Challenges and Advances in Complex Nutrient TMDL Modeling

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LimnoTech
Water Environment | Scientists Engineers
Tufts UNIVERSITY
WERF
Water Environment Research Foundation
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Outline

- WERF Project
  - *"Modeling Guidance for Developing Site-specific Nutrient Goals"*
  - Developed Nutrient Modeling Toolbox
- Need and Value of Load-Response Models
  - Regulatory value
  - Quantifying connection between nutrient loads and water quality and ecological response indicators of beneficial uses
- Case Studies Demonstrate importance of Data-Model Compatibility
  - Massachusetts Estuary Program for TMDLs
  - Truckee River, NV, DO modeling
  - Yellowstone River, MT, NNC

Rationale for WERF Project

- Nutrient pollution is a serious concern
  - More than 10,000 water bodies impaired nationally
- EPA calling for Numeric Nutrient Criteria
  - EPA Guidance exists for only two of the three recommended approaches
    - Reference condition approach
    - Empirical stressor-response analysis
  - WERF wanted to provide guidance for the 3rd EPA approach: process-based (mechanistic) modeling
    - Describe systems using process-based load-response models, calibrated to site-specific data

Rationale: Relationships between Nutrients and Responses Are Complicated

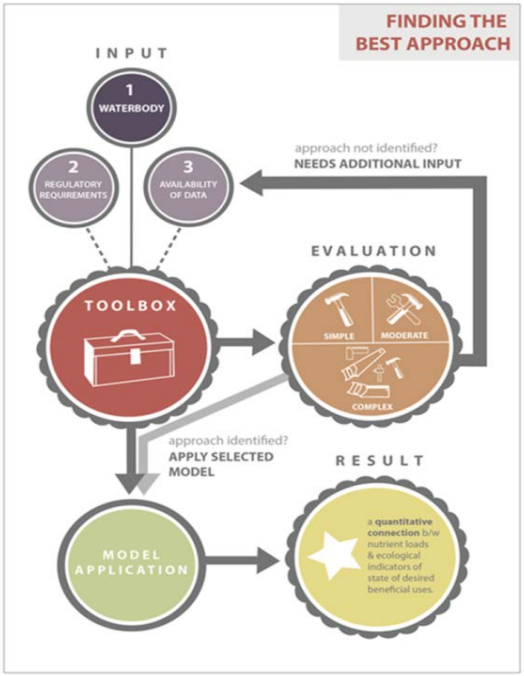
- Responses of aquatic plants to nutrient loads are highly dependent on site-specific factors
  - Hydrology, spatial-temporal variability, temperature, water clarity, shading, habitat
- Multiple potential response indicators
  - Hypoxia, harmful algal blooms, biotic indices, aesthetics
- Many response indicators require consideration of multiple trophic levels
  - Nutrients → aquatic plants → fish productivity

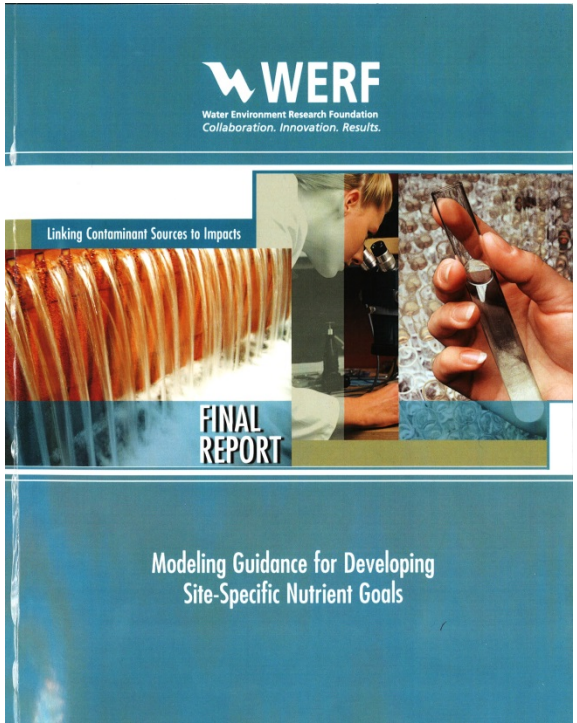
Rationale: Guidance Is Needed on More Rigorous Site-Specific Approaches

- NNC – original impetus for the project
  - Guidance on deriving NNC using site-specific load-response models
  - Guidance on reviewing/assessing/refining NNC derived using reference and/or empirical stressor-response approaches
- TMDLs, NPDES permits, Use Attainability
  - Guidance on developing quantitative linkages between nutrient loads and water quality/ecological response indicators
- **This WERF project is designed to fill these gaps in available guidance**

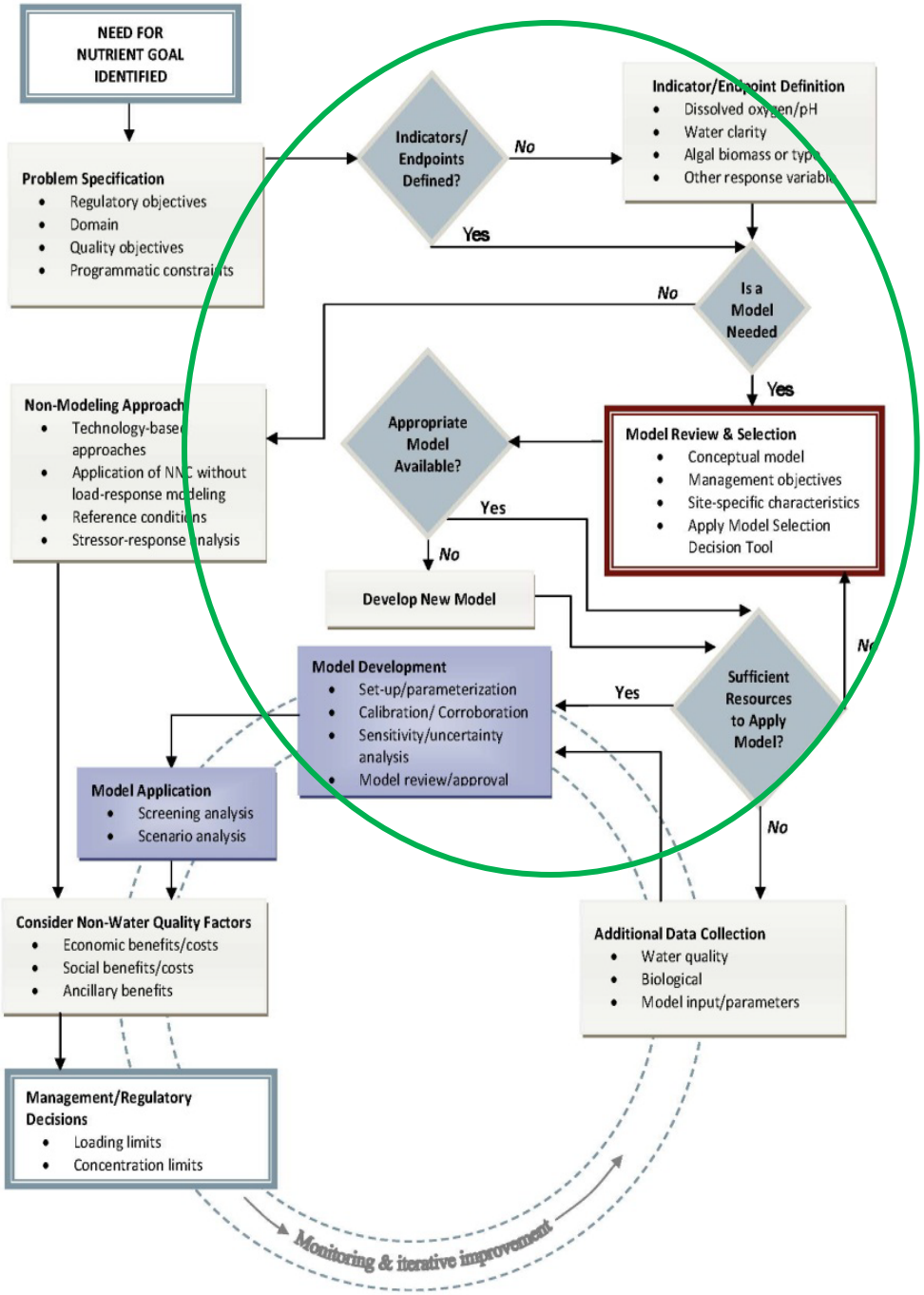
Project Objectives

- Build a Nutrient Modeling Toolbox (Toolbox) identifying models that can quantitatively link nutrient loads to water quality and ecological response indicators on a site-specific basis
- Provide nutrient modeling guidance (including selection, development, and application of models in the Toolbox) in the form of a project report





Overall Process for Setting Site-specific Nutrient Goals



Concept of Load – Response Models for Setting Nutrient Goals

Point and Nonpoint Source Loads

Other Factors

- Solar radiation
- Temperature
- Wind
- Invasive species
- contaminants

Nutrient Loads

Solids Loads

Hydrologic Inputs

Either measure or use a Watershed Model

Water Body

(physical, chemical, biological processes operate on loads)

Water Quality and Ecological Responses

Nutrient concentrations

Algal biomass and species distributions

Dissolved Oxygen

Water clarity

Taste and odor

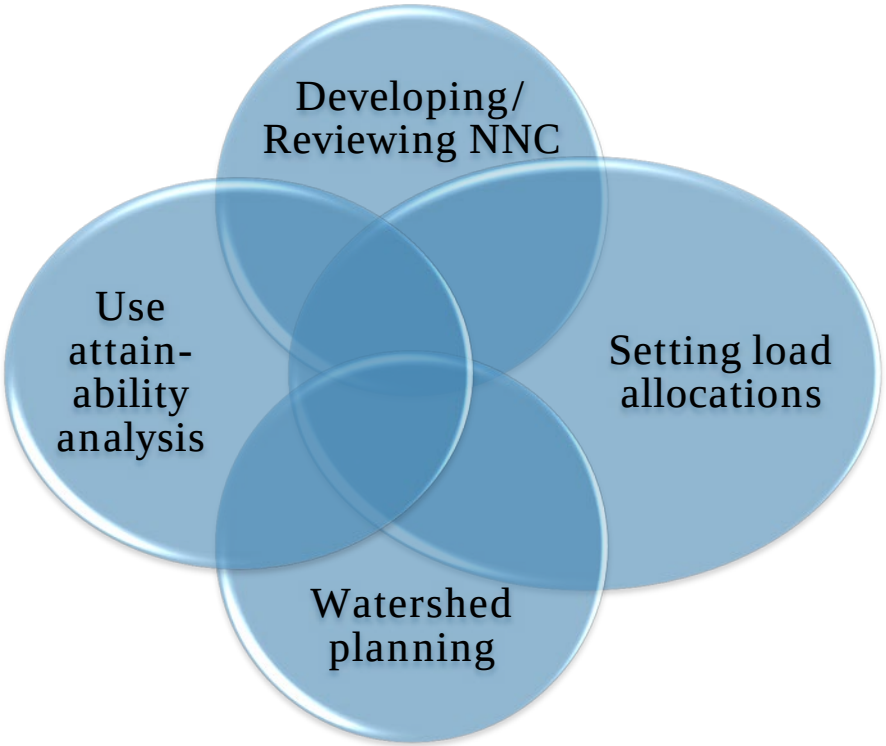
Benthic algae

Fish and benthic invertebrate communities

Supports the EPA guiding principles (September 12, 2013) for developing NNC that integrate causal and response parameters ("Bioconfirmation")

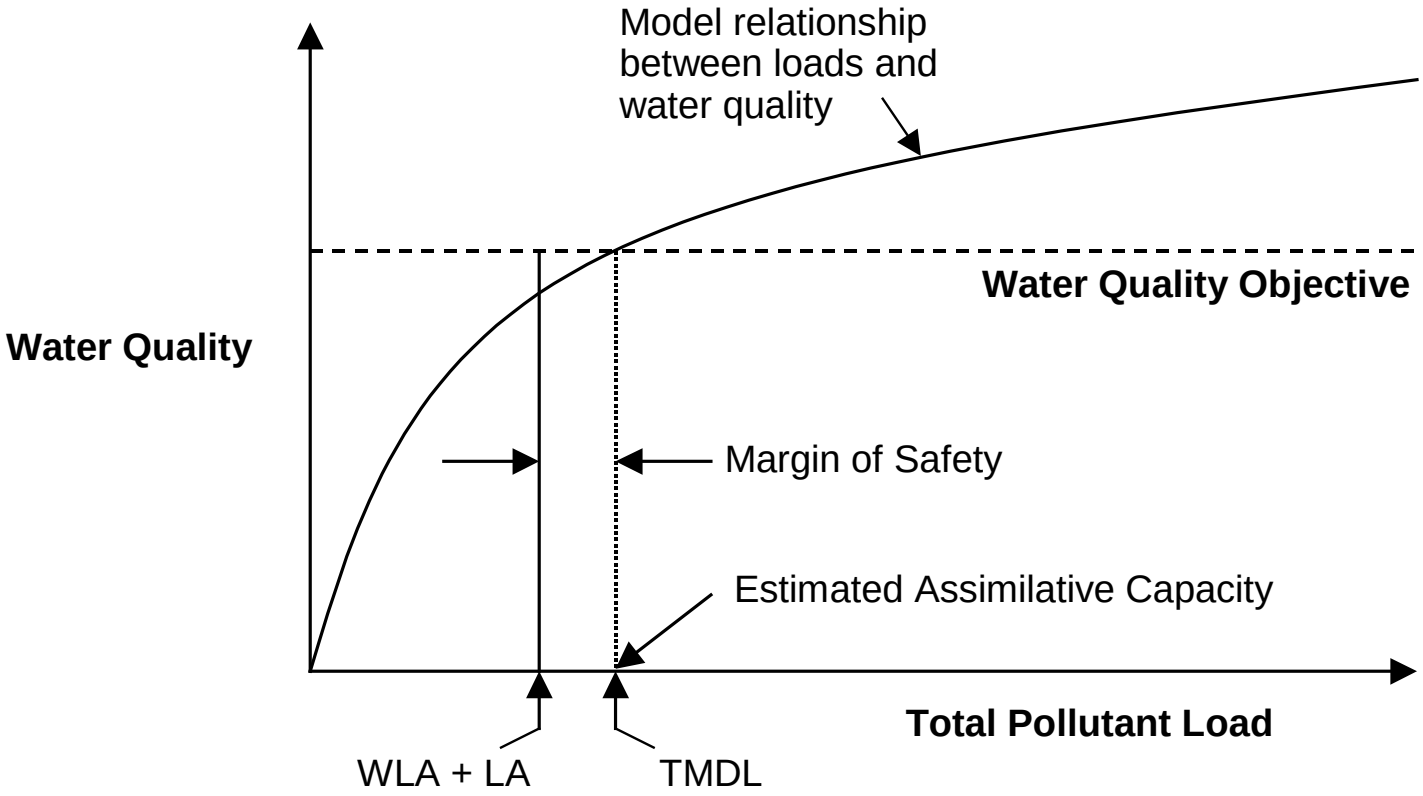
Desired Regulatory Outcomes

- Accuracy
- Defensibility
- Understanding of attainability
- Transparency



Load-response modeling approaches support these goals

Nutrient Load-Response Modeling for TMDL Process



Project Components

- Identification of water quality and biological response indicators
- Criteria for and selection of models to be included in the **Nutrient Modeling Toolbox**
- Develop guidance for selection of appropriate models from Toolbox **(Model Selection Decision Tool (MSDT)**)
- Provide guidance and example case studies for development and application of Toolbox models
- Identify and prioritize needs for nutrient load – response model improvement

