Development of Multiple Tributary Model (MTM)
-- Review of current ICM and version comparisons

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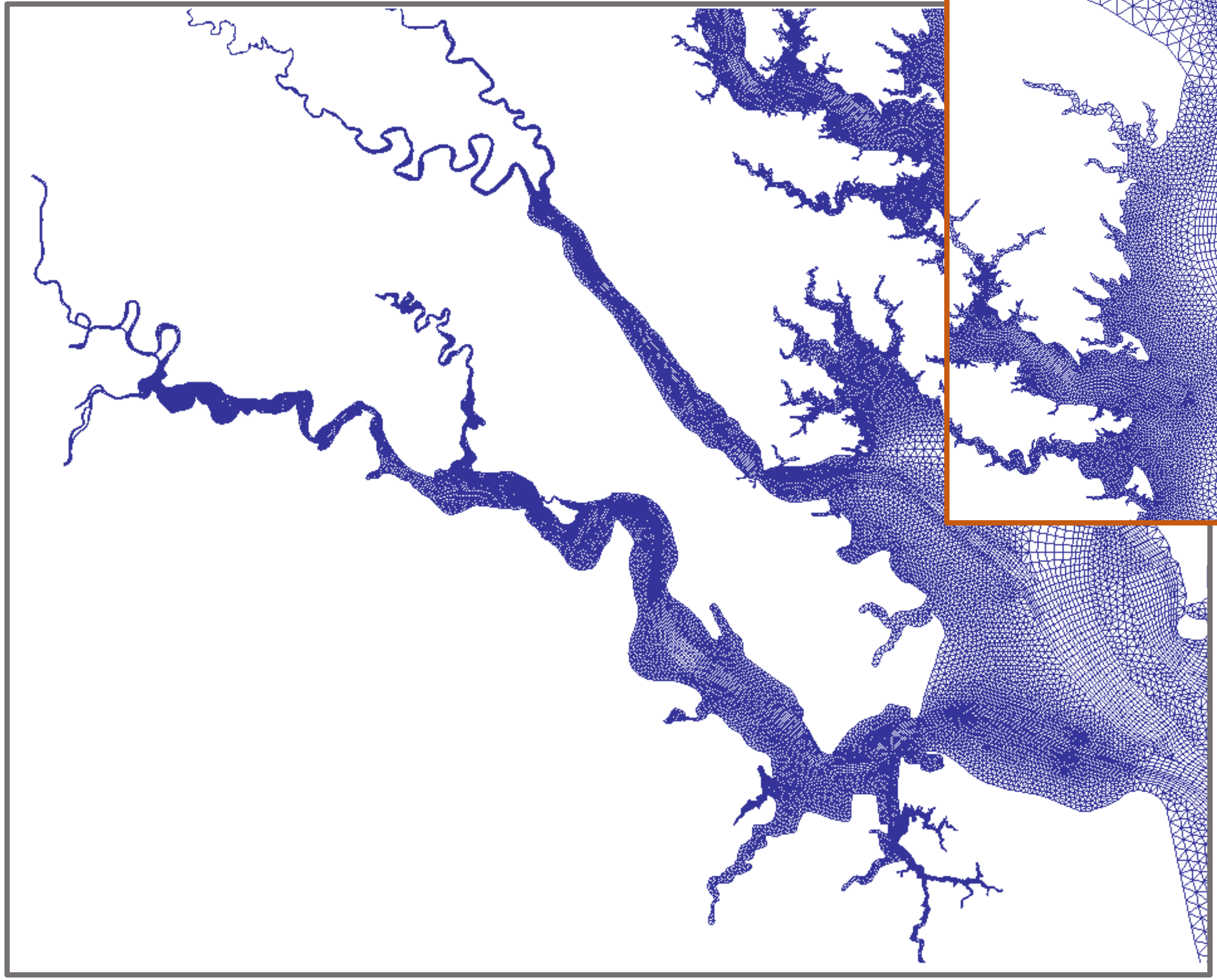
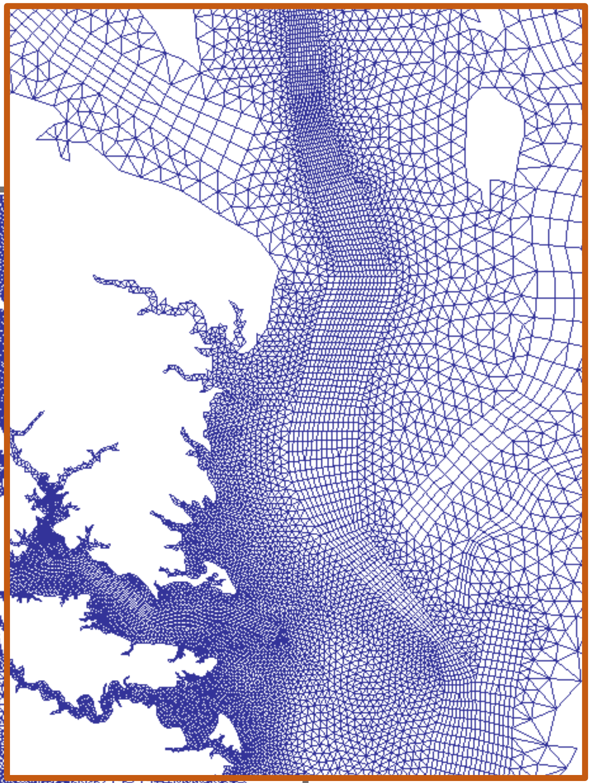
Modeling Quarterly Review, July 13, 2022

