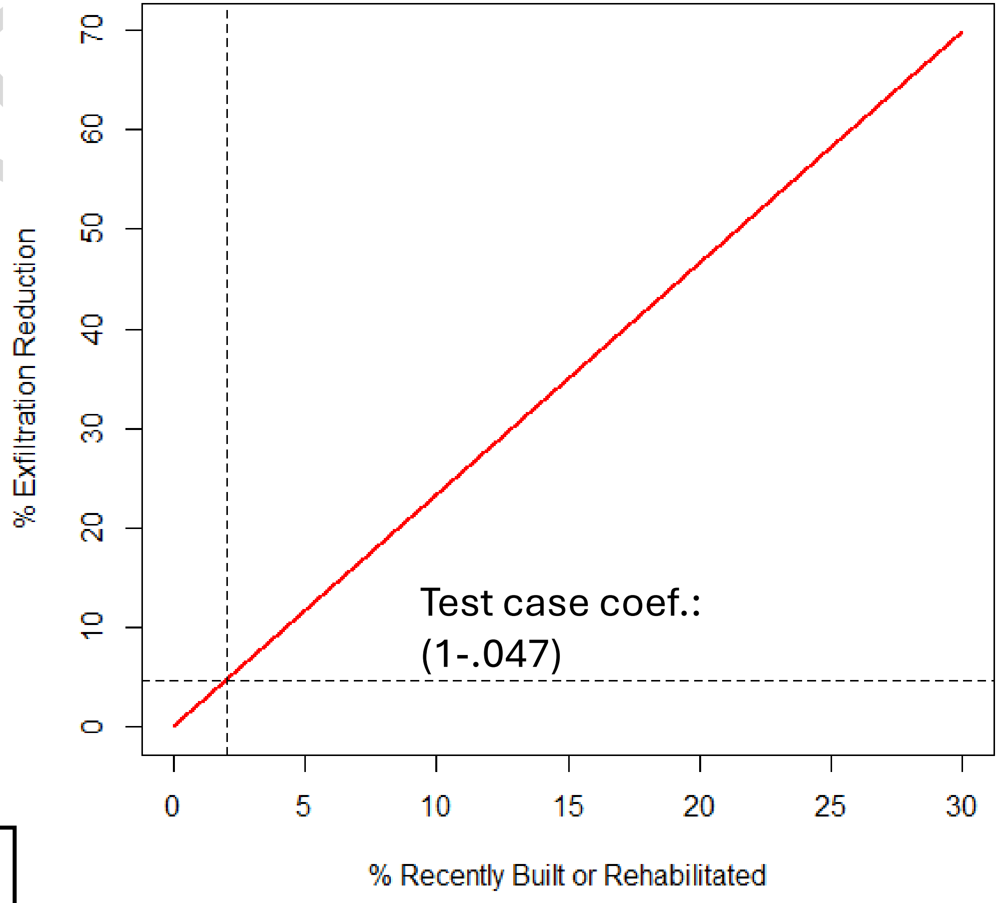
Test Case B at this step:
245344.5 lbs. N/yr
11.78 % of Developed Load

DETAILS

New and Newly Rehabilitated Sewer Coefficient

Exfiltration Vol. = Fraction exfiltration * Annual system treatment volume * Fraction gravity line* Geologic coef. * New or rehabbed coef. * Soil atten. factor * GW atten. factor

- Exfiltration primarily occurs from a fraction of the total system, 20-50%.
- Rehabilitation reduces exfiltration by 50-90%.
- Central values were selected
- A10-year timeframe is used to define new or newly rehabilitated
- Reporting of these values is intended to be optional, and therefore the impact should be conservative

