A Watershed Response Modeling Approach for the Wisconsin River TMDL

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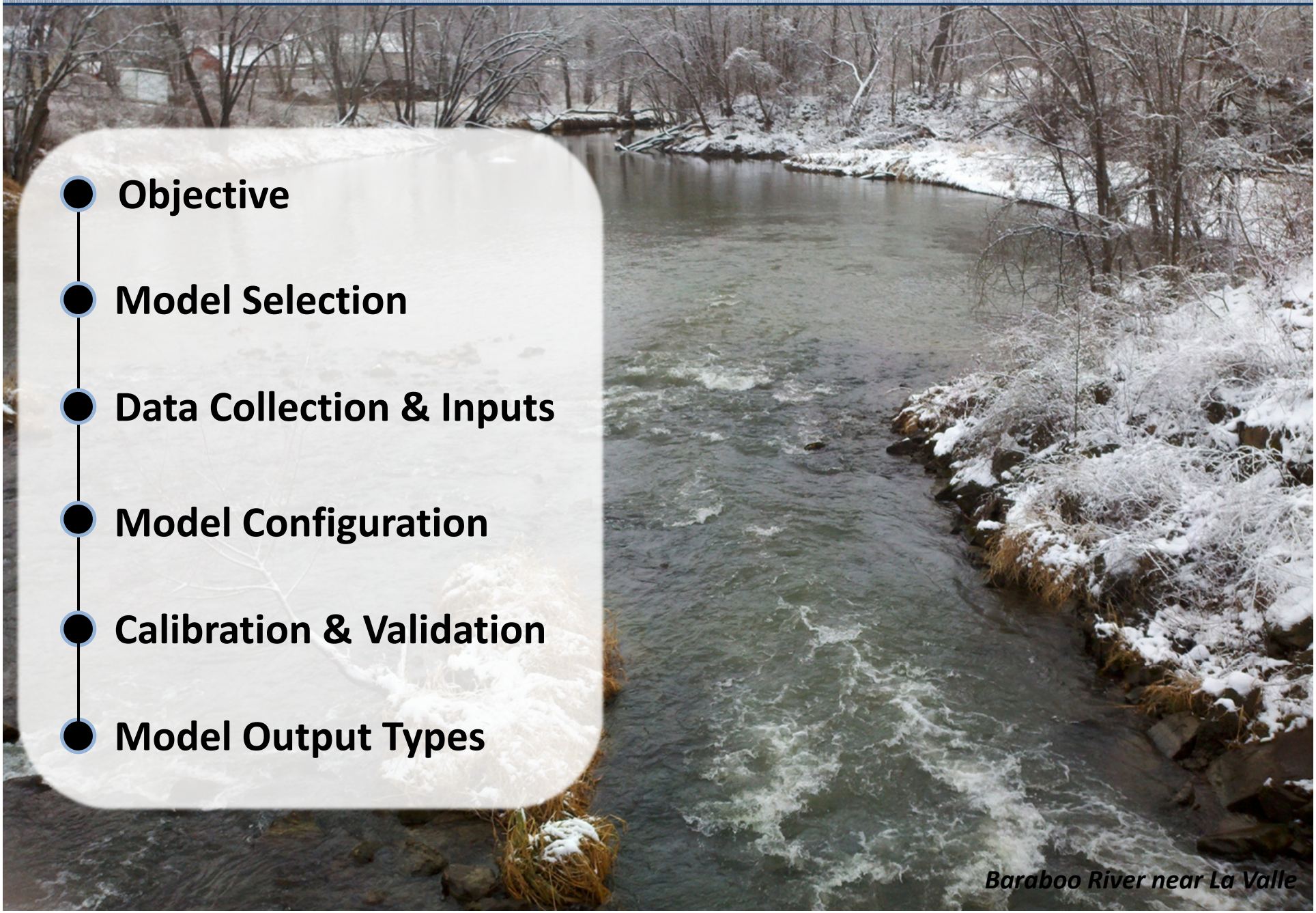
Wisconsin Department of Natural Resources
Wisconsin River TMDL Technical Stakeholder Meeting
November 6, 2013

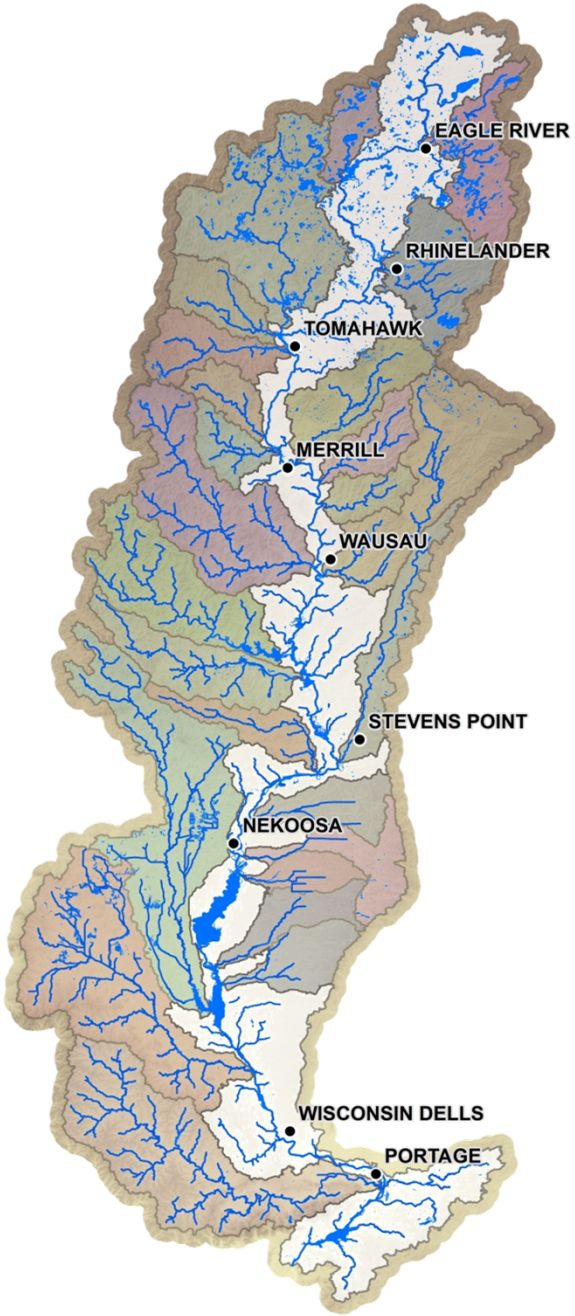
Watershed Response Modeling Approach



- **Objective**
- **Model Selection**
- **Data Collection & Inputs**
- **Model Configuration**
- **Calibration & Validation**
- **Model Output Types**

Baraboo River near La Valle

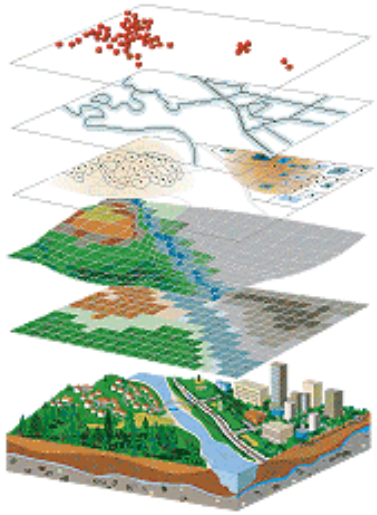
Objective



- Simulate monthly discharge and total suspended sediment and total phosphorus loading for each subwatershed within the Wisconsin River Basin
- Define the distribution of sediment and phosphorus sources within each subwatershed

Process Overview

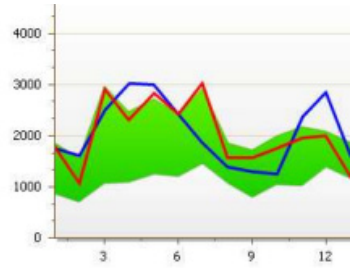
MODEL SELECTION



MONITORING & LANDSCAPE DATASET DEVELOPMENT

MODEL SET-UP

INITIAL MODEL RUN

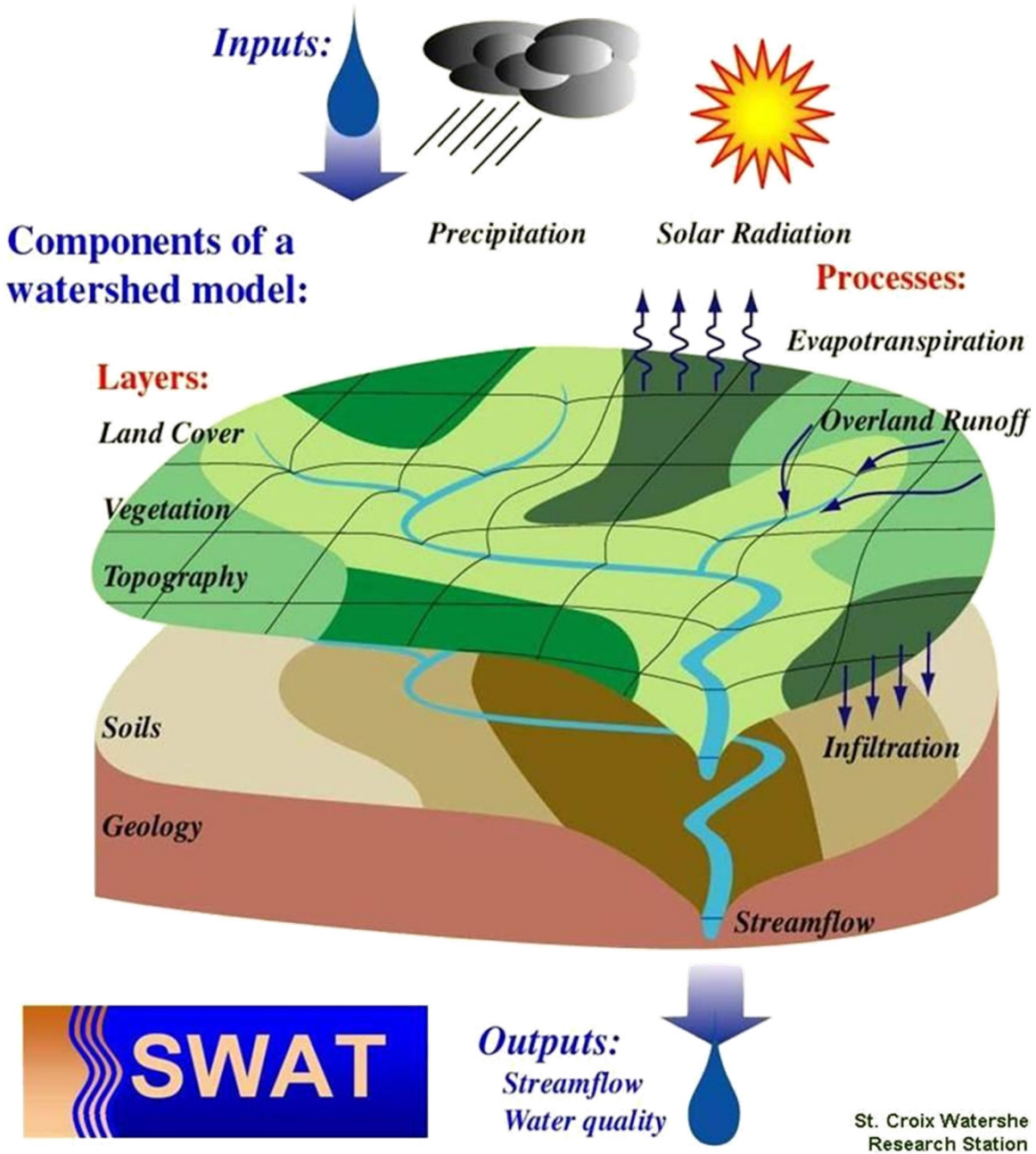


CALIBRATION & VALIDATION

Good Fit?

CURRENT CONDITIONS SIMULATION COMPLETE

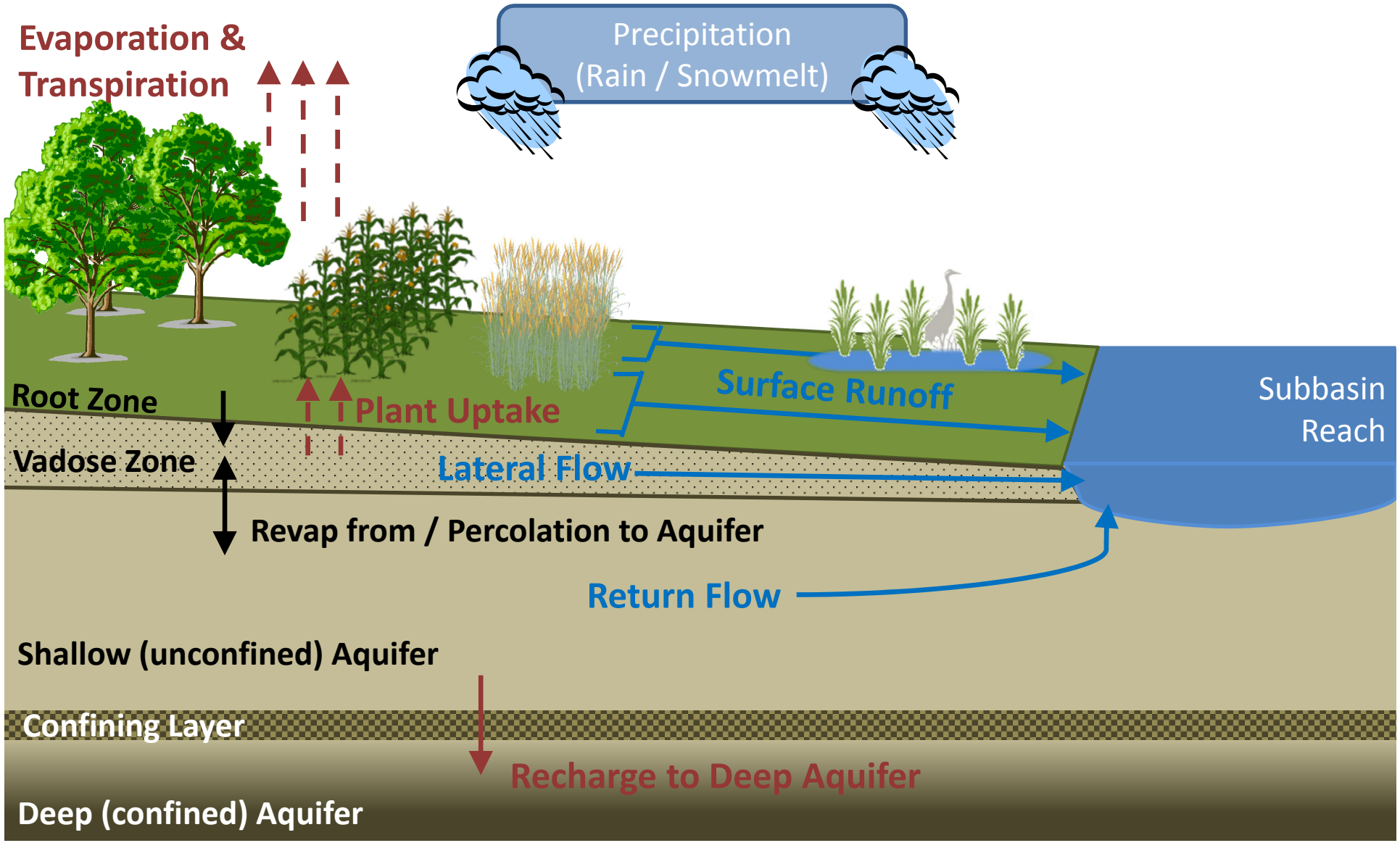
Model Selection: Soil and Water Assessment Tool (SWAT)



- Simulates conditions on landscape each day based on climate data
- Input data, parameter intensive
- Output information is provided for each subwatershed defined (TMDL reach)
- Outputs include crop yields, water balance, discharge, sediment, & water chemistry

Model Selection: Soil and Water Assessment Tool (SWAT)

SWAT Hydrologic Cycle (Daily Water Balance)



Model Selection: Soil and Water Assessment Tool (SWAT)

SWAT Governing Equations

Not complete list

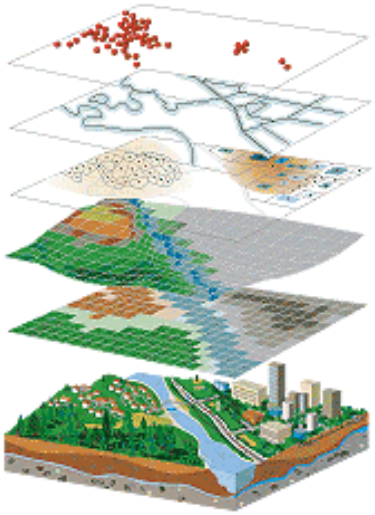
Location	Process	Governing Equation
Landscape	Hydrology - Runoff	SCS Curve Number
	Hydrology – Peak Flow	Rational Method
	Hydrology - Lateral	Lateral Flow - Kinematic Storage Model
	Hydrology - Groundwater	Daily Water Balance
	Sediment	Modified Universal Soil Loss Equation
	Phosphorus	Partitioning Factor (runoff) Load Function (sediment adsorbed) Crop supply and demand
Channel	Hydrology	Manning's equation Variable Storage Coefficient Method or Muskingum
	Sediment	Bagnold's stream power
	Phosphorus	QUAL2E
Pond, Wetland, & Reservoirs	Hydrology	Water balance / user-provided outflow
	Sediment	Based on volume / concentration of inflow, outflow & storage
	Phosphorus	Simple transformation routines that assume water body to be completely mixed

Model Selection: Soil and Water Assessment Tool (SWAT)

Why choose SWAT?