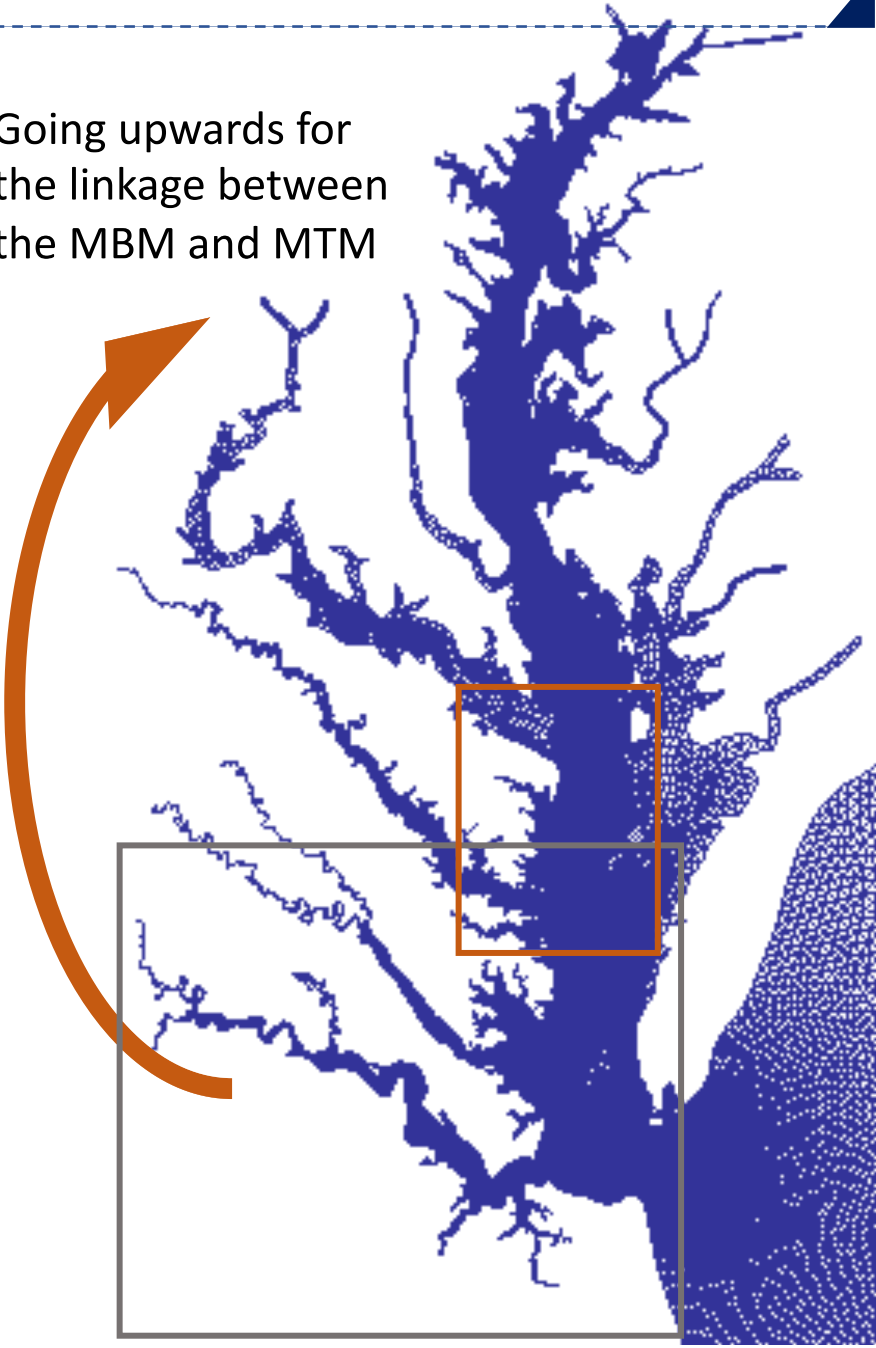
Progress of MTM development

Tidal James and York Rivers



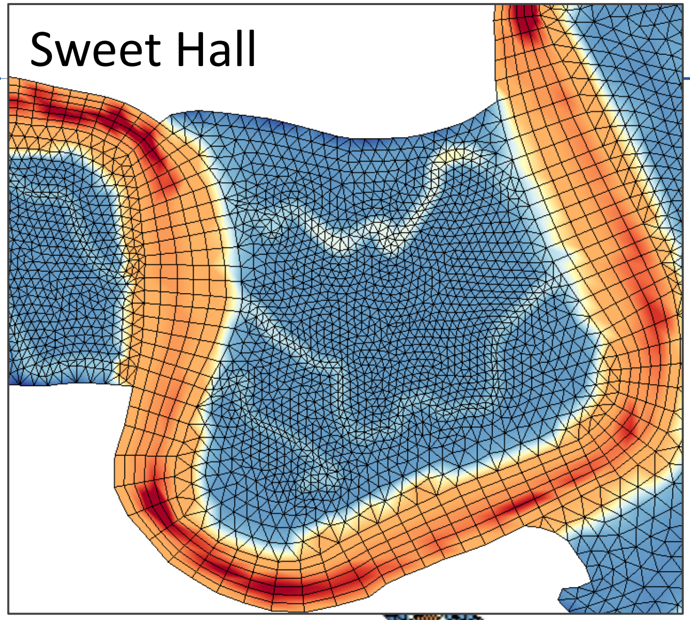


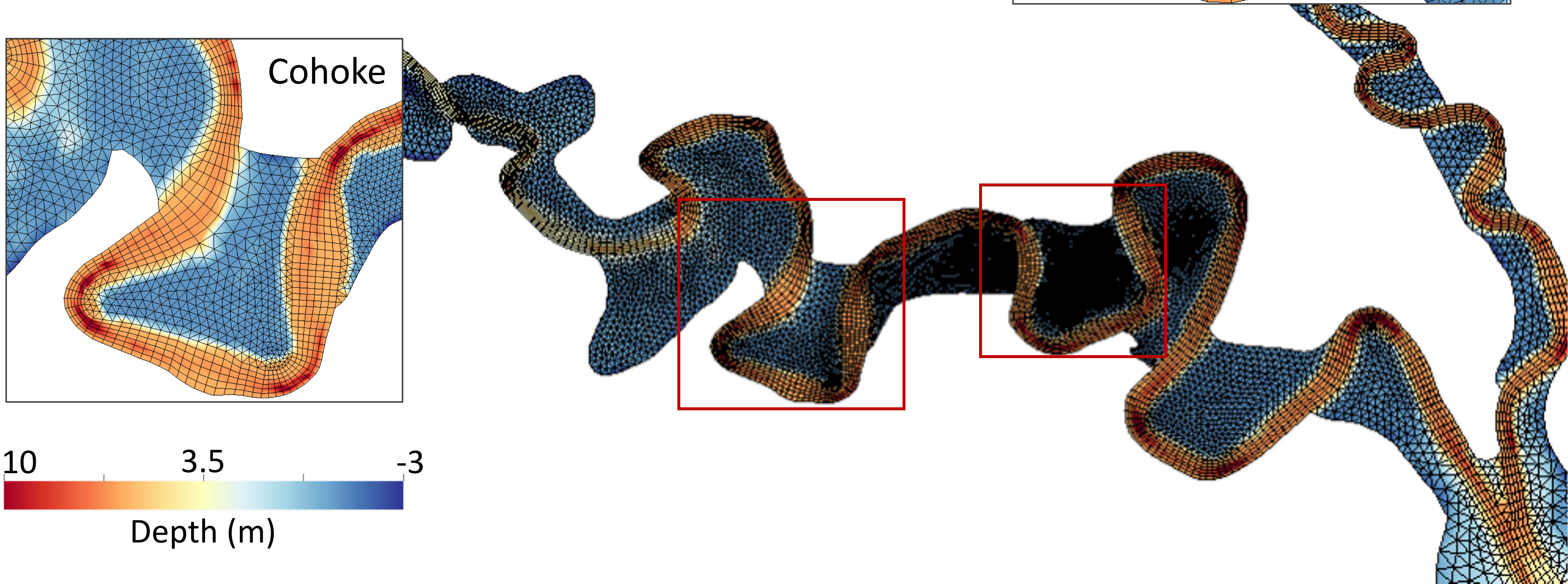
Going upwards for the linkage between the MBM and MTM