Summary of Indicators Currently Used

Indicators Used by States	Rivers and Streams	Lakes and Reservoirs	Estuaries	Indicator in Toolbox?
Dissolved Oxygen	●	●	●	DO
Chlorophyll a	◒	◒	◒	Phytoplankton – total
Clarity	◔	◒	◔	Clarity
Alkalinity	○	○	○	
pH	◒	◒	◒	pH
Taste & Odor	○	○	○	
Composite Indices: Water Quality	○	○	○	
Macrophyte Density	○	◔	◔	Submerged aquatic vegetation
Periphyton Abundance, Community Structure, or Filament Length	◔	○	○	Attached algae-total
Fish Community Structure	◔	○	○	Fish
Benthic Macroinvertebrate Community Structure	◒	○	◔	Macroinvertebrates
Harmful Algal Blooms and Toxins	◔	◔	◔	
Algal Species	○	○	◔	Phytoplankton-groups
Fish Kills	◔	◔	◔	
Fungi or Filamentous Bacteria	○	○	○	

● = used by essentially all states
◒ = used by most states
◔ = common, but used by less than half of all states
○ = rare

Nutrient Modeling Toolbox

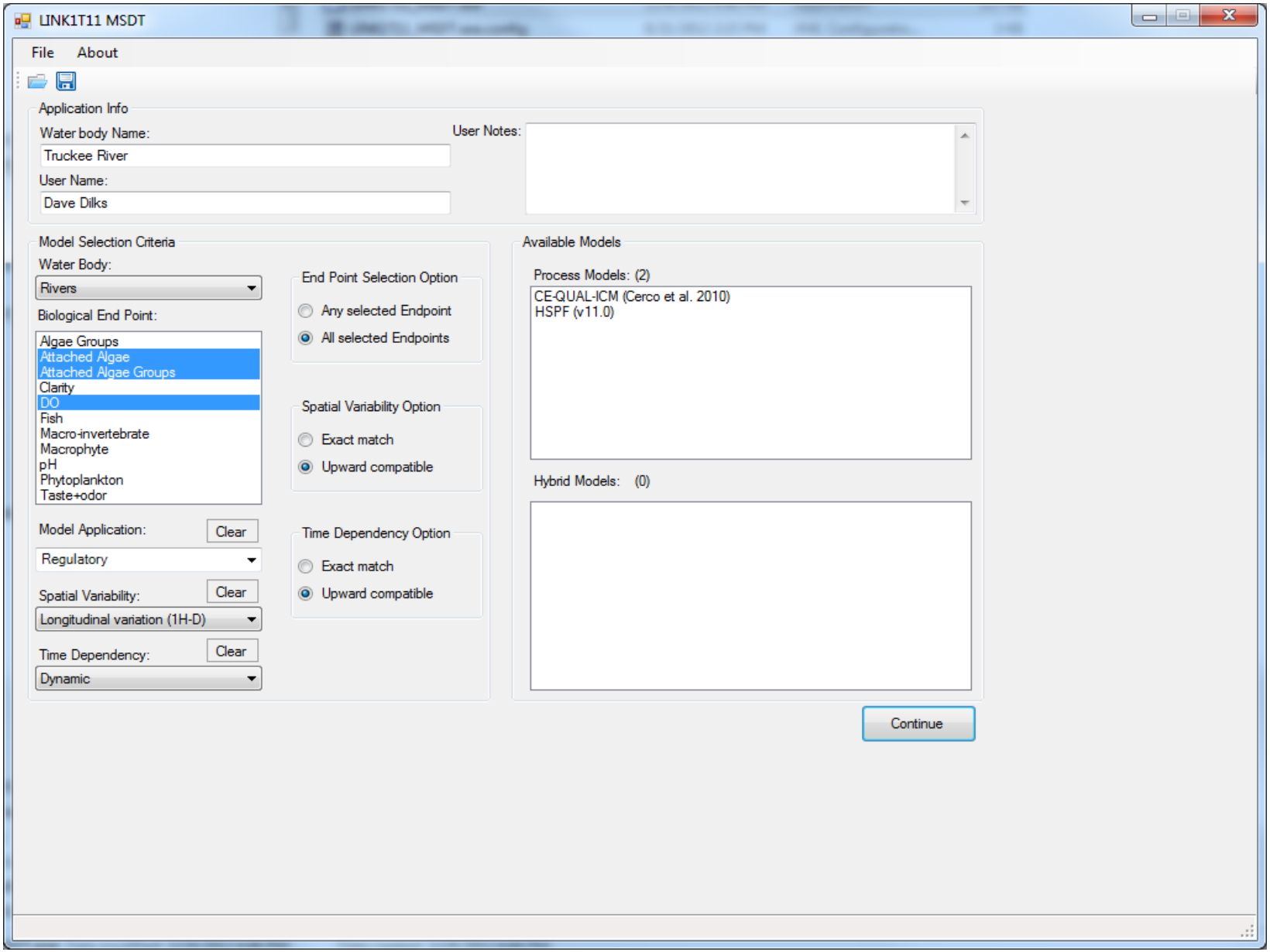
- Contains 30 models
  - 25 process-based models
  - 5 empirical load-response models or stressor-response relationships
    - Limited to those developed from datasets spanning many sites at a national or global scale
- Key characteristics of Toolbox models
  - Must be able to predict a receiving water body's response to nutrient loads
  - Freely available (completely in public domain or distributed without cost, and at least nominally supported through model user guides and manuals)

Model Review and Selection (MSDT)

Need to consider:

- Response indicators
- Site-specific characteristics
- Management objectives
  - Establish site-specific numeric nutrient criteria
    - Quantitatively connecting loads to ecological response indicators and evaluating the nutrient conditions that are present
    - Without consideration of site-specific nutrient loads.
  - Nutrient load management for screening, planning or regulatory (e.g., TMDL) intent

Demonstration of Model Selection Decision Tool



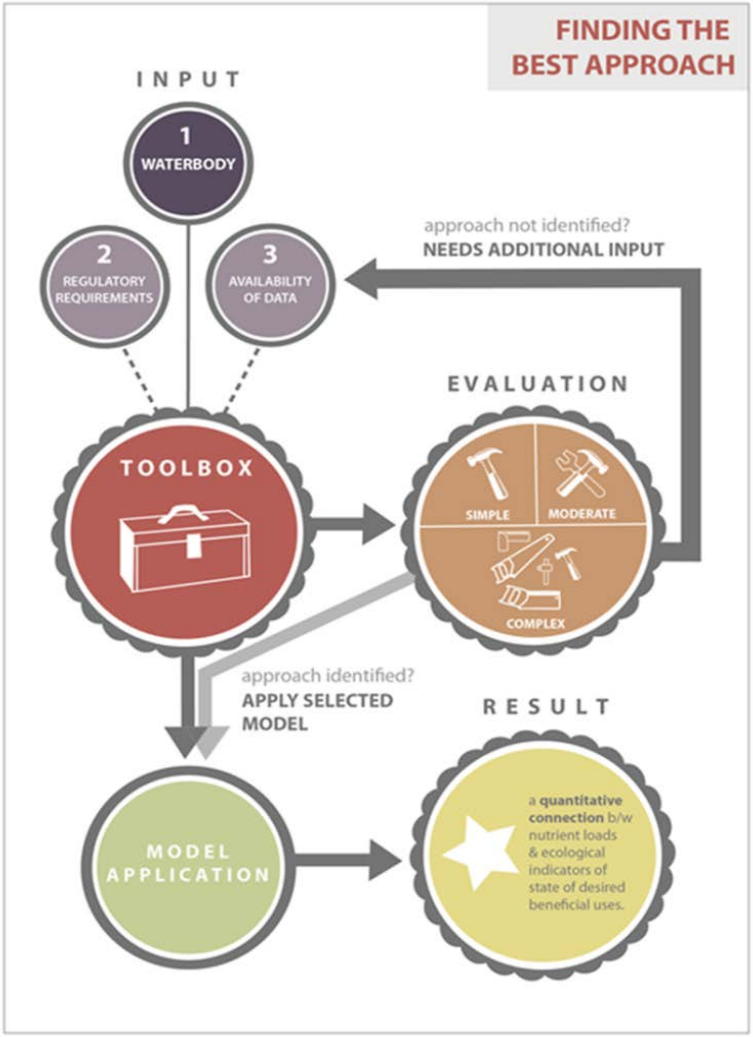
Fact Sheet Example

QUAL2K Fact Sheet

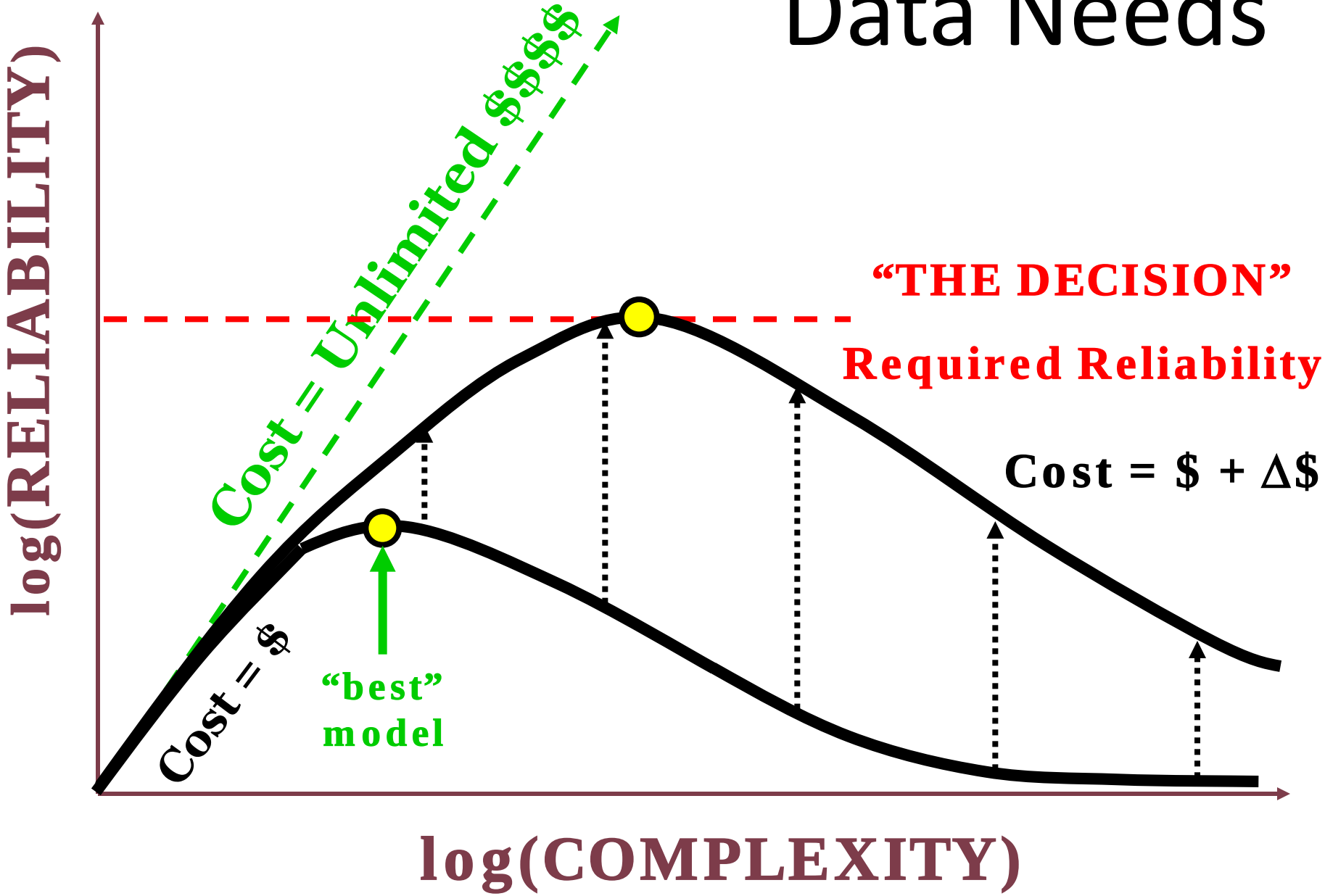
Name and Acronym:	QUAL2K / Q2K - A Modeling Framework for Simulating River and Stream Water Quality
Brief Description of Model and Other Notes:	QUAL2K (or Q2K) is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E (or Q2E) model (Brown and Barnwell 1987). It employs steady, non-uniform hydraulics and simulates diel variations of oxygen, nutrients, pH, phytoplankton and bottom plant biomass.
Developed by:	Steven C. Chapra, Gregory J. Pelletier and Hua Tao, Tufts University
Current Version:	2.11b8 (January 2009)
Distributed by:	U.S. EPA Watershed & Water Quality Technical Support Center (WWQTSC) http://www.epa.gov/athens/wwqtsc/html/qual2k.html
Contact Info:	Tim Wool, Watershed and Water Quality Modeling Technical Support Center (404)562-9260 wool.tim@epa.gov
Model Availability:	☒ Public Domain w/ Source ☐ Public Domain w/o Source
Waterbody Type	☒ Wadeable stream ☒ River ☐ Lake ☐ Estuary
Physical Dimensions	1-D (longitudinal)
Temporal Variability	Steady-state (diel variability)
State Variables (response variables shown in bold)	State Variables: **Dissolved oxygen, phytoplankton biomass, bottom algae biomass**, temperature, conductivity, inorganic suspended solids, , CBOD (slow, fast reacting), organic nitrogen, ammonia nitrogen, organic phosphorus, inorganic phosphorus, phytoplankton nitrogen, phytoplankton phosphorus, detritus, pathogen, alkalinity, total inorganic carbon, bottom algae nitrogen, bottom algae phosphorus. Other Response Variables: **pH**, sediment flux (SOD, ammonia, inorganic phosphorus, methane).
Input Data Needs:	• Stream geometry characterizing steady-state hydraulic conditions. • Steady-state inputs at receiving water boundaries and other locations (e.g., point and non-point sources) o Flow o Concentration of all state variables • Heat sources/sinks (including sediment bed) • Meteorological conditions o solar radiation o wind • Kinetic coefficients for the following processes o Plant photosynthesis and respiration o Nitrification, denitrification o Fast and slow CBOD decay rates o Algal stoichiometry o Detritial dissolution and settling o Hydrolysis o Reaeration coefficient (or formulation type) o Prescribed sediment fluxes (if not simulated) • Observed data on state variables for model calibration
Estimated Model Resource Need (Data, Level of Effort)	• Minimum of two synoptic sampling events during conditions reasonably approximating steady state. • Weeks to months of time for input preparation and calibration.

