How Not to Design and Regulate Onlot Residential Sewage Systems
(Someone Might Be Paying Attention)

Presented to the American Water Resources Association
Philadelphia Metropolitan Area Section

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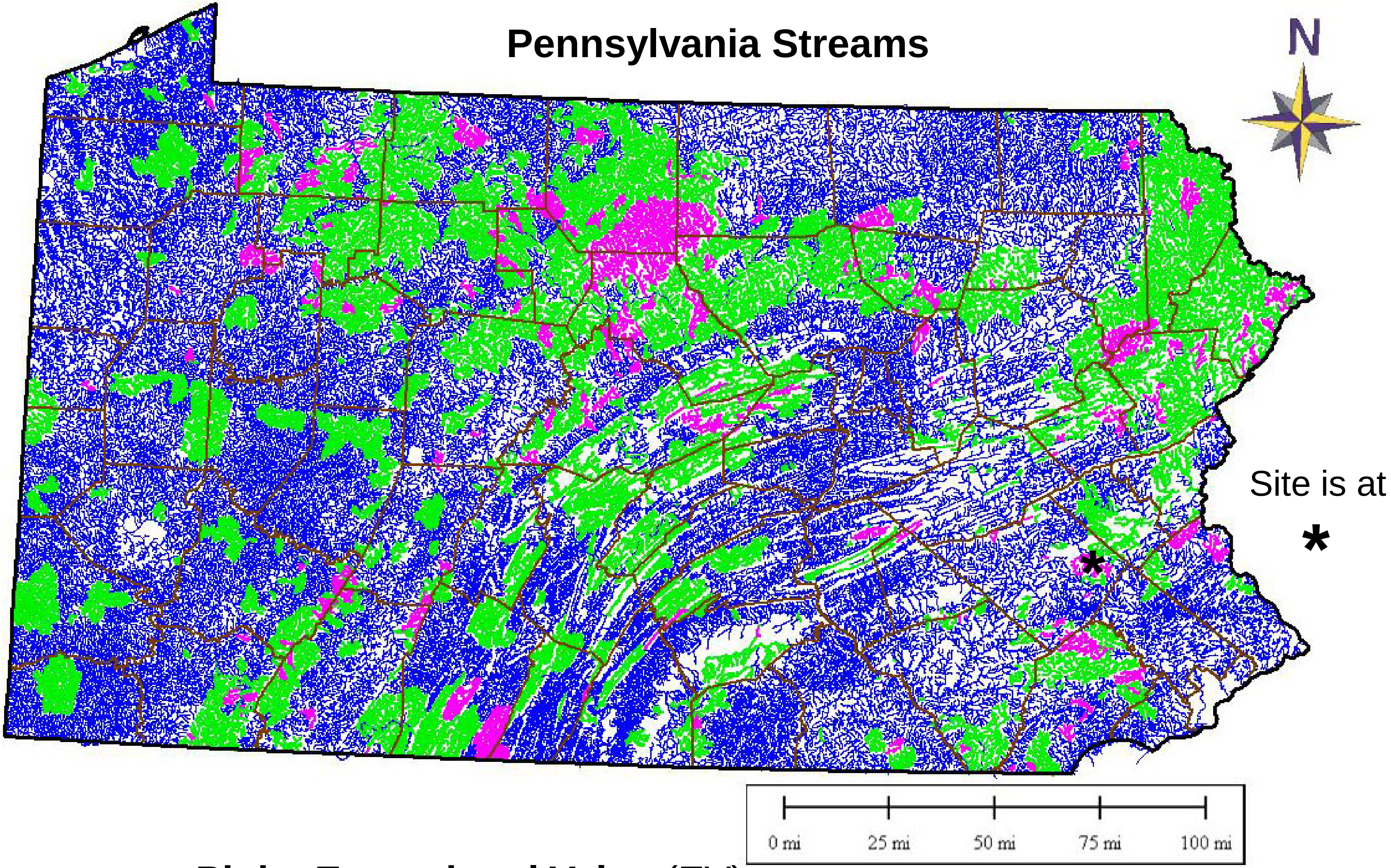
Media, Pennsylvania   www.schmidco.com

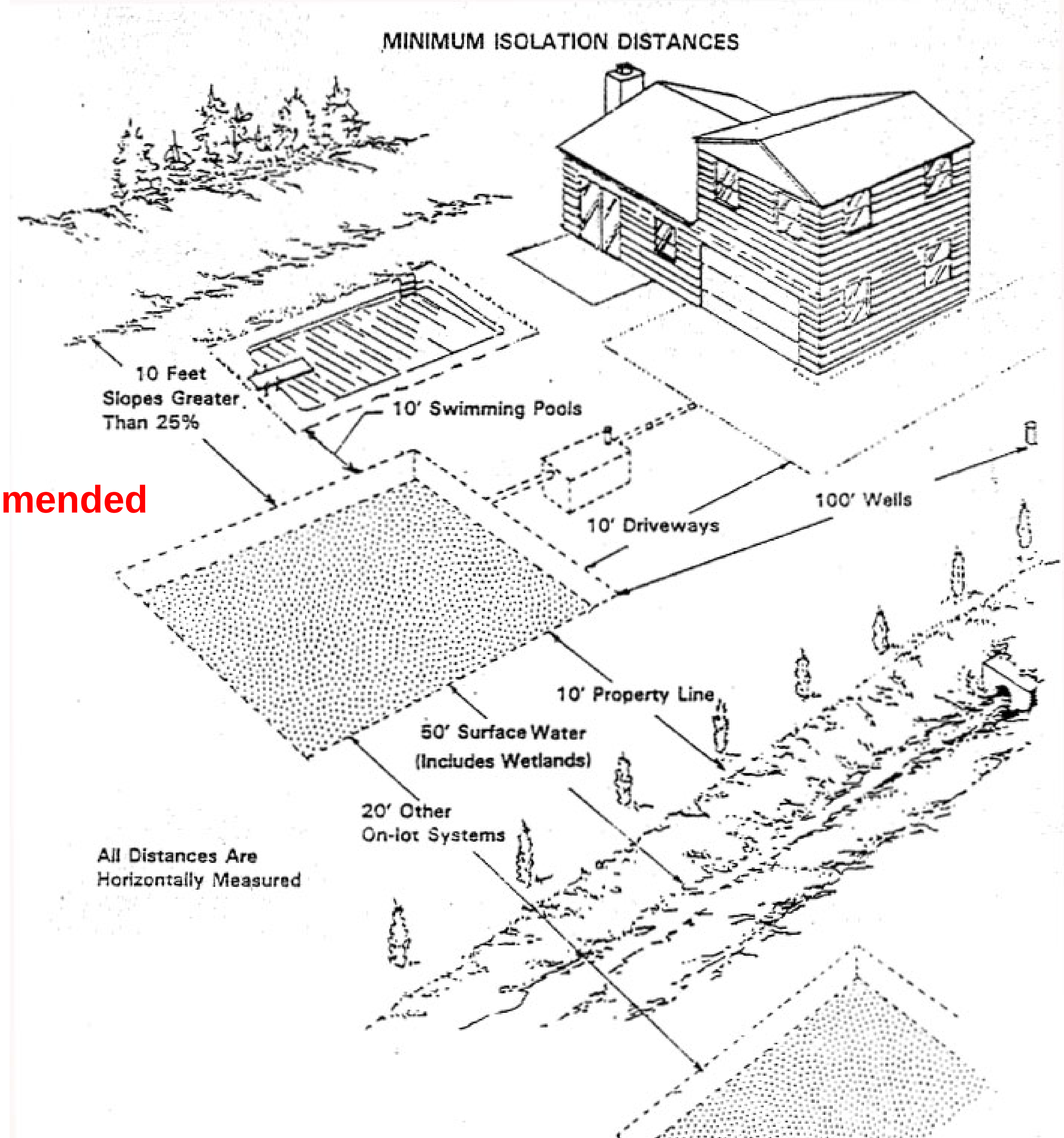
11 February 2015

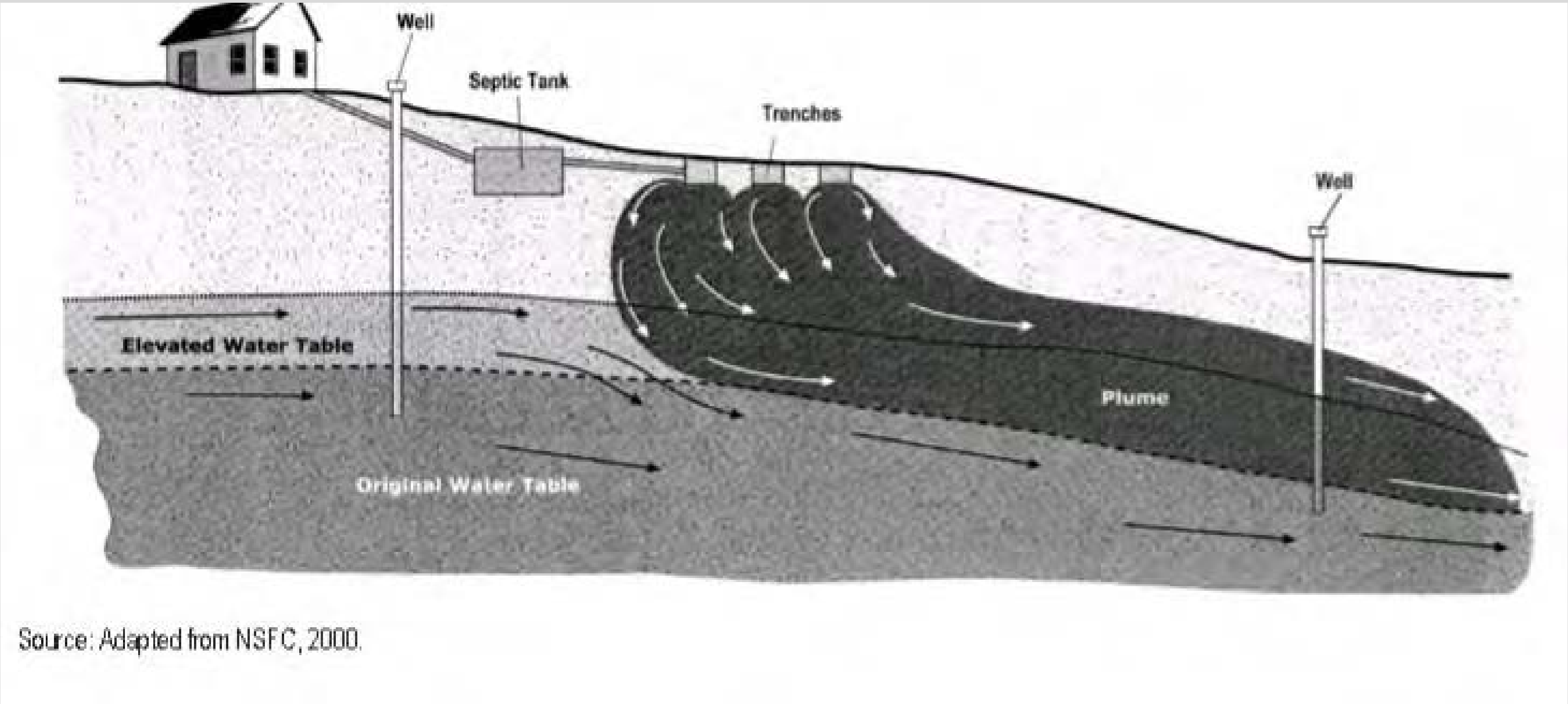
Fredericksville Farms site, District Township, Berks County, PA



Pink: Exceptional Value (EV)
Green: High Quality (HQ)
Blue: “Ordinary” Quality (TSF, CWF, WWF)

20-year old State recommended onlot layout





Conventional onlot residential septic tank and drainfield

Developer claimed plenty of capacity to denitrify effluent from 8 houses in the 11 acres of onsite wetlands. But no distribution system was proposed to spread the effluent beyond gravity plumes.

