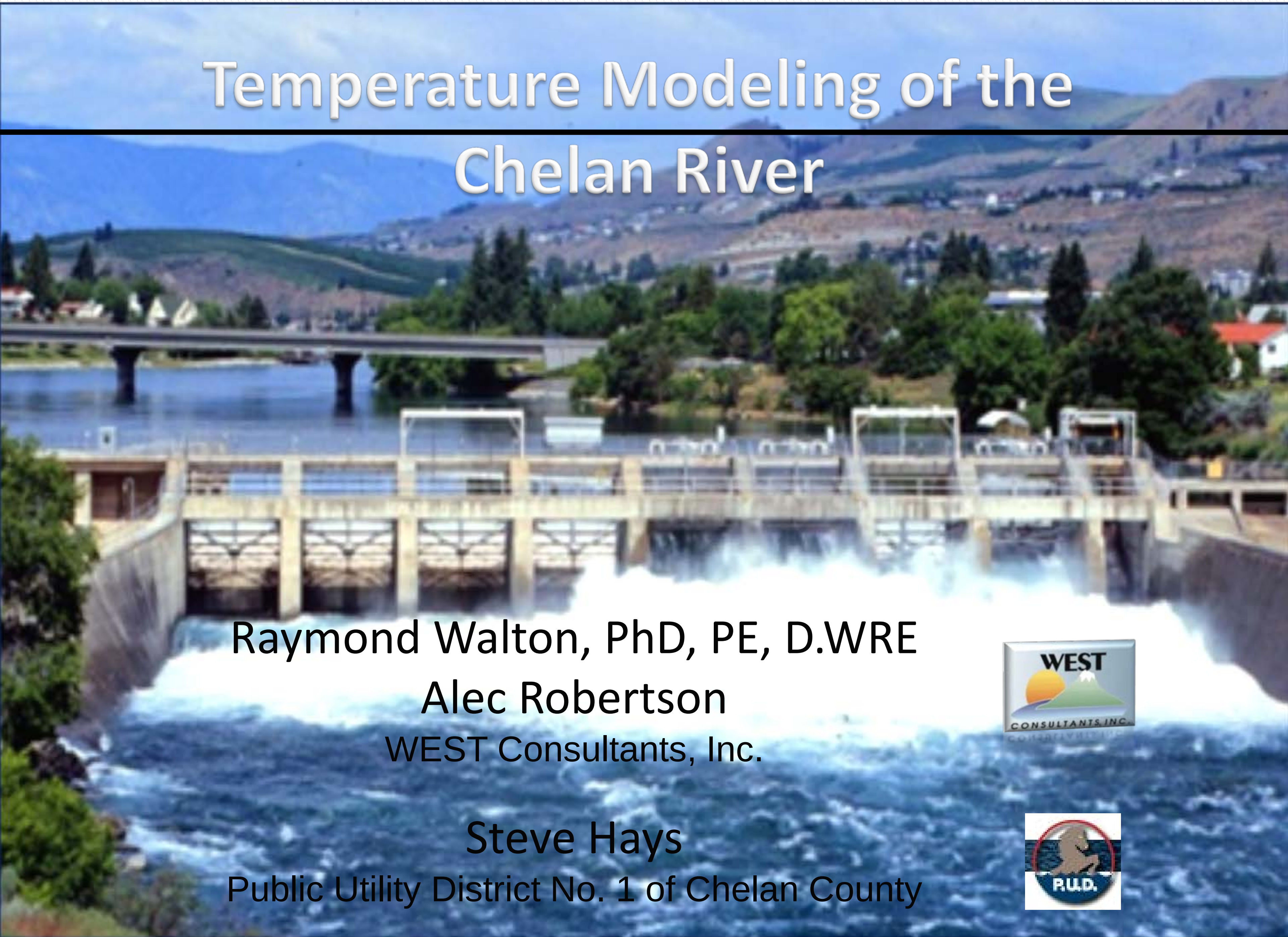

# Temperature Modeling of the Chelan River


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WEST Consultants, Inc.

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Public Utility District No. 1 of Chelan County

# Outline

- Background
- Model Selection
- QAPP
- Temperature Model Development and Calibration
- Next Steps

# Background

- June 1, 2004, Ecology amended and reissued a 401 Certification to the Chelan PUD for the Lake Chelan Hydroelectric Project
- November 6, 2006, FERC issued a license to Chelan PUD to operate the project for 50 years
- in 2008, Chelan PUD submitted an application to Ecology to amend the 401 Certification as part of a license amendment to modernize generating units at the Project
- November 2008, Ecology issued a water quality certification for the amendment application under Section 401 of the federal Clean Water Act

# Background (cont)

- Ecology water quality certification required:
  - Conduct an additional study of water temperature at the dam face to determine how best to design the new outlet structure to maximize the potential for cold water withdrawal at the base of the dam
  - Develop a Quality Assurance Project Plan for water quality monitoring and temperature modeling
  - Conduct a study to determine the geomorphic influences on water temperatures in the Chelan River in order to address temperature, velocity, depth, and substrate to determine the best methods to achieve the biological objectives for cutthroat trout
  - Conduct a riparian feasibility study to better characterize the opportunities for the establishment of riparian vegetation on the banks of the Chelan River
  - Collect data on temperatures in the Chelan River and, if appropriate, evaluate its ability to comply with the temperature standards

# Background (cont)

- A discussion with Ecology:

"concluded that a temperature study of the Chelan River should focus on developing a Use Attainability Analysis (UAA), as defined in WAC 173-201A-510(5), rather than analyzing temperatures changes caused by the Project"

# Project Status

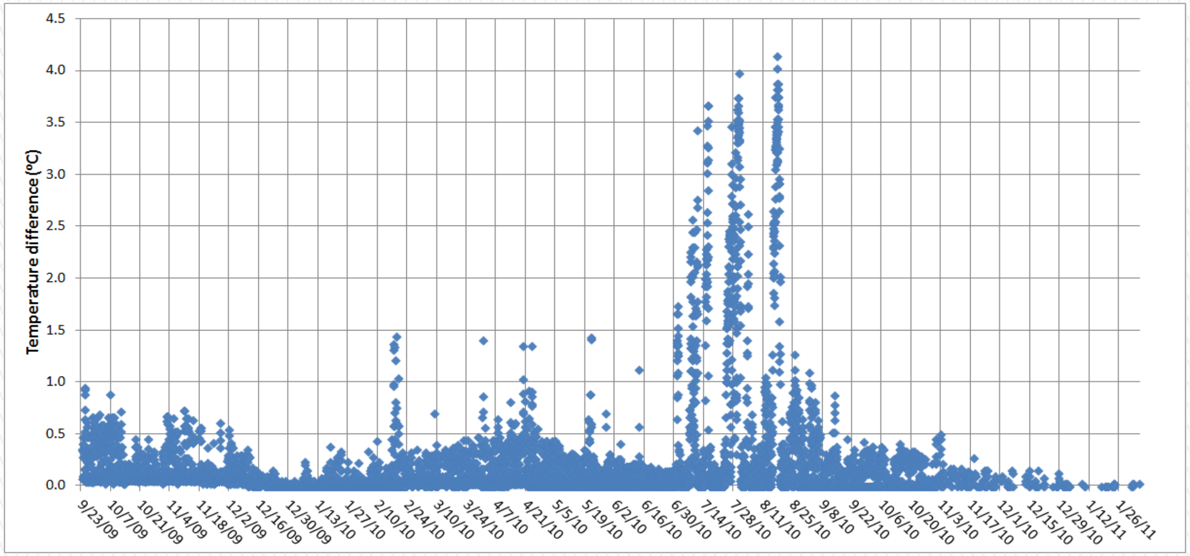
- Model Selection Report (March 12, 2014)
- QAPP (April 2014, revised June 23, 2015)
- Temperature Model Calibration Report (draft June 4, 2015)
- Analysis of Alternatives

# Model Selection

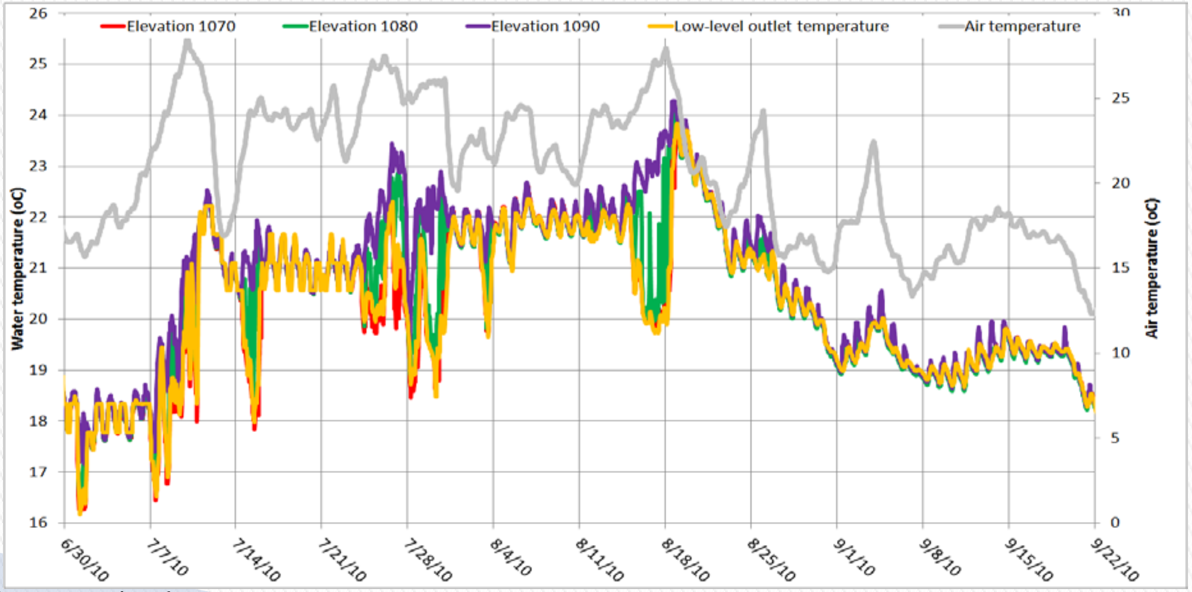
- Evaluation of processes
- Model candidates
- Model selection