Model implementation in the York River

- Refined channel from the river mouth to heads
- Explicitly included tidal marsh wetlands (Cai et al., 2022; Cai et al., submitted)

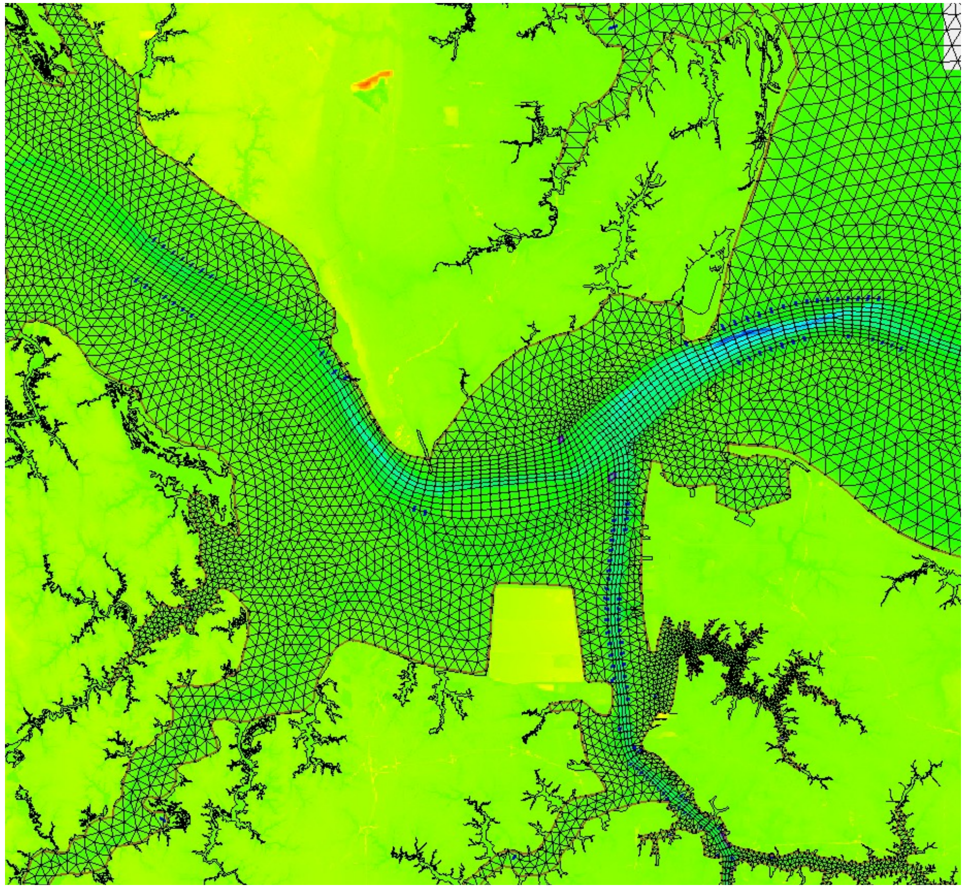


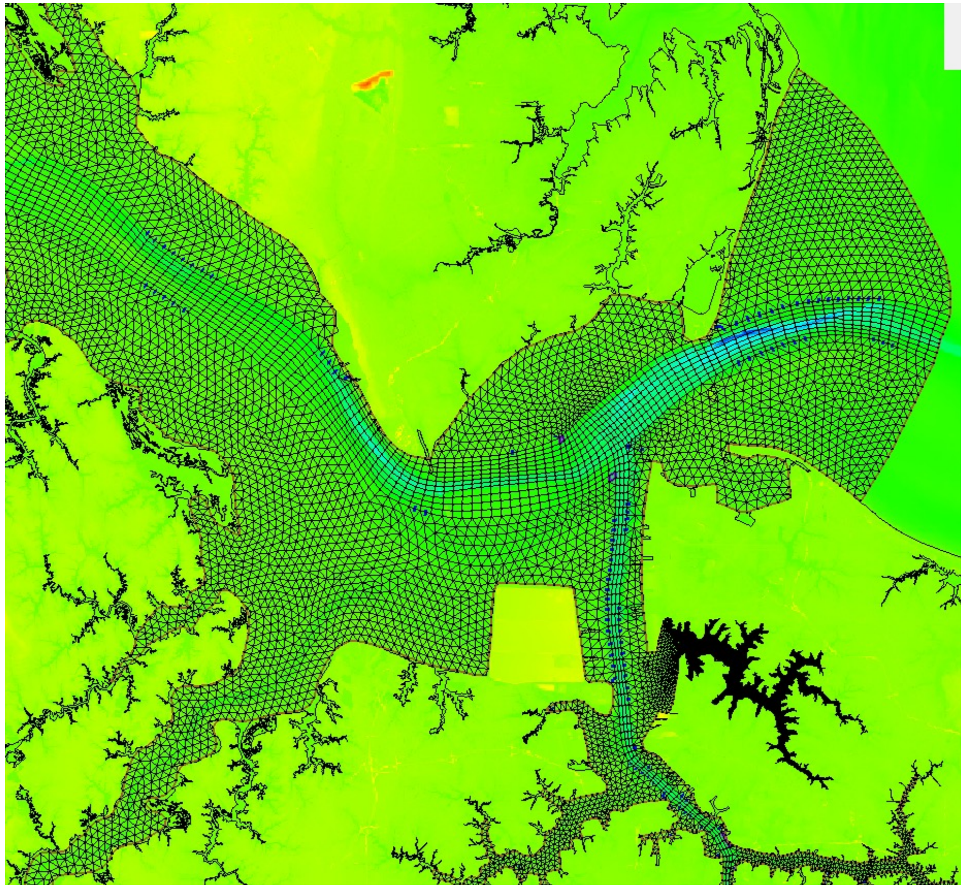


Model Implementation in the James River

Phase I: James River connected to the whole Bay grid

Phase II: single James River grid





Refined and stabilized shipping channels

Progress of MTM development

ICM equations and code

Grid

- Main Bay Model grid
- Tributary grid (James R., Potomac R. etc.)

