WQGIT Office Hours: Sanitary Sewer Exfiltration

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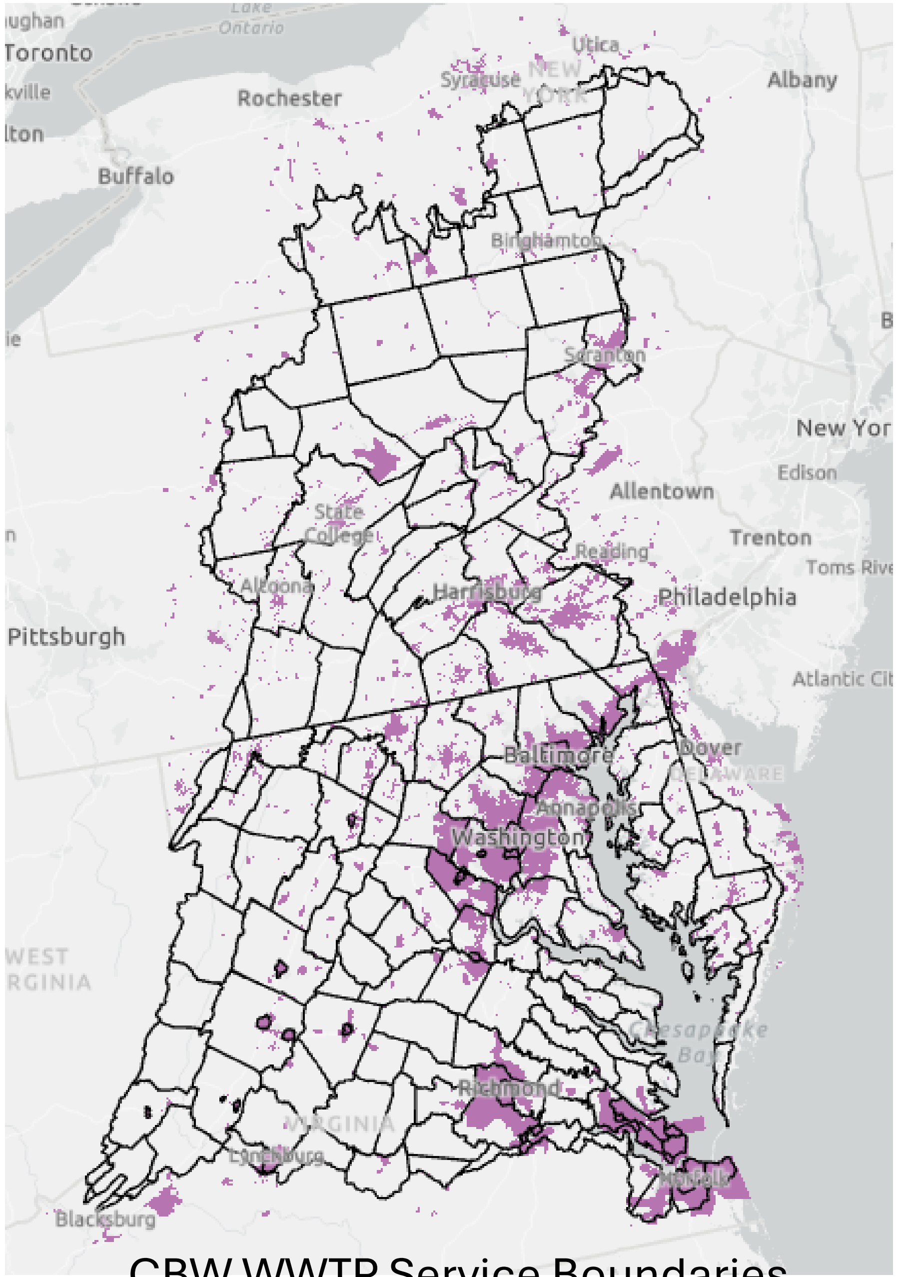


CBW WWTP Service Boundaries

- Humans convert food to wastewater

- And we depend on sanitary infrastructure to contain and treat this nitrogen source

Bernhardt et al.: *Urban Impacts on Surface Water Nitrogen Loading*

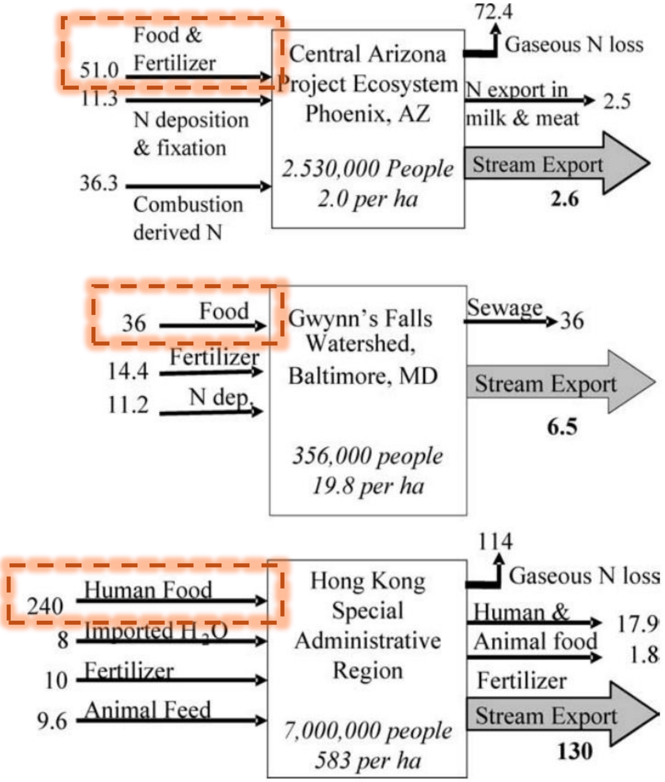
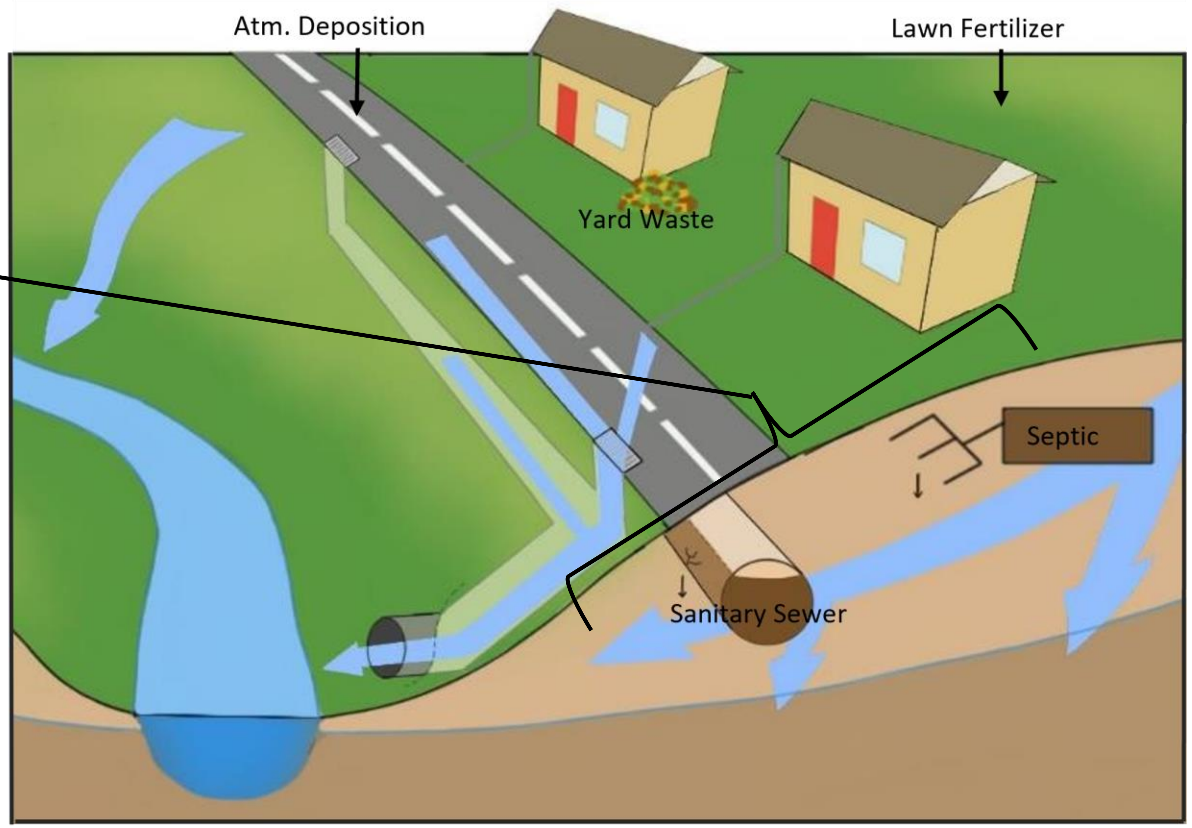


Figure 2. Compiled mass balance estimates for three cities (data in kg N ha^{-1} y^{-1}) arranged in order of increasing population density. Data for Phoenix from Baker *et al.* 2001, for Baltimore from Groffman *et al.* 2004, and for Hong-Kong from Warren-Rhodes and Koenig 2001. Note the discrepancies between the types of fluxes measured in each study.