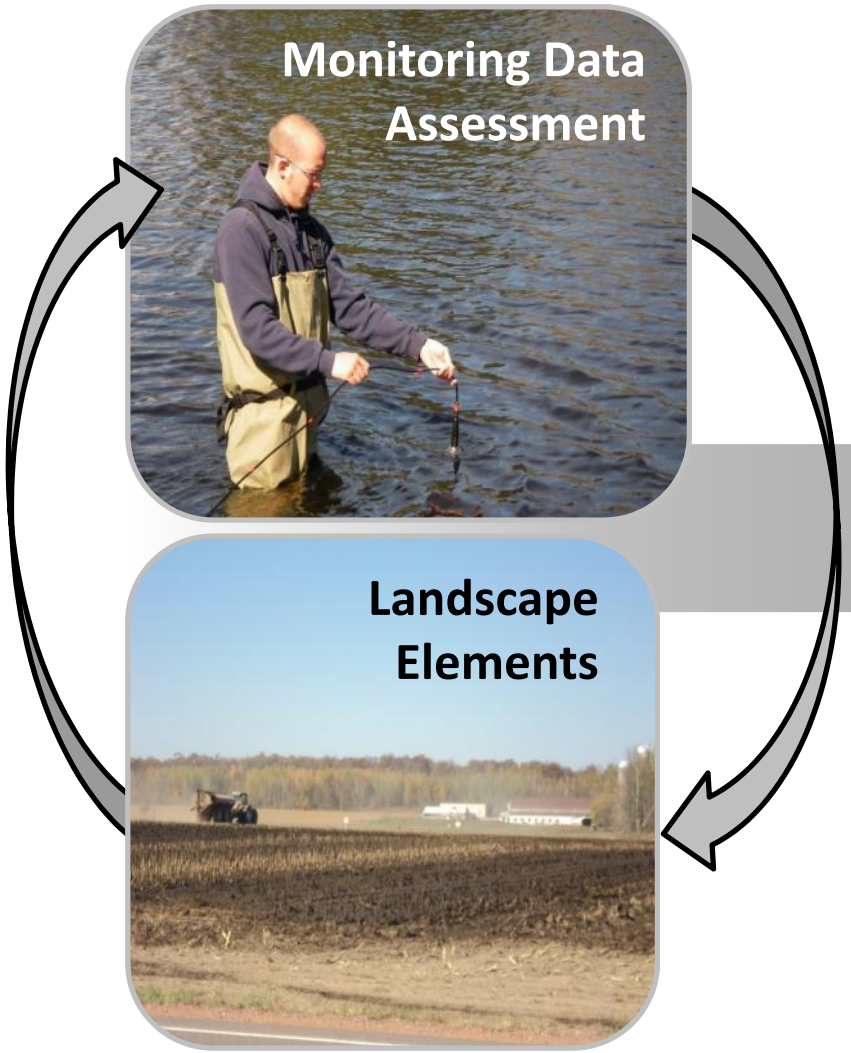
- Public domain, open source code, user support
- GIS-based user interface
- Previously applied to TMDLs throughout Wisconsin and the United States
- Ability to incorporate heterogeneity of agricultural management
- Ability to simulate monthly nutrient loads

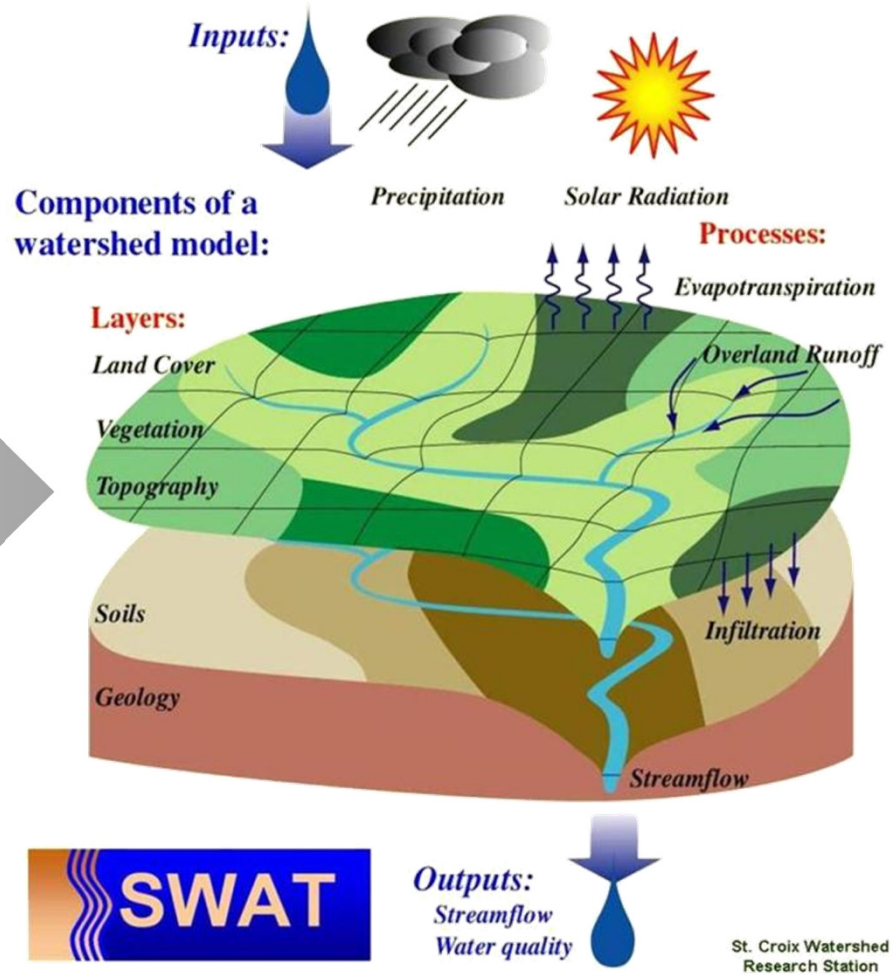
Process Overview



MODEL SELECTION → MONITORING & LANDSCAPE DATASET DEVELOPMENT

Data Collection



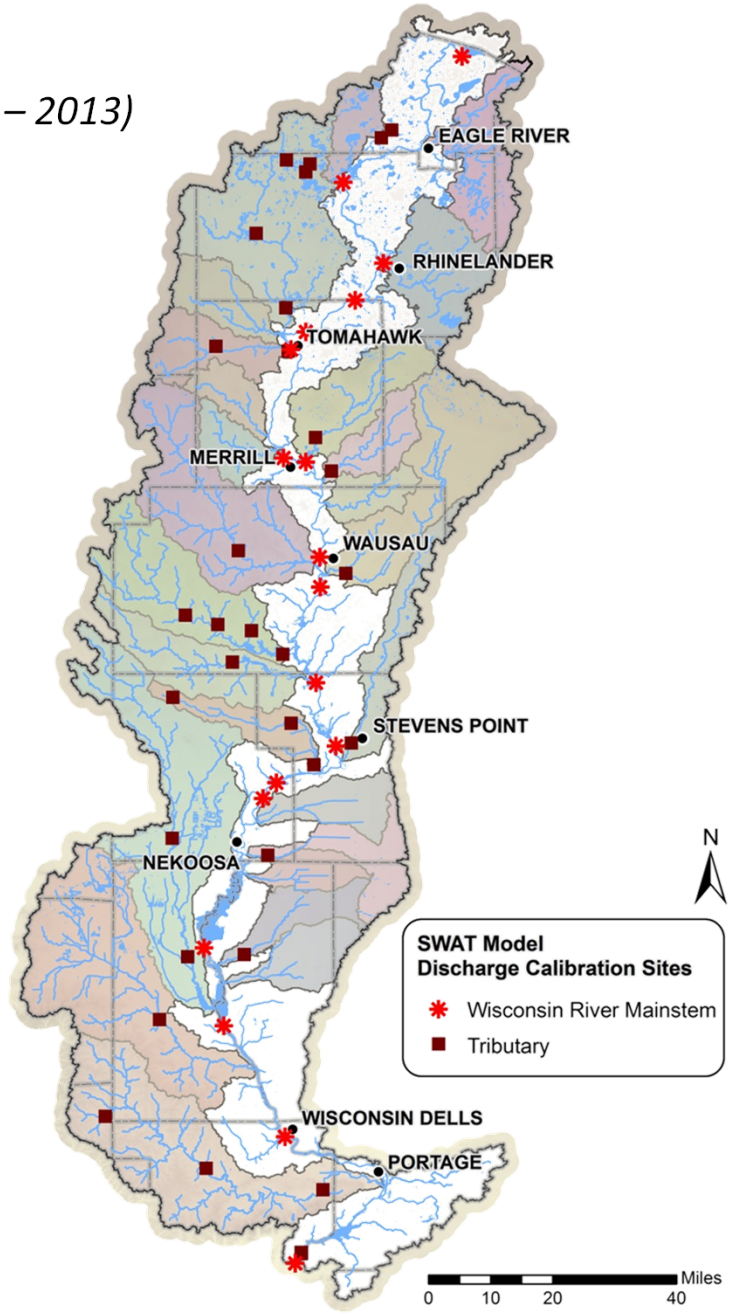


Data Collection: Discharge and Water Quality

- Measured Daily Discharge
  Collected during all or a portion of the simulation period (2002 – 2013)

  ✓ 18 Wisconsin River sites

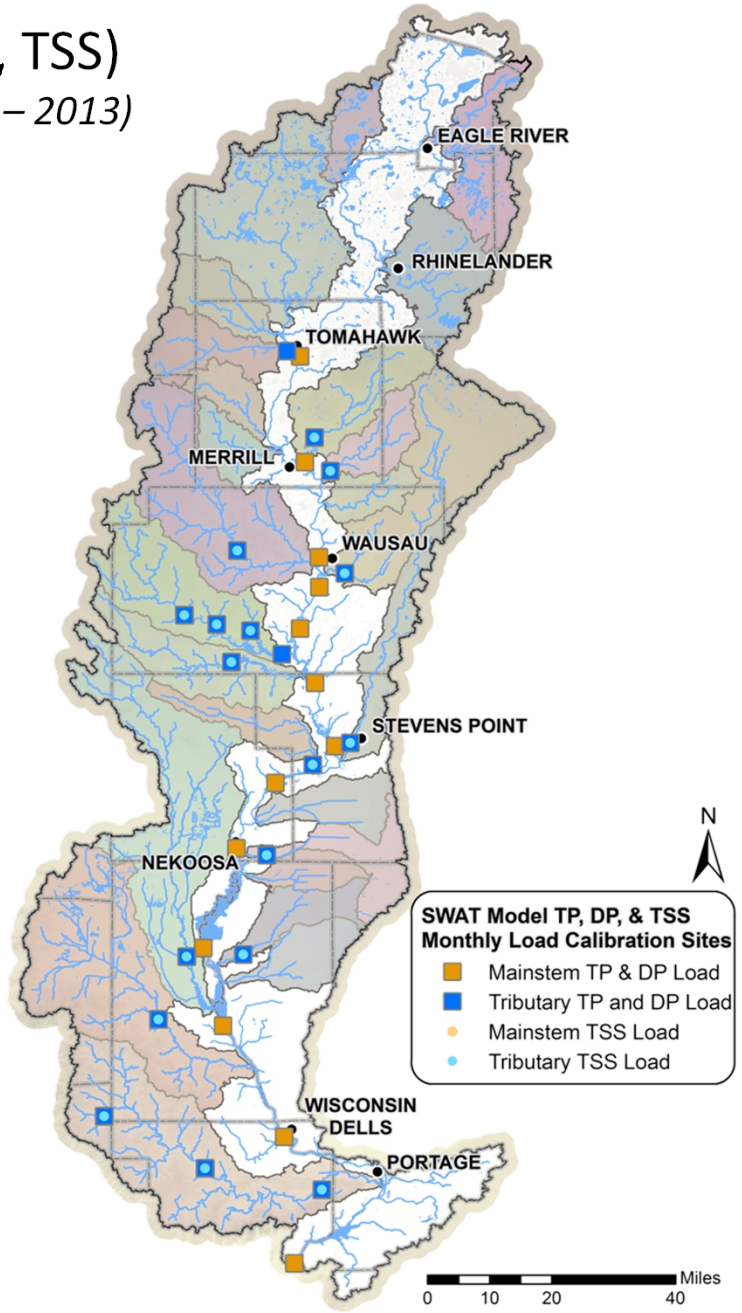
  ✓ 33 Tributary sites



Data Collection: Discharge and Water Quality

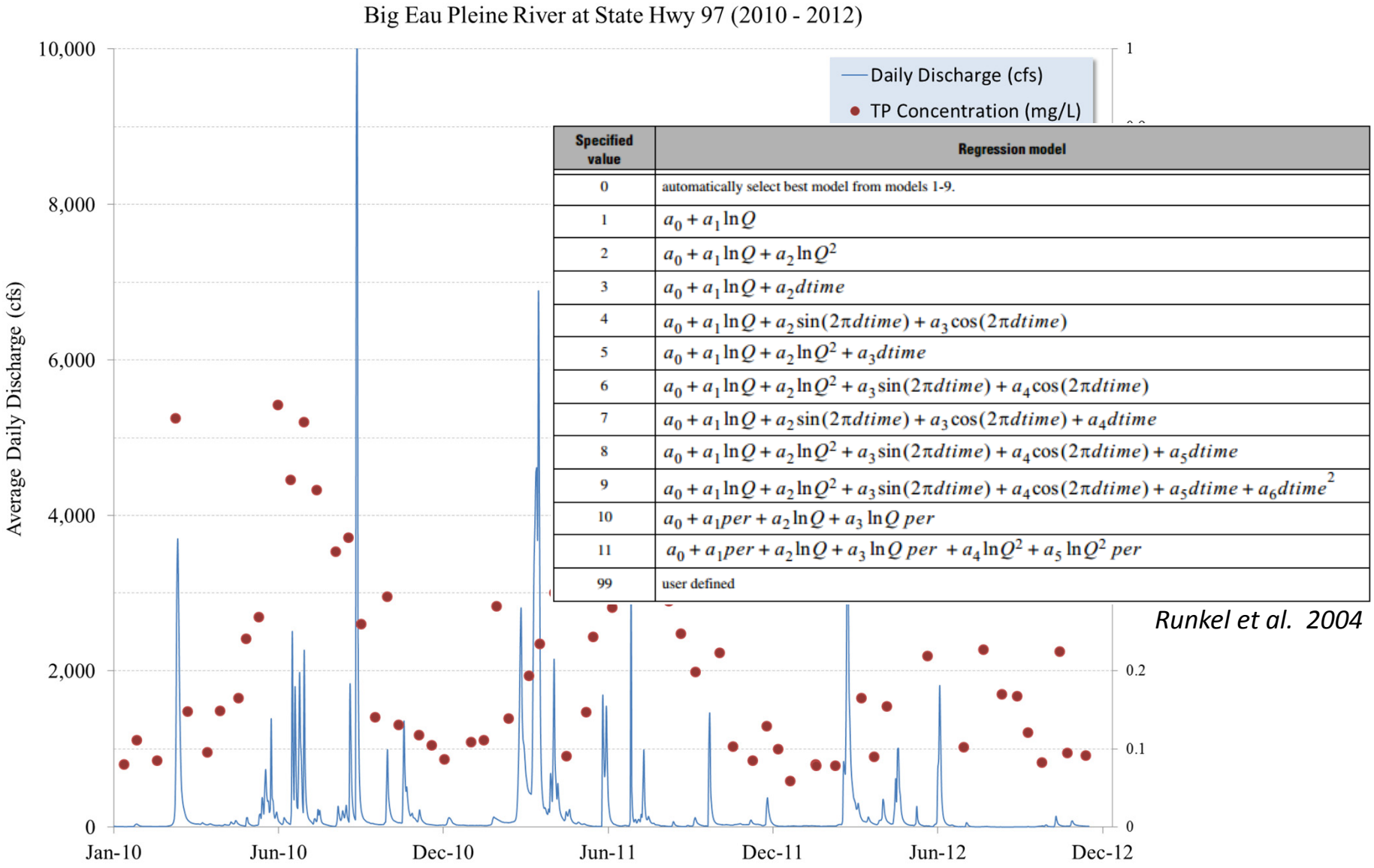
- Measured Bi-Weekly Water Chemistry (TP, DP, TSS)
  Collected during all or a portion of the simulation period (2002 – 2013)

  - ✓ 13 Wisconsin River sites with TP, DP Loads
  - ✓ 19 Tributary sites with TP, DP Loads
  - ✓ 17 Tributary sites with TSS Loads



Data Collection: Calculating Loads

- Monthly TP, DP, & TSS loads will be calculated by USGS using LOADEST

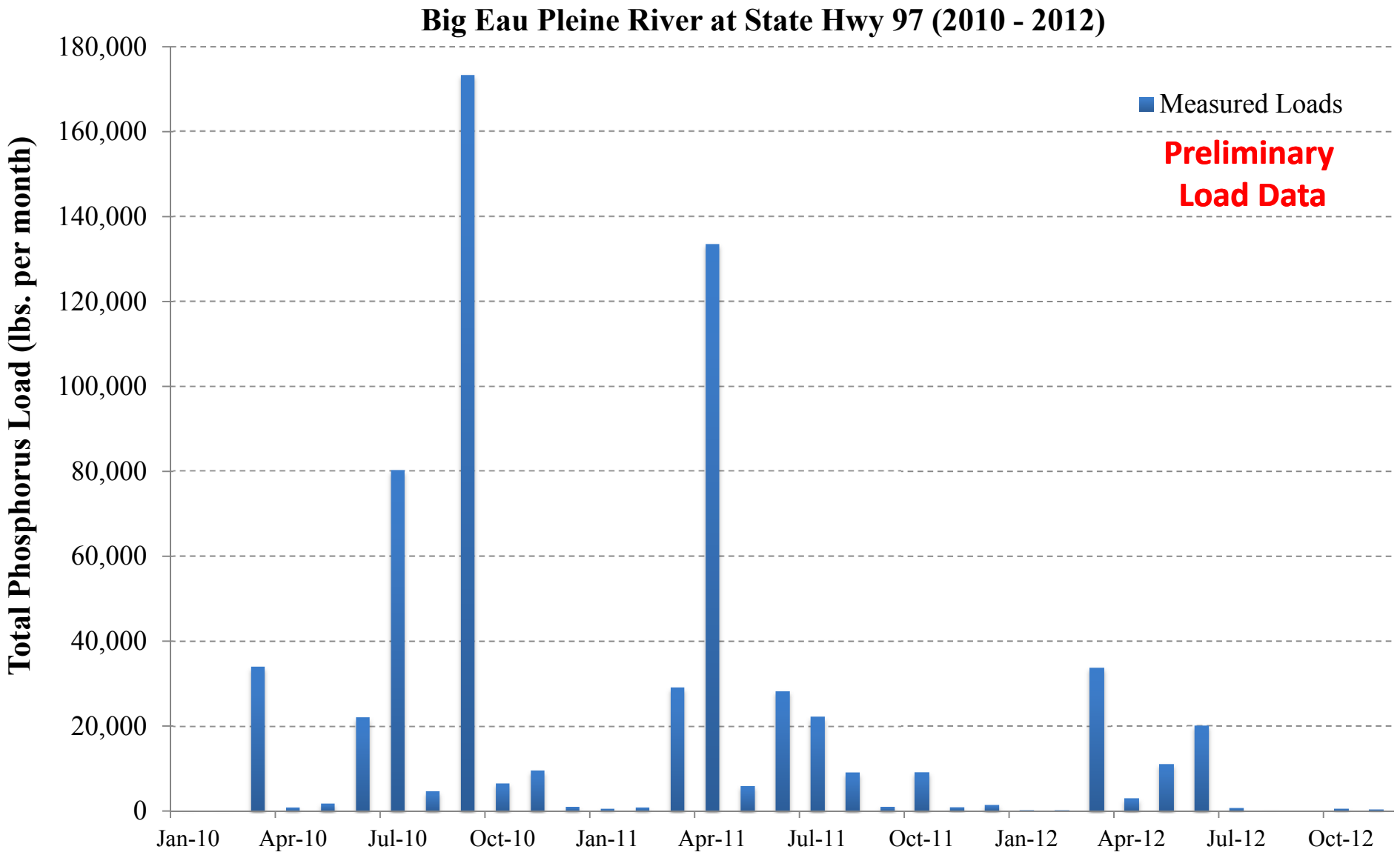


Specified value	Regression model
0	automatically select best model from models 1-9.
1	$a_0 + a_1 \ln Q$
2	$a_0 + a_1 \ln Q + a_2 \ln Q^2$
3	$a_0 + a_1 \ln Q + a_2 dtime$
4	$a_0 + a_1 \ln Q + a_2 \sin(2\pi dtime) + a_3 \cos(2\pi dtime)$
5	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 dtime$
6	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi dtime) + a_4 \cos(2\pi dtime)$
7	$a_0 + a_1 \ln Q + a_2 \sin(2\pi dtime) + a_3 \cos(2\pi dtime) + a_4 dtime$
8	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi dtime) + a_4 \cos(2\pi dtime) + a_5 dtime$
9	$a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi dtime) + a_4 \cos(2\pi dtime) + a_5 dtime + a_6 dtime^2$
10	$a_0 + a_1 per + a_2 \ln Q + a_3 \ln Q\, per$
11	$a_0 + a_1 per + a_2 \ln Q + a_3 \ln Q\, per + a_4 \ln Q^2 + a_5 \ln Q^2\, per$
99	user defined