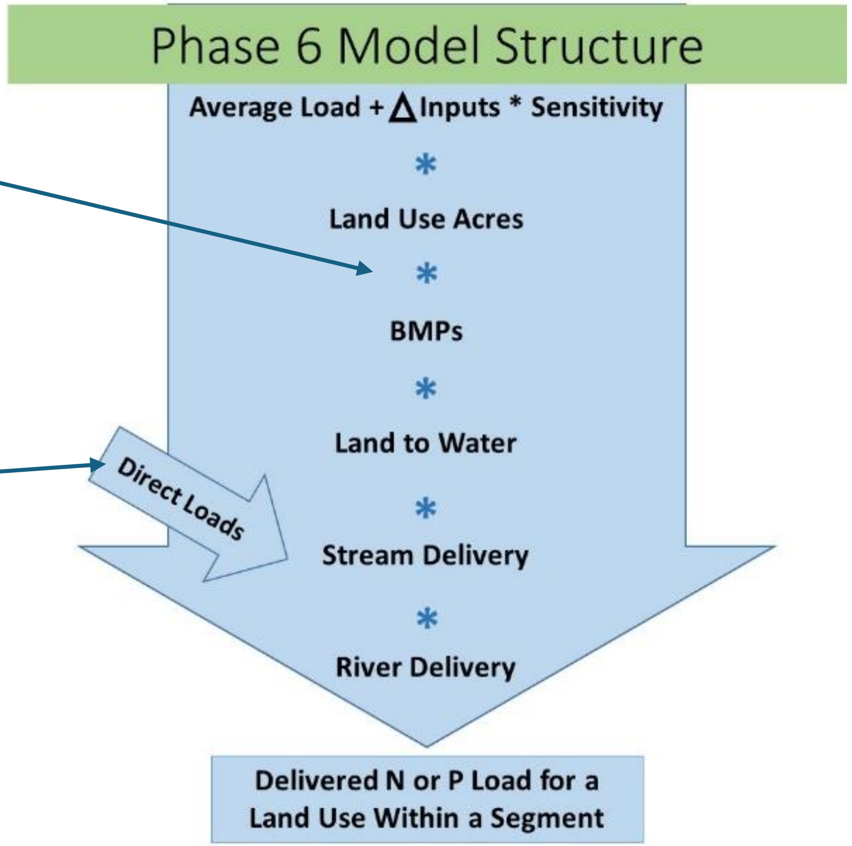


Test Case B at this step:
233911.4 lbs. N/yr
11.23 % of Developed Load

DETAILS

Attenuation in soil and groundwater (EOF to EOS)

- Option 1: Treat as a standard NPS and attenuate via Land-to-water factors.
  - Calibrated factors such as geology, soils, landscape connectivity, canopy cover, etc. which apply to all NPS.
- Option 2: Treat as a "direct load" where attenuation is defined separately (as part of the work group process).
  - There are still BMPs applied to "direct loads".



Attenuation (direct load)

Can we modify the existing framework and values for onsite wastewater attenuation for sanitary sewer exfiltration?

Possibly, but…

- septic systems are generally placed in uplands while sewers are preferentially placed near streams (Delesantro et al., 2021).
- Soil mapping and classification can be less accurate in urban areas.
- Sewer exfiltration is reduced lower in the soil column than septic effluent.
- Stormwater pipes can short circuit "attenuation zones".
- Urban soils can be N enriched reducing total % attenuation.
- The onsite wastewater report did not address phosphorous, but recommended future consideration.