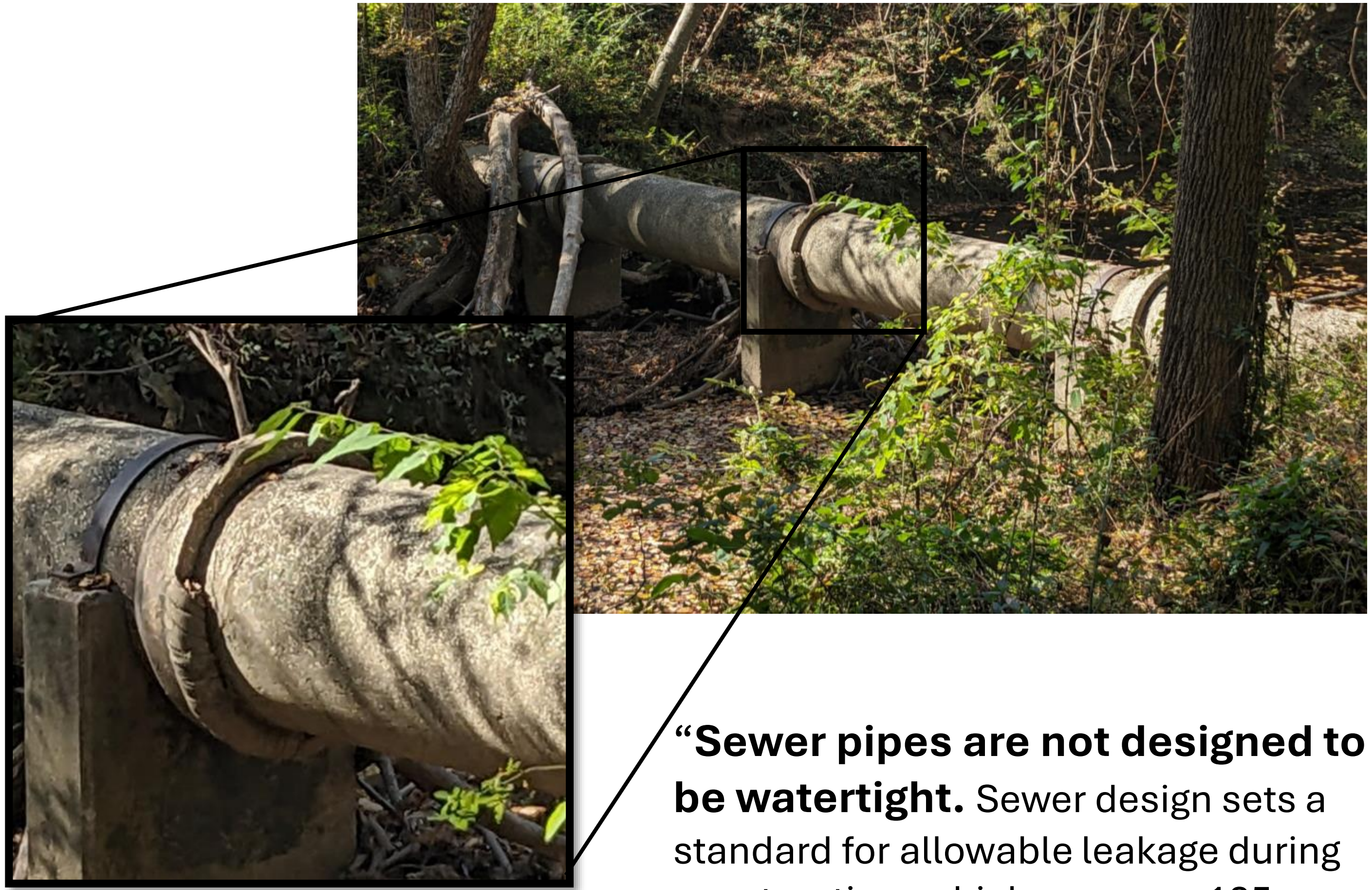


Bernhardt, E. S., Band, L. E., Walsh, C. J., & Berke, P. E. (2008). Understanding, managing, and minimizing urban impacts on surface water nitrogen loading. *Annals of the New York Academy of Sciences*, *1134*, 61–96.

Baker, L. A., Hope, D., Xu, Y., Edmonds, J., & Lauver, L. (2001). Nitrogen balance for the Central Arizona-Phoenix (CAP) ecosystem. *Ecosystems*, *4*(6), 582–602.

Groffman, P. M., Law, N. L., Belt, K. T., Band, L. E., & Fisher, G. T. (2004). Nitrogen Fluxes and Retention in Urban Watershed Ecosystems. *Ecosystems*, *7*(4), 393–403.

Warren-Rhodes, K. & A. Koenig. (2001). Ecosystem ap- propriation by Hong Kong and its implications for sustainable development. Ecol. Econ. 39: 347–359.

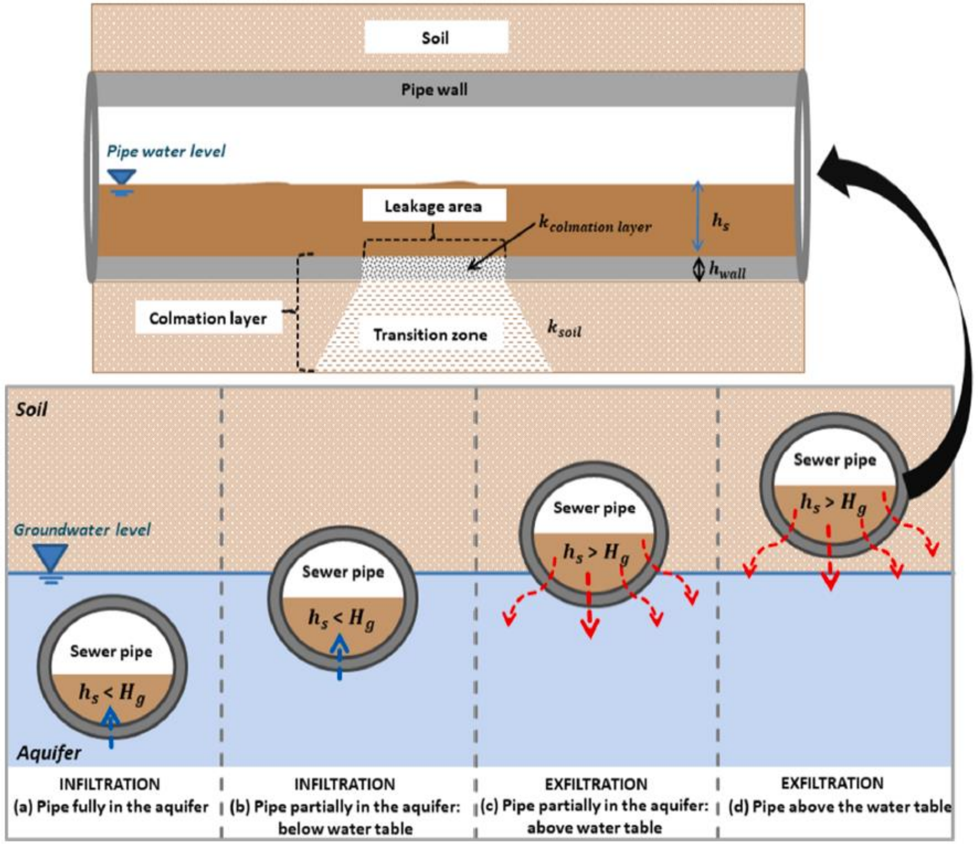


“**Sewer pipes are not designed to be watertight.** Sewer design sets a standard for allowable leakage during construction, which averages 125 gallons per 400 feet of pipe, which is the standard distance between sewer manholes (ASTM, 2009), or about 1,650 gallons per mile of standard sewer pipe.”

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

Net infiltration does not exclude exfiltration

- Net system infiltration does not exclude areas of exfiltration
- Segments may infiltrate in wet periods and exfiltrate in dry periods
- Because WW nutrient concentrations are 2-3 orders or magnitude greater than background, small amounts of exfiltration can represent significant loads



Nguyen, Hong Hanh, Aaron Peche, and Markus Venohr. "Modelling of sewer exfiltration to groundwater in urban wastewater systems: A critical review." *Journal of Hydrology* 596 (2021): 126130.

Why does this matter for the model?

- Proper appropriation of loads
  - Improved calibration
- Improved targeting and crediting of management actions
- Scenario analysis (E.g., remediation, septic/sewer conversion)

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

Most of the misappropriation is likely to stormwater and lawn fertilizers. These are surface sources, and many of the management practices applied will have little to no impact on subsurface sewer exfiltration.

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.

Model structure

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

EOS nutrient load = 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

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

Median value from literature selected: 2.4%

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)

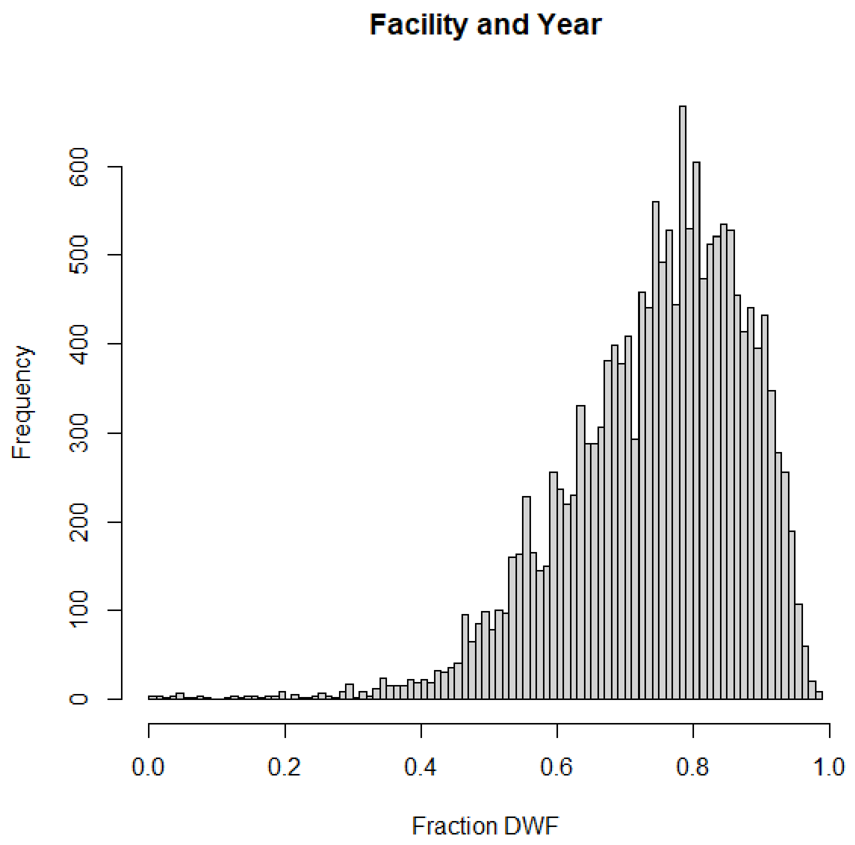
Notes:

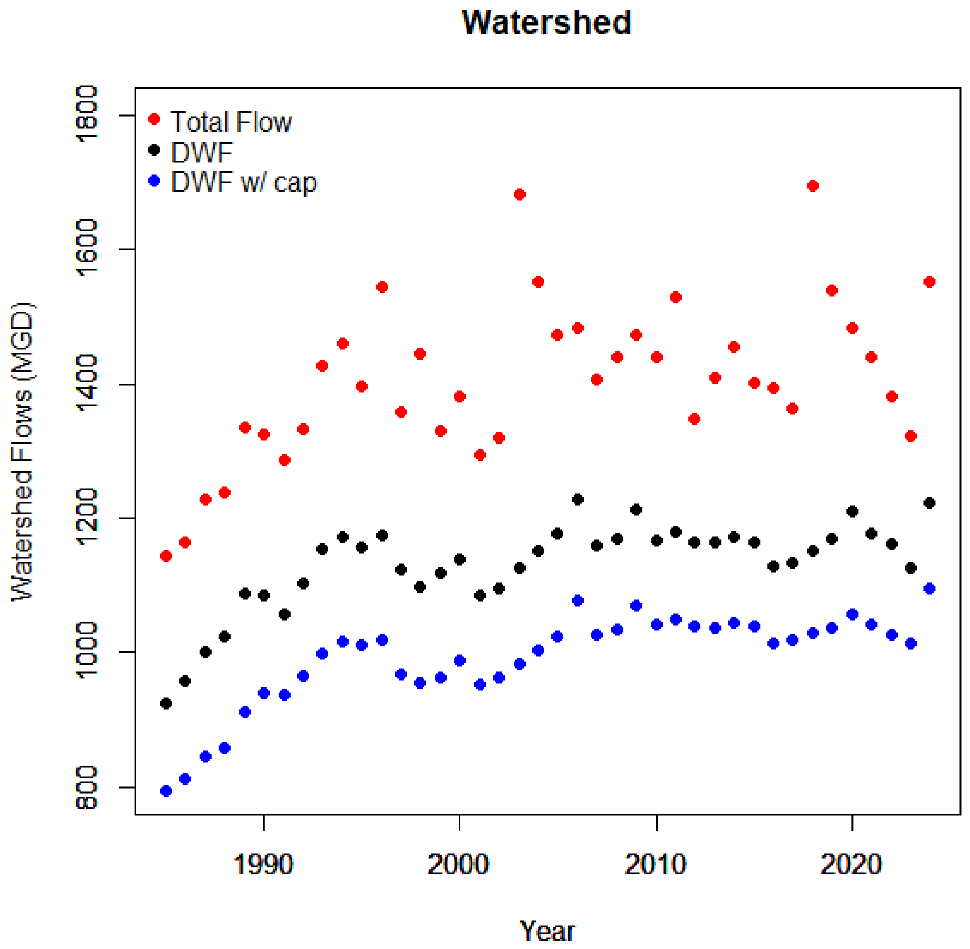
- Filtered to remove laboratory analyses which tend to be higher
- Amik et al., and CIRIA 1995 were removed as an outliers from subsequent analyses
- Delesantro et al., 2022: Assuming NO_3^- proportion from WW ~ TN proportion from WW
- Studies estimate exfiltration from pipe, to GW, or to streams
- Studies 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 Vol. = Fraction exfiltration * Annual system treatment volume (dry-weather) * Geologic coef. * Fraction gravity line * (Fraction new or rehabbed*Rehabbed coef.)

Annual dry weather flow is defined by the lowest monthly flow and capped based on model unit population

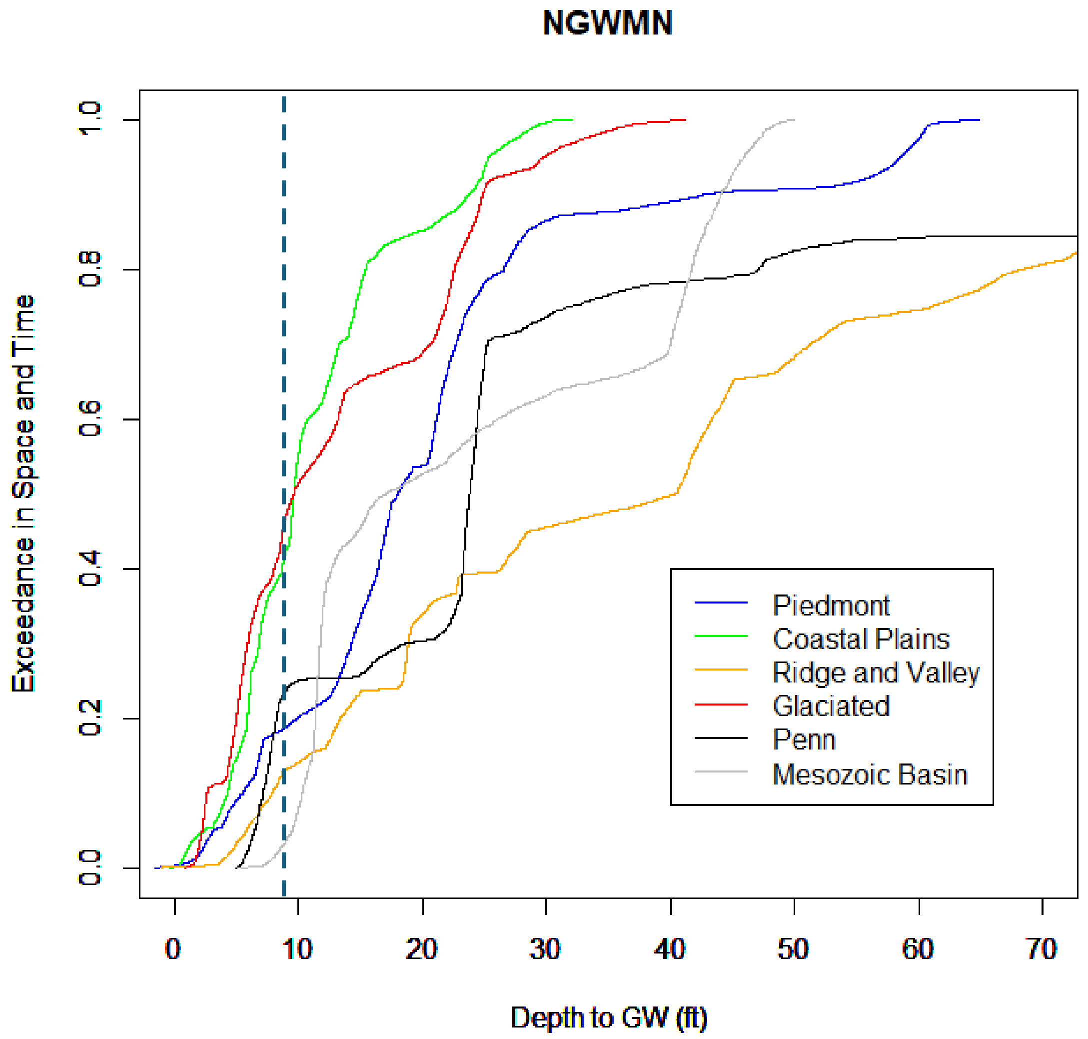




Exfiltration Vol. = Fraction exfiltration * Annual system treatment volume (dry-weather) * Geologic coef. * Fraction gravity line * (Fraction new or rehabbed*Rehabbed coef.)

One minus the estimated fraction of time and space within a hydrogeomorphic basin (or corresponding aquifer system) where pipes at a depth of 9.2 ft will be inundated, and therefore not exfiltrating.

- A critical depth of 9.2 ft was selected to represent a mean invert depth. This value is based on best professional judgement and an analysis by MD.
- Ground-water observations are queried from the National Ground-Water Monitoring Network. (https://www.usgs.gov/apps/ngwmn)
- This value is static in time.