Toolbox in Context: Model Selection

- Model selection will depend on many factors
  - Management objectives, data, programmatic considerations, resources, schedule
- Some subjective evaluation of models may still be necessary
- More than one model may be appropriate for a given situation
- Or Desired tool for specific application may not exist
- Model selection is not totally objective and modeling experience is important

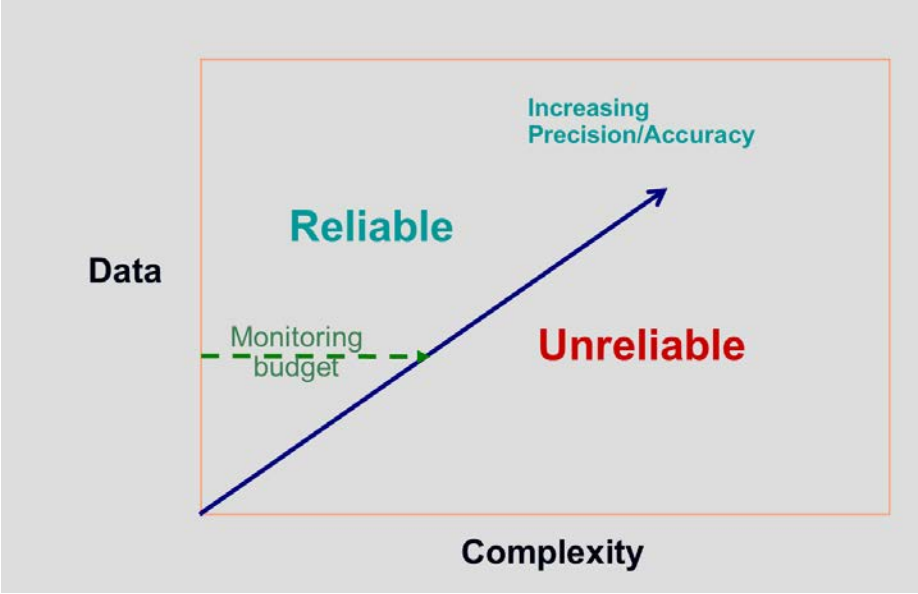


Data Needs


log(RELIABILITY)
Cost = Unlimited $$$$
"THE DECISION"
Required Reliability
Cost = $ + Δ$
Cost = $
"best" model
log(COMPLEXITY)

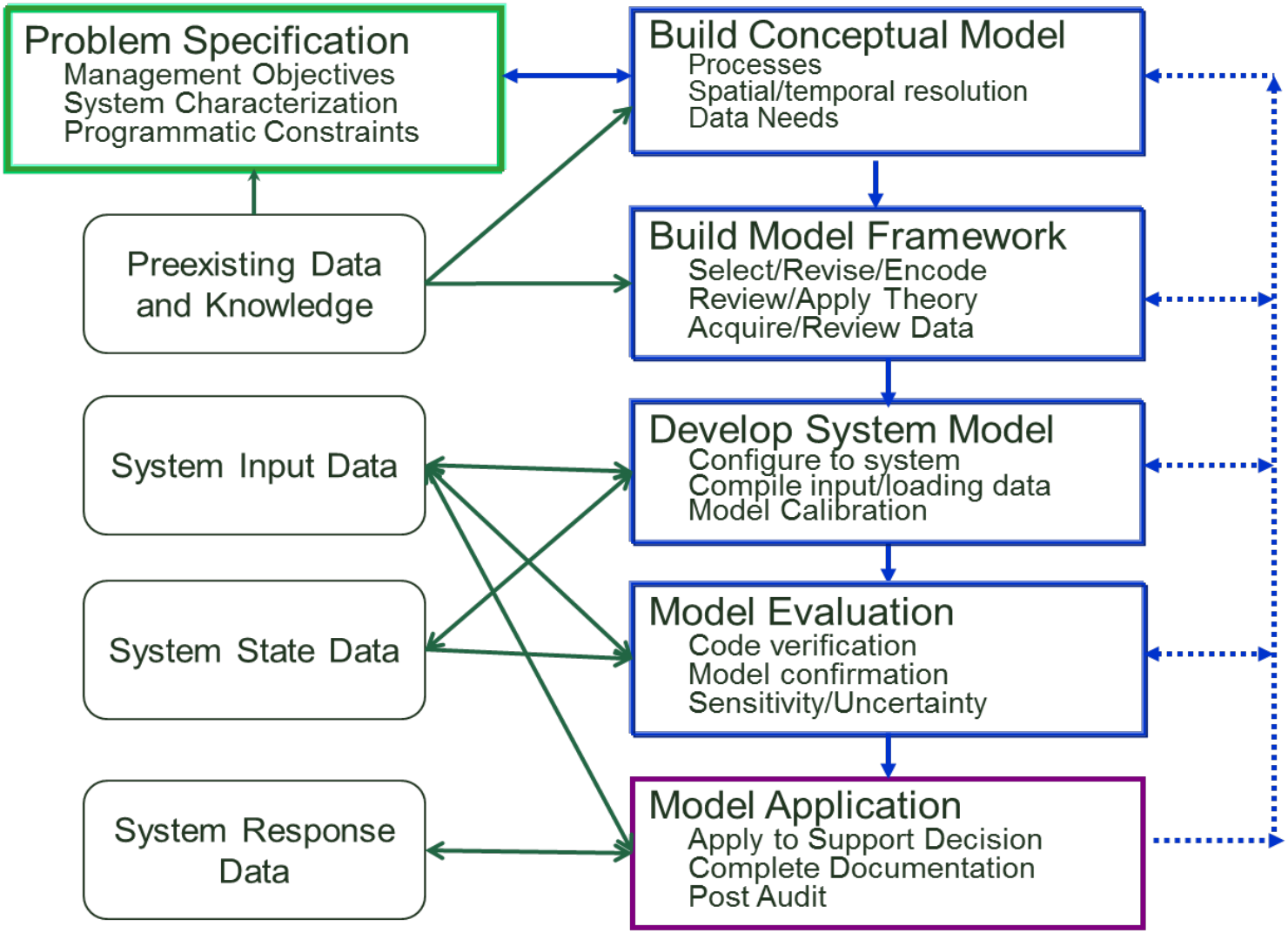
Toolbox in Context: Model Application

- Adequate site-specific data and modeling expertise are keys to success
- Site-specific model development and application typically requires ≥ 90 percent of the total effort and resources
  - Resources = Time, data, and/or expertise



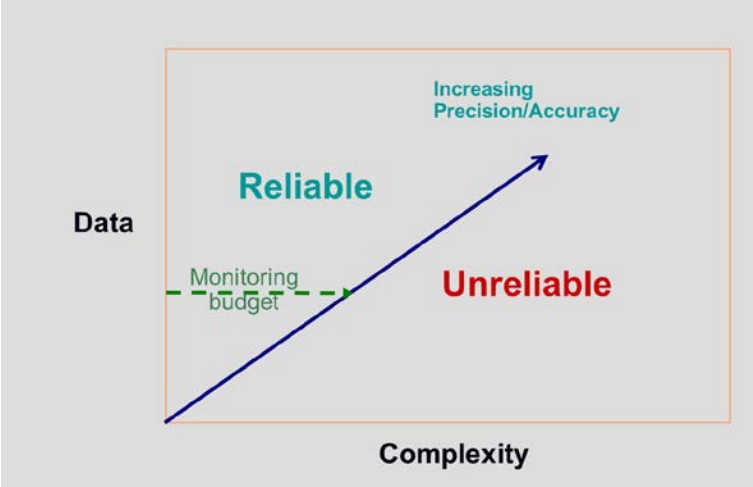
Nutrient Modeling Guidance

Modeling Steps Showing Interaction with Data Throughout the Process



Path Forward: Data and Research Needs

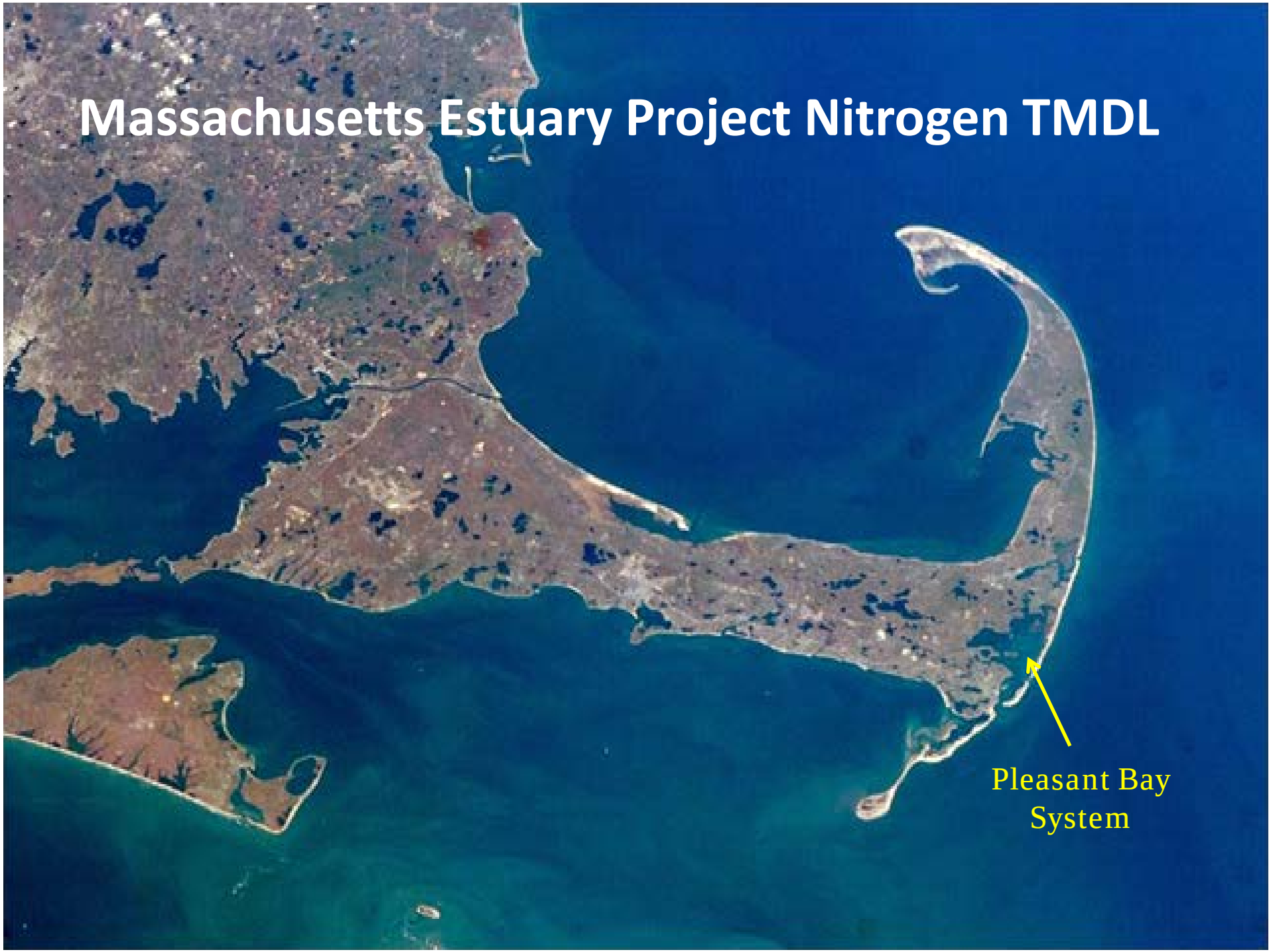
- Toolbox contains a wide range of eutrophication models from simple to complex
- But still room for improvement
  - Paucity of site-specific data for model development and application
  - Improvements needed in model conceptualization and formulation for:
    - Harmful algal blooms (HABs)
    - Model uncertainty
    - Ecosystem structure and function (biological response variables)



Path Forward: Recommendations

- Data-intensive site-specific case studies that involve integrated monitoring and modeling components
  - Follow up with Post-audit of model
- Emphasis on chemical-biological processes that are less well-understood than physical and hydrodynamic processes
  - Multiple phytoplankton groups, nutrient bioavailability, dual nutrient limitation, HABs, higher-order ecological endpoints
- Develop, apply and compare multiple load-response models on same "training datasets"
  - Compare models (simple to complex) for individual response endpoints

Massachusetts Estuary Project Nitrogen TMDL



Pleasant Bay, Massachusetts

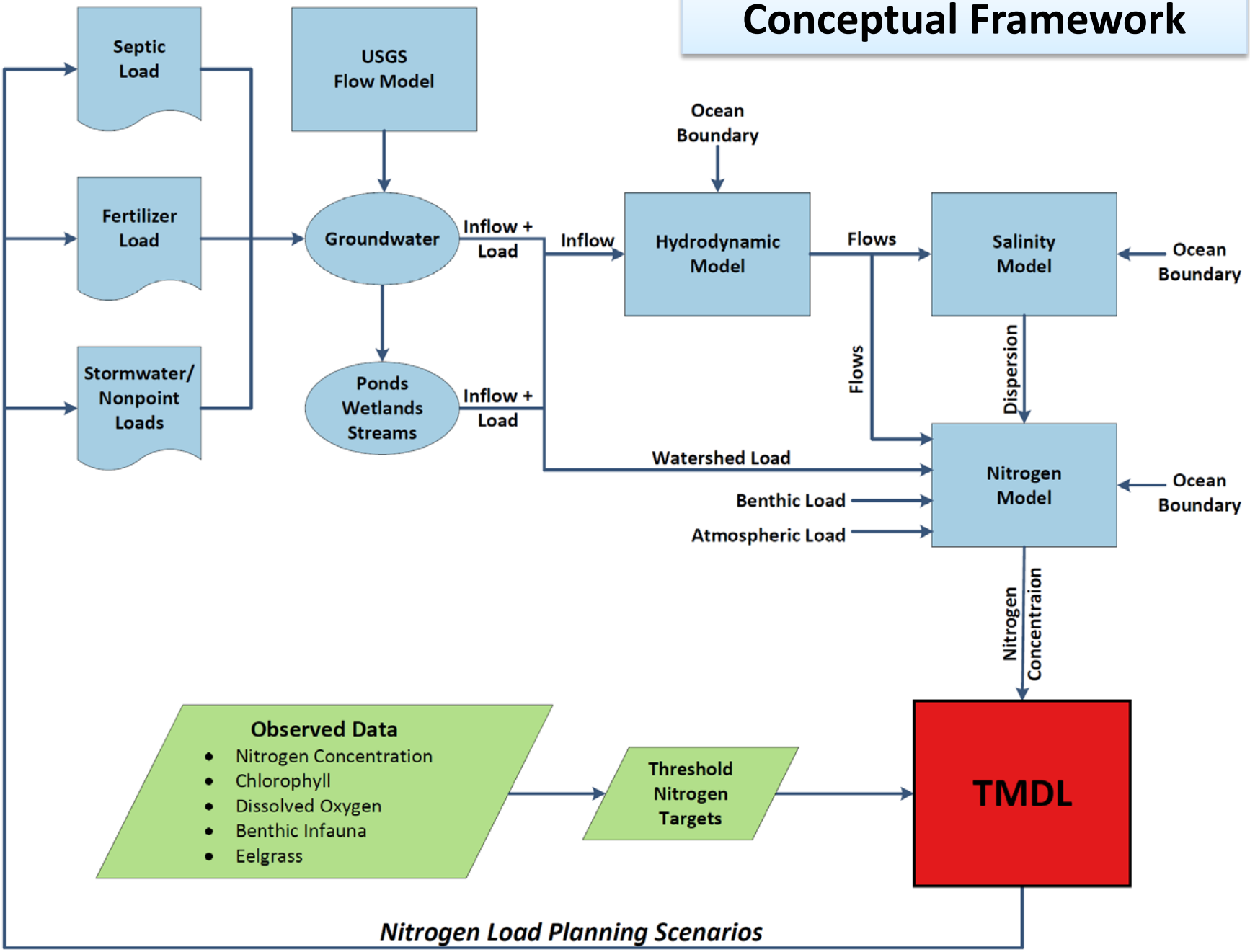
- Largest embayment on Cape Cod
- Sixteen (16) sub-embayments impaired due to excessive nitrogen loads, each requiring a TMDL
- Ecological response indicators
  - Eelgrass loss (primary concern)
  - Dissolved oxygen, chlorophyll a, macroalgae and benthic infauna (secondary concerns)
- Freshwater inputs dominated by direct groundwater seepage which delivers nitrogen loads primarily from onsite septic systems
- Bay circulation dominated by tidal exchange directly with the Atlantic Ocean

