University of
New Hampshire

Water Systems
Analysis Group

# Natural vs. Anthropogenic Aquatic Infrastructure:

## How much do Rivers Contribute to Wastewater Nitrogen Treatment in the Northeast US?

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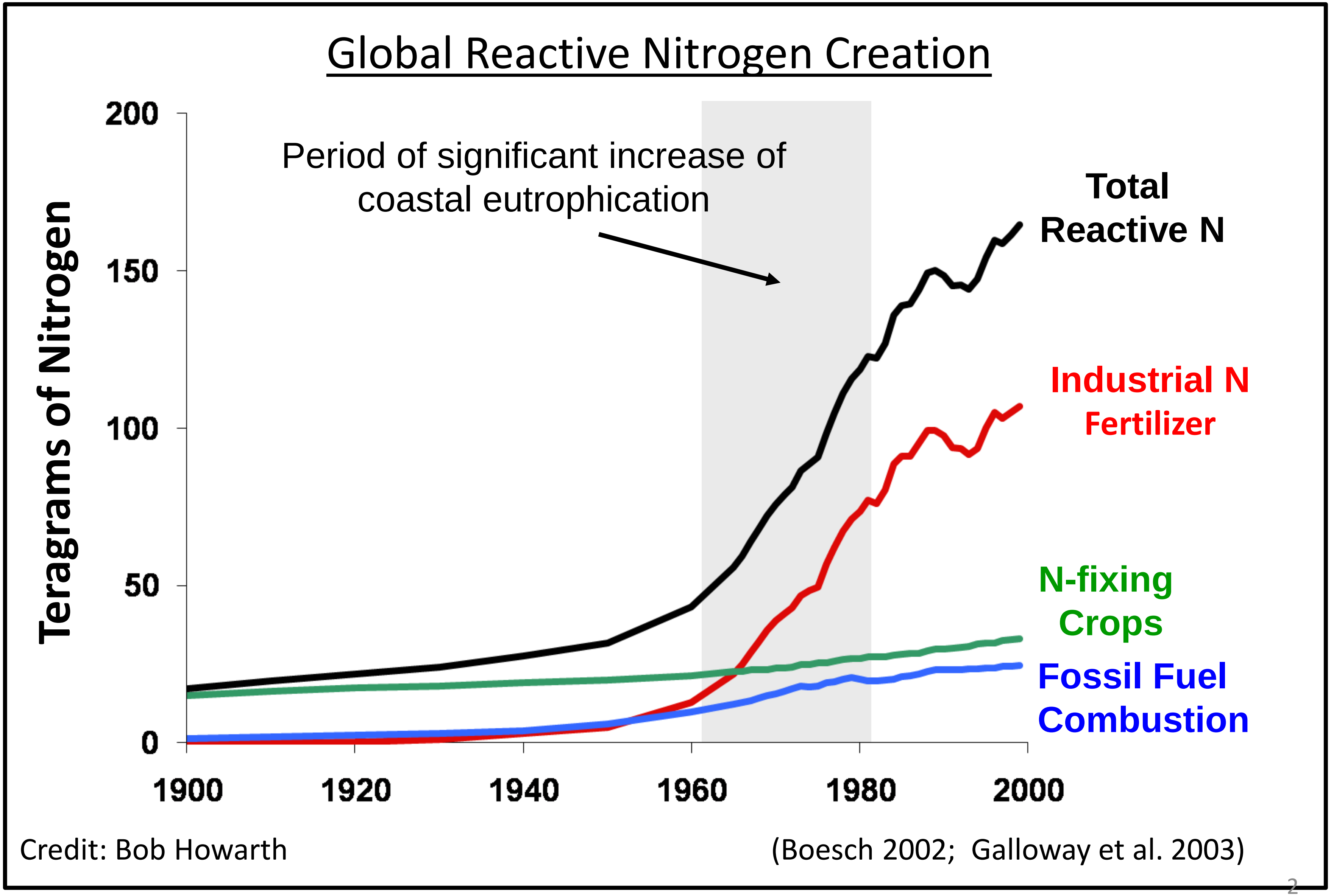
Funding provided by NSF-EaSM and NSF-EPSCoR

# Why is N Removal (i.e. denitrification) Important?



Credit: Bob Howarth

(Boesch 2002; Galloway et al. 2003)

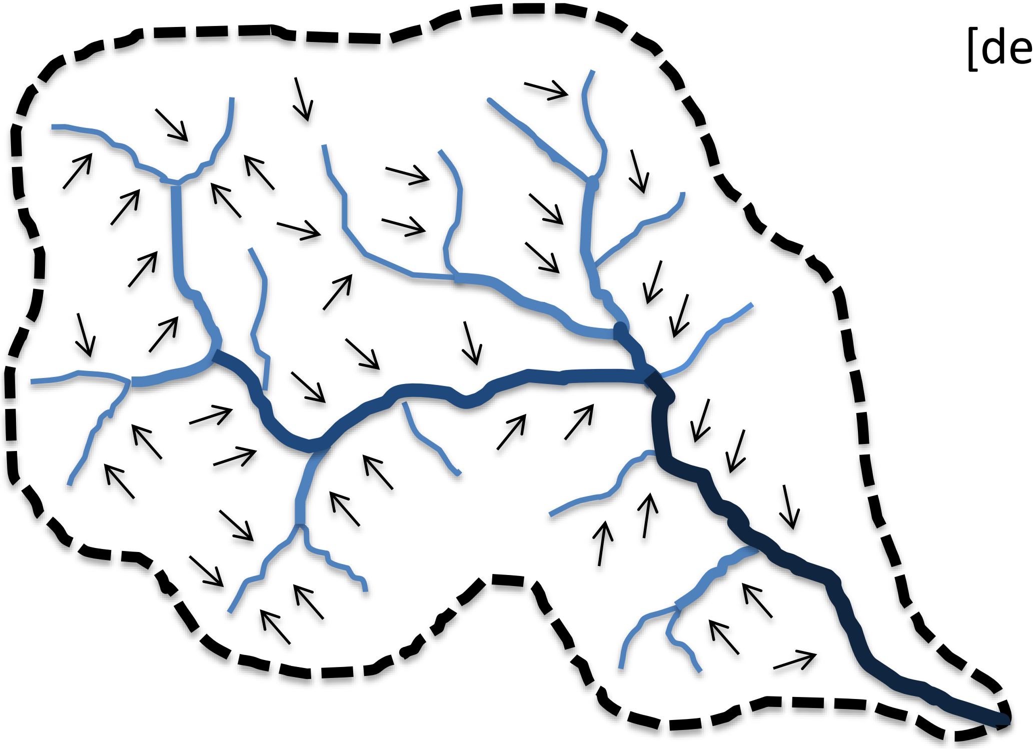
# Nitrogen Pollution Is An Expensive Problem

- Potential health and environmental damages due to anthropogenic N total **$210 billion $yr^{-1}$** (Sobota et al. 2015)
  - Human health
  - Fisheries
  - Climate change
  - Property value
  - etc.

- Wastewater Infrastructure is failing (ASCE 2013) and capital investments of **$15 billion $yr^{-1}$** are needed to address needs
  - Inadequate capacity
  - Aging pipes
  - Increasing permitting standards

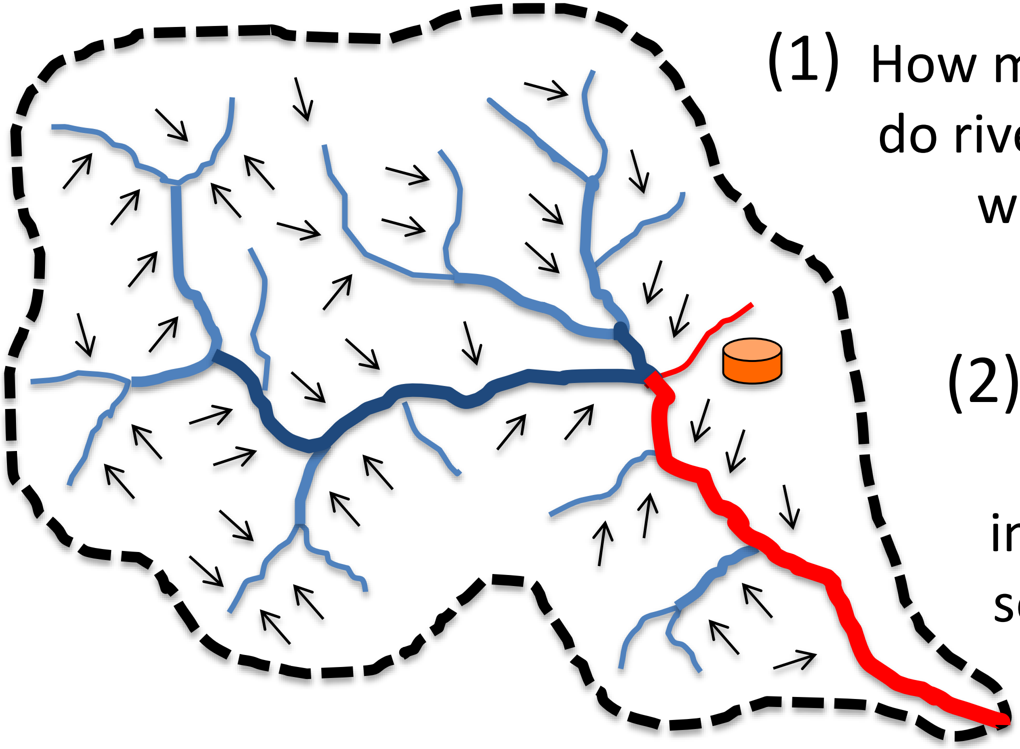
# Instream Nitrogen Removal Capacity of Networks

= 15 to 76 % removal (denitrification) of **nonpoint** dissolved inorganic nitrogen (DIN) inputs [depending on climate]



Seitzinger et al. 2002
Bernhardt et al. 2005
Wollheim et al. 2008
Stewart et al. 2011