# Model Selection (processes)

- Vertical temperature difference in Lake Chelan forebay (2009-2011)

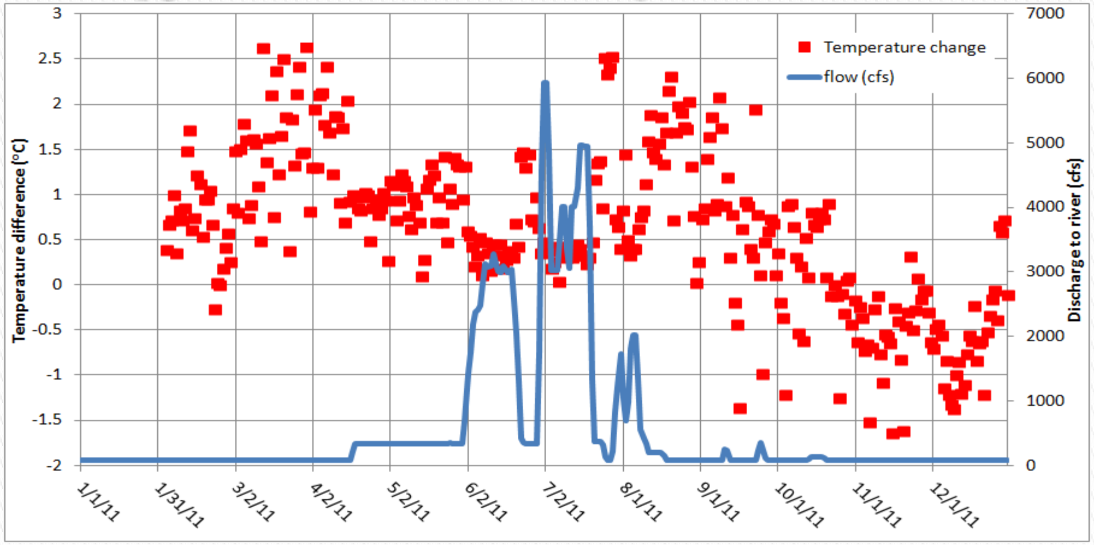



- Time series of water temperatures in Lake Chelan forebay during summer of 2010

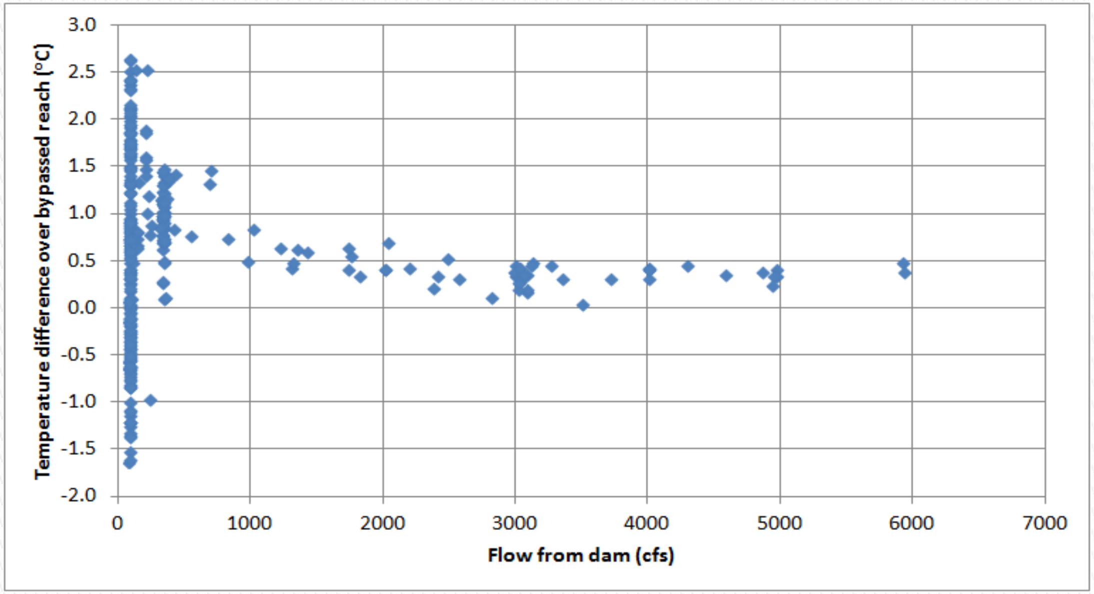


# Model Selection (processes)

- Comparison of flow and temperature change in bypassed reach (1-3)




- Comparison of flow and temperature change in bypassed reach (1-3) during 2011



# Model Selection (candidates)

- CE-QUAL-W2
  - U.S. Army, Engineer Research and Development Center
  - Portland State University is lead developer
  - Most commonly used reservoir model in world
- HEC-RAS
  - Corps of Engineers, Hydrologic Engineering Center
  - Most commonly used 1D model in world
- QUAL2Kw
  - Initial development at U. Colorado (by Pelletier et al.)
  - Continued development and support by Pelletier at Ecology

# Model Selection (selection)

| Process | CE-QUAL-W2 | HEC-RAS | QUAL2Kw |
|---|---|---|---|
| Air temperature | ✓ | ✓ | ✓ |
| Dew point temperature | ✓ | ✓ | ✓ |
| Relative humidity | Dew point temperature | ✓ | ✓ |
| Wind speed | ✓ | ✓ | ✓ |
| Wind direction | ✓ | x | x |
| Cloud cover | ✓ | ✓ | ✓ |
| Solar radiation | ✓ | ✓ | ✓ |
| Static shading | ✓ | Modify solar radiation externally | ✓ |
| Dynamic shading | ✓ | Modify solar radiation externally | ✓ |
| Wind sheltering | ✓ | Modify wind speed externally | ✓ |
| Dynamic linkage to flow | direct | direct | Transfer to input – 1 year only |
| Ground water interactions | ✓ | ✓ | ✓ |
| Hyporheic flow | ✓ | x | ✓ |

# Model Selection (selection)

- QUAL2Kw
  - Has all important processes
  - Continued development and support from Ecology
- HEC-RAS
  - Has most of important processes, but some under development
  - Continued development and support from Hydrologic Engineering Center
  - HEC-RAS useful to define QUAL2Kw hydrodynamics

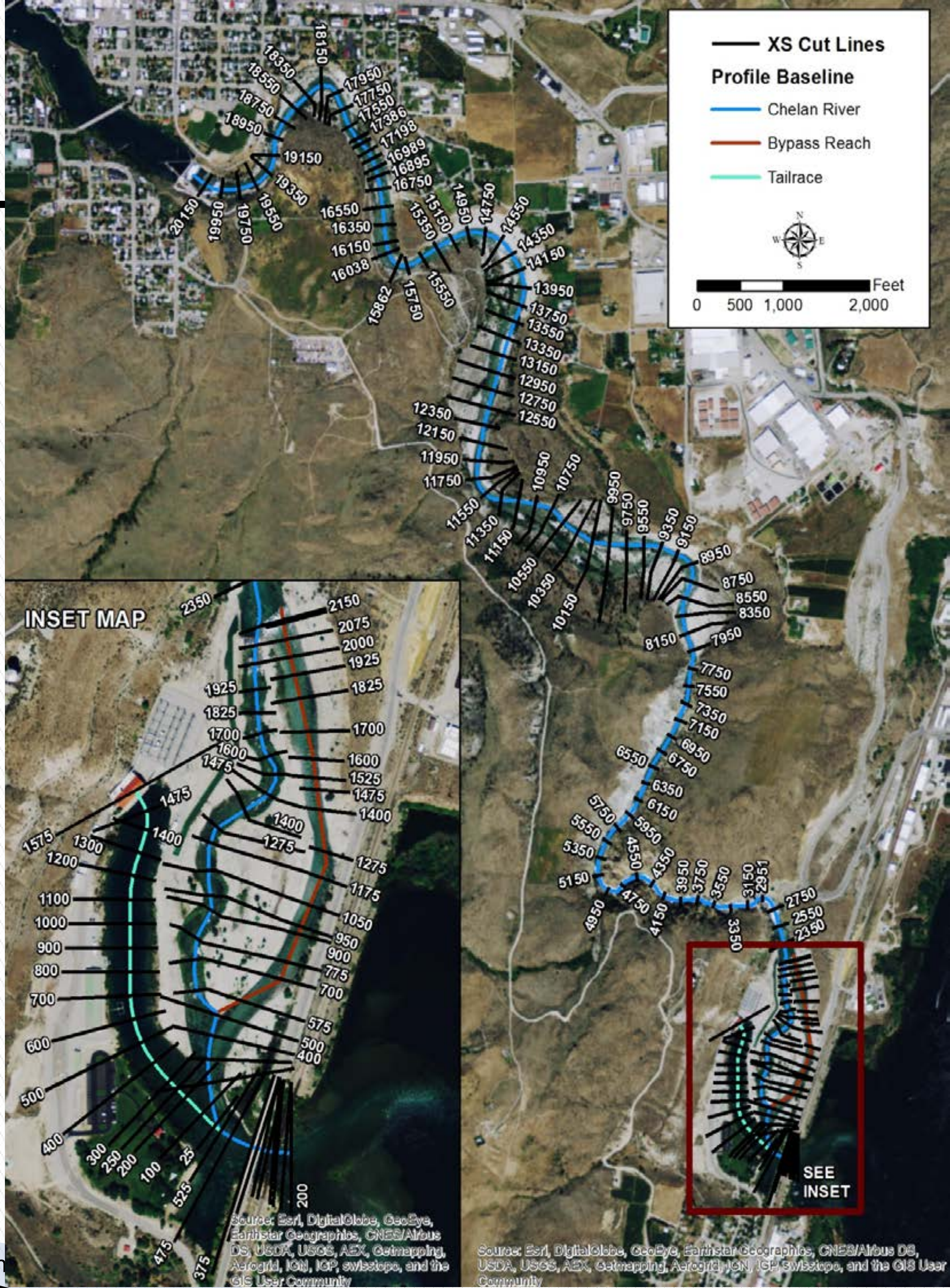
# Quality Assurance Project Plan

- Project Description
- Study Design
- Quality Objectives and Decision Criteria
- Quality Control Procedures
  - Model data
  - Monitoring data
- Data Review, Quality Assessment, Validation
- Project Responsibilities
- Project Schedule