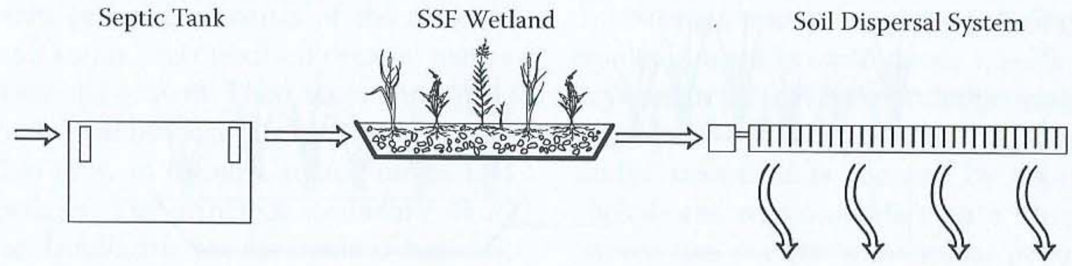


FIGURE 1.6 Application of a HSSF wetland to domestic wastewater treatment. (From Wallace and Knight (2006) *Small-scale constructed wetland treatment systems: Feasibility, design criteria, and O&M requirements*. Final Report, Project 01-CTS-5, Water Environment Research Foundation (WERF): Alexandria, Virginia. Reprinted with permission.)

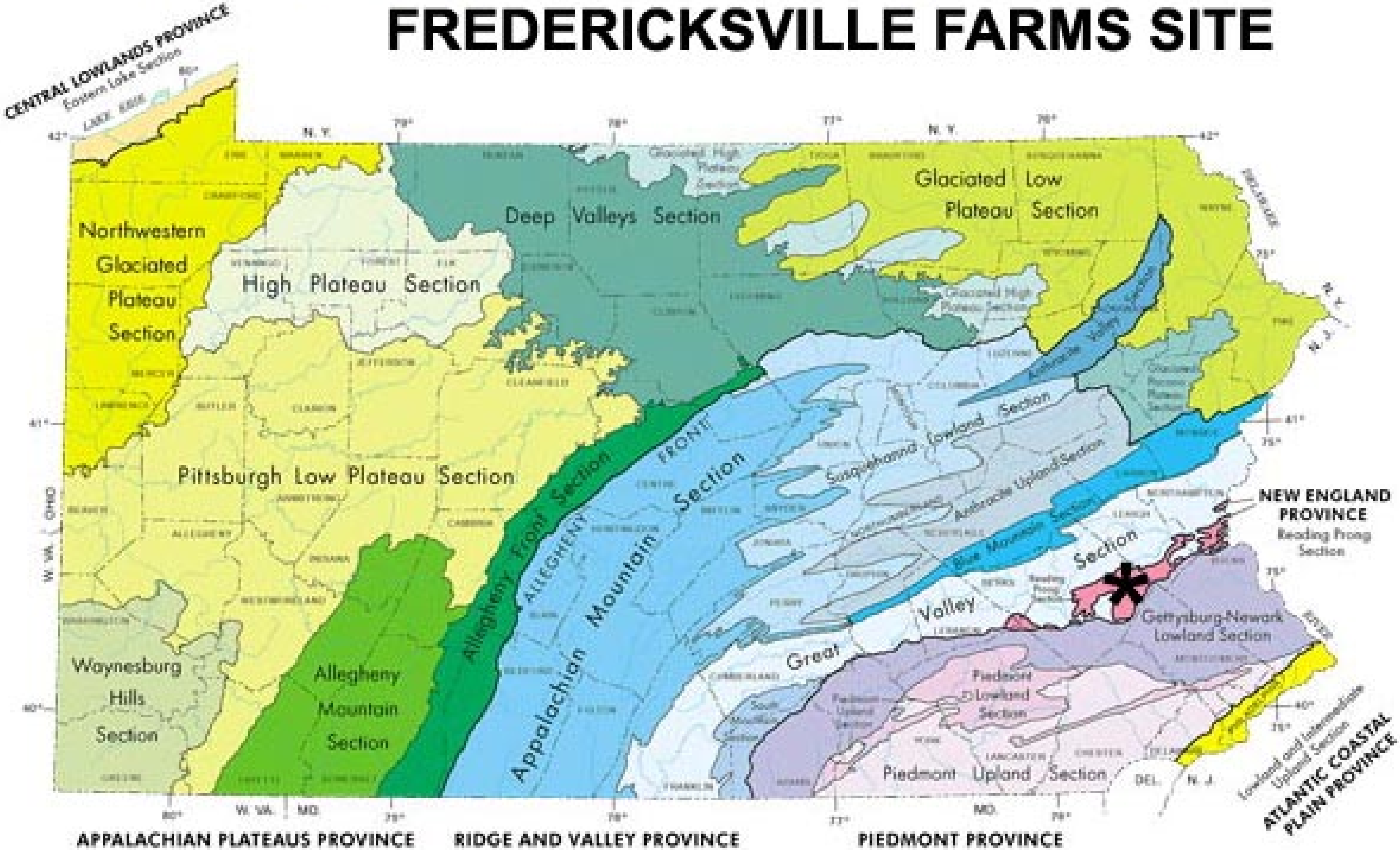
FIGURE 1.13 Single-home HSSF wetland in Comfort Lake, Minnesota.

Sample textbook artificial wetland for residential application

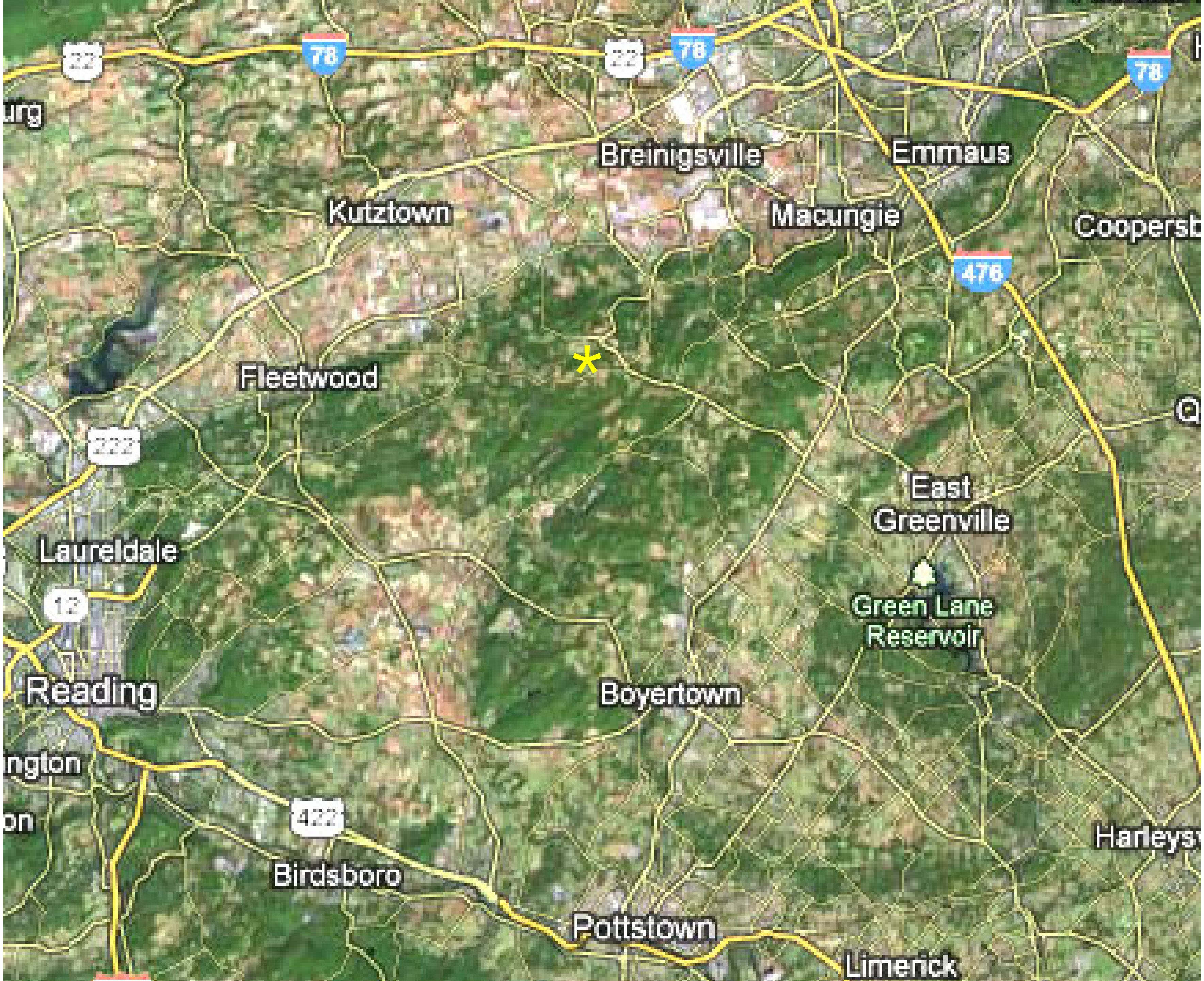
“The Southcentral Regional Office of the Department of Environmental Protection issued three experimental permits for three individual constructed wetland systems during the early 1990s. Monitoring was conducted. None of the systems met their limits, and total nitrogen removal from the system[s] was not significant. The Department’s experience will not allow it to issue permits for individual on site constructed wetland cells for the purpose of denitrification. Interposing a wetland cell as part of the individual system treatment cell has proved to be simply an ineffective measure, and a waste of money” [Sigouin 2010:21].

Yet natural wetlands will do this ok?

