James River PCB TMDL Study: Numerical Modeling Approach

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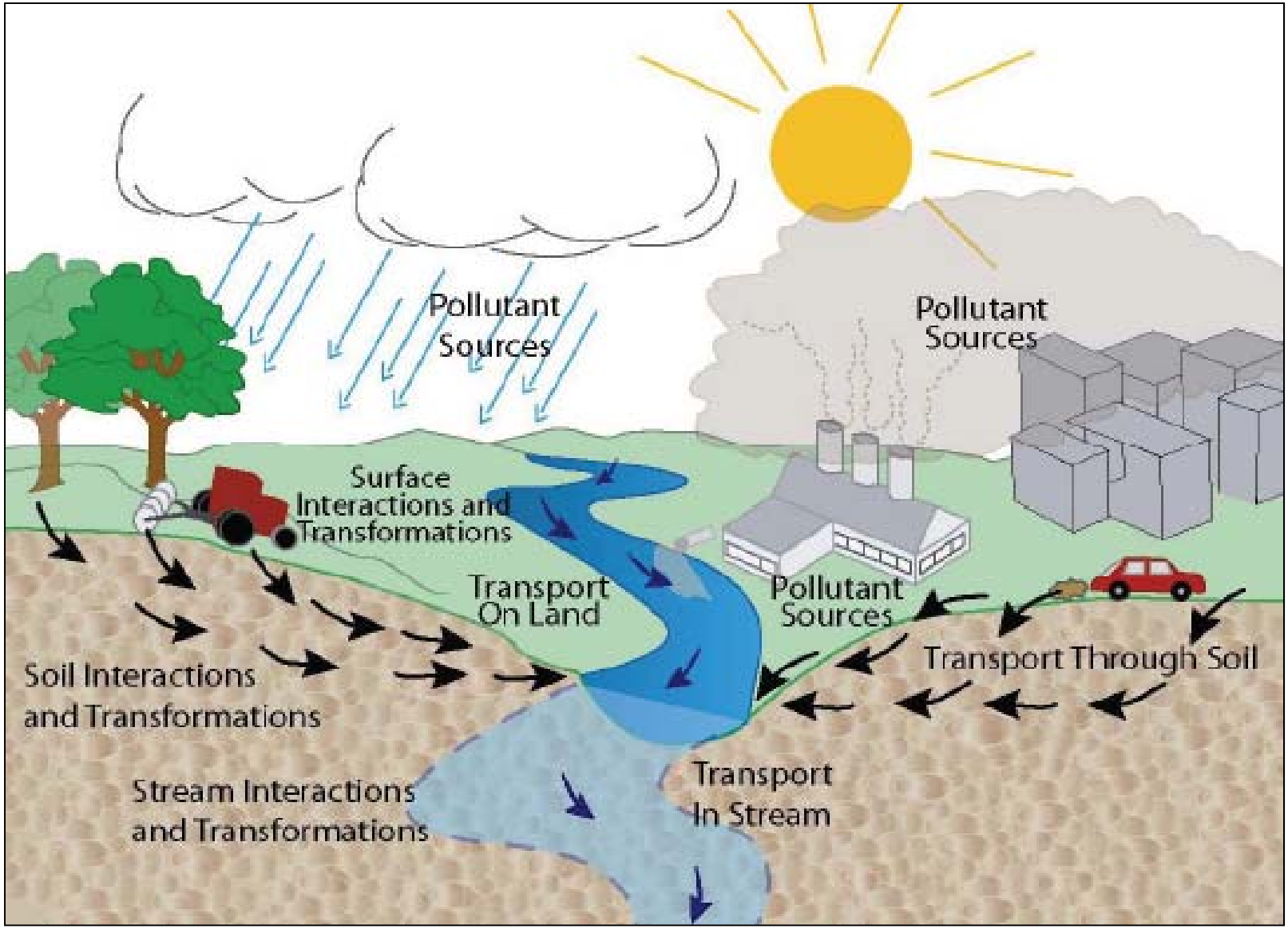
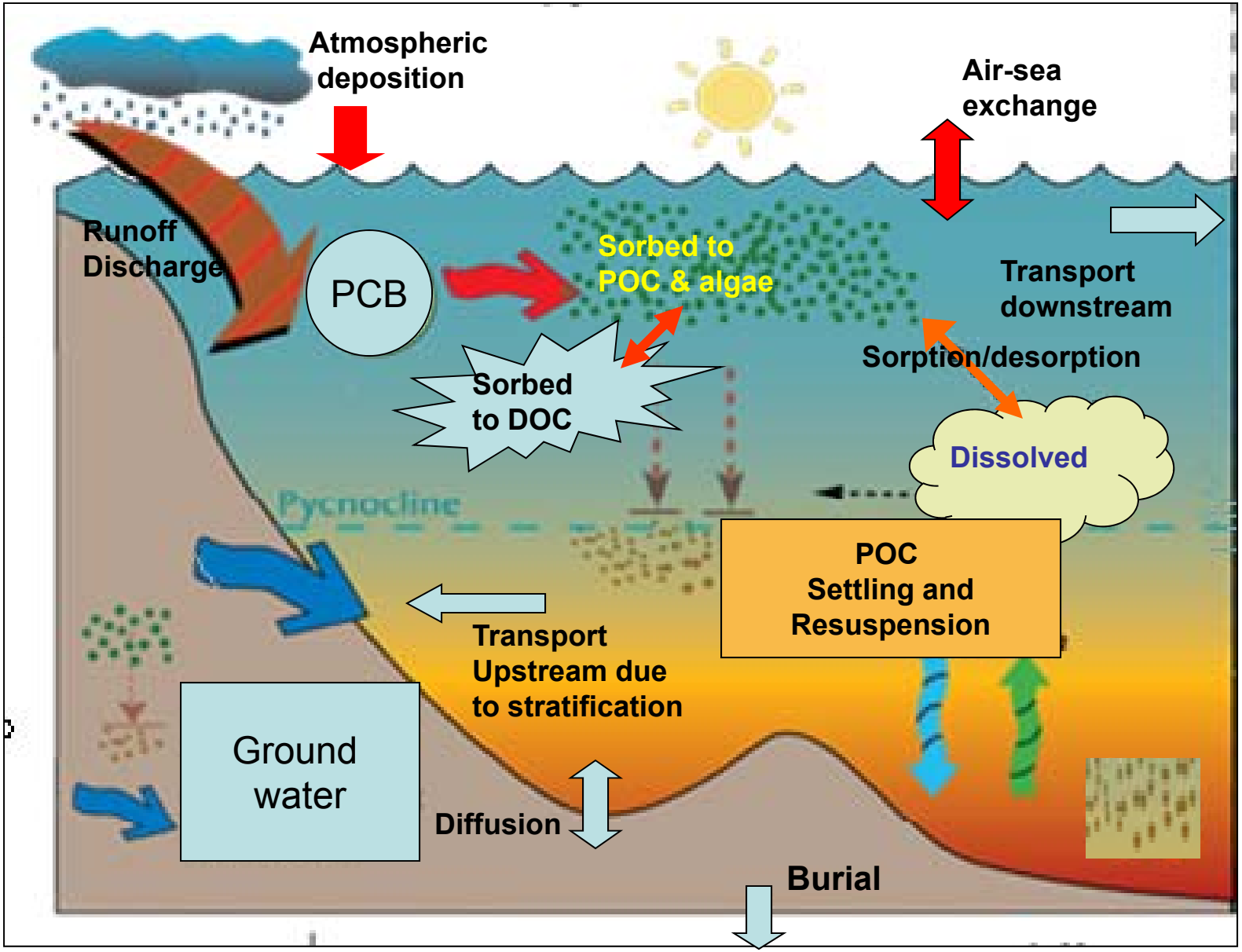
Pollutant Sources from Watershed