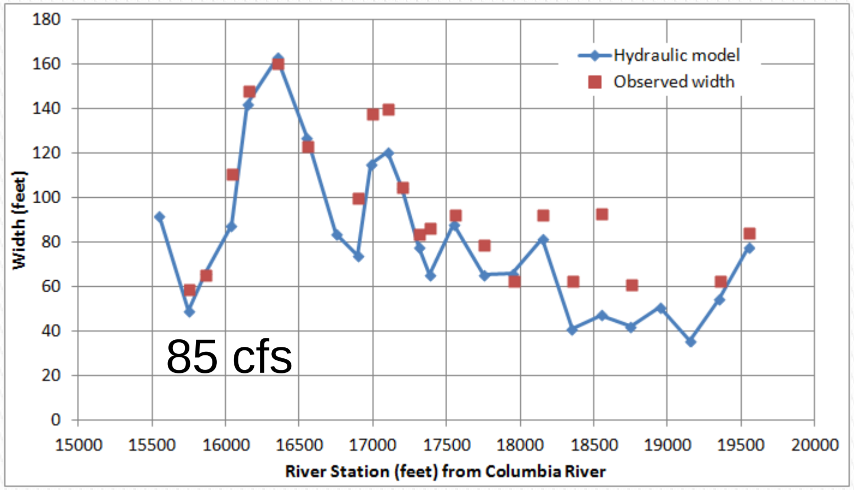
# Model Development and Calibration

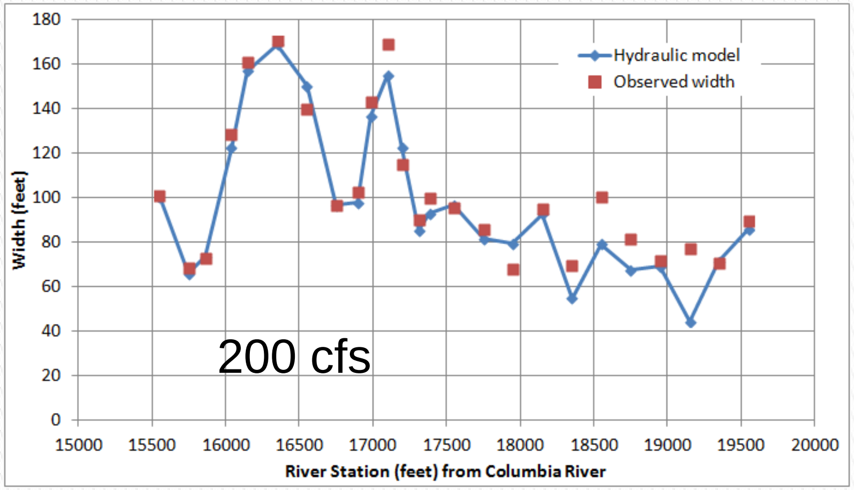
# Model Development (geometry)

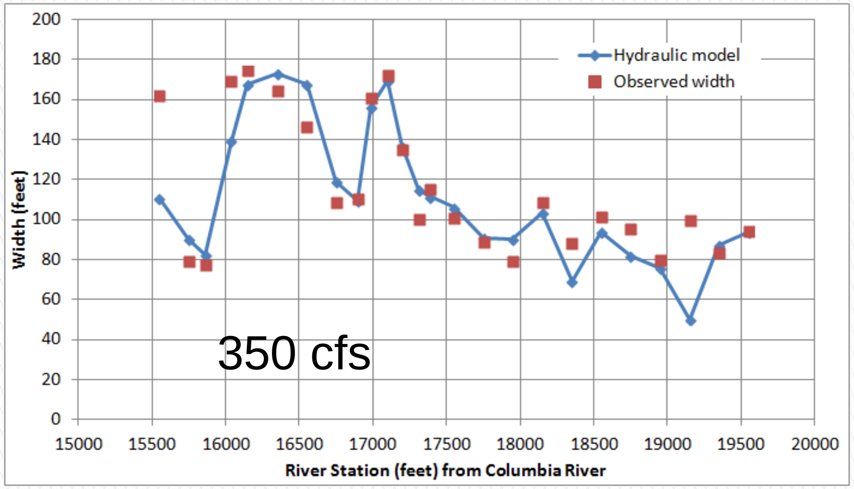
- LiDAR (2009)
- HEC-RAS hydraulic model of Reach 4
  - Modified with new Ecology sections in Habitat Reach
- HEC-RAS model developed with nominal resolution of 200 feet
- Used to develop power functions for QUAL2Kw



# Model Development (hydraulic calibration)



# Model Development (hydraulic calibration)

- Values estimated from aerial photographs and existing hydraulic model

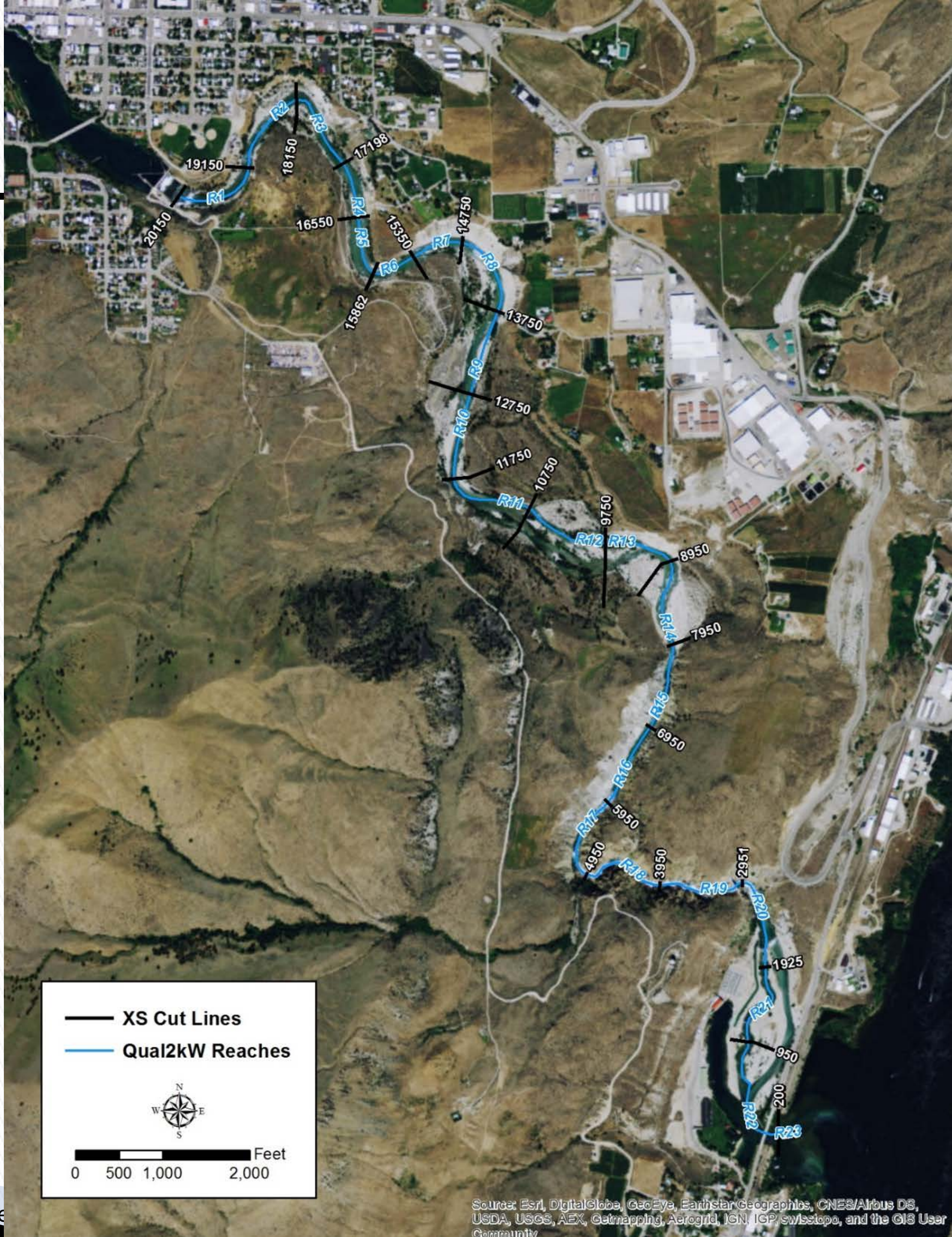
| River Reach | Channel values | Overbank values |
|---|---|---|
| Reach 1 | 0.07-0.12 | 0.12 |
| Reach 2 | 0.07-0.12 | 0.12 |
| Reach 3 ("The Falls") | 0.15 | 0.15 |
| Habitat Channel | 0.05 | 0.06 |
| Bypass Reach | 0.05 | 0.07 |
| Tailrace | 0.05 | 0.05 |
| Confluence Reach | 0.03 | 0.06 |

