The Importance of Temporal Inequality in Quantifying Vegetated Filter Strip Removal Efficiencies

Heather E. Preisendanz[1], Daniel Schultz[1], Tamie Veith[2], Sarah Goslee[2], Alfonso Mejía[1],
Ciaran J. Harman[3], Cibin Raj[1], and Paul Patterson[1]

[1]Pennsylvania State University, [2]USDA-Agricultural Research Service (ARS), and [3]Johns Hopkins University

Abstract

Vegetated filter strips (VFSs) are best management practices (BMPs) commonly implemented adjacent to row-cropped fields to trap overland transport of sediment and other constituents present in agricultural runoff. VFSs are generally reported to have high sediment removal efficiencies (i.e., 70-95%); however, these values are typically calculated as an average of removal efficiencies observed or simulated for individual events. We argue that due to: (i) positively correlated sediment concentration-discharge relationships; (ii) strong temporal inequality exhibited by sediment transport; and (iii) decreasing VFS performance with increasing flow rates, VFS removal efficiencies over annual time scales may be significantly lower than the per-event values or averages typically reported in the literature and used in decision-making models. By applying a stochastic approach to a two-component VFS model, we investigated the extent of the disparity between two calculation methods: averaging efficiencies from each event over the course of one year, versus reporting the total annual load reduction. We examined the effects of soil texture, concentration-discharge relationship, and VFS slope to reveal the potential errors that may be incurred by ignoring the effects of temporal inequality in quantifying VFS performance. Simulation results suggest that errors may be as low as < 2% and as high as > 20%, with the differences between the two methods of removal efficiency calculations greatest for: (i) soils with high percentages; (ii) VFSs with higher slopes; and (iii) strongly positive concentration-discharge relationships. These results can aid in annual-scale decision-making for achieving downstream water quality goals.

Water Quality and The Chesapeake Bay TMDL

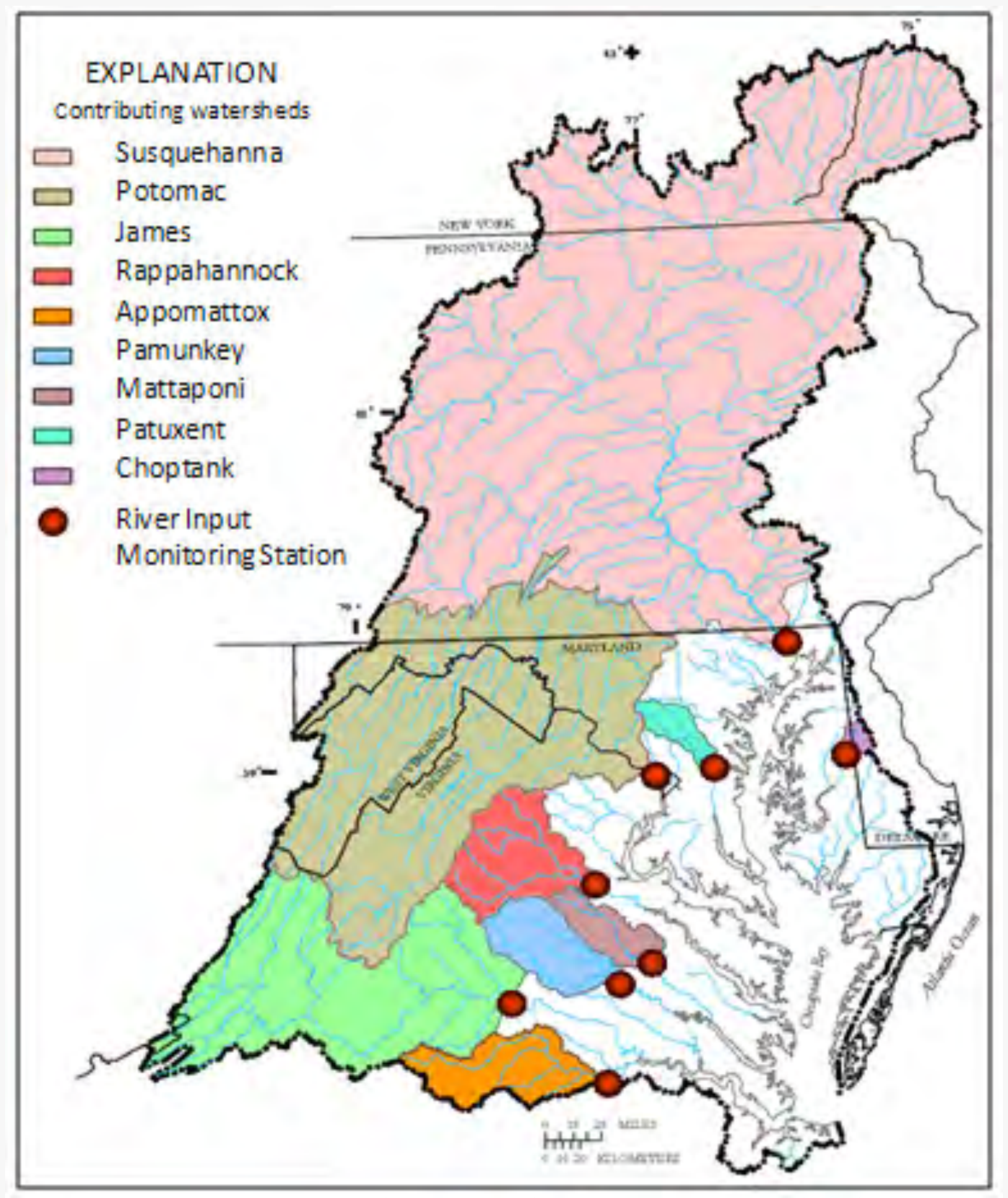


Figure 1. Chesapeake Bay Watershed
Source: USGS, 2011

- The Susquehanna River Basin, which drains much of Pennsylvania (**Fig. 1**), is a major contributor of nutrient and sediment loads to the Chesapeake Bay (**Fig. 2**).
- The Chesapeake Bay TMDL requires that states within the Bay watershed implement best management practices to reduce nutrient loads by 2025.
- In 2017, PA was the only state not on track to meet load reduction goals (**Fig. 3**).

