Lake Petenwell and Castle Rock

CE-QUAL-W2 Model

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WI River Tech Stakeholder Meeting

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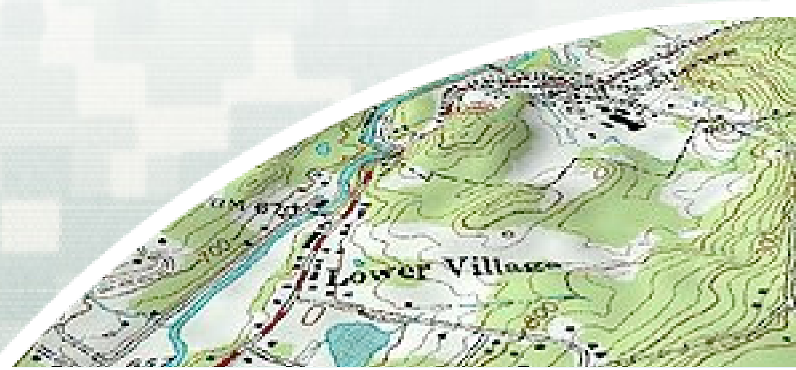

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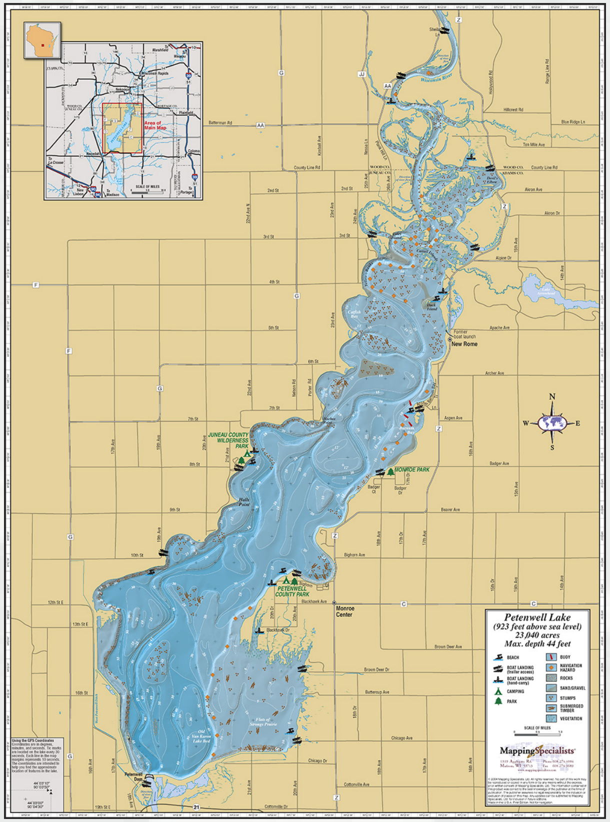
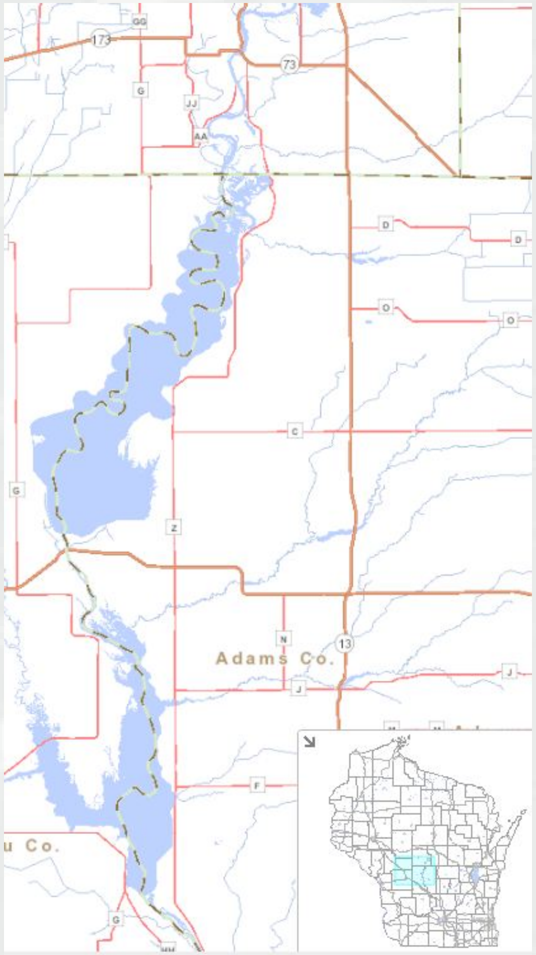
Outline

- Study Area -Petenwell and Castle Rock Flowages
- Purpose of the 2-D Modeling Petenwell and Castle Rock
- Modeling Overview
- CE-QUAL-W2 Design
- Model inputs and monitoring data
- Model Calibration and Verification
- Model Sensitivity
- Questions



Petenwell and Castle Rock

- Study Area
  - Petenwell and Castle Rock Flowages are located at the downstream section of the central portion of the Wisconsin River Mainstem.
  - Petenwell Flowage is 23,173 acres with a maximum depth of 44 feet. 2^{nd} largest Lake in Wi.
  - Castle Rock Flowages is 12,981 acres with a maximum depth of 36 feet



Petenwell and Castle Rock

Petenwell and Castle Rock summer Chl a averages

Productivity/Trophic Status	What does the water look like?	Maximum chlorophyll concentration (µg/L)
Oligotrophic	Clear	Less than 8
Oligo-mesotrophic	Usually clear	Occasionally over 8
Mesotrophic	Sometimes green	8 to 25
Eutrophic	Green most of summer	26 to 75
Hyper-eutrophic	Frequent dense algal blooms	Over 75

Table adapted from: Atlas of Alberta Lakes, http://sunsite.ualberta.ca/Projects/Alberta-Lakes

Petenwell and Castle Rock

- Both Flowages are listed on the EPA 303 (d) list as impaired waterbodies.
- Impaired beneficial uses include:
- Impaired recreation and aesthetics
- Undesirable blue-green algae blooms, some toxic algae
- Phosphorus loading from both point and nonpoint sources, causing eutrophication
- Dioxin, Mercury and PCB contaminated fish and sediments
- Dissolved oxygen and fish (carp) kills on the Petenwell Flowage

Petenwell and Castle Rock CE-QUAL-W2 Objectives

- Develop a calibrated CE-QUAL-W2 hydrodynamic and water quality model that successfully:
  - Captures phosphorus, dissolved oxygen and chlorophyll dynamics for the monitoring period of record (2009-2013)
  - Links with SWAT watershed loading outputs (Dr. Zhonglong Zhang)
  - Predicts future water quality conditions for Petenwell and Castle Rock Flowages for selected TMDL scenarios

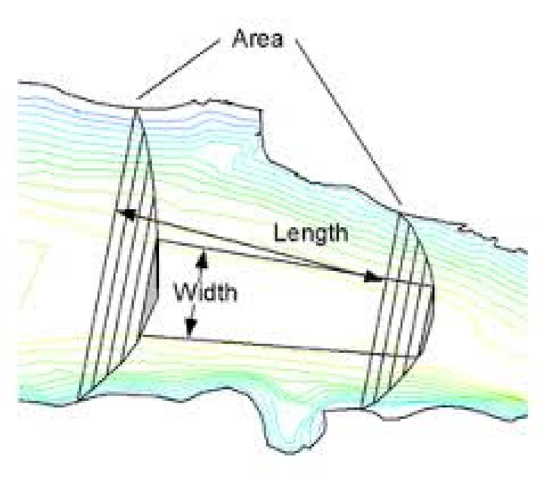
CE-QUAL-W2 Model Overview

- Longitudinal/vertical hydrodynamic and water quality model
- Original model was known as LARM (Laterally Averaged Reservoir Model) developed by Edinger and Buchak (1975).
- Under continuous development since 1975
- Maintained by the US Corps of Engineers and Portland State University
- Includes algal/nutrient/dissolved oxygen interactions
- Has been applied to hundreds of rivers, lakes and reservoirs around the world.