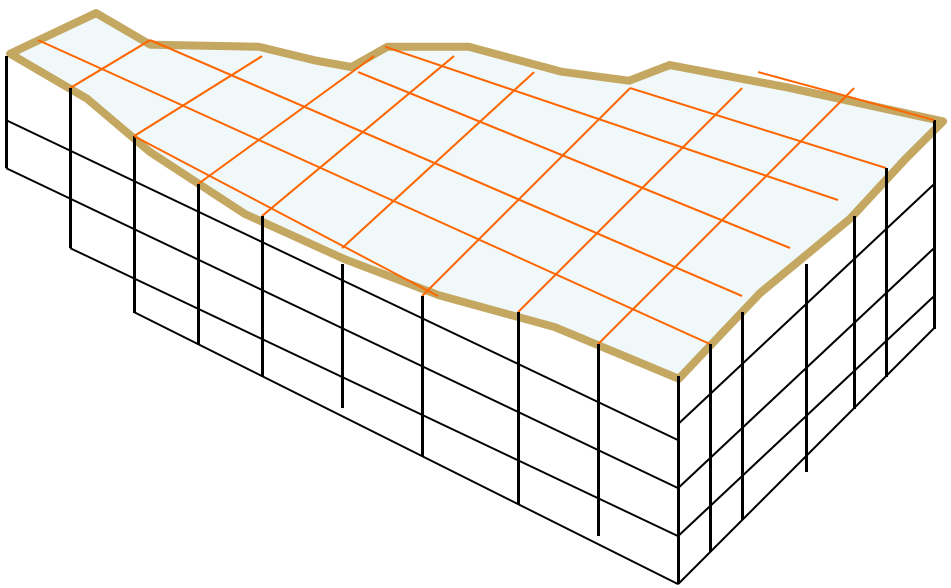


PCB Transport in Estuary

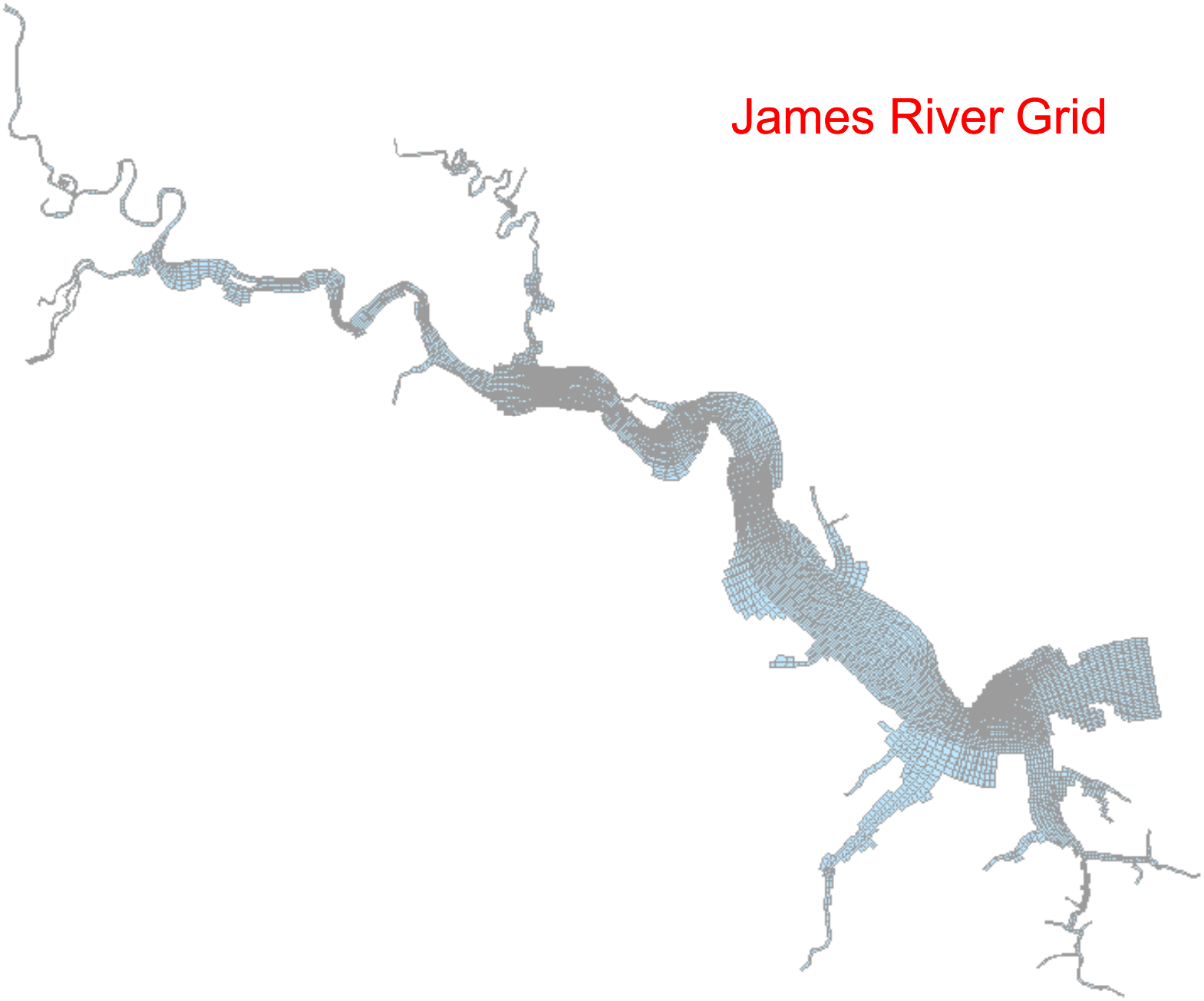


Modeling PCB concentrations in an Estuary

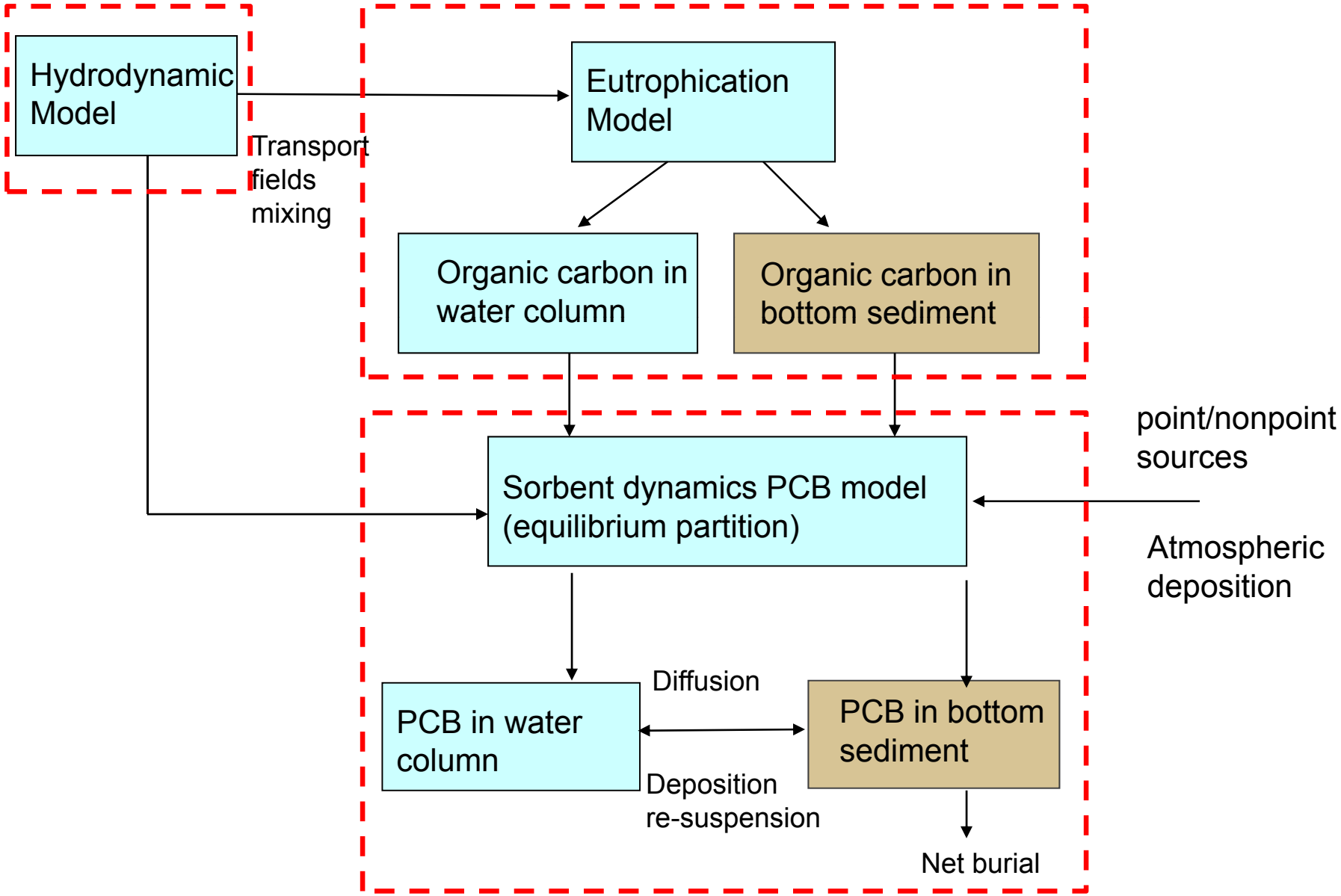
- Use environmental computer model to simulate PCB transport in the estuary
- Environmental computer models are mathematical representations of real-world conditions and are used to estimate environmental events and future changes.



James River Grid



Model Framework



Hydrodynamic Model

Tide, Temperature, Salinity, TSS, Meteorological forcing (wind, atm. pressure, dry & wet temperature, cloud cover, solar radiation)