# Temperature Model Development

- Selection of temperature reaches
- Selection of calibration and validation periods
- Flow and temperature data
- Meteorological data

# Temperature Model (reaches)

- 23 reaches of approximately 1000 feet, between HEC-RAS cross sections
- Hydraulic power functions developed at boundary HEC-RAS sections from hydraulic model results
  - $U = aQ^b$ $H = \alpha Q^\beta$

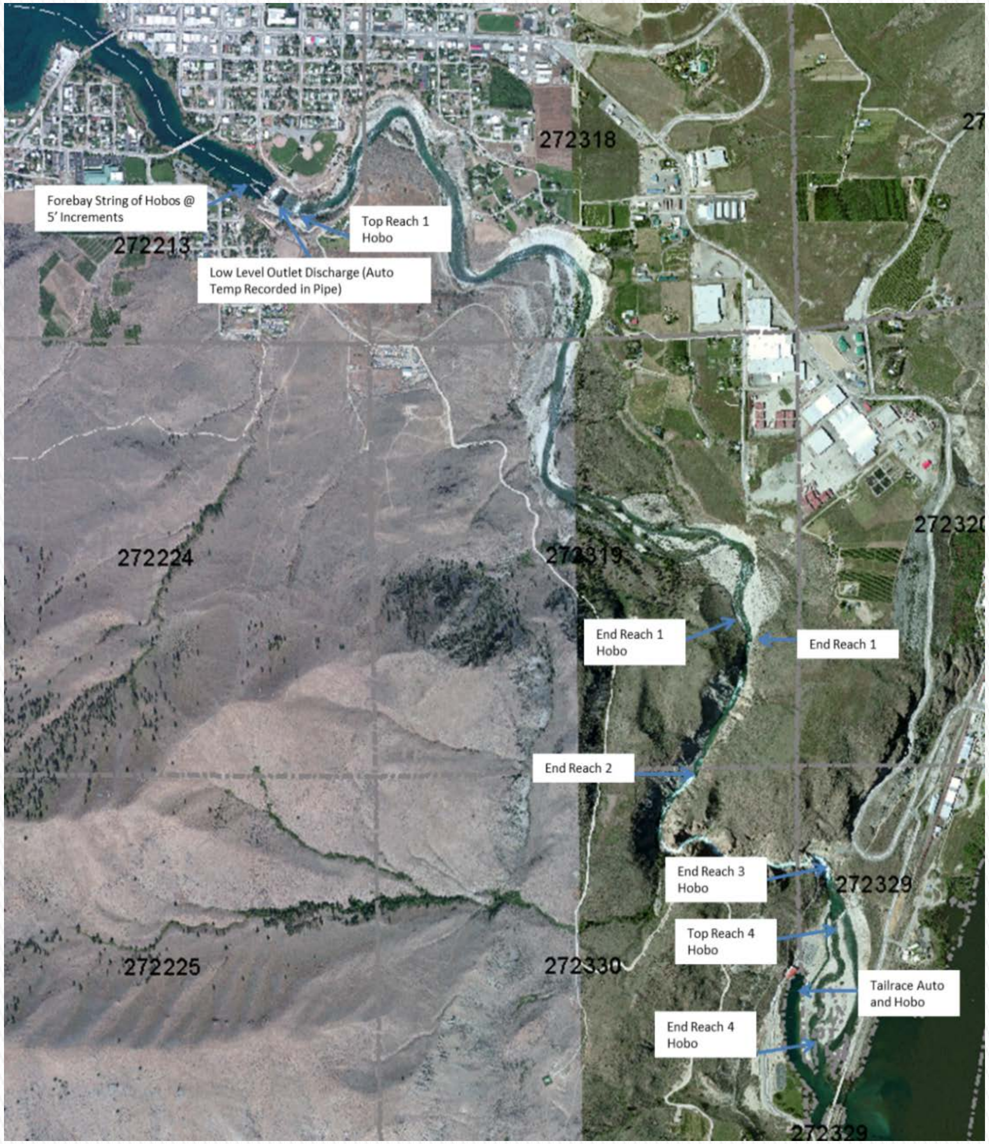


# Temperature Model (calibration and validation periods)

| Simulation Time Period | Simulation Type | Avg. Low Level Outlet Temperature (°C) | Avg. Air Temperature (°C) | Avg. Low Level Outlet Flow (cfs) |
|---|---|---|---|---|
| **April 7-12: 2010** | Validation | 8.6 | 6.6 | 92 |
| **May 1-7: 2013** | Validation and Sensitivity | 13.6 | 17 | 126 |
| **September 1-7: 2013** | Calibration | 21.6 | 21.5 | 86 |
| **July 27 – August 3: 2014** | Validation | 21.7 | 27.7 | 85 |
| **March 23-30: 2015** | Validation | 9.6 | 11.2 | 84 |

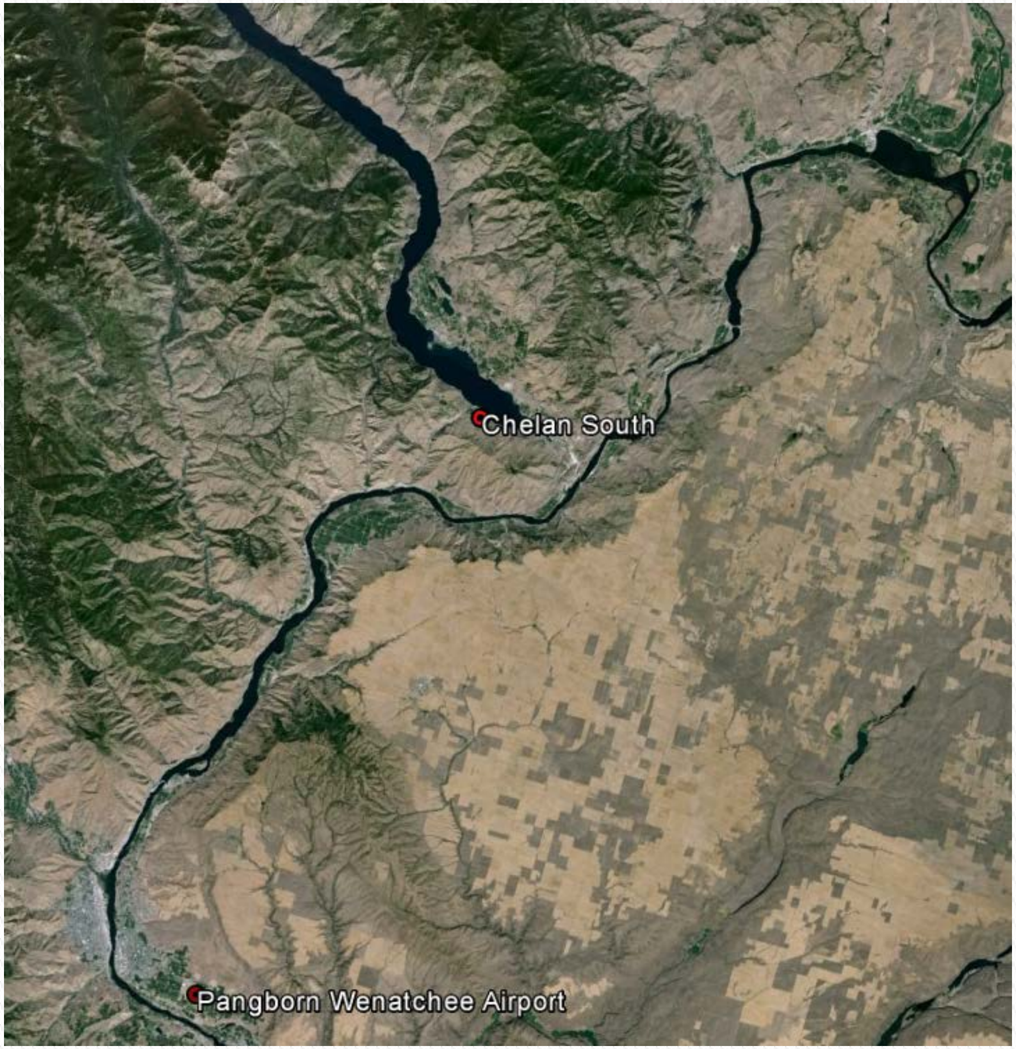
# Temperature Model (flow and temperature data)

- Flows through low-level outlet
- Temperatures in low level outlet
- Temperatures measured at ends of Reaches 1, 3, and 4



# Temperature Model (meteorology)

- AgWeatherNet station at Chelan South
  - Air temperature
  - Dew point temperature/relative humidity
  - Wind speed and direction
  - Solar radiation
- Pangborn Wenatchee Airport
  - Cloud cover
- Shade
  - Used Ecology program Shade.xls with 30 m USGS DEM