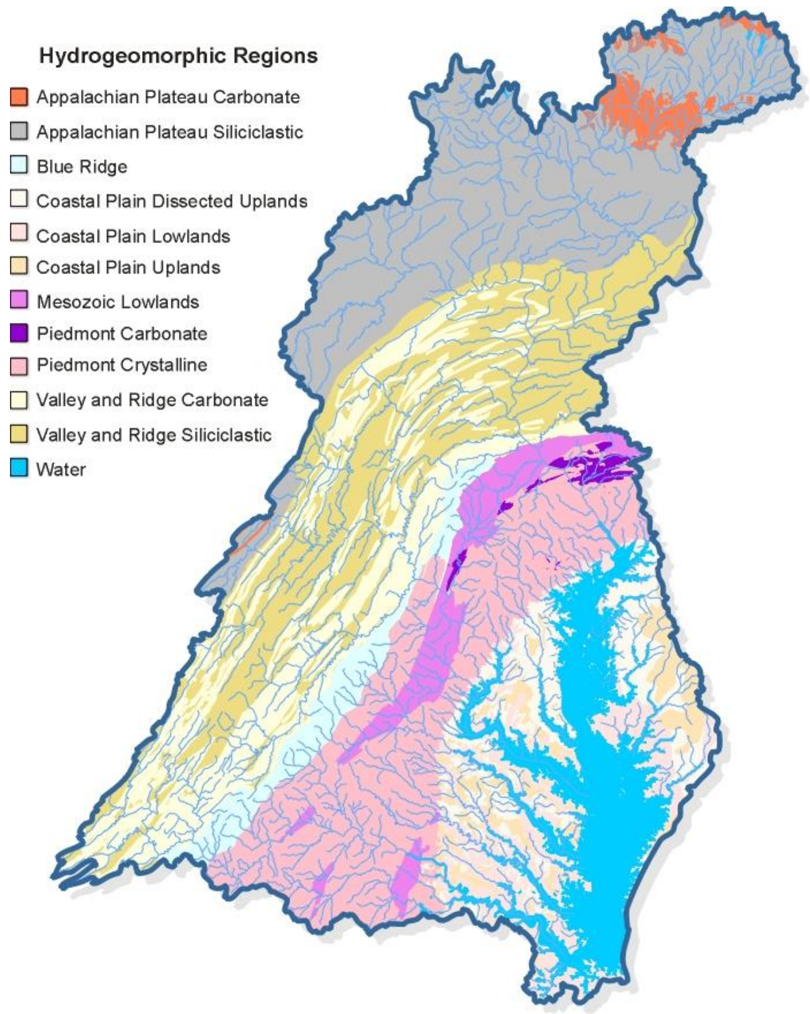


Note: Not all basins shown in this figure. There are 11.

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

HGMR	Inundation	Facility n	
Coastal Plains Upland	0.432	15	
Coastal Plains Dissected	0.432	48	
Coastal Plains Lowlands	0.432	54	
Valley and Ridge Siliciclastic	0.133	122	
Valley and Ridge Carbonate	0.133	51	
Appalachian Plateau Siliciclastic	0.482	2	
Appalachian Plateau Carbonate	0.93	1	
Piedmont Crystalline	0.191	47	
Piedmont Carbonate	0.013	20	Note: Only three wells in this basin
Mesozoic	0.041	34	
Blue Ridge	0.133	7	

Note: The coefficient as applied is 1- above value



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

Force mains are designed to be watertight and are less susceptible to chronic leaks.

- Optional reporting
- E.g., Baltimore area gravity line is 98% gravity line, Coastal SE VA is 84%.

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

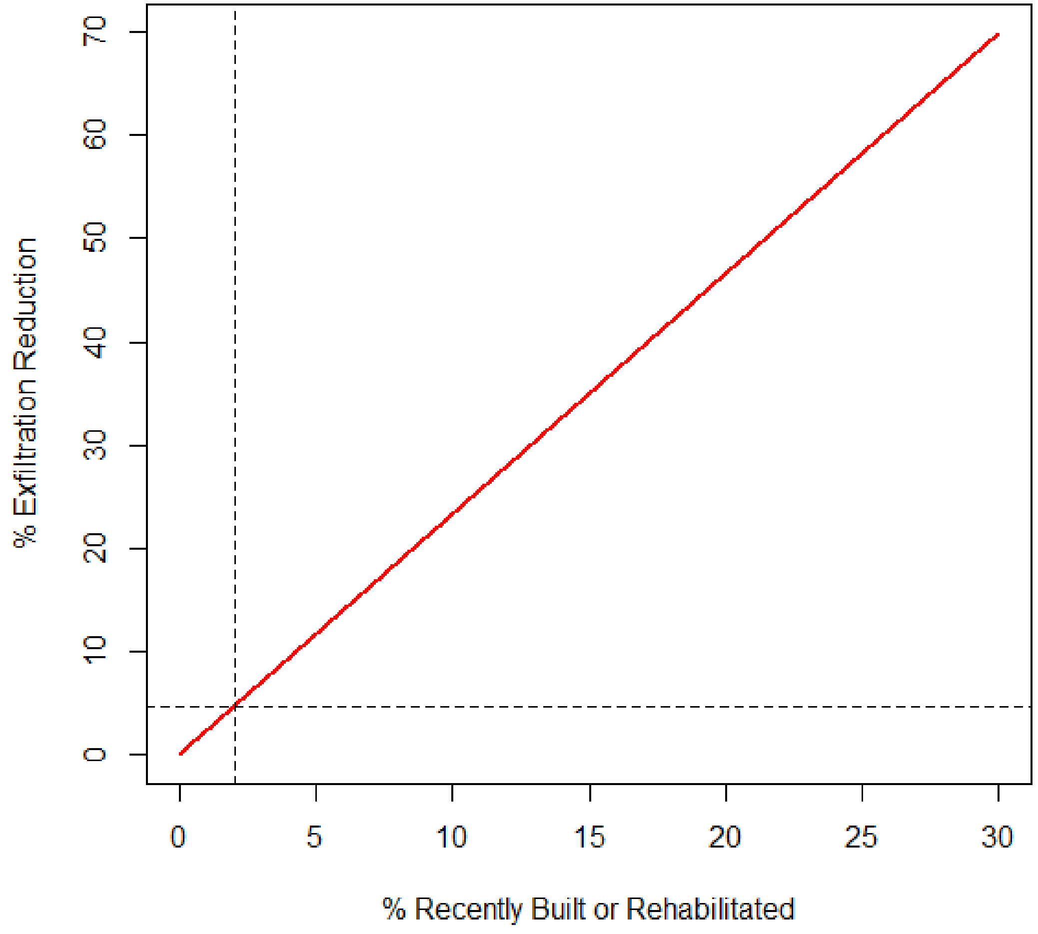
Exfiltration primarily occurs from a fraction of the total system, 20-50%.

Rehabilitation reduces exfiltration by 50-90%.

Central values were selected

A 10-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

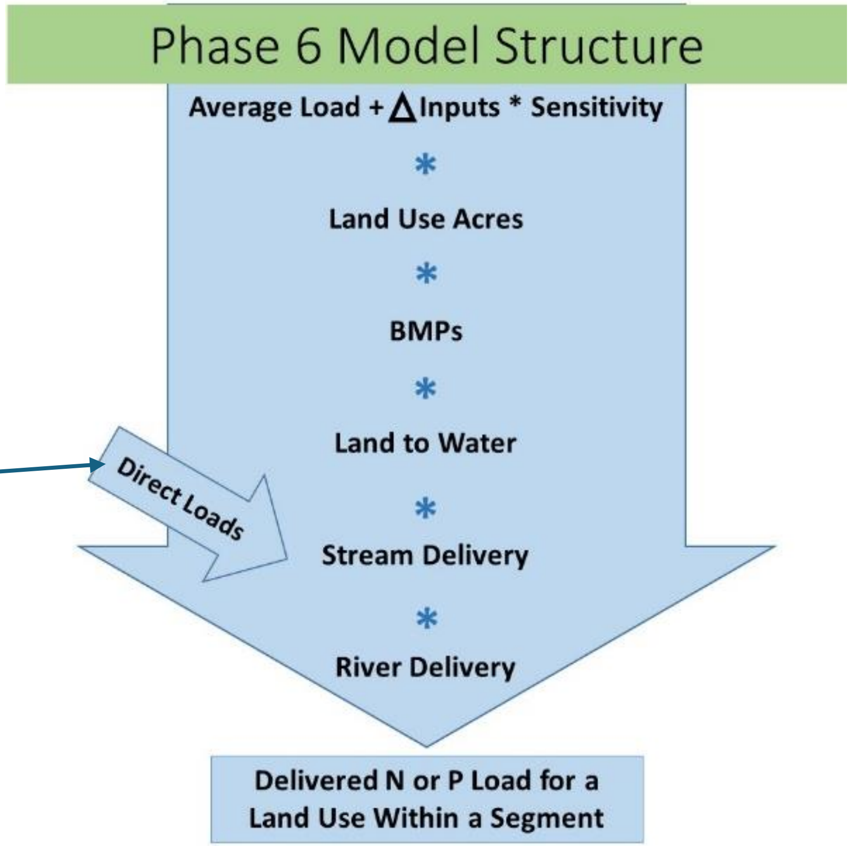


Attenuation in soil and groundwater (EOF to EOS)

EOS nutrient load = Exfiltration Vol. * concentration in raw WW *Soil Treatment*GW Transmission

Treated as a "direct load" where attenuation is defined separately (as part of the work group process).

- There are still BMPs applied to "direct loads".