Surface elevation
Current

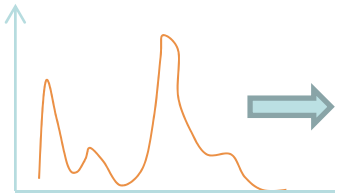
Temperature

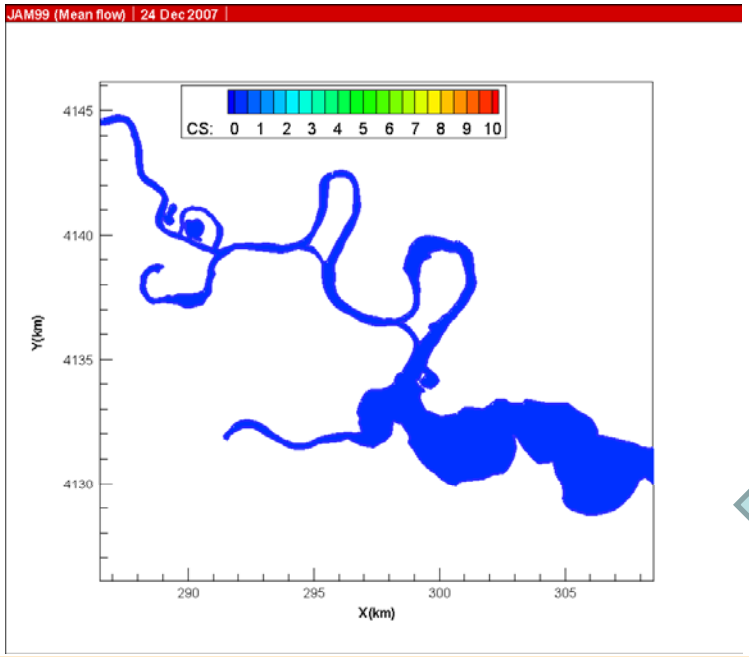
Salinity

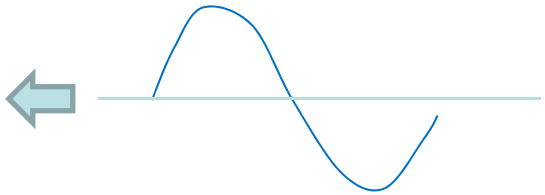
Suspended sediment

Dynamic Model

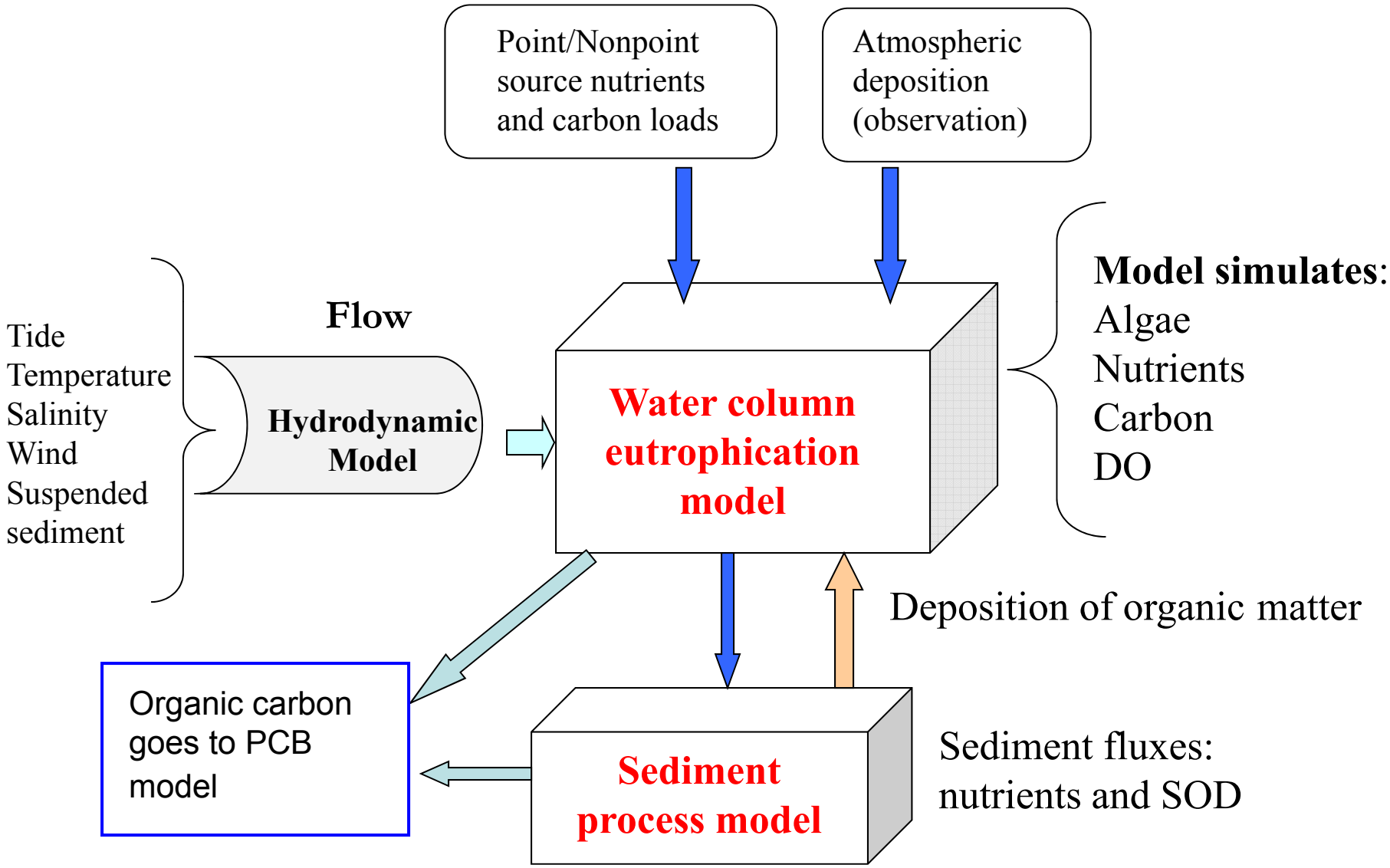
Provide transport fields for eutrophication and PCB models