# Instream Nitrogen Removal Capacity of Networks



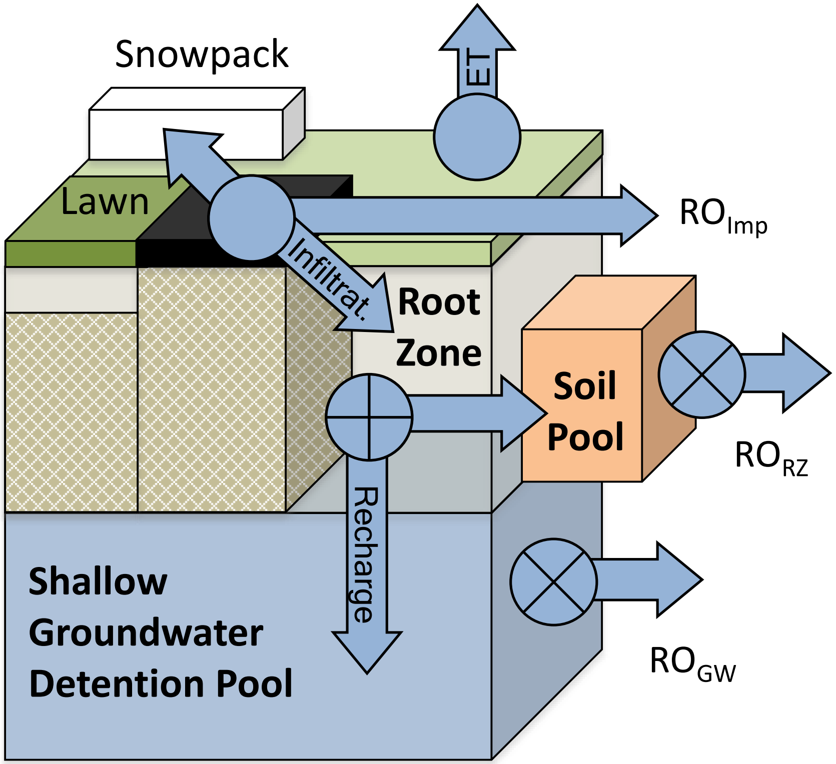
## Research Questions

(1) How much N removal (denitrification) do rivers contribute to contemporary wastewater treatment in the northeast US?

(2) How do WWTP regulations (i.e. TN removal efficiencies) influence this aquatic ecosystem service and total river N export?

# Modeling Approach

# Framework for Aquatic Modeling in the Earth System (FrAMES)



**Vertical Water Balance:**

- Inputs: precip, airT, soil data, and land use
- Simulated at daily time step

**Horizontal Discharge Routing:**

- Muskingum channel routing

**Channel Width and Depth:**

- Simulated using discharge scaling functions

**Discharge Calibration:**

- Utilized headwater discharge data from USGS

**Biogeochemical Applications:**

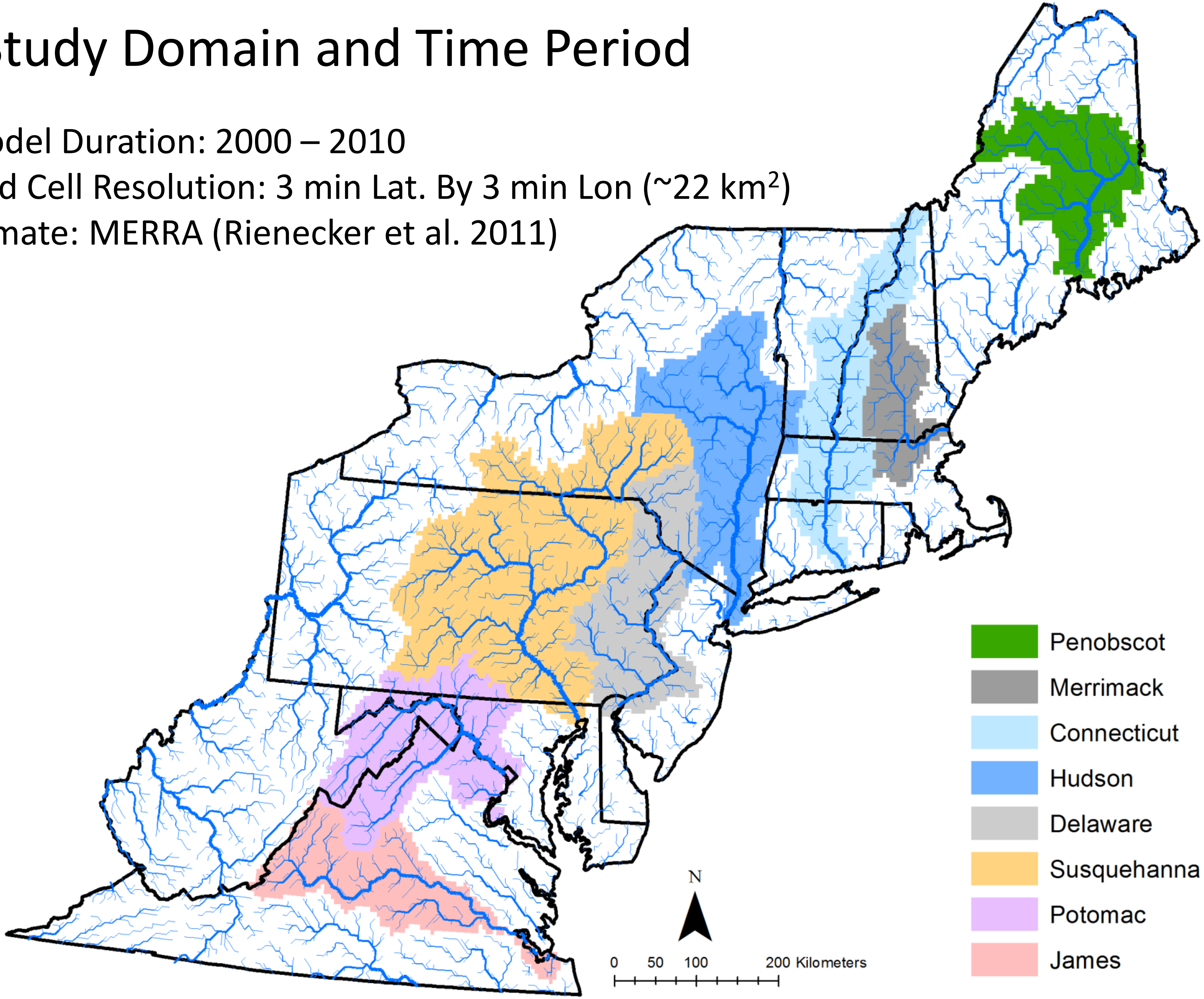
- DIN removal (Wollheim et al. 2013)
- Water temperature (Stewart et al. 2013)
- Chloride mass balance (Zuidema, In Review)
- Fecal Coliform processing (Huang, In Prep.)
- Terrestrial-aquatic linkages (Samal, In Prep)

# Study Domain and Time Period

Model Duration: 2000 – 2010

Grid Cell Resolution: 3 min Lat. By 3 min Lon (~22 $km^2$)

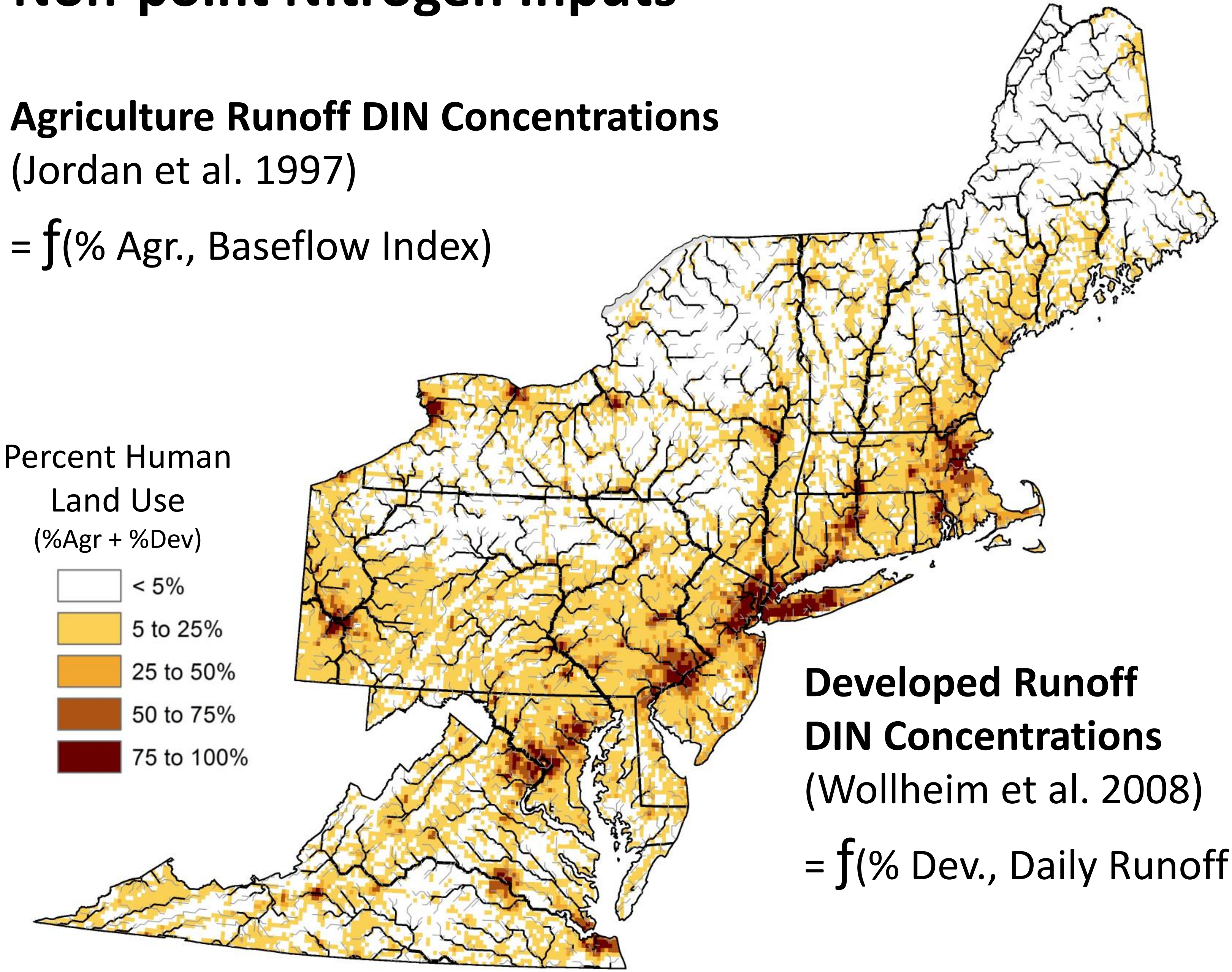
Climate: MERRA (Rienecker et al. 2011)