Chesapeake Bay Estuary Model

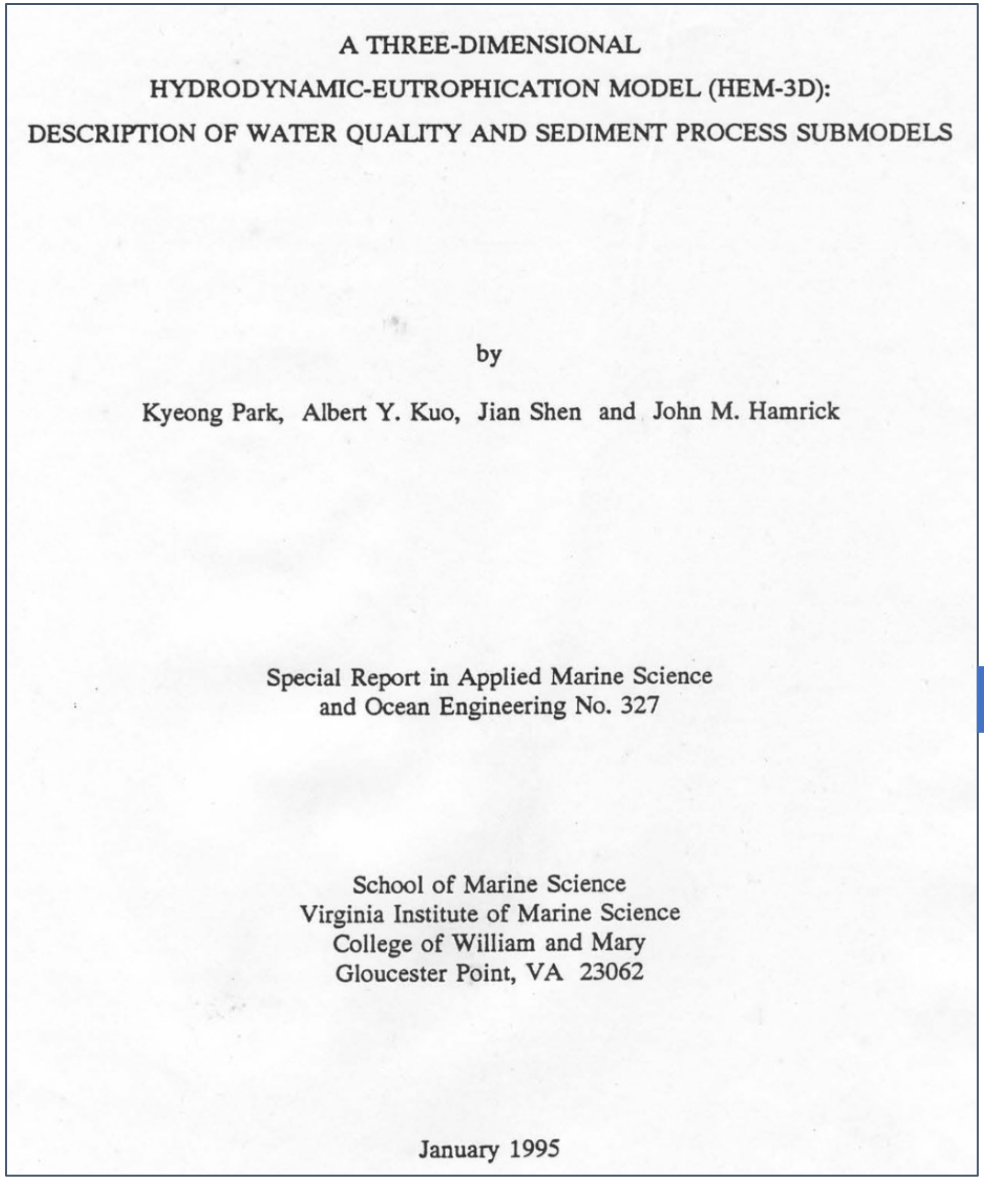
- Sub-BGC modules (SAV, marsh etc.)
- Sediment transport
- Wind wave

Modules and linkage

- Watershed
- Airshed
- Open boundary

Forcings

In the process of including and updating



A THREE-DIMENSIONAL
HYDRODYNAMIC-EUTROPHICATION MODEL (HEM-3D):
DESCRIPTION OF WATER QUALITY AND SEDIMENT PROCESS SUBMODELS

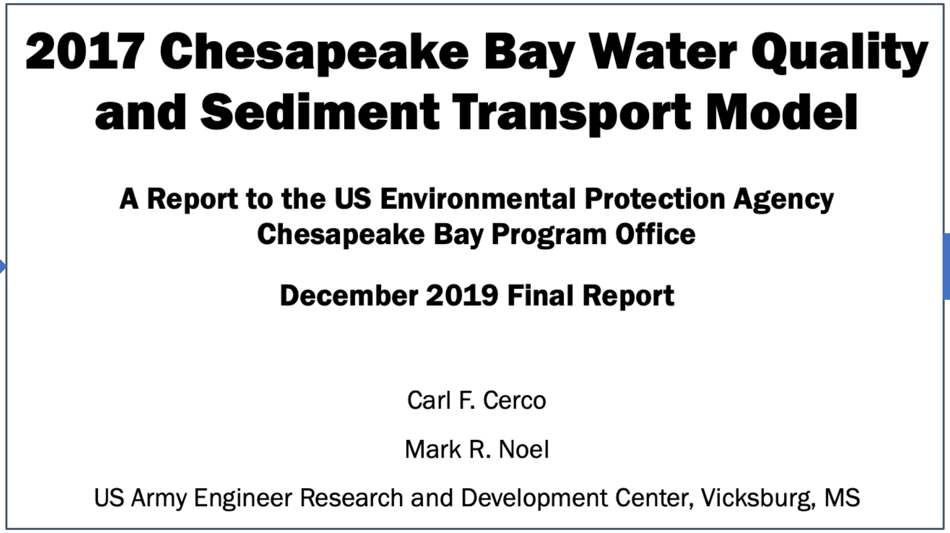
by

Kyeong Park, Albert Y. Kuo, Jian Shen and John M. Hamrick

Special Report in Applied Marine Science
and Ocean Engineering No. 327

School of Marine Science
Virginia Institute of Marine Science
College of William and Mary
Gloucester Point, VA 23062