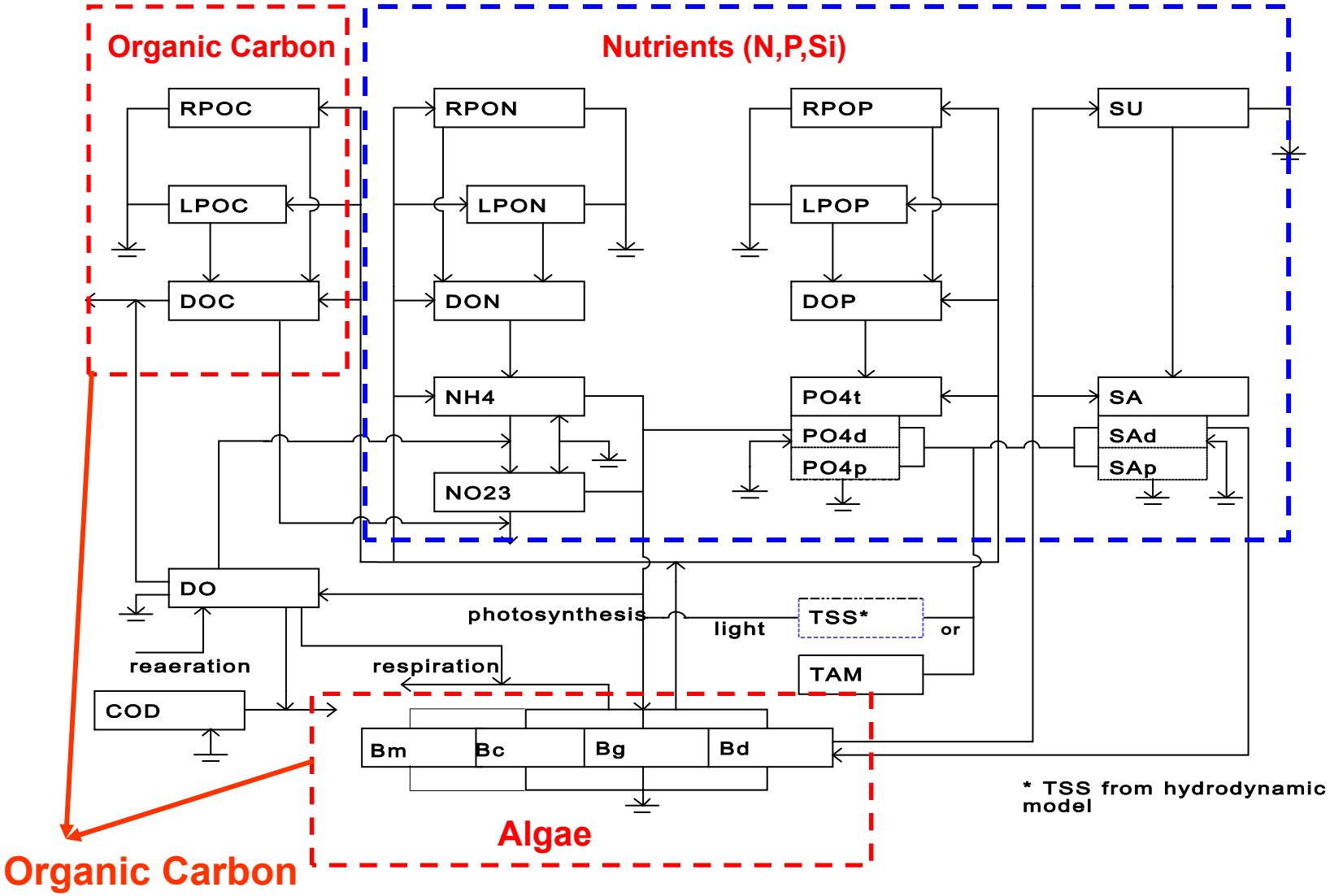




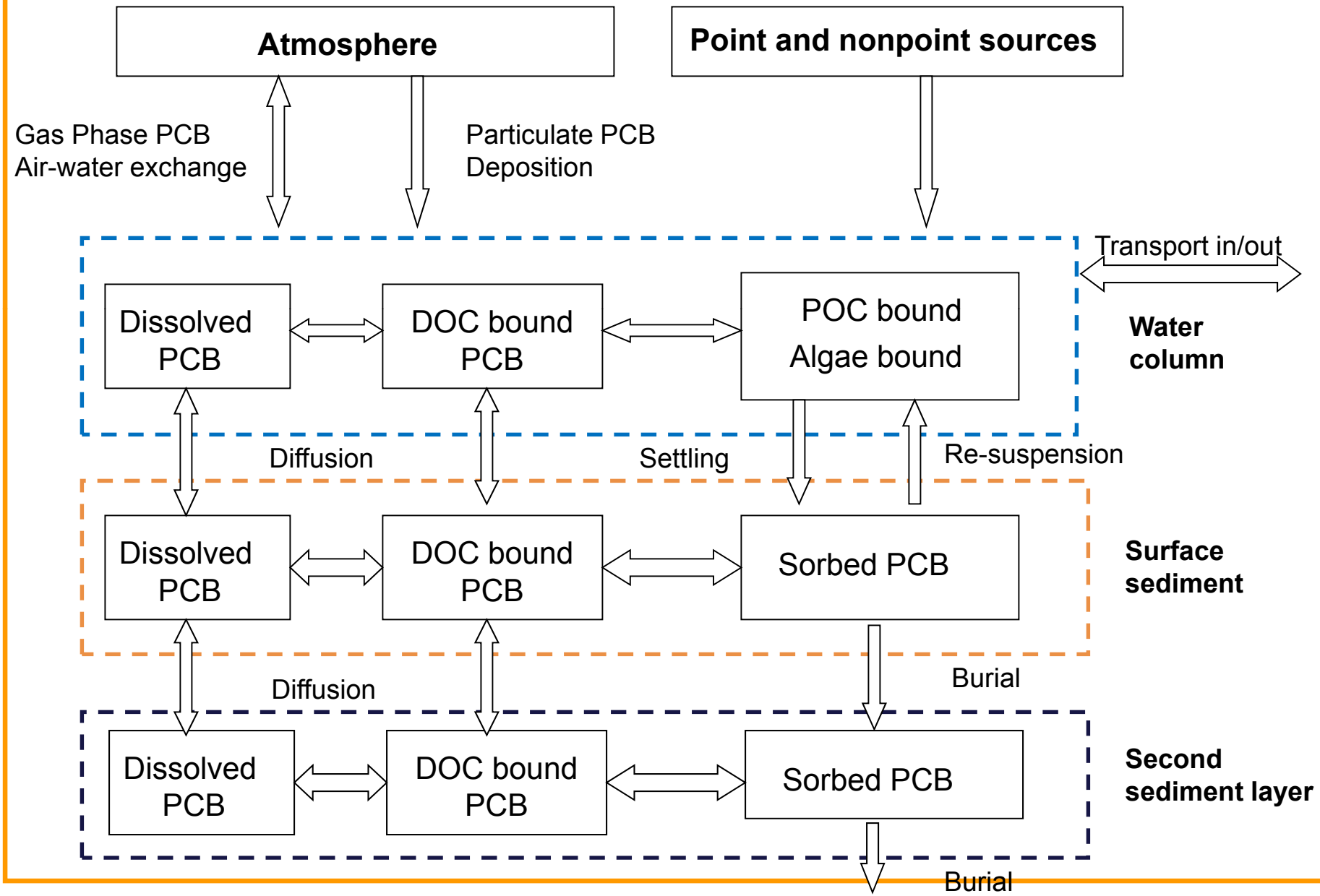
Eutrophication Model



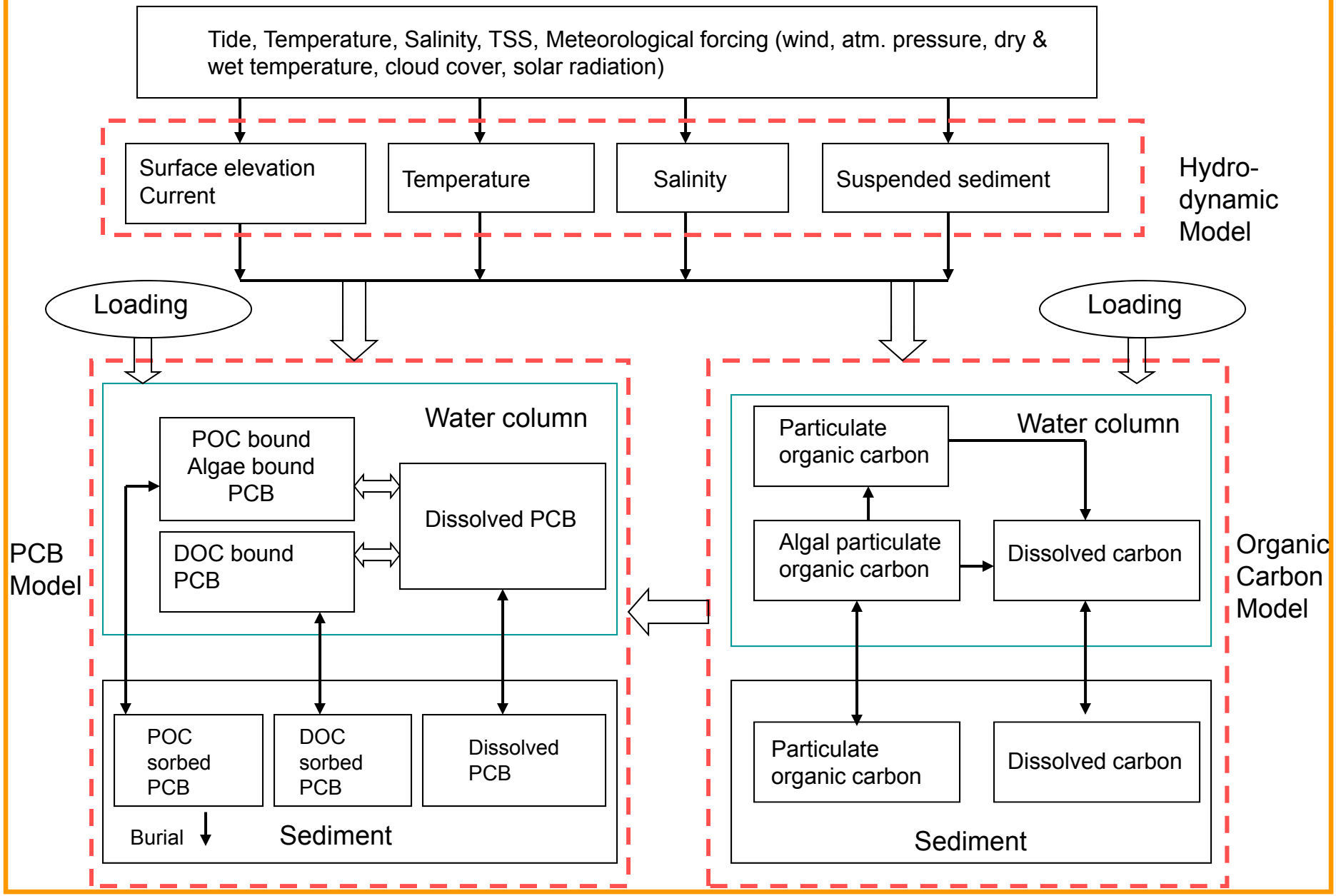
Eutrophication (Organic carbon) Model



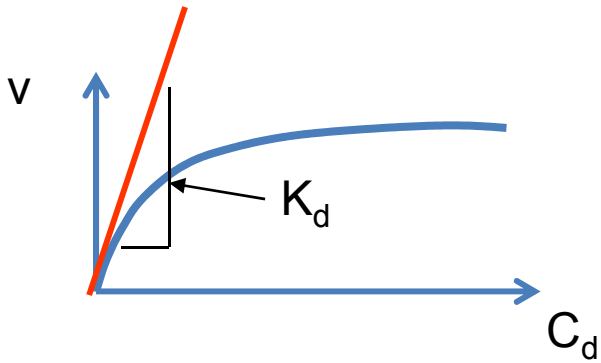
PCB Model


Atmosphere
Point and nonpoint sources
Gas Phase PCB
Air-water exchange
Particulate PCB
Deposition
Transport in/out
Dissolved PCB
DOC bound PCB
POC bound
Algae bound
Water column
Diffusion
Settling
Re-suspension
Dissolved PCB
DOC bound PCB
Sorbed PCB
Surface sediment
Diffusion
Burial
Dissolved PCB
DOC bound PCB
Sorbed PCB
Second sediment layer
Burial

Model Link Summary



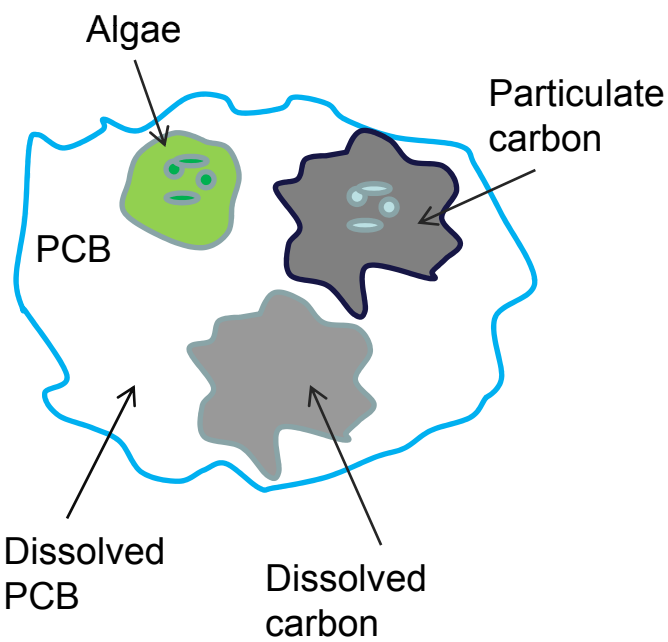
PCB Model Sorption Processes



v = PCB concentration on the solid / carbon (ng/g)
C_d =dissolved concentration (ng/L)

Equilibrium model assumes:

$$v = K_d \times C_d$$



The relationships between total PCB, dissolved PCB, particulate carbon bound PCB, algal bound PCB, and dissolved carbon bound PCB are:

Dissolved PCB (C_w):	$C_w = f_w \times C$
Particulate Carbon pound PCB (C_P^1):	$C_P^1 = f_P^1 \times C$
Algae bound PCB (C_P^2):	$C_P^2 = f_P^2 \times C$
Dissolved organic carbon bound PCB (C_D):	$C_D = f_D \times C$

f_x = fraction of each component
C = total PCB

$$f_w + \sum_i f_P^i + f_D = 1 \qquad (1)$$

$$fw = \frac{Cw}{C} = \frac{\phi}{\phi + \sum_i K_P^i m_P^i + K_D m_D} \qquad (2)$$

$$f_P^i = \frac{C_P^i}{C} = \frac{K_P^i m_P^i}{\phi + \sum_i K_P^i m_P^i + K_D m_D} \qquad (3)$$

$$f_D = \frac{C_D}{C} = \frac{K_D m_D}{\phi + \sum_i K_P^i m_P^i + K_D m_D} \qquad (4)$$

Where m_P^1, m_P^2, m_D are particulate organic carbon, particulate algal carbon, and dissolved organic carbon. K_P^1, K_P^2, and K_D denote the partition coefficients, respectively for three carbon species.

Dissolved PCB (C_w):	$C_w = f_w \times C$
Particulate Carbon pound PCB (C_P^1):	$C_P^1 = f_P^1 \times C$
Algae bound PCB (C_P^2):	$C_P^2 = f_P^2 \times C$
Dissolved organic carbon bound PCB (C_D):	$C_D = f_D \times C$

PCB Transport Model Equation

$$\partial_t\left(m_x m_y HC\right)+\underbrace{\frac{1}{m_x m_y}\partial_x\left(m_y HuC\right)+\frac{1}{m_x m_y}\partial_y\left(m_x HvC\right)+\partial_x\left(m_x m_y wC\right)}_{\text{Transport}}$$

$$-\underbrace{\partial_x\left(m_x m_y \sum_i w_s^i f_p^i C\right)}_{\text{Settling}}=\underbrace{\partial_z\left(m_x m_y \frac{A_b}{H}\partial_z C\right)}_{\text{Diffusion}}-\left(m_x m_y H\gamma C\right)$$

Where *H* is water depth, C is total PCB concentration, A_b is eddy diffusivity, and w_s^i (i=1,2) are settling velocities associated with particulate organic carbon and algal organic carbon, γ is decay constant, *u*, *v*, *w* are velocity at x-, y-, and z- directions, m_x and m_y are scale factors of the horizontal coordinates.

The boundary condition at the water column sediment interface, z = 0, is:

$$-\frac{A_b}{H}\partial_z C-\sum_i w_s^i f_s^i C=$$

$$=\sum_i\left[\max\left(\frac{J_P^i f_P^i}{m_P^i},0\right)C\right]_S+\sum_i\left[\min\left(\frac{J_P^i f_P^i}{m_P^i},0\right)C\right]_W-q_{dif}\left(\frac{f_w+f_D}{\phi}C\right)_W+q_{dif}\left(\frac{f_w+f_D}{\phi_s}C\right)_S$$

Where $J_P^i\,(\mathrm{i}=1,2)$ are POC and algal carbon fluxes between sediment bed, and water column (mass per unit area per second), defined as positive from the bed, ϕ and ϕ_s are porosities in water column and sediment. The subscripts 'w' and 's' denote water column and sediment, respectively, and q_{dif} is diffusion velocity.

The volatilization which occurs at the surface depends on the mass transfer coefficient at the air-water interface and the concentration of PCB in the water column. The boundary condition at the water column and air interface, z = 1, is:
(Bamford, et al., 2002)

$$-\frac{A_b}{H}\partial_z C-\sum_i w_s^i f_s^i C=\frac{K_V}{\Delta Z}\left[f_w C-\frac{C_a}{K_{H'}}\right]$$

Where K_v is the volatilization mass transfer coefficient (L/T), ΔZ is the thickness of the first layer near the surface, *Ca* is the vapor phase PCB concentration in air (M/L^3) and K_H is the dimensionless, temperature-corrected Henry's law constant.