# Non-point Nitrogen Inputs

**Agriculture Runoff DIN Concentrations**
(Jordan et al. 1997)

= ƒ(% Agr., Baseflow Index)



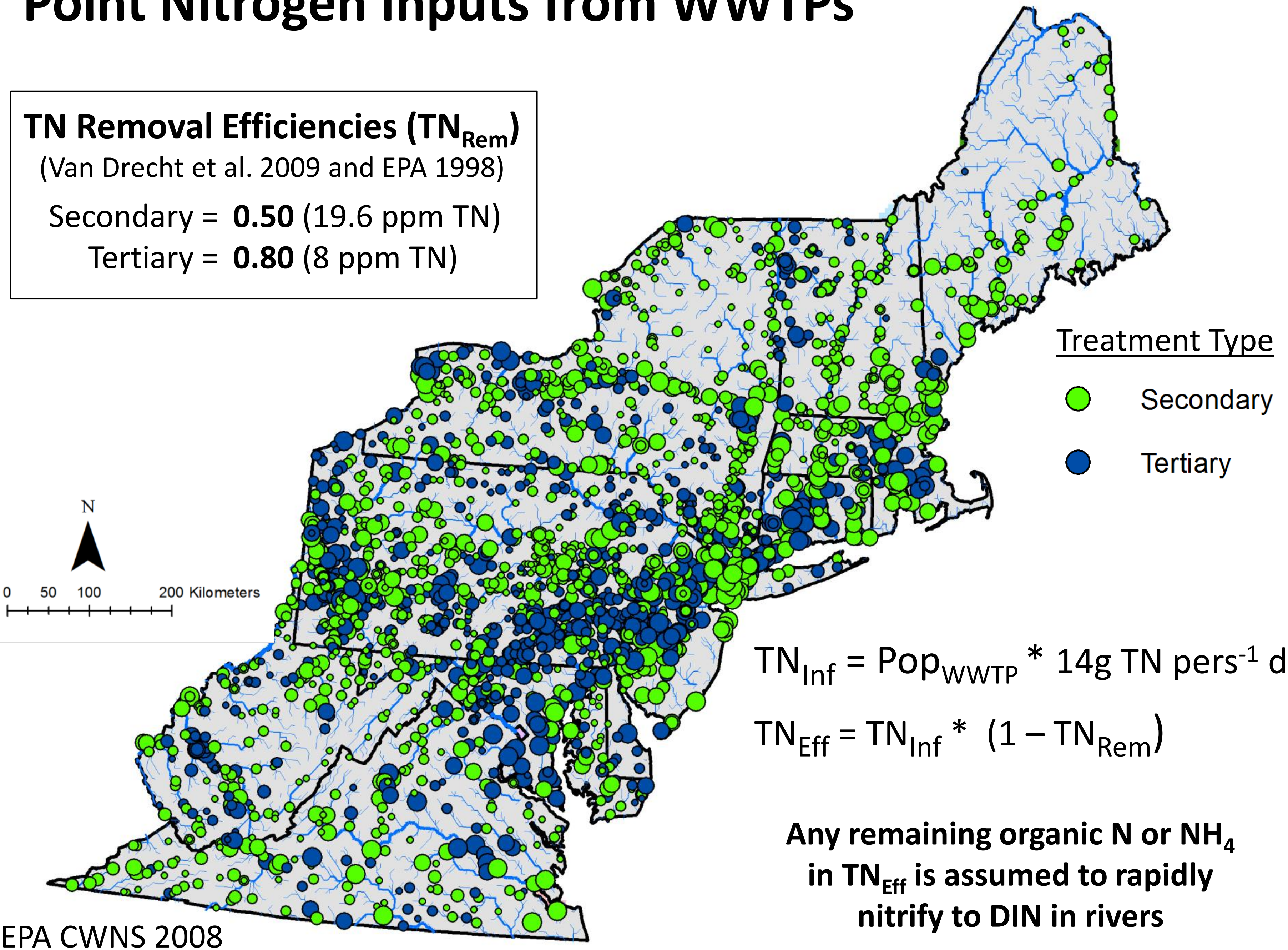
**Developed Runoff DIN Concentrations**
(Wollheim et al. 2008)

= ƒ(% Dev., Daily Runoff)

# Point Nitrogen Inputs from WWTPs

**TN Removal Efficiencies ($TN_{Rem}$)**
(Van Drecht et al. 2009 and EPA 1998)

Secondary = **0.50** (19.6 ppm TN)
Tertiary = **0.80** (8 ppm TN)



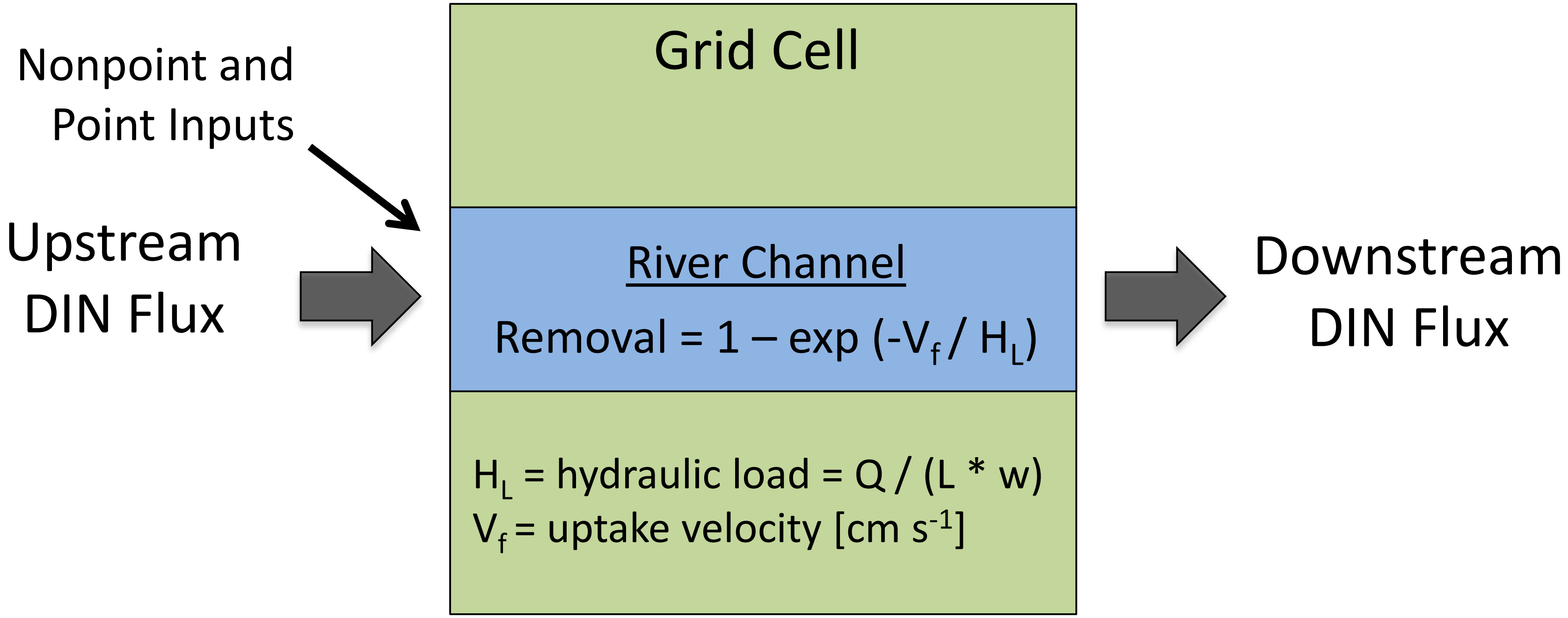
$$TN_{Inf} = Pop_{WWTP} * 14\text{g TN pers}^{-1}\text{ d}^{-1}$$

$$TN_{Eff} = TN_{Inf} * (1 - TN_{Rem})$$

**Any remaining organic N or $NH_4$ in $TN_{Eff}$ is assumed to rapidly nitrify to DIN in rivers**

EPA CWNS 2008

# Instream N Removal



Nonpoint and
Point Inputs

Upstream
DIN Flux

Grid Cell

River Channel

Removal = 1 – exp $(-V_f / H_L)$

$H_L$ = hydraulic load = Q / (L * w)
$V_f$ = uptake velocity [cm $s^{-1}$]