January 1995



2017 Chesapeake Bay Water Quality and Sediment Transport Model

A Report to the US Environmental Protection Agency
Chesapeake Bay Program Office

December 2019 Final Report

Carl F. Cerco

Mark R. Noel

US Army Engineer Research and Development Center, Vicksburg, MS

MBM
MTM

- CE-QUAL-ICM (Cerco & Cole, 1994)
- Sediment diagenesis model (DiToro & Fitzpatrick, 1993)
- CH3D-ICM (Cerco et al., 2010)

Cai et al. (2020, 2021)

State variables

CH3D-ICM, 22 state variables		SCHISM-ICM, 21 state variables
TSS (sediment transport and shoreline erosion)		TSS (simplified or linked)
PB1, PB2, PB3		PB1, PB2, PB3
ZB1, ZB2	In module already →	ZB1, ZB2
DOC, LPOC, RPOC, **SRPOC**	To add a SR group →	DOC, LPOC, RPOC
NH4, NO3, DON, LPON, RPON, **SRPON**	To add a SR group →	NH4, NO3, DON, LPON, RPON
PO4, **PIP**, DOP, LPOP, RPOP, **SRPOP**	To add a SR group →	PO4t, DOP, LPOP, RPOP
PBS,DSil	To be put in a separate module →	PBS, DSil
COD, DO		COD, DO

Additional modules

CH3D-ICM	SCHISM-ICM
Sediment transport	Sediment transport (exists but is not commonly used)
Bivalve filter feeders (Oyster)	
SAV	SAV
Wetlands	Marsh (explicit)
Shoreline erosion	
	Benthic algae
	PH

Algae

CH3D-ICM	SCHISM-ICM

$$\frac{\delta}{\delta t}B = \left(G - BM - Wa \times \frac{\delta}{\delta z}\right)B - PR$$

B = algal biomass, expressed as carbon (g C m^{-3})
G = growth (d^{-1})
BM = basal metabolism (d^{-1})
Wa = algal settling velocity (m d^{-1})
PR = predation (g C m^{-3} d^{-1})
z = vertical coordinate

$$\frac{\partial B_x}{\partial t} = (P_x - BM_x - PR_x)B_x + \frac{\partial}{\partial z}(WS_x \cdot B_x) + \frac{WB_x}{V}$$

B_x = algal biomass of algal group x (g C m^{-3})

t = time (day)

P_x = production rate of algal group x (day^{-1})

BM_x = basal metabolism rate of algal group x (day^{-1})

PR_x = predation rate of algal group x (day^{-1})

WS_x = settling velocity of algal group x (m day^{-1})

WB_x = external loads of algal group x (g C day^{-1})

V = cell volume (m^3).

Algae growth

CH3D-ICM

SCHISM-ICM

- Similar in format
- Carbon-to-chlorophyll ratio incorporated to convert to a carbon-specific growth rate

$$P_x = PM_x \cdot f_1(N) \cdot f_2(I) \cdot f_3(T)$$

PM_x = maximum growth rate under optimal conditions for algal group x (day^{-1})

$f_1(N)$ = effect of suboptimal nutrient concentration ($0 \le f_1 \le 1$)

$f_2(I)$ = effect of suboptimal light intensity ($0 \le f_2 \le 1$)

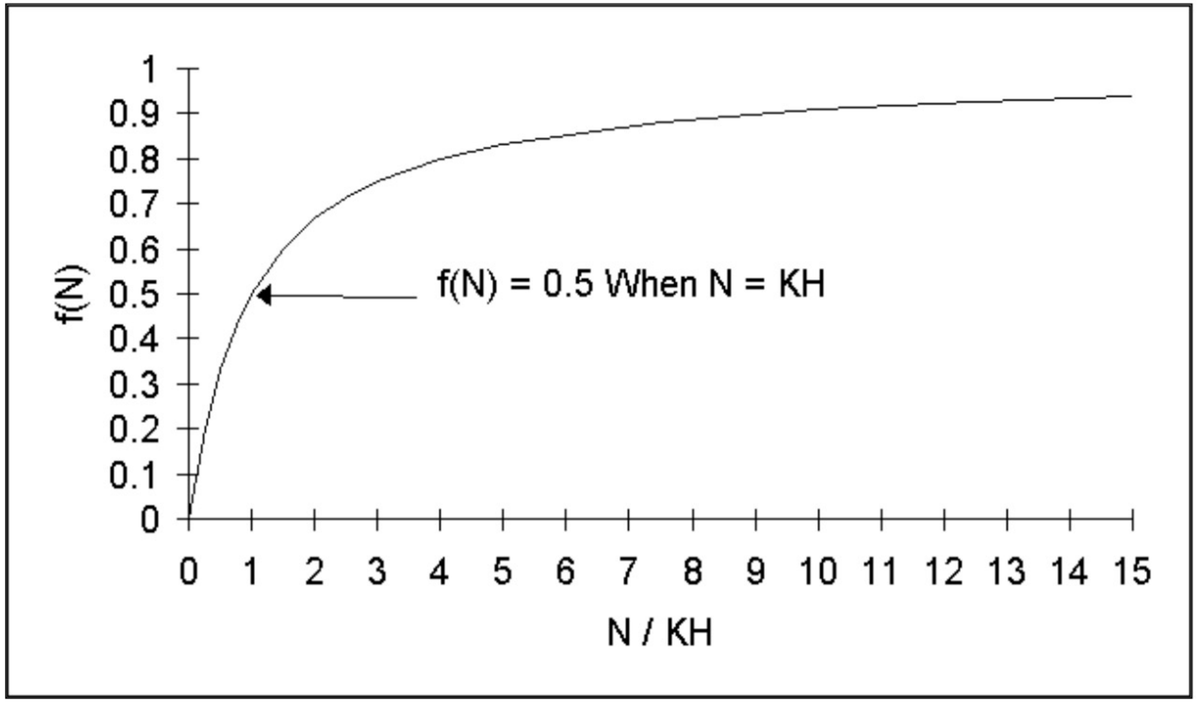
$f_3(T)$ = effect of suboptimal temperature ($0 \le f_3 \le 1$).

Nutrient limitation function

CH3D-ICM	SCHISM-ICM
$$f(N) = \frac{D}{KHd + D}$$	Same

$f(N)$ = nutrient limitation on algal production ($0 \le f(N) \le 1$)
D = concentration of dissolved nutrient (g m^{-3})
KHd = half-saturation constant for nutrient uptake (g m^{-3})

Figure 2-2. Monod formulation for nutrient-limited growth.