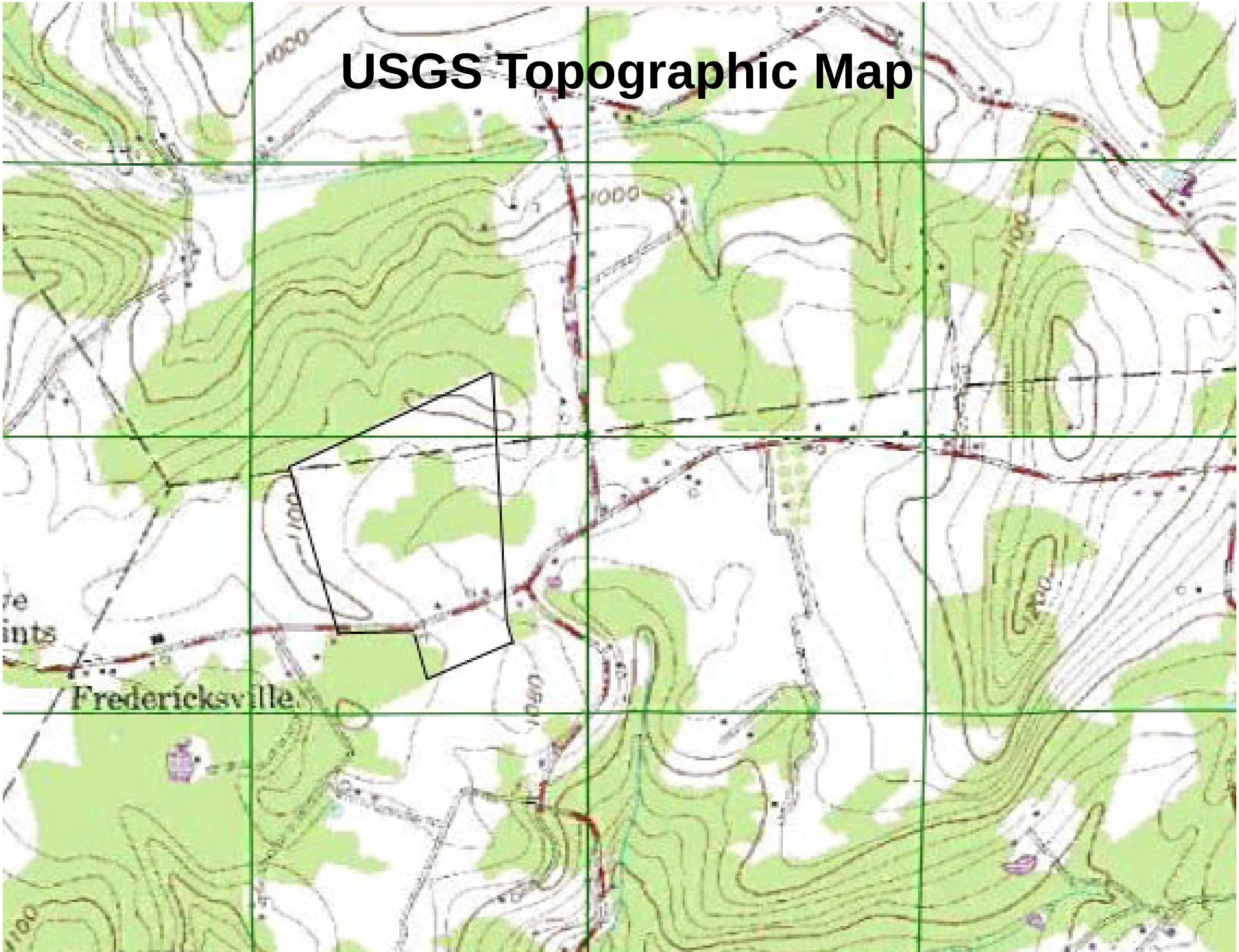
FREDERICKSVILLE FARMS SITE

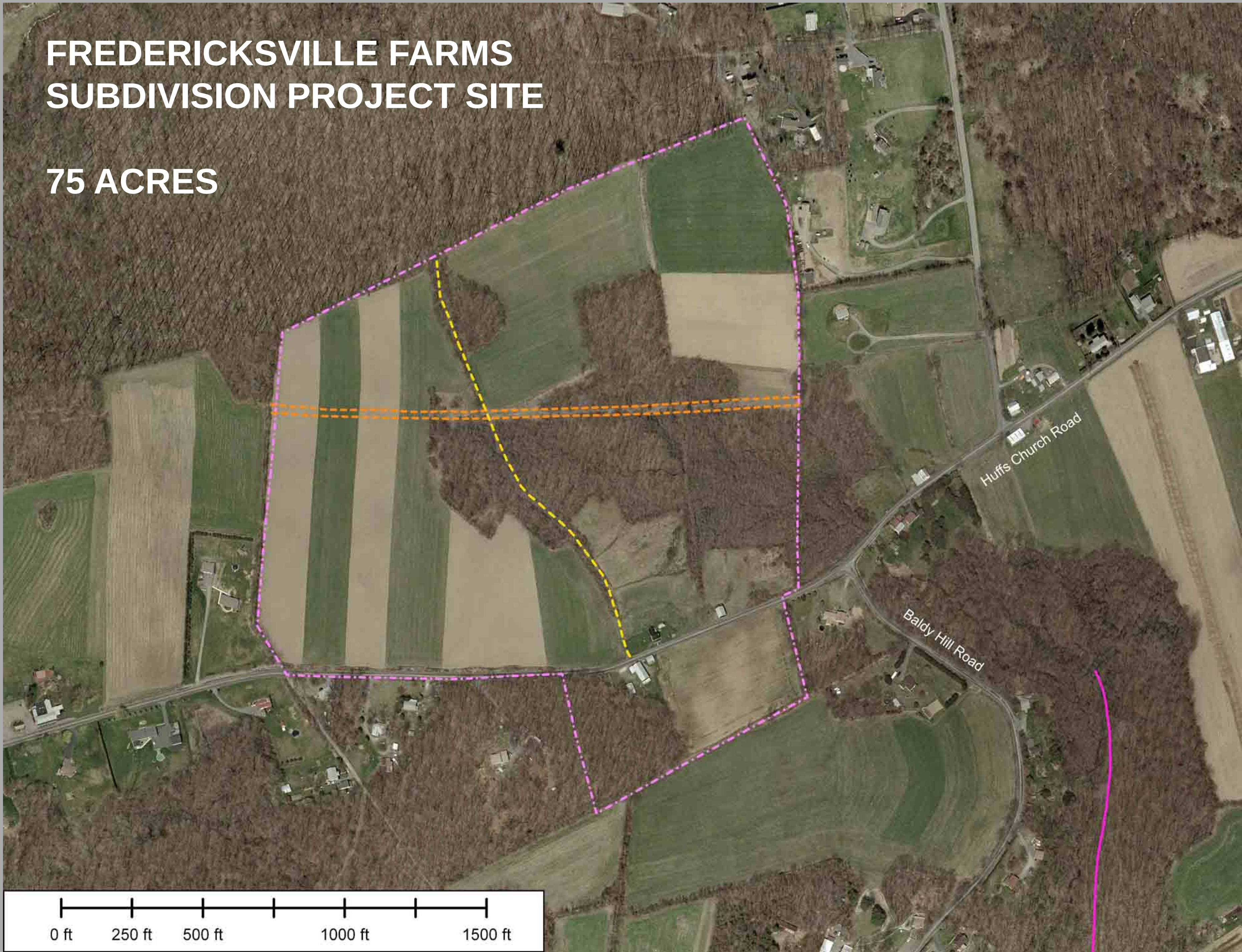


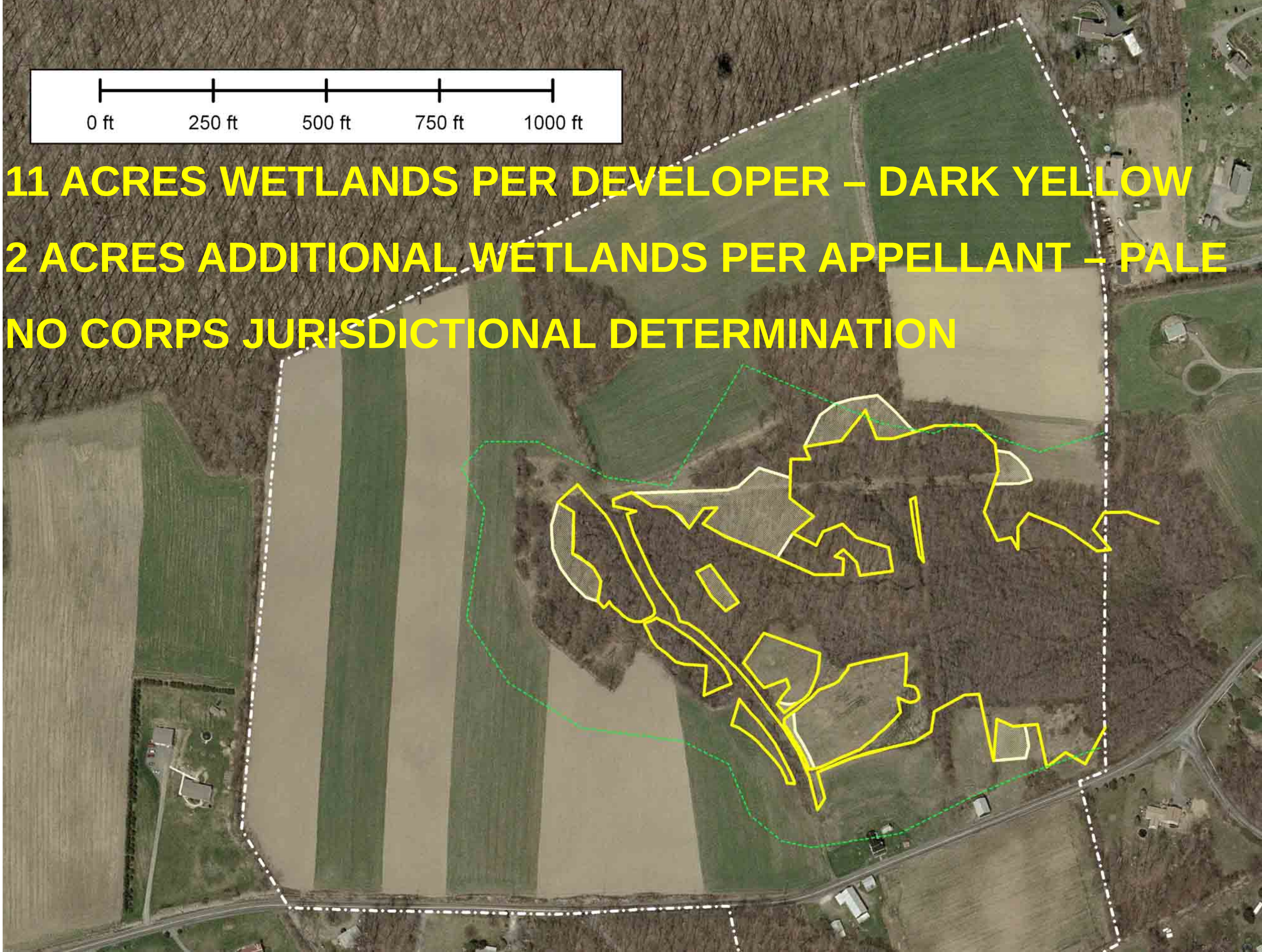
Pennsylvania Physiography

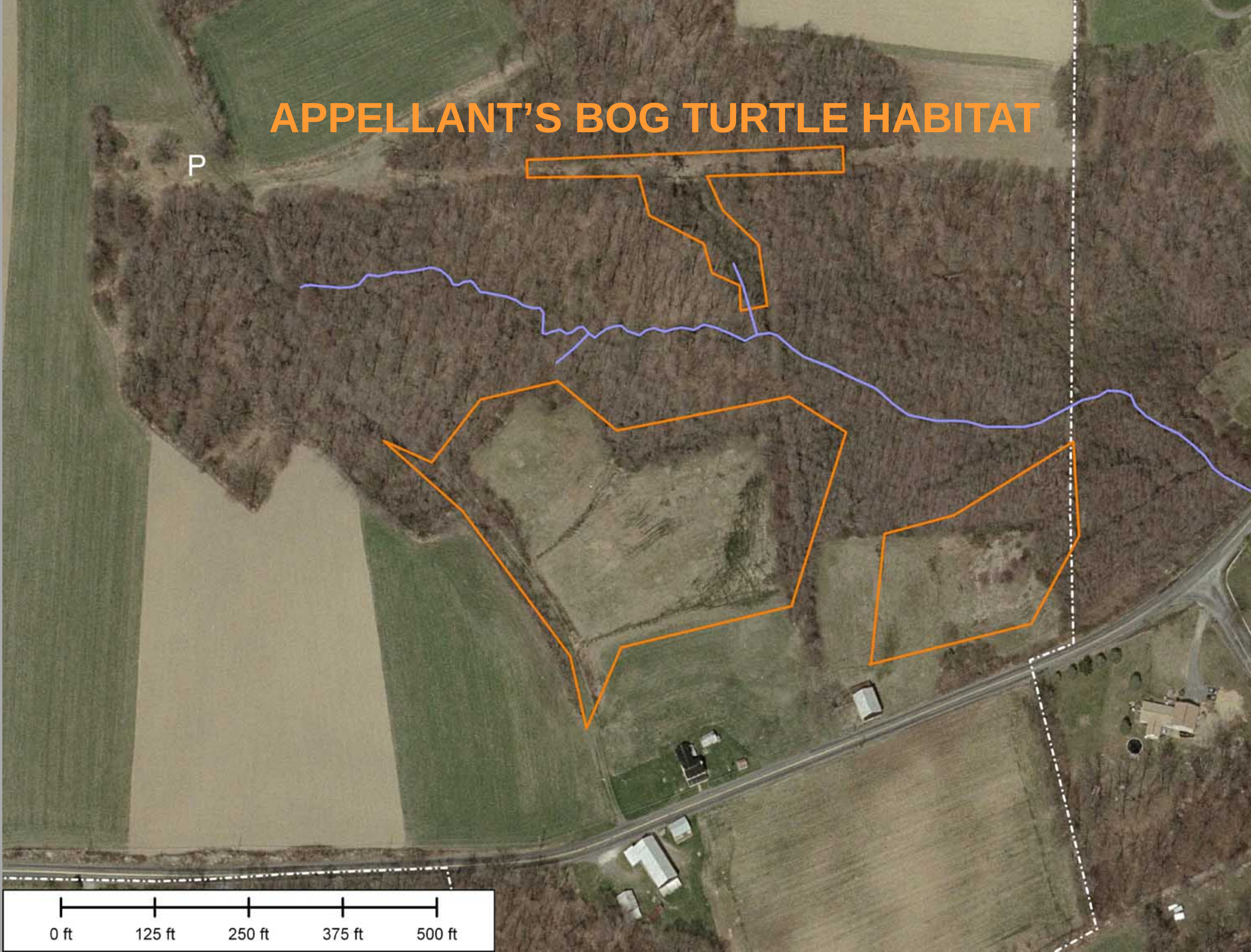

22
78
22
78
78
Breinigsville
Emmaus
Kutztown
Macungie
476
Fleetwood
222
East
Greenville