Howes et al. 2006

Pleasant Bay Embayment System

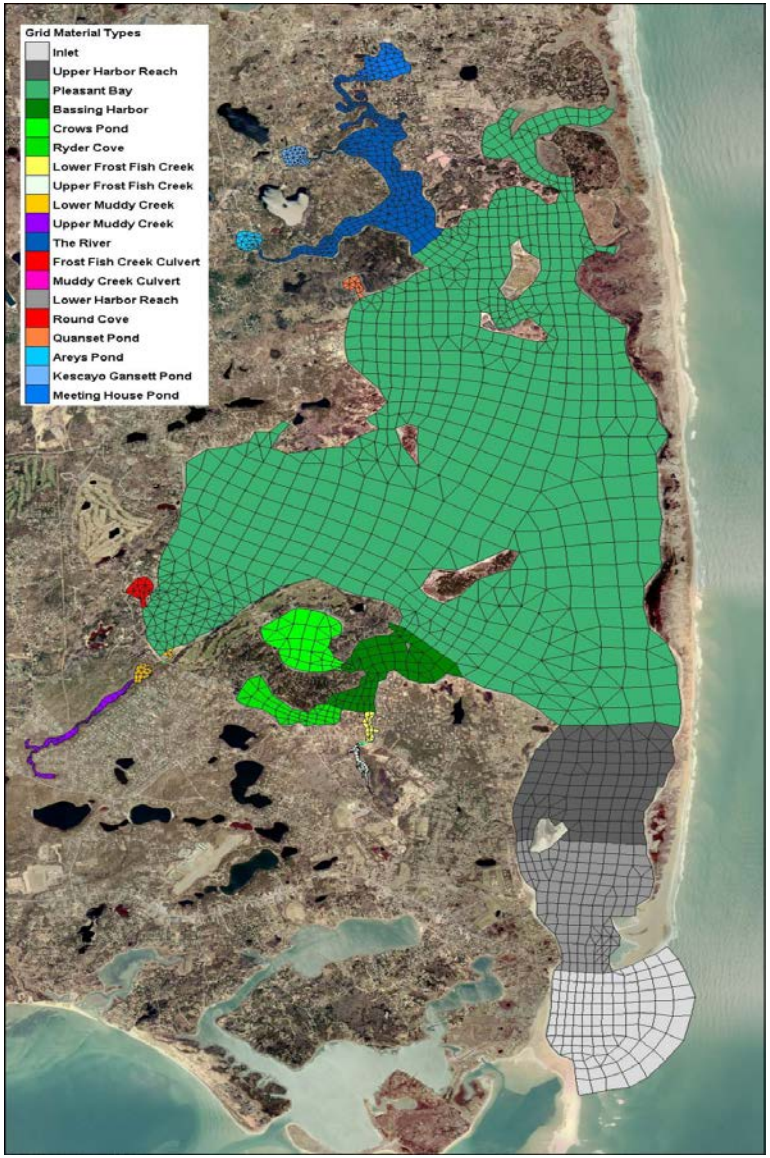
- Surface area 7,000 acres
- Average depth 6 feet
- Sub-embayments of varying size and limited flushing rates
- Approximately 96% of freshwater inflow is via groundwater or groundwater-fed surface water

Conceptual Framework



Hybrid Modeling Approach

- Load-response component
  - Septic, fertilizer and stormwater nitrogen sources delivered to bay via a groundwater model (MODFLOW)
  - RMA2/RMA4 hydrodynamic and water quality transport model links delivered loads to water column nitrogen concentrations
- Empirical stressor-response component
  - Reference condition approach
  - Site-specific data for water quality and ecological endpoints linked to water column nitrogen concentrations to develop TMDL targets



Howes et al. 2006

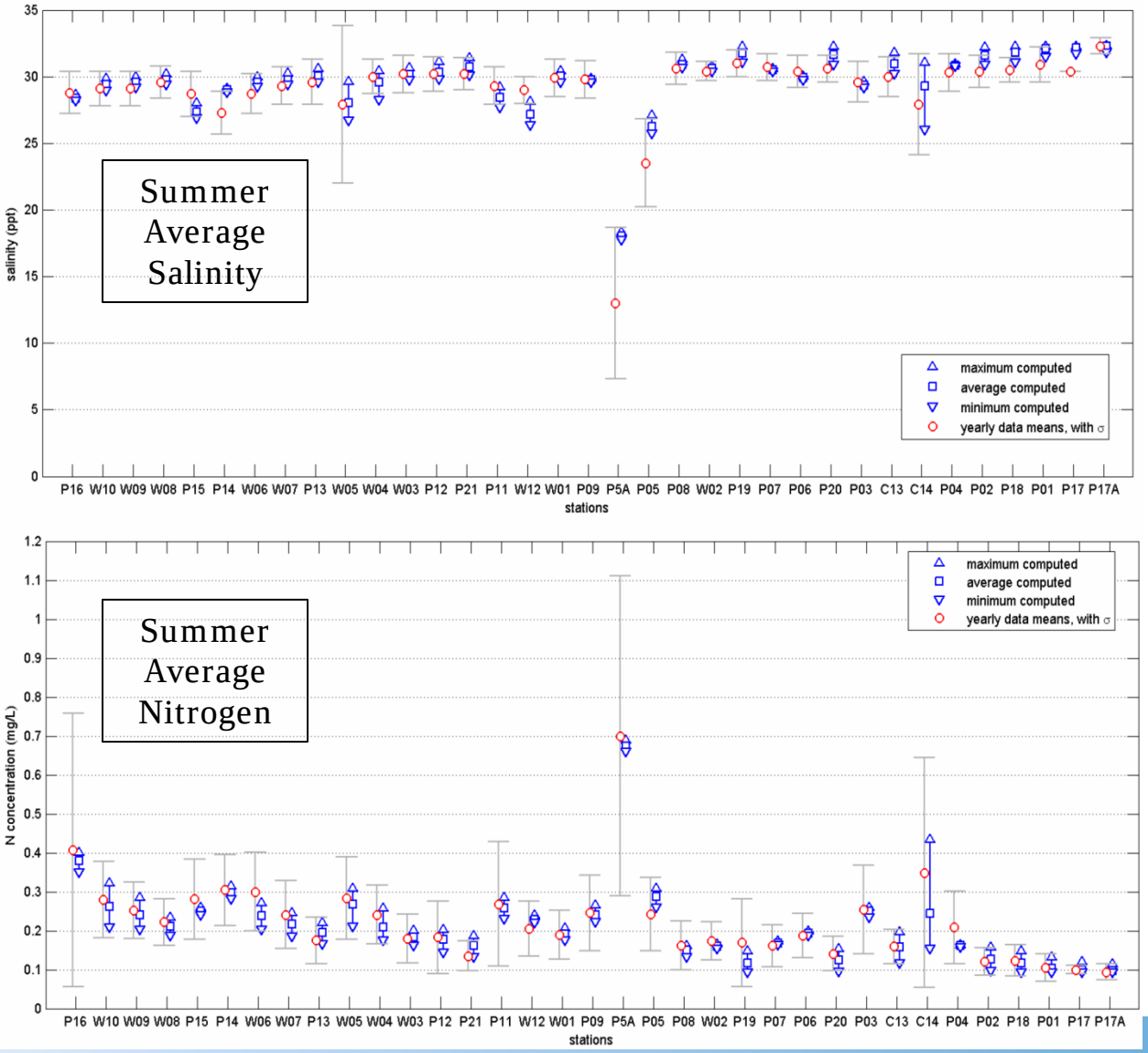
RMA2/RMA4 Model Segmentation Grid

- 6,753 nodes
- 2,339 two-dimensional, depth-average elements
- Color patterns indicate different model material types used to vary model calibration parameters

Site-Specific Data Requirements

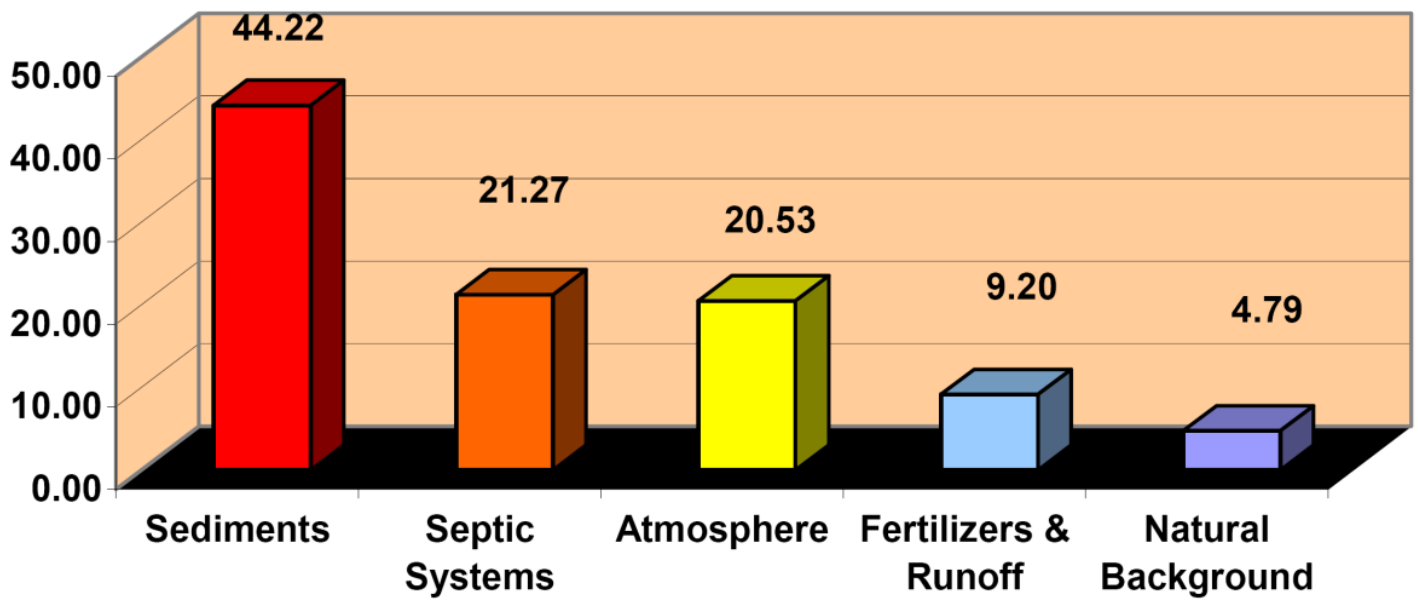
- Load-response component
  - Hydrodynamics
    - Groundwater inflows
    - Bathymetry
    - Tidal heights
    - Current velocities
  - Water quality transport
    - Salinity
    - Nitrogen loads from the watershed, atmosphere and sediments
    - Water column nitrogen concentrations
- Stressor-response component
  - Nitrogen, chlorophyll and dissolved oxygen concentrations
  - Macroalgae
  - Benthic infauna
  - Eelgrass distributions

RMA4 Calibration Results



Howes et al. 2006

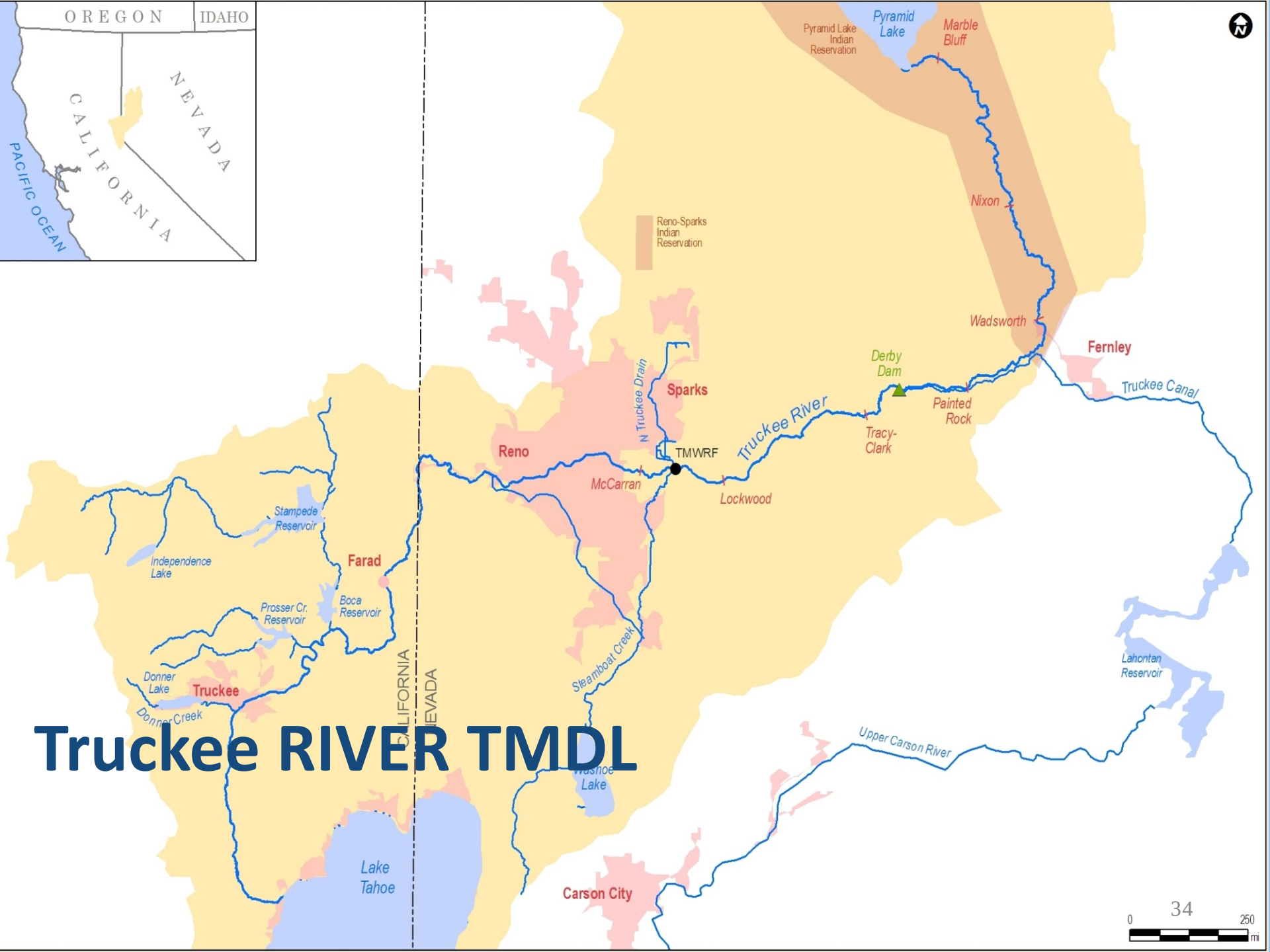
Relative Contributions of Nitrogen Sources