Effects of temperature on algae growth

CH3D-ICM

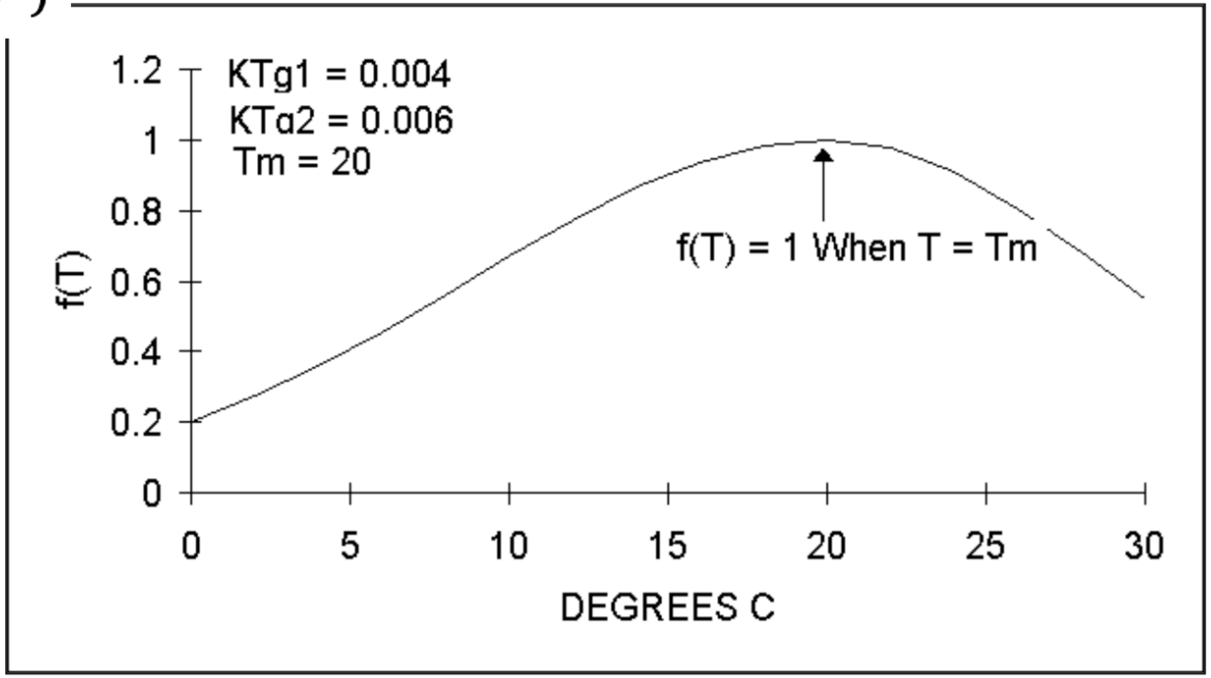
$$f(T) = e^{-KTg1 \cdot (T - Topt)^2} \quad when \quad T \leq Topt$$
$$= e^{-KTg2 \cdot (Topt - T)^2} \quad when \quad T > Topt$$

T = temperature (°C)
$Topt$ = optimal temperature for algal growth (°C)
$KTg1$ = effect of temperature below Topt on growth (°C^{-2})
$KTg2$ = effect of temperature above Topt on growth (°C^{-2})

SCHISM-ICM

Same

Figure 2-3. Relation of algal production to temperature.



Light limitation function

CH3D-ICM

$$P^B = P^B m \frac{I}{\sqrt{I^2 + Ik^2}}$$

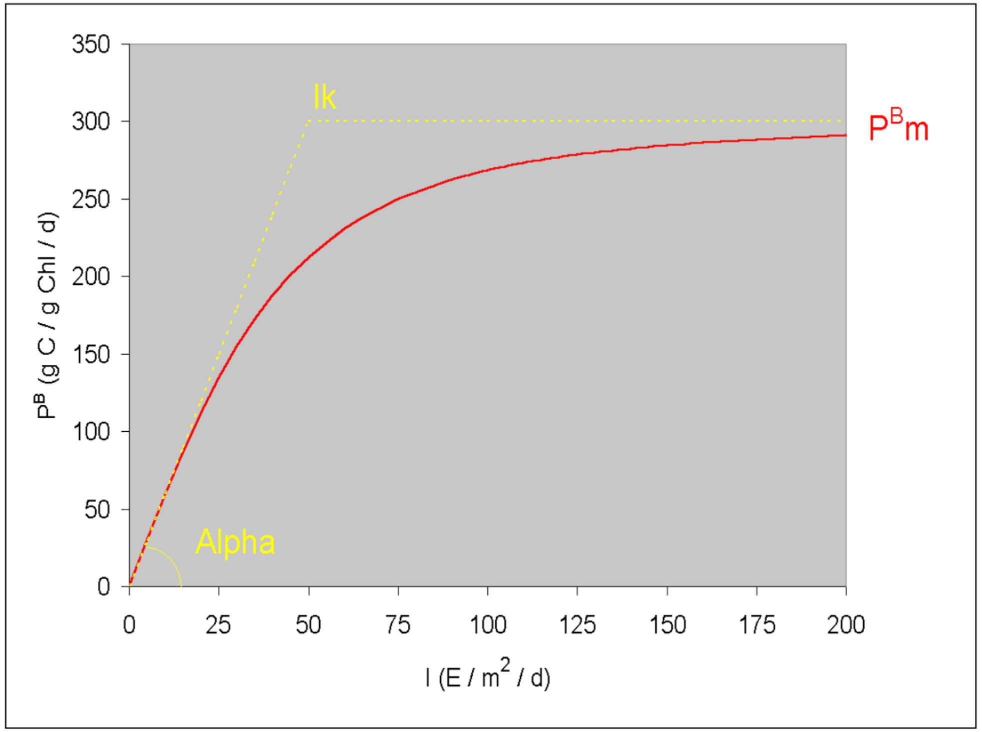
P^B = photosynthetic rate (g C g^{-1} Chl d^{-1})
$P^B m$ = maximum photosynthetic rate (g C g^{-1} Chl d^{-1})
I = irradiance (E m^{-2} d^{-1})

$$Ik = \frac{P^B m}{\alpha}$$

SCHISM-ICM

Incorporated as default

Figure 2-1. Photosynthesis versus irradiance curve.



Irradiance

CH3D-ICM	SCHISM-ICM

$$Io = \frac{\Pi}{2 \times FD} \times IT \times \sin\left(\frac{\Pi \times DSSR}{FD}\right)$$

Io = irradiance at water surface (E m^{-2} d^{-1})
IT = daily total irradiance (E m^{-2})
FD = fractional daylength ($0 < FD < 1$)
$DSSR$ = time since sunrise (d)

$$\frac{1 - FD}{2} \leq DSM \leq \frac{1 + FD}{2}$$

DSM = time since midnight (d)

Incorporated,
But default to take short wave from sflux (NARR)

Predation – 2nd order formula

CH3D-ICM

$$PR = F \times B \times M$$

F = filtration rate (m^3 g^{-1} predator C d^{-1})
M = planktivore biomass (g C m^{-3})

$$PR = Phtl \cdot B^2$$

$Phtl$ = rate of water-column planktivore predation (m^3 g^{-1} C d^{-1})

SCHISM-ICM

$$PR_x = PRR_x \cdot \exp(KTB_x[T - TR_x])$$

PRR_x = predation rate at TR_x for algal group x (day^{-1}).