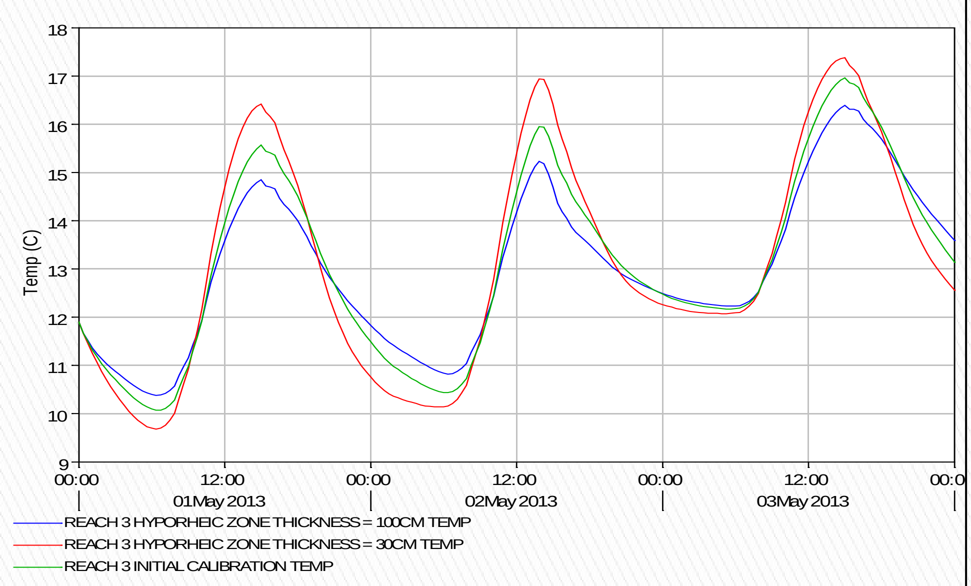


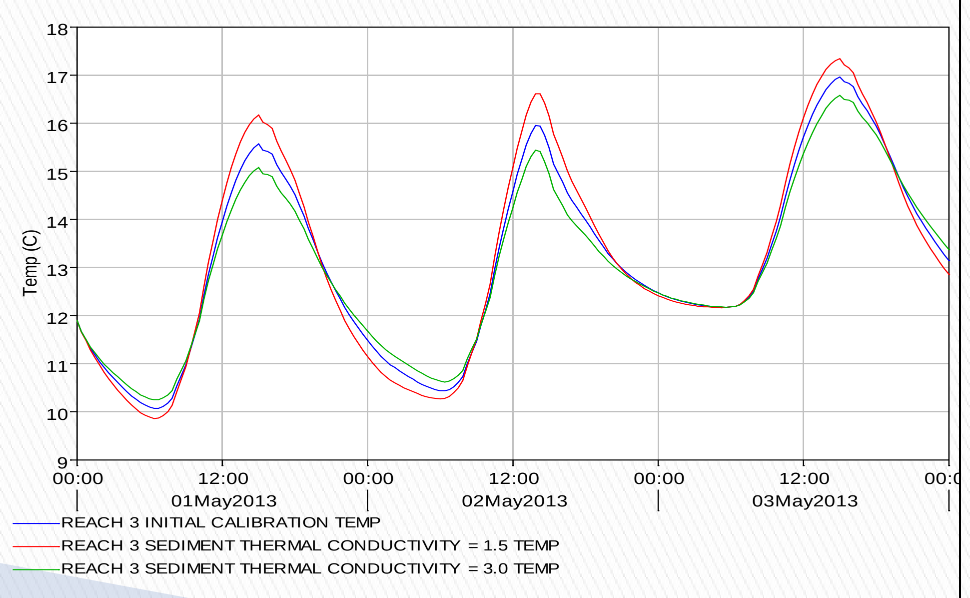
# Temperature Model Sensitivity

| | Reach 1 | | | Reach 3 | | |
|---|---|---|---|---|---|---|
| Parameter (value) | Mean Error (°C) | Mean Absolute Error | Root Mean Square Error | Mean Error (°C) | Mean Absolute Error | Root Mean Square Error |
| Sediment Thermal Diffusivity (0.005 cm^2/sec) | -0.047 | 0.141 | 0.172 | -0.056 | 0.191 | 0.233 |
| Sediment Thermal Diffusivity (0.0095 cm^2/sec) | 0.031 | 0.115 | 0.141 | 0.038 | 0.161 | 0.197 |
| Sediment Thermal Conductivity (1.5 W/m/°C) | 0.063 | 0.145 | 0.182 | 0.077 | 0.200 | 0.253 |
| Sediment Thermal Conductivity (3.0 W/m/°C) | -0.070 | 0.136 | 0.168 | -0.085 | 0.182 | 0.227 |
| Hyporheic Zone Thickness (30cm) | -0.012 | 0.237 | 0.274 | -0.020 | 0.336 | 0.391 |
| Hyporheic Zone Thickness (100cm) | -0.050 | 0.213 | 0.255 | -0.057 | 0.287 | 0.345 |
| Hyporheic Sediment Porosity (35%) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Hyporheic Sediment Porosity (50%) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Hyporheic Flow Fraction (0.1) | 0.010 | 0.113 | 0.145 | 0.011 | 0.138 | 0.180 |
| Hyporheic Flow Fraction (0.4) | -0.008 | 0.080 | 0.105 | -0.009 | 0.098 | 0.126 |
| Deep Sediment Temperature (7 °C) | -0.059 | 0.059 | 0.059 | -0.073 | 0.073 | 0.074 |
| Deep Sediment Temperature (13 °C) | 0.058 | 0.058 | 0.058 | 0.073 | 0.073 | 0.074 |
| Shade.xls Incision (0.5 m) | 0.013 | 0.013 | 0.017 | 0.021 | 0.021 | 0.027 |
| Shade.xls Incision (2.5 m) | -0.006 | 0.006 | 0.009 | -0.008 | 0.008 | 0.011 |
| Background Light Extinction (0.1/m) | 0.000 | 0.000 | 0.002 | 0.001 | 0.001 | 0.005 |
| Background Light Extinction (0.4/m) | 0.002 | 0.002 | 0.002 | 0.001 | 0.001 | 0.005 |

# Temperature Model Sensitivity

- Very sensitive to hyporheic flow
  - Zone thickness
  - sediment thermal conductivity
  - sediment thermal diffusivity
- Moderately sensitive to:
  - hyporheic flow fraction
  - deep sediment temperature

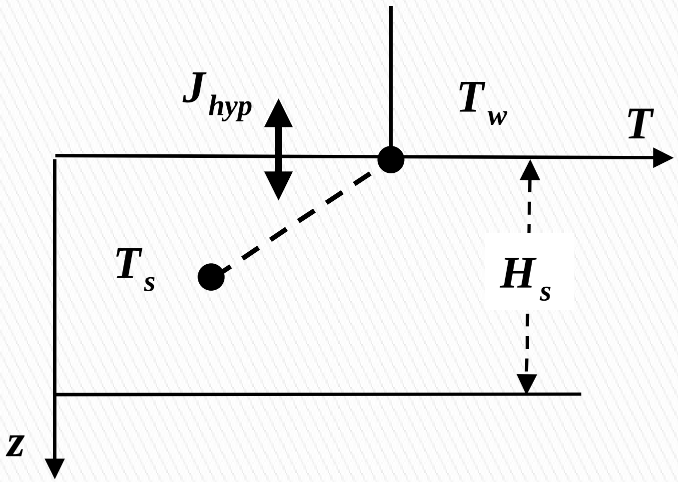


# What is Hyporheic Zone

"The **hyporheic zone** is a region beneath and alongside a streambed, where there is mixing of shallow groundwater and surface water. The flow dynamics and behavior in this zone (termed **hyporheic flow** or **underflow**) is recognized to be important for surface water/groundwater interactions" (Wikipedia)

Simple model for heat flux from hyporheic flow exchange




Jhyp = (Ehyp/Asf) * (Ts – Tw) * rhow * Cpw
(e.g. units of cal/cm^2/s)

Ehyp = bulk diffusive flow exchange between water and hyporheic sediment (cm^3/s)

Asf = surface area of sediment (cm^2)

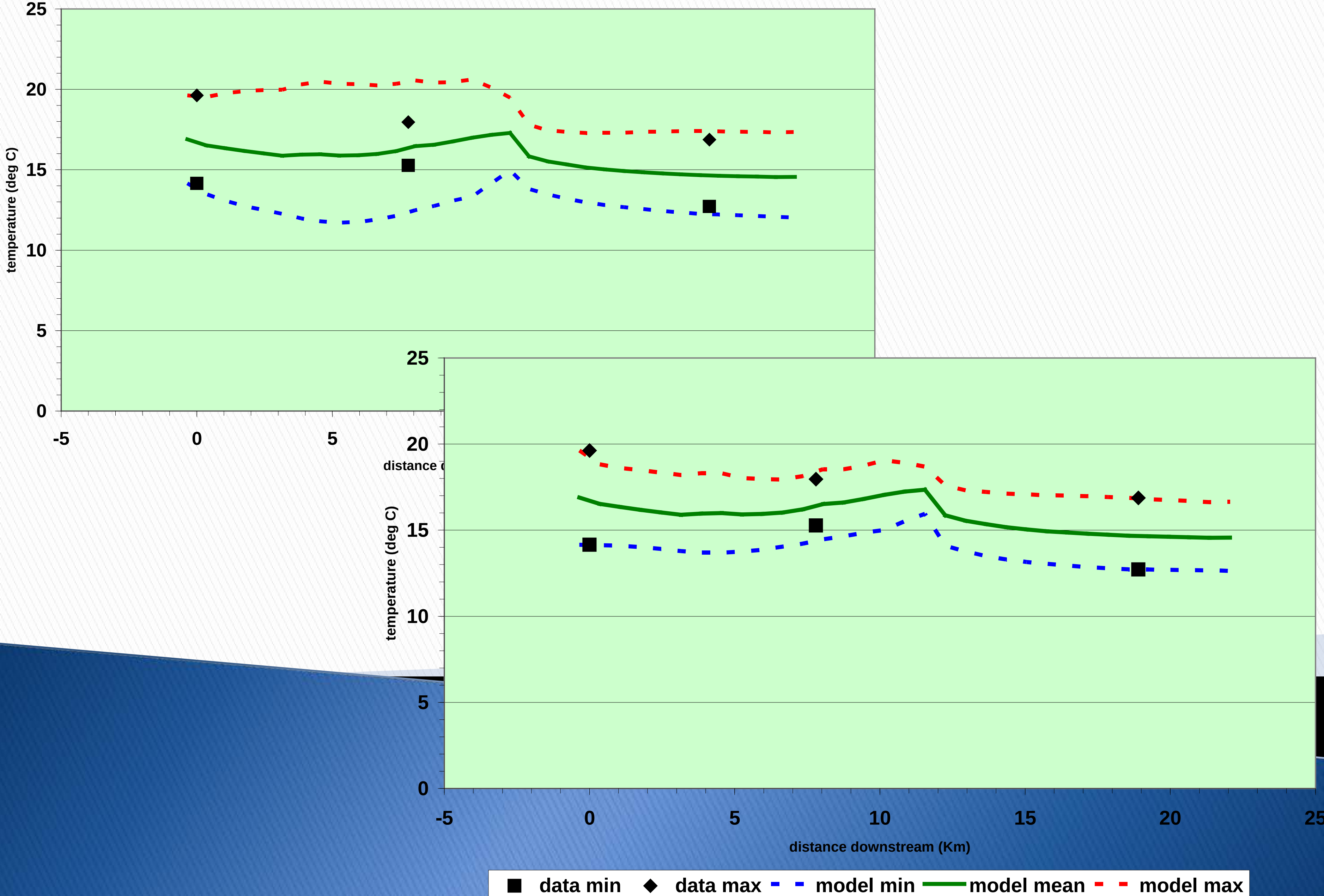
Ts = hyporheic sediment temperature (deg C)