Commonwealth of Massachusetts, 2007

TMDL Development

- Assumes sediment nitrogen load is an internal source that will decrease linearly over time as external nitrogen loads are reduced
- Considers locally controllable sources to be septic systems, stormwater runoff and fertilizer
- The nitrogen TMDLs call for reductions in controllable nitrogen loads from 25-83 percent across the 16 sub-embayments
- EPA approved the TMDLs for the Pleasant Bay system on October 24, 2007



Truckee RIVER TMDL

Truckee Background

- Historically impaired by low dissolved oxygen
  - Caused by periphyton respiration during extremely low stream flow
- TMDL developed in 1994
  - Based on proprietary DSSAMt model
  - Rigorous phytoplankton kinetics
- Recent desire on behalf of regulated community to update TMDL
  - Develop “third party” TMDL
  - Allow credit for watershed restoration activities

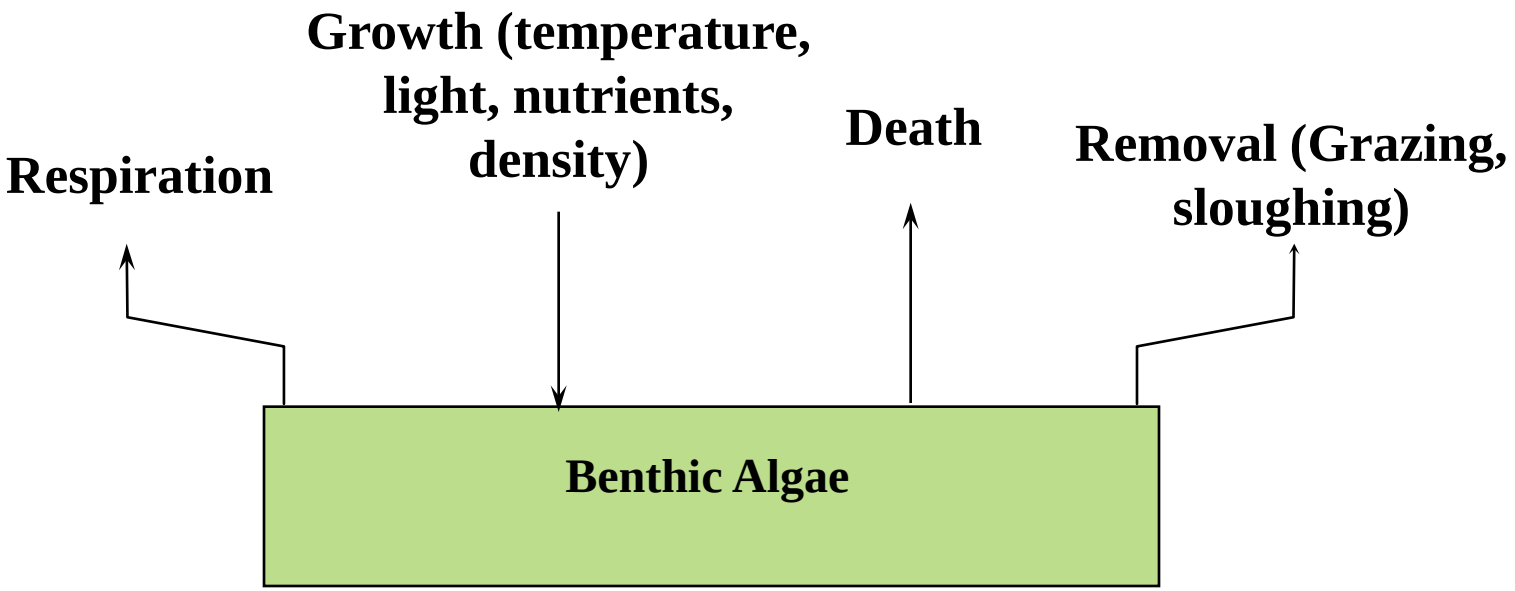
Model Selection

- DSSAMt model used for original TMDL no longer acceptable due to its proprietary nature
- USGS had previously developed a hydraulic model of the river using HSPF
- Result
  - Project team built rigorous periphyton kinetics into HSPF code
  - Updated kinetics incorporated into HSPF Version 11

HSPF Enhancements - Benthic algae

- Performed literature review on benthic algae modeling
- Conceptualized desired changes to HSPF
- Developed new model subroutines
- Incorporated changes into HSPF

Benthic algae growth equations



Δ[Algae]/Δ t = (Growth – Respiration – Death –Sloughing) x [Algae] – Grazing

Growth = Maximum growth(Temperature) *minimum[Φ_N, Φ_L]*Density limitation factor

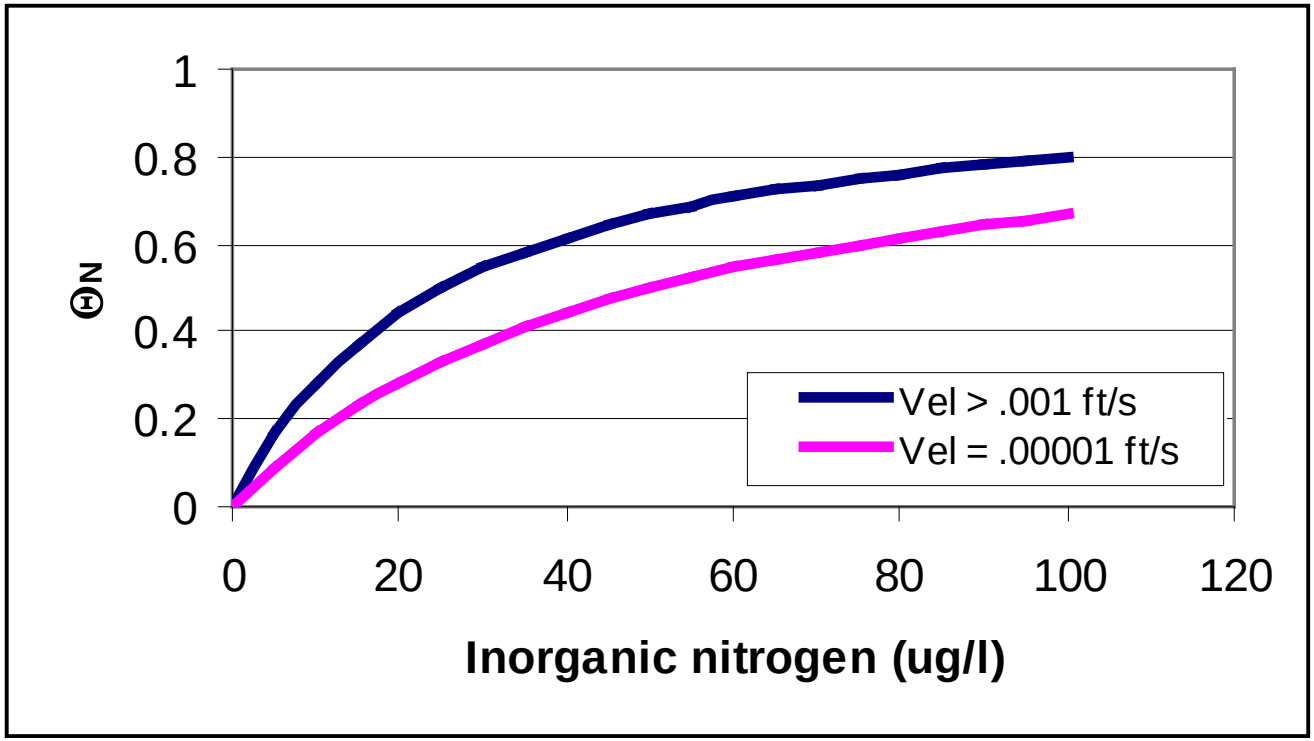
Nutrient limitation

Velocity factor added to standard half-saturation equation

$$\Phi_N = \frac{[N] \cdot VelocityFactor}{(K_{1/2} + [N] \cdot VelocityFactor)}$$

$$VelocityFactor = \frac{Velocity}{(K_{1/2} + Velocity)}$$

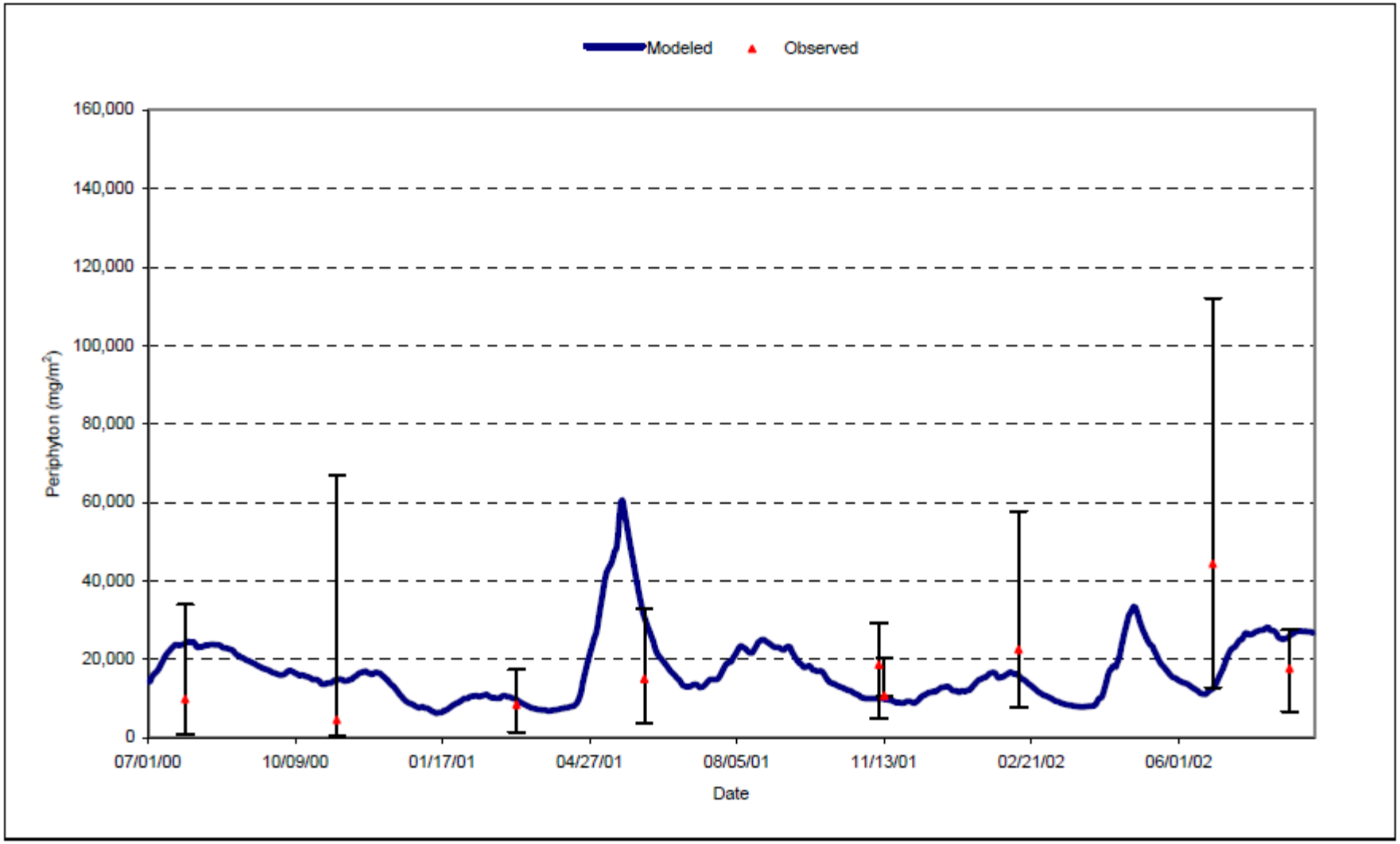
Nutrient limitation (continued)



$$\Phi_N = \text{minimum}(\Phi_{Nitrogen}, \Phi_{Phosphorus})$$

Model Calibration

- Model as applied for original TMDL was calibrated only to DO data
  - No periphyton data available at time of TMDL
- Comprehensive monitoring program developed to support TMDL revision
  - Periphyton measurements, continuous DO monitors, nutrients
  - Spanned period 2000-2002



Comparison of modeled and observed periphyton densities at Dead Ox (Reach 334).

TRHSPF Calibration Results: Dissolved Oxygen

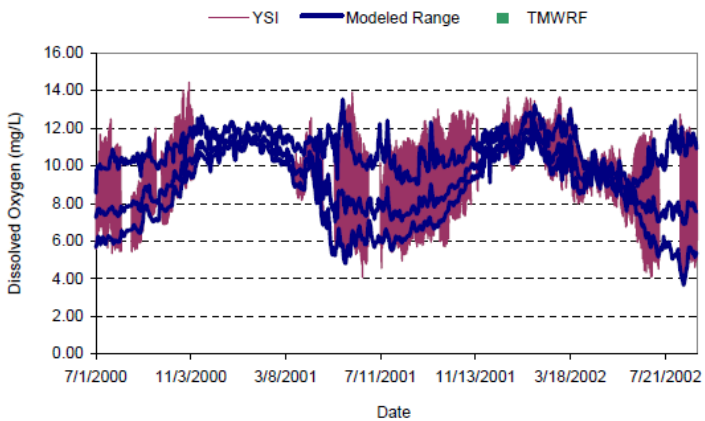


Figure A-95. Comparison of Observed and Modeled Dissolved Oxygen (mg/L) at Tracy between July 1, 2000 and August 31, 2002.

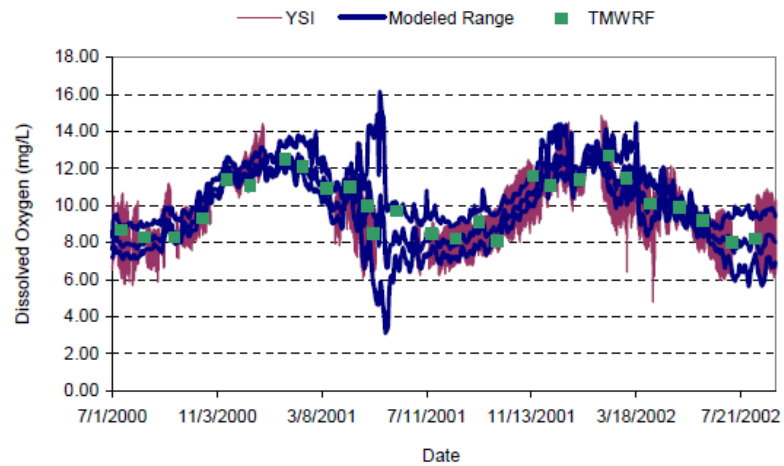


Figure A-96. Comparison of Observed and Modeled Dissolved Oxygen (mg/L) at Painted Rock between July 1, 2000 and August 31, 2002.