Downstream
DIN Flux

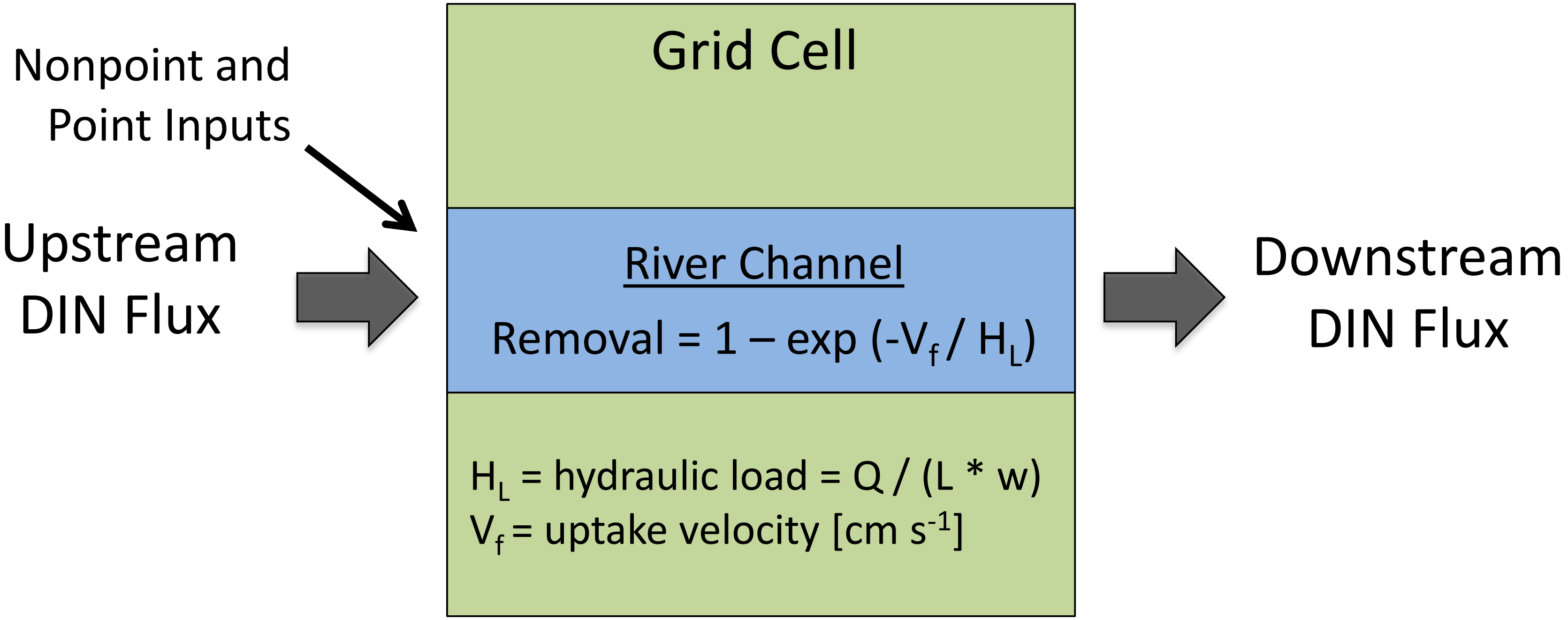
Removal is sensitive to:

1) River discharge (Q)
2) Channel width (w)
3) Biological uptake rate $(V_f)$
    - Water temperature
    - $NO_3$ concentrations

Previous network
scale applications:

- Donner et al. 2004
- Wollheim et al. 2006
- Wollheim et al. 2008
- Stewart et al. 2011

# Instream N Removal



Nonpoint and Point Inputs

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Removal is sensitive to:

1) River discharge (Q)
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   - Water temperature
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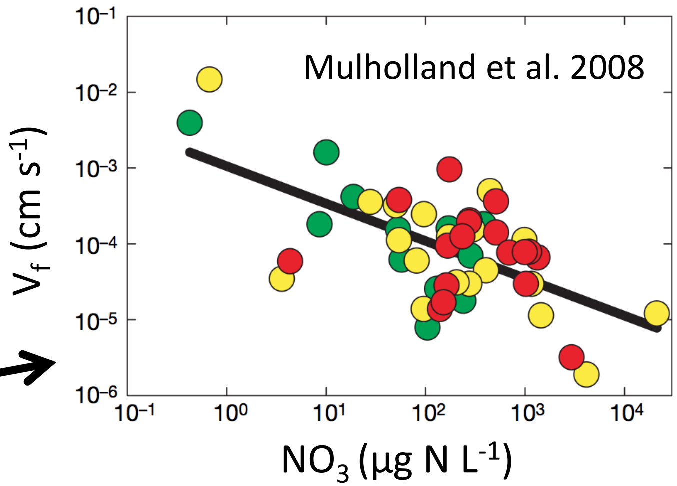

Mulholland et al. 2008

# Model Validation

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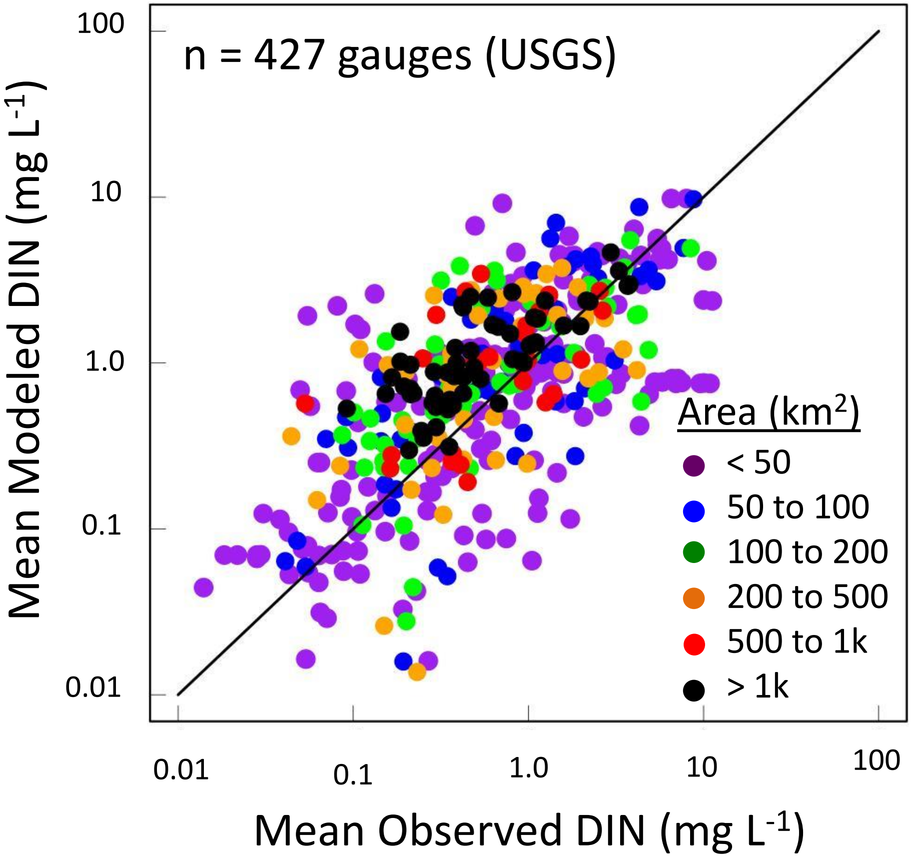
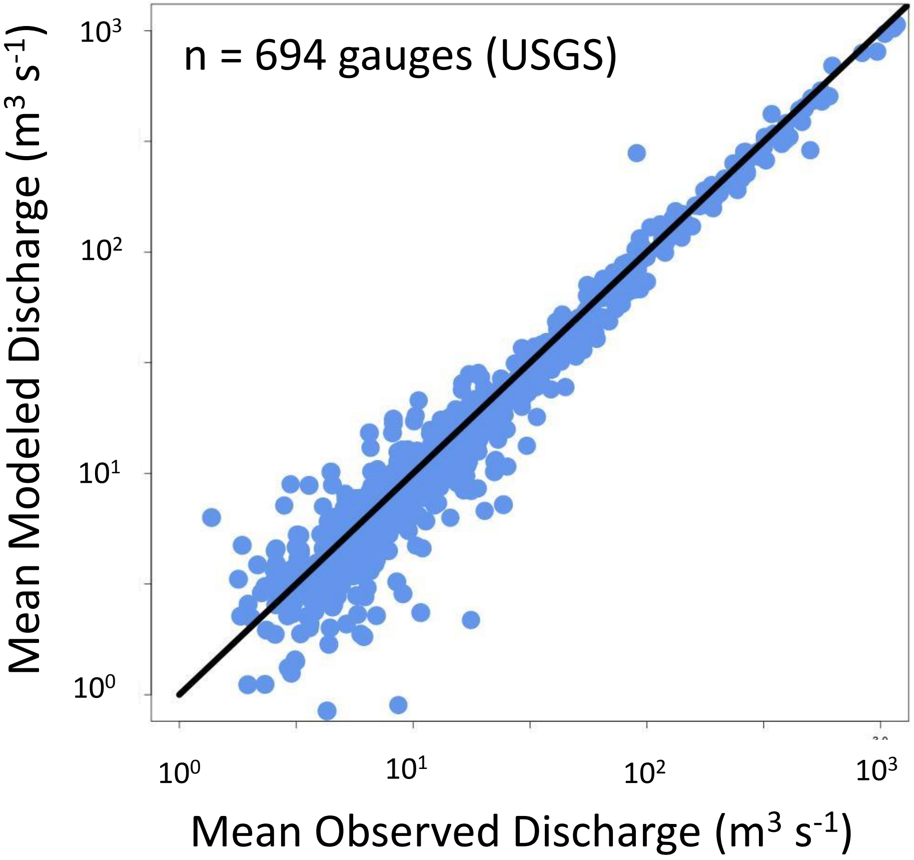
Overestimation of DIN concentrations



Underestimation of river discharge

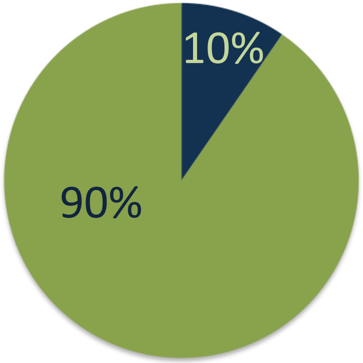


# Model Results

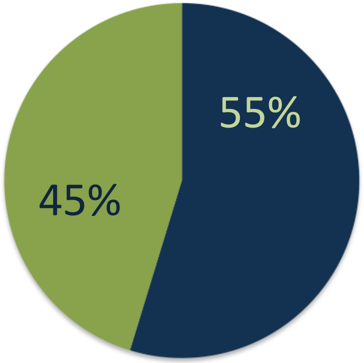
# Point vs. Non-Point Annual DIN Loadings