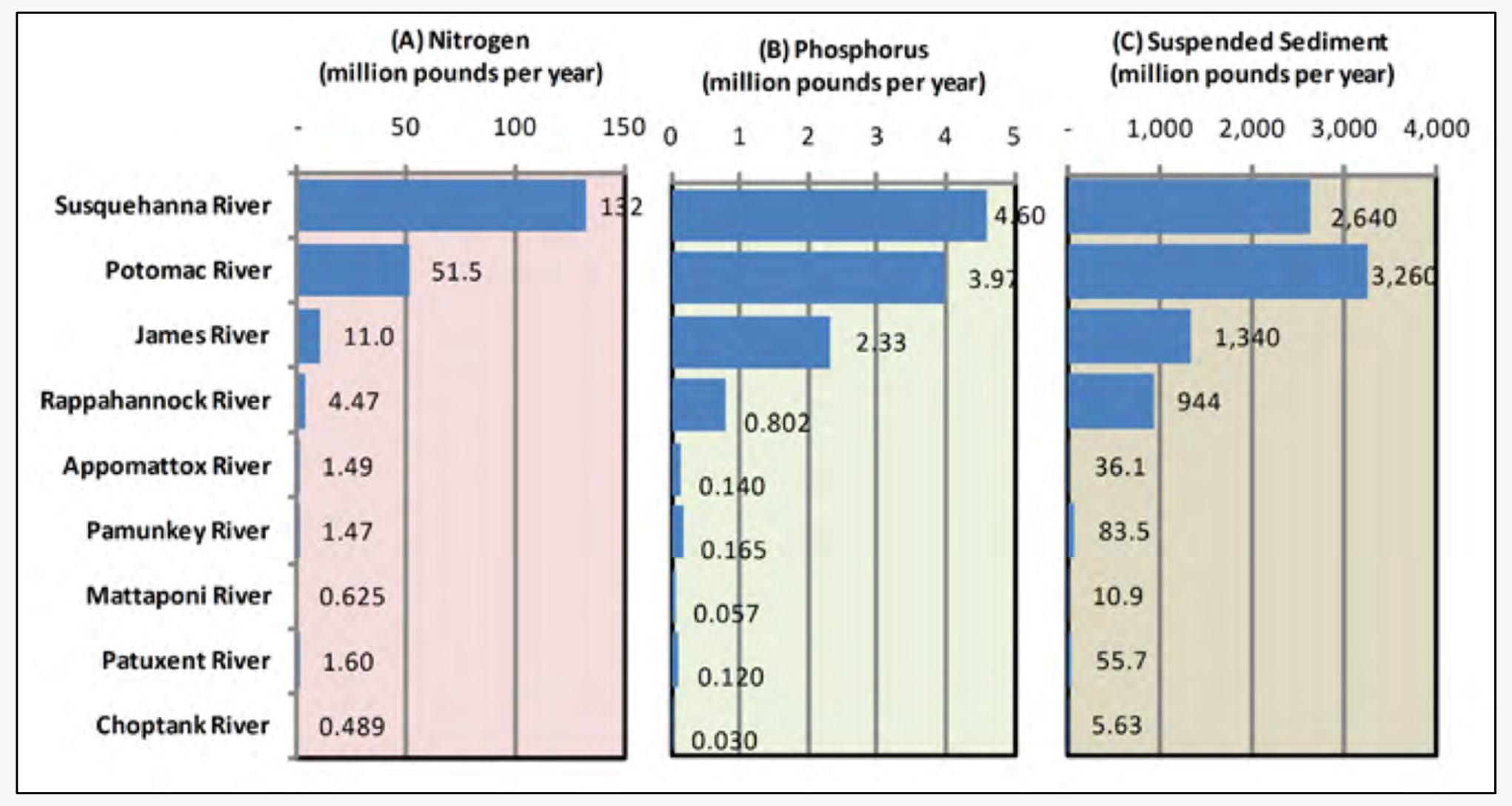
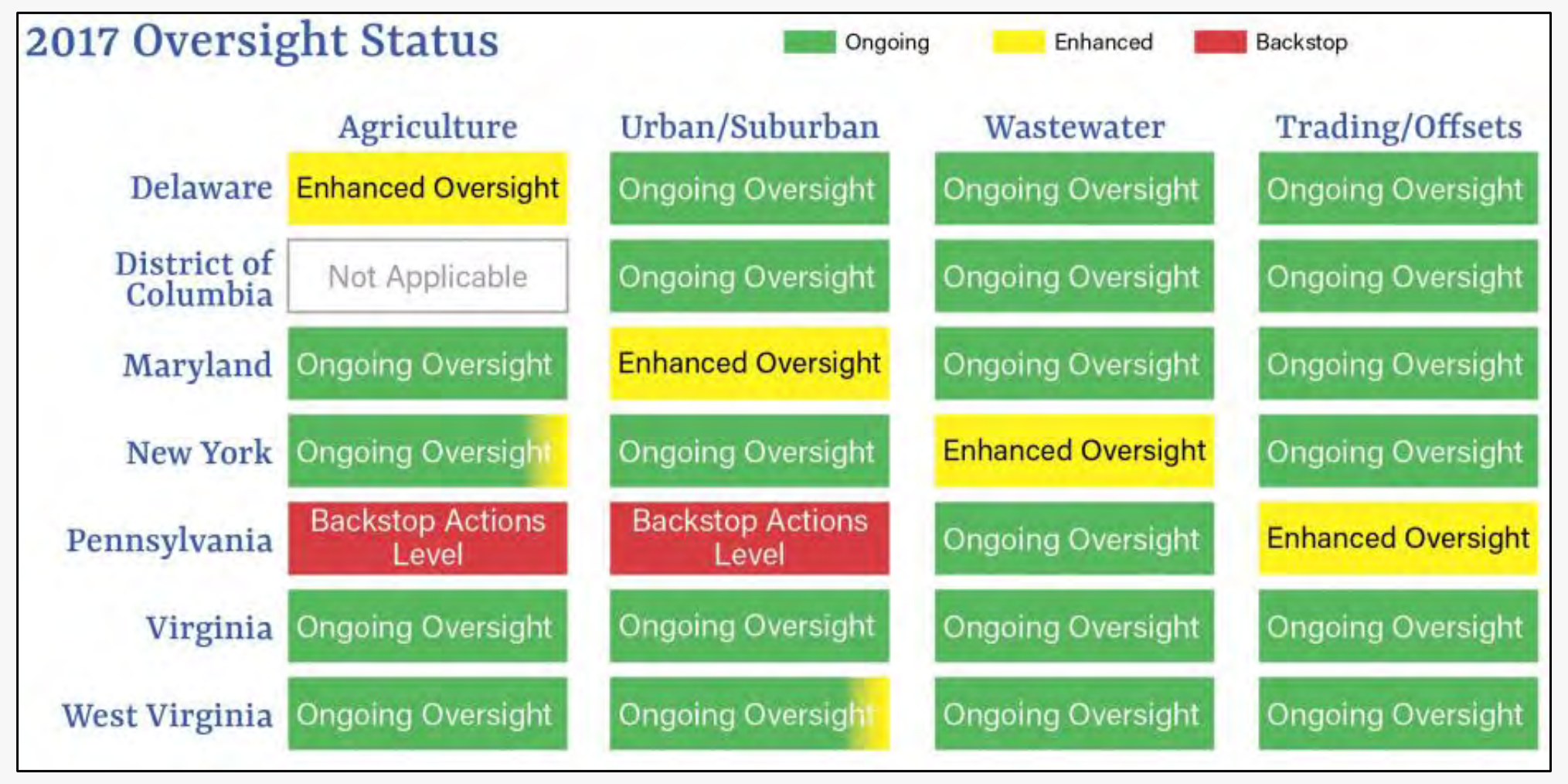