CE-QUAL-W2 Model Overview

<u>Possible Model Limitations for this study</u>:

- Semi-predictive sediment compartment
- Well-mixed in lateral direction
  - CE-QUAL-W2 is a two dimensional reservoir model, thus all water quality parameters are averaged laterally across a segment. Each layer within a segment acts as a fully mixed reactor for each time step.



CE-QUAL-W2 Model

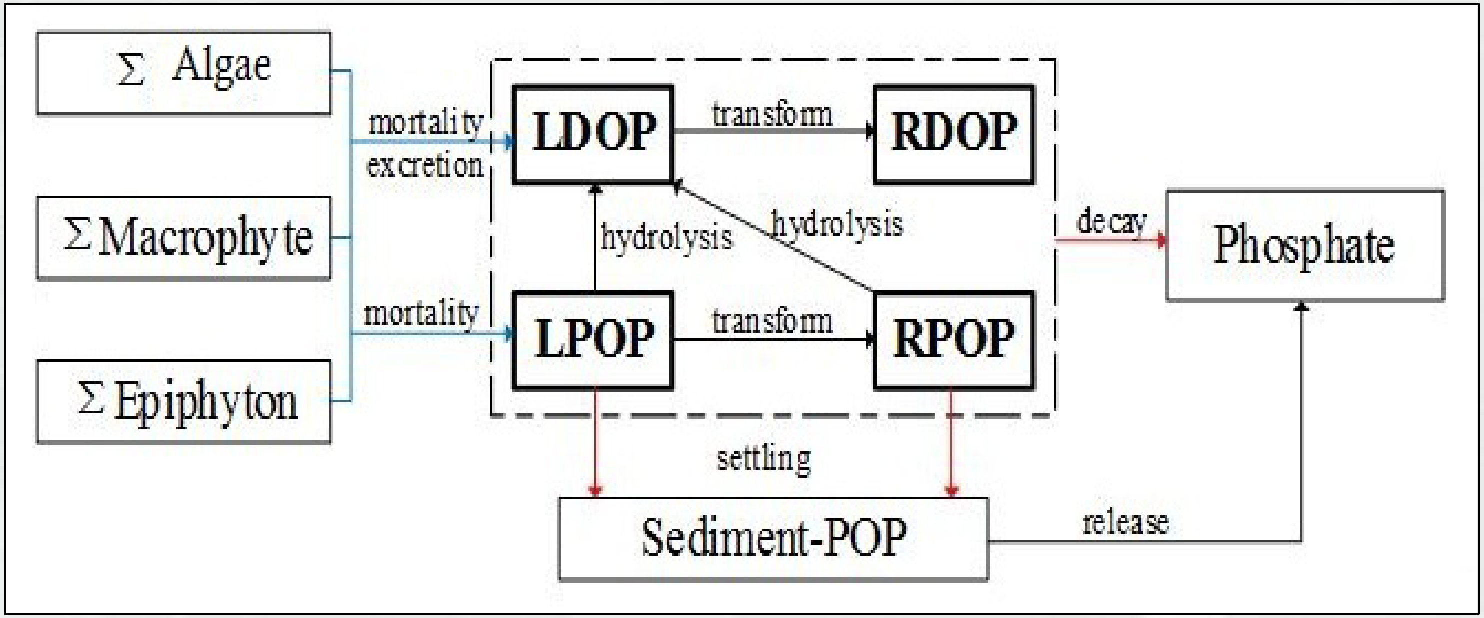
Estimated CE-QUAL-W2 Project Timeline

Time Period	Status	Project Task
2013	completed	Data Analysis and Model Preparation
Fall 2013	underway	Calibration and Validation for temperature and flow/stage
2014		Calibration and Validation for water quality constituents
Spring 2015		Training
Fall 2015		Reporting and Scenario application