🟦 Point (WWTP)
🟩 Non-point

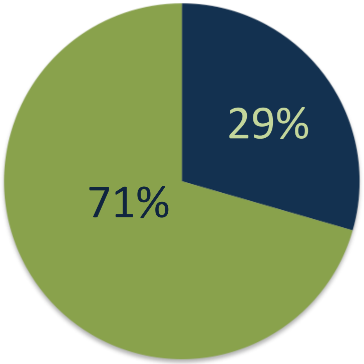
Penobscot
[1.8 Gg yr$^{-1}$]



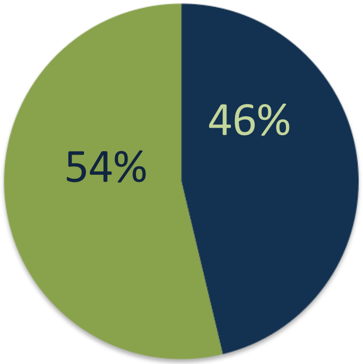
Merrimack
[2.3 Gg yr$^{-1}$]



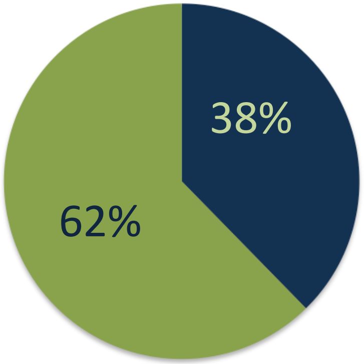
Connecticut
[7.7 Gg yr$^{-1}$]



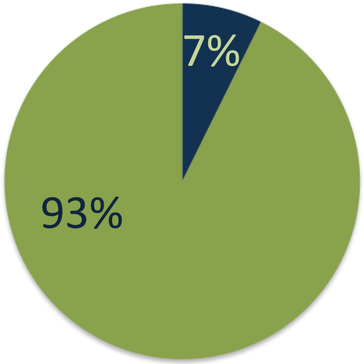
Hudson
[23.6 Gg yr$^{-1}$]



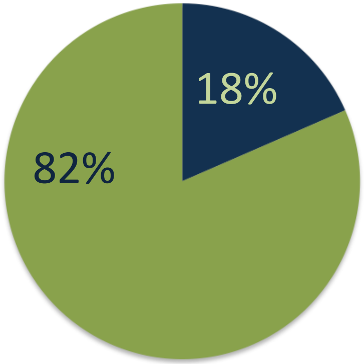
Delaware
[18.5 Gg yr$^{-1}$]



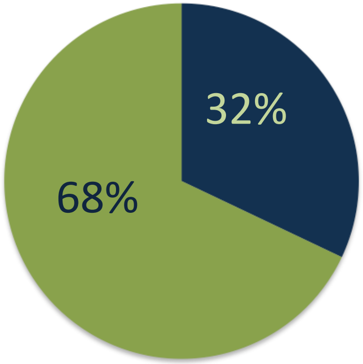
Susquehanna
[60.1 Gg yr$^{-1}$]



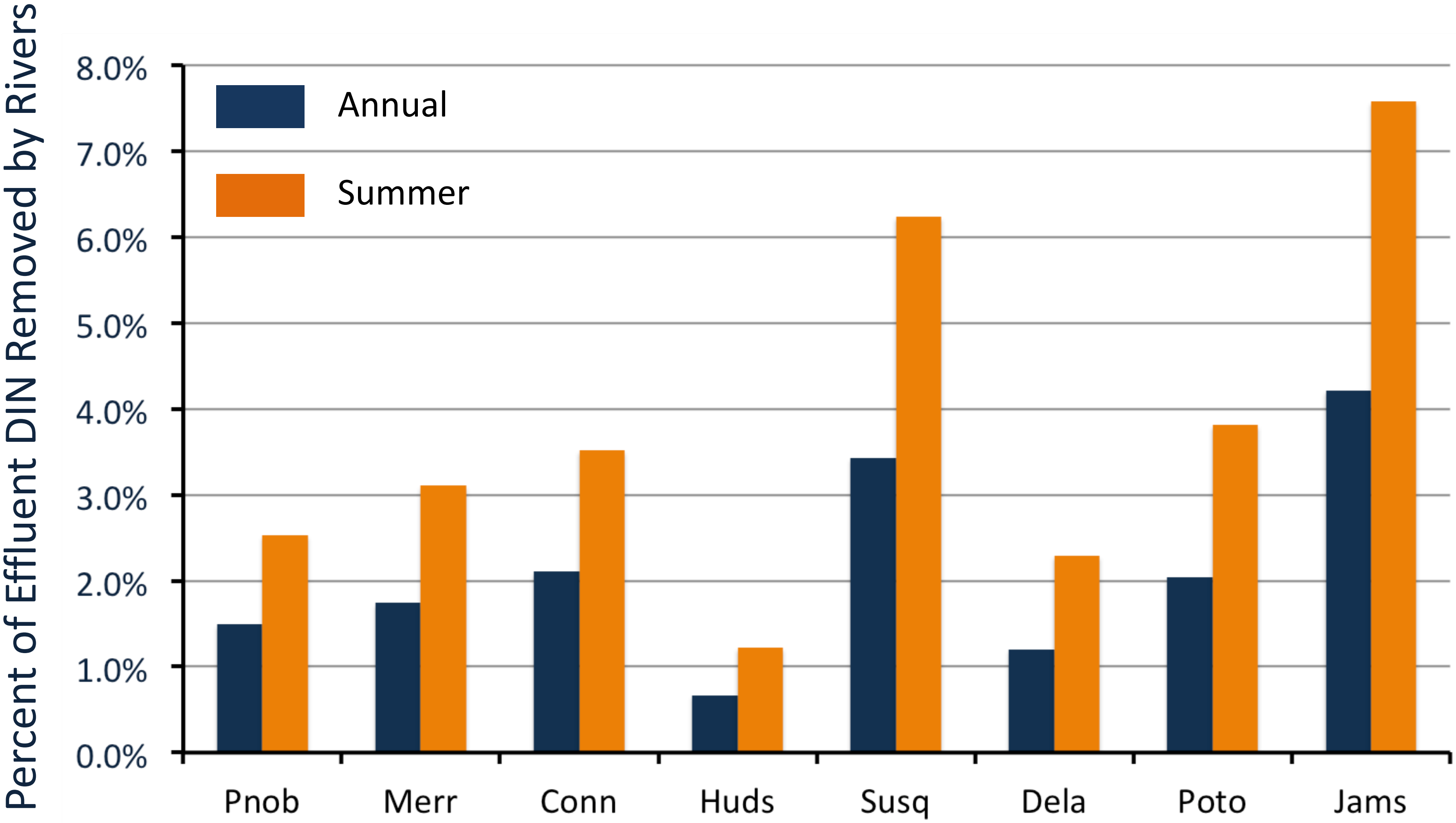
Potomac
[21.6 Gg yr$^{-1}$]



James
[8.0 Gg yr$^{-1}$]