Tw = surface water temperature (deg C)

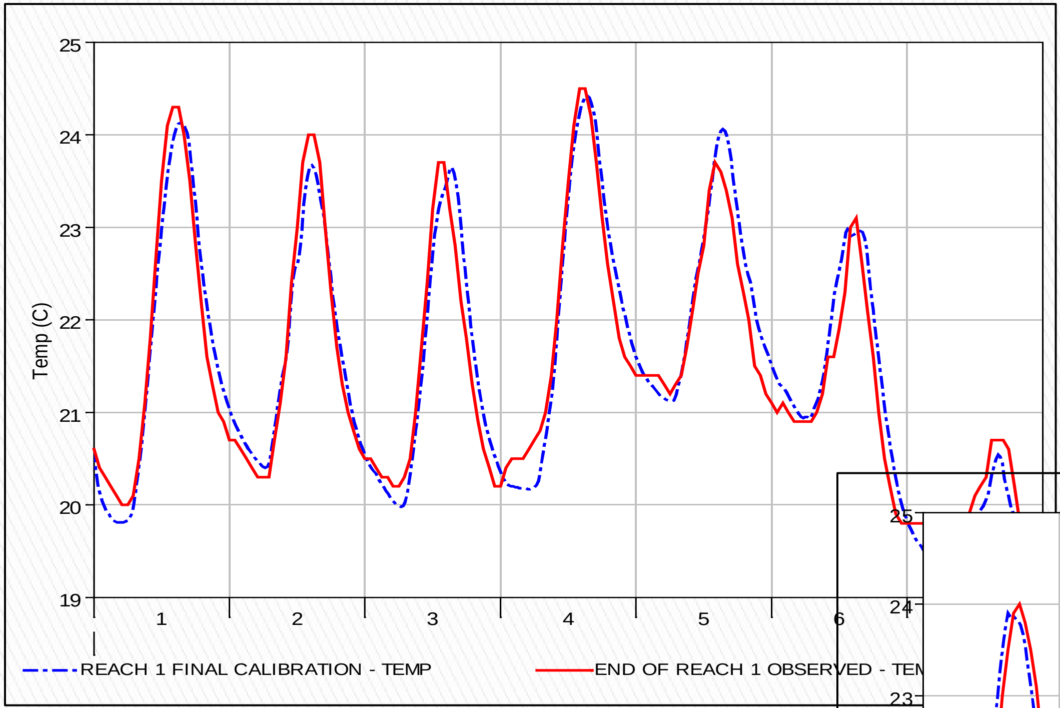
rhow = density of water (1 g/cm^3)

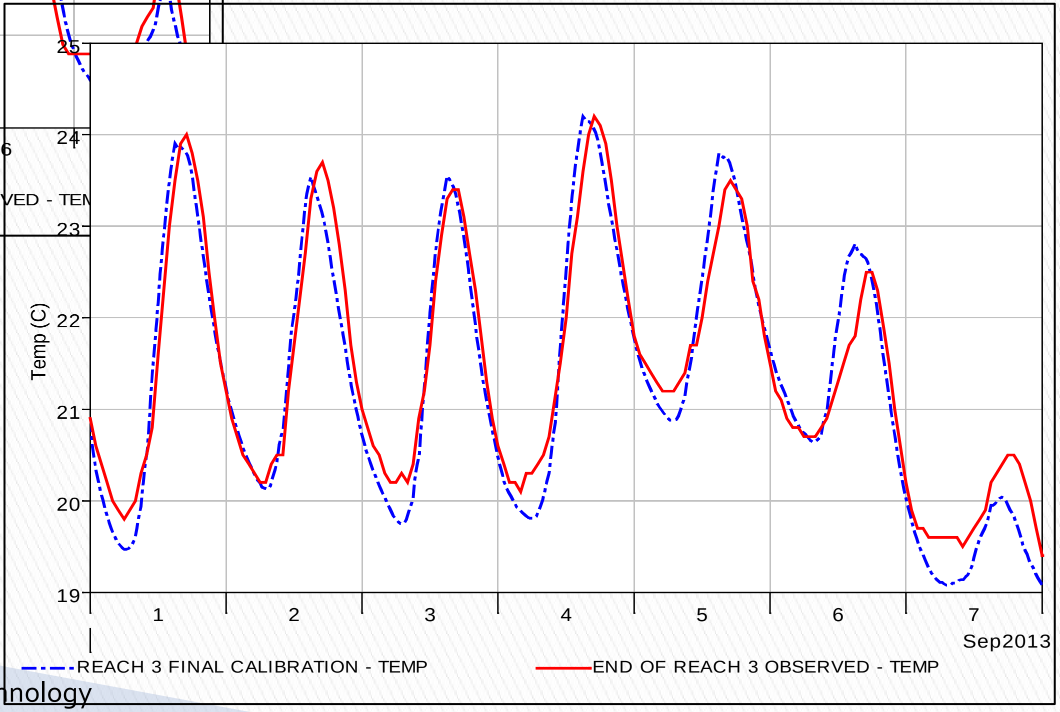
Cpw = heat capacity of water (1 cal/g/deg C)

*NF Stillaguamish R (8/12/2001)*

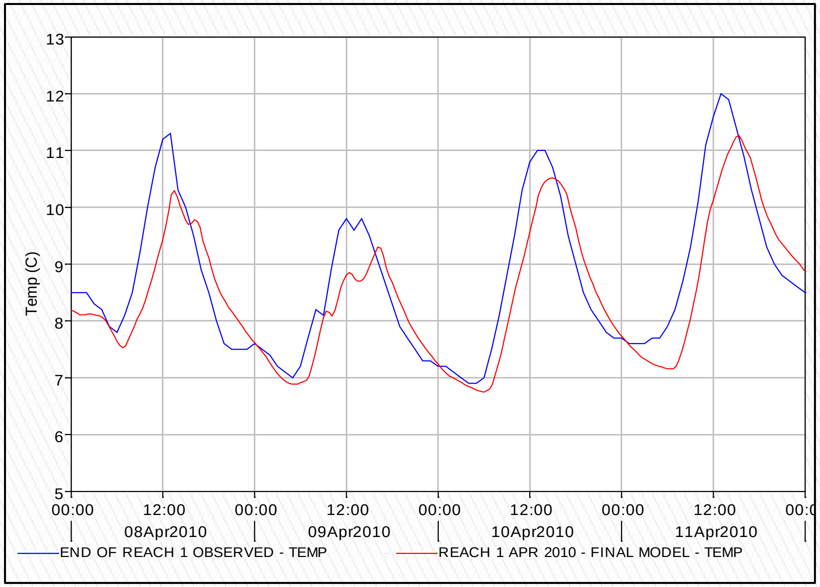


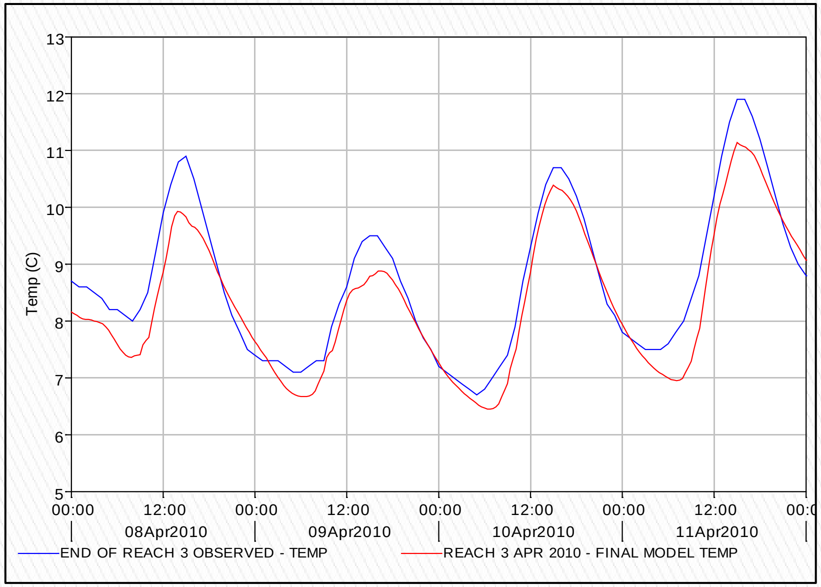
# Temperature Model Calibration (Sept 2013)