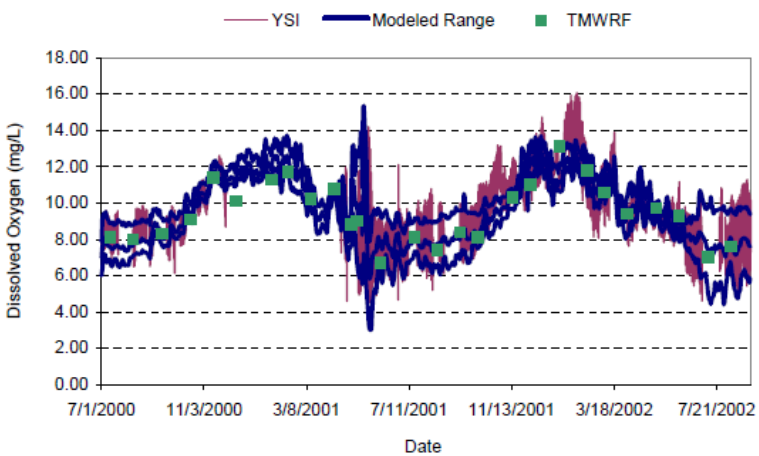


Figure A-97. Comparison of Observed and Modeled Dissolved Oxygen (mg/L) at Wadsworth between July 1, 2000 and August 31, 2002.

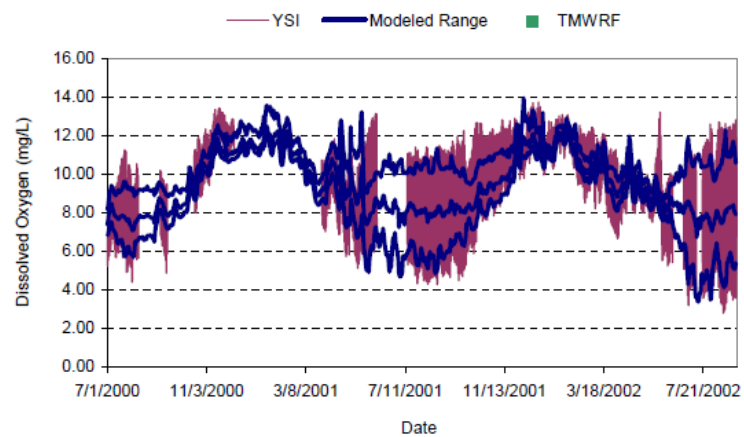


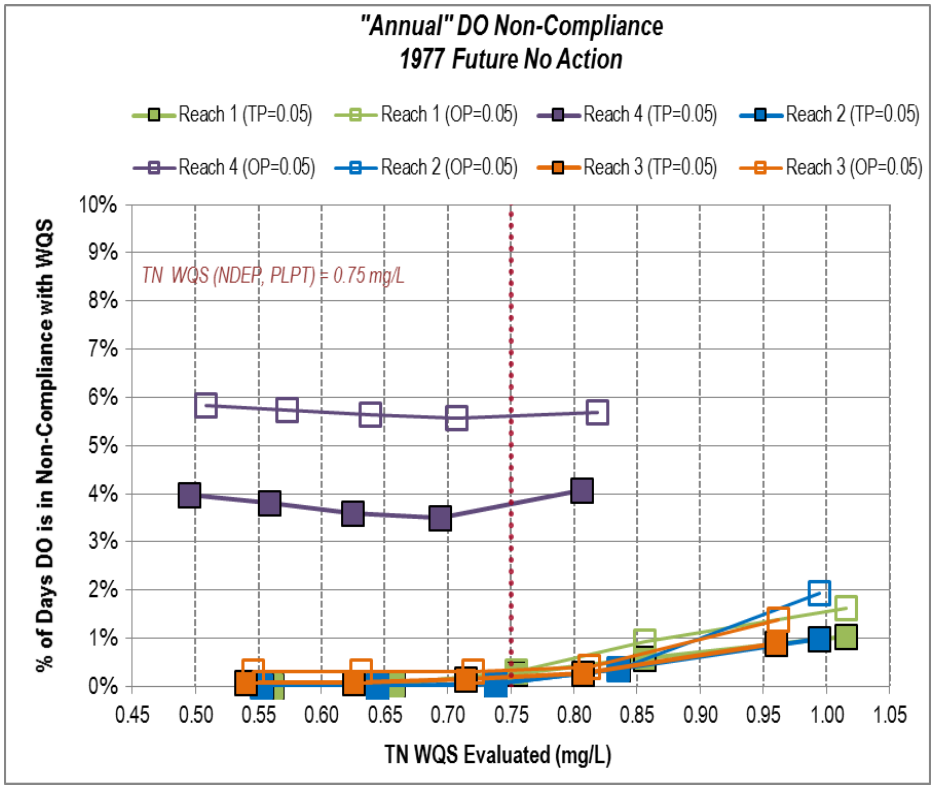
Figure A-99. Comparison of Observed and Modeled Dissolved Oxygen (mg/L) at Marble Bluff Dam between July 1, 2000 and August 31, 2002.

Status

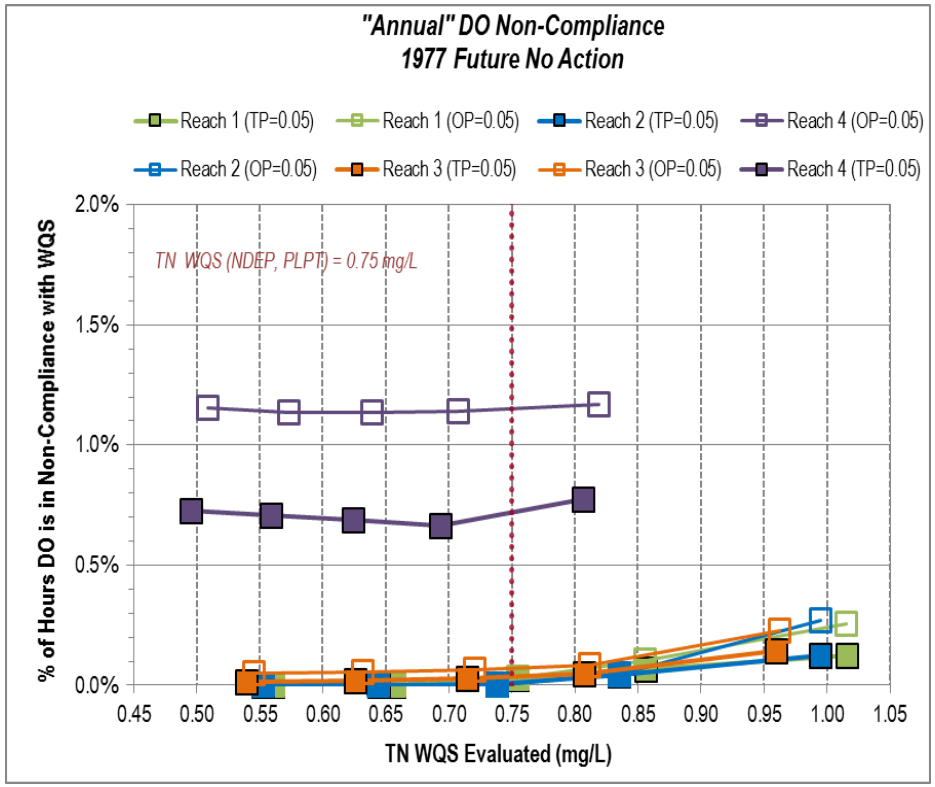
- TMDL development temporarily on hold
  - Regulatory decision to verify appropriateness of existing numeric nutrient criteria prior to revising TMDL
  - Model calibration re-confirmed each year as new data are collected
- Now using HSPF to evaluate alternative N and P criteria
- TMDL development to proceed once WQS are finalized
  - Mid 2014?

Analysis of Nutrient Criteria
(10th Percentile Flow: Reach Averaged)