Runkel et al. 2004

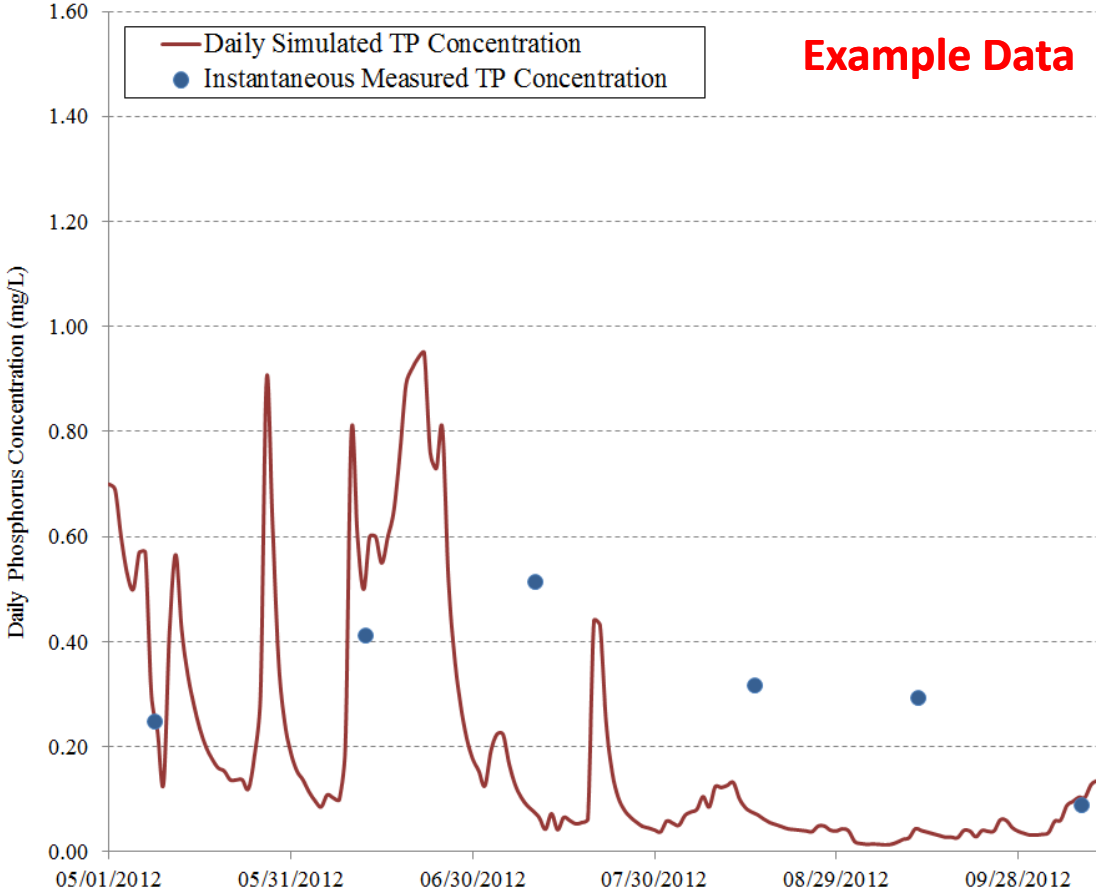
Data Collection: Calculating Loads

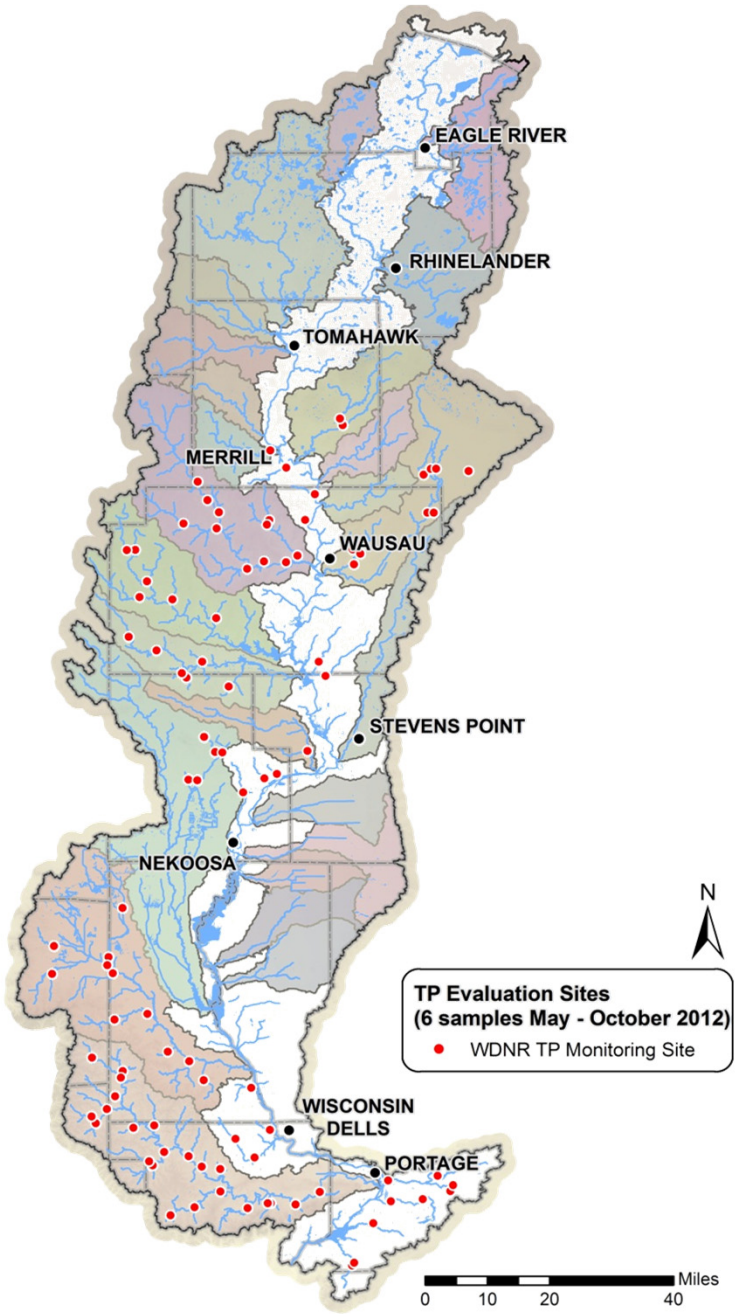
- Monthly TP, DP, & TSS loads will be calculated by USGS using LOADEST



Data Collection: Instantaneous Grab Samples

- What about other data such as tributary & main stem grab samples?
  - ✓ Secondary model evaluation
  - ✓ Conceptualization (DP vs. TP)





Data Collection: Annual Water Budget

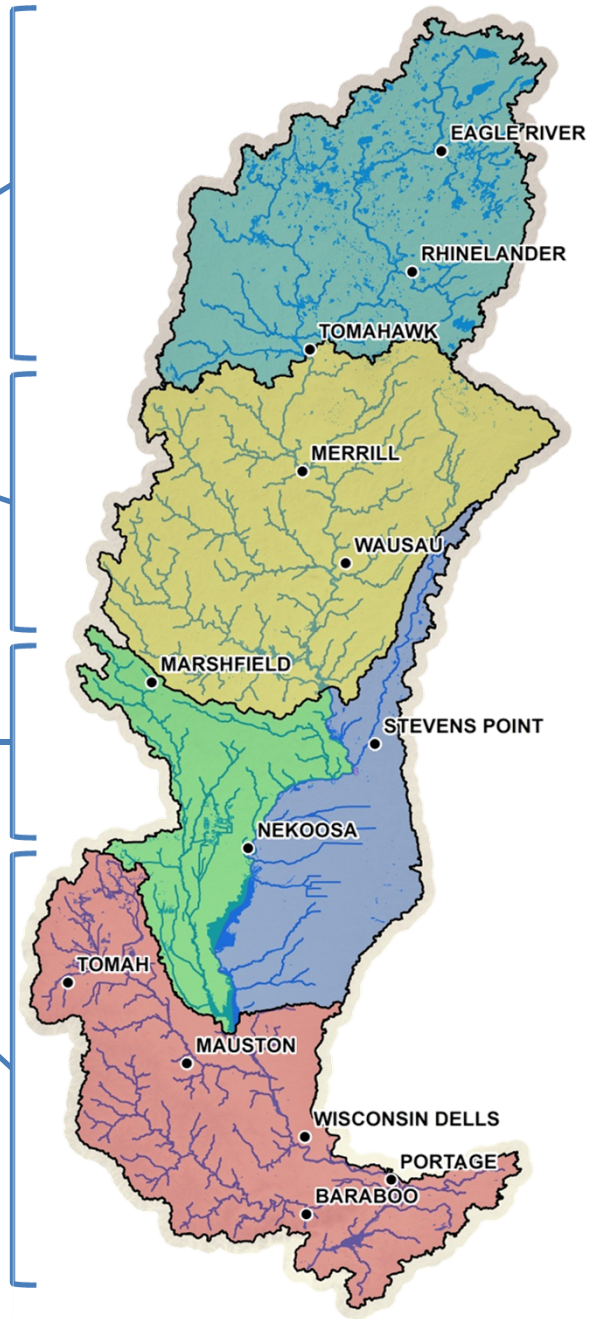
- What is the estimated average annual water budget for the segments of the watershed?

Precipitation	Runoff	Recharge	ET	Water Yield
33”	2.4”	6.4”	24”	9”

Precipitation	Runoff	Recharge	ET	Water Yield
34”	1.5”	4.1”	26”	9”

Precipitation	Runoff	Recharge	ET	Water Yield
34” (EAST)	1.6”	8.0”	26”	9”
34” (WEST)	2.9”	2.4”	26”	9”

Precipitation	Runoff	Recharge	ET	Water Yield
35”	1.8”	6.6”	24”	10”

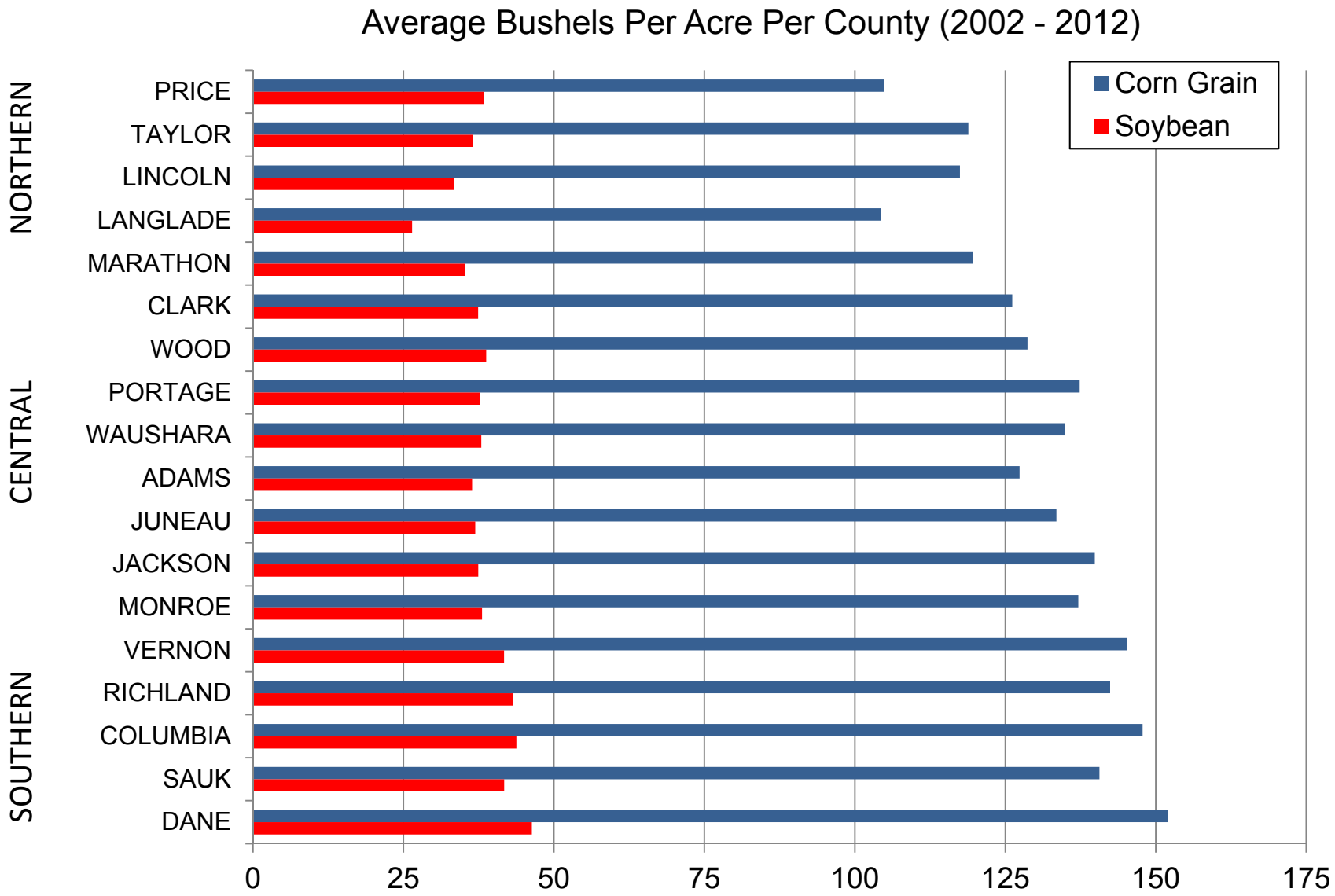


Data Sources

1. Precipitation from NASA’s DayMet (1980-2011)
2. Runoff estimates modeled by WDNR Science Services (Mednick *et al.* 2012). Includes snowmelt and baseflow
3. Recharge estimates from USGS OFR 2009-2010 (1970-1999)
4. ET estimates from UW-Extension Ag Science Center (2002-2012)

Data Collection: Crop Yield

- What are the crop yields during the simulation period for specific areas?



Data Collection: Model Inputs

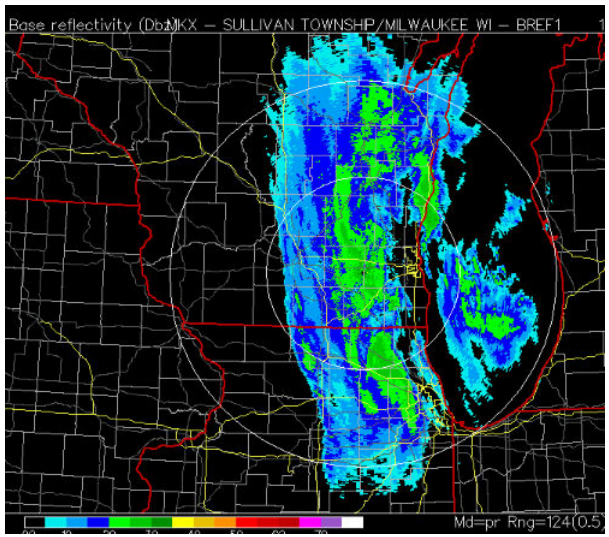
2002 – 2013 Conditions

- **Climate**
  Precipitation, Temp, etc.
- **Hydrology**
  Flow accumulation, Internal drainage, groundwater
- **Topography**
  Slope
- **Soils**
  Type and Attributes
- **Land Cover**
- **Land Management**
  Agriculture, Urban
- **Point Sources**

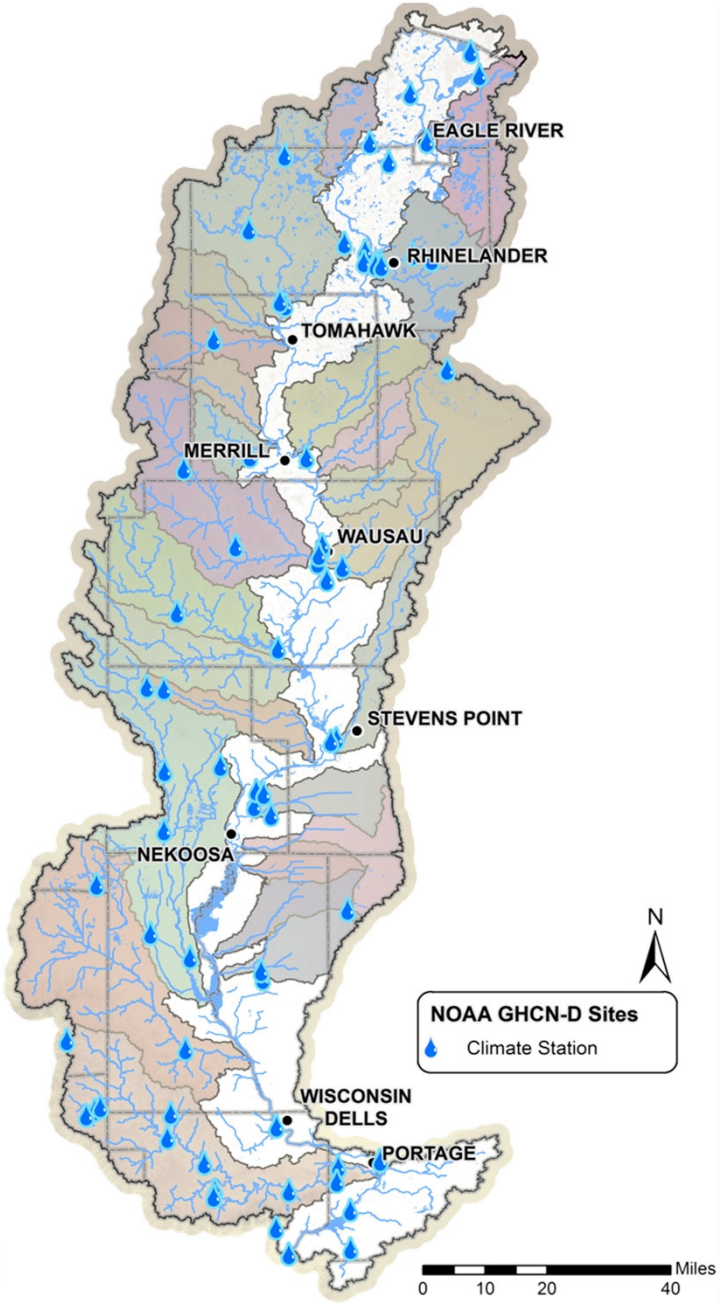
Data Collection: Climate

- **Climate**
- Elevation
- Hydrology
- Soils
- Land cover
- Land Management
- Point Sources

- Primary Data
  - Daily Precipitation
  - Min/Max Temperature
- Other Climate Data
  - Solar Radiation
  - Relative Humidity
  - Wind



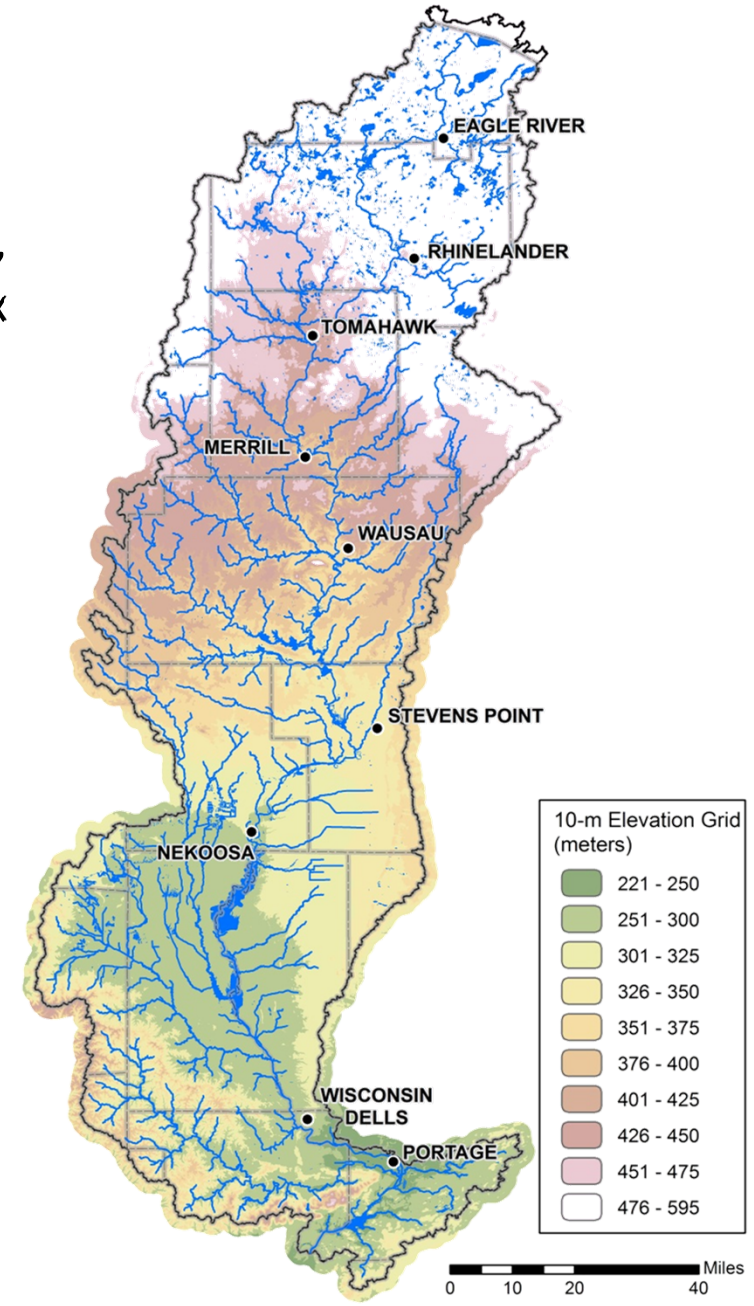
NEXRAD (Gridded Precipitation Data)



Data Collection: Elevation

- Climate
- **Elevation**
- Hydrology
- Soils
- Land cover
- Land Management
- Point Sources