Bottom Sediment Model Equation

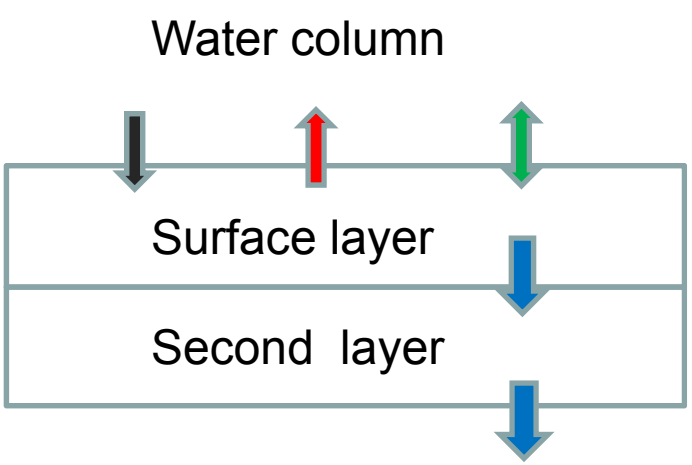
$$\partial_t (BC)_T = -\gamma (BC)_T$$

$$-\sum_i \left[\max\left(\frac{J_P^i f_P^i}{B m_P^i}, 0 \right) BC \right]_{T+} - \sum_i \left[\min\left(\frac{J_P^i f_P^i}{m_P^i}, 0 \right) C \right]_W - \sum_i \left[\min\left(\frac{J_P^i f_P^i}{B m_P^i}, 0 \right) BC \right]_{T-}$$

Lost due to re-suspension **Settling from water column** **Settling to deep sediment layer**

$$+q_{dif}\left(\frac{f_w + f_D}{\phi} C \right)_W - q_{dif}\left(\frac{f_w + f_D}{\phi_s} C \right)_T$$

Diffusion between water column and sediment

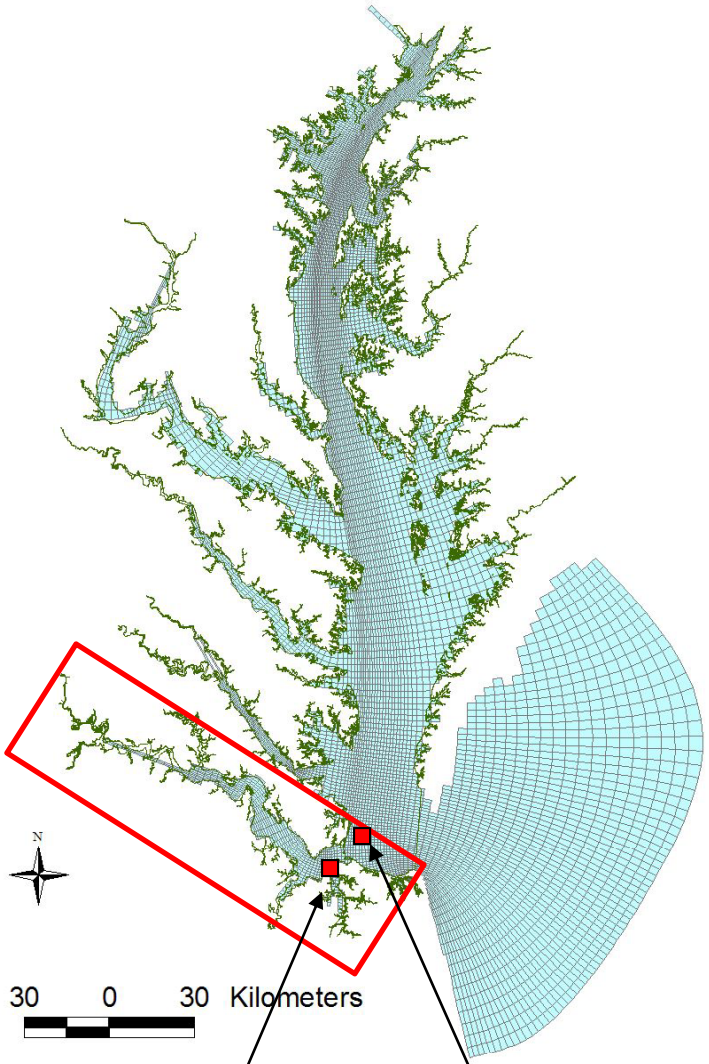


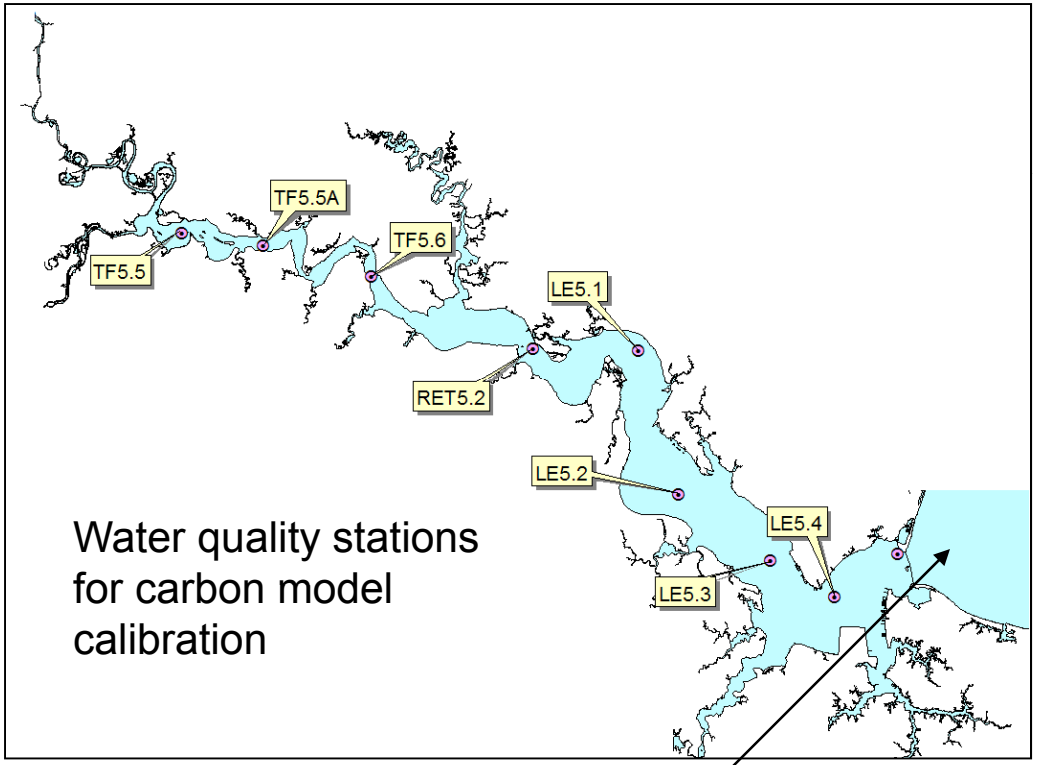
Where B is the thickness of the sediment layer.

Data Needed for Hydrodynamic Model Calibration

- Tide
  - use NOAA observation data at Sewells Point
- Salinity at open boundary
  - use the Chesapeake Bay model output (available from 1997-2007)
- Flow data
  - use USGS upstream daily flow (Appomattox River USGS02041650 and Richmond station USGS37500)
- Meteorological forcing data
  - use NOAA data at Sewells and Gloucester Point
    - wind, atmospheric pressure
    - dry & wet temperature
    - cloud cover and solar radiation

Link James River Model to the Bay Model



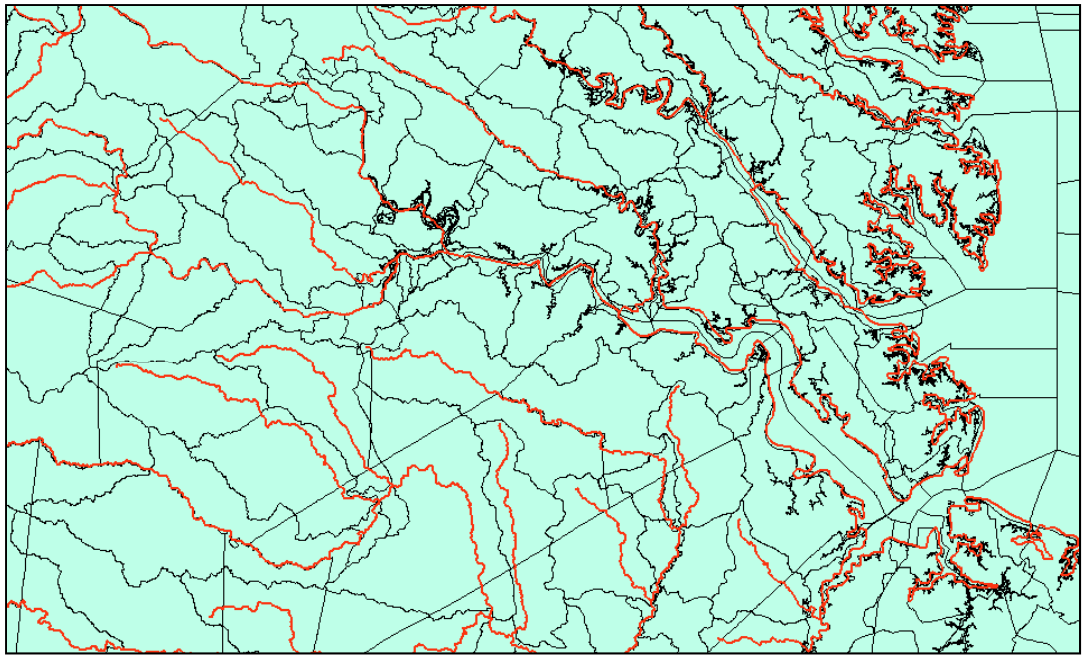


Sewells Point

Output salinity will be used for James River model boundary condition at the mouth