Laureldale
12
Green Lane
Reservoir
Reading
Boyertown
422
Birdsboro
Pottstown
Limerick

USGS Topographic Map

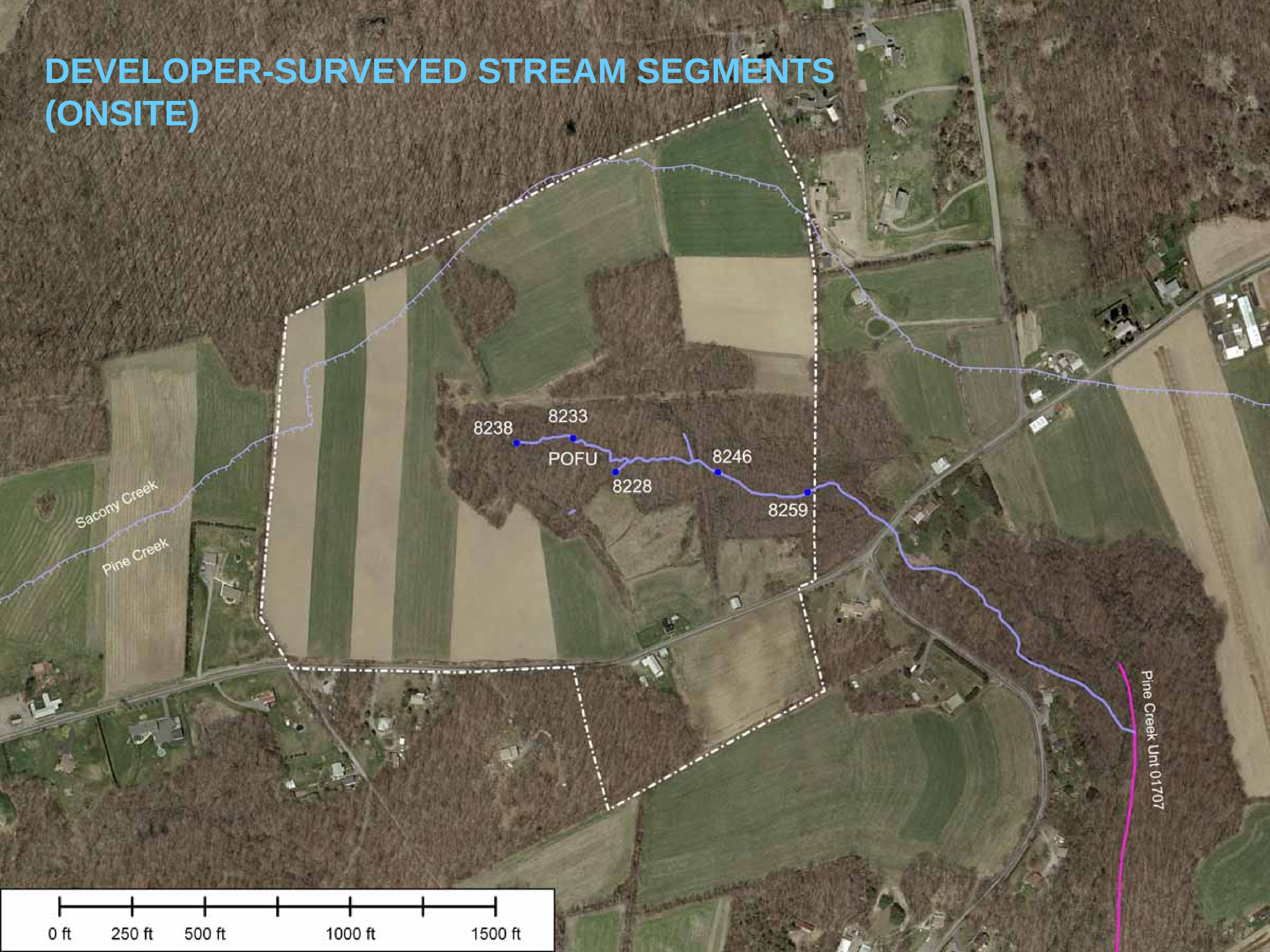


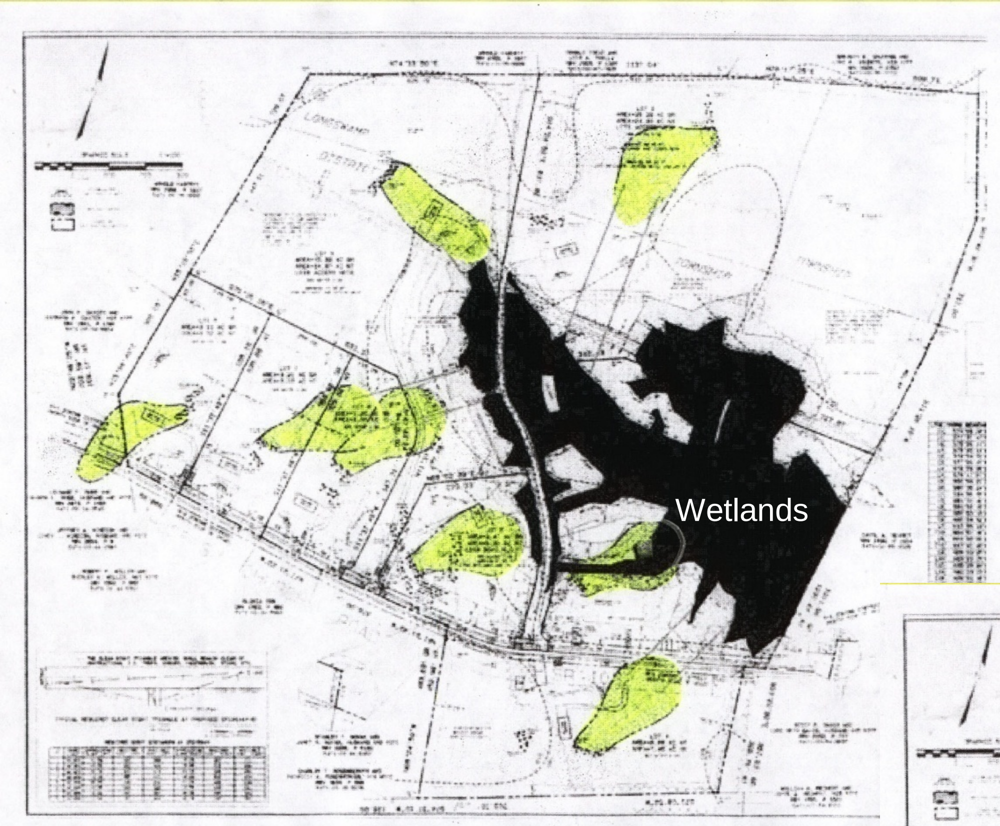

FREDERICKSVILLE FARMS
SUBDIVISION PROJECT SITE
75 ACRES
Huffs Church Road
Baldy Hill Road
0 ft
250 ft
500 ft
1000 ft
1500 ft