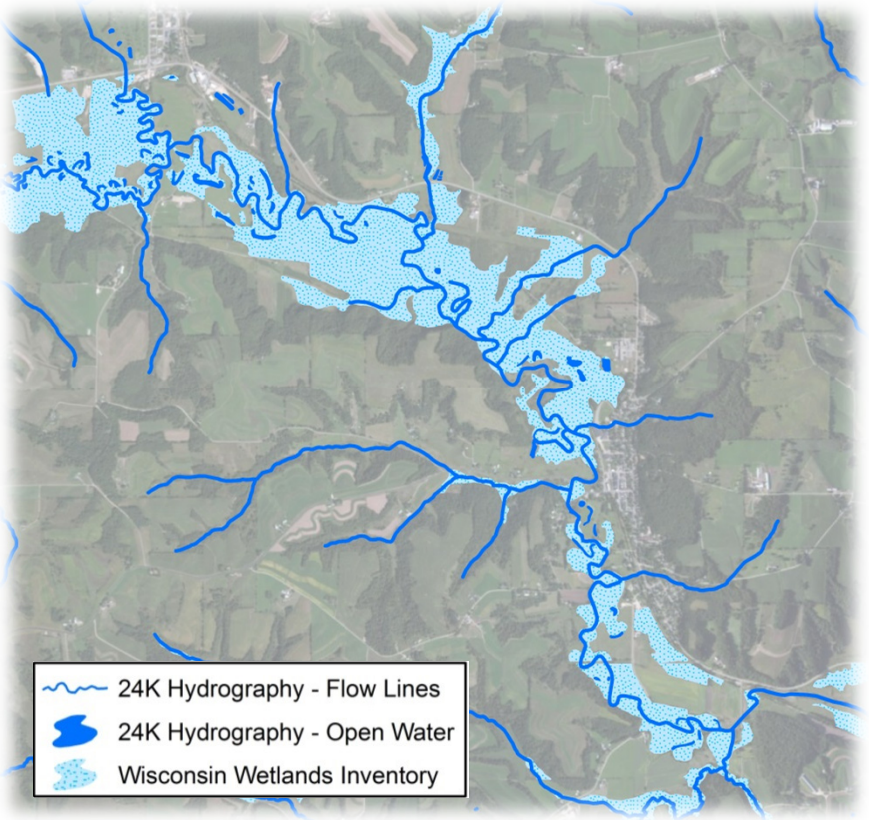
- 10-meter DEM from NRCS
- Used for calculating slope, slope length, min and max elevation



Data Collection: Hydrologic Network

- Climate
- Elevation
- **Hydrology**
- Soils
- Land cover
- Land Management
- Point Sources

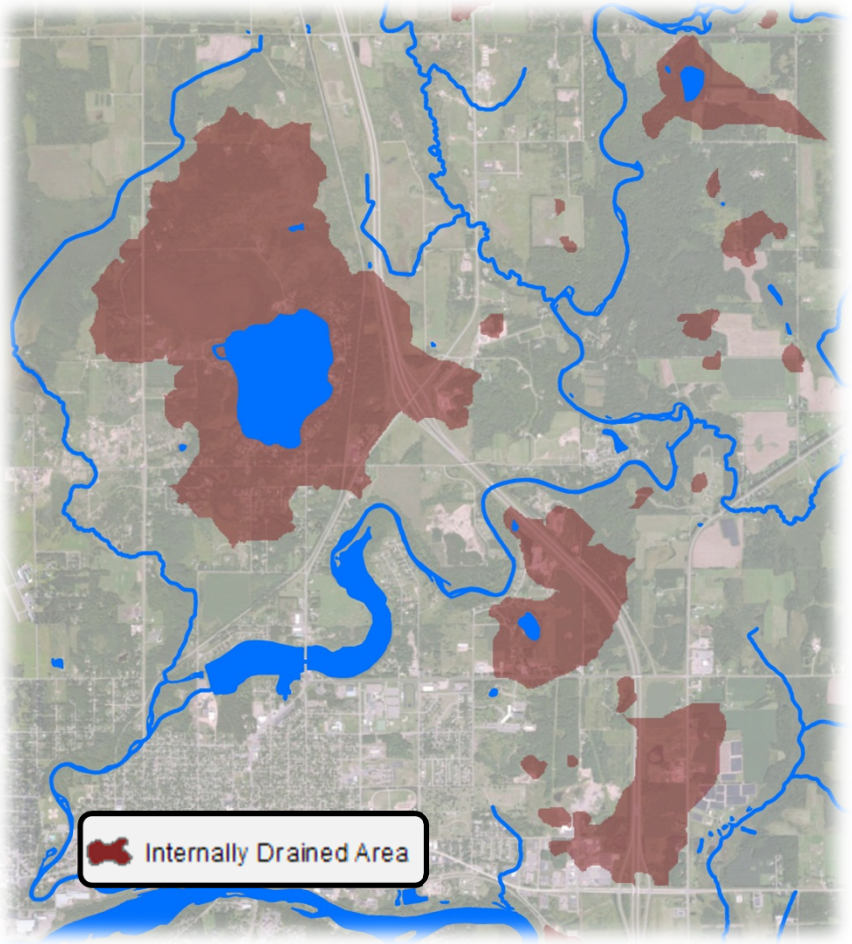
- Hydrologic information includes:
  - ✓ Streamlines - 24K Hydrography WDNR Flow lines
  - ✓ Open Water – 24K Hydrography WDNR Open Water
  - ✓ Wisconsin Wetland Inventory
- Used for stream reach properties, routing through ponds & wetlands



Data Collection: Internally Drained Areas

- Climate
- Elevation
- **Hydrology**
- Soils
- Land cover
- Land Management
- Point Sources

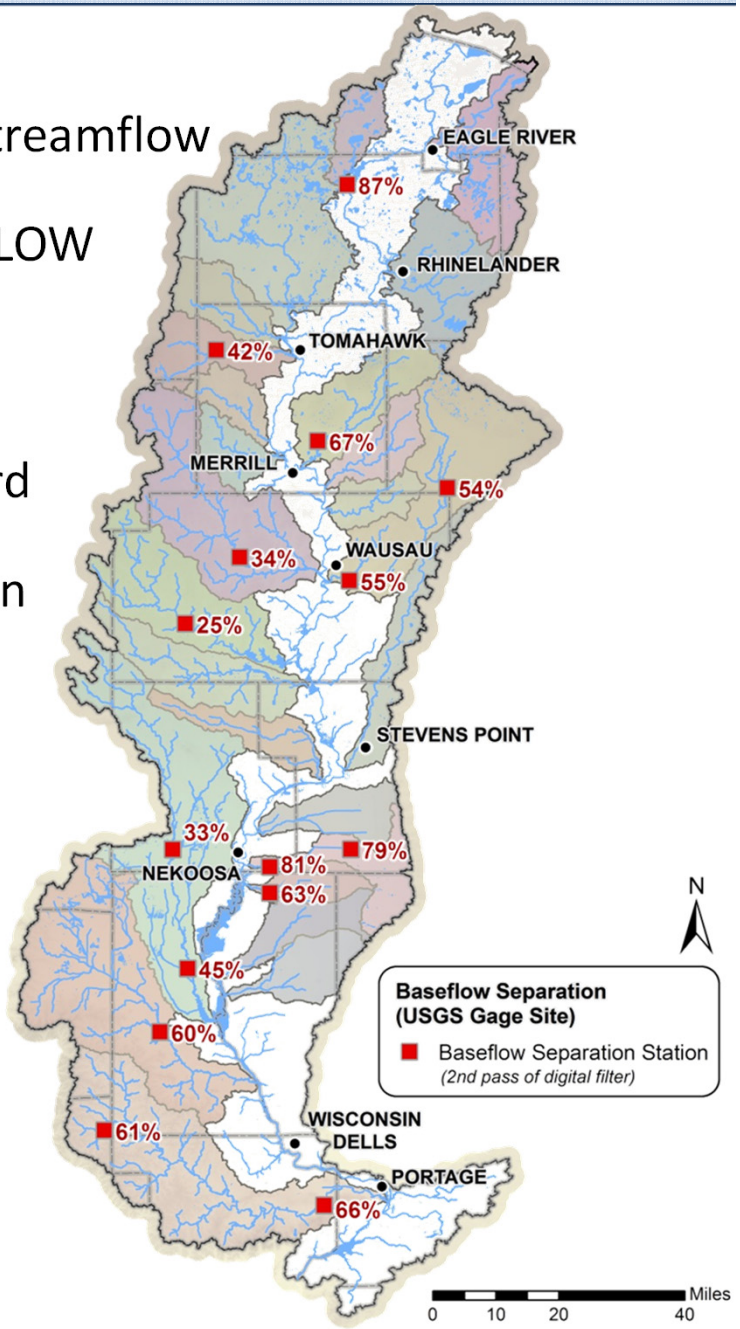
- Delineated using 10-m DEM with 10-yr, 24-hr event threshold (~ 4” event)
- Areas that typically drain to subsurface



Data Collection: Baseflow

- Climate
- Elevation
- **Hydrology**
- Soils
- Land cover
- Land Management
- Point Sources

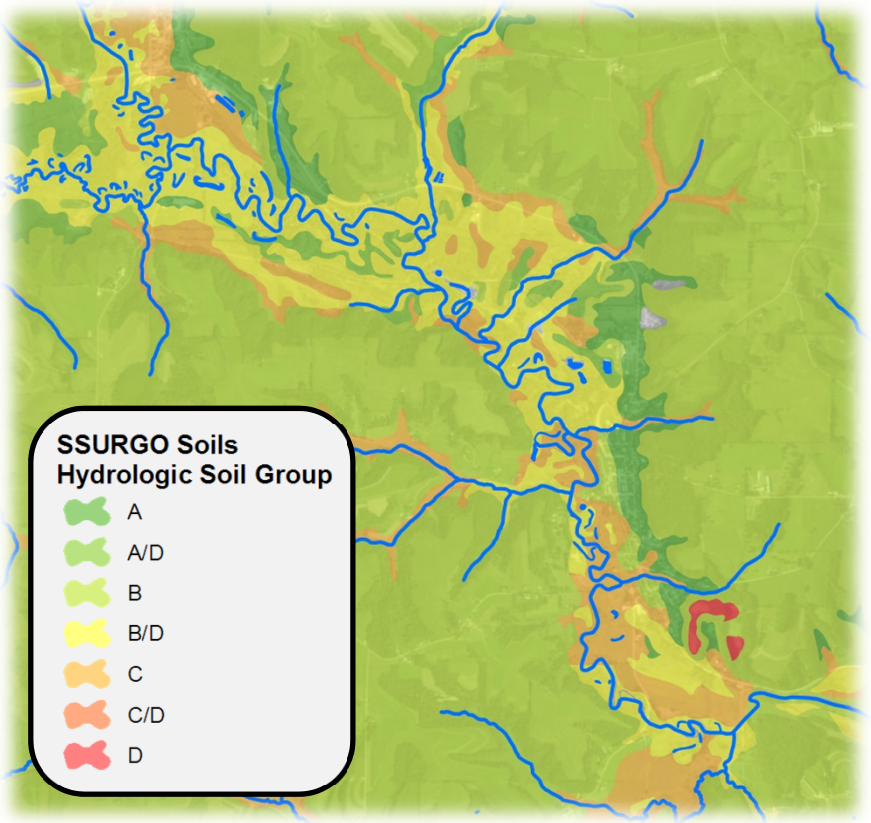
- Baseflow contribution to streamflow
  - ✓ Calculated through BFLOW program
  - ✓ Used USGS gage sites with at least 5-yr record
- Provides baseflow recession constant groundwater parameter



Data Collection: Soils

- Climate
- Elevation
- Hydrology
- **Soils**
- Land cover
- Land Management
- Point Sources

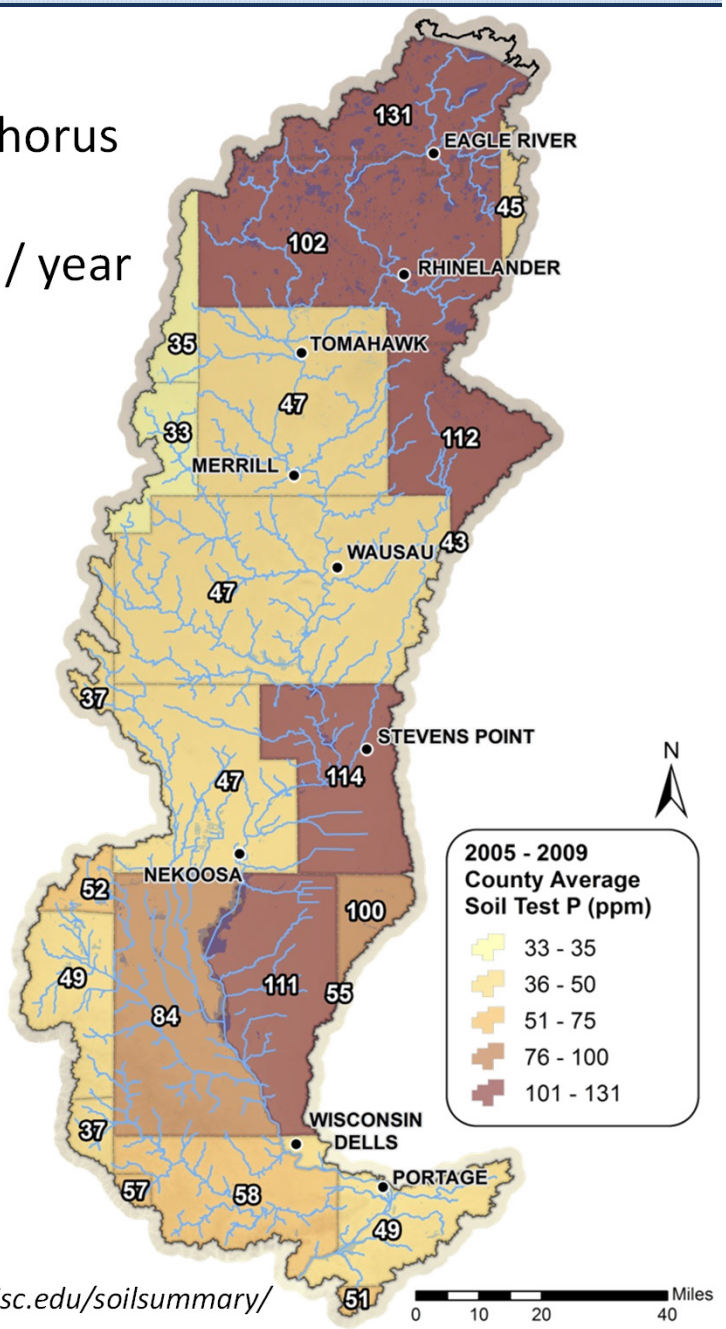
- NRCS SSURGO Soils
- Used for soil properties including runoff potential and soil profiles & depths



Data Collection: Soil Phosphorus

- Climate
- Elevation
- Hydrology
- **Soils**
- Land cover
- Land Management
- Point Sources

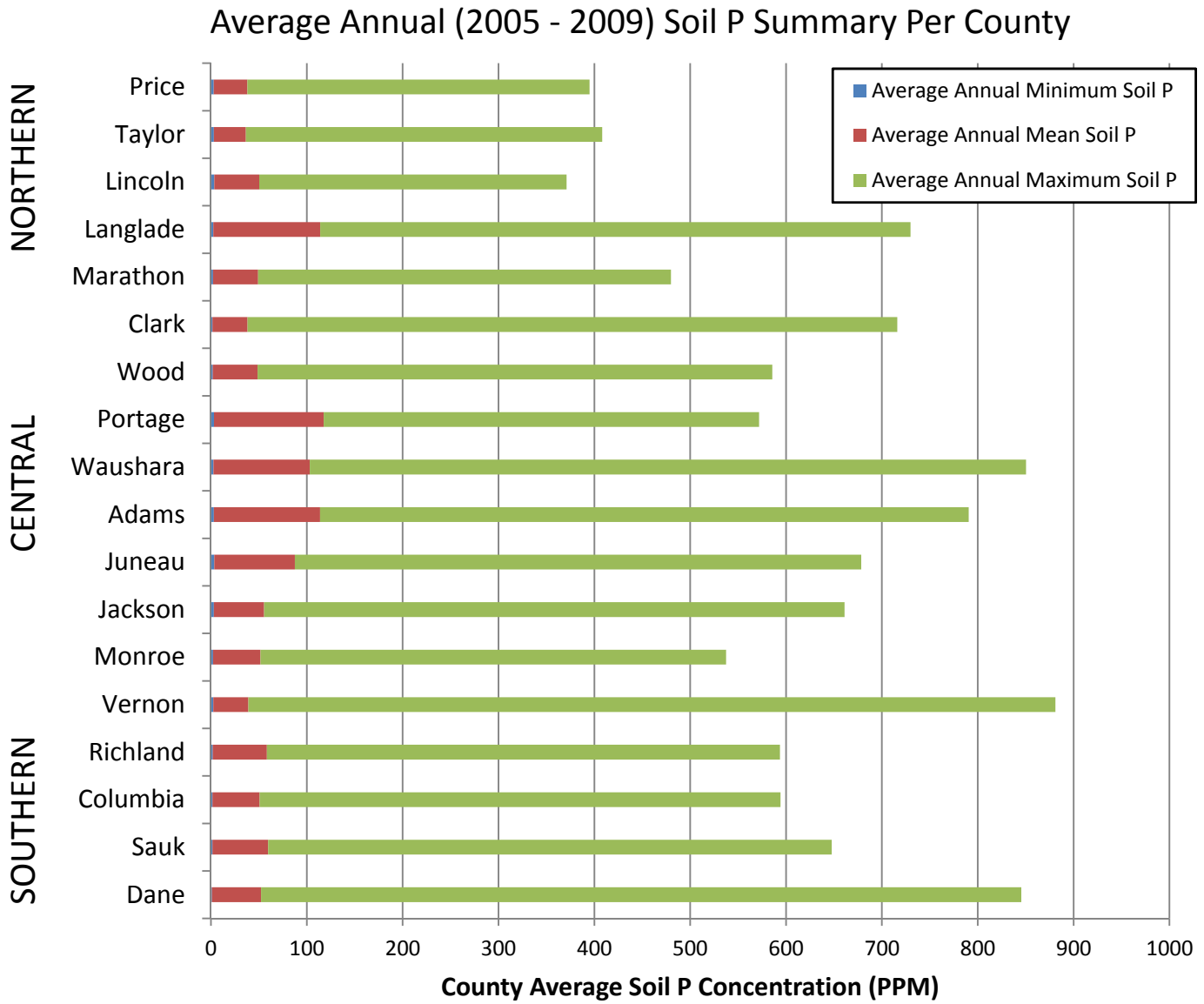
- UW Soil Test Lab Soil Phosphorus
  - ✓ Average soil P / county / year



http://uwlab.soils.wisc.edu/soilsummary/

Data Collection: Soil Phosphorus

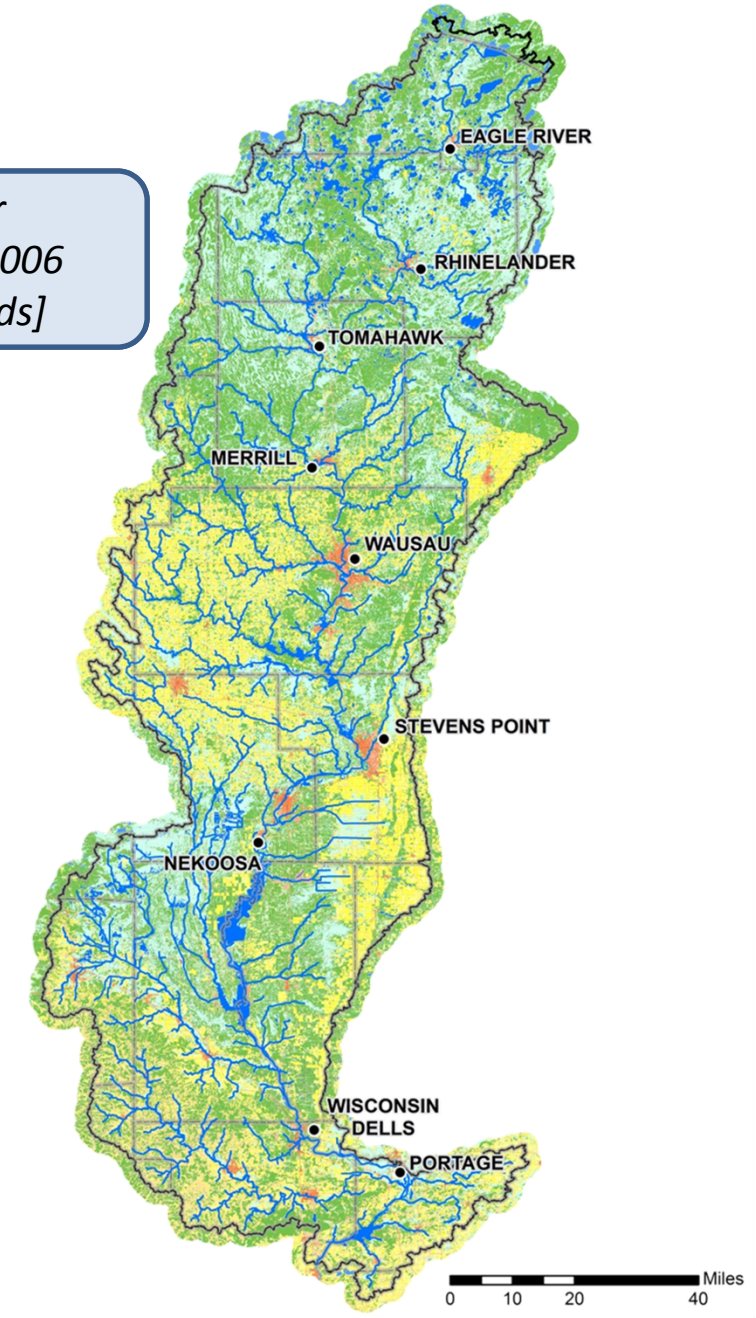
- Climate
- Elevation
- Hydrology
- **Soils**
- Land cover
- Land Management
- Point Sources