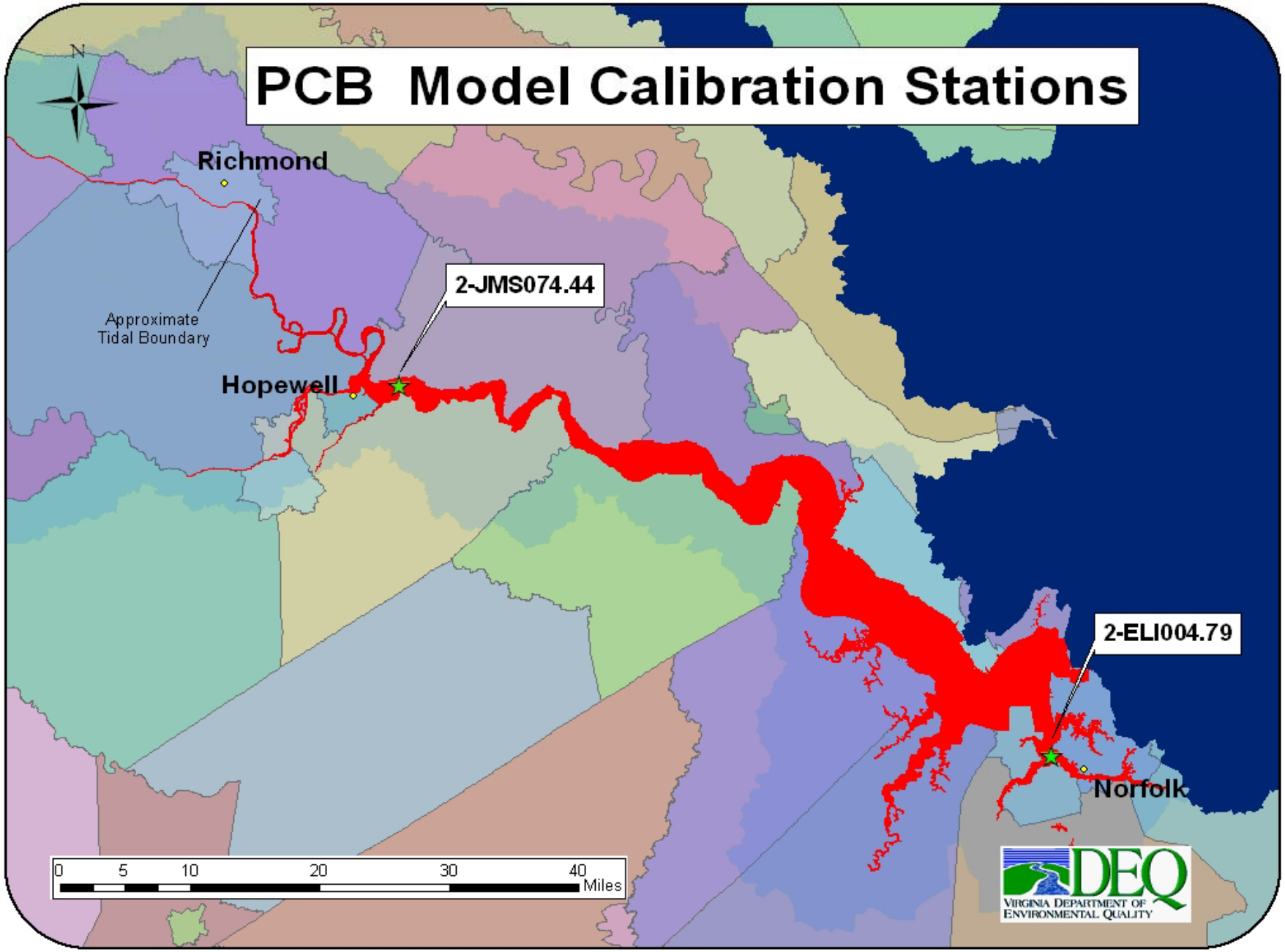
Data Needed for Eutrophication Model Calibration

- Point source loading
  - Chesapeake Bay program/DEQ
- James River mouth open boundary
  - Monthly observations
- Nonpoint source loading
  - Chesapeake Bay Phase V watershed model output, 1980-2005
    - Flow
    - Nitrogen
    - Phosphorus
    - Carbon
    - Algae



Data Needed for PCB Model Calibration

- Bottom sediment PCB data
  - use for initial sediment condition (sediment study)
- Upstream PCB data
  - estimate upstream PCB inflow
- Loading from contaminated sides
- Storm water data ?
- Point source data ?
- Nonpoint source loading (background, unknown loadings)
  - estimate based on event driven concentration and flow
- Atmospheric deposition
  - Historical observations/new observations
- Model calibration data
  - Collect short-term data covering large area
  - Intensive survey data
    - monthly or bimonthly PCB data for a year at 2-3 stations (i.e., 2-JMS074.44, 2-ELI04.79)


PCB Model Calibration Stations
N
Richmond
Approximate
Tidal Boundary
2-JMS074.44
Hopewell
2-ELI004.79
Norfolk
0 5 10 20 30 40
Miles
DEQ
Virginia Department of
Environmental Quality

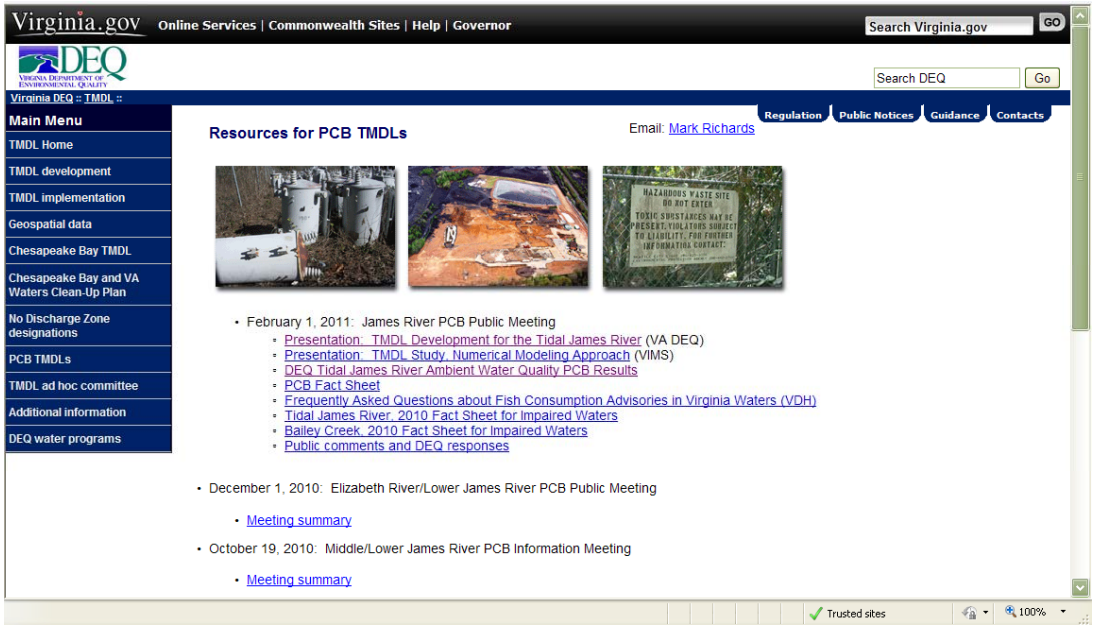
Next Steps…

- Data collection
- Nonpoint source estimation
- Pollutant source estimation
- Model setup
- Hydrodynamic model calibration
- Eutrophication model calibration
- PCB Model calibration procedure

Questions / Discussion

DEQ PCB TMDL website:

http://www.deq.virginia.gov/tmdl/pcb.html



Contacts:

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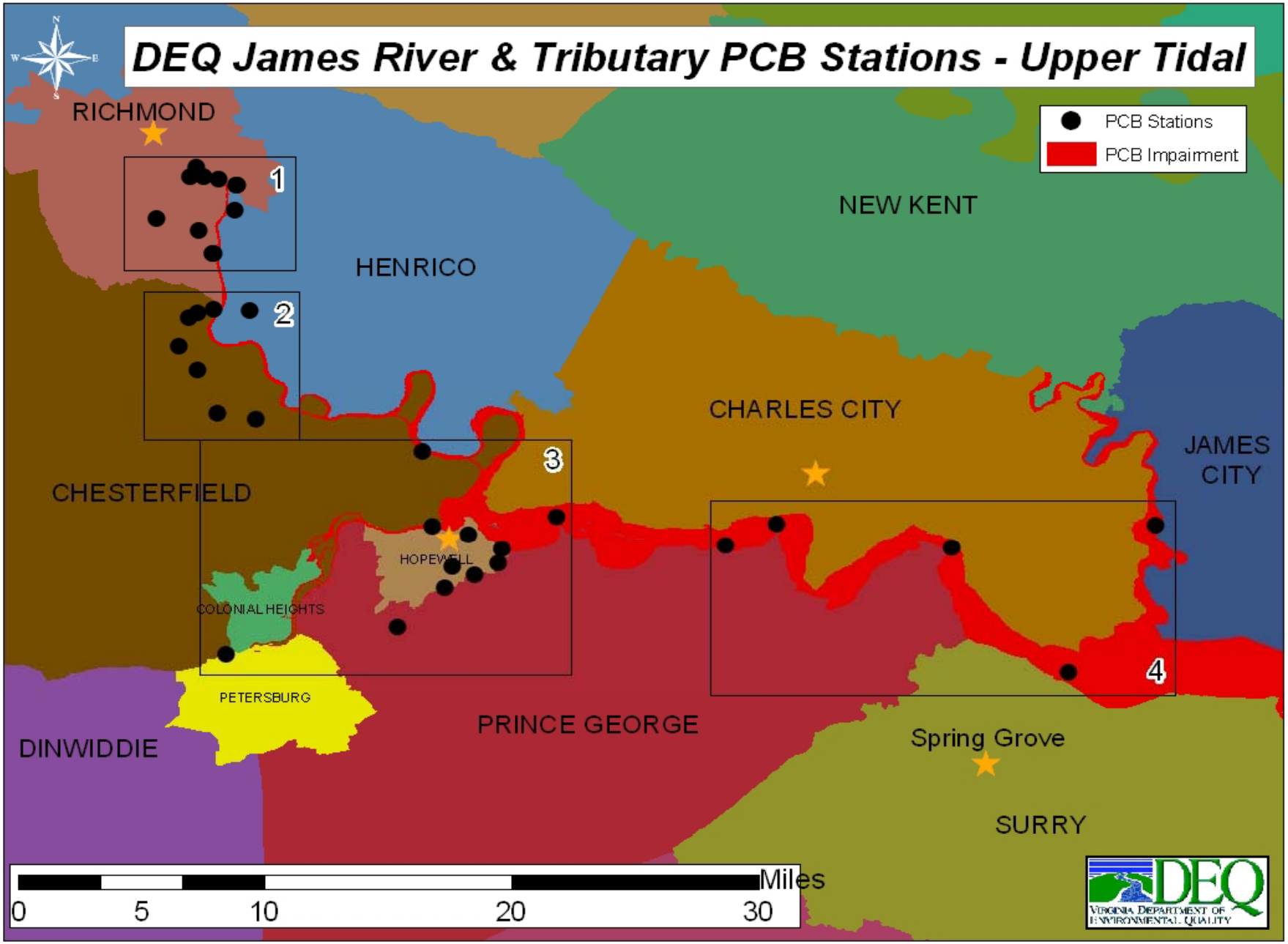
Tidal James River Ambient Water PCB Results