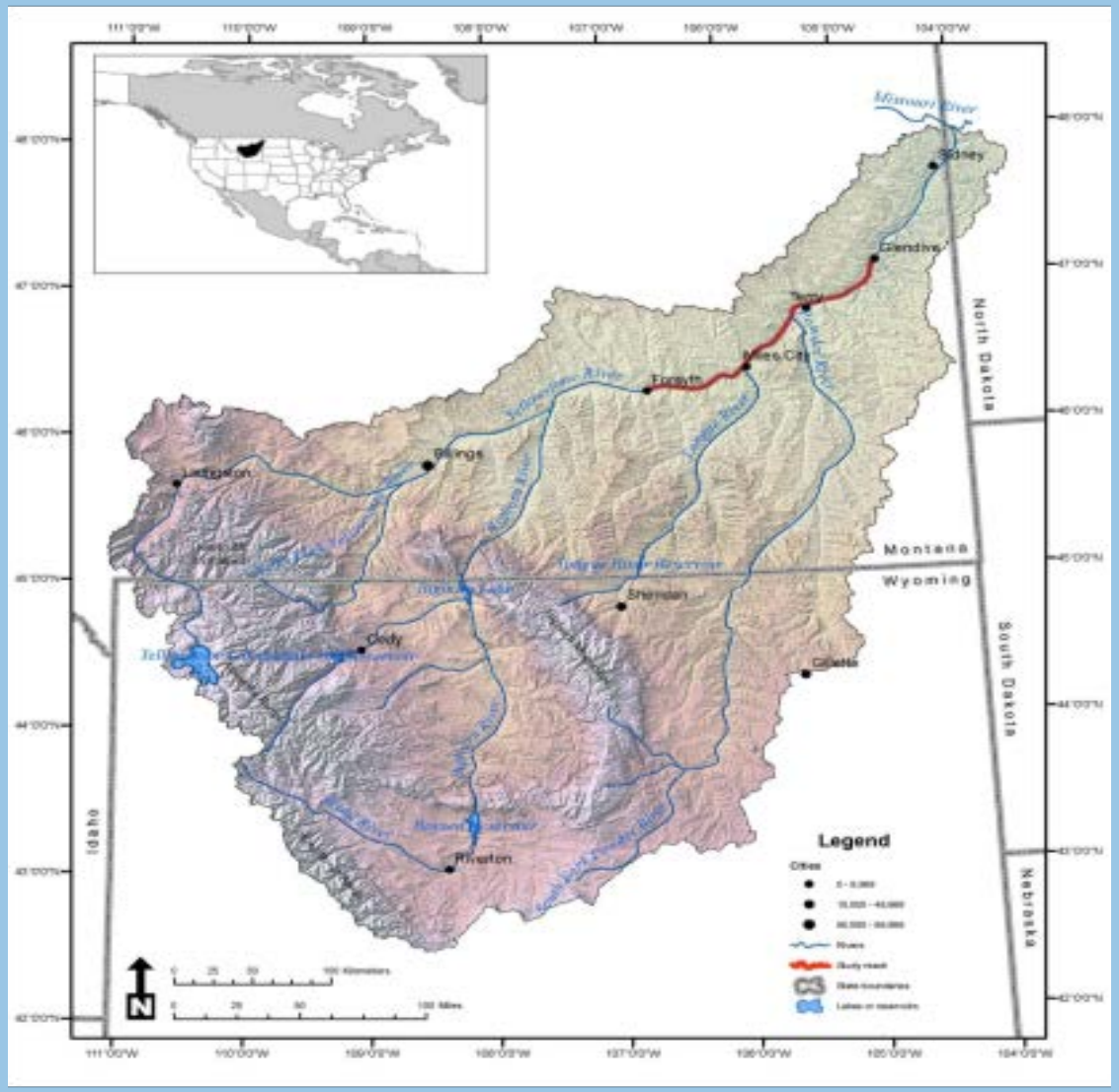
% of Days



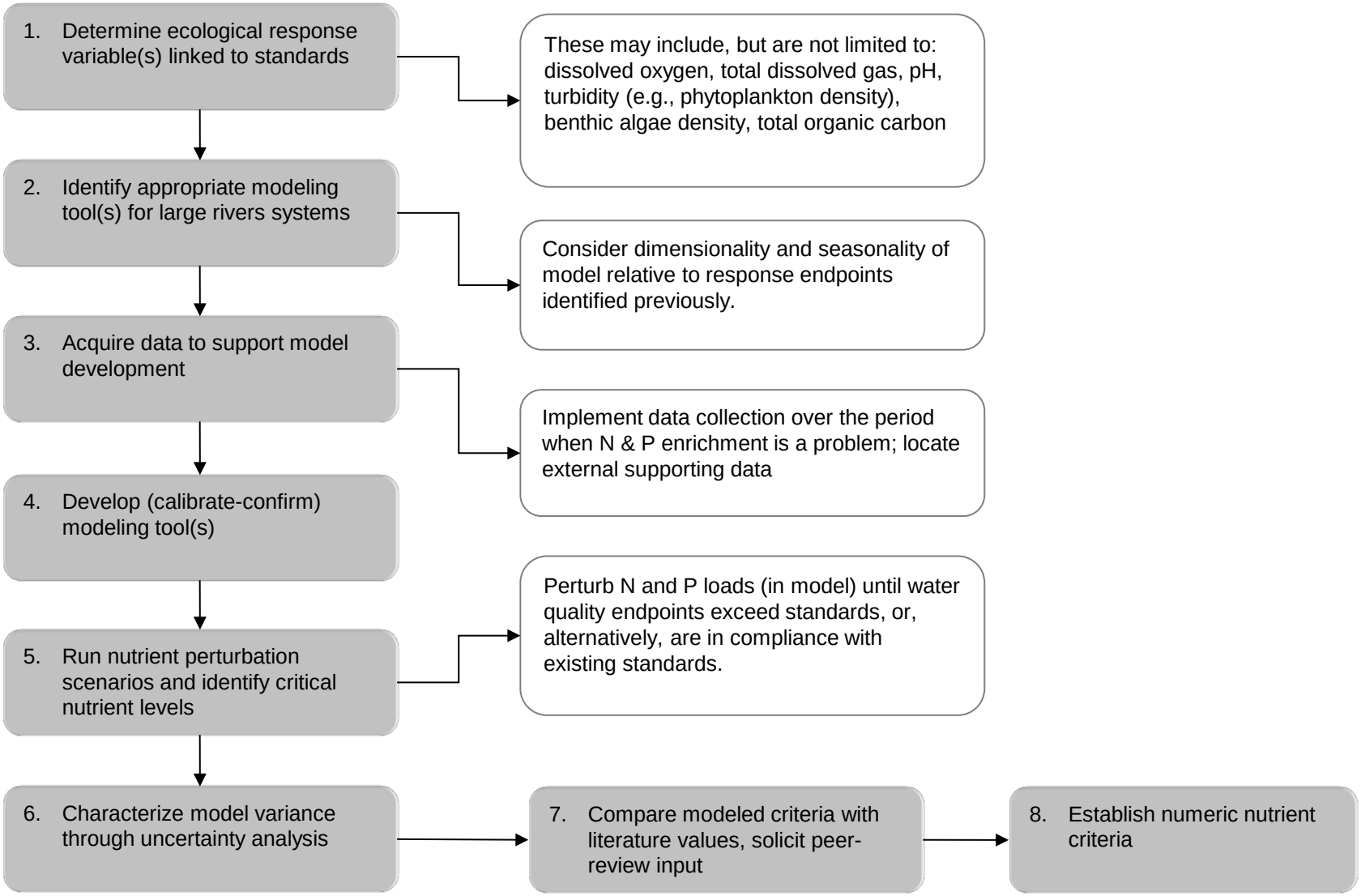
% of Hours



Yellowstone River Numeric Nutrient Criteria



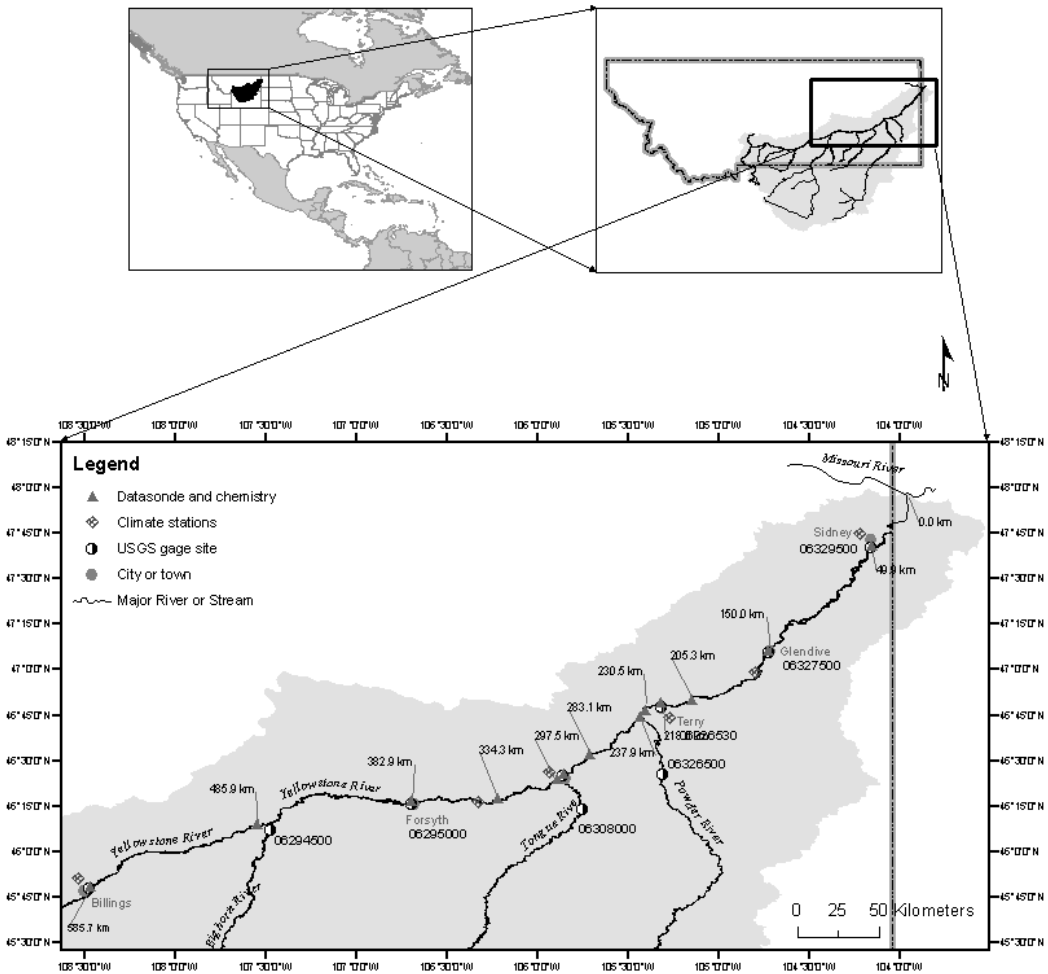
Montana approach for NNC in Large Rivers



Modeling approach and associated process steps used for large river numeric nutrient criteria development.

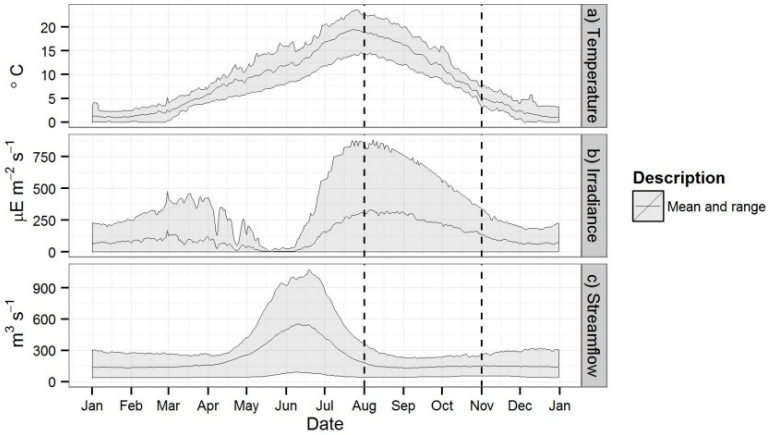
Case Study: Yellowstone River

- Large river
  - 181,480 km^2
  - 586 km long
- 55% in Great Plains province
- Population 323,000
- 38 WWTP, 48 CAFO, 78 stormwater
- Mean Q=348.3 cms, peaks=1,430 cms, low flows=100 cms



Determine ecological response variables

- DO, pH, turbidity, ***benthic chlorophyll a***, etc.
- Temporal considerations
- Spatial considerations



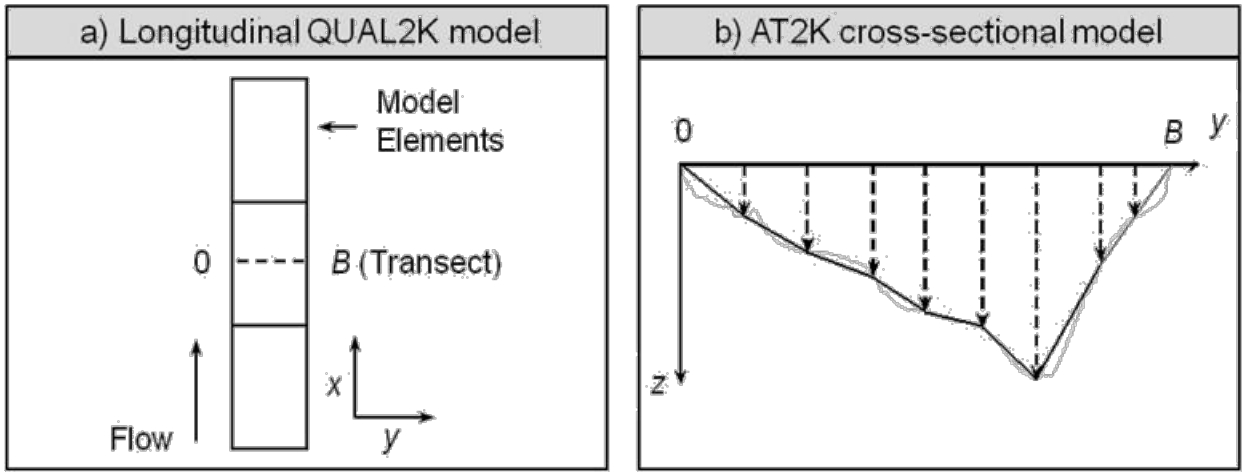
Segment Description	Use Class	Beneficial Uses
Yellowstone River mainstem from Billings to the North Dakota state line	B-3	Drinking, recreation, non-salmonid fishery, aquatic life, waterfowl and furbearers, agricultural and industrial water supply

Standards for B-3 waters (e.g. lower Yellowstone River) are:

1. **Dissolved oxygen levels ≥ 5 mg L^{-1} in order to protect aquatic life and fishery uses (early life stages; DEQ 2012).**
2. **Total dissolved gas levels, which must be ≤ 110% of saturation to protect aquatic life (Montana Department of Environmental Quality, 2012).**
3. **Induced variation of hydrogen ion concentration (pH), which must be less than 0.5 pH units within the range of 6.5 to 9.0, or without change if natural is outside this range [ARM 17.30.625(2)(c)] to protect aquatic life.**
4. **Turbidity levels, which a maximum increase of 10 nephelometric turbidity units (NTU) is acceptable; except as permitted in 75-5-318, MCA [ARM 17.30.625(2)(d)] to protect aquatic life.**
5. **Benthic algae levels, which DEQ interprets per our narrative standard (ARM 17.30.637(1)(e) should be maintained below a nuisance threshold of 150 mg Chla m^{-2} to protect recreational use.**

Models Used

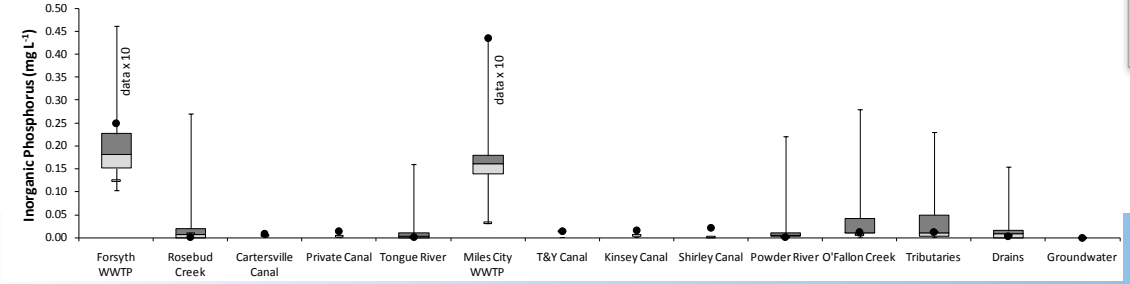
- Qual2K – 1-D advection-dispersion model used to simulate longitudinal response of given response variables (e.g., DO, pH, phytoplankton, etc.).
- AT2K - Tool to map the spatial distribution (lateral dimension) of benthic algae (chl*a*) at a river transect (i.e., element), in order to evaluate recreational use support.



Conceptual representation of QUAL2K and AT2K. (a) 1-D longitudinal basis for QUAL2K reach network and associated computational elements. (b) 1-D cross-section from AT2K reflecting changes in depth over the width of a QUAL2K model element and computations laterally over the channel.

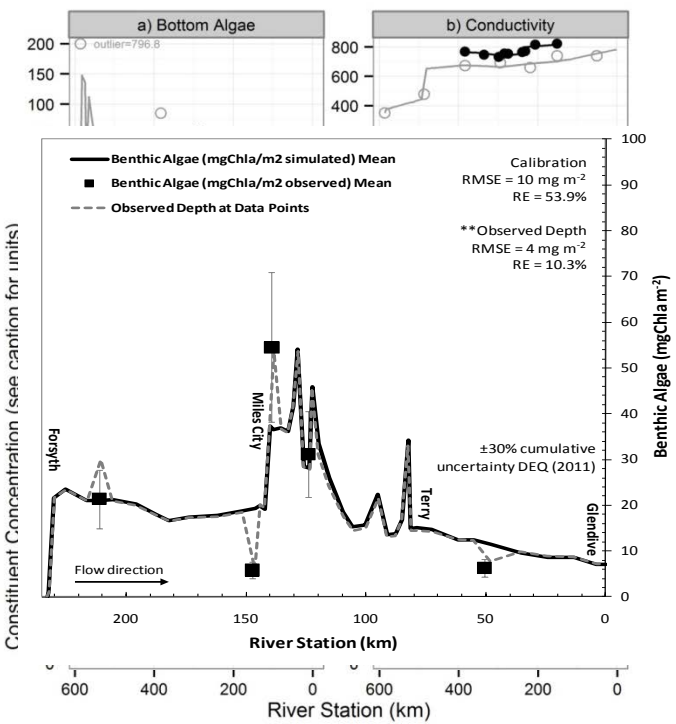
Data for model development

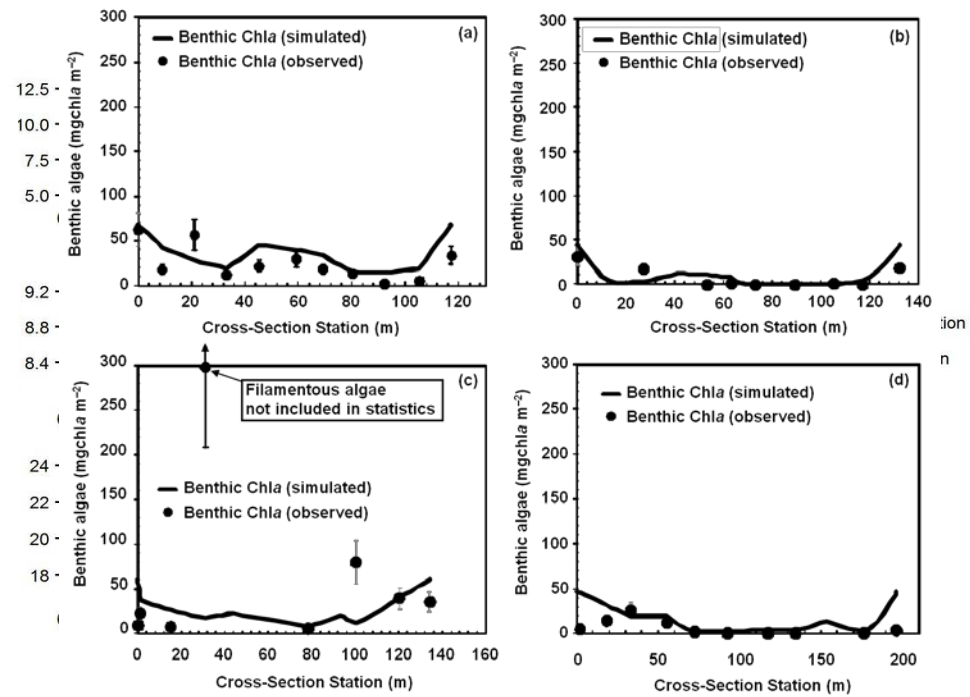
Data	Description
Physical network	Stationing, gradient, etc.
Streamflow	Continuous and instantaneous measurements
Transport	Dye tracer study, width/depth observations, rating data
Meteorology	Air temperature, dew point, wind speed, solar radiation
Calibration data	Real-time YSI 6600 sondes (DO, pH, chl*a*, turbidity, SC). Integrated chemistry samples (N species, P species, benthic chl*a*, CBOD, TSS, VSS, etc.)
Inflow boundaries	Instantaneous streamflow/water quality at all significant inflows.
Reaeration	From delta-method (see Chapra and Di Toro, 1991).
Light	Extinction profiles
Shade	Analysis with Shadev3.0.xls (Pelletier, 2007).
Algal taxonomy	Species composition, life cycle, etc.



Results (benthic chlorophyll a, etc.)