CE-QUAL-W2 Design

Main focus

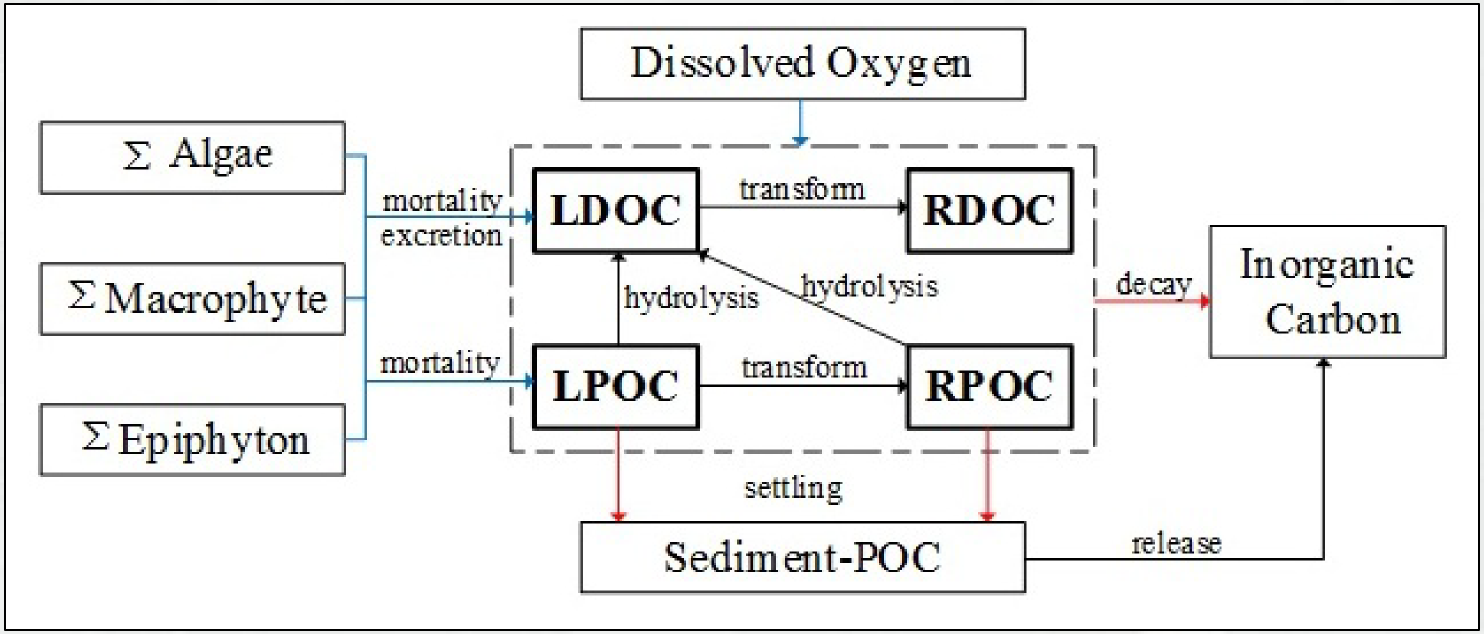
- Fate and transport of phosphorus



CE-QUAL-W2 Design

Also need

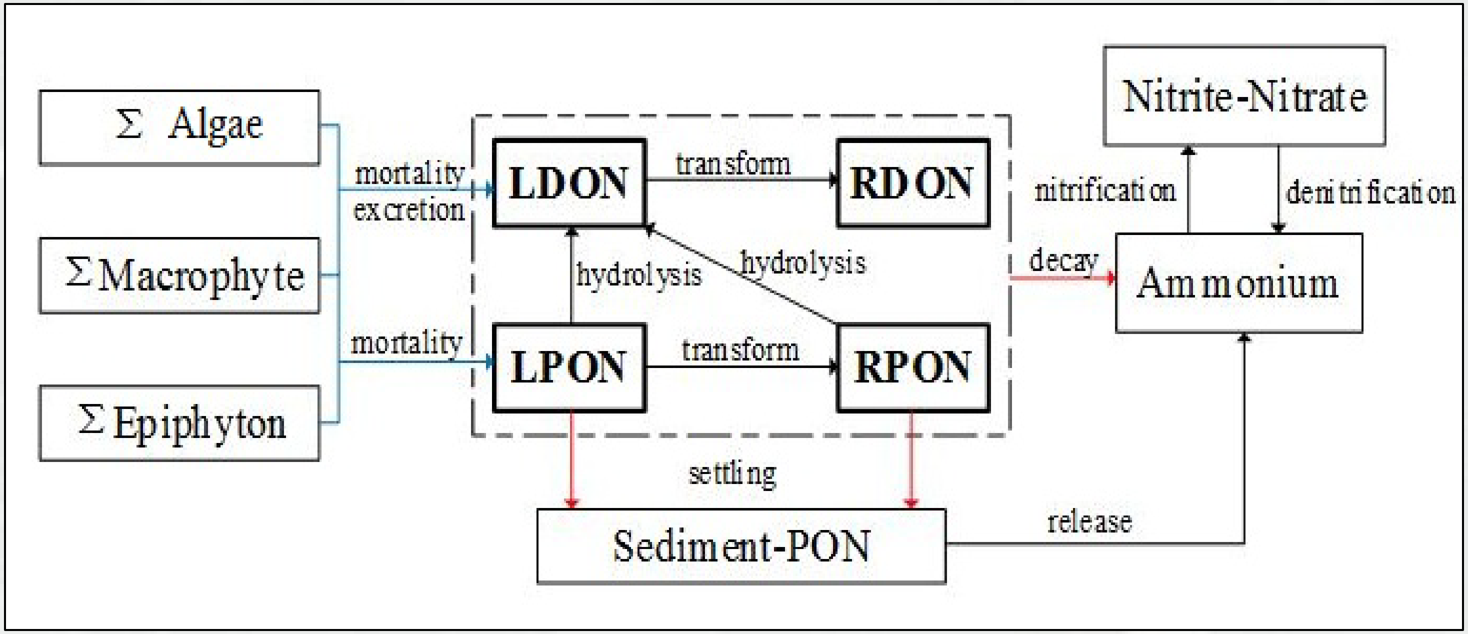
Carbon



CE-QUAL-W2 Design

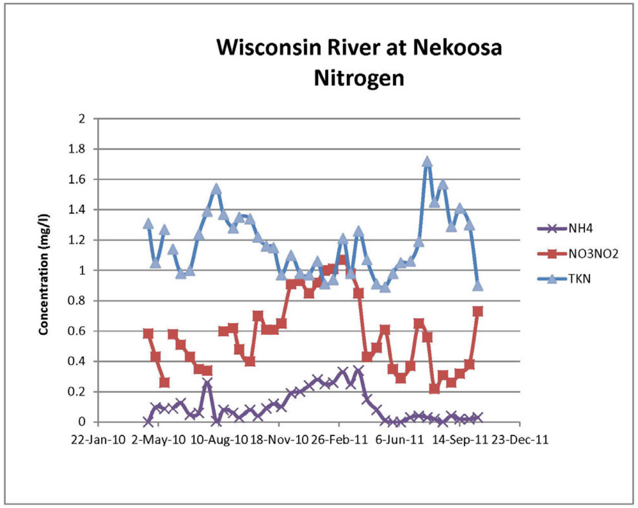
and

Nitrogen



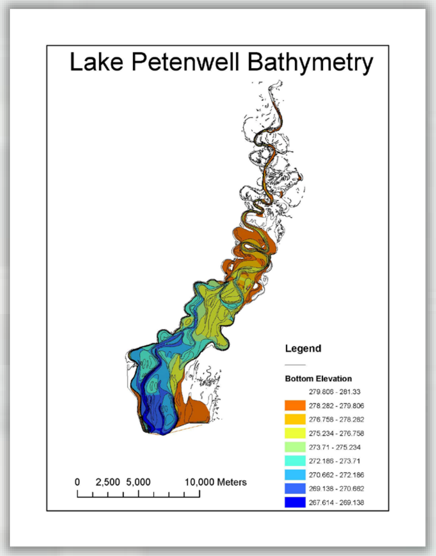
Input data for the model

- Bathymetry
- Initial conditions
- Boundary conditions
- Calibration data
- Hydraulic parameters
- Kinetic parameters



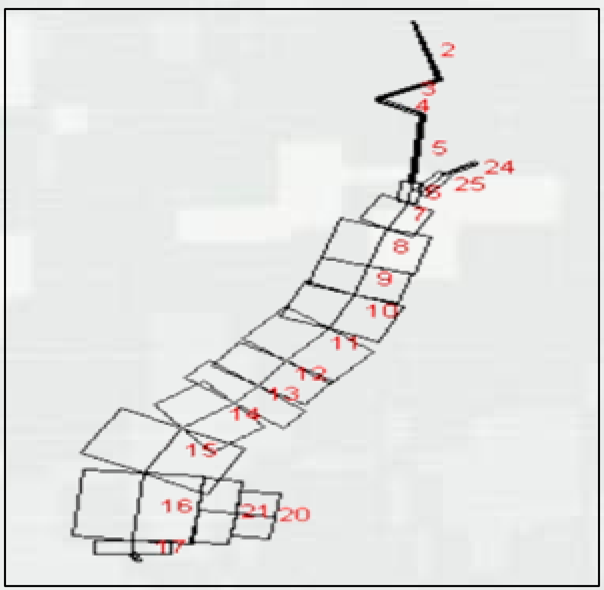
Bathymetry

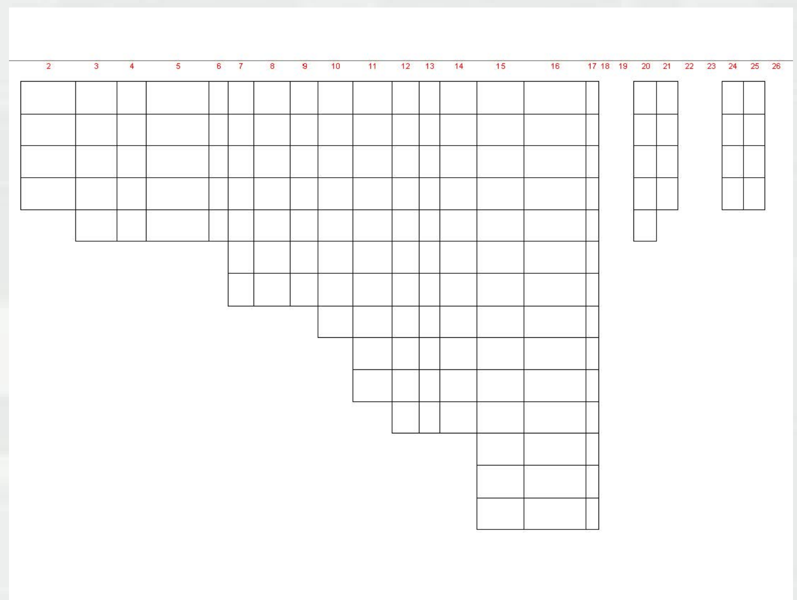
- Topographic GIS shapefile provided by Fishing Hot Spots, Inc.
- Transformed into a 10-meter grid and then into a Triangulated Irregular Network (TIN)