0 ft
250 ft
500 ft
750 ft
1000 ft
11 ACRES WETLANDS PER DEVELOPER – DARK YELLOW
2 ACRES ADDITIONAL WETLANDS PER APPELLANT – PALE
NO CORPS JURISDICTIONAL DETERMINATION


APPELLANT'S BOG TURTLE HABITAT
P
0 ft
125 ft
250 ft
375 ft
500 ft

DEVELOPER-SURVEYED STREAM SEGMENTS (ONSITE)





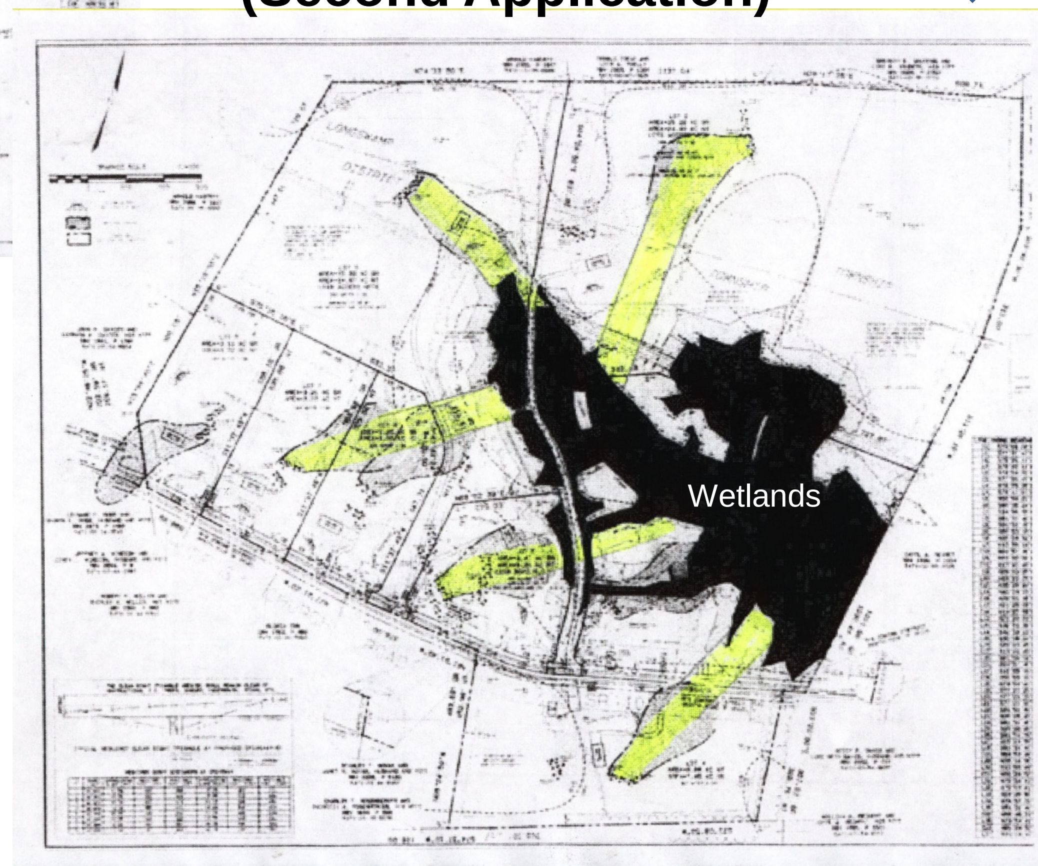
DEVELOPER HYDROGEOLOGIST'S NITRATE PLUMES – YELLOW

DISAPPEAR AS BLOBS

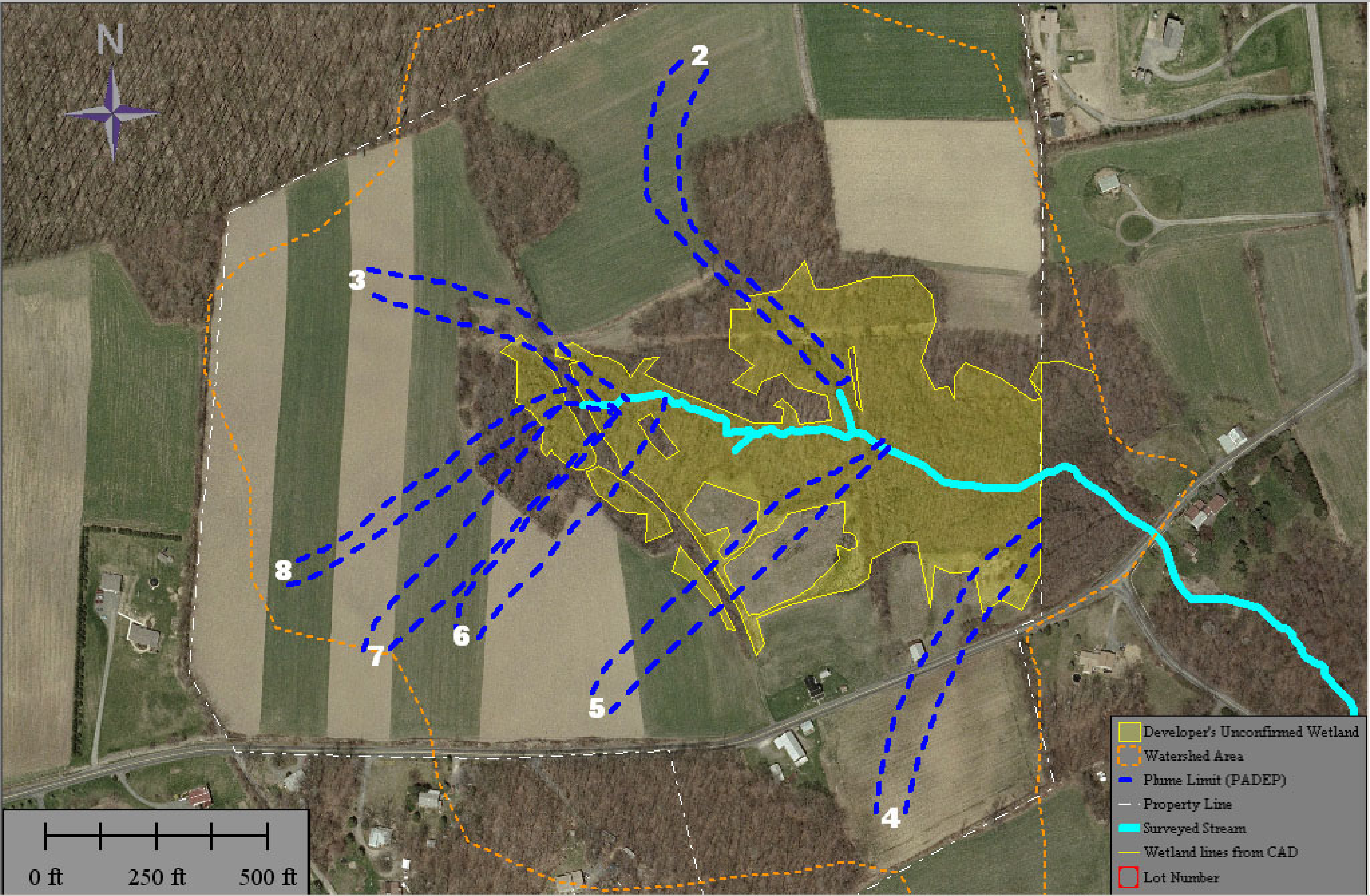
(First Application)

DEVELOPER WETLAND DESIGNER'S 100-FOOT WIDE NITRATE PLUMES – YELLOW

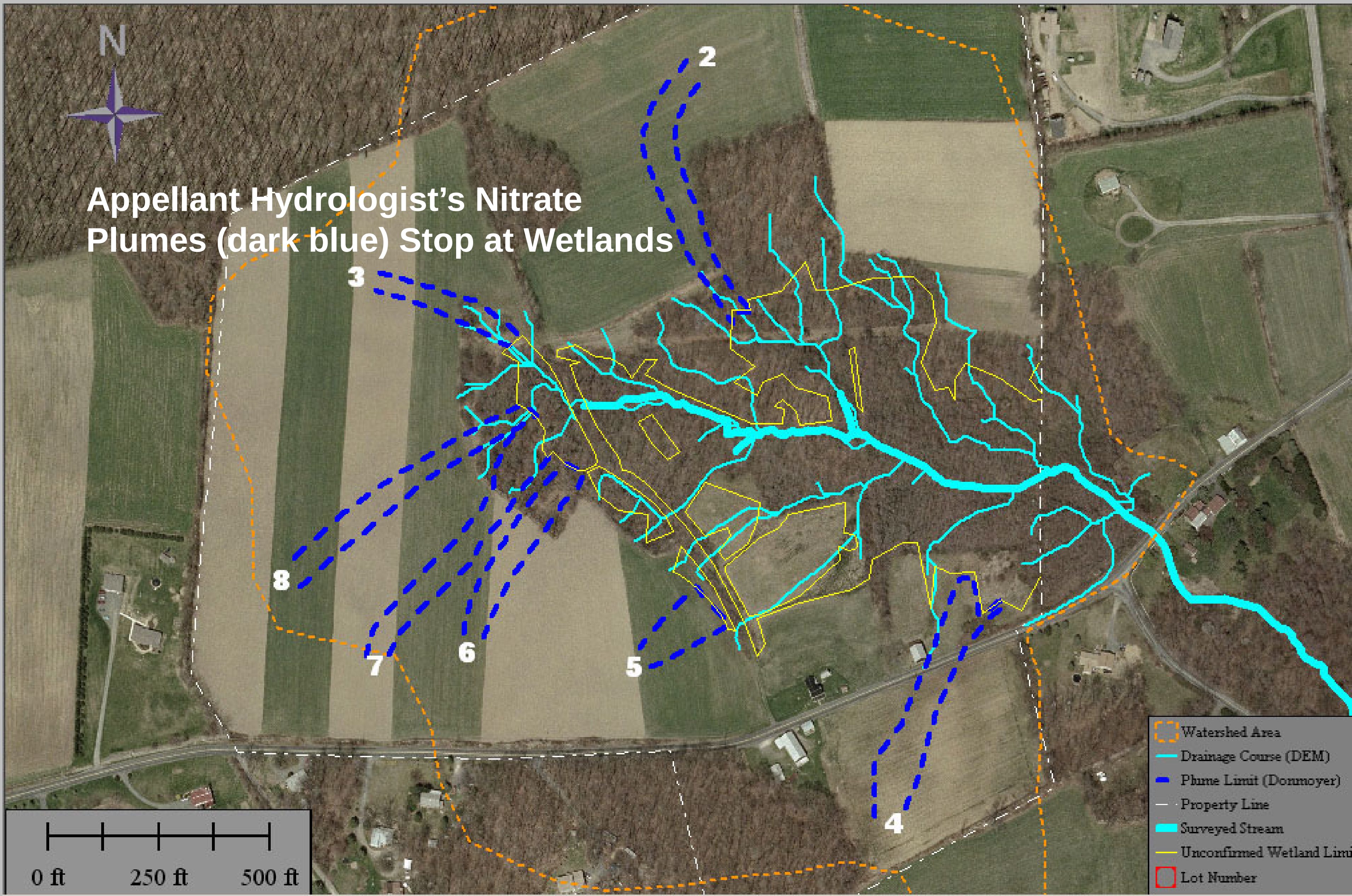
EXTEND TO MAIN STREAM (Second Application)