Data Collection: Land Cover

- Climate
- Elevation
- Hydrology
- Soils
- **Land cover**
- Land Management
- Point Sources

- Composite Land Cover
  - 2011 USDA Cropland Data Layer
    [2011 cropland extent with 2006 NLCD defining remaining lands]
    - \+ Wisconsin Wetland Inventory
    - \+ 24 Hydrography Open Water - *[Cranberry Bogs]*
    - − Areas modeled with urban model
  - SWAT Input Composite Land Cover

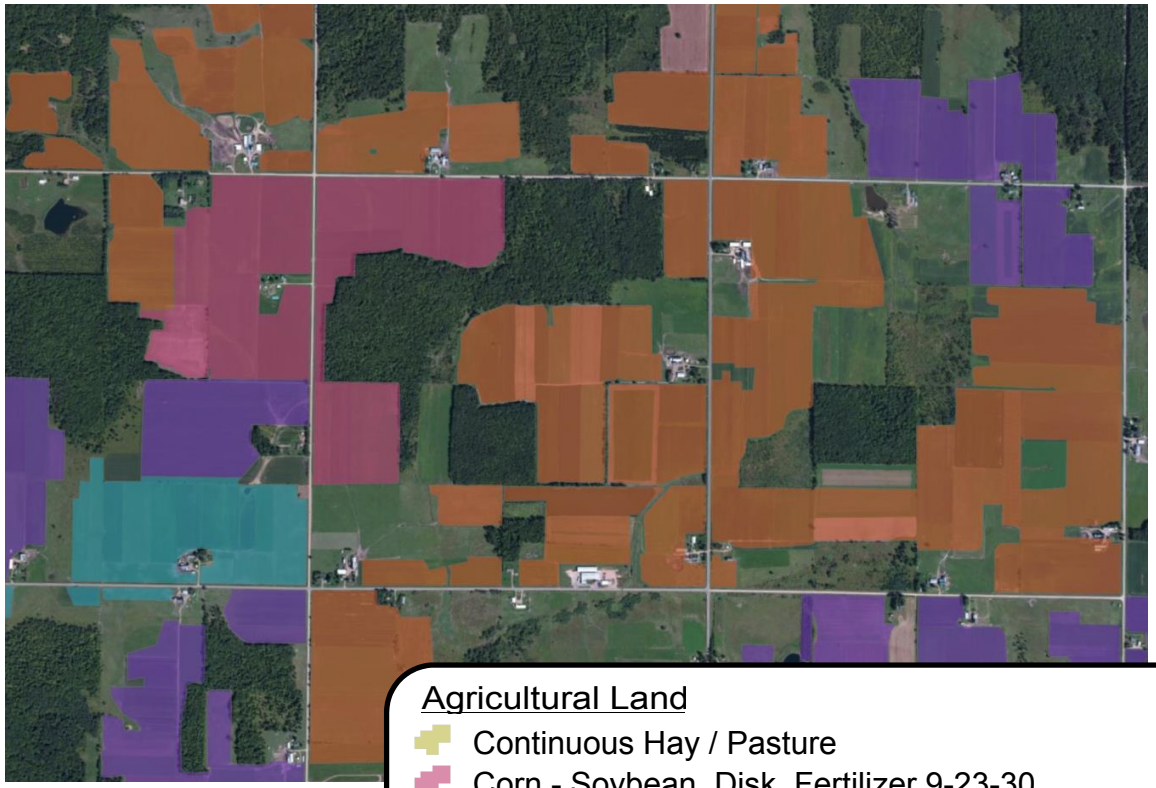


Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management

Spatially and temporally define agricultural land management throughout the basin

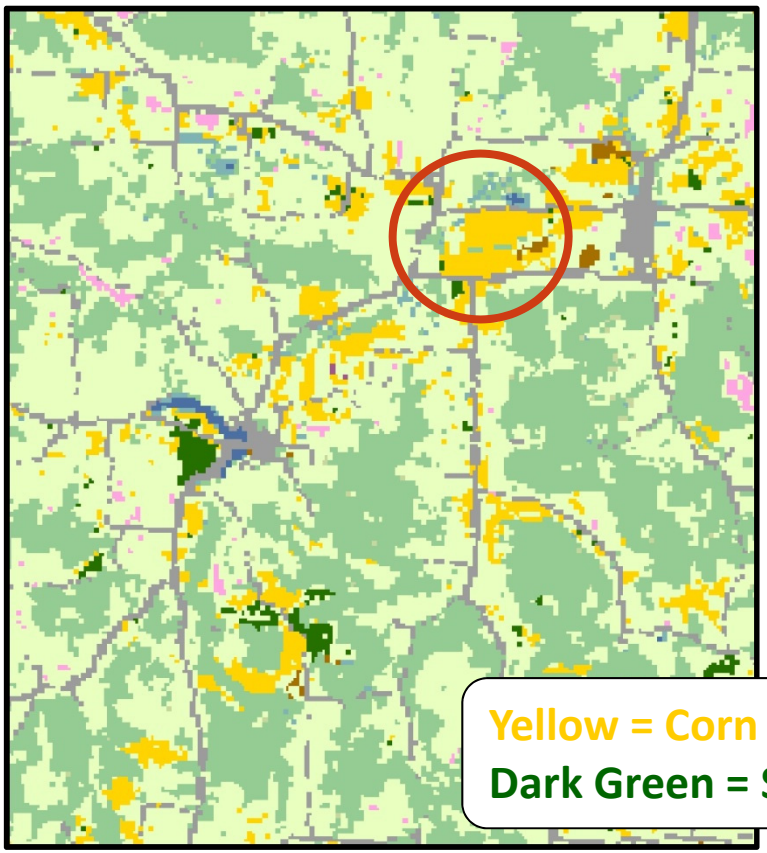


Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 1

  Use USDA NASS cropland data layers (2008 – 2012) to define annual crop sequence for each ¼ section with agricultural land



2008

Corn

Yellow = Corn
Dark Green = Soybean

Data Collection: Land Management

- Climate
- Elevation
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- Soils
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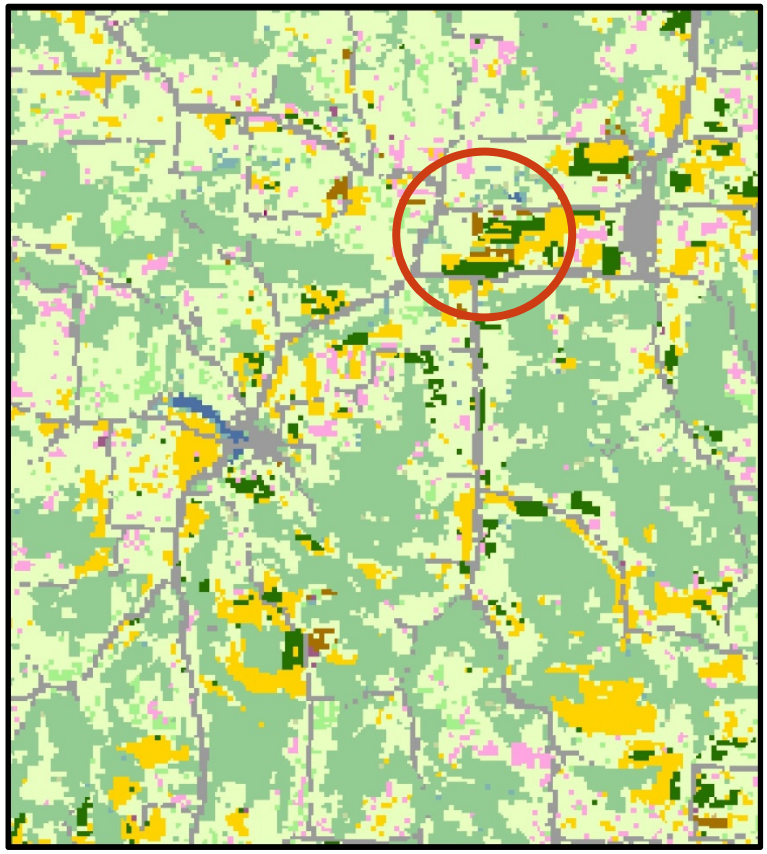
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 1

  Use USDA NASS cropland data layers (2008 – 2012) to define annual crop sequence for each ¼ section with agricultural land



Data Collection: Land Management

- Climate
- Elevation
- Hydrology
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- **Land Management**
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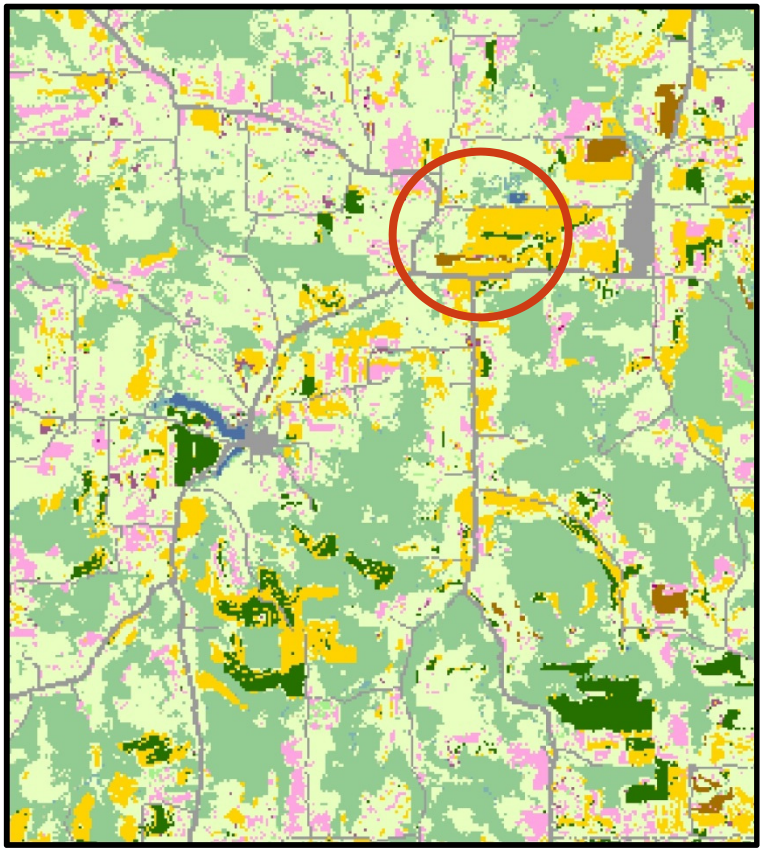
- Agricultural Land Management – Step 1

  Use USDA NASS cropland data layers (2008 – 2012) to define annual crop sequence for each ¼ section with agricultural land



2010

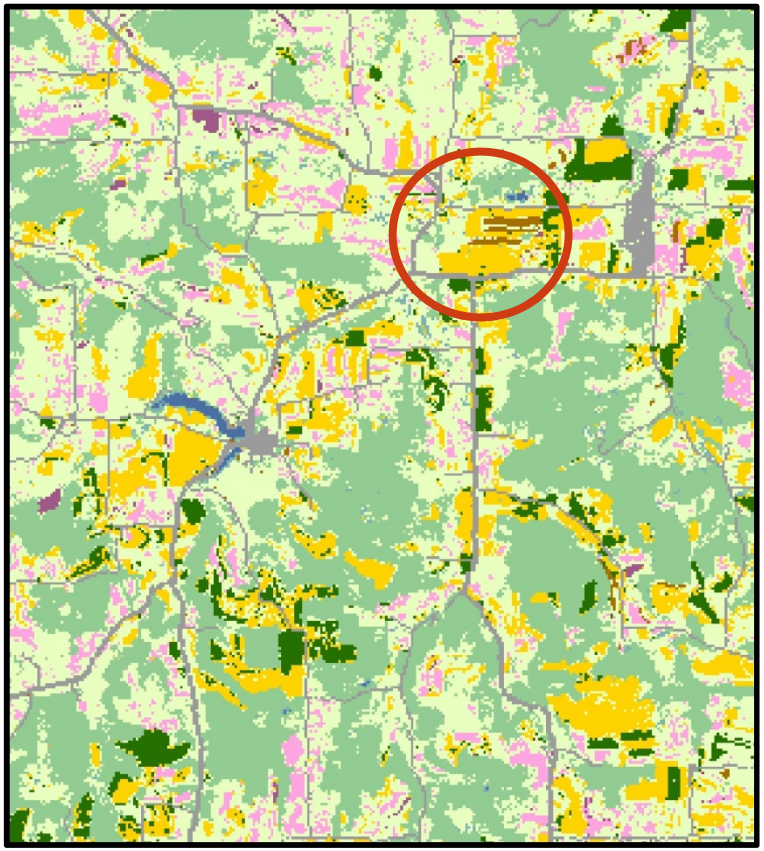
Corn

Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 1

  Use USDA NASS cropland data layers (2008 – 2012) to define annual crop sequence for each ¼ section with agricultural land



2011

Corn

Data Collection: Land Management

- Climate
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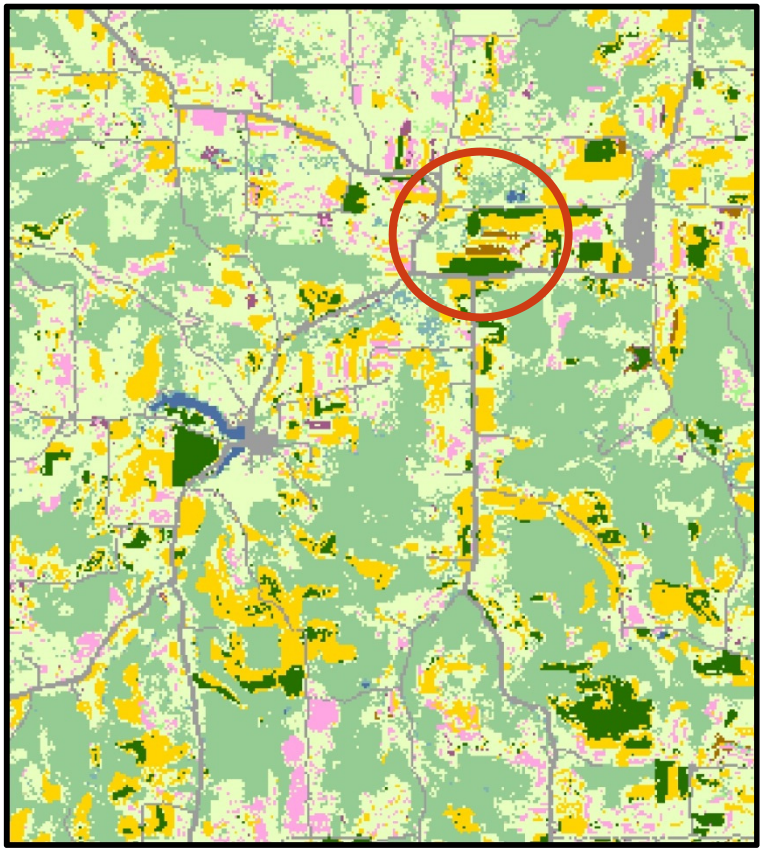
  Use USDA NASS cropland data layers (2008 – 2012) to define annual crop sequence for each ¼ section with agricultural land



Data Collection: Land Management

- Climate
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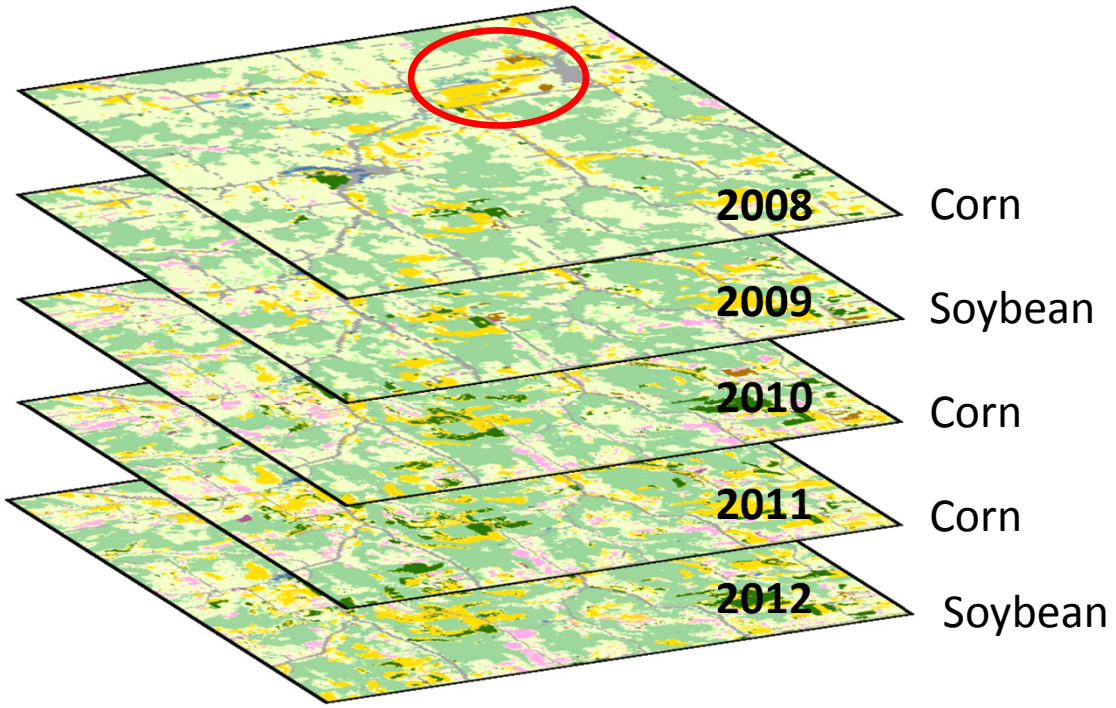
- Agricultural Land Management – Step 1

  Use USDA NASS cropland data layers (2008 – 2012) to define annual crop sequence for each ¼ section with agricultural land