Bathymetry

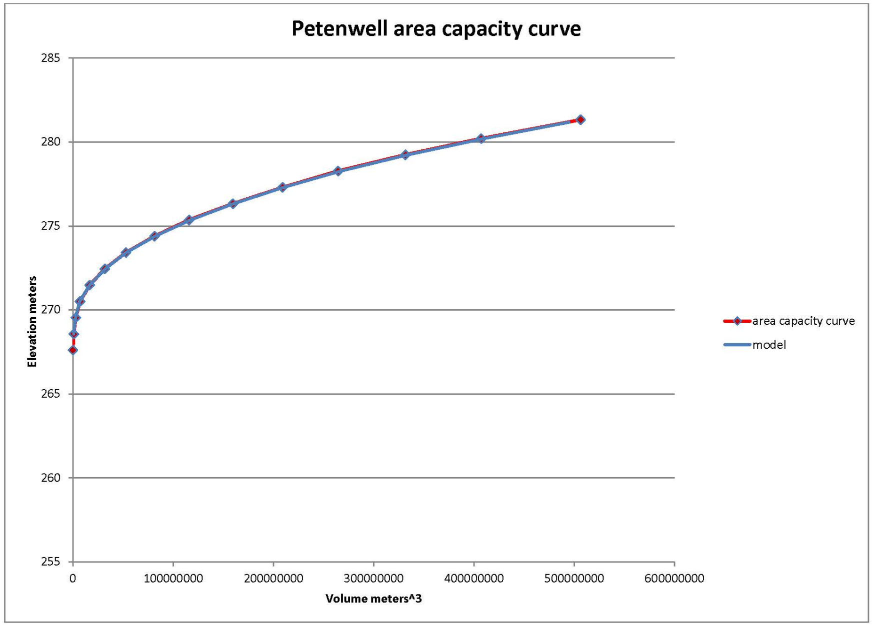
Divided into user-defined longitudinal segments and vertical layers using the Watershed Modeling System (WMS)



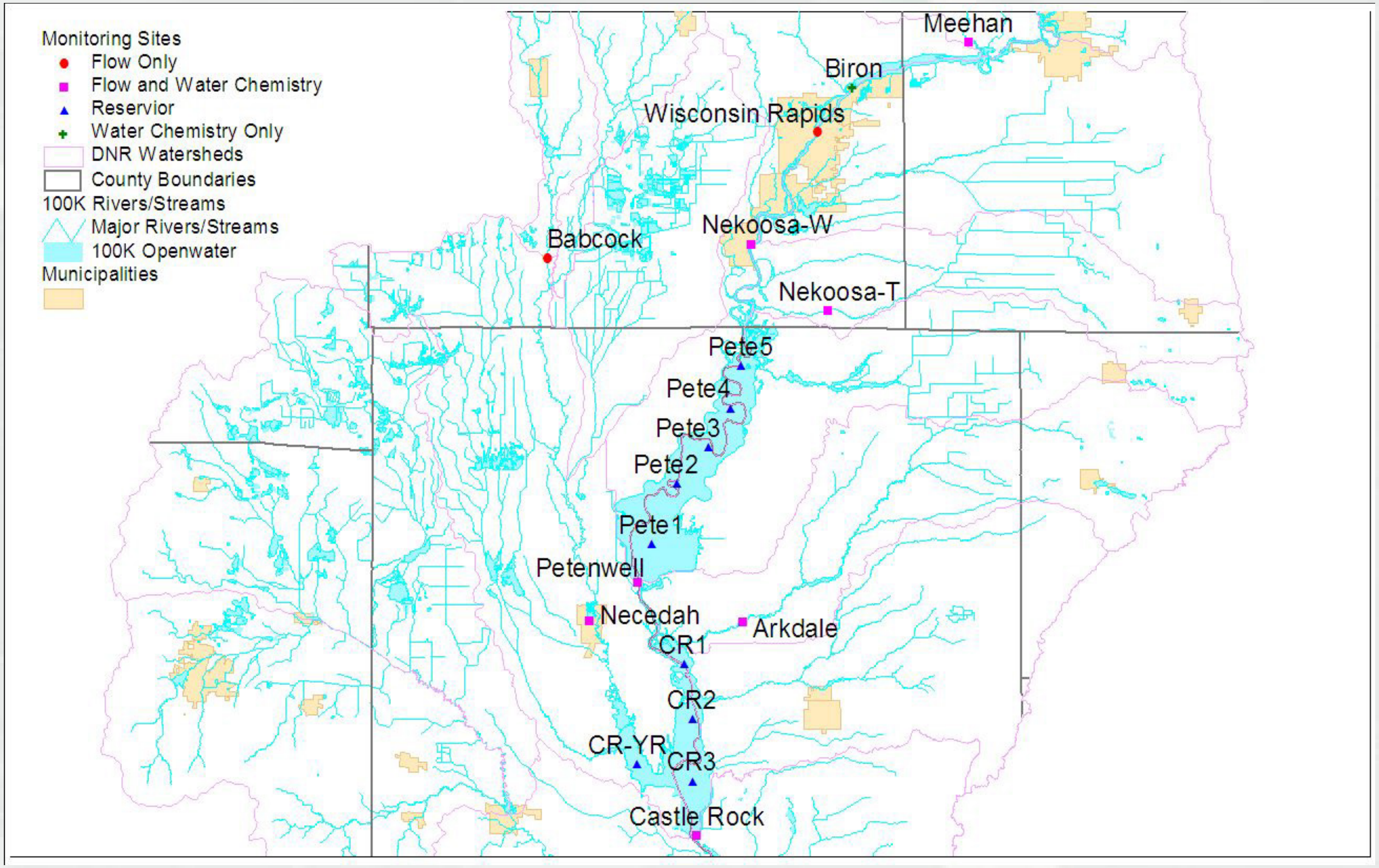


Bathymetry

- Checked by comparing the model and observed volume vs. depth curves
- bathymetry file is very important to hydrodynamic calibration



monitoring data

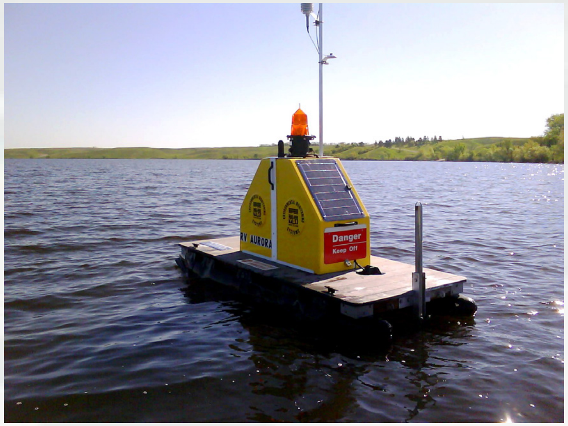


CE-QUAL-W2 monitoring data

Initial conditions and calibration data

Dam Sites	River	Flow Frequency	Semi-monthly parameters [1]	Purpose
Petenwell	Wisconsin	Hourly	TP, OP, Chl-a, TOC, DOC, TDS, TKN, NH3, NOx , Algal ID	Initial Stage and Flow/WQ Calibration
Castle Rock	Wisconsin	Hourly	TP, OP, Chl-a, TOC, DOC, TDS, TKN, NH3, NOx	Initial Stage and Flow/WQ Calibration

Reservoir	# Sites and Depths	Semi-monthly parameters	Purpose
Petenwell	(5 sites/3 depths)	TP, OP, Chl-a, TOC, TDS, TKN, NH_3, NO_x , Algal ID	WQ Calibration
Castle Rock	(4 sites/3 depths)	TP, OP, Chl-a, TOC, TDS, TKN, NH_3, NO_x , Algal ID	WQ Calibration