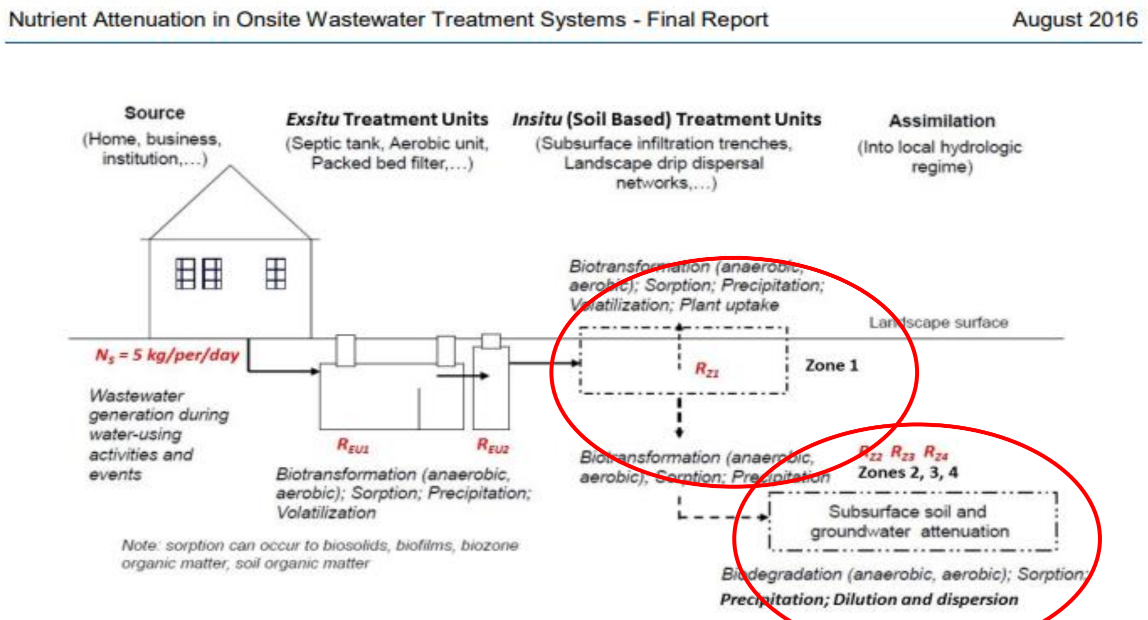


Attenuation in soil and groundwater (EOF to EOS)

Modified the existing framework and values for onsite wastewater attenuation for sanitary sewer exfiltration.

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

Ground-water attenuation is modified to account for proximity of pipes to streams, a static factor based on the literature comparing septic and sewer locations relative to streams



Septic example

Phosphorus Attenuation

Phosphorus attenuation is effectivity 100% in the onsite wastewater. However, the literature suggests that phosphorus from leaking sewers and septic systems can be an important source of P in developed landscapes (Delesantro et al., 2021, Nguyen and Venohr, 2020, Humphrey et al. 2014, Humphrey et al. 2015, Iverson et al. 2018, Humphrey et al. 2020).

Set P attenuation proportional to the change in N attenuation from septic to sewer.

- 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

Soil and GW attenuation in testing:

Mean N attenuation is 47%

Mean P attenuation is 89%

Preliminary Results

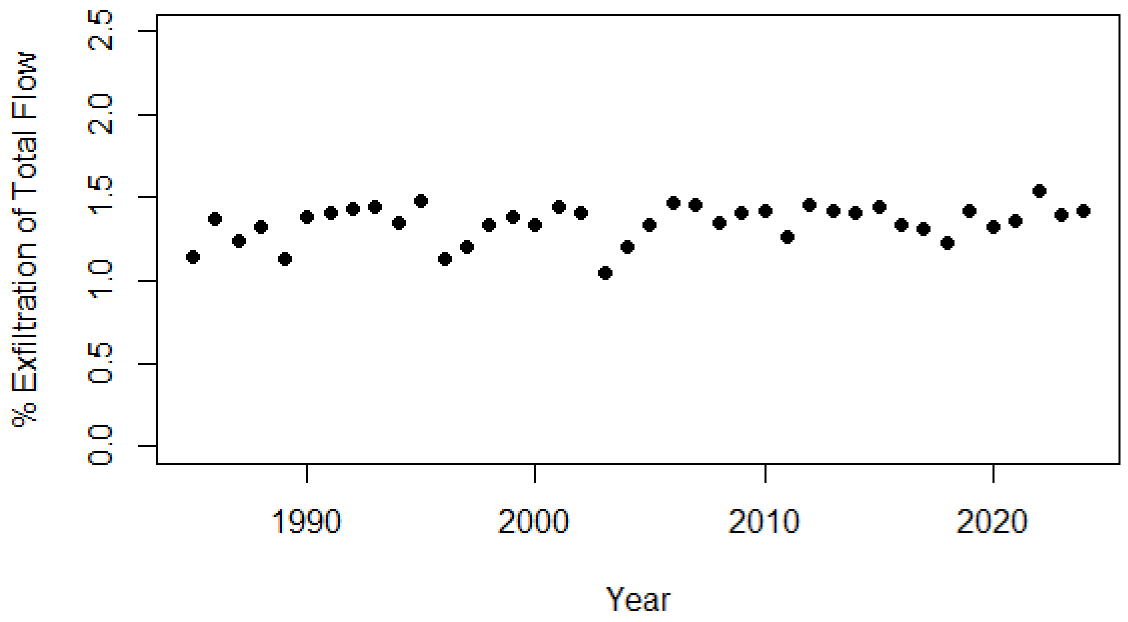
Notes

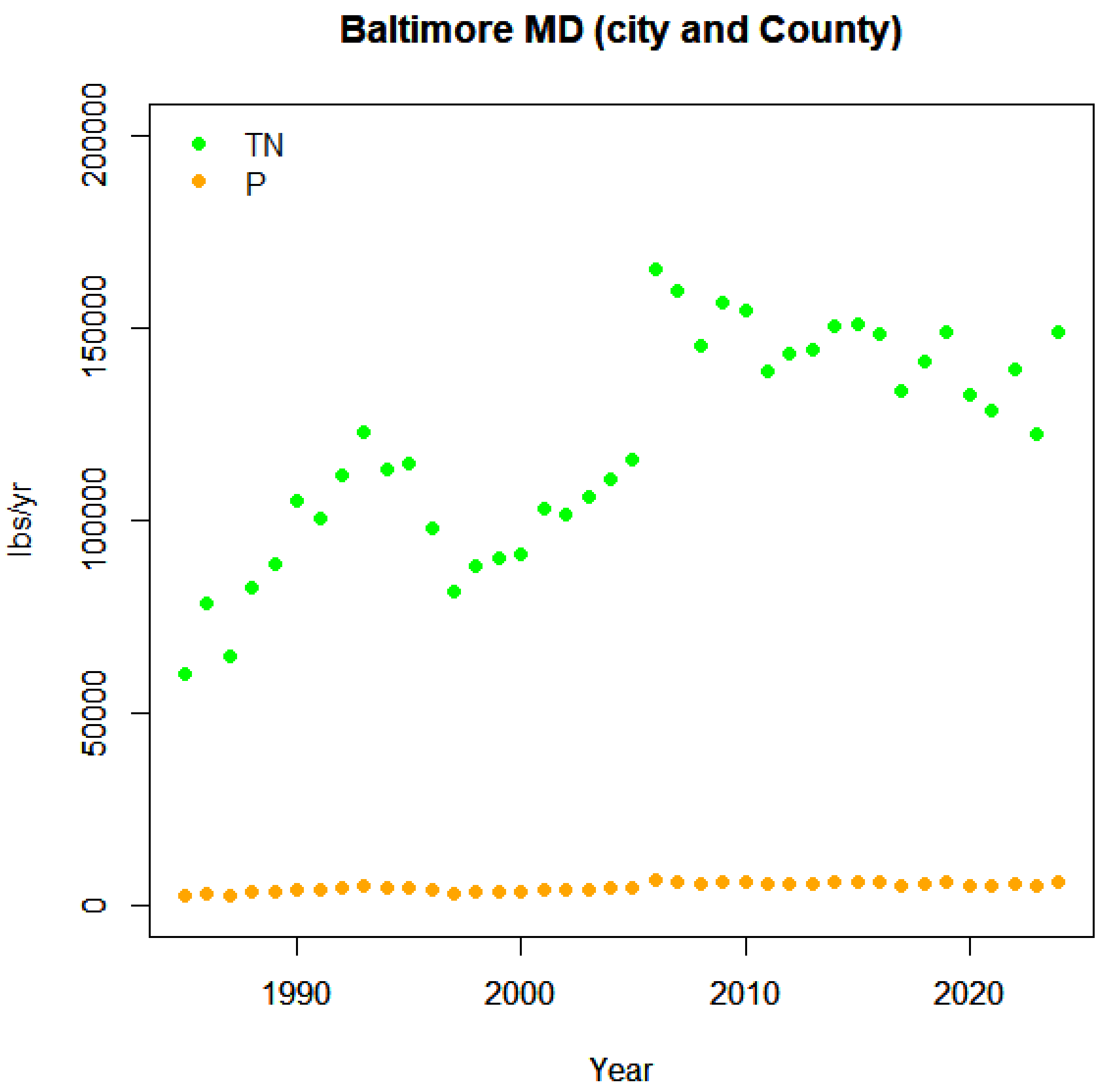
- P6 input datasets are used for testing and development. Final results will vary.
- This testing does not include optional inputs, those have been tested and reported for Baltimore (city and co) and SE VA (HRSD).
- In testing 1.9% of discharges have no associated exfiltration due to NAs which will be resolved for P7.