C-C-S-C-C, C-S-C-S-C, S-C-C-S-C, C-C-C-C-S, S-S-S-S-C

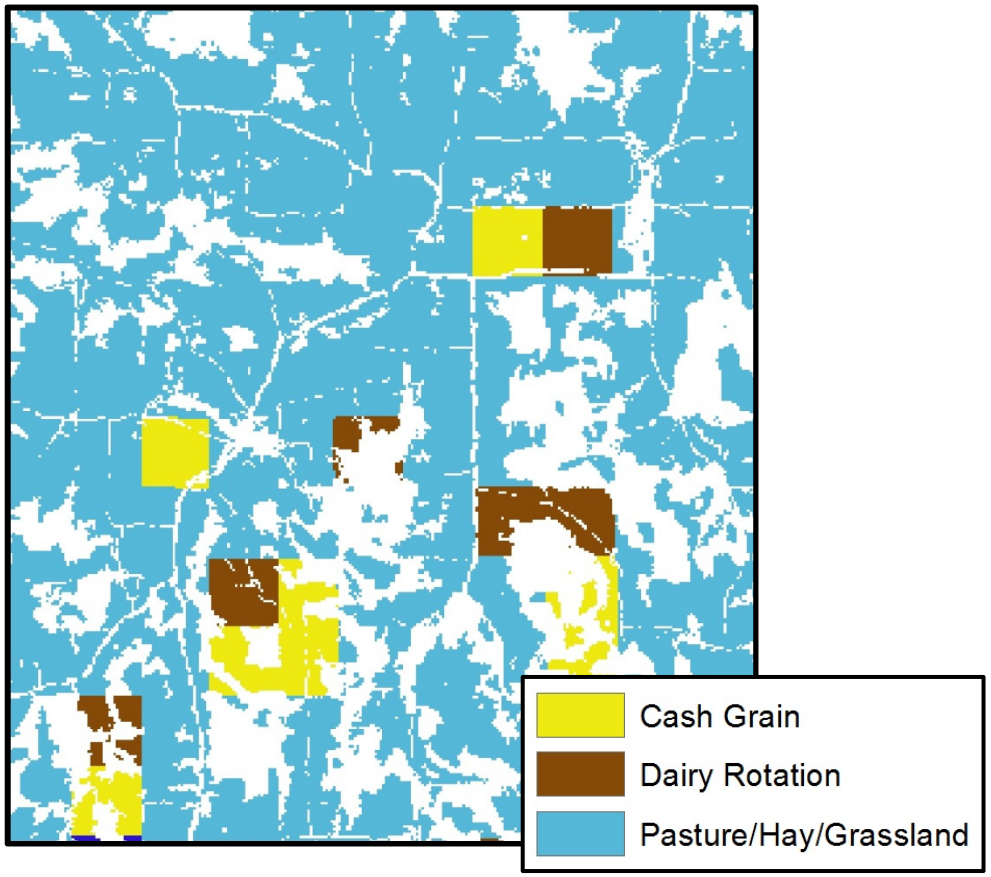
= **Cash Grain**

Data Collection: Land Management

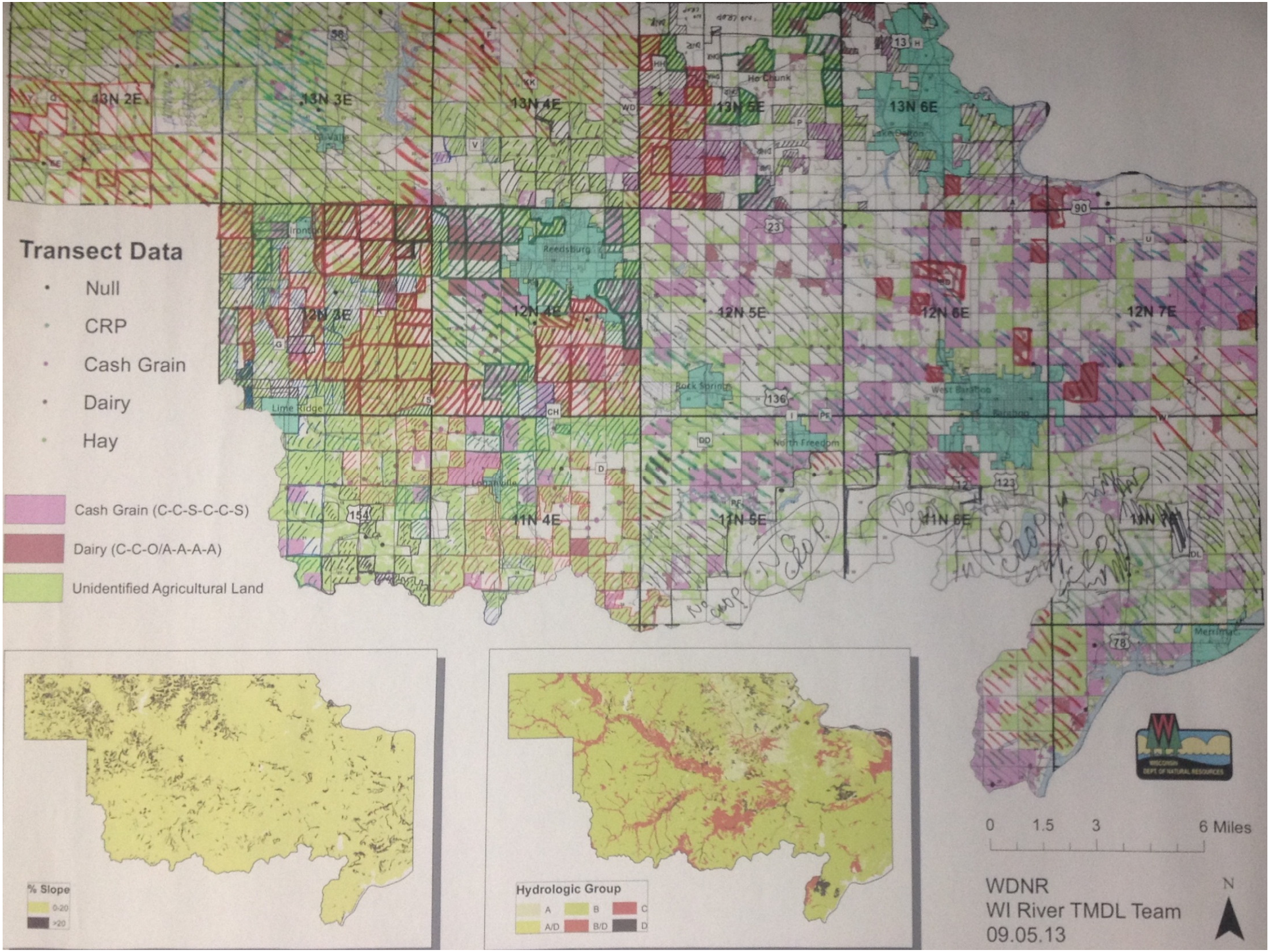
- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 2

  Bin the 5-year crop sequences into specific rotations such as dairy, cash, continuous corn, or potato



G-G-G-G-G = Pasture/Hay/Grassland
C-C-O/A-A-A = Dairy Rotation
C-C-S-C-C-S = Cash Grain

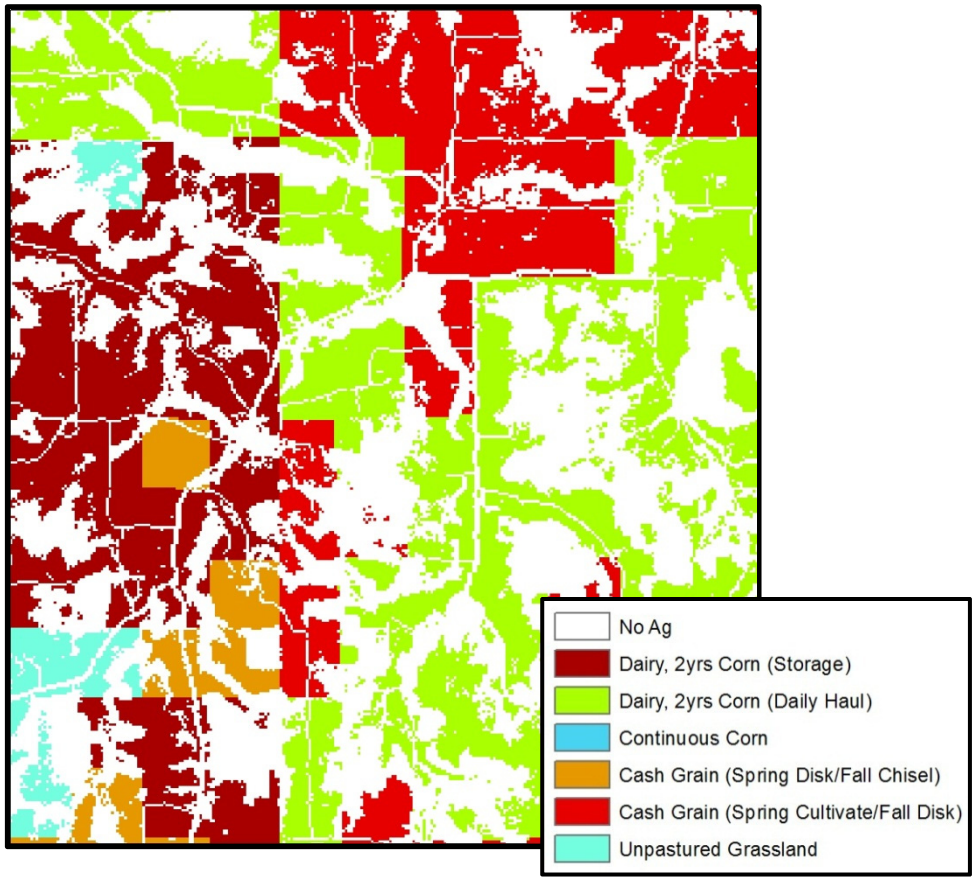

Transect Data
Null
CRP
Cash Grain
Dairy
Hay
Cash Grain (C-C-S-C-C-S)
Dairy (C-C-O/A-A-A-A)
Unidentified Agricultural Land
13N 2E
13N 3E
13N 4E
13N 5E
13N 6E
12N 3E
12N 4E
12N 5E
12N 6E
12N 7E
11N 4E
11N 5E
11N 6E
11N 7E
Reedsburg
Lime Ridge
Rock Springs
West Baraboo
Baraboo
North Freedom
Merrimac
% Slope
0-20
>20
Hydrologic Group
A
B
C
A/D
B/D
D
0 1.5 3 6 Miles
WDNR
WI River TMDL Team
09.05.13
N

Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 3

  Meet with county conservation offices to confirm spatial extent and define temporal variation of rotations (sequence, tillage, nutrient management)

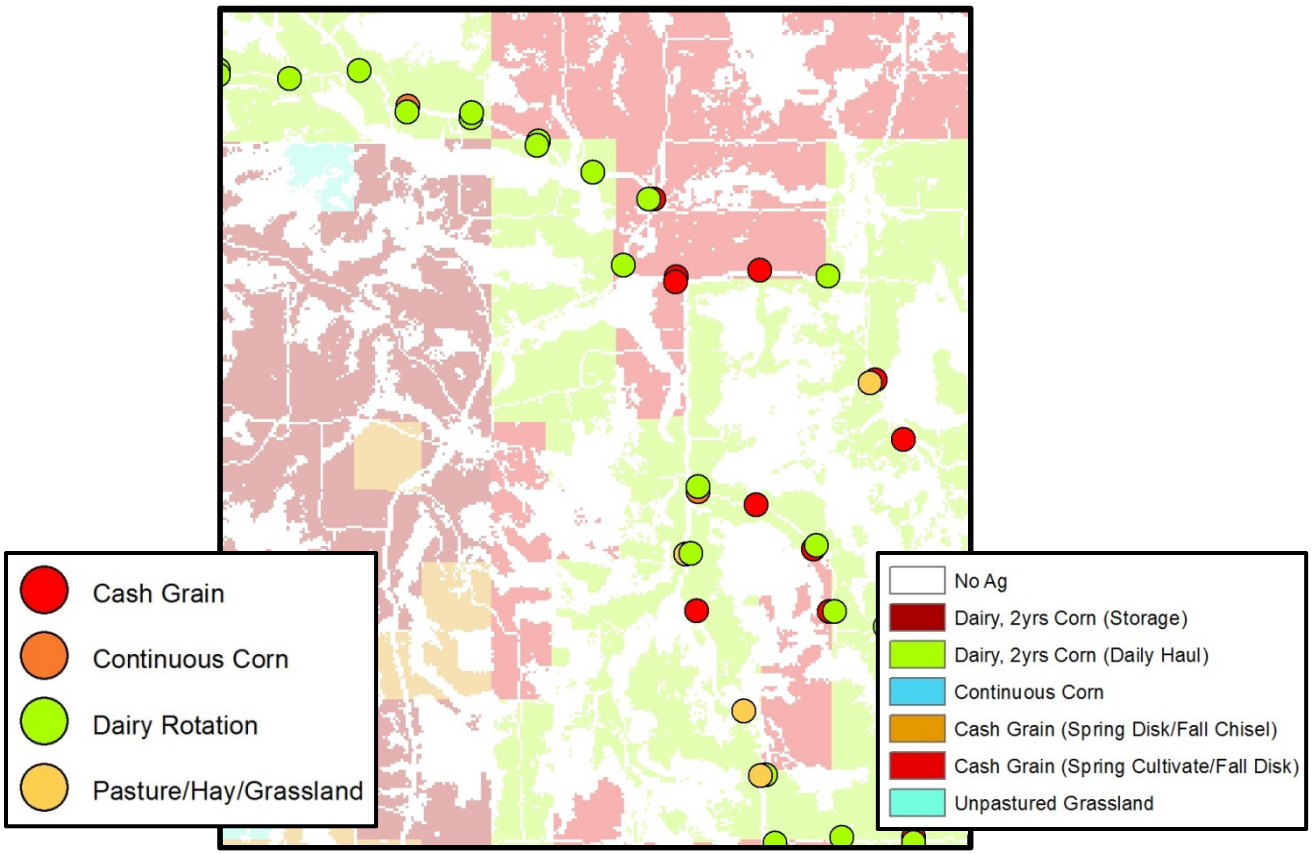


Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 4

  Apply combination of transect data, dairy producer locations, and county conservation staff knowledge to spatially and temporally identify of agricultural management

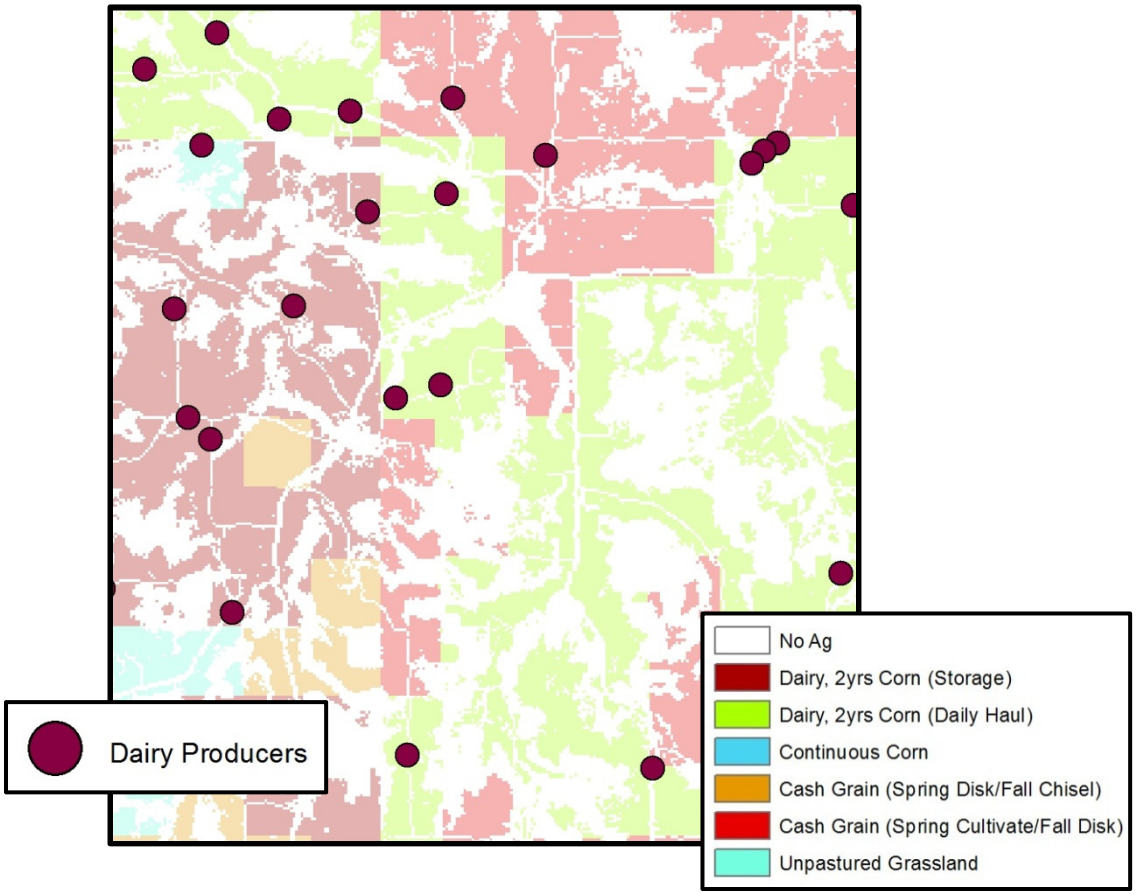


Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 4

  Apply combination of transect data, dairy producer locations, and county conservation staff knowledge to spatially and temporally identify of agricultural management

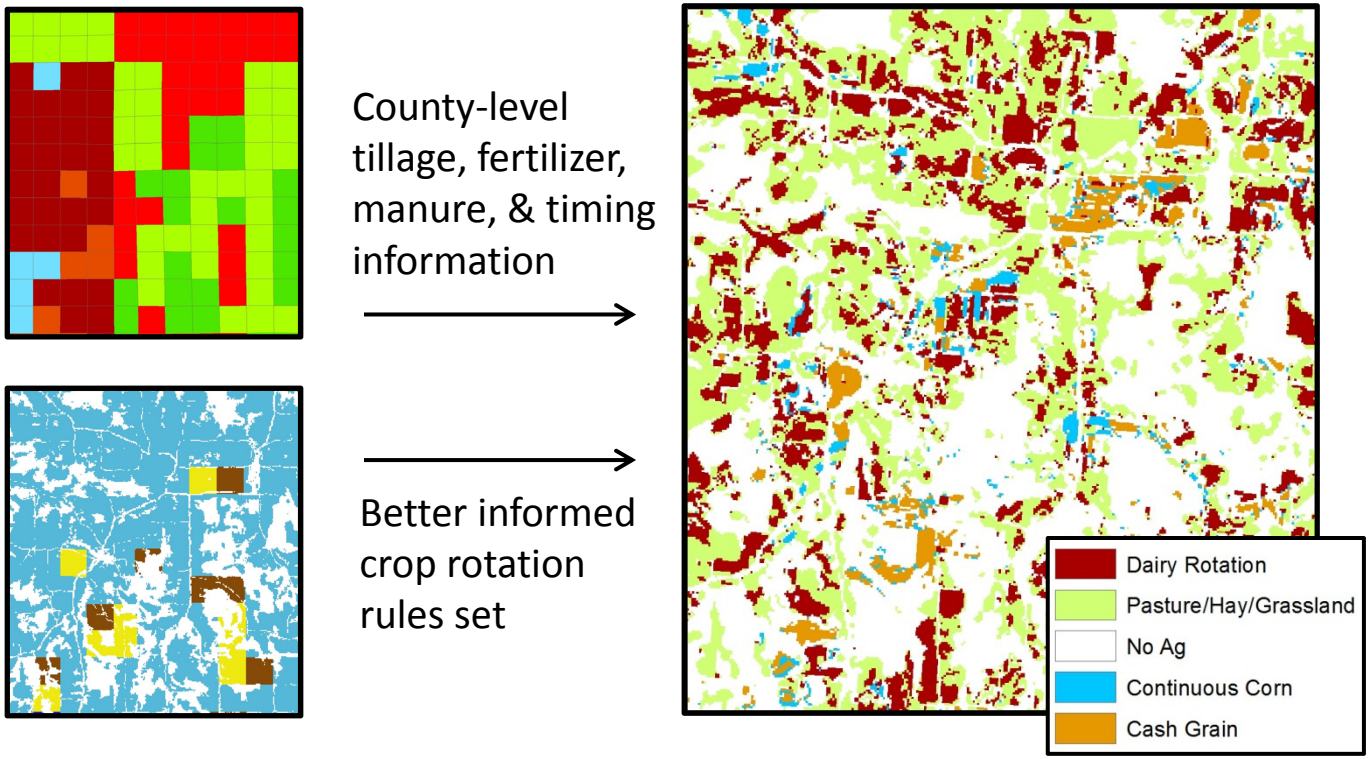


Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

- Agricultural Land Management – Step 5

  Reclassify CDL crop sequence identification based on county meeting information, and attach management information to create generalized crop rotations.