CE-QUAL-W2 monitoring data

Boundary conditions

Meteorological and water flow/quality

Site Name	River	Flow Frequency	USGS Station ID	Drainage Area (mi^2)	Semi-monthly parameters [1]	Purpose
Wisconsin Rapids	Wisconsin	15 min	05400760	5,420	TP, OP, Chl-a, TOC, TDS, TKN, NH3, NOx, TSS	Upstream boundary
Nekoosa-W	Wisconsin	Hourly	05400975	5,640	TP, OP, Chl-a, TOC, DOC, TDS, TKN, NH3, NOx, Algal ID	Upstream boundary
Nekoosa-T	Tenmile	15 min	05401050	73	TP, OP, TOC, DOC, TDS, TKN, NH_3, NO_x, TSS	Tributary boundary
Petenwell	Wisconsin	Hourly	05401400	5,970	TP, OP, Chl-a, TOC, DOC, TDS, TKN, NH3, NOx , Algal ID	Petenwell outflow
Necedah	Yellow	15 min	05403000	491	TP, OP, Chl-a, TOC, DOC, TDS, TKN, NH3, NOx, TSS	Tributary boundary
Arkdale	Big Roche a Cri	15 min	05401558	151	TP, OP, Chl-a, TOC, DOC, TDS, TS, TKN, NH3, NOx, TSS	Tributary boundary
Castle Rock	Wisconsin	Hourly	05403200	7,060	TP, OP, Chl-a, TOC, DOC, TDS, TKN, NH3, NOx	Castle Rock outflow

Hydraulic and Kinetic Coefficients

Can be obtained in four ways:

- Direct Measurement
- Estimation from Field Data
- Literature Values
- Model Calibration

Sediment Oxygen Demand and Ammonium and Nitrate Flux

Sampling stations and incubation conditions for sediment cores collected in Petenwell and Castle Rock Lakes. Numbers represent the replicates for each condition

Lake	Location	Sediment Oxygen Demand	Oxic Ammonium and Nitrate Flux	Anoxic Ammonium and Nitrate Flux
Petenwell	PL-2 Thalweg	2	2	2
	PL-4 Thalweg	2	2	2
Castle Rock	CRL-WI R. 1 ~20 ft. contour	2	2	2
	CRL-WI R. 3 ~ 10-15 ft. contour	2	2	2
	CRL-Yellow R. 4 ~10-15 ft. contour	2	2	2

Phosphorus Release from Sediments

Sampling stations and incubation conditions for sediment cores collected in Petenwell and Castle Rock Lakes. Numbers represent the replicates for each condition

Lake	Location	Anoxic	Condition	
			Oxic pH ~8	Oxic pH ~9
Petenwell	PL-2 Thalweg	3	3	
	PL-4 Thalweg	3	3	3
	PL-4 ~15 ft. contour		3	3
Castle Rock	CRL-WI R. 1 ~20 ft. contour	3	3	
	CRL-WI R. 3 ~ 10-15 ft. contour	3	3	3
	CRL-Yellow R. 4 ~10-15 ft. contour		3	3

Sensitivity Analysis

First Order Variance Analysis (FOVA) (Porter et al. 1999).

S_i is the index describing the sensitivity of the output result Y for input x_i. Thus, when x_i varies 1%, the output F will be changed S_i%. The equation is formed as:

$$S_i = \left[\frac{Y(x_{i0} + \Delta x_i) - Y(x_{i0})}{Y(x_{i0})}\right] / \left[\frac{\Delta x_i}{(x_{i0})}\right]$$

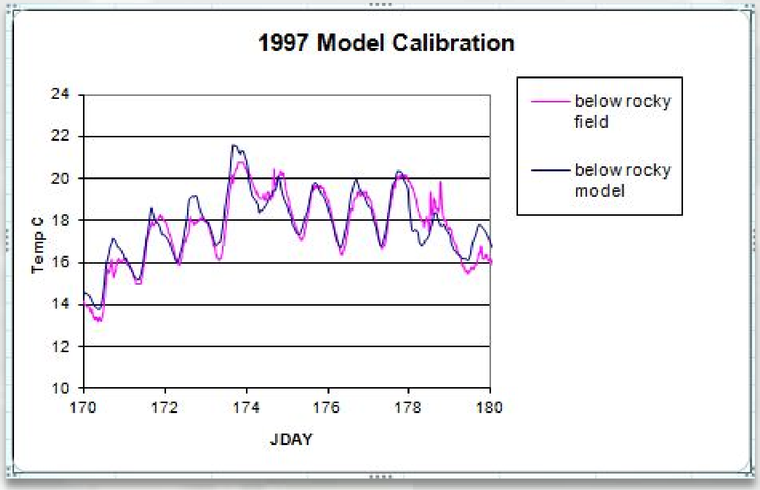
- Provide general assessment of model precision when used to assess system performance for alternative scenarios

- Detailed information addressing the relative significance of errors in various parameters

Calibration

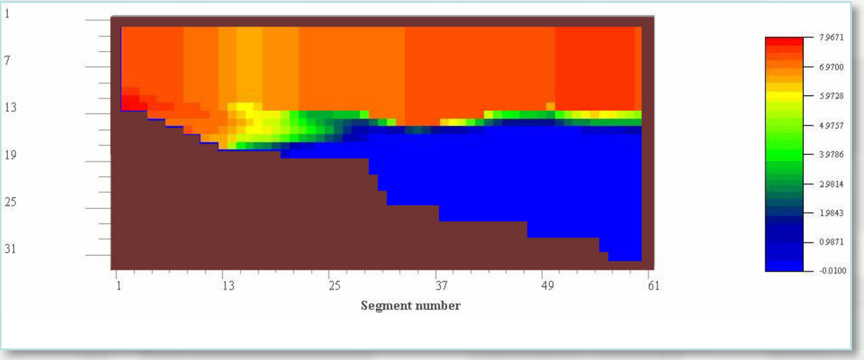
- Two evaluation criteria will be used

- The first criteria are visual comparisons of plots of modeled and observed values.
- The second evaluation criteria involved error statistics that quantitatively measured the agreement between modeled and observed values.
    - Coefficient of determination (R^2),
    - Nashe-Sutcliffe efficiency (NSE),
    - Percent error (PBIAS),
    - ratio of the root mean square error (RMSE) to observations standard deviation (RSR) are used as evaluators of model performance.



Validation

- The primary goal of model validation is to confirm that the W2 model can be used to simulate flow and water quality and be able to apply to other magnitudes.
- Calibration and validation of W2 will be based on a balanced, split-sample approach. Available historical data will be divided into two datasets: 2 years for calibration and 2 years for validation.