STATE HYDROGEOLOGIST'S NITRATE PLUMES – DARK BLUE EXTEND THROUGH WETLANDS TO MAIN STREAM

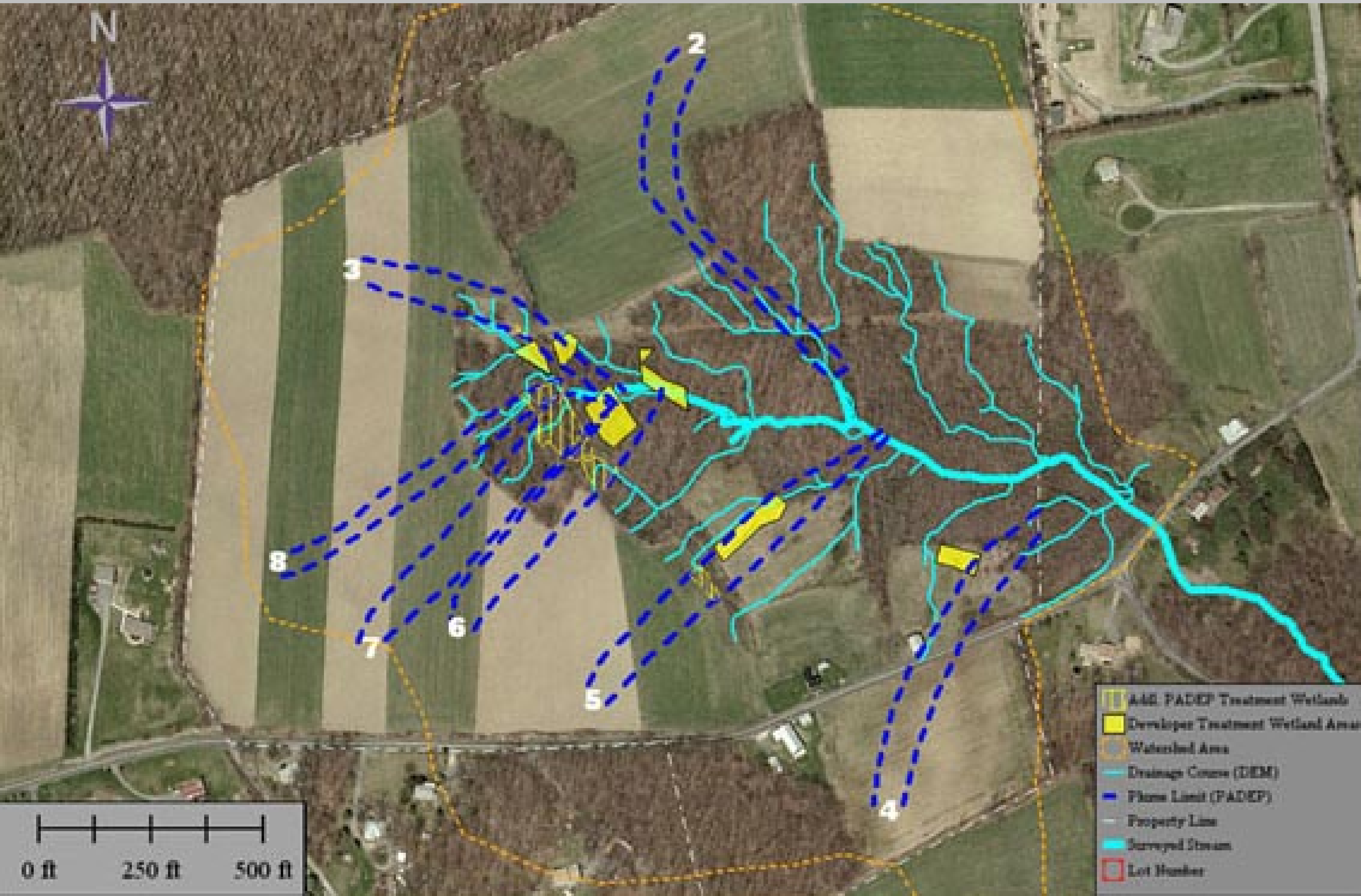


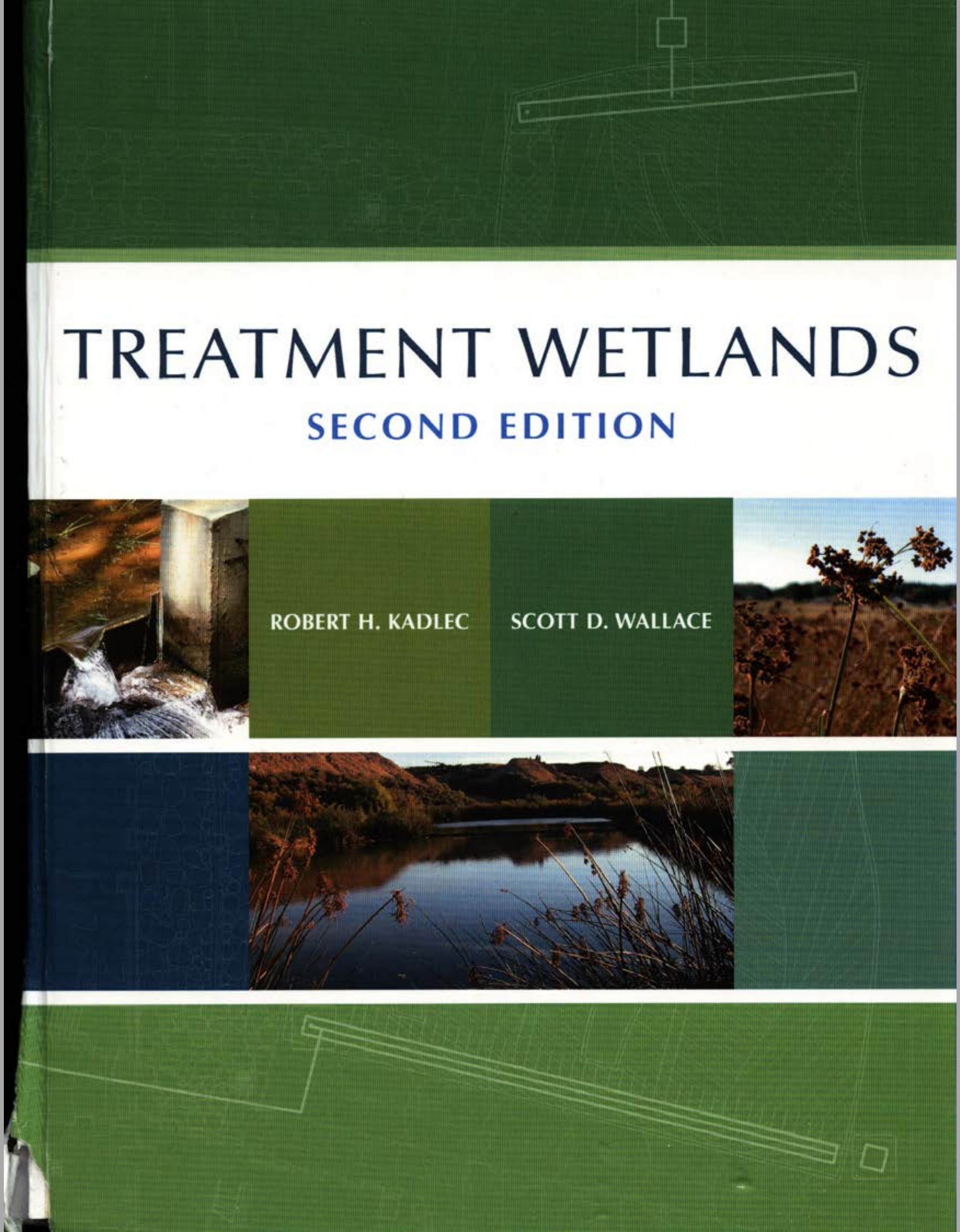
LIDAR STREAM CHANNELS (thin blue) NOT FULLY FIELD-CHECKED



DEVELOPER WETLAND TREATMENT AREAS – SOLID YELLOW

STATE WETLAND TREATMENT AREAS – SOLID PLUS HATCHED YELLOW





DEVELOPER WETLAND DESIGNER'S CHOSEN TEXT

2009 1,016 p.