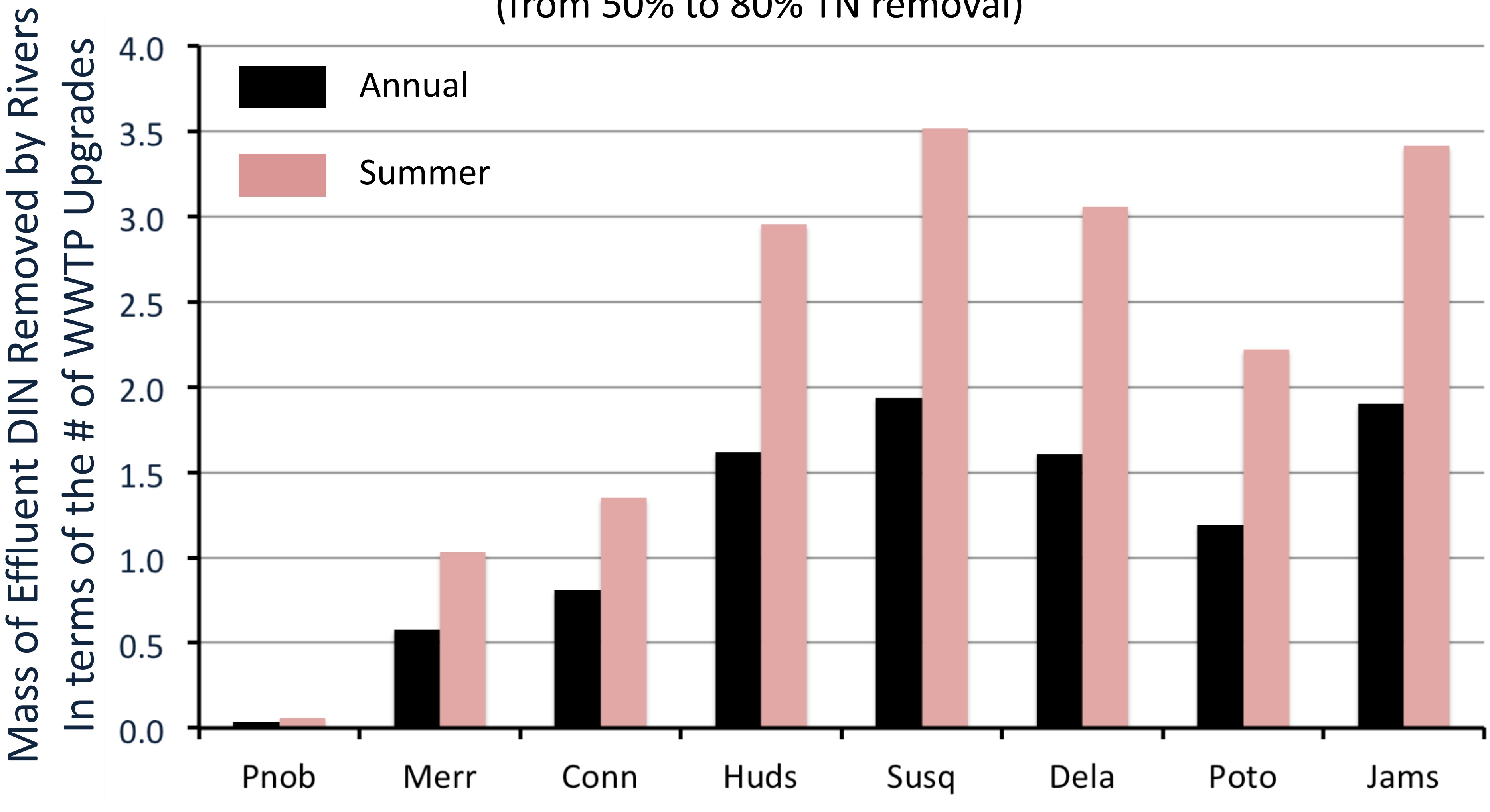


# Rivers Remove Some Effluent DIN (but it's not much)



# How Many WWTP Upgrades* is this Ecosystem Service Equivalent to?

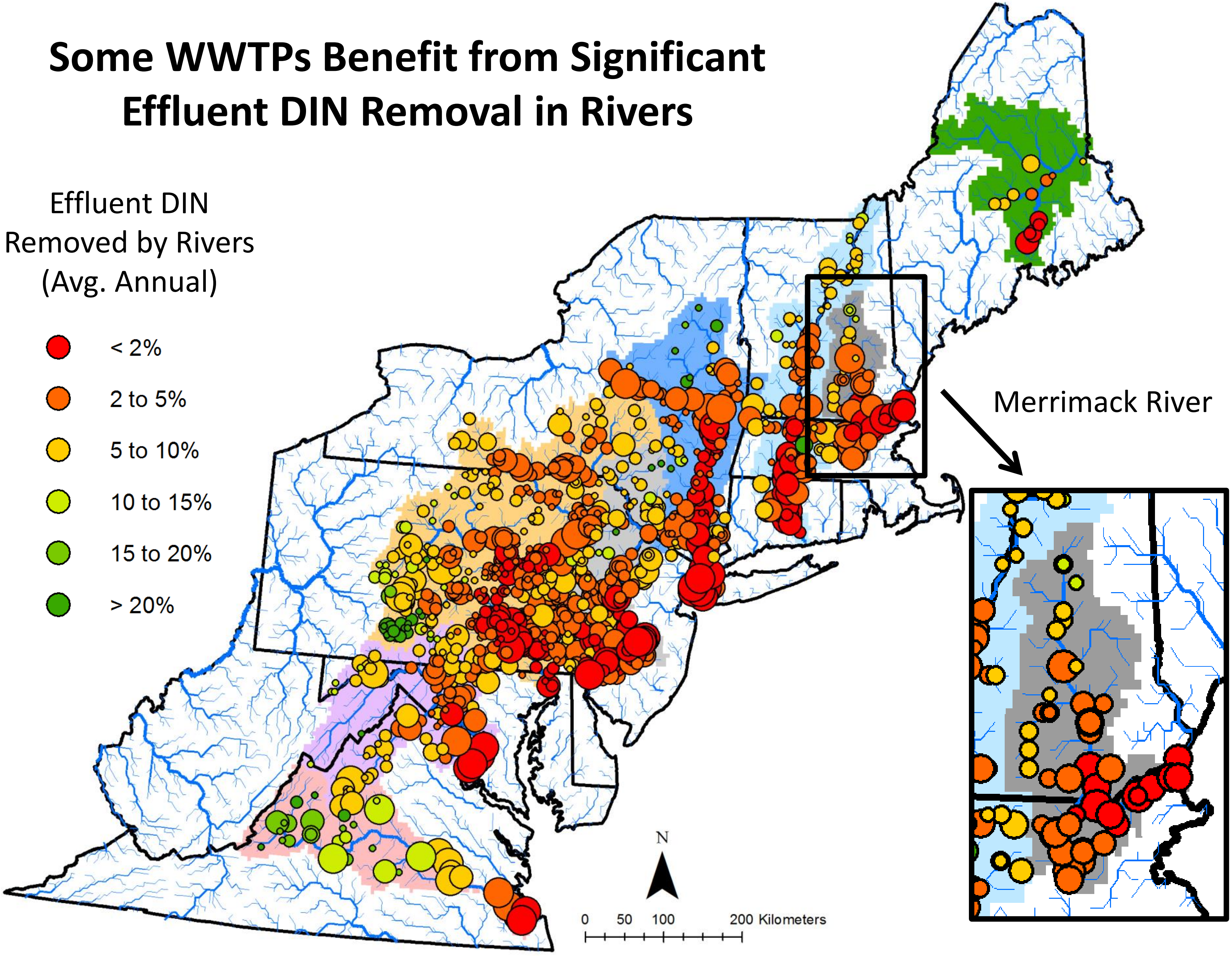
*Upgrade = From Secondary Treatment to Tertiary Treatment
(from 50% to 80% TN removal)



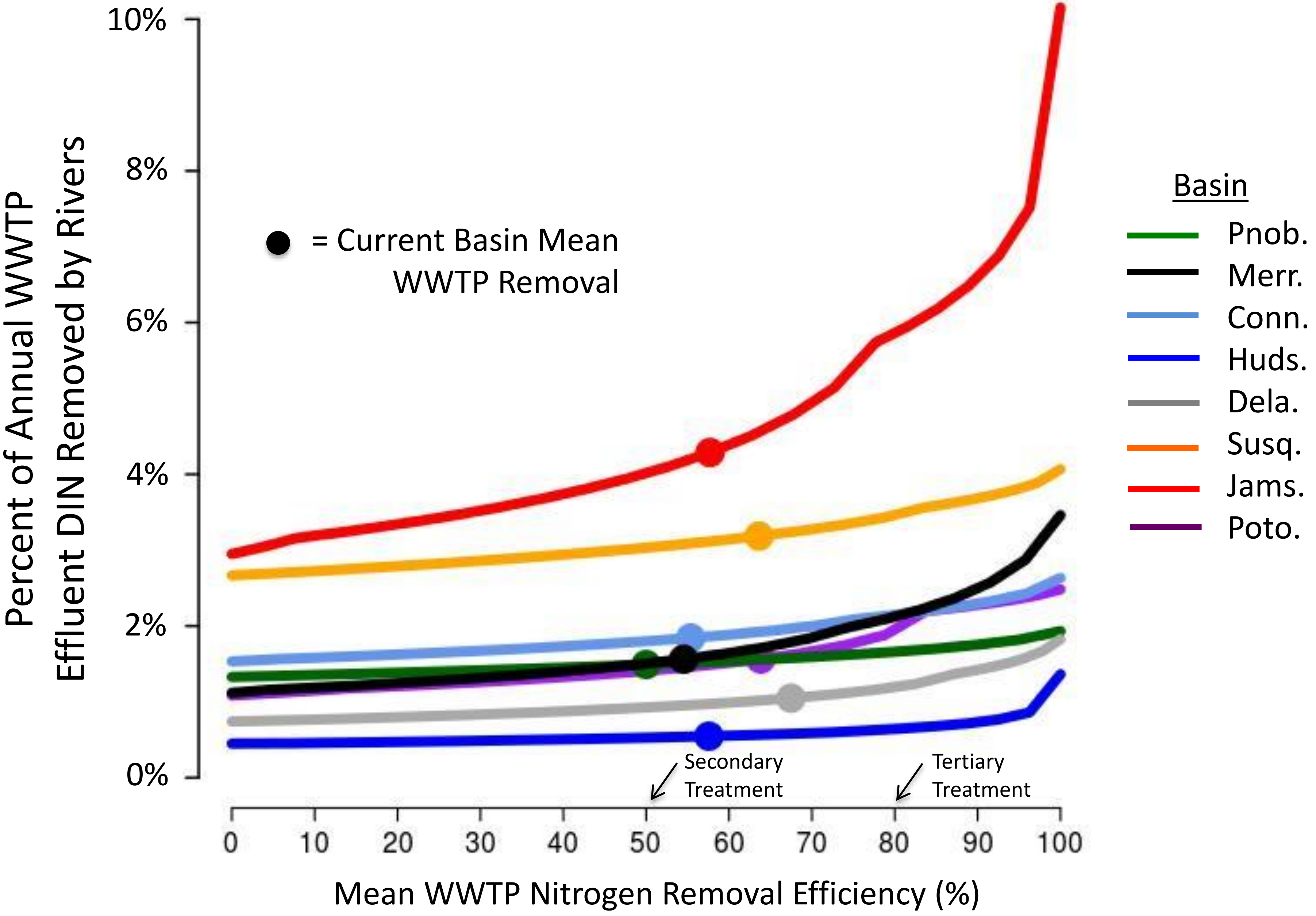
# Some WWTPs Benefit from Significant Effluent DIN Removal in Rivers

Effluent DIN
Removed by Rivers
(Avg. Annual)