Summary

- CE-QUAL-W2 model for Petenwell and Castle Rock
  - 2-D Hydrodynamic and Water Quality Model
  - Robust, well vetted model. Great support from developers
  - 2009-2013 full data set
  - New input/output tool for SWAT and CE-QUAL-W2
  - Possible integration of full sediment digenesis sub-model (if needed)

Questions

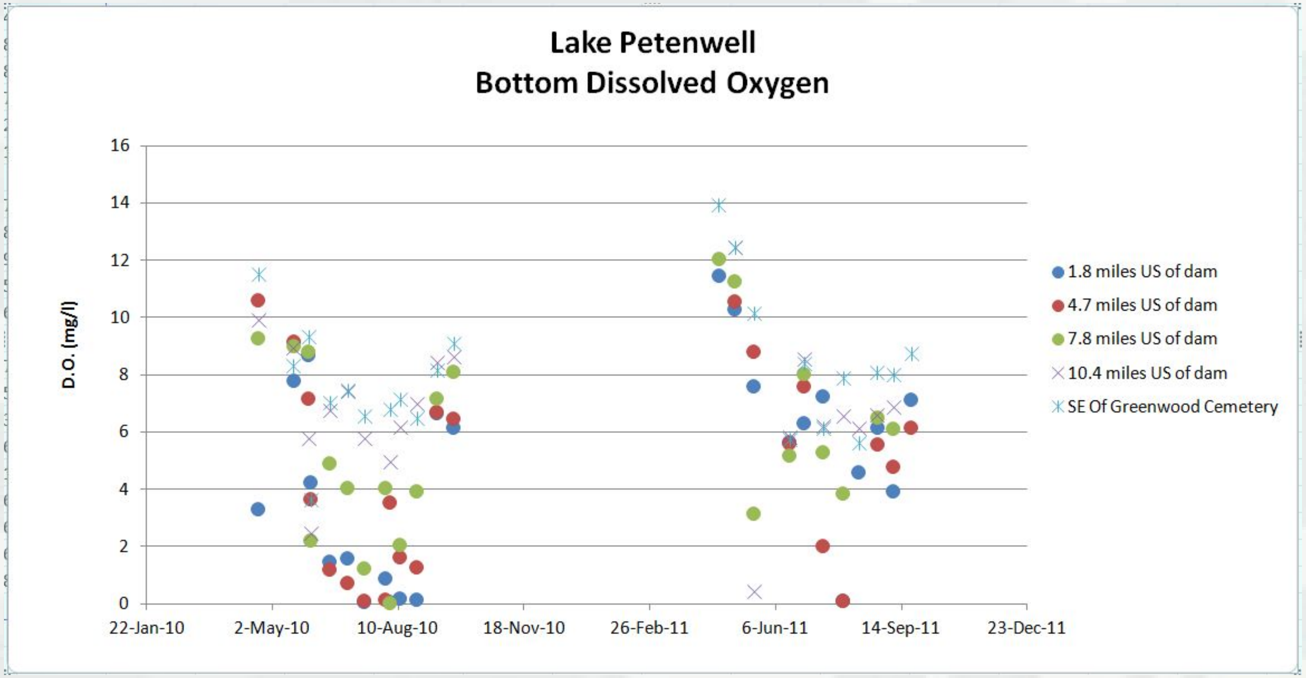
How will legacy phosphorus in the lake be accounted for in the model?

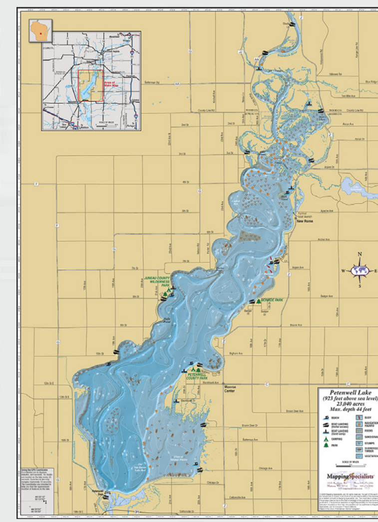
Modeling Approaches for Sediment Oxygen Demand

Process	Advantages	Disadvantages
Explicit modeling Zero Order Model	Simple, based on field data, accounts for both aerobic decay and anaerobic nutrient flux	Unclear how management strategies can change SOD, back calculation of SOD may be problematic
Explicit modeling First Order Model for aerobic layer	Simple, more predictive than zero order model, accounts for 1st order decay in aerobic layer	Must have mechanism for anaerobic flux of nutrients
Explicit modeling Sediment diagenesis modeling	Specification of the aerobic and anaerobic layer processes	Complex, very dependent on initial conditions, uncertainty in sediment diagenesis parameter values which are often expensive to obtain and are heterogeneous, can lead to longer simulation times
Statistical correlation models Relationships between Total P, chlorophyll a, and oxygen demand	Simple (KISS), good for a very big picture overview	Can be misapplied, often too simplistic to account for complexities of oxygen demand

Questions

Do you think the buffering effect of internal loading may result in a very long response time of lake water total phosphorus to reductions in external loads, as has occurred in other shallow eutrophic lakes (Sas, 1989).





Or, maybe once external loads are reduced, frequency of anoxic events will decline and thereby reducing internal loading of DRP? (Malecki, 2004)

Contact Info

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Questions

- CE-QUAL-W2

Will lake property landowner contributions be evaluated as a source?

- Provided in Presentation

How will legacy phosphorus in the lake be accounted for in the model?

- Large Group Discussion Topic

More detail on the ability of this model to look at the fate of phosphorus and its availability to biota

- Provided in Presentation

Not convinced the legacy phosphorus re-suspension will be accurately addressed

- Large Group Discussion Topic

What affects SOD?

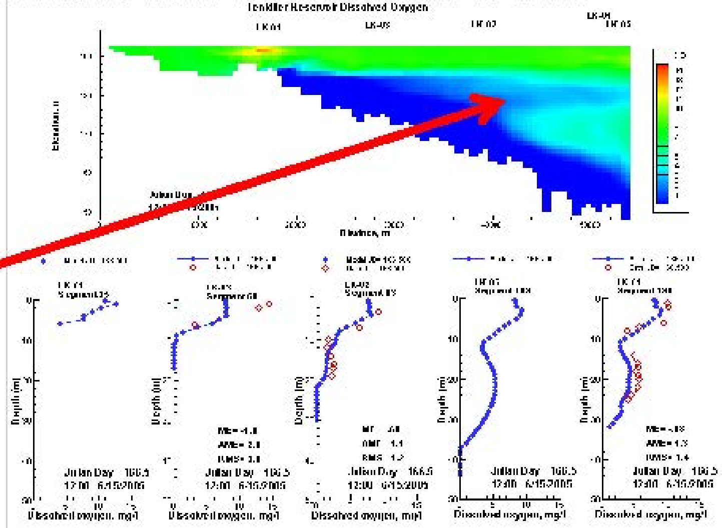
- Temperature dependence on O_2 uptake
- Accumulating organics (creating both a carbonaceous and nitrogenous oxygen demand) → more organics, more SOD; data and theory show this is not a linear relationship. Note that some relate SOD to Total P. Why?
- Oxygen – as dissolved oxygen approaches zero, SOD→0

Data Needs of SOD Models

Model	Initial conditions required?	Required model parameters	Comments
Zero Order	None	Zero order decay rate, anaerobic C:N:P release rates as a f(SOD); O_2 level in overlying water; temperature	Note that the anaerobic release rates are multiplied by the SOD
First Order	Initial organic matter in sediments and C:N:P content	First order decay rate, sloughing rates, and flux rates of C, N, P; O_2 level in overlying water; temperature; burial rate	Note this only applies to aerobic decay
Sediment Diagenesis	Initial organic matter in sediments and C:N:P:S:Si content	Flux rates of C, N, P to the sediments, SO4, NH4, NO3, PO4, and O2 levels in overlying water; temperature; Nitrification, denitrification rates for aerobic and anaerobic layers, methane oxidation rate, sulfide oxidation rate rates; burial rates; mineralization rates for POC, PON, POP; Henry's Law constants for CH4, NH3, H2S, CO2; fractions of labile, refractory and inert organic matter fractions; pore water diffusion rate; particle mixing rate,…	There can be many more parameters if one tries to model bubble formation.

How to Determine SOD?

- From field data or calibration of a dissolved oxygen model to field data
  - Issue: Assumes we know all other DO processes correctly. Stratified systems can make this a tad easier though….



Side point: What is cause of metalimnetic DO minimum?