Don’t Analyze the Site

Just Use Theory

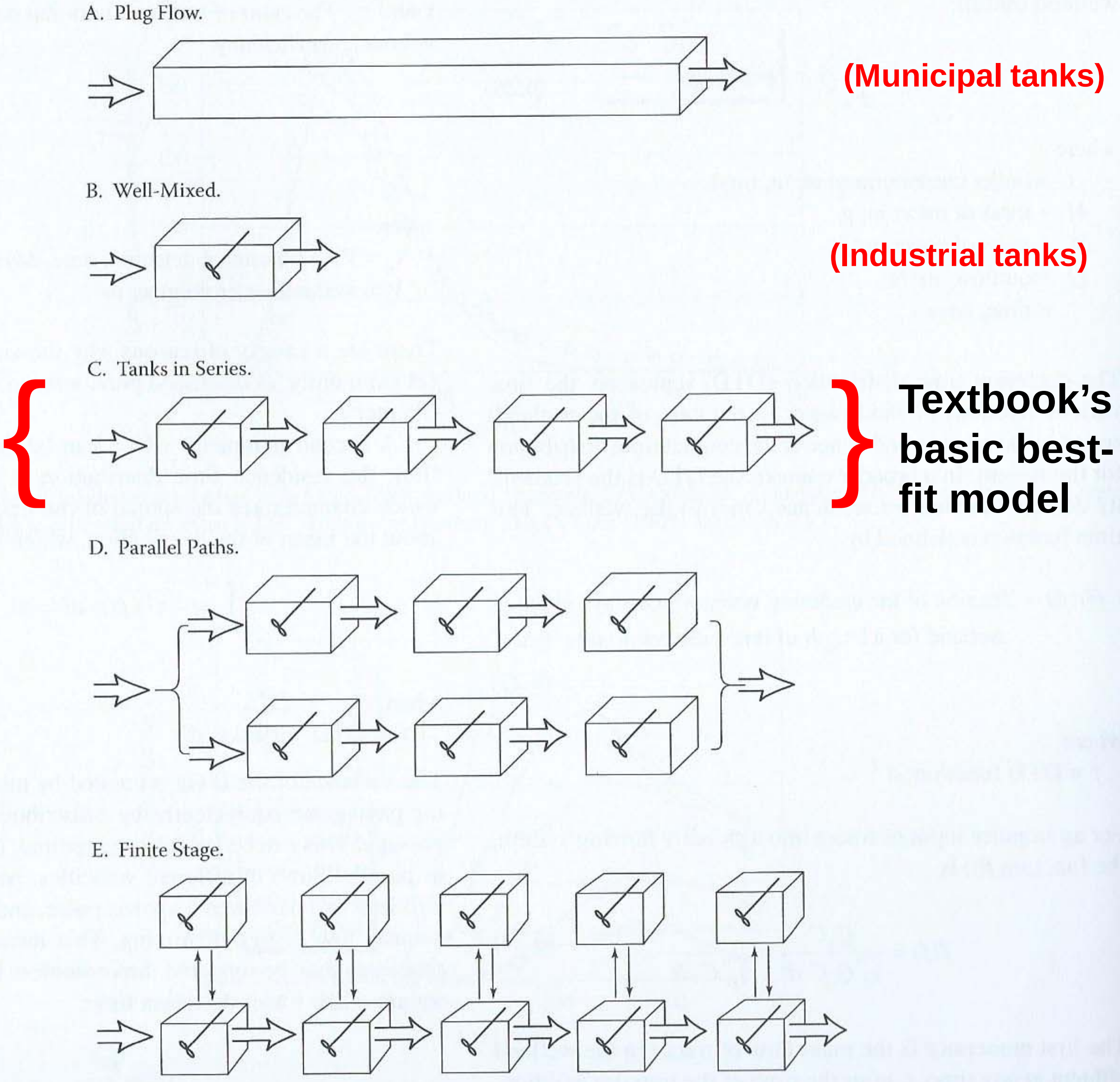


FIGURE 6.16 A sample of various models to represent wetland tracer responses. The plug flow model (A) produces an impulse output at one detention time. The well-mixed model (B) produces an exponential decline. Models (C), (D), and (E) produce skewed bell-shaped responses.

The Tanks in Series (P-k-C^*) Model for Pollutant Reduction

The primary deterministic part of the Tanks in Series textbook model selected by the developer and adopted by the State is described as follows (Eq. 6.57, Kadlec & Wallace 2009:191):

$$\left(\frac{C-C^*}{C_i-C^*}\right)=\frac{1}{(1+k/Pq)^P}=\frac{1}{(1+k_V\tau/P)^P} \qquad (6.57)$$

where

k = modified first-order areal rate constant, m/d

k_V = modified first-order volumetric rate constant, d^{-1}

P = apparent number of TIS

and perhaps more clearly (Eq. 15.7, Kadlec & Wallace 2009:585) as:

$$\frac{(C-C^*)}{(C_i-C^*)}=\left(1+\frac{ky}{Pq}\right)^{-P}=\left(1+\frac{k\tau y}{Ph_V}\right)^{-P}=\left(1+\frac{k_V\tau y}{P}\right)^{-P}$$

A B C

(15.7)

where

C = concentration at fractional distance y, g/m^3

C_i = inlet concentration, g/m^3

C^* = background concentration, g/m^3

h_V = wetland free-water depth, m

k = first-order areal constant, m/d

k_V = first-order volumetric rate constant, d^{-1}

P = apparent number of TIS

q = hydraulic-loading rate, (= h_V/τ) m/d

y = fractional distance, unitless

τ = nominal detention time, days

In these, it is clear that:

$$k_V=\left(\frac{k}{\varepsilon h}\right)=\left(\frac{k}{h_V}\right) \qquad (15.8)$$

where

ε = wetland porosity, dimensionless

h_V = wetland water depth, m

It should be clear that there is no fundamental difference among Equations 15.7A,B,C other than the presumption of the depth variability of the rate constant—which is important.

All these textbook abstract model parameters must be quantified in this fundamental equation using tables in the textbook

- suspended solids
- carbon demand
- biochemical oxygen demand
- nitrogen, various forms
- phosphorus
- halogens
- sulfur
- metals and metalloids
- pathogens
- organic chemicals

The concentration of nitrate-nitrogen is modified in constructed wetlands and in natural wetlands by various kinds of anaerobic bacteria, whose activity varies predictably with temperature: denitrification rates double with a 10°C rise in ambient temperature. Neither the developer's application nor the State's reports included the equation for incorporating temperature into their denitrification rates, necessary inasmuch as the textbook tables following normal conventions express their data at a standard 20°C (68°F.), not representative of this project site (Kadlec & Wallace 2009:248, Eq. 8.24):

$$k_{V1} = k_{V1,20}\theta^{(T-20)}$$

where

k_{V1} = rate constant at temperature T, d^{-1}

$k_{V1,20}$ = rate constant at 20°C, d^{-1}

T = water temperature, °C

θ = modified Arrhenius temperature factor, dimensionless

Critical temperature modification for denitrification rate

Similarly, neither the developer nor the State ever mentioned that the following additional equation is indispensable for conversion of concentrations in the basic formula into surface area as reported in square meters or square feet for the project site (Kadlec & Wallace 2009:22):

$$q = \frac{Q}{A} \quad (2.1)$$

where

q = hydraulic loading rate (HLR), m/d

A = wetland area (wetted land area), m^2

Q = water flow rate, m^3/d

Critical conversion of concentration to area

Step by Step Computation

Schmid Area Requirements using January Denitrification for a Single Septic Tank using Theoretical Constructed Herbaceous Marsh Wetland Model. Fredericksville Farms, Berks County, PA.

Kadlec & Wallace (2009) Eq. 2.1, 8.4, and 6.57

$$k_{vi,1.5} = k_{vi,20}\,\theta^{(1.5-20)}$$

$$k_{vi,1.5} = (0.0726)(1.11)^{(-18.5)} = (0.0726)(0.17149) = \boxed{0.01245\ m/d}$$

$$A = \left[\left(\frac{C_i}{C}\right) - 1\right] \cdot \left[\frac{Q}{k_{vi}}\right]$$

$$A = \left[\left(\frac{45}{0.44}\right) - 1\right] \cdot \left[\frac{0.994\ m^3/d}{0.01245\ m/d}\right]$$

$$A = (102.273 - 1)(79.839\ m^2)$$

$$A = 8085.5\ m^2 = \boxed{87{,}032\ sq.ft.}$$

Winter temperature in Pennsylvania affects bacterial growth rates and resulting area of wetlands needed for denitrification during “winter bottleneck”

TABLE 9.39 20°C standard temperature

Annual Denitrification in HSSF Wetlands

Stipulations

1. The decomposition of 2,000 g/m²·yr of biomass causes production of 36 gN/m²·yr of organic nitrogen.
2. Inlet oxidized nitrogen above 9 mg/L.
3. Annual averages are used in calculations.
4. For *k*-value calculations, the following *P*-*k*-*C** parameters are selected:
   a. $C^* = 0.0$ mg/L
   b. $P = 8$ TIS
5. Ranges of variables:

Example of a rate table

	(q) HLR (cm/d)	(Ci) NO_x-N In (mg/L)	(C) NO_x-N Out (mg/L)
Mean	12.9	18.7	10.0
Median	10.9	19.4	11.3
Max	41.2	36.3	25.9
Min	1.5	3.4	0.5

Results (N = 22; N·*t* = 40 wetland-years)

Percentile	Denitrification (g/m²·yr)	($k_{VI,20}$) Rate Coefficient (m/yr) @20°C
0.05	3.3	3.3 ← 95% higher than 3.3
0.10	7.4	7.4 ←
0.20	27.8	27.7
0.30	32.7	32.0
0.40	40.7	40.1
0.50 (median)	**42.3**	**41.8**
0.60	46.9	46.4
0.70	75.4	73.0
0.80	104.9	103.2
0.90	161.5	151.8
0.95	188.9	173.2 ← 5% higher

Neither the developer's expert nor the State read this:

"Historically, Kadlec and Knight (1996) determined multipliers corresponding to the 100th percentile of monthly means from NADB [the North American Treatment Wetland Database]. These were relative to the long-term mean value for a particular wetland, and therefore seasonal variations, whether temperature driven or not, were included in the multiplier. In this [2009] book, an annual trend is computed as the basis of the multiplier, thus excluding seasonal phenomena from this measure of random scatter" [Kadlec & Wallace 2009: 609].