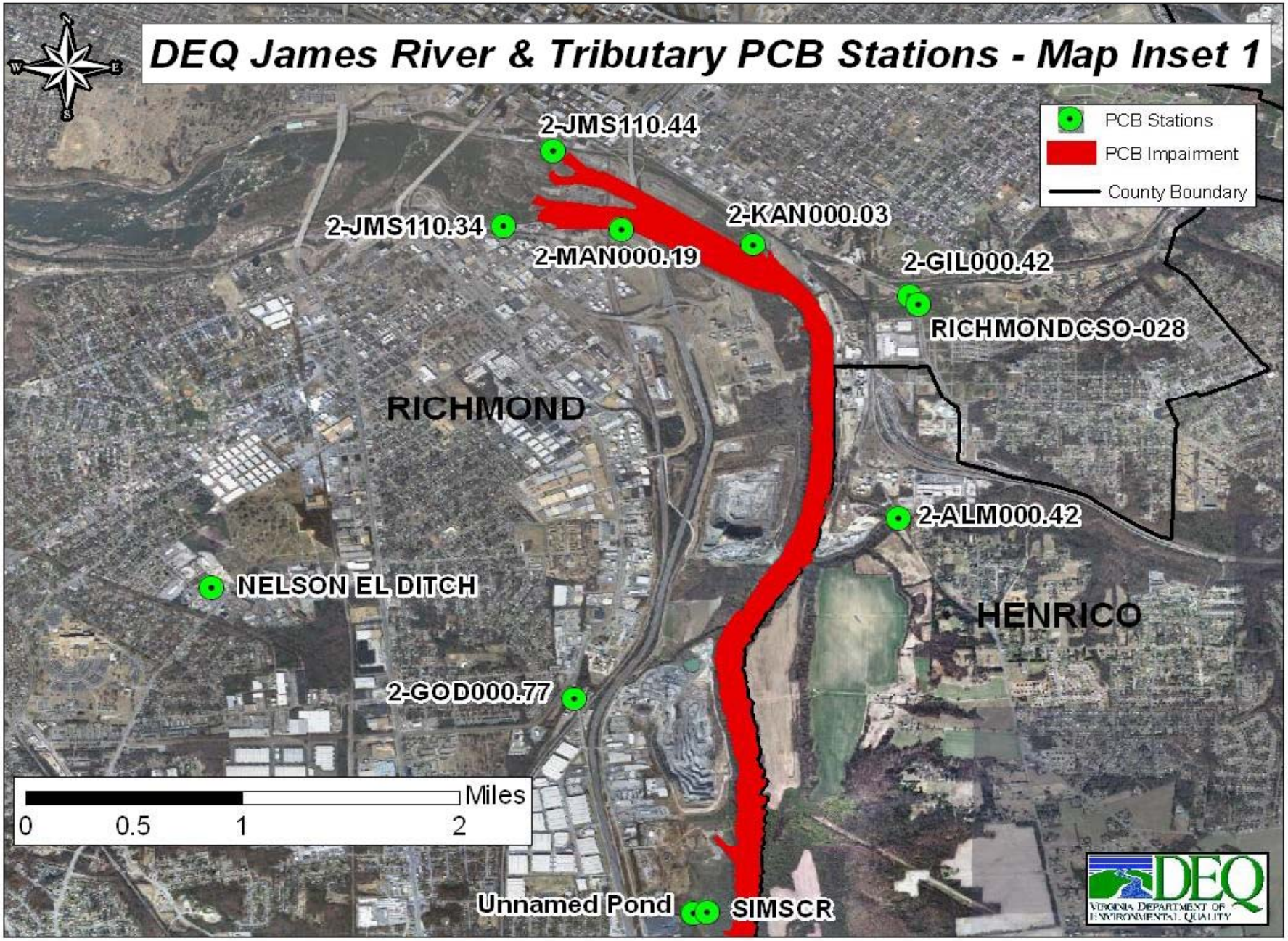
(Revised 4/27/2011)

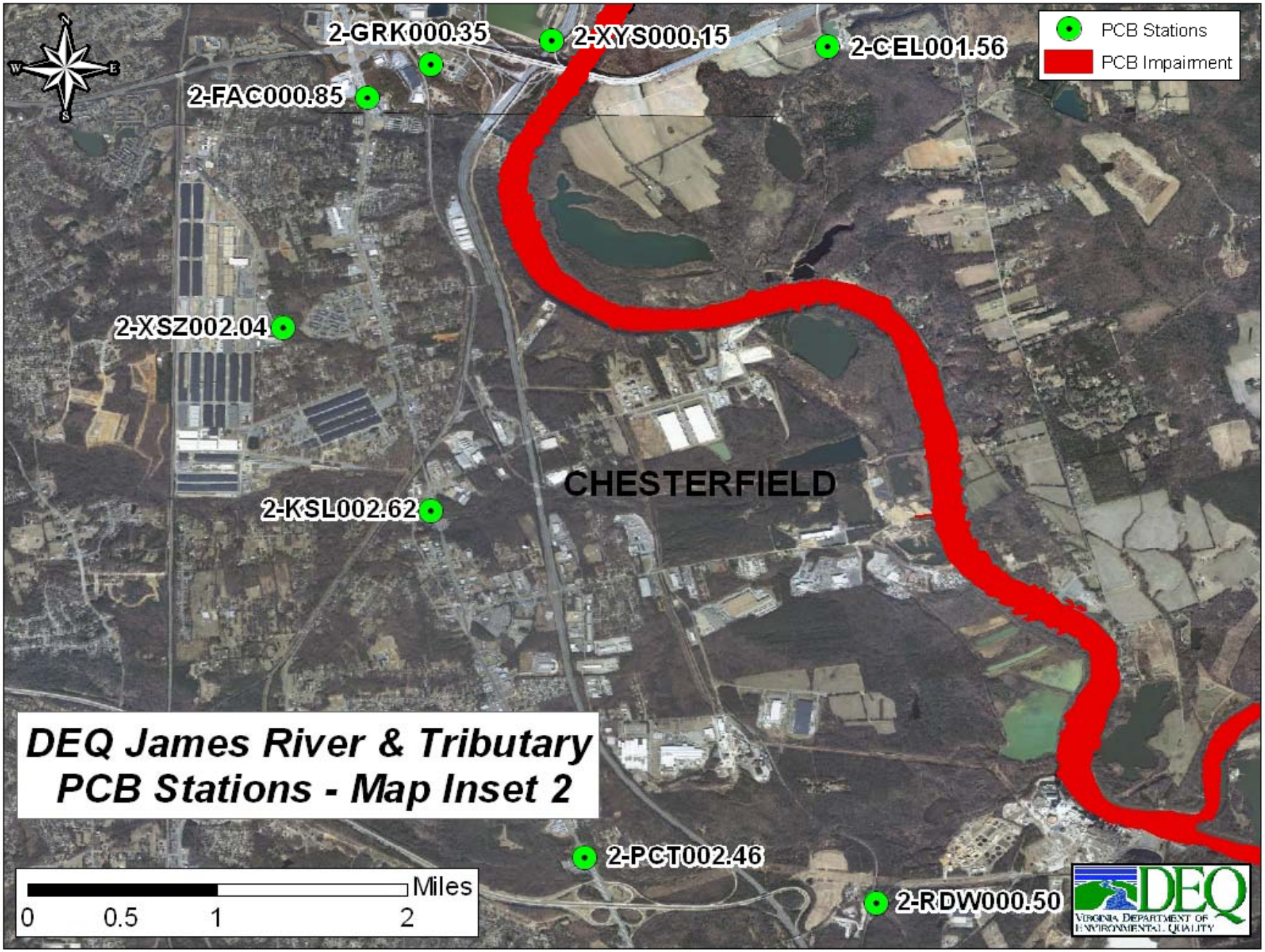
Inset	Station ID	Station Description	Date	Sample Type	Total PCBs (pg/L)
		James River Mainstem			
1	2-JMS110.34	South Channel last riffle above Mayos Bridge (Fall line)	4/15/2009	Dry	843
			5/7/2009	Wet	505
1	2-JMS110.44	North Channel (Fall line)	5/7/2009	Wet	589
3	2-JMS087.01	James River at Buoy 137	5/19/2009	Dry	1,413
			4/16/2009	Wet	894
3	2-JMS074.44	James R. at Rt 156, Benjamin Harrison Bridge	5/19/2009	Dry	212
			4/16/2009	Wet	214
4	2-JMS069.08	James River opposite Herring Creek, Buoy 91	4/28/2010	Dry	429
4	2-JMS066.88	James R. at powerline at Windmill Pt., Buoy 86	5/19/2009	Dry	254
			4/21/2009	Wet	492
4	2-JMS057.69	James River at Bachelor Pt, Buoy 74A	4/28/2010	Dry	666
			10/4/2010	Wet	593
4	2-JMS050.57	James River opposite Dancing Pt, Buoy 66	8/3/2010	Dry	452
			5/19/2010	Wet	388
		Appomattox River			
3	2-APP012.79	Appomattox R. at Rt. 36, Petersburg	5/20/2009	Dry	398
			4/16/2009	Wet	221
3	2-APP001.53	Appomattox R. at Rt. 10, Hopewell	5/19/2009	Dry	162
			4/16/2009	Wet	245
		Chickahominy River			
4	2-CHK006.14	Chickahominy River, 700 meters above Shields Pt.	4/28/2010	Dry	352
			5/19/2010	Wet	188
		Richmond Area Tributaries (James River)			
1	2-KAN000.03	Kanawha Canal outfall to James R. just above Great Ship Lock	4/15/2009	Dry	17,993
			5/26/2009	Wet	301
1	2-GIL000.42	Gillie Creek at Williamsburg Rd	5/26/2009	Dry	2,936
			5/7/2009	Wet	2,552 †
1	Richmond CSO-028	Gillie Creek Open CSO	5/26/2009	Dry	982
			5/7/2009	Wet	887
1	2-ALM000.42	Almond Creek at Rt. 5	6/18/2009	Dry	3,719
			5/26/2009	Wet	5,290
1	2-GOD000.77	Goode Creek at Commerce Rd.	4/15/2009	Dry	965
			5/26/2009	Wet	777
2	2-FAC000.85	Falling Creek at Rt. 1	5/20/2009	Dry	32
			5/7/2009	Wet	203
1	2-MAN000.19	Manchester Canal below CSO #014	6/30/2009	Dry	5,061
2	2-CEL001.56	Cornelius Creek at Mill Rd	6/30/2009	Dry	21
2	2-PCT002.46	Proctors Creek at Rt. 1	6/30/2009	Wet (?)	130
2	2-XYS000.15	DuPont Spruance East Ditch	5/7/2009	Wet	1,012
2	2-XSZ002.04	No Name Crk from DGS Center	5/7/2009	Wet	704
2	2-GRK000.35	Grindall Creek at Station Rd	6/30/2009	Dry	970
2	2-RDW000.50	Redwater Crk below transformer cracking facility	5/7/2009	Wet	462
2	2-KSL002.62	Kingsland Crk at Rt. 1 below DGSC stormwater	6/18/2009	Wet	976*
		Hopewell Area Tributaries			
3	2-BLY000.65	Bailey Creek at Rt. 10	5/20/2009	Dry	1,335
			4/16/2009	Wet	4,091
3	2-BLY003.42	Bailey Creek at Rt. 156	5/20/2009	Dry	333
			4/16/2009	Wet	167
3	2-BLY005.73	Bailey Creek below Ft. Lee at Rt. 630	6/18/2009	Dry	300