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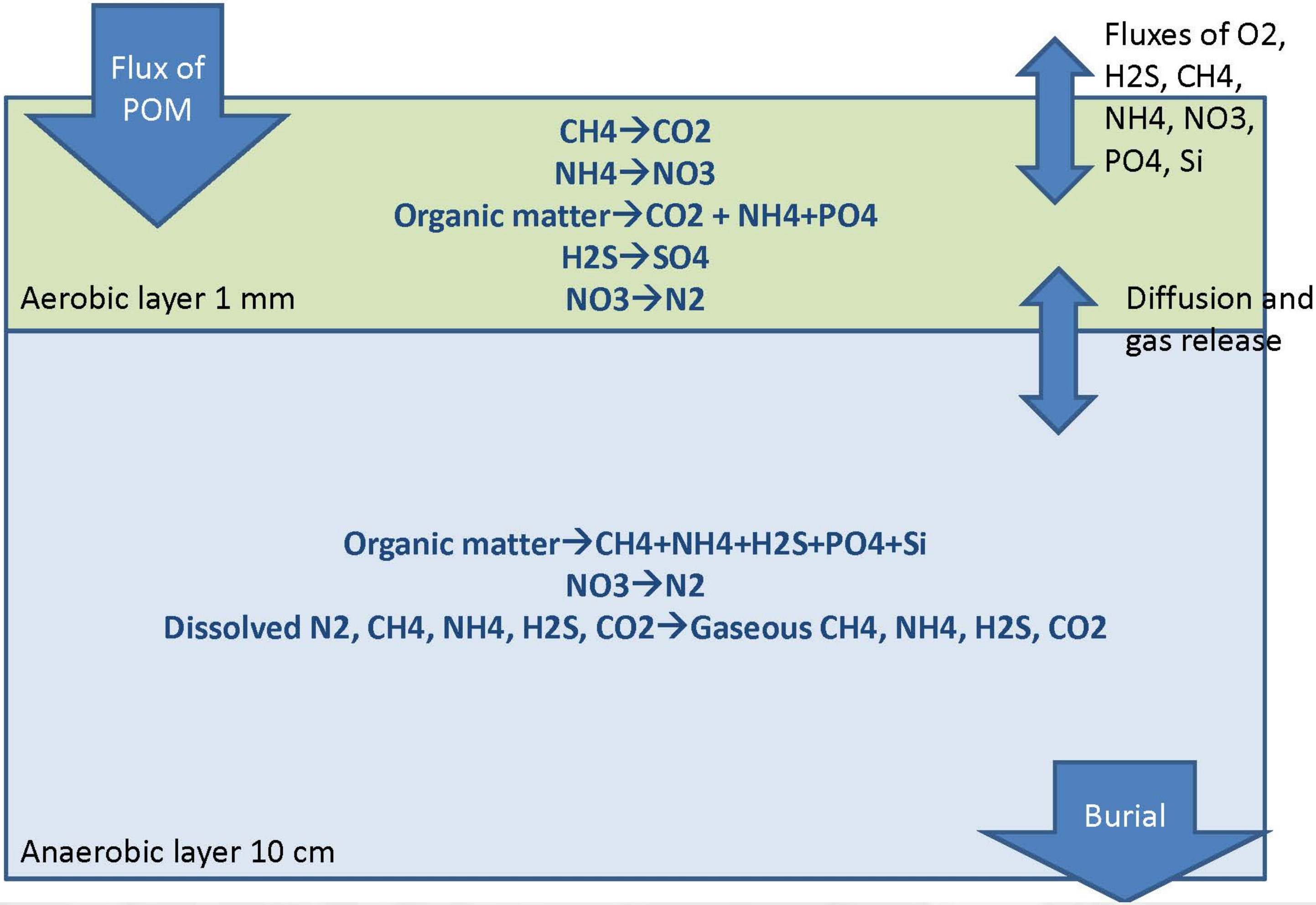
What is happening in the sediments?

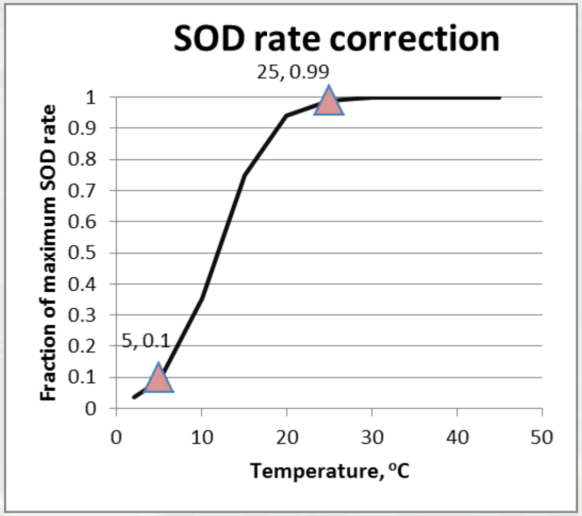


W2 Zero Order SOD Approach

SOD rate is specified as

$$SOD = k_{SOD}$$

where k_{SOD} is a zero order decay coefficient [M/L2/T] that is only adjusted by temperature.



The zero order approach is simple, based on field data, accounts for both aerobic decay and anaerobic nutrient flux.

•*The zero order rates of SOD are often obtained through direct measurement.*

•*Cost and spatial heterogeneity is problematic*

W2 First Order Sediment Approach

Apply first order decay model to organic sediment decay under aerobic conditions:

$$\frac{dC_{sed}}{dt} = -kC_{sed} + r_{sed}$$

where k is a first order decay coefficient [1/T] that also accounts for temperature effects and C_{sed} is the organic matter concentration in the aerobic layer and r_{sed} is the source sink term [M/L3/T].

Then SOD rate is

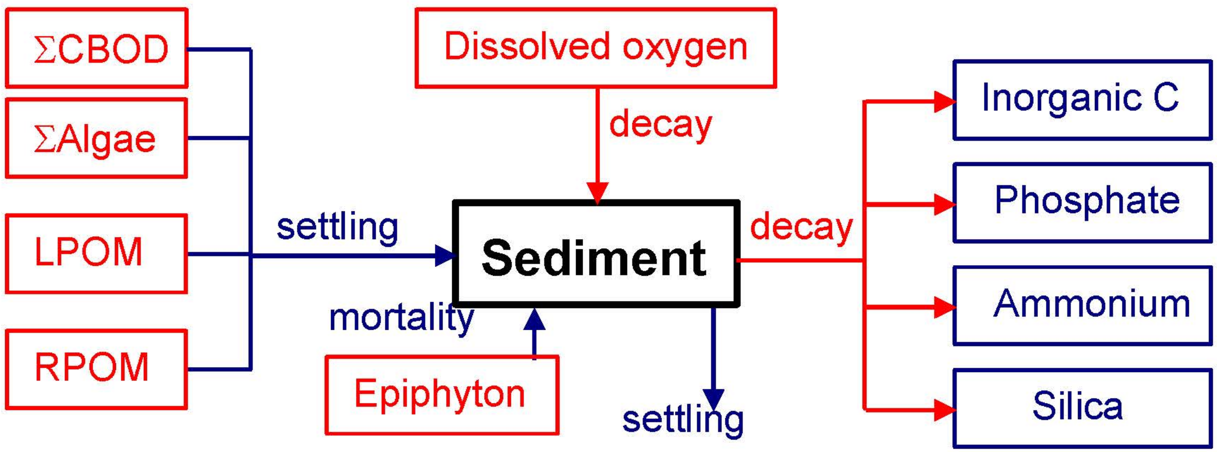
$$SOD = \frac{dC_{sed}}{dt}\frac{Volume}{Area}r_{oc}$$

where Area is the surface area of the model segment in contact with the bottom, Volume is the volume of that model segment,

and r_{oc} is the stoichiometric coefficient between oxygen and organic matter (approximately 1.4 gO_2/g organic matter)

The first-order rate approach is simple, more predictive than zero order rate, accounts for 1st order decay in aerobic layer.