Data Collection: Land Management

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- **Land Management**
- Point Sources

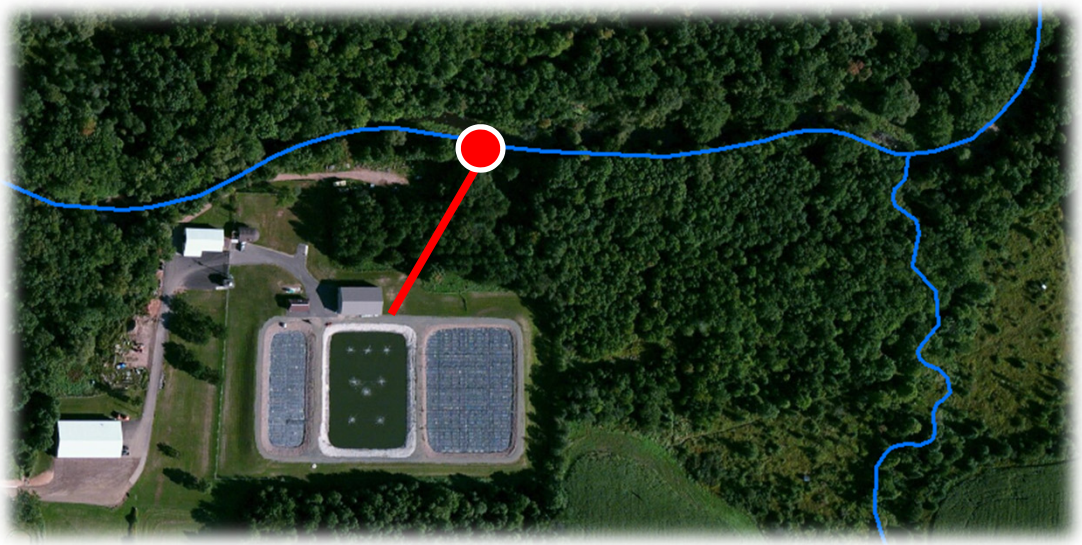
- Agricultural Land Management – Model Input

Dairy Rotation with 2 years Corn Silage and Manure Storage						
Year	**Month**	**Day**	**Operation**	**Type**	**Amount**	**Unit**
2008	April	29	Manure	Liquid	10000	ga/acre
2008	May	1	Tillage	Disk Plow		
2008	May	15	Plant	Corn Silage		
2008	May	15	Fertilizer	9:23:30	200	lbs/acre
2008	September	15	Harvest	Corn Silage		
2008	September	25	Tillage	Chisel Plow		
2009	April	29	Manure	Liquid	10000	ga/acre
2009	May	1	Tillage	Disk Plow		
2009	May	15	Plant	Corn Silage		
2009	May	15	Fertilizer	9:23:30	200	lbs/acre
2009	September	15	Harvest	Corn Silage		
2009	September	25	Tillage	Chisel Plow		
2010	April	15	Manure	Liquid	10000	ga/acre
2010	April	17	Tillage	Disk Plow		
2010	April	25	Plant	Oats		
2010	April	25	Plant	Alfalfa		
2010	August	10	Harvest	Oatledge		
2011	June	1	Harvest	Alfalfa		
2011	July	15	Harvest	Alfalfa		
2011	August	30	Harvest	Alfalfa		
2011	September	15	Manure	Liquid	10000	ga/acre
2012	June	1	Harvest	Alfalfa		
2012	July	15	Harvest	Alfalfa		
2012	August	30	Harvest	Alfalfa		
2013	June	1	Harvest	Alfalfa		
2013	July	15	Harvest	Alfalfa		
2013	August	30	Harvest	Alfalfa		
2013	October	15	Tillage	Chisel Plow		

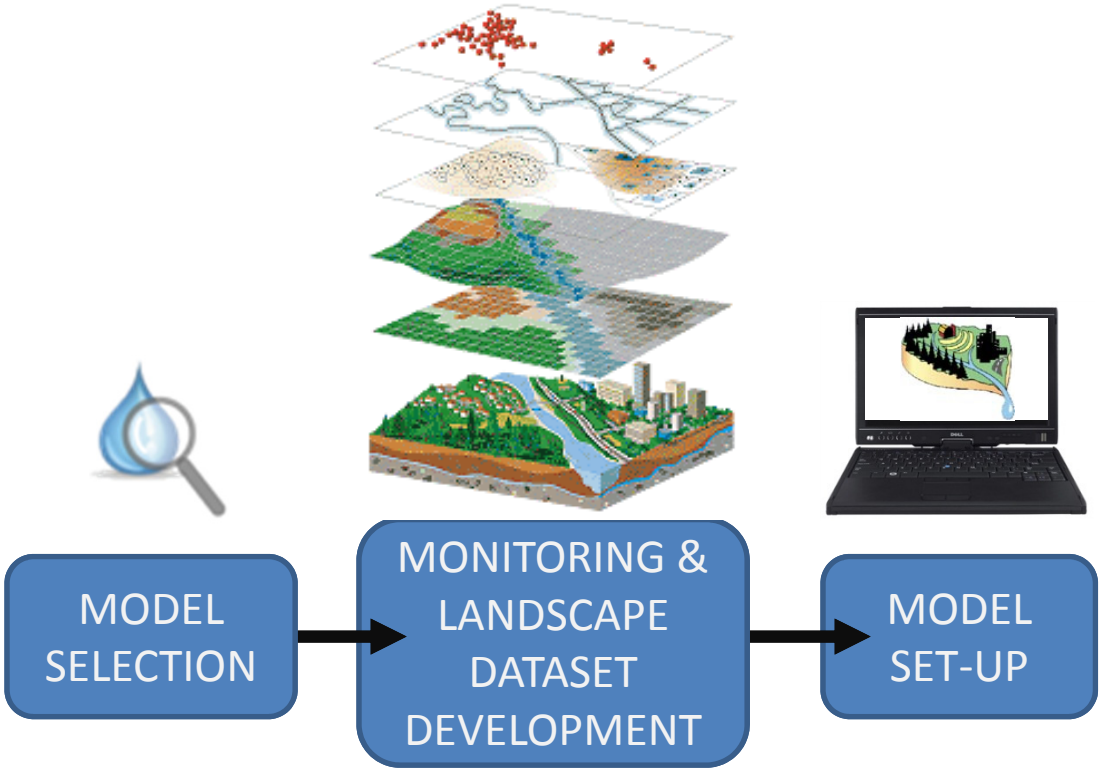
Data Collection: Surface Water Effluent

- Climate
- Elevation
- Hydrology
- Soils
- Land cover
- Land Management
- **Point Sources**

- Monthly surface water surface water effluent flow and water chemistry from the following:
  - ✓ Municipal and industrial permits
  - ✓ General Permits
- MS4 contributions (from urban modeling)

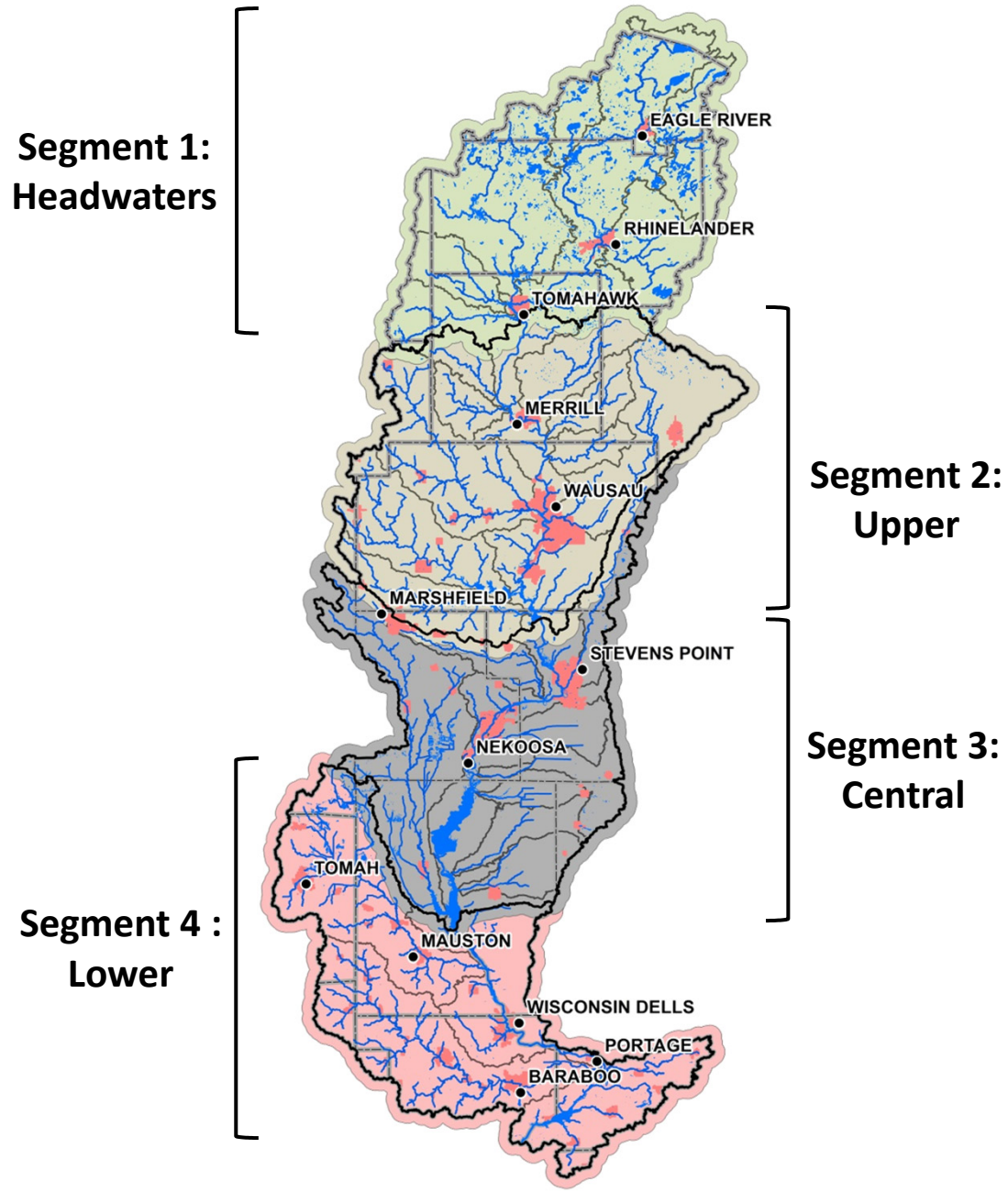


Process Overview



SWAT Configuration

- **Model Domain & Segments**
- Boundary Conditions
- Reach Definition
- HRUs
- PET Method
- Simulation Period
- Time Step



SWAT Configuration

Model Domain & Segments

Boundary Conditions

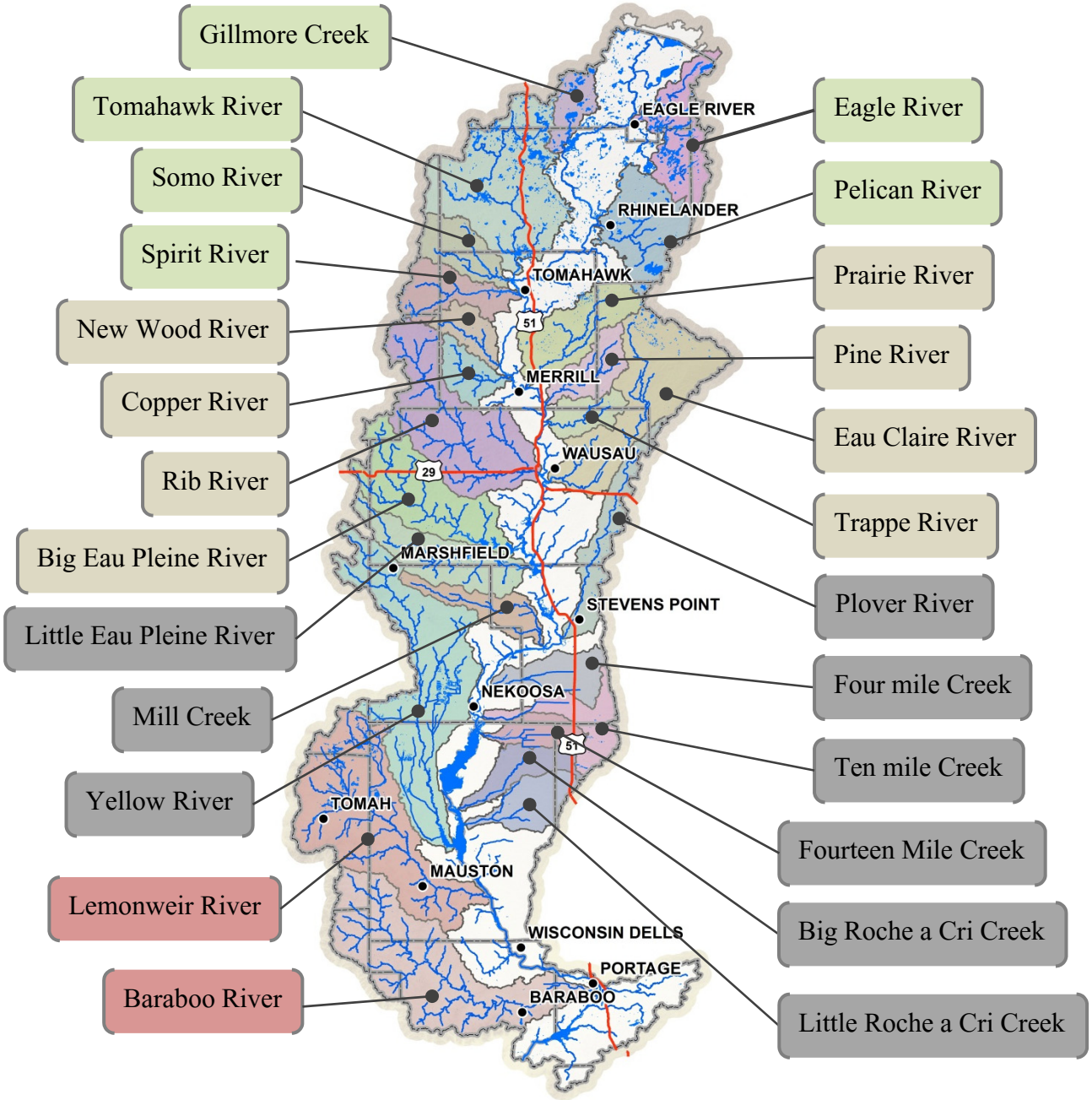
Reach Definition

HRUs

PET Method

Simulation Period

Time Step



SWAT Configuration

- Model Domain & Segments
- **Boundary Conditions**
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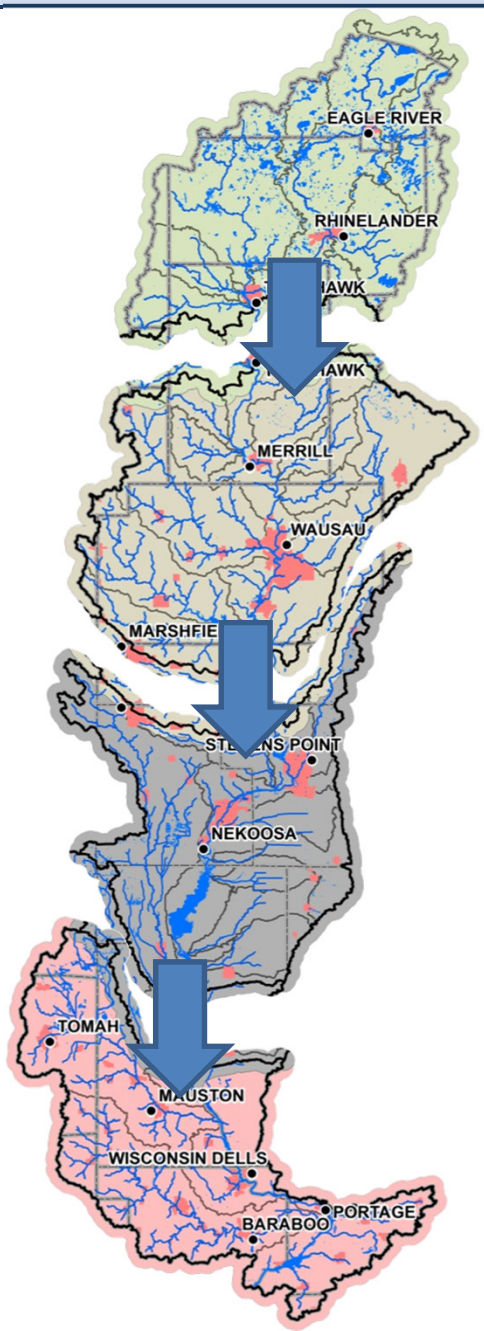
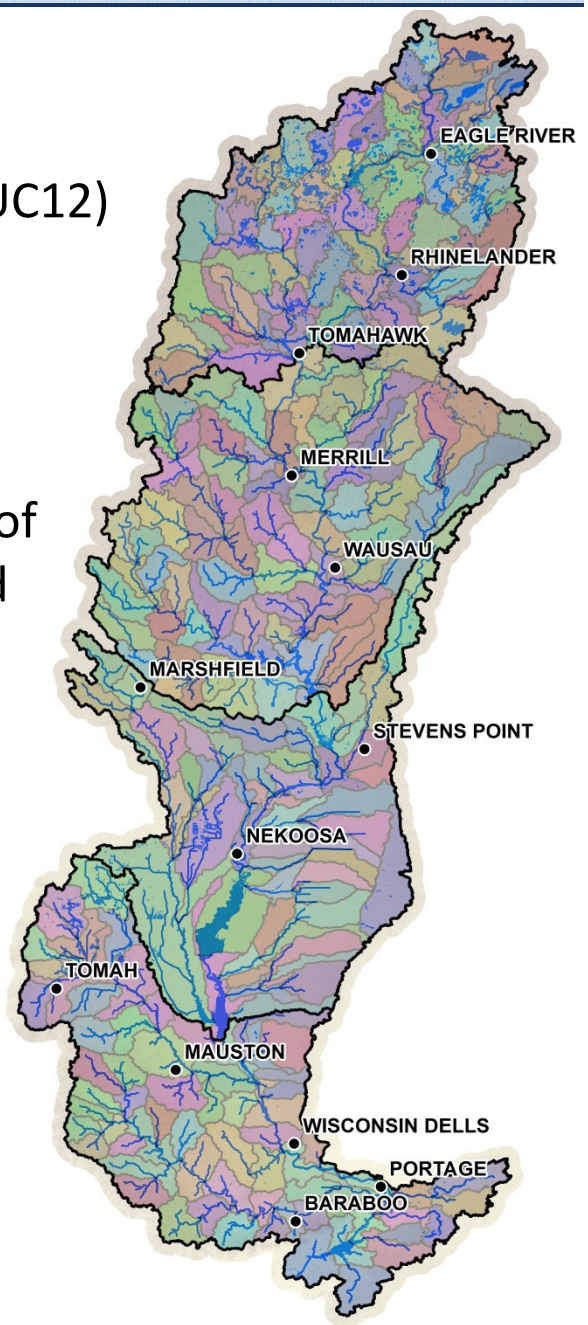


SWAT Configuration

- Model Domain & Segments
- Boundary Conditions
- **Reach Definition**
- HRUs
- PET Method
- Simulation Period
- Time Step

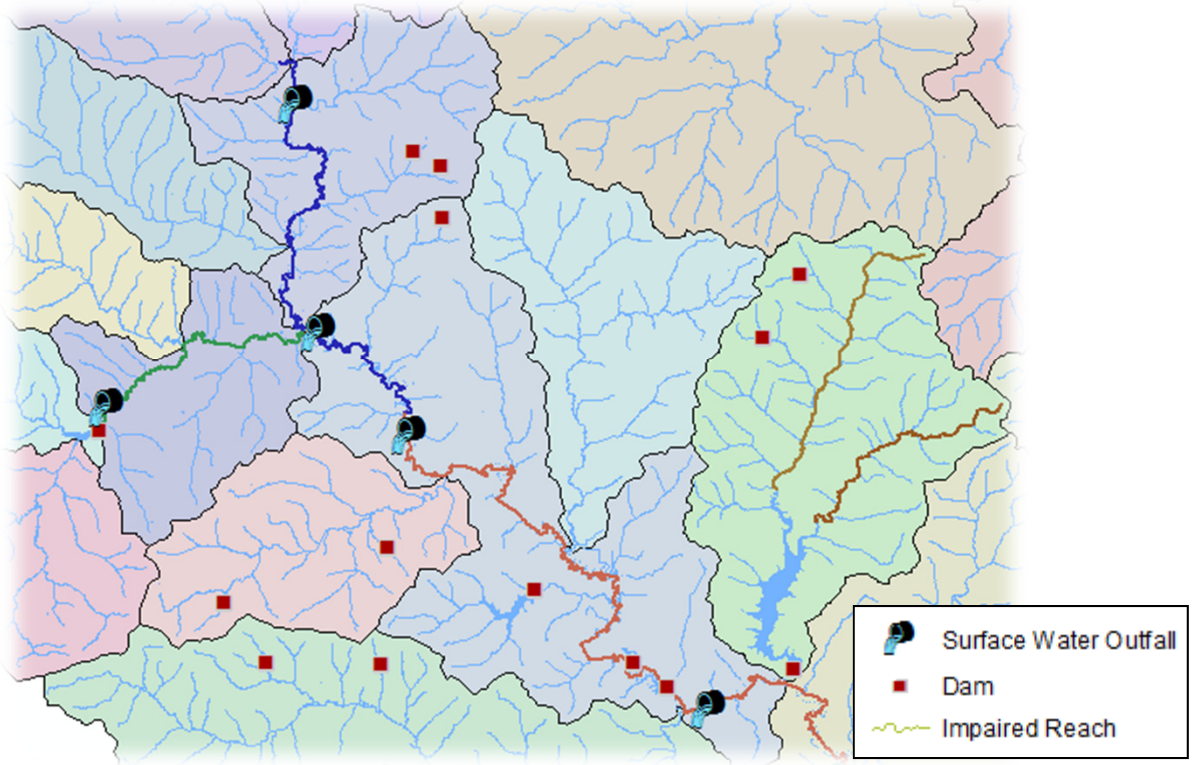
- Reaches definition begins with pre-defined subwatersheds (HUC12)
- 266 HUC12 basins (average size = 34 mi^2)
- Additional lumping or splitting of HUC12 subwatersheds required



SWAT Configuration

- Model Domain & Segments
- Boundary Conditions
- **Reach Definition**
- HRUs
- PET Method
- Simulation Period
- Time Step