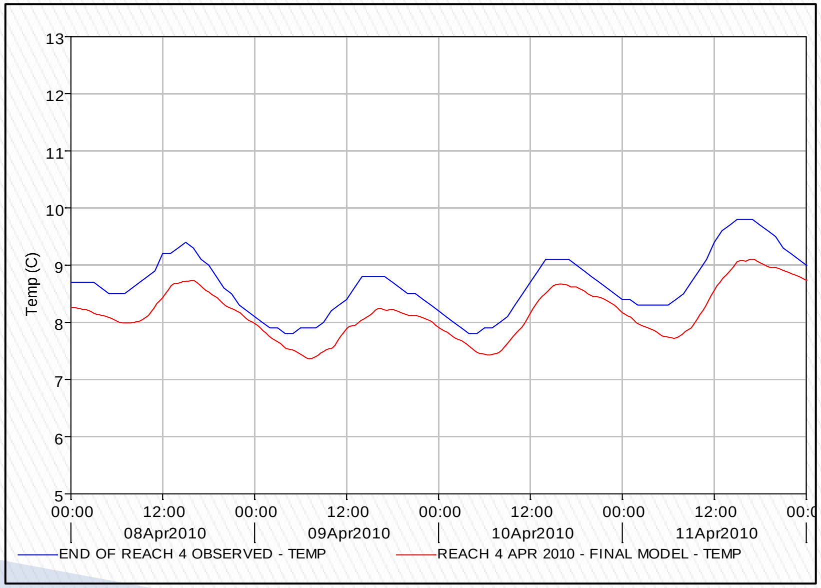


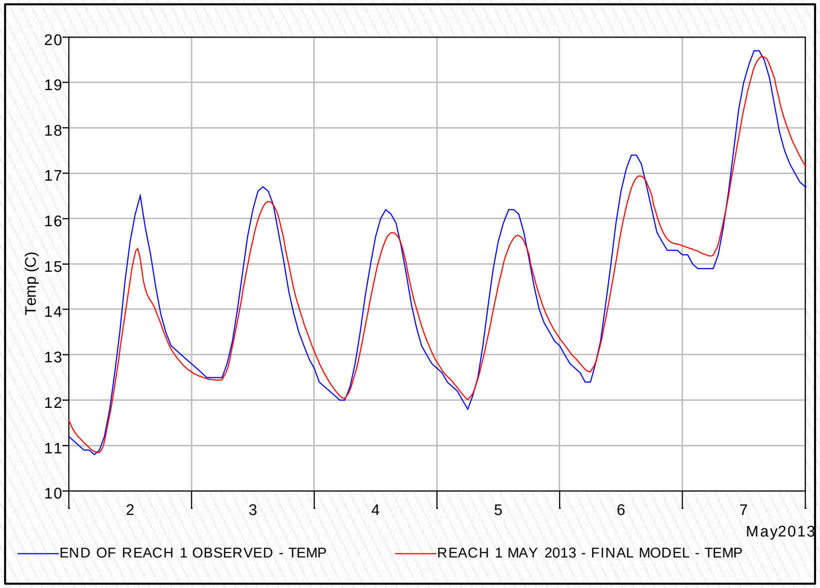
# Temperature Model Validation(April 2010)

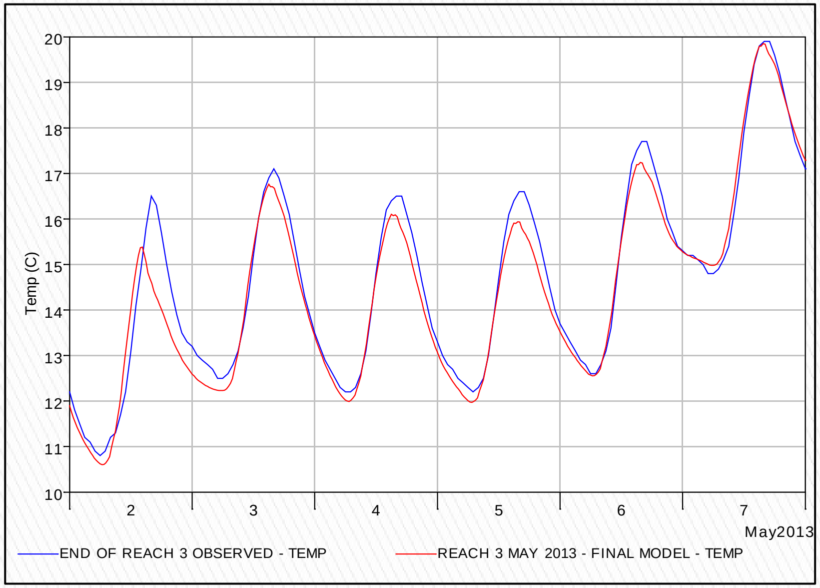


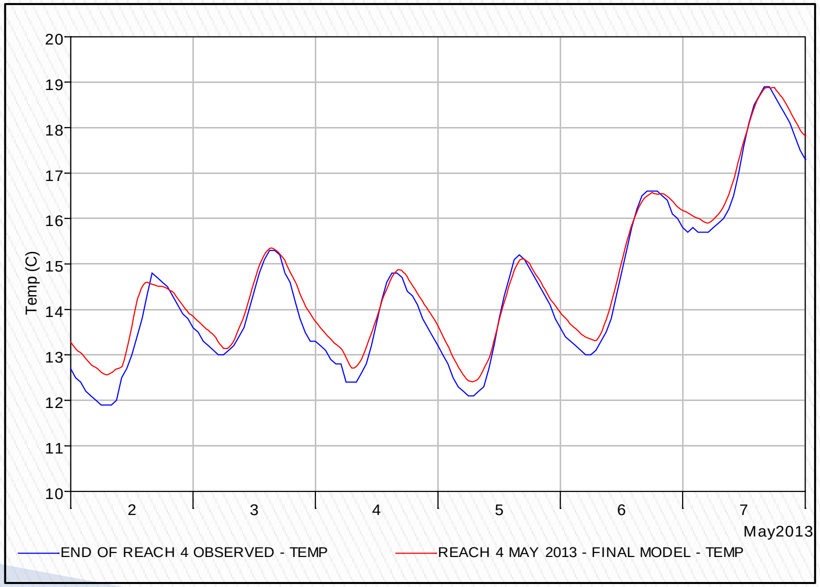



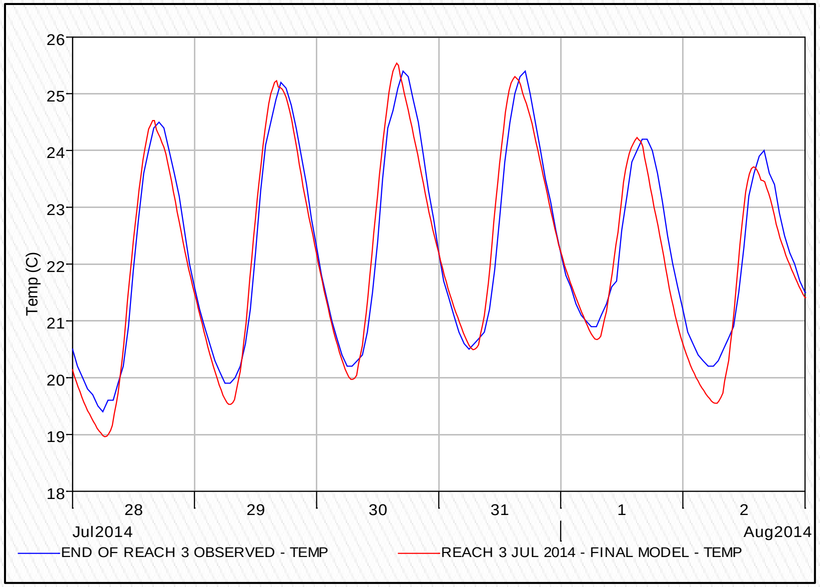
# Temperature Model Validation(May 2013)