Watershed wide	TN			P		
	1995	2020	mean	1995	2020	mean
Lbs/yr	1010642	1048515	987587	40383	42223	39817
% total EOS load	0.18%	0.20%		0.10%	0.14%	
% EOS developed load	1.35%	1.16%		0.74%	0.81%	

Preliminary Results

Baltimore (city+county)	TN			P		
	1995	2020	mean	1995	2020	mean
Lbs/yr	114785	132735	119597	4549	5223	4730
% of developed load	5.73%	6.35%		2.71%	5.74%	





Discussion

Details on soil and GW attenuation

Zone 1 Attenuation

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

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

For example, if the soil group is loamy and the GW factor is 0.036: 34% * 0.8 * (1-0.36) = 17.41%

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

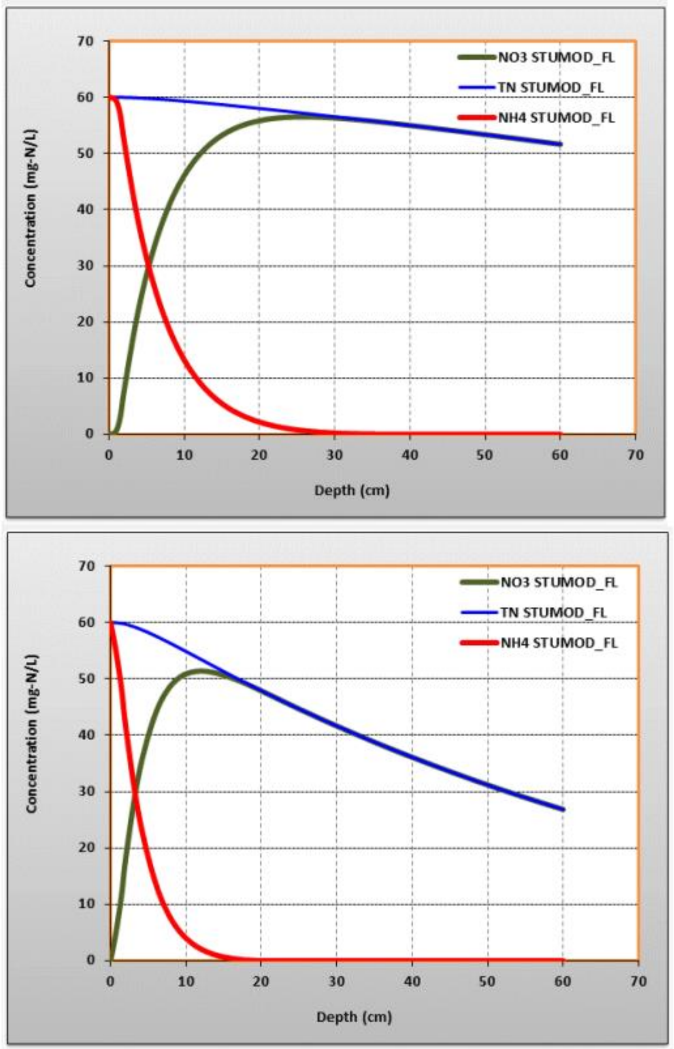


Figure 5. Concentrations from STUMOD of NH_4^+, NO_3^-, and TN as a function of depth below the infiltrative surface for a loamy sand soil (top graph) and a clay (bottom graph) for conventional systems with a water table at 60 cm and 100 percent of the design hydraulic loading rate (see Table 2).

Nutrient Attenuation in Onsite Wastewater Treatment Systems - Final Report

Zone 3 Attenuation

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

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

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

For example, if the service area is in the high transmission class with an attenuation factor of 45%: 1-exp(ln(0.55)*(1-.36))=0.32 or 32% attenuation factor

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

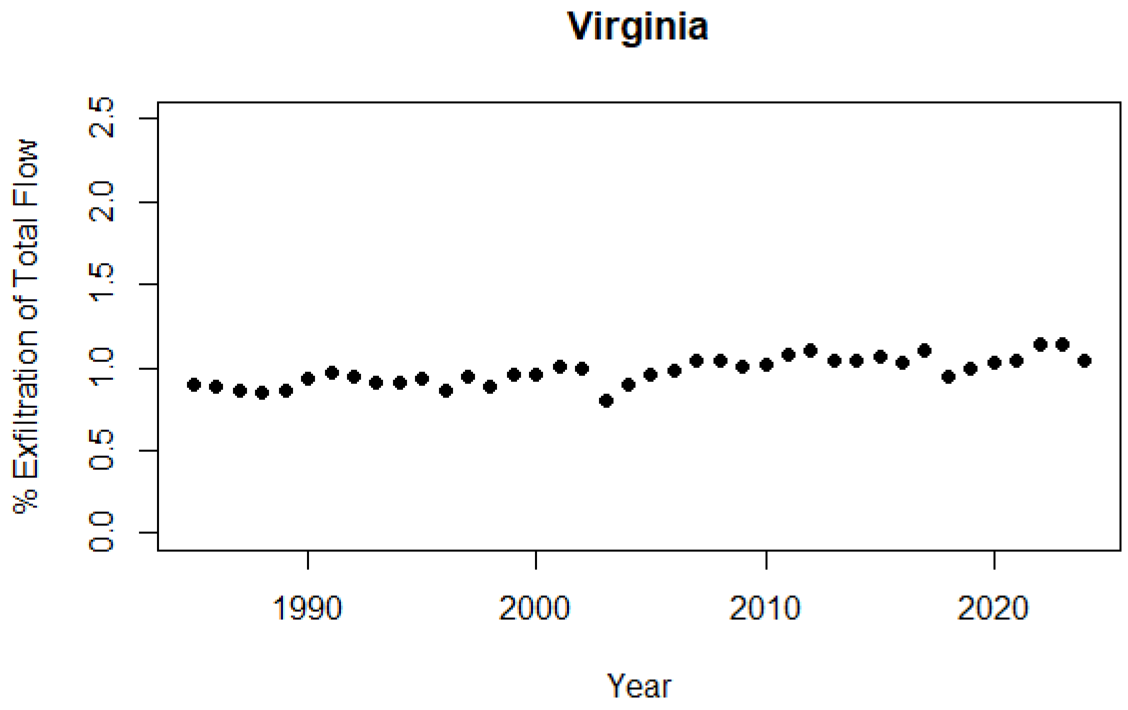
Hydrogeomorphic Region[1]	Relative TN Transmission Classification	Recommended Zone 3 Attenuation Factor (Transmission Factor)
Fine Coastal Plain - Coastal Lowlands	Low	75% (25%)
Fine Coastal Plain - Alluvial and Estuarine Valleys	Low	75% (25%)
Fine Coastal Plain - Inner Coastal Plain - Upland Sands and 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%)

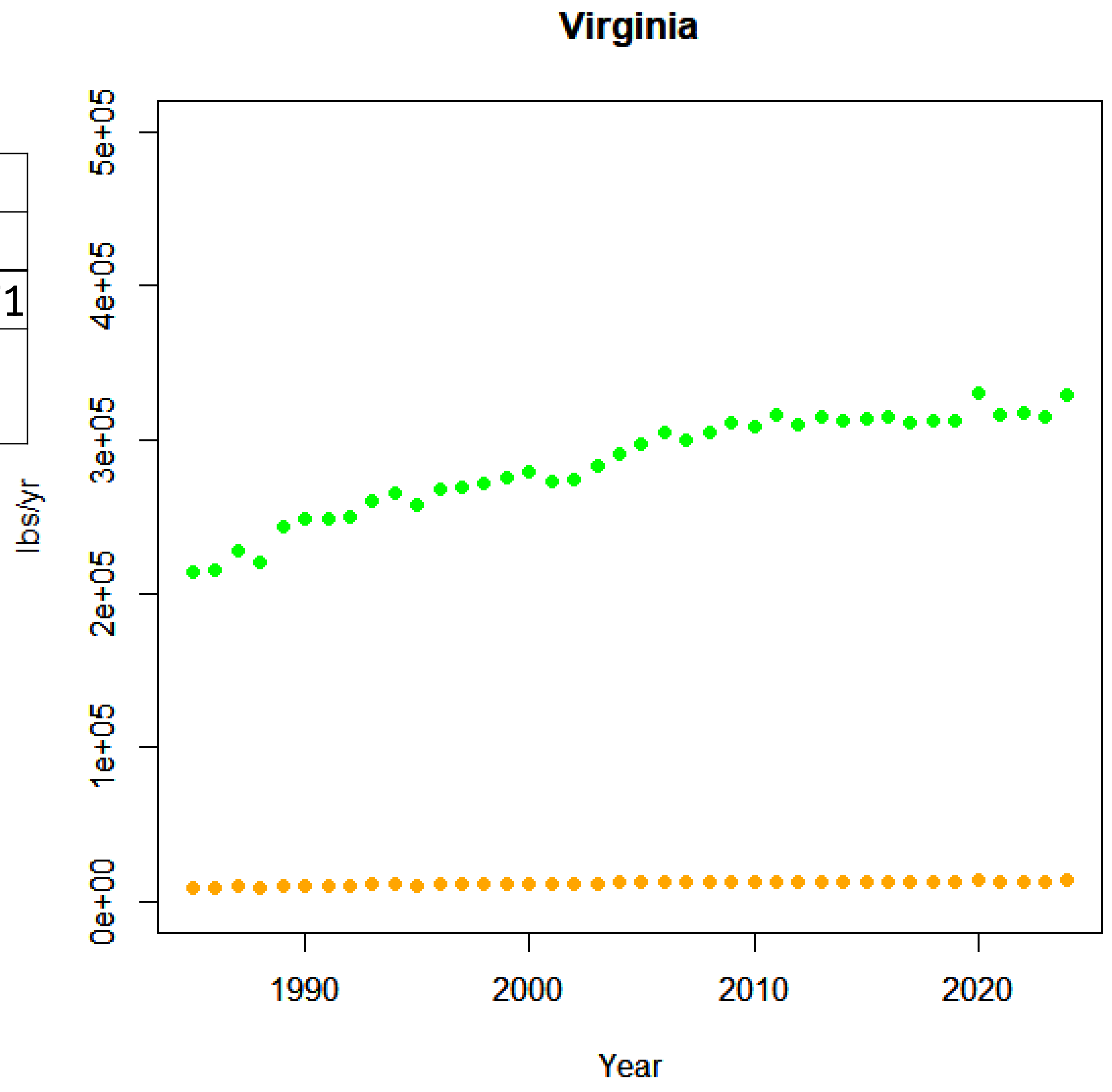
[1] Generalized Geology from Greene et al., 2005; Subdivisions from Bachman et al., 1998, and Ator et al., 2005 for coastal plain