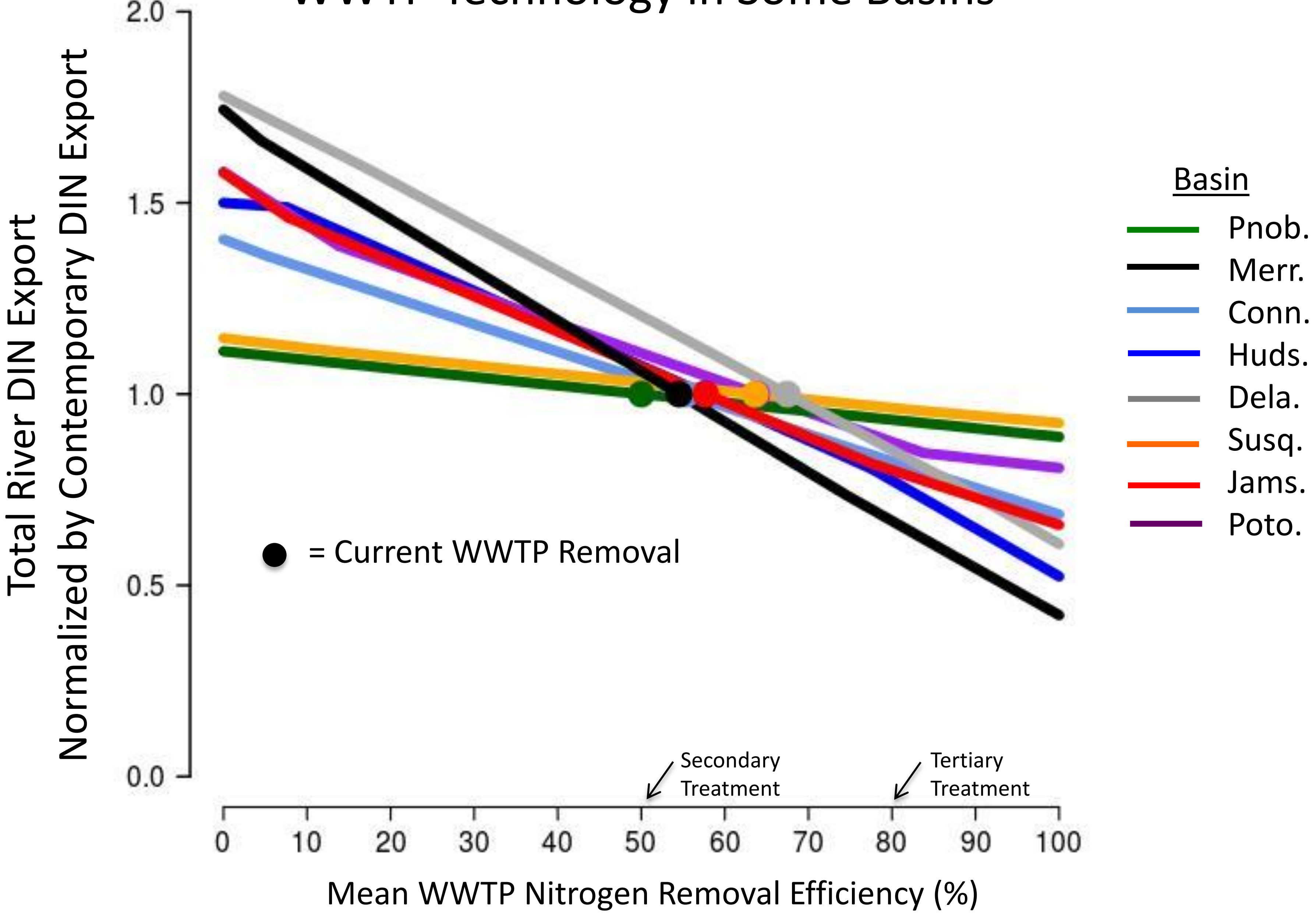
- ● < 2%
- ● 2 to 5%
- ● 5 to 10%
- ● 10 to 15%
- ● 15 to 20%
- ● > 20%



# Improvements in WWTP Technology Result in More Efficient DIN Removal in Rivers



# River DIN Export is heavily Influenced by WWTP Technology in Some Basins



# Major Findings

- **Rivers remove relatively small proportions of effluent DIN** - Conservative estimates are that 0.5 to 4.0% of effluent DIN is removed by rivers and this equates to upgrades of 0.1 to 2.7 WWTPs in northeast basins

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# Major Findings

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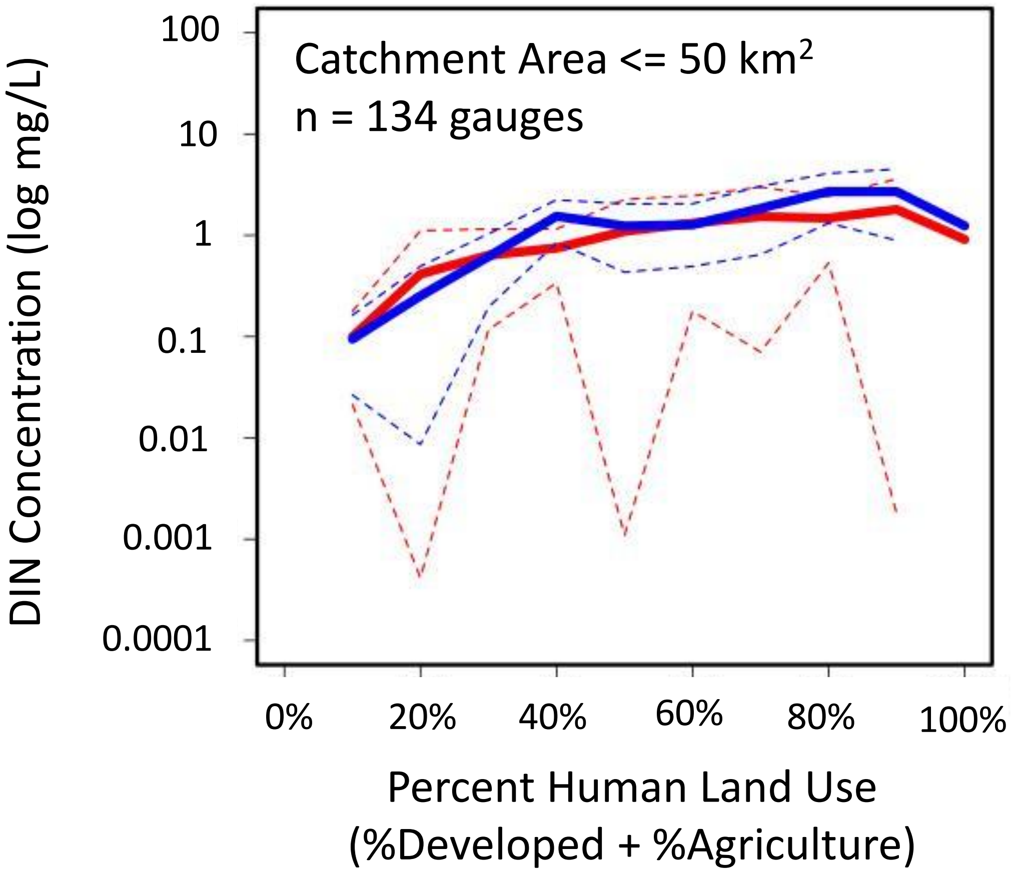
- **The location of WWTPs in the basin is important** - Some WWTPs in the headwaters of the Merrimack River benefit significantly from downstream river processes with 11% of their effluent DIN removed
- **A positive but weak feedback between engineered and natural systems** - Adjustment of WWTP TN removal efficiencies directly increase or decrease the effectiveness of in-stream removal
- **Relative to other basins, Merrimack River DIN export is highly leveraged by wastewater treatment** – Investments in WWTPs should lead to considerable improvements in water quality and coastal health