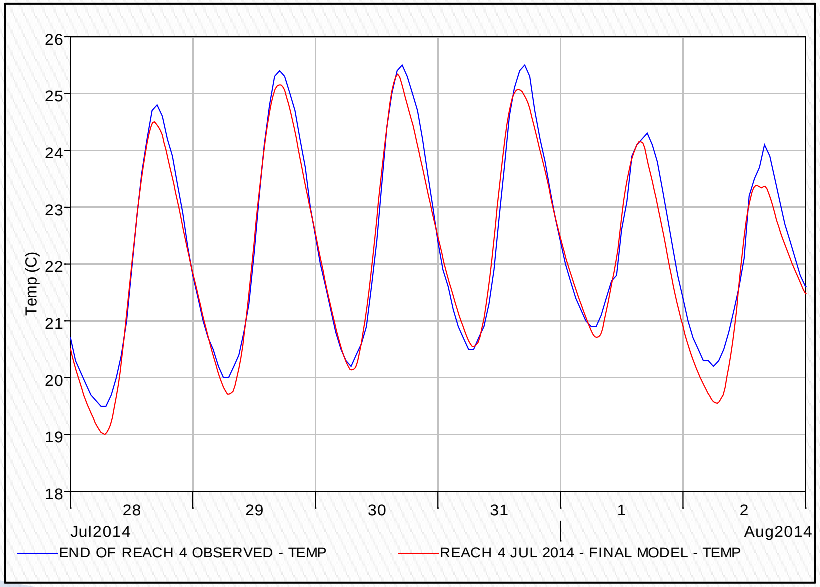


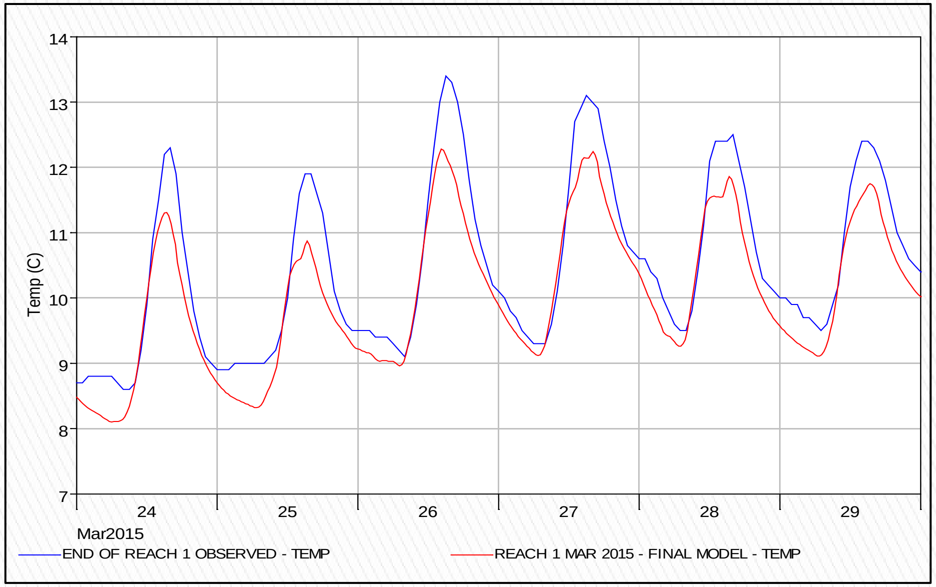



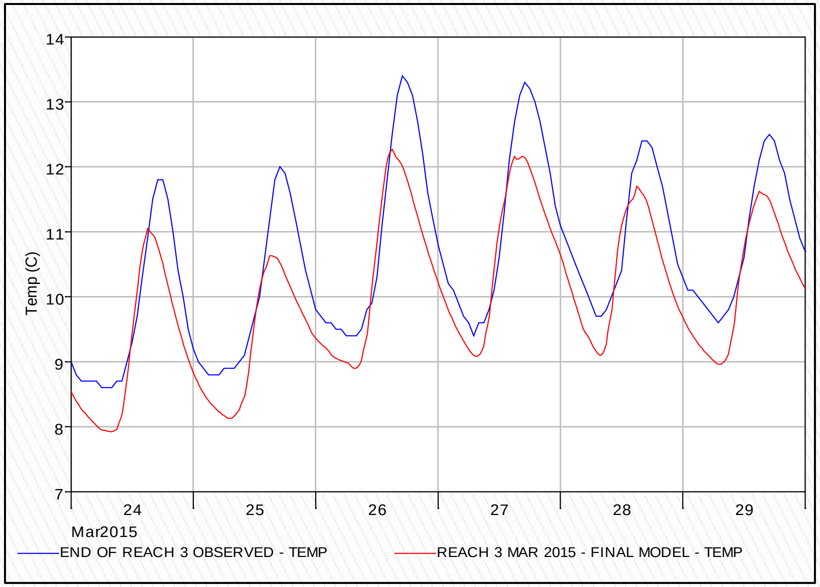
# Temperature Model Validation(July 2014)

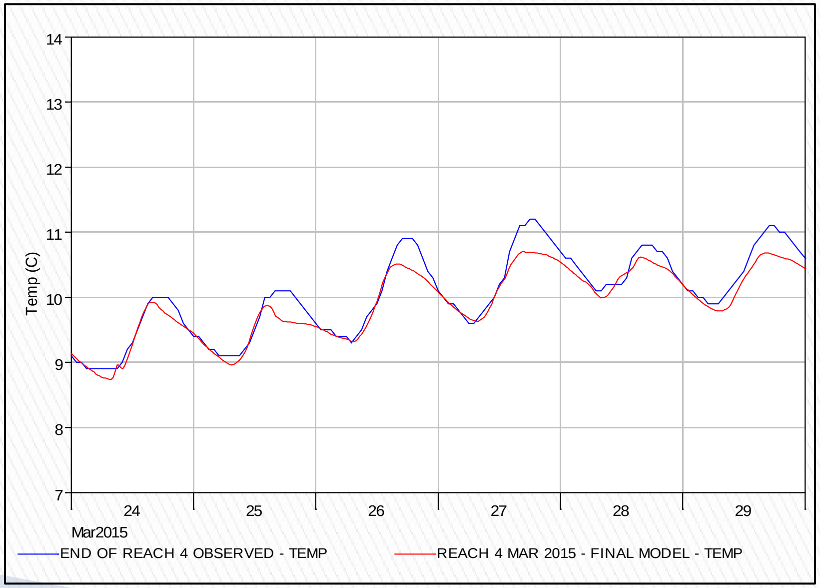


# Temperature Model Validation(March 2015)



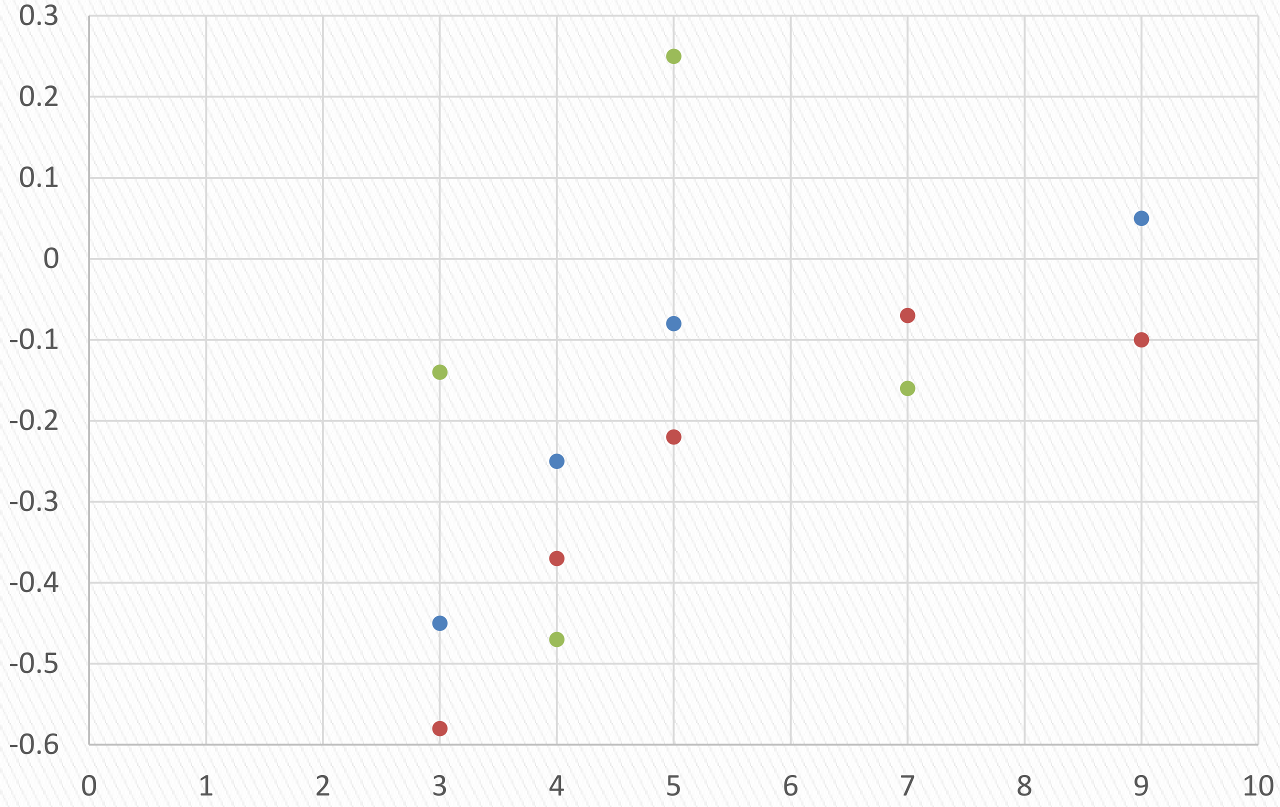



# Temperature Model Validation(Statistics)

| Simulation | Temperature Sensor Location | Mean Error (°C) | Mean Absolute Error (°C) | Root Mean Square Error (°C) |
|---|---|---|---|---|
| April 2010 | End of Study Reach 1 | -0.25 | 0.56 | 0.71 |
| April 2010 | End of Study Reach 3 | -0.37 | 0.43 | 0.51 |
| April 2010 | End of Study Reach 4 | -0.47 | 0.47 | 0.51 |
| May 2013 | End of Study Reach 1 | -0.08 | 0.36 | 0.45 |
| May 2013 | End of Study Reach 3 | -0.22 | 0.33 | 0.47 |
| May 2013 | End of Study Reach 4 | 0.25 | 0.28 | 0.34 |
| July 2014 | End of Study Reach 1 | * | * | * |
| July 2014 | End of Study Reach 3 | -0.07 | 0.35 | 0.42 |
| July 2014 | End of Study Reach 4 | -0.16 | 0.27 | 0.33 |
| March 2015 | End of Study Reach 1 | -0.45 | 0.48 | 0.57 |
| March 2015 | End of Study Reach 3 | -0.58 | 0.65 | 0.74 |
| March 2015 | End of Study Reach 4 | -0.14 | 0.15 | 0.21 |

# Temperature Model Validation(Statistics)



# Discussion

- Temperature model needs hyporheic zone
- Month-to-month results may have groundwater temperature influence
- Calibration/validation graphs and statistics support accurate model
- Temperature model considered only topographic shading, not vegetative shading
- If low-flow channel is proposed, need to consider impact on hyporheic zone (excavation)

# Next Steps

- Review model calibration report
- Define UAA alternatives
- Simulate UAA alternatives
- Recommendations, Report, Meetings

# QUESTIONS?