If You're Going To Rely on a Book

At Least Read It First

Developer's Spreadsheet

Target Co	0.88 mg/L			Tank P	1
Effluent Multiplier	2.02 95% compliance (Table 9.41 TW2)				
Design Co	0.44				
Flow Rate	0.994 m3/d	Ci =	39 mg/L	4477.79 Square Feet	
Precipitation =	0 mm/d	C* =	0 mg/L		
ET =	0 mm/d	ka =	26.5 m/yr (50th percentile TW2)	4477.79 square feet	
Infiltration =	0 mm/d		0.0726 m/d		
PTIS =	3	Theta	1.11 (Table 9.40 TW2)		
Area =	416.0 m2	Temp	9.70		
Area per Tank =	138.7 m2	adjusted ka	0.0248 m/d		
Porosity =	0.95				
Bed Depth	0.3 m				
Volume per Tank =	39.5 m3				

$$\left(\frac{C-C^*}{C_i-C^*}\right)=\frac{1}{\left(1+k/Pq\right)^P}=\frac{1}{\left(1+k_V\tau/P\right)^P}$$

		System Inlet	Tank 1	Tank 2	Tank 3	System Outlet
Qi	m3/d	0.994	0.994	0.994	0.994	0.994
Precipitation	m3/d	0.000	0.000	0.000	0.000	
ET	m3/d	0.000	0.000	0.000	0.000	
Infiltration	m3/d	0.000	0.000	0.000	0.000	
Qo	m3/d		0.994	0.994	0.994	
Average HRT	days		39.75	39.75	39.75	119.26
			(each tank)	(each tank)	(each tank)	(overall system)
Concentration, C	mg/L	39.0	8.8	2.0	0.4	0.4

Influent Flow	m3/d	0.99	Influent Mass Load g/d	38.766
Effluent Flow	m3/d	0.99	Effluent Mass Load g/d	0
Average Flow	m3/d	0.99	Percent Reduction	98.9%

Nominal Detention Time	days	119.26
Detention Time based on Average Flow	days	119.26
Detention Time based on PTIS	days	119.26

Note: Calculations based on TW2 (Kadlec & Wallace 2008)

Concentration Factor (for TDS) 1.00

A Mack Sennett image of reviewers

RESULTS --- Area of natural wetlands NEEDED for denitrification

First Developer claim: 3,475 sf (0.08 ac) per residential septic tank

Revised Developer claim: 4,478 sf (0.10 ac) per residential septic tank (up 29% from Developer's initial claim) --- approved by State

State claim at trial: 4,200 sf (0.096 ac) for worst lot (up 21% from Developer's initial claim)

Developer claim at trial: 17,330 sf (0.40 ac) per residential septic tank (up 399% from Developer's initial claim) after elevation temperature correction

Appellant claim at trial: 87,000+ sf (2+ ac) per residential septic tank (up 2,400% from Developer's initial claim) to accommodate winter bottleneck in bacterial denitrification --- hypothetically using Developer's methods without any "safety factor" --- larger than any effluent plume in onsite wetlands, not enough wetlands exist onsite

My spreadsheet version of the deterministic equation for comparing six major variables affecting wetland area required for denitrification

Solving directly for area, the *P-k-C** model can be calculated from the following expression, nowhere provided in the source textbook or by the permittee or the State, but supplied by appellants:

$$A = \left[\sqrt[3]{\frac{(Ci - C^*)}{(C - C^*)}} - 1 \right] \cdot \left[\frac{P \cdot Q}{k} \right]$$

Without this last equation none of the proffered surface area calculations can be checked efficiently.

Area Requirements for LaBrake's constructed herbaceous marsh wetlands, per house, at Fredericksville Farms subdivision, Berks County, Pennsylvania

	Variable	LaBrake Oct 45 inlet Jan T = 1	LaBrake Oct 45 inlet Ann T = 9.7	LaBrake Oct 39 inlet Ann T = 7.4	LaBrake Oct 39 inlet Ann T = 9.7	Desai June 45 inlet Jan T = 1	Desai June 45 inlet Ann T = 9.7	Desai June 45 inlet Ann T = 20	LaBrake Feb 45 inlet Jan T = 1	LaBrake Feb 45 inlet Ann T = 7.4	LaBrake Feb 45 inlet Ann T = 9.7	(deg C)
Target	*C* mg/L	0.44	0.44	0.44	0.44	1.86	1.86	1.86	0.9	0.9	0.9	
Backgrnd	*C** mg/L	0	0	0	0	1.5	1.5	1.5	0	0	0	
Inlet	*Ci* mg/L	45	45	39	39	45	45	45	45	45	45	
Rate	*k* m/d	0.0099	0.0248	0.0195	0.0248	0.0099	0.0248	0.0726	0.0099	0.0195	0.0248	
Tanks	*P*	3	3	3	3	3	3	3	3	3	3	
Flow	*Q* m^3/d	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	
Area	*A* (m^2)	1107.4	442.1	528.9	415.9	1187.9	474.2	162.0	808.5	410.5	322.7	
Sq. Ft	*A* (sq ft)	11,919.98	4,758.38	5,693.12	4,476.44	12,786.71	5,104.37	1,743.64	8,702.21	4,418.05	3,473.87	

Developer **4,477.79**

Variables are related using the following equations:

$$A = \left[\sqrt[3]{\frac{(Ci - C^*)}{(C - C^*)}} - 1 \right] \cdot \left[\frac{P \cdot Q}{k} \right]$$

$$where : Q = \frac{q}{A}$$

q : Hydraulic Loading Rate (m / day)

$$k_{V1} = k_{V1,20}\theta^{(T-20)}$$

where
k_{V1} = rate constant at temperature T, d^{-1}
$k_{V1,20}$ = rate constant at 20°C, d^{-1}
T = water temperature, °C
θ = modified Arrhenius temperature factor, dimensionless = 1.11

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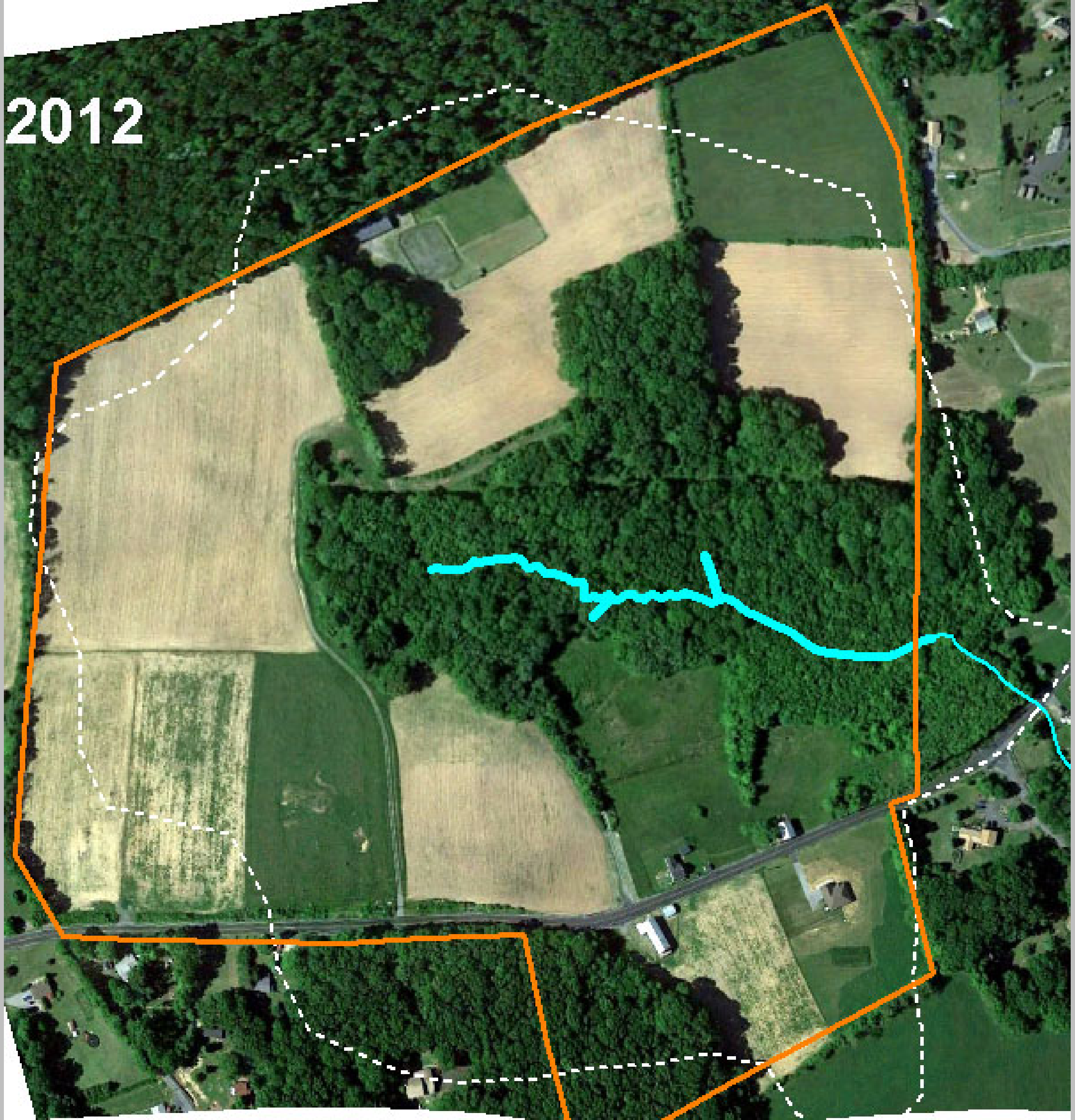
$$\left(\frac{C - C^*}{C_i - C^*}\right) = \frac{1}{(1 + k/Pq)^P} = \frac{1}{(1 + k_V\tau/P)^P}$$

Table 2. Values for parameters used by various parties in the *P-k-C** model for calculating the area of constructed treatment wetlands needed for denitrification of residential septic tank effluents at Fredericksville Farms, Berks County, Pennsylvania. FWS = free water surface, HSSF = horizontal gravel subsurface flow, within wetland "tanks in series".

	Parameter	**Developer**	**State**	**Appellant**
	C (target concentration, assuming 95% mean trend multiplier of 10 FWS systems = 2.02, Kadlec & Wallace 2009:342)			
		1.86 mg/L; 0.88 mg/L	1.86, 0.88, 0.84, 0.82 mg/L	0.88 mg/L
	C* (onsite natural wetland background concentration, nitrate-nitrogen)			
Major disagreement		1.86 mg/L, 0 mg/L	1.86 mg/L; 1.5 mg/L 0 mg/L	2.71 mg/L (the only measured value from this site); 0 mg/L
	P (mathematical factor expressing apparent number of tanks in series, dimensionless; ***P*** = 1 represents perfect mixing; ***P*** = ∞ represents "plug flow")			
Major disagreement		3 (FWS)	3 (FWS) 8 (HSSF)	1 (no basis for any other; no tanks at all in existing wetlands; no hydrologic measurements)
	ε (wetland volume occupied by water, or bare media porosity, dimensionless; ε = 1 represents unobstructed water; Kadlec & Wallace 2009:22-26)			
		0.95 (FWS)	0.95 (FWS <u>and</u> HSSF)	0.95 (FWS)
	k (first-order pollutant removal rate constant, highly temperature sensitive)			
Major disagreement		0.0248 m/d (annual avg.) @49.5°F (9.7°C); at trial 45.3°F (7.4°C) FWS model	0.0726 m/d (annual avg.) @68°F (20°C); at trial 0.0248 m/d @49.5°F (9.7°C) HSSF model	0.01245 m/d (January avg.) @34.7°F (1.5° C) FWS model
	θ (modified Arrhenius temperature factor, mean of 20 FWS systems, dimensionless, Kadlec & Wallace 2009:340)			
		1.11	1.11	1.11

Note: According to USEPA (1993a:144), standard rectangular wastewater treatment tanks typically have lengths ranging from 5x to 10x their width, but that is not what the developer anticipated here (as addressed below). Plug flow is typical in municipal wastewater treatment tanks; well mixed flow, in industrial wastewater treatment tanks.


2012

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Presented to the American Water Resources Association
Philadelphia Metropolitan Area Section

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