Figure 2. Load Contributions of the Nine Major Rivers Discharging to the Chesapeake Bay
Source: USGS, 2011



2017 Oversight Status

🟩 Ongoing 🟨 Enhanced 🟥 Backstop

	Agriculture	Urban/Suburban	Wastewater	Trading/Offsets
Delaware	Enhanced Oversight	Ongoing Oversight	Ongoing Oversight	Ongoing Oversight
District of Columbia	Not Applicable	Ongoing Oversight	Ongoing Oversight	Ongoing Oversight
Maryland	Ongoing Oversight	Enhanced Oversight	Ongoing Oversight	Ongoing Oversight
New York	Ongoing Oversight	Ongoing Oversight	Enhanced Oversight	Ongoing Oversight
Pennsylvania	Backstop Actions Level	Backstop Actions Level	Ongoing Oversight	Enhanced Oversight
Virginia	Ongoing Oversight	Ongoing Oversight	Ongoing Oversight	Ongoing Oversight
West Virginia	Ongoing Oversight	Ongoing Oversight	Ongoing Oversight	Ongoing Oversight

Figure 3. 2017 EPA Oversight Status for Bay States
Source: EPA, 2017

Best Management Practice Portfolio for PA

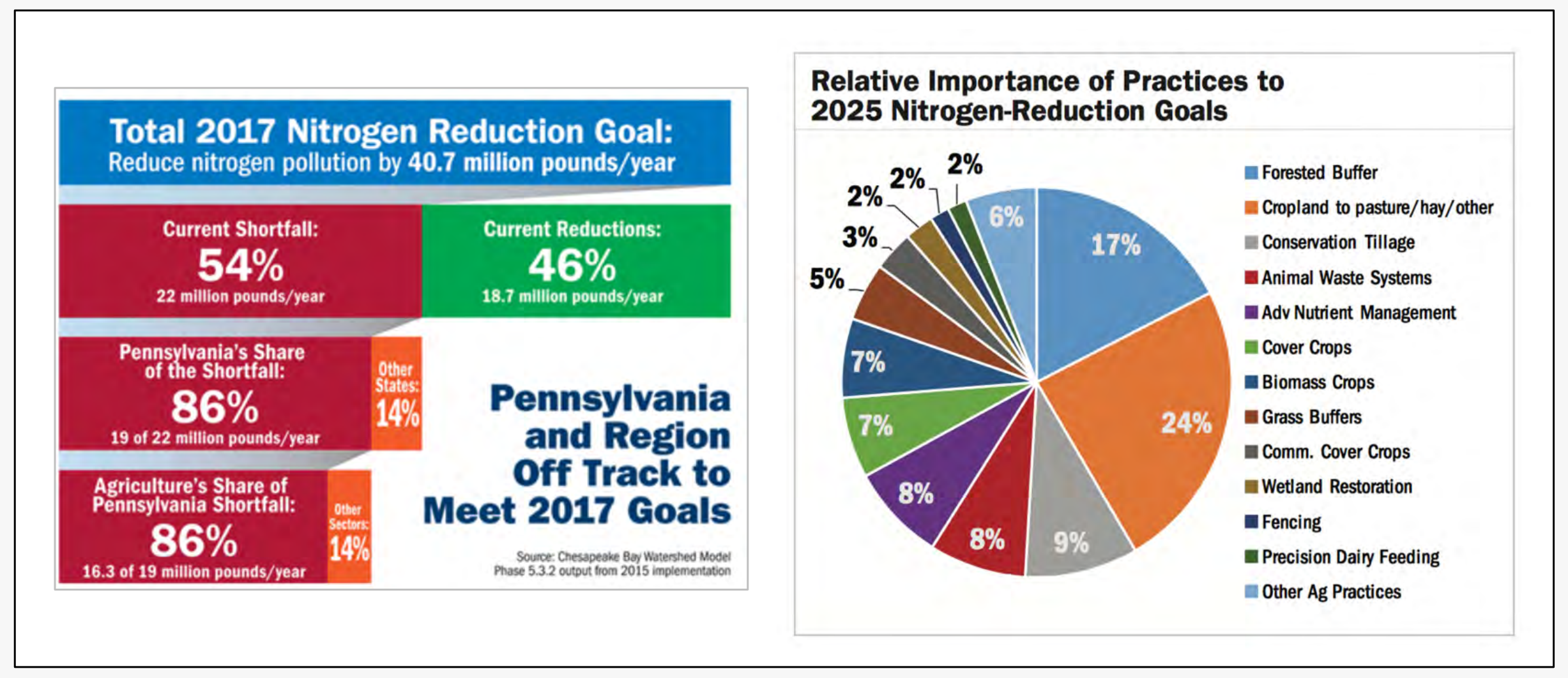


Figure 4. Pennsylvania BMP Portfolio to meet Nitrogen Reduction Goals
Source: Chesapeake Bay Watershed Model, 2015

Effectiveness of Vegetated Filter Strips as BMPs

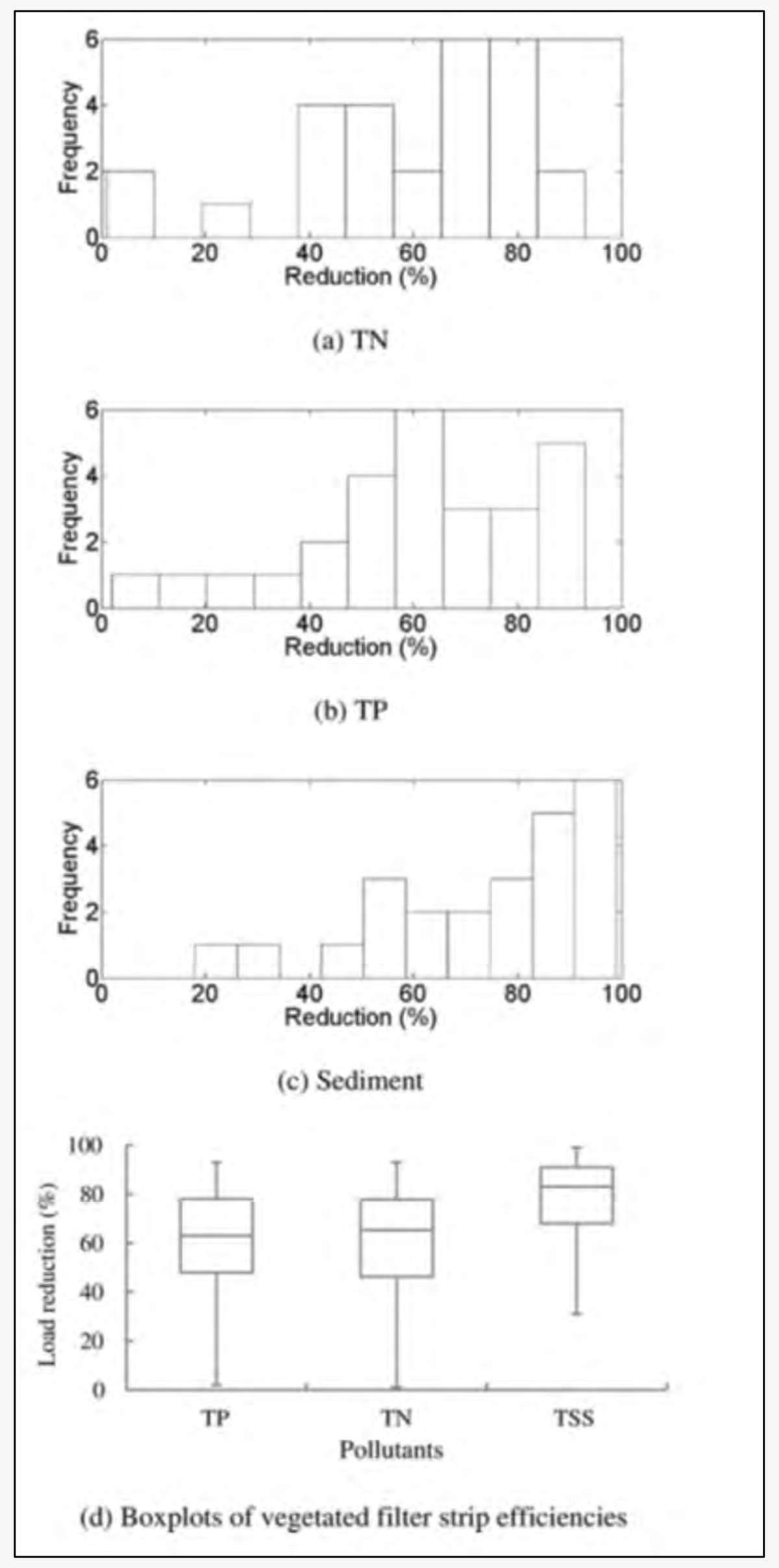
- Generally thought to be one of the most effective agricultural BMPs for water quality improvement
- Widespread adoption across the Susquehanna River Basin, and another 385 km^2 are expected to be adopted in PA between now and 2025