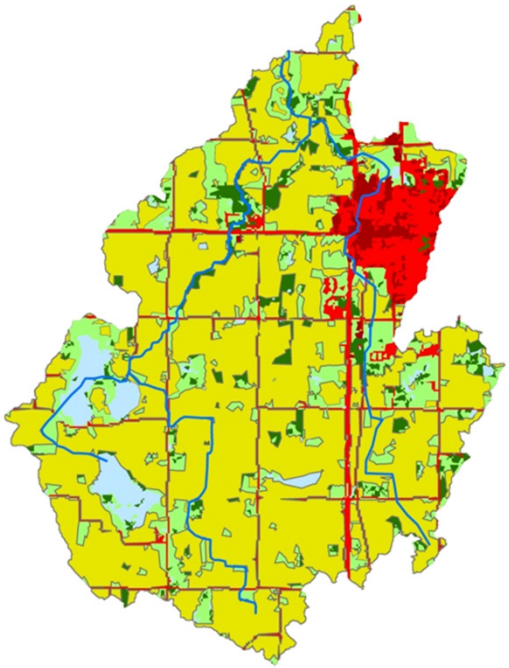
- Reaches will be defined by:
  - ✓ Changes in stream reach phosphorus criteria
  - ✓ Impaired stream reaches
  - ✓ Location of point source outfalls
  - ✓ Variation in land cover or management
  - ✓ Location upstream or downstream of reservoirs
  - ✓ Significant changes in flow

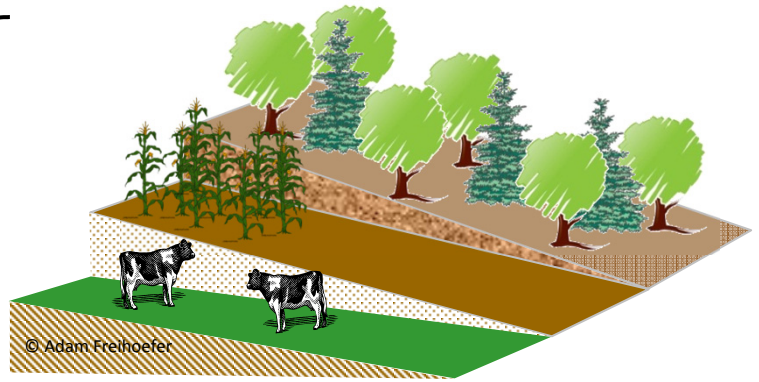


SWAT Configuration

- Model Domain & Segments
- Boundary Conditions
- Reach Definition
- **HRUs**
- PET Method
- Simulation Period
- Time Step

HRU Input	Threshold per Subwatershed
Land cover / management	Maintain integrity
SSURGO soils	>20%
Slope	0% – 3% 4% – 7% 8% – 12% 13% – 100%





Unique Combinations of Land Use – Soil – Slope

Pasture / Silt Loam / 0 - 5% Slope

SWAT Configuration

- Model Domain & Segments
- Boundary Conditions
- Reach Definition
- HRUs
- **PET Method**
- Simulation Period
- Time Step

- Potential Evapotranspiration (PET) Methods
  - ✓ Priestly-Taylor
    [Solar Radiation, Temperature, Relative Humidity]
  - ✓ Penman – Monteith
    [Solar Radiation, Temperature, Relative Humidity, Wind]
  - ✓ Hargreaves
    [Temperature]

SWAT Configuration

- Model Domain & Segments
- Boundary Conditions
- Reach Definition
- HRUs
- PET Method
- **Simulation Period**
- Time Step

- 1996 – 2001 Warm-up Period (6 years)
- 2002 – 2013 Simulation Period (12 years)

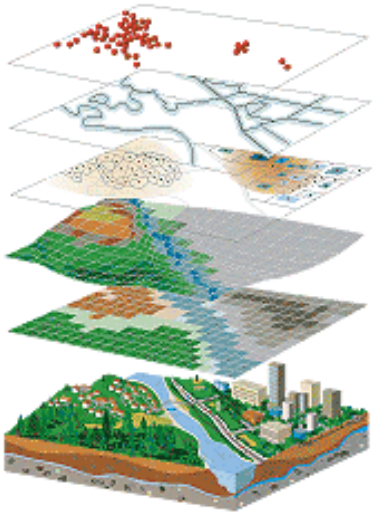
SWAT Configuration

- Model Domain & Segments
- Boundary Conditions
- Reach Definition
- HRUs
- PET Method
- Simulation Period
- **Time Step**

- Daily Time Step

Process Overview

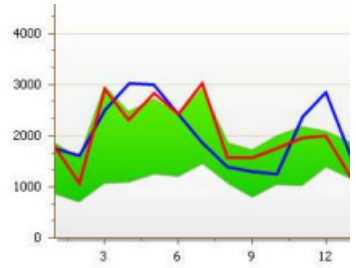
MODEL SELECTION



MONITORING & LANDSCAPE DATASET DEVELOPMENT

MODEL SET-UP

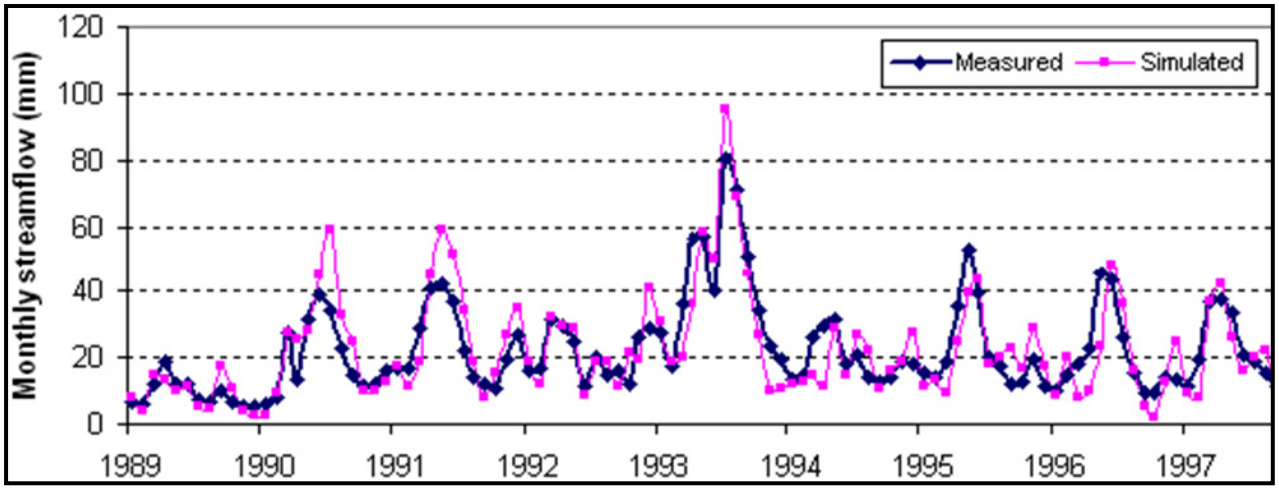
INITIAL MODEL RUN



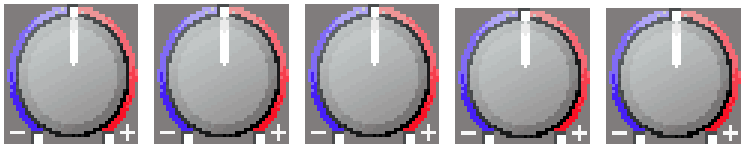
CALIBRATION & VALIDATION

SWAT Calibration & Validation

- Calibration is process of matching the simulation to measured data



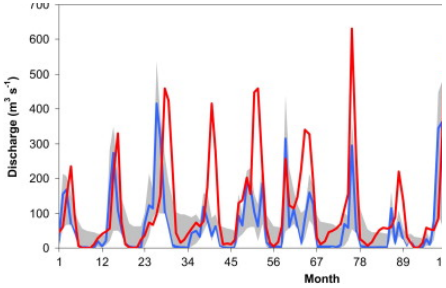
- Modeler adjusts parameters to allow for better fit



Input Parameter Controls

SWAT Calibration & Validation

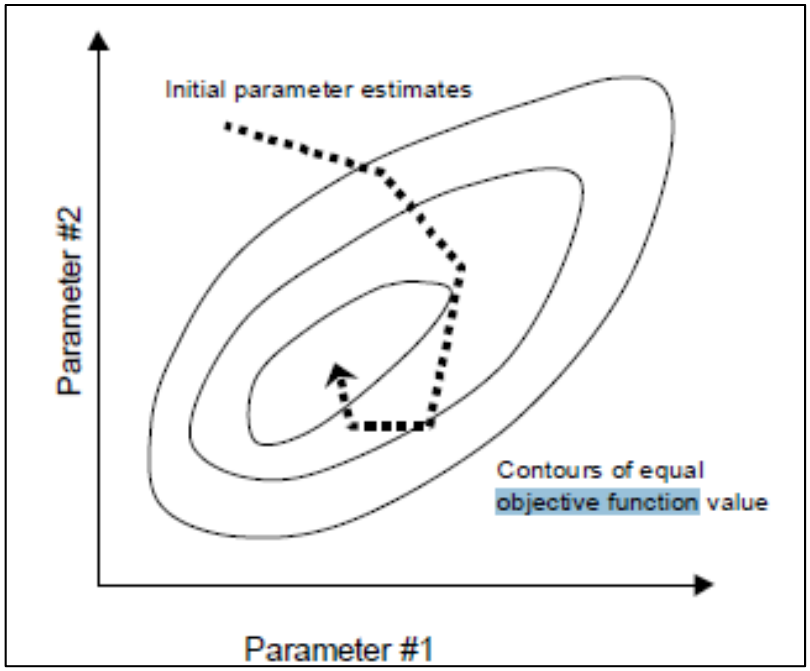
- Period of Evaluation
  - ✓ 2009 – 2013 Calibration Period
  - ✓ 2002 – 2008 Validation Period



- Order of Calibration Process
  1. Check Annual Water Budget
  2. Complete Sensitivity Analysis
  3. Autocalibration of
     - Daily discharge
     - Monthly total suspended sediment load
     - Monthly dissolved and total phosphorus load

SWAT Calibration & Validation

- Autocalibration Process
  - ✓ Completed using Parameter Estimation (PEST) and/or SWAT – Calibration and Uncertainty Program (CUP)
  - ✓ Multi-site (multiple gages), multi-objective (R^2, Nash Sutcliffe)

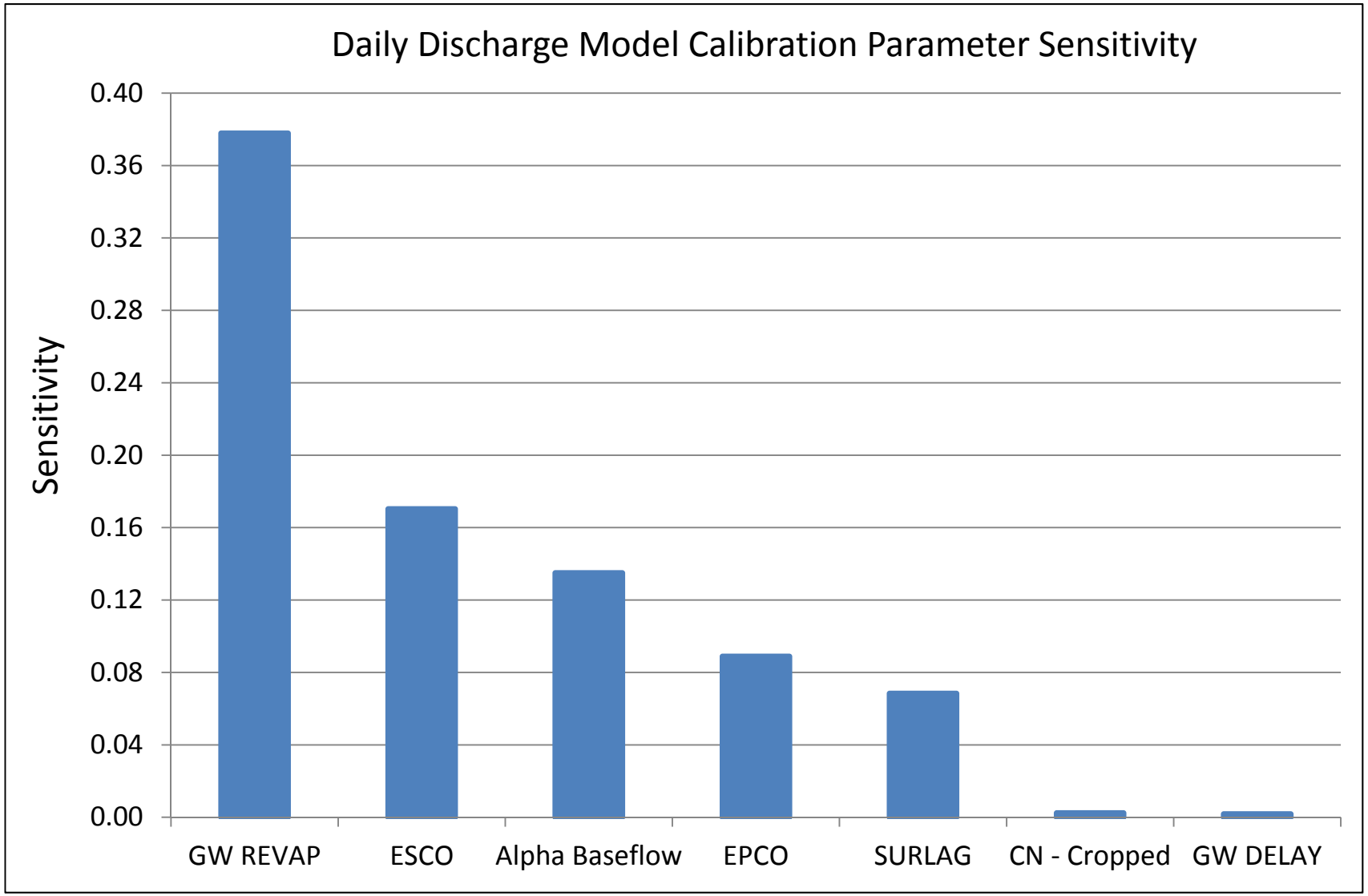


http://www.pesthomepage.org/

SWAT Calibration & Validation

- Parameter Sensitivity Analysis

EXAMPLE DATASET



SWAT Calibration & Validation

- Parameter Bounds

EXAMPLE DATASET

Parameter	Default Value	Minimum Value	Maximum Value	Calibrated Value
CN - CORN *(corn curve number)*	78	66	85	70
ESCO *(soil evaporation compensation factor)*	0.95	0	1	0.83
ALPHA_BF *(baseflow recession constant)*	0.048	0	1	0.708
SURLAG *stormflow lag time*	4	1	24	1

SWAT Calibration & Validation

- Evaluation Statistics (*not inclusive*)

  - ✓ **Coefficient of Determination (R^2)**
    Proportion of the variance in measured data explained by model
    Optimal = 1.0

  - ✓ **Nash-Sutcliffe Efficiency (NSE)**
    Indicates how well the plot of observed vs. simulated fits the 1:1 line
    Optimal = 1.0

  - ✓ **Percent Bias (PBIAS)**
    Average tendency of simulated data to be ↑↓ than observed
    Optimal = 0.0

  - ✓ **RMSE-observation Standard Deviation Ratio (RSR)**
    Standardized RMSE using observations standard deviation ratio
    Optimal = 0.0

SWAT Calibration & Validation

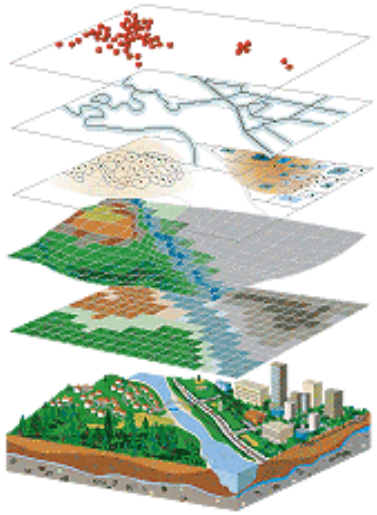
- General Performance Ratings

Statistic	Satisfactory Rating (Monthly Time Step)
R^2	> 0.50
NSE	> 0.50
PBIAS	< ± 25% (Discharge)
	< ± 55% (Sediment)
	< ± 70% (Phosphorus)
RSR	< 0.70

Moriasi et al. 2007

Process Overview

MODEL SELECTION



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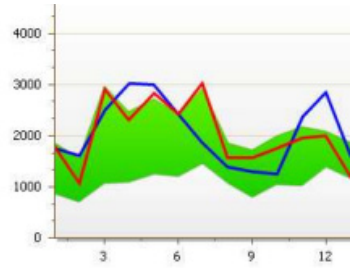


CALIBRATION & VALIDATION

Good Fit?

CURRENT CONDITIONS SIMULATION COMPLETE

SWAT Model Outputs

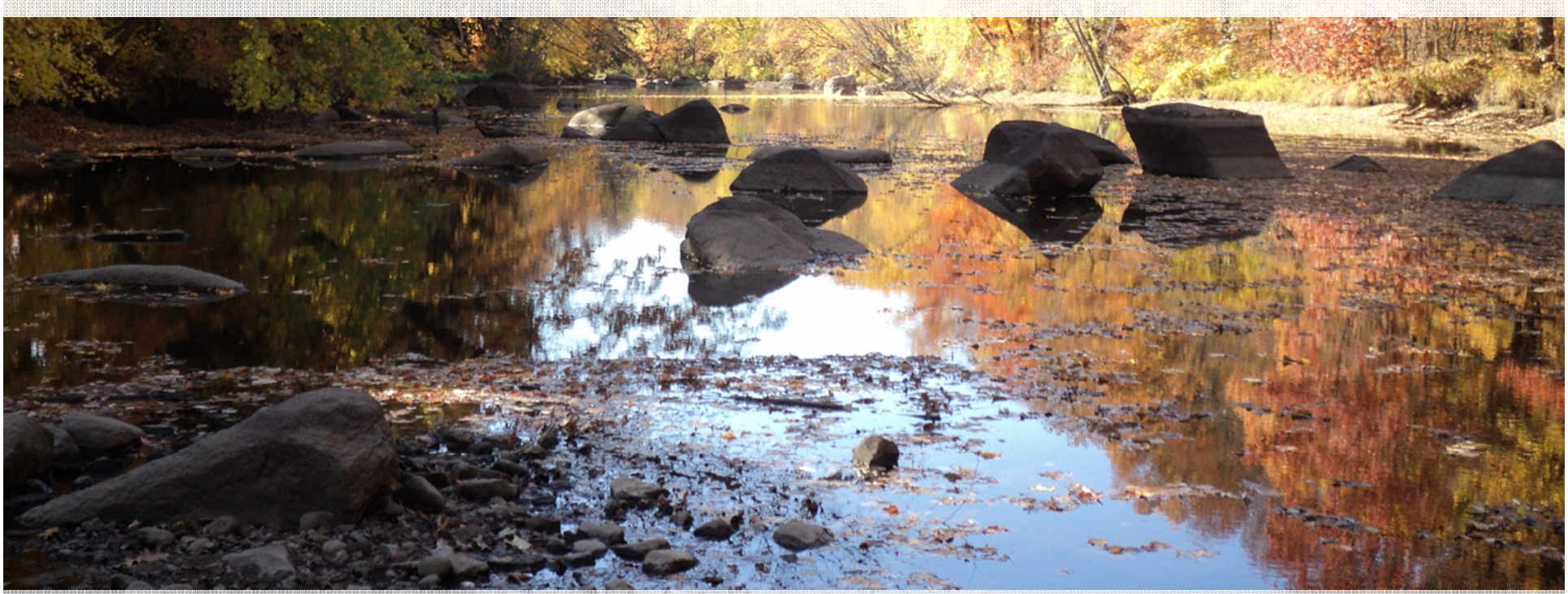
- For each subwatershed
  - ✓ Discharge (daily or monthly)
  - ✓ Total Suspended Sediment (monthly)
  - ✓ Dissolved and Total Phosphorus (monthly)

Large Group Discussion

dnrwisconsinrivertmdl@wisconsin.gov

Big Eau Pleine River at Cherokee Park

Defining the proportion of sediment lost from the landscape vs. other sources (gully, ravine, bank, and channel) is difficult without a robust collection of bank and channel erosion measurements. SWAT has the ability to simulate sediment losses from both sources. Does anyone have ideas of we might estimate the percent of TSS that originates from the landscape vs. other sources throughout this large study area?



dnrwisconsinrivertmdl@wisconsin.gov

Big Eau Pleine River at Cherokee Park

How would you try to quantify and simulate legacy phosphorus (phosphorus that is re-released, re-suspended, etc.) in the SWAT model?

dnrwisconsinrivertmdl@wisconsin.gov

Big Eau Pleine River at Cherokee Park

Currently the status of many of the SWAT model inputs are considered a work in progress. As details (inputs, calibration, etc.) of the watershed modeling approach are worked out would technical memos posted on the web be helpful for you reviewing our approach rather than waiting for the final modeling report?

dnrwisconsinrivertmdl@wisconsin.gov

Big Eau Pleine River at Cherokee Park