Subset of example results

Preliminary Results

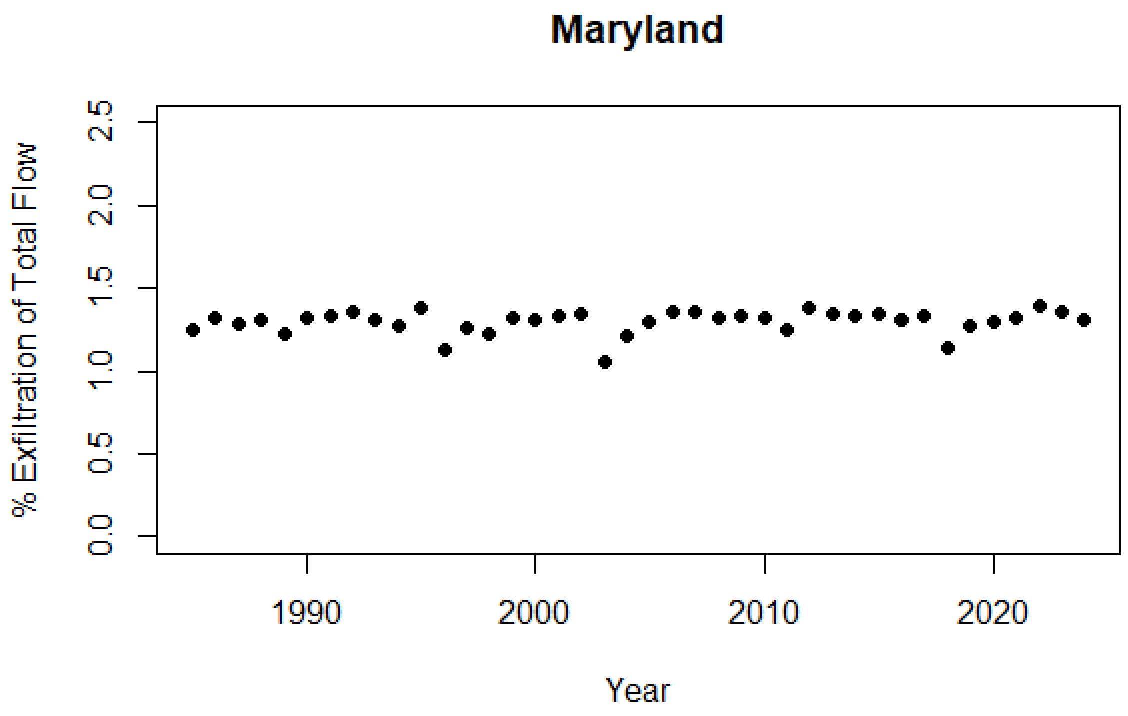
Virginia	TN			P		
	1995	2020	mean	1995	2020	mean
Lbs/yr	257629	329797	296464	10710	13453	12271
% of developed load	1.66%	1.63%		0.56%	0.68%	

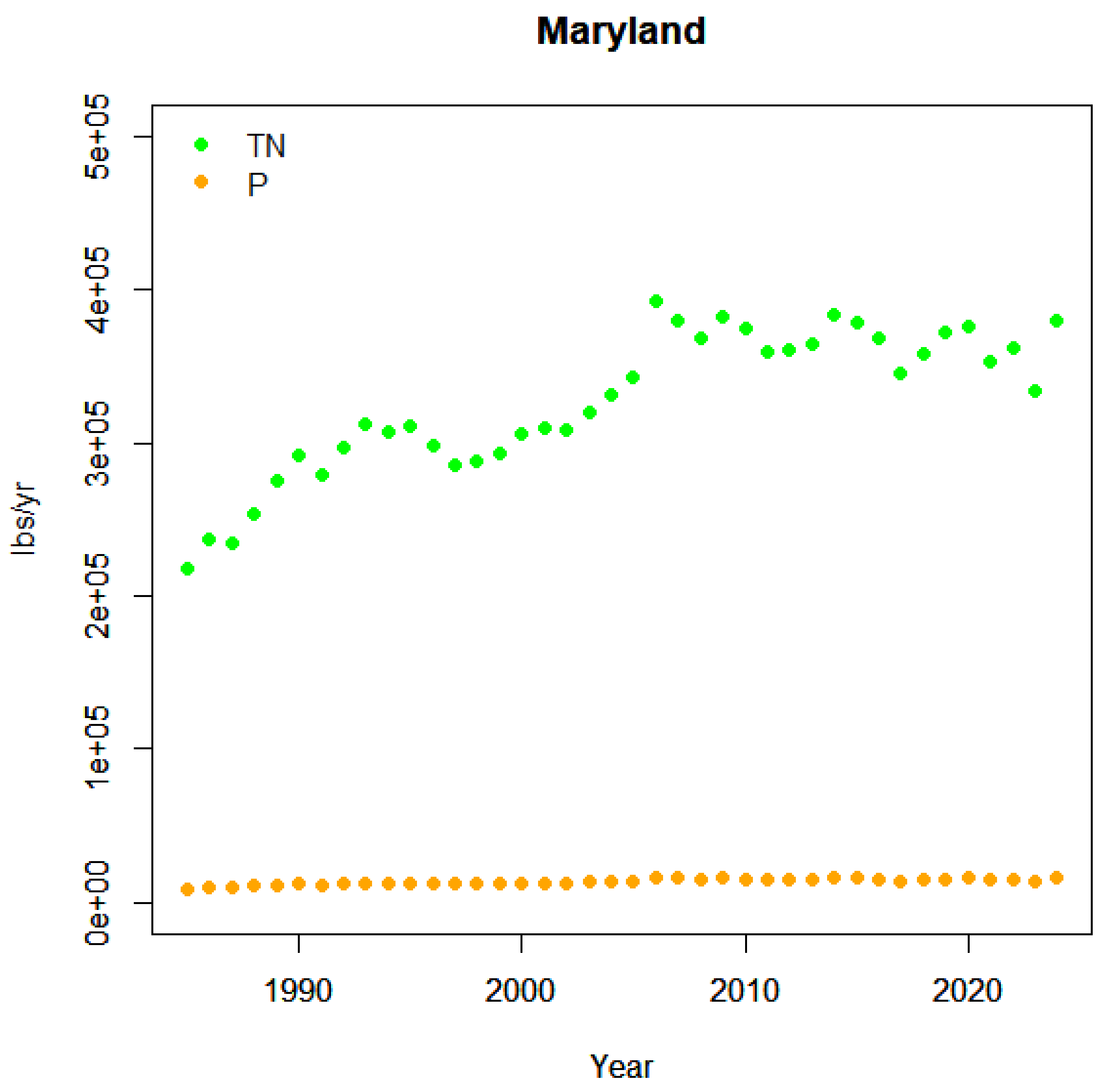




Preliminary Results

Maryland	TN			P		
	1995	2020	mean	1995	2020	mean
Lbs/yr	312664	363168	325787	13226	15452	13762
% developed load	2.10%	2.13%		1.07%	2.24%	