Lack of Understanding of Performance

- Wide variability in effectiveness **(Fig. 5)** reported in the literature
- Field studies on farm sites are lacking and the field data that do exist are largely from rainfall simulation experiments rather than from natural runoff events
- Long-term observational studies are also lacking (very few longer than 1-3 years)

Poor Representation in Models

- Watershed scale models typically represent the performance of VFSs with one number for their efficiency; Cannot capture spatial / temporal variability
- Field-scale models often estimate the effectiveness of VFSs on a per-event or design-storm basis; Cannot capture antecedent conditions
- Need a model structure that captures temporal variability in VFS performance



(a) TN

(b) TP

(c) Sediment

(d) Boxplots of vegetated filter strip efficiencies

Figure 5. Literature Review Results for VFS Efficiencies
Source: Liu et al., 2017

Two-Component Modeling Approach

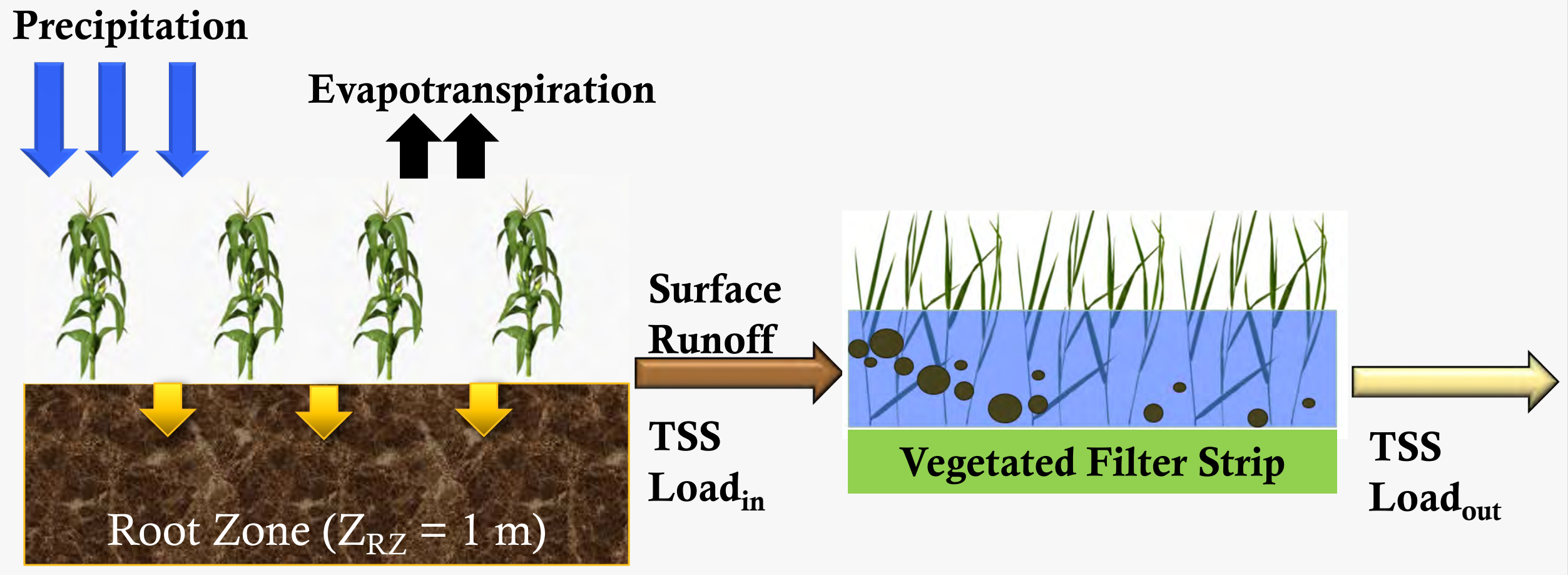


Figure 6. Schematic of the Two-Component Model: A field-scale water balance and total suspended solid (TSS) transport model coupled to a VFS model
Source: Gall et al., 2018

- Model was run at a daily time step for one year
- 1000 one-year simulations were run for each set of parameters
  - VFS slope (1, 2, 5, 8%)
  - Soil Texture (all 12 soil textures)
  - Concentration-Discharge relationship; $C = aQ^b$ (b = 0.5, 1.0, 1.5, 2.5)

Methods & Model Parameters

Table 1. Hydro-climatic Parameters for Lancaster County, PA, USA

Parameter	Description	Value	Units
λ	Mean rainfall inter-arrival frequency	0.36	day^{-1}
d	Mean rainfall depth	8.0	mm
δ	Mean rainfall duration	2	hr
A	Mean annual temperature	11.4	°C
B	Half-amplitude	12.6	°C
D_{min}	Day of the year with minimum temperature	19	day

Note: All parameters were determined based on 60 years of data available from the National Climatic Data Center, Station Number USC00364763

Table 2. Vegetated Filter Strip Physical Parameters

Parameter	Description	Value	Units
W	VFS Width	10.7	m
b_g	Average stem spacing	2.16[a]	cm
n	Manning's roughness coefficient	0.056[a]	s m$^{-1/3}$
V_c	Settling velocity for course particles	67[b]	mm s^{-1}
V_m	Settling velocity for medium particles	0.14	mm s^{-1}
V_f	Settling velocity for fine particles	0.0014	mm s^{-1}

[a] Values from Haan et al. (1994) for Kentucky Bluegrass
[b] Values from Haan et al. (1994). Sediment particles are classified as coarse if they have a diameter greater than 0.037 mm, fine if they have a diameter less than 0.004 mm, and medium if they have a diameter between 0.004 and 0.037 mm.