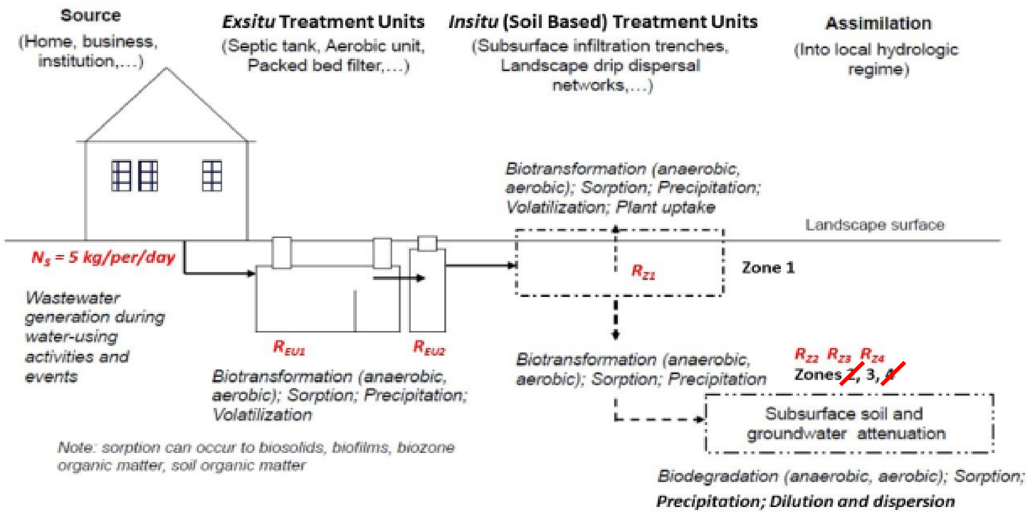


Figure 3. Nutrient Transformations associated with Treatment and Attenuation Zones (from Siegrist and Geza, 2014)

$$N_{LS} = \sum_{i=1}^{ST}\{\sum_{j=1}^{DU}[N_s(1-R_{EU1})(1-R_{EU2})(1-R_{Z1})(1-R_{Z2})(1-R_{Z3})(1-R_{Z4})]\}$$ **(Equation 1)**

Where:

N_{LS} = nutrient load from a land unit to the edge of stream (kg TN/day)
N_s = nutrient load from a source (e.g., house) (i.e., 5 kg TN/person/day)
R_{EU1} = fractional removal of TN in a 1st *exsitu* treatment unit (e.g., septic tank)
R_{EU2} = fractional removal of TN in a 2nd *exsitu* treatment unit (e.g., sand filter)
R_{Z1} = fractional removal of TN in Zone 1, Soil-Based Treatment
R_{Z2} = fractional removal of TN in Zone 2, Deep Vadose Zone
R_{Z3} = fractional removal of TN in Zone 3, Groundwater Zone
R_{Z4} = fractional removal of TN in Zone 4, Transitional Zones
ST = system type/characteristics 1, 2, 3
DU_i = dwelling units with system type *i*

The nitrogen reduction parameters referenced in Equation 1 and Figure 3 are further summarized in

Table 1, along with a brief summary of the Panel's source of information or approach used to characterize the parameter (in the "Comments" column).

Septic example

Modification for sewers

Soil attenuation is modified to account for urban short circuiting (static coefficient) and groundwater level relative to pipes (defined by groundwater level analysis by hydrogeomorphic basin)

Groundwater attenuation is modified to account for proximity of pipes to streams

- static factor based on the literature comparing septic and sewer locations relative to streams

Table 11. Recommended edge of Zone 1 TN load as a function of dominant soil texture for conventional onsite wastewater systems

Soil Textural Grouping	USDA Soil Textures	Zone 1 TN Reduction	TN Load at Edge of Zone 1
Sandy	Sand, Loamy Sand, Sandy Loam, Loam	16%	4.2 kg/cap/yr
Loamy	Silt loam, Clay Loam, Sandy Clay Loam, Silty Clay Loam, Silt	34%	3.3 kg/cap/yr
Clayey	Sandy Clay, Silty Clay, Clay	54%	2.3 kg/cap/yr

Table 12. Recommended Zone 3 attenuation factors for Chesapeake Bay HGMRs

Hydrogeomorphic Region[1]	Relative TN Transmission Classification	Recommended Zone 3 Attenuation Factor (Transmission Factor)
Fine Coastal Plain - Coastal Lowlands	Low	75% (25%)
Fine Coastal Plain - Alluvial and Estuarine Valleys	Low	75% (25%)
Fine Coastal Plain - Inner Coastal Plain - Upland Sands and Gravels	Medium	60% (40%)
Fine Coastal Plain - Middle Coastal Plain – mixed sediment texture	Medium	60% (40%)
Fine Coastal Plain - Middle Coastal Plain – fine sediment texture	Low	75% (25%)
Coarse Coastal Plain - Middle Coastal Plain – Sands with Overlying Gravels (also dissected)	High	45% (55%)
Coarse Coastal Plain - Inner Coastal Plain - Dissected Outcrop Belt	High	45% (55%)
Crystalline Piedmont	High	45% (55%)
Crystalline Blue Ridge	High	45% (55%)
Carbonate Piedmont	Very High	35% (65%)
Carbonate Valley and Ridge	Very High	35% (65%)
Carbonate Appalachian Plateau	Very High	35% (65%)
Siliciclastic Mesozoic Lowland	High	45% (55%)
Siliciclastic Valley and Ridge	Medium	60% (40%)
Siliciclastic Appalachian Plateau	Low	75% (25%)