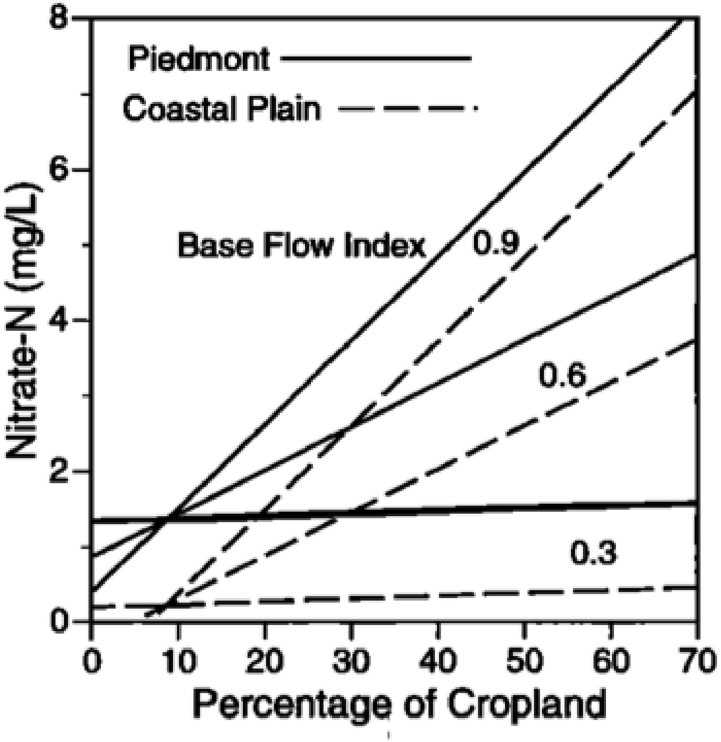
# Validation

## Mean DIN Concentrations in Headwater Catchments Across Spectrum of Land Use



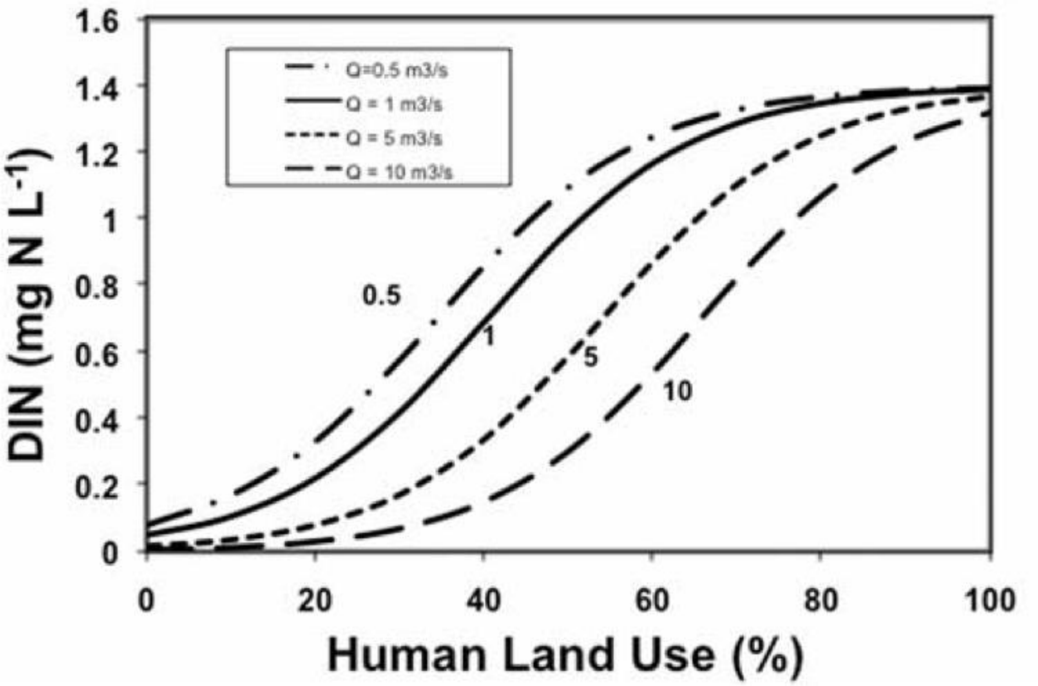
## Agriculture Land DIN Concentrations

Jordan et al. 1997



## Developed Land DIN Concentrations

Wollheim et al. 2008



# Watershed Characteristics & FrAMES Results

(Average Annual, 2000-2010)

| Basin | Climate | | WWTP Characteristics | | | | Land Cover | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean Annual AirT ($^{o}$C) | Mean Annual Runoff (mm d$^{-1}$) | WWTP Density (per 100 km$^{2}$) | Percent of Total Inputs from WWTP (%) | Mean WWTP %Rem. Eff. | Mean Dist. from WWTP to Ocean (km) | Mean Dist. Non-Point Centroid to Ocean (km) | Land Cover (%) | | Skewness Index | |
| | | | | | | | | Dev. | Agr. | Dev. | Agr. |
| Pnob | 5.2 | 1.82 | 0.06 | 10.8 % | 35.0 % | 49.6 | 126.4 | 2% | 2% | 0.56 | 0.60 |
| Merr | 7.9 | 1.74 | 0.36 | 57.7 % | 41.8 % | 52.9 | 116.0 | 16% | 5% | 0.69 | 0.86 |
| Conn | 7.1 | 1.85 | 0.42 | 32.0 % | 43.0 % | 111.6 | 261.0 | 10% | 7% | 0.67 | 0.93 |
| Huds | 7.8 | 1.80 | 0.53 | 49.3 % | 46.4 % | 56.4 | 271.8 | 11% | 14% | 0.64 | 0.98 |
| Dela | 10.2 | 1.56 | 0.89 | 40.3 % | 61.2 % | 76.0 | 209.9 | 20% | 18% | 0.61 | 0.86 |
| Susq | 9.2 | 1.32 | 0.55 | 8.1 % | 55.4 % | 247.0 | 365.6 | 8% | 25% | 0.81 | 0.94 |
| Poto | 11.6 | 0.97 | 0.34 | 19.9 % | 55.7 % | 106.8 | 249.6 | 13% | 28% | 0.74 | 0.96 |
| Jams | 13.1 | 0.98 | 0.16 | 34.6 % | 46.6 % | 75.5 | 302.5 | 10% | 14% | 0.75 | 0.99 |

* FrAMES output

# Watershed Characteristics & FrAMES Results

(Average Annual, 2000-2010)

| Basin | Climate | | WWTP Characteristics | | | | FrAMES Results | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean Annual AirT (°C) | Mean Annual Runoff (mm d$^{-1}$) | WWTP Density (per 100 km$^2$) | Percent of Total Inputs from WWTP (%) | Mean WWTP %Rem. Eff. | Mean Dist. from WWTP to Ocean (km) | Total Network Scale N Removal (%) | WWTP N Removed by Ecosystem Service | | |
| | | | | | | | | Effluent DIN | Influent TN | WWTP Upgrades |
| Pnob | 5.2 | 1.82 | 0.06 | 10.8 % | 35.0 % | 49.6 | 22.5 % | 1.5 % | 0.57 % | 0.05 |
| Merr | 7.9 | 1.74 | 0.36 | 57.7 % | 41.8 % | 52.9 | 9.8 % | 1.7 % | 0.56 % | 0.78 |
| Conn | 7.1 | 1.85 | 0.42 | 32.0 % | 43.0 % | 111.6 | 13.0 % | 2.1 % | 0.70 % | 1.12 |
| Huds | 7.8 | 1.80 | 0.53 | 49.3 % | 46.4 % | 56.4 | 6.0 % | 0.6 % | 0.24 % | 2.22 |
| Dela | 10.2 | 1.56 | 0.89 | 40.3 % | 61.2 % | 76.0 | 7.4 % | 1.2 % | 0.30 % | 2.17 |
| Susq | 9.2 | 1.32 | 0.55 | 8.1 % | 55.4 % | 247.0 | 8.9 % | 3.4 % | 0.88 % | 2.66 |
| Jams | 11.6 | 0.97 | 0.34 | 19.9 % | 55.7 % | 106.8 | 14.7 % | 4.1 % | 1.16 % | 2.56 |
| Poto | 13.1 | 0.98 | 0.16 | 34.6 % | 46.6 % | 75.5 | 9.5 % | 2.0 % | 0.38% | 1.60 |

* FrAMES output

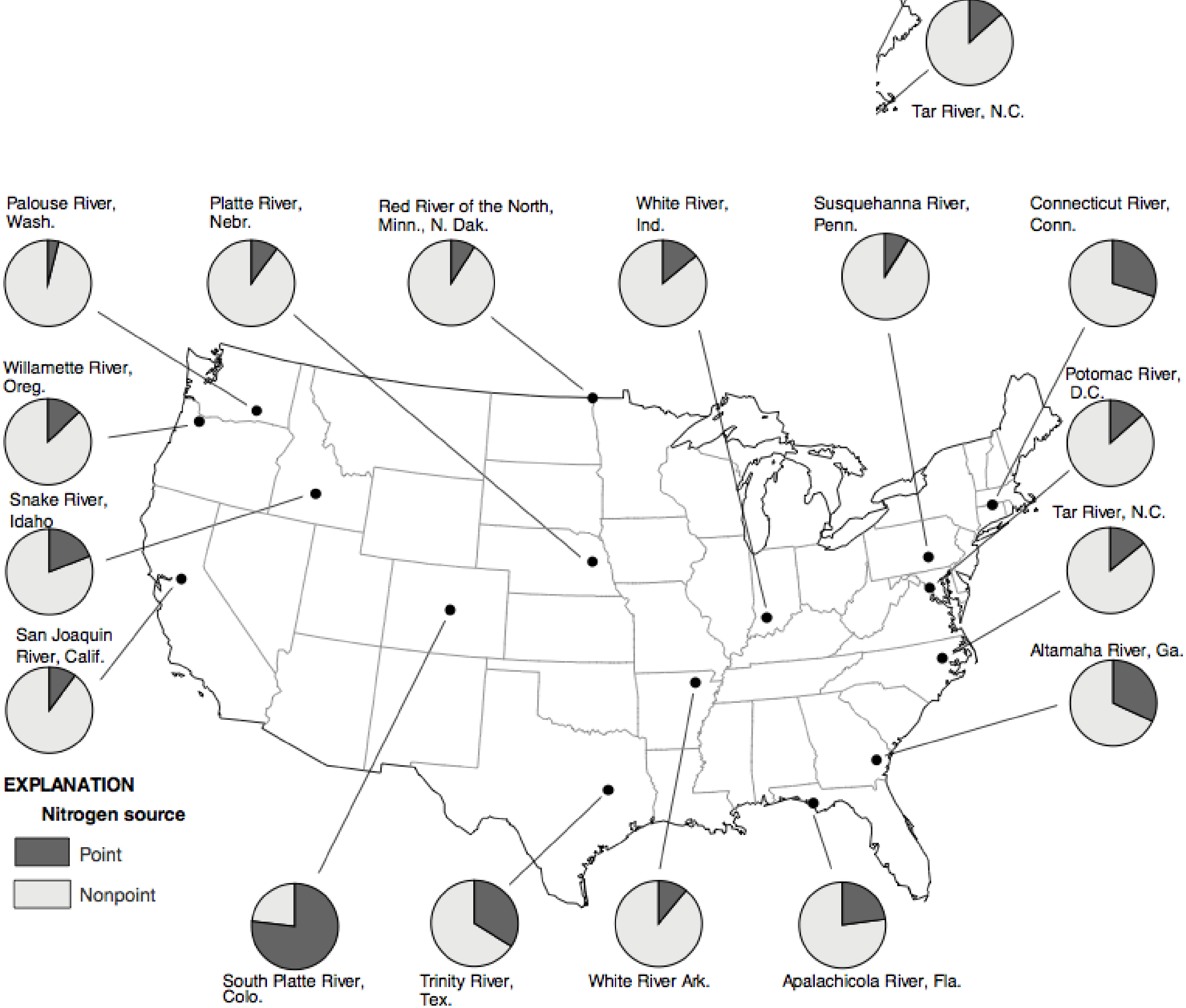


**Figure 7.** Proportion of in-stream nitrogen accounted for by point sources in selected National Water-Quality Assessment Program watersheds.

USGS, 1994

EcoService5

# Of Total Nonpoint DIN Inputs to Network
This is how much is removed by AES