Respiration – additional photorespiration term + multiple products

CH3D-ICM

$$R = Presp \times G + BM \times e^{KTb \times (T - Tr)}$$

$Presp$ = photorespiration ($0 \le Presp \le 1$)
BM = metabolic rate at reference temperature Tr (d^{-1})
KTb = effect of temperature on metabolism ($^oC^{-1}$)
Tr = reference temperature for metabolism (^oC)

R
- Consumption of DO
- Release as DOC
- Release as LPOC
- Release as RPOC
- Release as SRPOC

SCHISM-ICM

$$BM_x = BMR_x \cdot \exp(KTB_x[T - TR_x])$$

BMR_x = basal metabolism rate at TR_x for algal group x (day^{-1})
KTB_x = effect of temperature on metabolism for algal group x ($^\circ C^{-1}$)
TR_x = reference temperature for basal metabolism for algal group x ($^\circ C$).

BM
- Consumption of DO $(1 - FCD_x)\dfrac{DO}{KHR_x + DO}BM_x$ ← respiration
- Release as DOC $\left[FCD_x + (1 - FCD_x)\dfrac{KHR_x}{KHR_x + DO}\right]BM_x$ ← excretion

KHR_x, which is defined as the half-saturation constant of dissolved oxygen for algal dissolved organic carbon excretion in Eq. 3-4, can also be defined as the half-saturation constant of dissolved oxygen for algal respiration in Eq. 3-4d.

Effect of algae on DO

CH3D-ICM

SCHISM-ICM

Similar

- New respiration term
- Partition to POC from respirations

1-FCD-FCL-FCR-FCG3 R

$$\frac{\partial DO}{\partial t} = \sum_{x=c,d,g} \left((1.3 - 0.3 \cdot PN_x) P_x - (1 - FCD_x) \frac{DO}{KHR_x + DO} BM_x \right) AOCR \cdot B_x$$

$$PN_x = NH4 \frac{NO3}{(KHN_x + NH4)(KHN_x + NO3)} + NH4 \frac{KHN_x}{(NH4 + NO3)(KHN_x + NO3)}$$

PN_x = The preference of algae for ammonium

DOC – source from photorespiration and sink to denitrification

CH3D-ICM

Similar

- Contributions from G3 POC dissolution
- New form of predation term
- New respiration term
- Partition to POC from respirations
- Missing denitrification consumption

SCHISM-ICM

1-FCD-FCL-FCR-FCG3 R $FCDP \cdot PR$

$$\frac{\partial DOC}{\partial t} = \sum_{x=c,d,g}\left(\left[FCD_x + (1 - FCD_x)\frac{KHR_x}{KHR_x + DO}\right]BM_x + FCDP \cdot PR_x \cdot B_x\right)$$

$$+ K_{RPOC} \cdot RPOC + K_{LPOC} \cdot LPOC - K_{HR} \cdot DOC - Denit \cdot DOC + \frac{WDOC}{V}$$

$$+ Kg3poc \cdot G3OC$$

DOC = concentration of dissolved organic carbon (g C m^{-3})

FCD_x = fraction of basal metabolism exuded as dissolved organic carbon at infinite dissolved oxygen concentration for algal group x

KHR_x = half-saturation constant of dissolved oxygen for algal dissolved organic carbon excretion for group x (g O_2 m^{-3})

DO = dissolved oxygen concentration (g O_2 m^{-3})

FCDP = fraction of predated carbon produced as dissolved organic carbon

K_{HR} = heterotrophic respiration rate of dissolved organic carbon (day^{-1})

Denit = denitrification rate (day^{-1}) given in Eq. 3-41

WDOC = external loads of dissolved organic carbon (g C day^{-1}).

POC (LPOC as an example) – additional source from algae respiration

CH3D-ICM

SCHISM-ICM

$$\frac{\delta}{\delta t} LPOC = \boxed{FCL \times R \times B} + FCLP \times PR - Klpoc \times LPOC - Wl \times \frac{\delta}{\delta z} LPOC$$

FCL = fraction of algal respiration released as LPOC ($0 \leq FCL \leq 1$)
$FCLP$ = fraction of predation on algae released as LPOC ($0 \leq FCLP \leq 1$)
Wl = settling velocity of labile particles ($m\ d^{-1}$)

$$\frac{\partial LPOC}{\partial t} = \sum_{x=c,d,g} FCLP \cdot PR_x \cdot B_x - K_{LPOC} \cdot LPOC + \frac{\partial}{\partial z}(WS_{LP} \cdot LPOC) + \frac{WLPOC}{V}$$

FCLP = fraction of predated carbon produced as labile particulate organic carbon

DOP – modified DOP mineralization rate

CH3D-ICM

SCHISM-ICM

$$\frac{\delta}{\delta t}DOP = APC \cdot (\ R \ \cdot B \cdot FPD + PR \cdot FPDP) + Klpop \cdot LPOP + Krpop$$
$$RPOP + Kg3op \cdot G3OP - \boxed{Kdop} \cdot DOP$$

- *DOP* = dissolved organic phosphorus (g P m^{-3})
- *LPOP* = labile particulate organic phosphorus (g P m^{-3})
- *RPOP* = refractory particulate organic phosphorus (g P m^{-3})
- *G3OP* = slow refractory particulate organic phosphorus (g P m^{-3})
- *FPD* = fraction of algal metabolism released as DOP ($0 \le FPD \le 1$)
- *FPDP* = fraction of predation on algae released as DOP ($0 \le FPDP \le 1$)
- *Klpop* = hydrolysis rate of LPOP (d^{-1})
- *Krpop* = hydrolysis rate of RPOP (d^{-1})
- *Kg3op* = hydrolysis rate of G3OP (d^{-1})
- *Kdop* = mineralization rate of DOP (d^{-1})

$$\frac{\partial DOP}{\partial t} = \sum_{x=c,d,g} (FPD_x \cdot BM_x + FPDP \cdot PR_x) APC \cdot B_x$$
$$+ K_{RPOP} \cdot RPOP + K_{LPOP} \cdot LPOP - K_{DOP} \cdot DOP + \frac{WDOP}{V}$$