[1] Generalized Geology from Greene et al., 2005; Subdivisions from Bachman et al., 1998, and Ator et al., 2005 for coastal plain

DETAILS

Zone 1 Attenuation

Exfiltration Vol. = Fraction exfiltration * Annual system treatment volume * Fraction gravity line* Geologic coef. * New or rehabbed coef. * Soil atten. factor * GW atten. factor

Proposals:

1 - Reduce the TN reduction to account for urban hydrologic connectivity and N enrichment and modify based on depth to GW via the groundwater coefficient.

2 – No soil attenuation due to the depth of SSE

For example: 34% * 0.8 * (1-0.36) = 17.41%

Test Case B:
194146.5 lbs. N/yr
9.32 % of Urban Load

Table 11. Recommended edge of Zone 1 TN load as a function of dominant soil texture for conventional onsite wastewater systems

Soil Textural Grouping	USDA Soil Textures	Zone 1 TN Reduction	TN Load at Edge of Zone 1
Sandy	Sand, Loamy Sand, Sandy Loam, Loam	16%	4.2 kg/cap/yr
Loamy	Silt loam, Clay Loam, Sandy Clay Loam, Silty Clay Loam, Silt	34%	3.3 kg/cap/yr
Clayey	Sandy Clay, Silty Clay, Clay	54%	2.3 kg/cap/yr

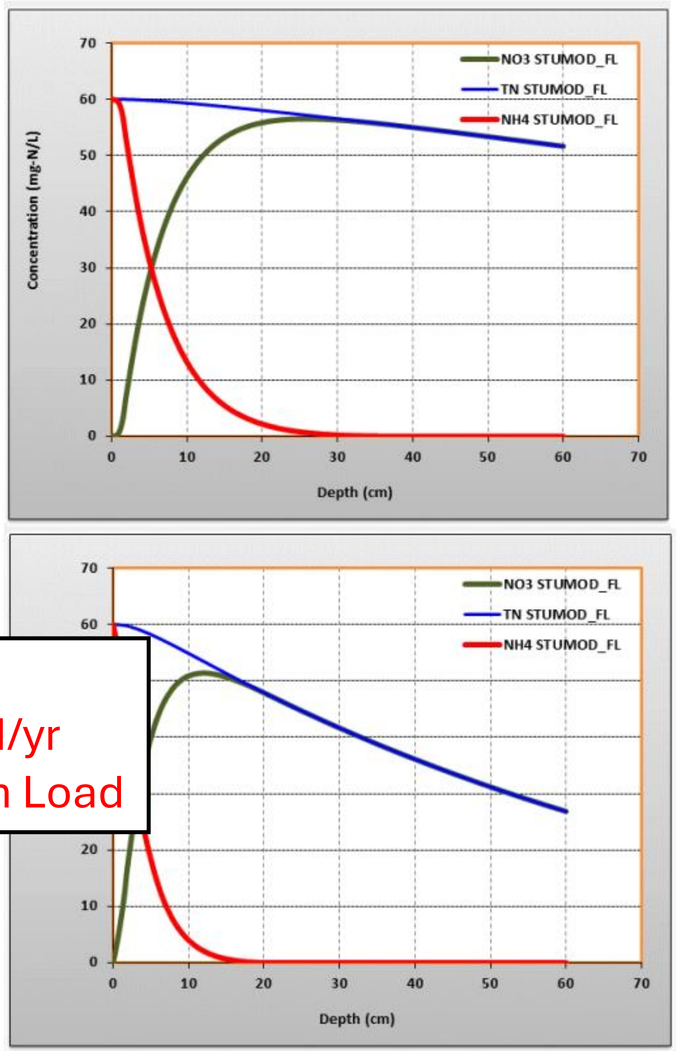


Figure 5. Concentrations from STUMOD of NH_4^+, NO_3^-, and TN as a function of depth below the infiltrative surface for a loamy sand soil (top graph) and a clay (bottom graph) for conventional systems with a water table at 60 cm and 100 percent of the design hydraulic loading rate (see Table 2).