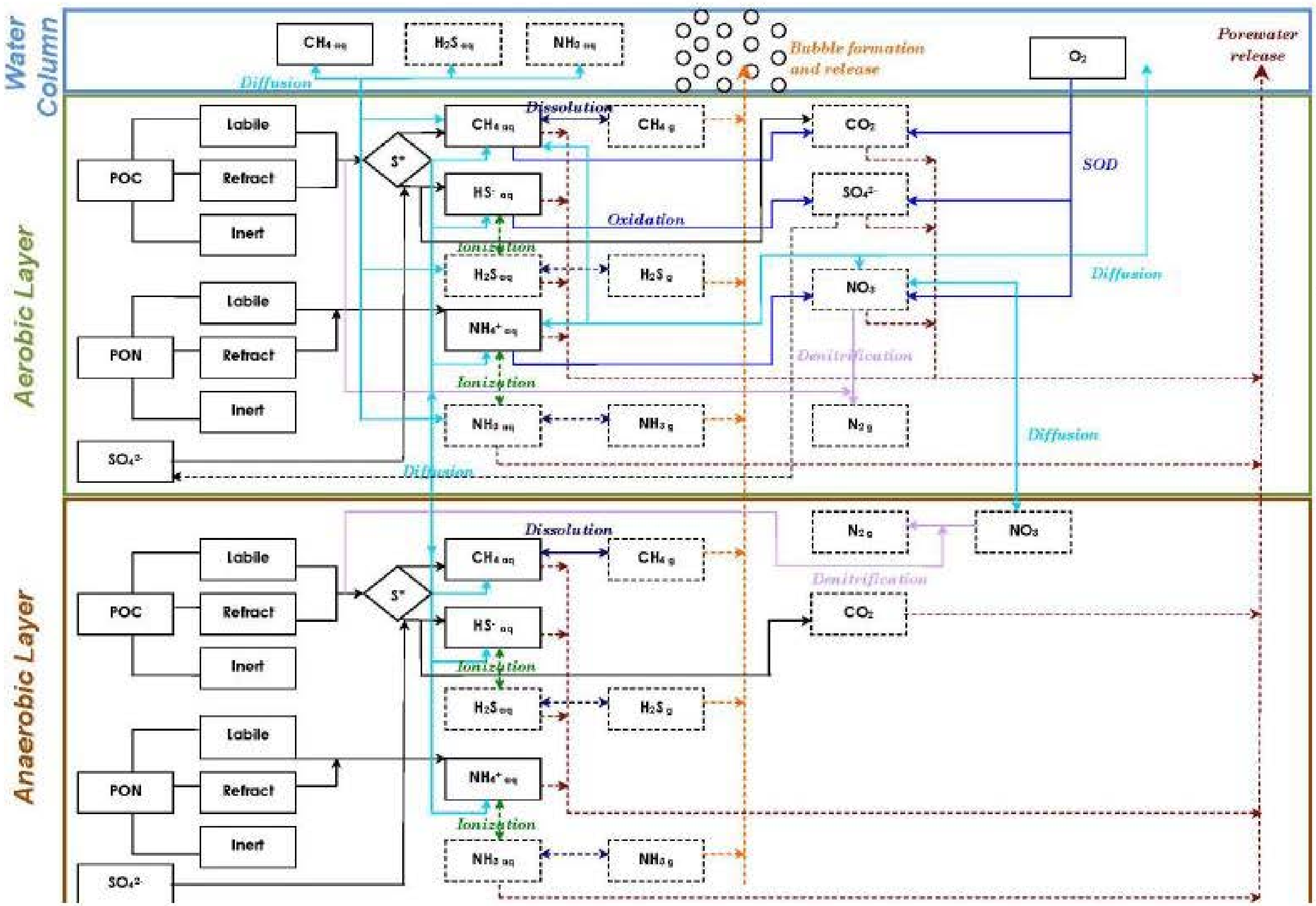
Aerobic Layer First Order Sediment Model



$$r_{sed} = \underbrace{\frac{\omega_{POMR} A_{bottom}}{Vol_{cell}} \Phi_{POMR}}_{\text{POMR sedimentation}} + \underbrace{\frac{\omega_{POML} A_{bottom}}{Vol_{cell}} \Phi_{POML}}_{\text{POML sedimentation}} + \sum \underbrace{\frac{\omega_{a} A_{bottom}}{Vol_{cell}} \Phi_{a}}_{\text{algae sedimentation}} - \underbrace{\gamma_{om} K_{s} \Phi_{s}}_{\text{sediment decay}} + \underbrace{K_{epom} K_{eb} \Phi_{e}}_{\text{epiphyton burial}} - \underbrace{\frac{\omega_{SED} A_{bottom}}{Vol_{cell}} \Phi_{s}}_{\text{sediment sedimentation}} + \underbrace{\frac{\omega_{CBOD} A_{bottom}}{Vol_{cell}} \Phi_{CBOD}}_{\text{CBOD sedimentation}}$$

CE-QUAL-W2

Sediment Diagenesis Model



DEFINITIONS:

POC: Particulate organic carbon
PON: Particulate organic nitrogen
Refract: Refractory
SOD: Sediment oxygen demand
aq: aqueous
g: gaseous

S. Prakash, J.A. Vandenberg, and E. Buchak (2011)

Sediment Diagenesis Model

Sediment diagenesis modeling capability has been incorporated into CE-QUAL-ICM, HEC-RAS/NSM, QUAL2K and WASP models. However, W2 presently describes rather than predicts SOD and sediment nutrient releases. The use of a zero order rate, or first-order rate in W2 water quality model applications has a major limitation. That is it does not provide for a mechanistic link between sediment organic matter and its conversion into oxygen demand and nutrient release. In the absence of this missing link, one of two alternative approaches have commonly been employed. The first, and most commonly used approach has been to assume the rates of SOD and nutrient release are unchanged following waste load reductions, or implementation of other water quality management alternatives. Clearly, this should not be the case in that reduction in loads of organic matter to a water body should impact organic loads to sediments and the resulting SOD and nutrient release.

The preferable approach would be the utilization of mechanistic models that provide a link between the influxes of organic materials to sediments, physical, biological and chemical processes occurring within the sediments, and consequent SOD and nutrient release.

Why? Organic matter decay in sediments:

CH_2O --> CO_2 + CH_4

Then the CH_4 is oxidized creating an SOD; CH_4 + O_2 --> CO_2 + H_2O.

But other processes occur which mitigate this:

- Use of CH_4 in denitrification in aerobic layer. Some of the nitrified NO_3 is denitrified using CH_4. [Mitigating factor]
- Release of bubbles of CH_4 as organic loading increases (loss of organic C which does not exert an SOD)

W2 benthic sediment diagenesis modeling framework (version 3.9)

The benthic sediment diagenesis module is based upon the framework developed by Di Toro (2001) and consists of three basic processes: 1) Deposition of particulate organic matter (POC, PON, POP) from the water column directly to the second bed sediment layer due to the negligible thickness of the upper layer; 2) Diagenesis of the particulate organic matter within the second bed sediment layer; 3) Transfers of the reaction products produced by diagenesis to the upper sediment layer, to the water column, and to deep, inactive sediments.

This model calculates SOD and nutrient release as functions of the downward flux of carbon, nitrogen, and phosphorus from the water column. The sediment diagenesis model has been verified against a wide-range of nutrient conditions using an extensive nutrient flux data set obtained in Chesapeake Bay and MERL mesocosms from the University of Rhode Island. The model successfully reproduced the observed sediment nutrient composition and nutrient flux data using essentially the same parameter set as was used for Chesapeake Bay. This approach, well founded in sediment diagenetic theory and supported by field and laboratory measurements, was an important advancement in the field of sediment-water interactions.