Precipitation (P): Marked Poisson Process in which depth (d) and inter-arrival frequency (λ) are simulated randomly from exponential distributions (Rodriguez-Iturbe, 1999)

Evapotranspiration (ET): Blaney-Criddle Model (Sammis et al., 1982), modified to account for seasonal crop growth changes (Basu et al., 2010), and soil moisture stress

Surface Runoff (Q):

- Horton Runoff: $Q(t) = P(t) - \min(K_{sat}\delta, (\theta_{sat} - \theta(t))Z_{RZ})$
- Dunne Runoff: $Q(t) = P(t) - \max(0, (\theta_{sat} - \theta(t))Z_{RZ})$

Sediment Transport (TSS L_{in}): Sediment leaving the row-cropped field and entering the VFS was simulated as $TSS\ Lin = CQ = aQ^{b+1}$

Vegetated Filter Strip Removal Efficiency: Sediment trapping was calculated for each particle size separately and then a weighted removal efficiency was calculated (on a per-event basis) based on the fractions of each particle size in the sediment.

- Removal efficiency (F_d) for each particle size: $F_d = \exp(-1.05 * 10^{-3}\, Re^{0.82}\, N_f^{-0.91})$
  - Re = Reynold's Numer
  - N_f = Fall number (Haan et al., 1994)
- Total Removal Efficiency (F_t): $F_t = f_C F_{d,C} + f_M F_{d,M} + f_F F_{d,F}$
  - f_C = fraction of coarse particles
  - f_M = fraction of medium particles
  - f_F = fraction of fine particles

Data Analysis Methods: To quantify the effects of temporal inequality on the disparity between reporting sediment removal efficiency as simple event-specific means versus annual load reductions, we calculated sediment trapping efficiency using two different methods.

- Annual Per-Event Average (APEA) = $\frac{\sum_{i=1}^{n} F_{t,i}}{n}$
- Annual Load Reduction (ALR) = $\frac{\sum_{i=1}^{n} F_{t,i} L_{in,i}}{\sum_{i=1}^{n} L_{in,i}}$

  where n is the number of runoff events in a one-year period

Example of Differences in the Data Analysis Methods:
Consider a series of three runoff events, n =3, that occur during one year with the following loads and trapping efficiencies:

Event #1: $F_{t,1} = 0.90$, $L_{in,1} = 1$ kg
Event #2: $F_{t,2} = 0.50$, $L_{in,2} = 10$ kg
Event #3: $F_{t,3} = 0.75$, $L_{in,3} = 4$ kg

Using the average of the per-event removal efficiencies (APEA) performance of the VFS would be calculated as:

$$APEA = \frac{\sum_{i=1}^{n} F_{t,i}}{n} = \frac{0.90+0.50+0.75}{3} = 0.72$$

However, using the total load reduction (or annual load reduction, if the three events are the only events over the course of one year), the performance of the VFS would be calculated as:

$$ALR = \frac{\sum_{i=1}^{n} F_{t,i} L_{in,i}}{\sum_{i=1}^{n} L_{in,i}} = \frac{0.90*1+0.50*10+0.75*4}{1+10+4} = 0.59$$