DOP mineralization rate – effects from temperature

CH3D-ICM

$$Kdop = Kdp + \frac{KHp}{KHp + PO_4} \times Kdpalg \times B$$

$Kdop$ = mineralization rate of dissolved organic phosphorus (d^{-1})
Kdp = minimum mineralization rate (d^{-1})
KHp = half-saturation concentration for algal phosphorus uptake (g P m^{-3})
PO_4 = dissolved phosphate (g P m^{-3})
$Kdpalg$ = constant that relates mineralization to algal biomass (m^3 g^{-1} C d^{-1})

SCHISM-ICM

$$K_{DOP} = (K_{DP} + \frac{KHP}{KHP + PO4d} K_{DPalg} \sum_{x=c,d,g} B_x) \cdot \exp(KT_{MNL}[T - TR_{MNL}])$$

PO4 – partition of dissolved PO4 and PIP

CH3D-ICM

$$\frac{\delta}{\delta t} PO_4 = Kdop \cdot DOP + Kpip \cdot PIP - APC \cdot G \cdot B$$

$$+ APC \cdot [FPI \cdot R \cdot B + FPIP \cdot PR] - Wpo_4 \cdot \frac{\delta}{\delta z} PO_4$$

$$\frac{\partial}{\partial t} PIP = -Kpip \cdot PIP - Wpip \cdot \frac{\delta}{\delta z} PIP$$

SCHISM-ICM

$$\frac{\partial PO4t}{\partial t} = \sum_{x=c,d,g} (FPI_x \cdot BM_x + FPIP \cdot PR_x - P_x) APC \cdot B_x + K_{DOP} \cdot DOP$$

$$+ \frac{\partial}{\partial z}(WS_{TSS} \cdot PO4p) + \frac{BFPO4d}{\Delta z} + \frac{WPO4t}{V}$$

PIP = particulate inorganic phosphorus (g P m^{-3})

$Kpip$ = dissolution rate of particulate inorganic phosphorus (d^{-1})

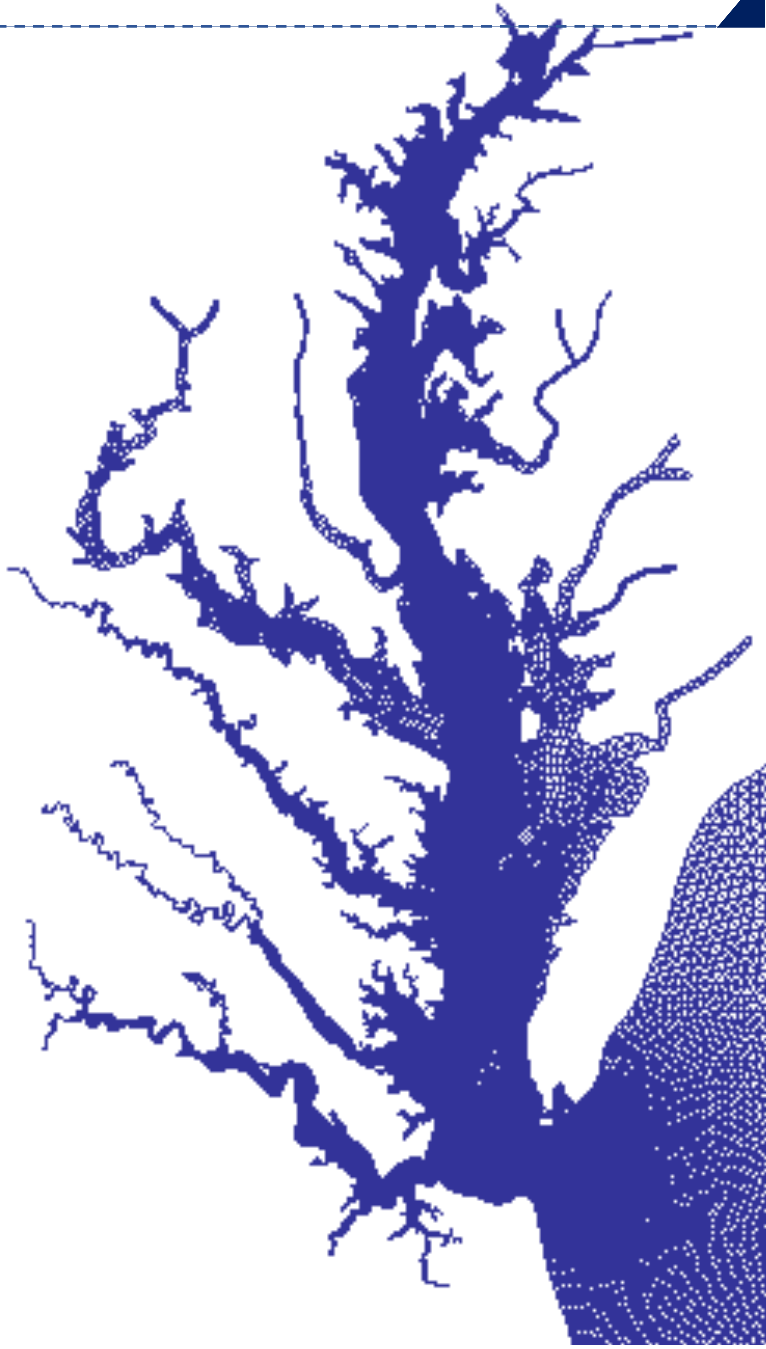
FPI = fraction of algal metabolism released as dissolved phosphate ($0 \le FPI \le 1$)

$FPIP$ = fraction of predation released as dissolved phosphate ($0 \le FPIP \le 1$)

Wpo_4 = settling rate of precipitated phosphate (m d^{-1})

Discussion, questions, and summary

- Existing modules to be incorporated
- Algae respiration and predation terms need to be updated
- Partitioning of PO4 and PIP to be added
- Water column denitrification process on DOC
- Application of radiation (short wave) from NARR



Questions?

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VIRGINIA INSTITUTE OF MARINE SCIENCE

NO3 – sink to denitrification

CH3D-ICM	SCHISM-ICM

$$\frac{\delta}{\delta t} NO_{23} = - ANC \cdot (1 - PN) \cdot P \cdot B + NT$$

$$\frac{\partial NO3}{\partial t} = - \sum_{x=c,d,g} (1 - PN_x) P_x \cdot ANC_x \cdot B_x + Nit \cdot NH4 - \boxed{ANDC \cdot Denit \cdot DOC} + \frac{BFNO3}{\Delta z} + \frac{WNO3}{V}$$

Denit = denitrification rate (day^{-1}) given in Eq. 3-41