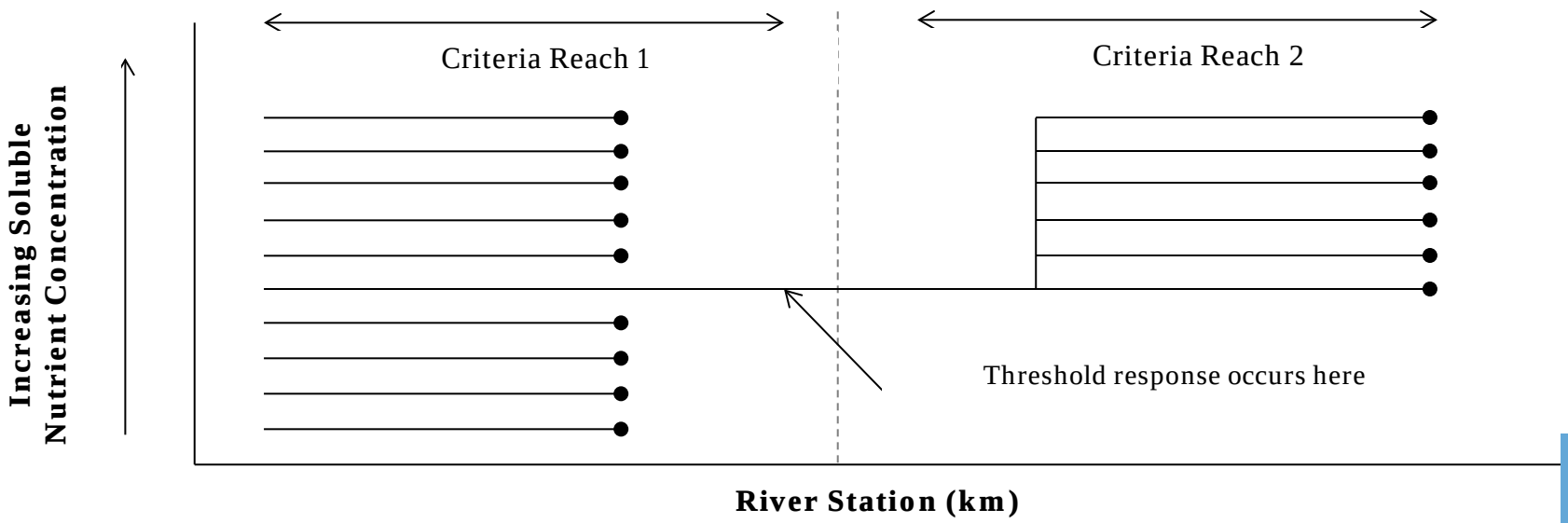
State-variable	August 2007 (calibration)			August 2000 (confirmation)		
	RMSE (units)	RE (%)	met	RMSE (units)	RE (%)	met
Benthic Algae (mgChla m^{-2})	4	10.3	yes	*9.6	*161.8	no
Phytoplankton (µgChla L^{-1})	1.9	-2.0	yes	1.8	18.5	yes
Dissolved Oxygen (mgO_2 L^{-1})	0.59	-2.5	yes	0.36	1.8	yes
pH (S.U.)	0.16	0.9	n/a	0.07	-0.2	n/a





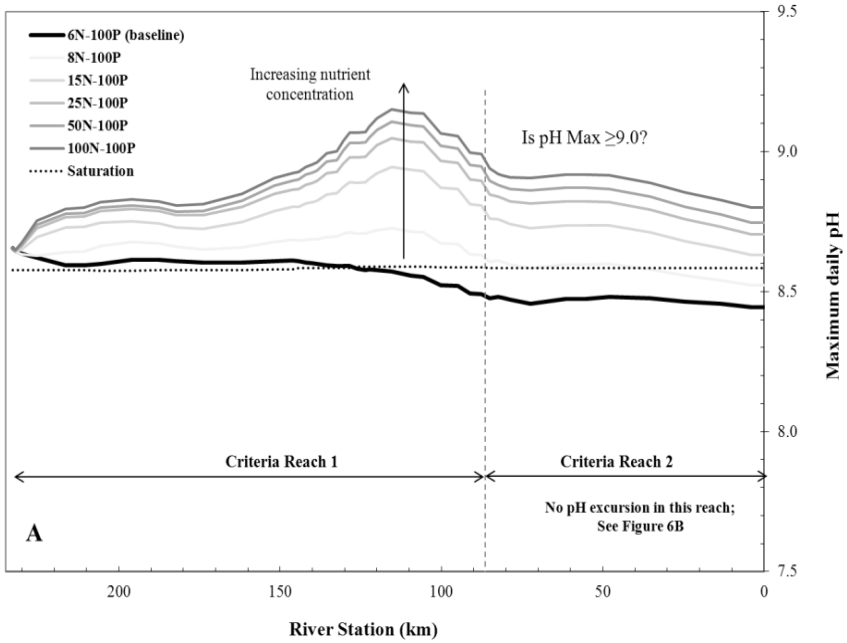
Nutrient perturbation scenarios/ analysis

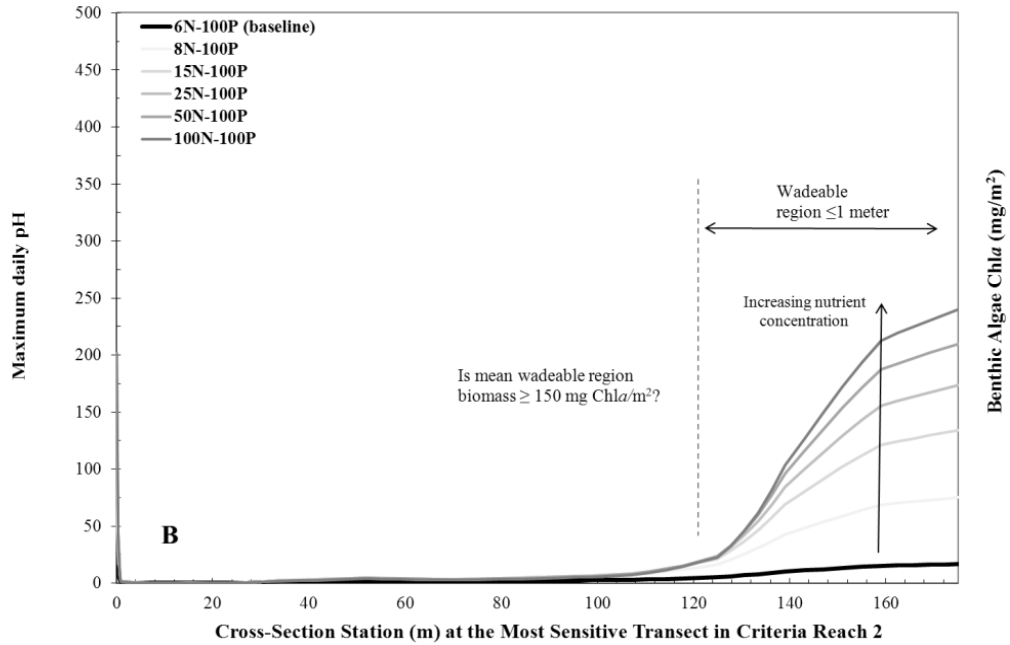
- Define critical conditions
  - Hydrologic design flow (14Q5)
    - Duration – defined by critical loading period (prior slide)
    - Frequency – defined by allowable excursions (5-yr)
  - Meteorological conditions (TMY)
  - Boundary conditions
- Perturb N & P
  - Adjust soluble nutrients in the model until a water-quality limiting eutrophication response occurs
  - Put river into state where ambient nutrient concentrations are approximately constant across modeling extent.



Typical Results

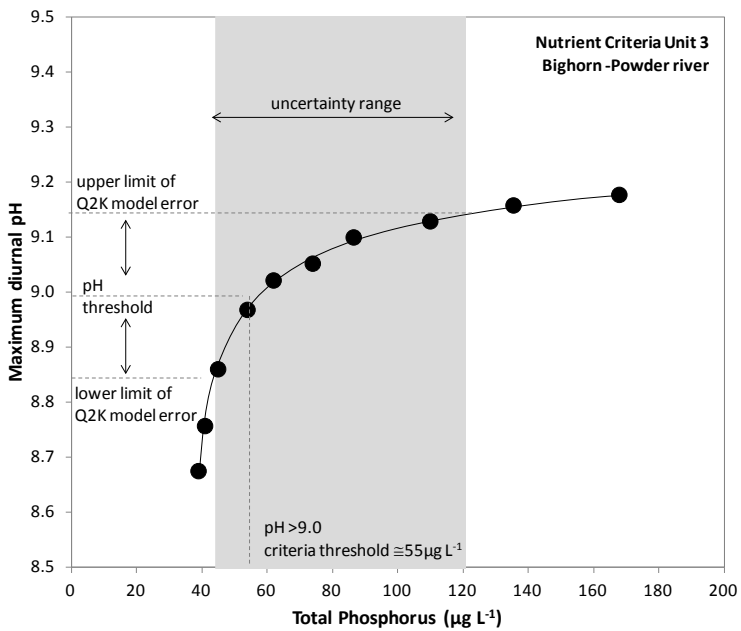
Trial	Nitrogen Limiting		Phosphorus Limiting	
	NO_3 (µg/L)	SRP (µg/L)	NO_3 (µg/L)	SRP (µg/L)
1	6	100	1,000	2
2	8	100	1,000	3
3	10	100	1,000	4
4	15	100	1,000	6
5	20	100	1,000	8
6	25	100	1,000	10
7	30	100	1,000	15
8	50	100	1,000	20
9	70	100	1,000	30
10	100	100	1,000	50

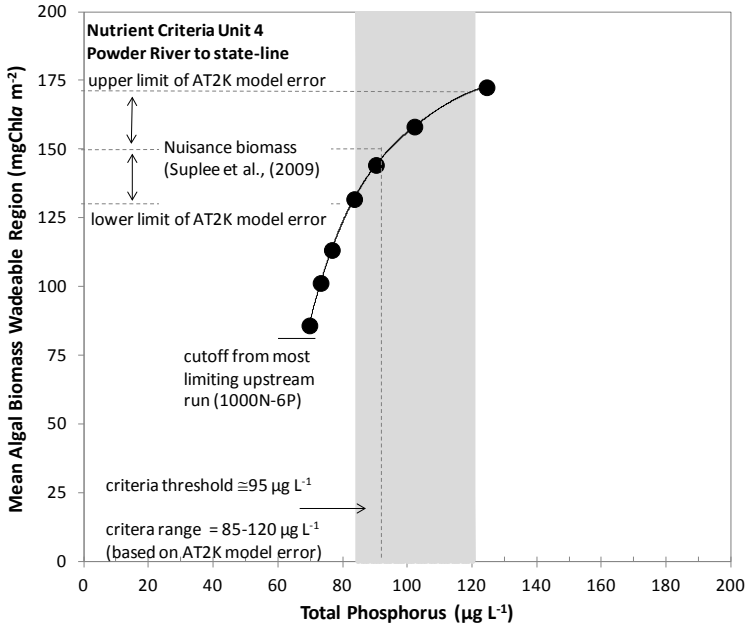




Response summary

- pH limiting in upper river; benthic algae in lower river
- Criteria would be set accordingly





Location	Total Nitrogen ($\mu g\ L^{-1}$)	Total Phosphorus ($\mu g\ L^{-1}$)
Criteria Assessment Unit 3 Big Horn River to Powder River	655	55
Criteria Assessment Unit 4 Powder River to state-line	815	95

Questions/Comments?

Contact:

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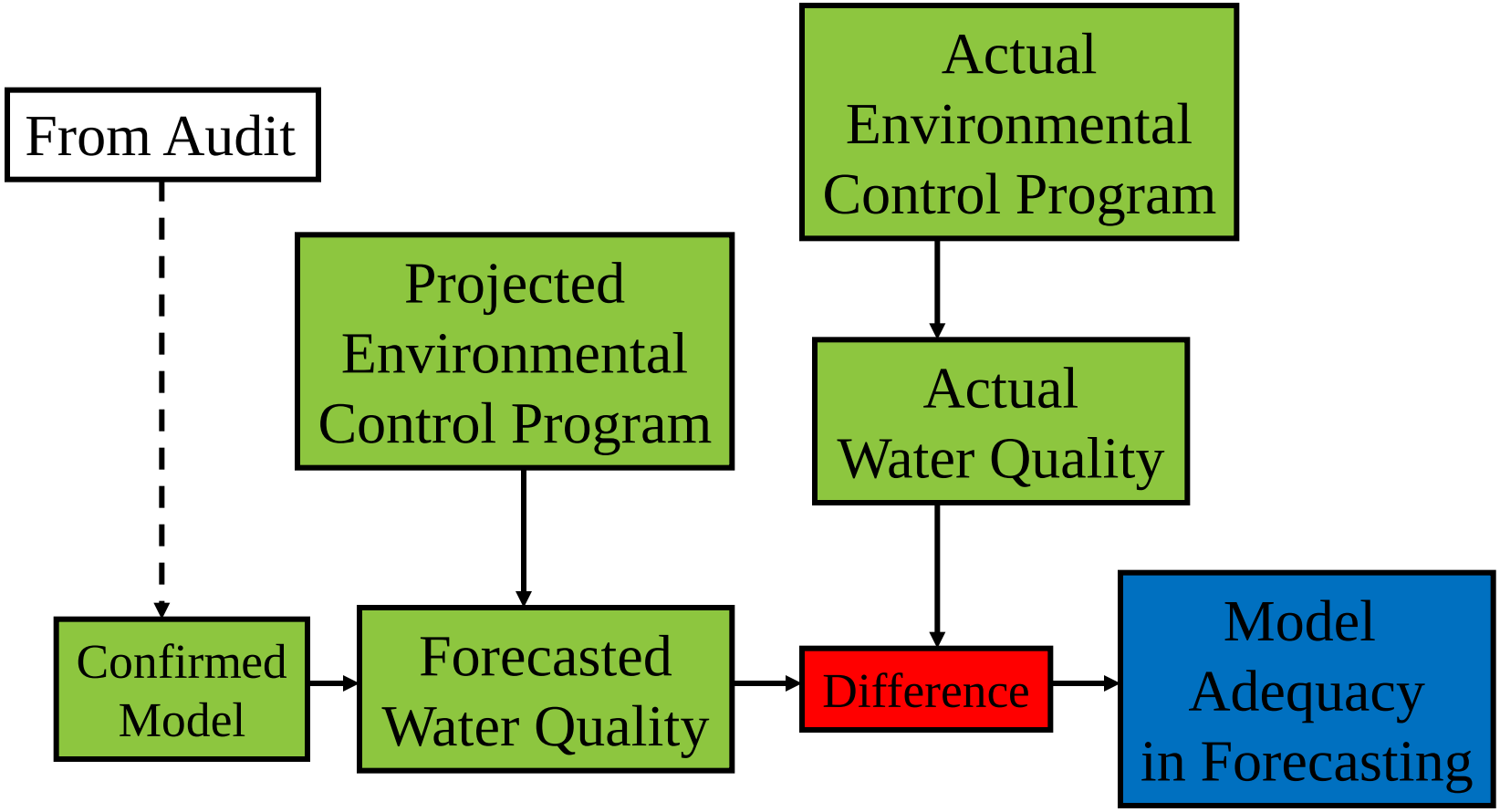
jdepinto@limno.com

Where to find the Toolbox and Guidance Document:

http://www.werf.org/a/ka/Search/ResearchProfile.aspx?ReportId=LINK1T11

Also available from EPA Nutrient Toolkit site for NNC

http://www2.epa.gov/nutrient-policy-data/toolkit-resources-provide-states-flexibility-adopting-and-implementing-numeric

Post-audit of Models