DETAILS

Zone 3 Attenuation

Exfiltration Vol. = Fraction exfiltration * Annual system treatment volume * Fraction gravity line* Geologic coef. * New or rehabbed coef. * Soil atten. factor * GW atten. factor

In the North Carolina Piedmont, sewer lines are 36% closer to streams than septic systems (via flow path distance).

Proposal: Reduce the attenuation factor based on the exponential of relative distance to streams.

For example: Case B is in the high transmission class 1-exp(ln(0.55)*(1-.36))=0.32 or 32% attenuation factor

Test Case B at this step:
132019.6 lbs. N/yr
6.34 % of Urban Load

Table 12. Recommended Zone 3 attenuation factors for Chesapeake Bay HGMRs

Hydrogeomorphic Region[1]	Relative TN Transmission Classification	Recommended Zone 3 Attenuation Factor (Transmission Factor)
Fine Coastal Plain - Coastal Lowlands	Low	75% (25%)
Fine Coastal Plain - Alluvial and Estuarine Valleys	Low	75% (25%)
Fine Coastal Plain - Inner Coastal Plain - Upland Sands and Gravels	Medium	60% (40%)
Fine Coastal Plain - Middle Coastal Plain – mixed sediment texture	Medium	60% (40%)
Fine Coastal Plain - Middle Coastal Plain – fine sediment texture	Low	75% (25%)
Coarse Coastal Plain - Middle Coastal Plain – Sands with Overlying Gravels (also dissected)	High	45% (55%)
Coarse Coastal Plain - Inner Coastal Plain - Dissected Outcrop Belt	High	45% (55%)
Crystalline Piedmont	High	45% (55%)
Crystalline Blue Ridge	High	45% (55%)
Carbonate Piedmont	Very High	35% (65%)
Carbonate Valley and Ridge	Very High	35% (65%)
Carbonate Appalachian Plateau	Very High	35% (65%)
Siliciclastic Mesozoic Lowland	High	45% (55%)
Siliciclastic Valley and Ridge	Medium	60% (40%)
Siliciclastic Appalachian Plateau	Low	75% (25%)

[1] Generalized Geology from Greene et al., 2005; Subdivisions from Bachman et al., 1998, and Ator et al., 2005 for coastal plain

Phosphorus Attenuation

Phosphorus attenuation is effectivity 100% in the onsite wastewater. However, the literature suggests that phosphorus from leaking sewers (and septic) can be an important source of P in developed landscapes (Delesantro et al., 2021, Baltimore LTER, Nguyen and Venohr, 2020, Humphrey et al. 2014, Humphrey et al. 2015)

Proposal: Set P attenuation proportional to N attenuation.

- Extend the N attenuation method to P assuming 100% baseline attenuation and applying the sewer discounting via the percent difference in septic to sewer N attenuation
- Currently testing

Preliminary estimates of SSE load to streams

Baltimore (Co and City)

- 132,019.6 lbs./yr TN
- 6.34% of CAST '23 developed TN load
- 14,435 lbs./yr TP
- 15.85% of CAST '23 developed TP load

HRSD

- 122,581.8 lbs./yr TN
- 2.90% of CAST '23 developed TN load
- 10,810 lbs./yr TP
- 3.6% of CAST '23 developed TP load

Watershed (without soil/GW attenuation, preliminary)

- 2.6 million lbs./yr TN
- 3.1% CAST '23 developed TN load

Values are on the conservative end of the literature range as a percent of the urban load.

Agricultural inputs

New crop yields have been approved by the Agriculture Modeling Team

- Modeled based on time, weather, and economics
  - Crop yield attracting applications
  - Weather-independent yield informing crop uptake

Currently working to update fertilizer input datasets (with Tom Butler and Jess Rigelman, presenting Friday at AMT)

Discussion