Results & Implications

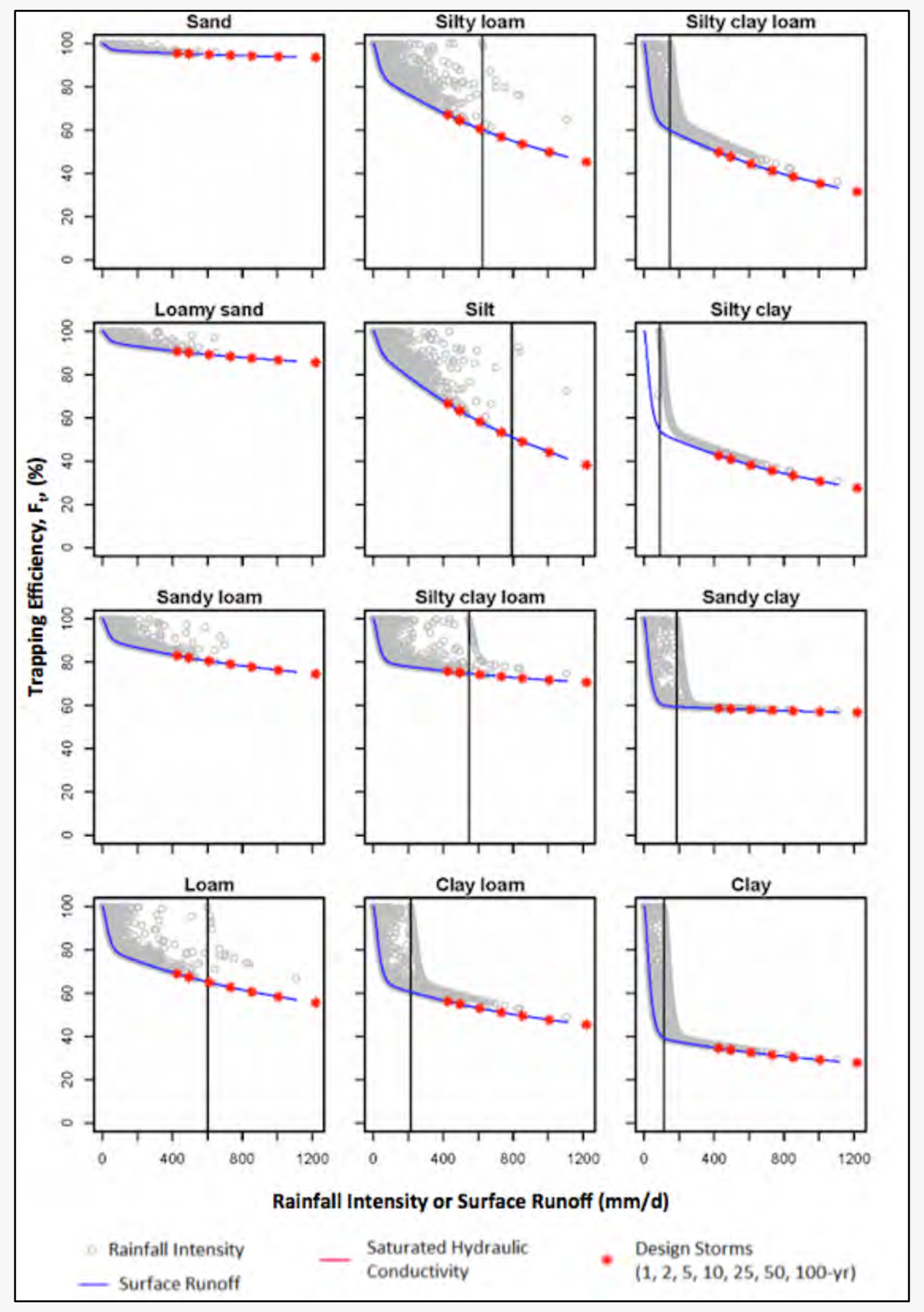


Figure 7. Event-specific trapping efficiencies

- Intensities of storm events with return periods of 1, 2, 5, 10, 25, 50, and 100 years for the area of interest (Lancaster County, PA) are indicated with red asterisks.
- The black lines indicate the saturated hydraulic conductivity for each soil texture. Simulation results shown here were run with a VFS slope of 2% and average values of F_t across b values.

- Simulation results reveal that reporting the average of the trapping efficiency for each runoff event over the course of a year overestimates the performance of the VFS relative to calculating the annual-scale load reduction.
- The extent of the disparity between the APEA and ALR values varied by soil texture, with the differences generally greater for soils with a higher fraction of fine particles, as the removal efficiency is higher for coarse and medium-sized particles.
- Simulation results revealed the importance of antecedent conditions on VFS performance and suggest that water quality models need to explicitly consider variability in the relationship between the performance of structural BMPs and rainfall events.
- Simply averaging the removal efficiencies of each observed (or simulated) event is not necessarily an accurate indicator of the overall removal efficiency of VFSs.
- Temporal inequality and non-stationarity of F_t must explicitly be considered when structural BMPs are simulated in water quality models.