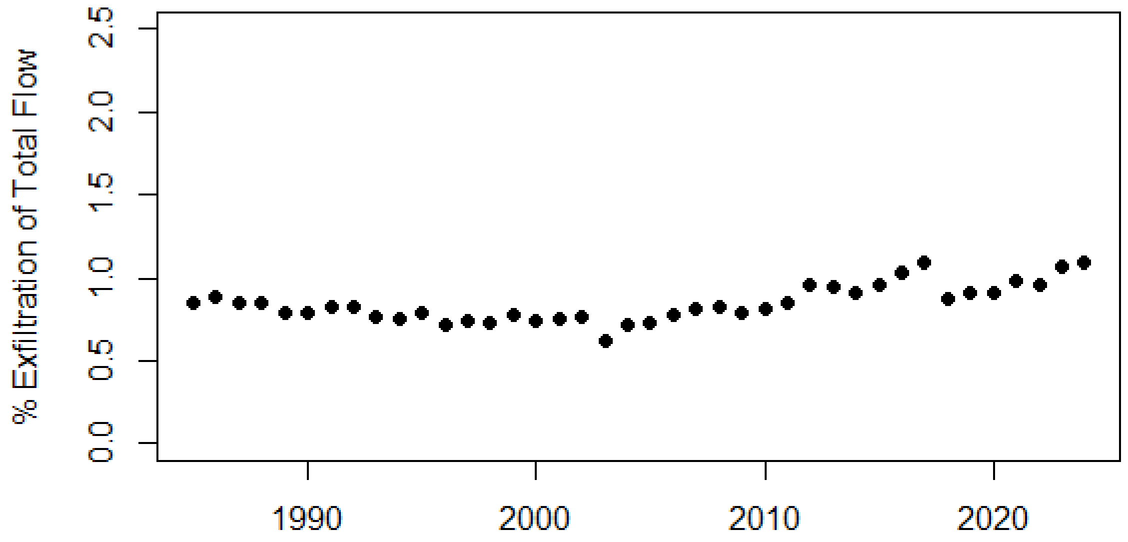


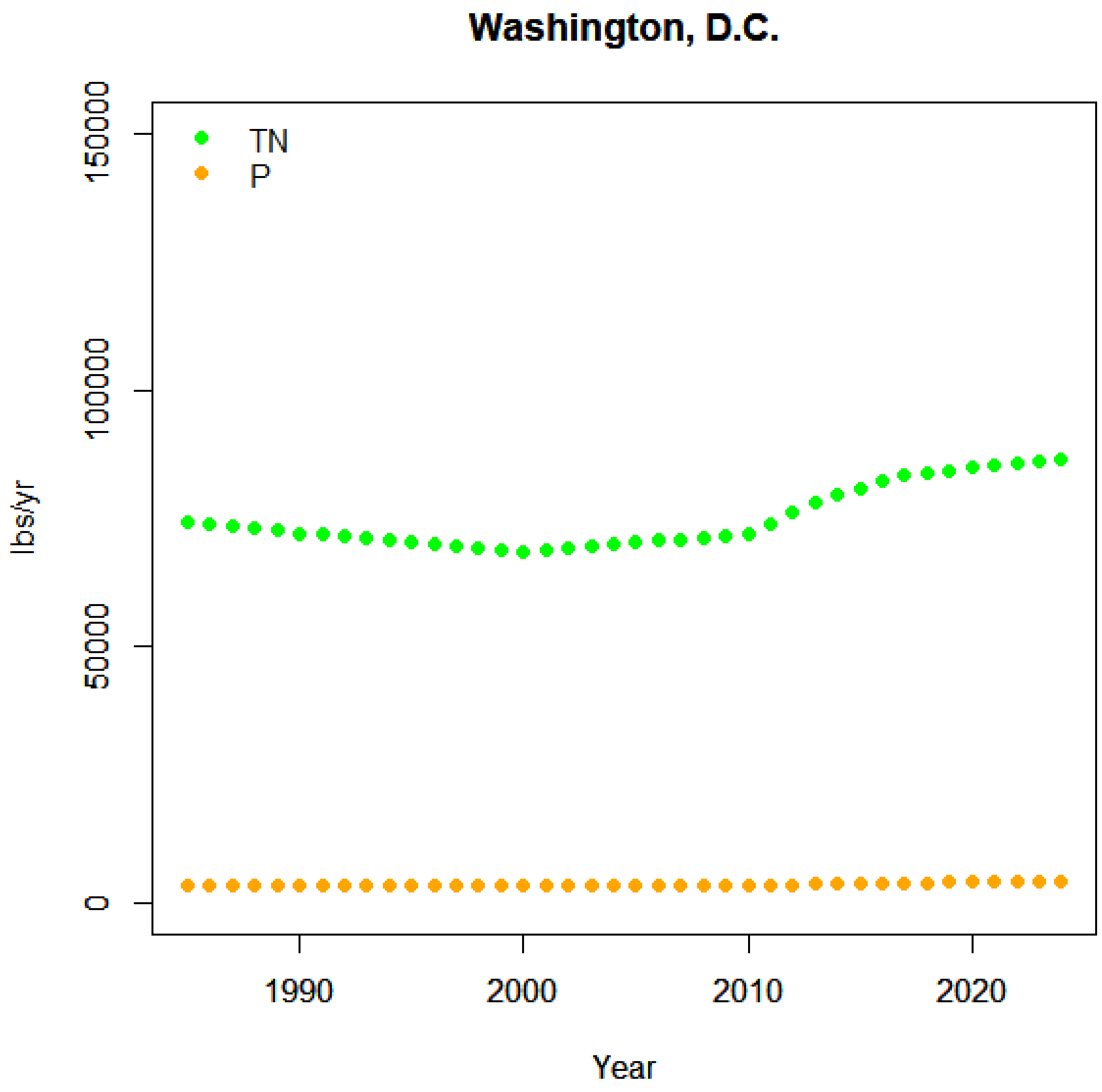


Preliminary Results

Washington D.C.	TN			P		
	1995	2020	mean	1995	2020	mean
Lbs/yr	70342	84757	74870	3321	4002	3535
% developed load	25.81%	39.00%		9.55%	22.98%	

Note: The SSE load is consistent with similar areas, but the % of developed is high because the CAST estimated dev. load is small.





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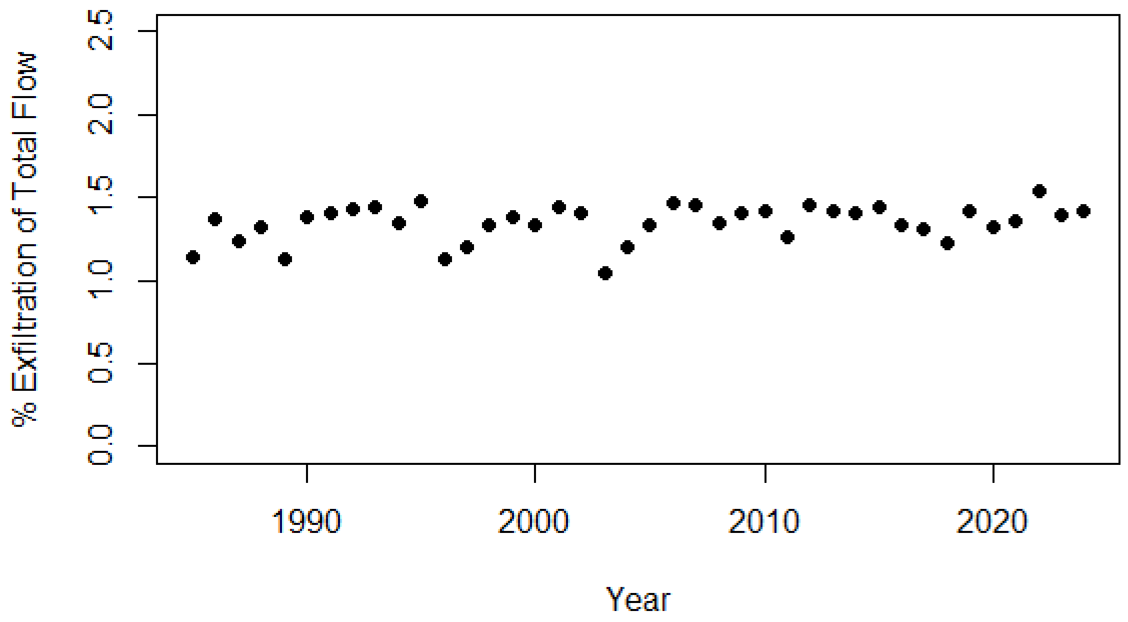

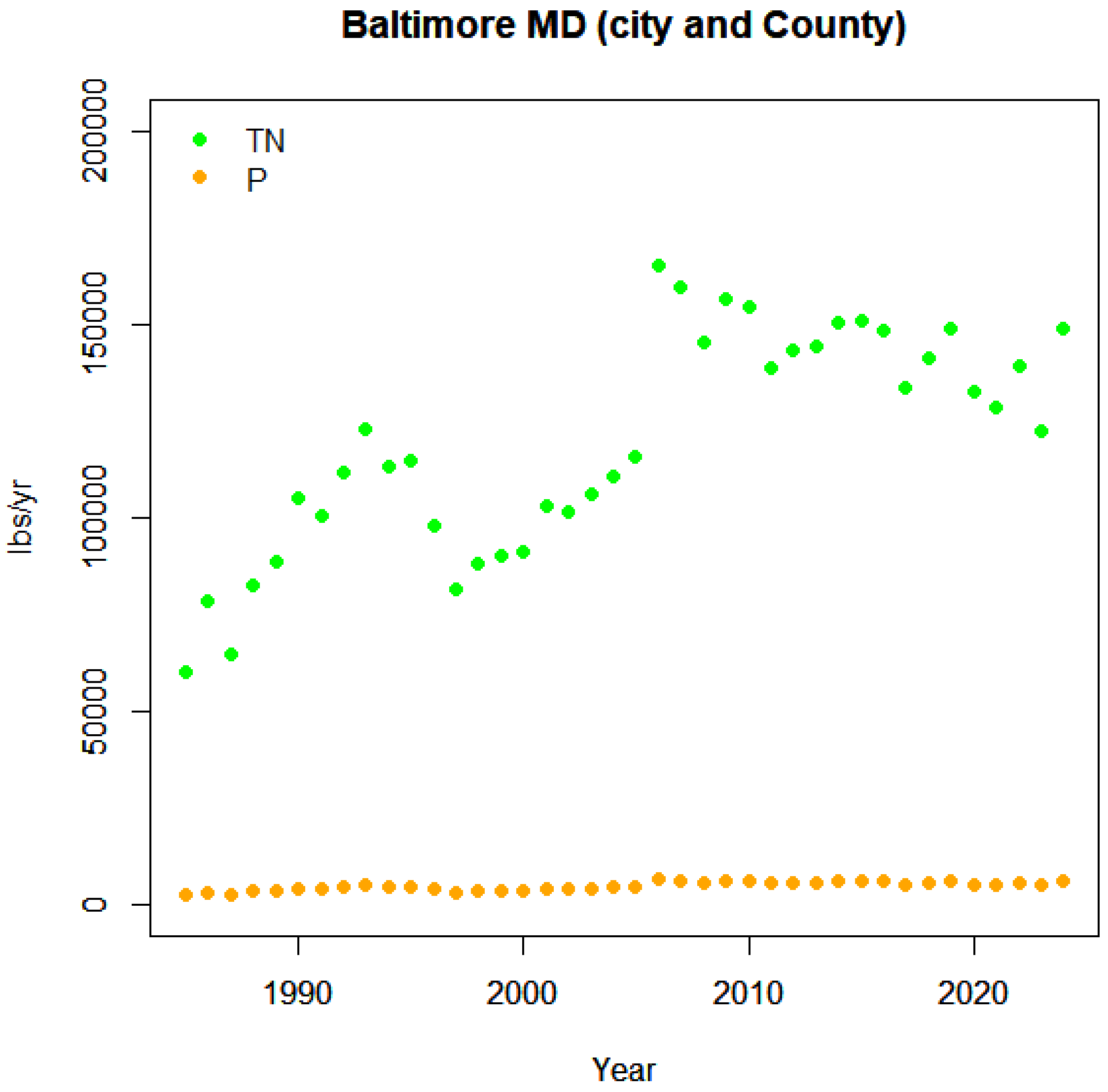

Preliminary Results

Henrico, VA	TN			P		
	1995	2020	mean	1995	2020	mean
Lbs/yr	12568	16257	14635	760	984	886
% of developed load	2.51%	2.49%		1.37%	1.72%