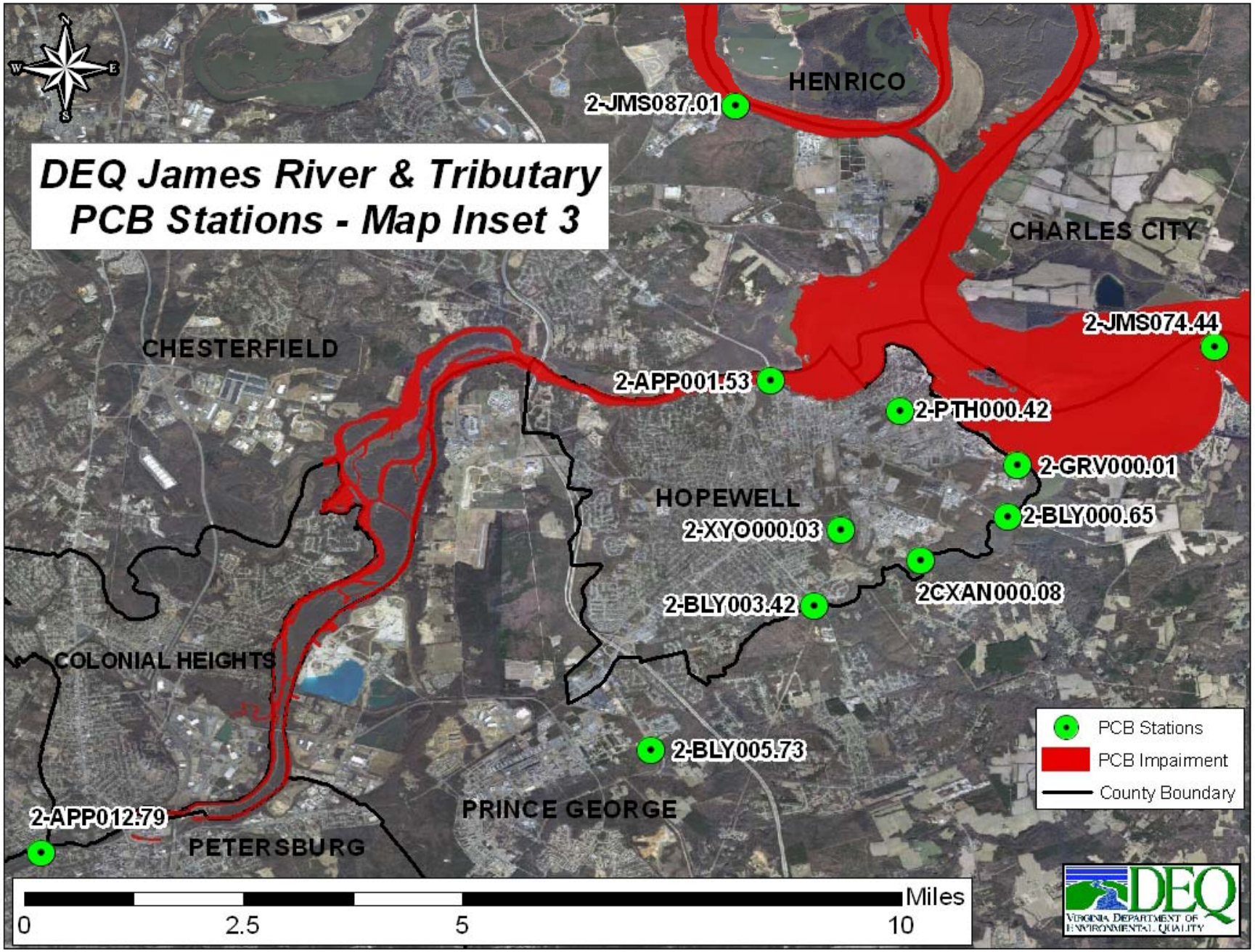
3	2-CXAN000.08	UT to Bailey Crk. (Bear Crk.)	6/4/2009	Wet	8,770
3	2-GRV000.01	Gravelly Run 15 M above mouth	5/27/2009	Dry	490
			4/21/2009	Wet	1,684
3	2-XYO000.03	UT to Cattail Creek at private rd. culvert	5/20/2009	Dry	3,952
			4/21/2009	Wet	3,214
3	2-PTH000.42	Poythress Run at Station Street	5/20/2009	Dry	233,484
			4/21/2009	Wet	168,606
	Misc. PCB Sample Results				
1	Nelson Ditch	Drainage ditch from Nelson Electric	6/18/2009	Wet	434,768
1	SIMSCR	South channel draining Sims Metals	6/18/2009	Dry	6,988*
1	Unnamed Pond	Unnamed Pond between Commerce Rd and the James River; below Peck Metals Fluff Pile	6/18/2009	Dry	37,760*

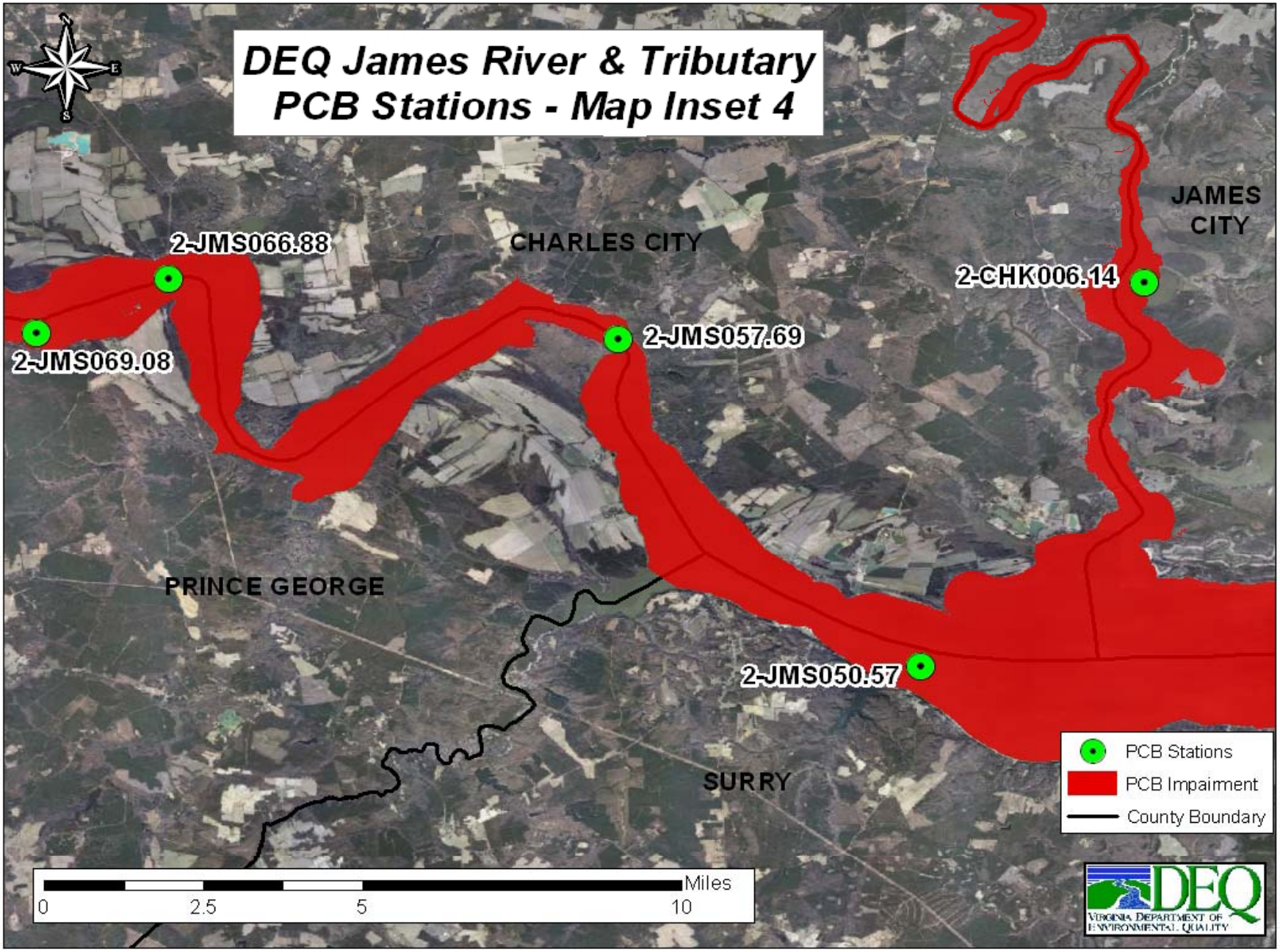
* Average of 2 samples; † = Sample qualified as low due to reduced surrogate recoveries.


DEQ James River & Tributary PCB Stations - Upper Tidal
PCB Stations
PCB Impairment
RICHMOND
HENRICO
NEW KENT
CHARLES CITY
JAMES CITY
CHESTERFIELD
HOPEWELL
COLONIAL HEIGHTS
PETERSBURG
PRINCE GEORGE
DINWIDDIE
Spring Grove
SURRY
1
2
3
4
0
5
10
20
30
Miles
DEQ
Virginia Department of Environmental Quality


DEQ James River & Tributary PCB Stations - Map Inset 1
PCB Stations
PCB Impairment
County Boundary
2-JMS110.44
2-JMS110.34
2-MAN000.19
2-KAN000.03
2-GIL000.42
RICHMOND CSO-028
RICHMOND
2-ALM000.42
NELSON EL DITCH
HENRICO
2-GOD000.77
Miles
0
0.5
1
2
Unnamed Pond
SIMSCR
DEQ
Virginia Department of Environmental Quality


PCB Stations
PCB Impairment
2-GRK000.35
2-XYS000.15
2-CEL001.56
2-FAC000.85
2-XSZ002.04
2-KSL002.62
CHESTERFIELD
2-PCT002.46
2-RDW000.50
DEQ James River & Tributary
PCB Stations - Map Inset 2
Miles
0
0.5
1
2
DEQ
Virginia Department of Environmental Quality


DEQ James River & Tributary
PCB Stations - Map Inset 3
HENRICO
CHARLES CITY
CHESTERFIELD
HOPEWELL
COLONIAL HEIGHTS
PRINCE GEORGE
PETERSBURG
2-JMS087.01
2-JMS074.44
2-APP001.53
2-PTH000.42
2-GRV000.01
2-BLY000.65
2-XYO000.03
2CXAN000.08
2-BLY003.42
2-BLY005.73
2-APP012.79
PCB Stations
PCB Impairment
County Boundary
Miles
0
2.5
5
10
DEQ
Virginia Department of Environmental Quality


DEQ James River & Tributary
PCB Stations - Map Inset 4
W
E
S
JAMES CITY
CHARLES CITY
2-JMS066.88
2-CHK006.14
2-JMS057.69
2-JMS069.08
PRINCE GEORGE
2-JMS050.57
SURRY
PCB Stations
PCB Impairment
County Boundary
Miles
0
2.5
5
10
DEQ
Virginia Department of Environmental Quality