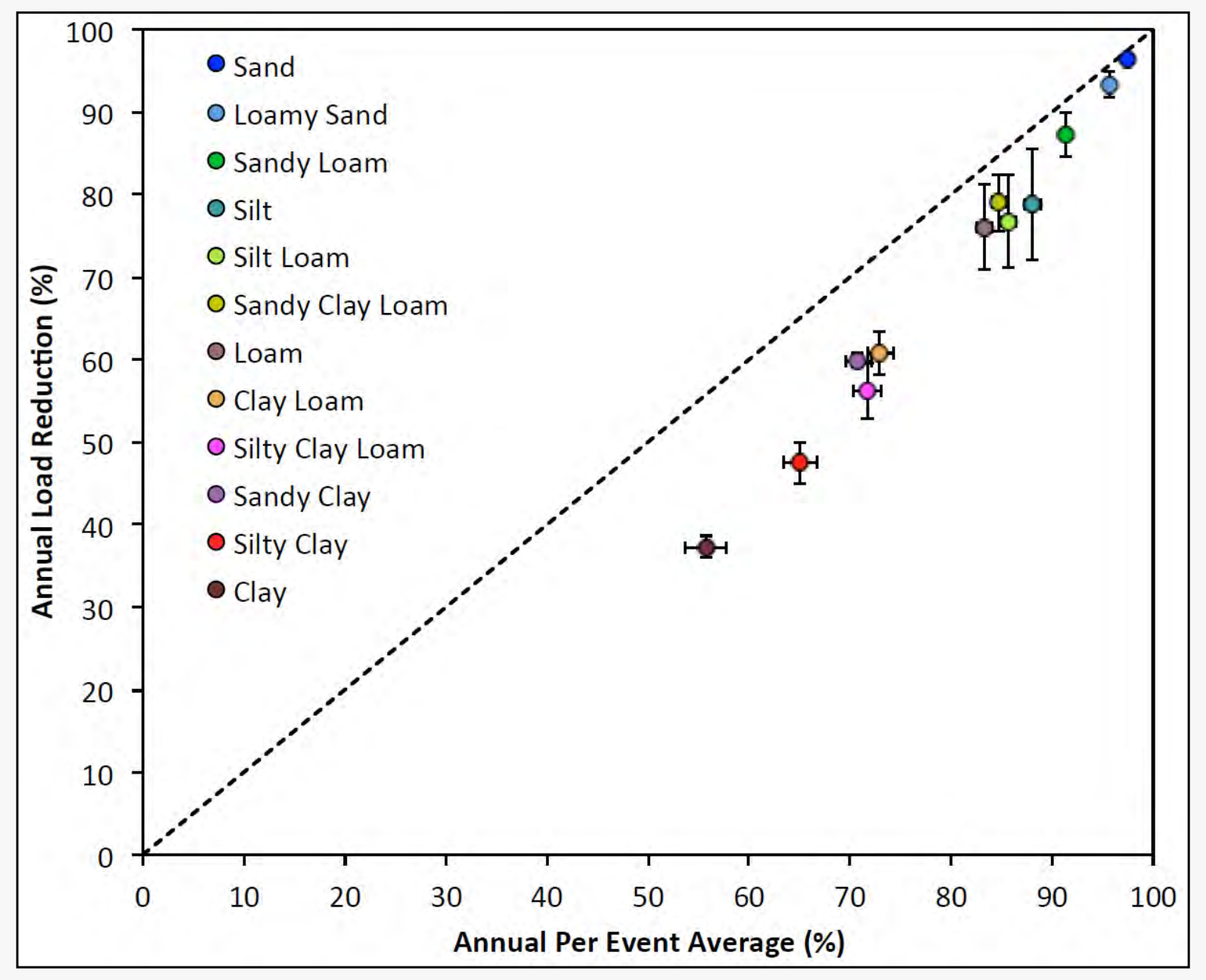


Figure 8. Deviation from the 1:1 line for the ALR versus APEA method of assessing annual VFS performance
Source: Gall et al., 2018

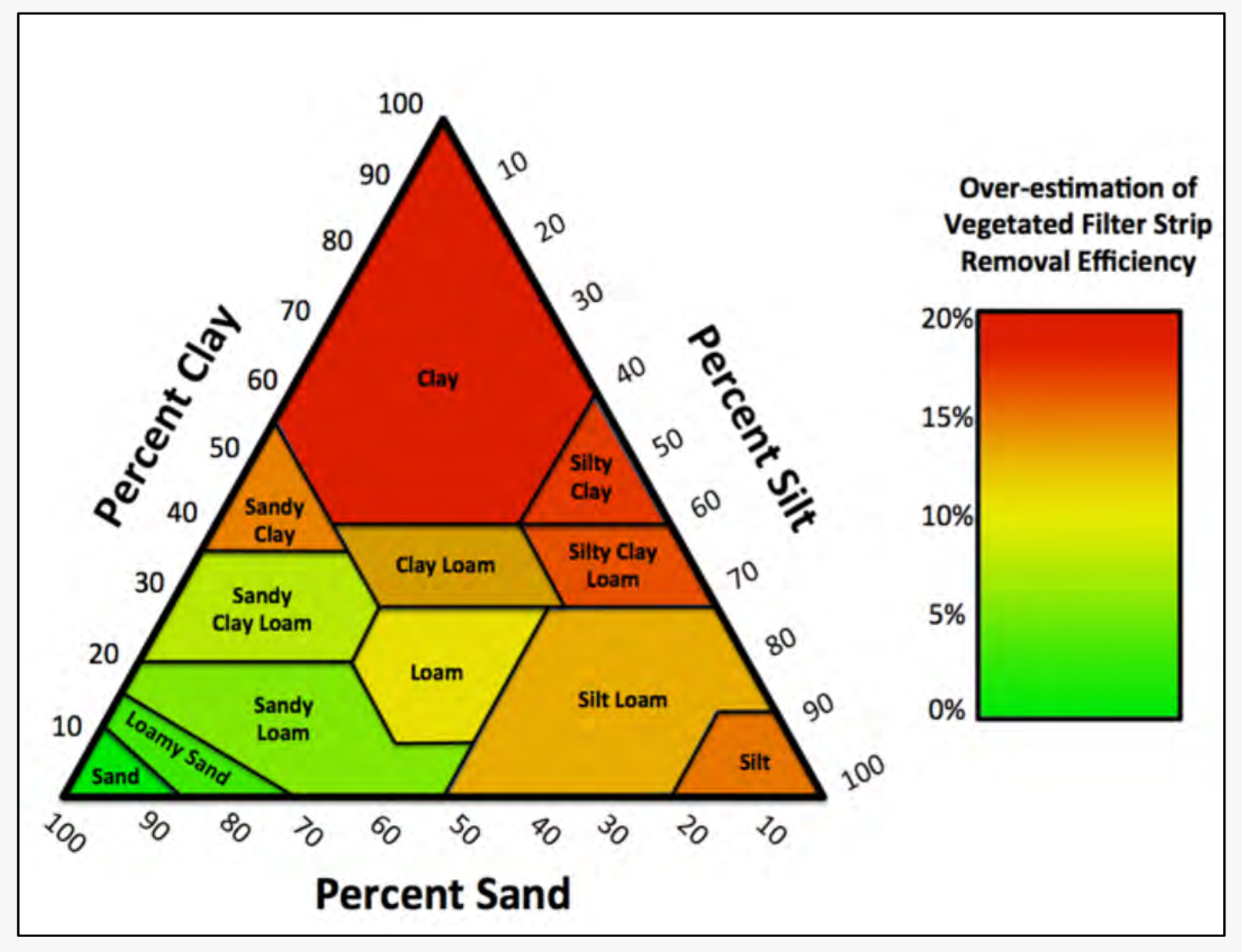


Figure 9. Visual representation of the average differences APEA values and ALR values
Source: Gall et al., 2018

Funding

This research was supported, in part, by a USDA-Conservation Innovation Grant and USDA Grant #12219509. Heather Preisendanz (formerly Gall) is supported, in part, by the Penn State Institutes of Energy and the Environment. Daniel Schultz worked on this research as an undergraduate student in the Department of Agricultural and Biological Engineering at Penn State and was funded by several undergraduate research programs at Penn State (College of Engineering Research Experience for Undergraduates and the Erickson Discovery Grant).