



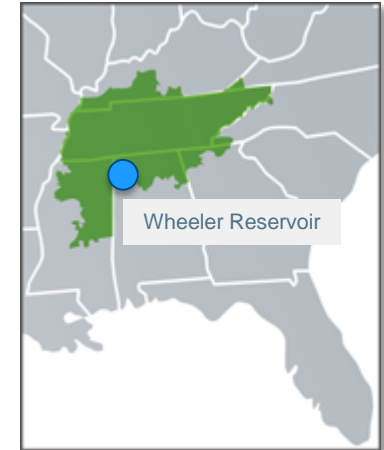
Operational River Temperature Forecasting Using A Coupled Delft3D Framework

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March 2019

Thermal Compliance at TVA

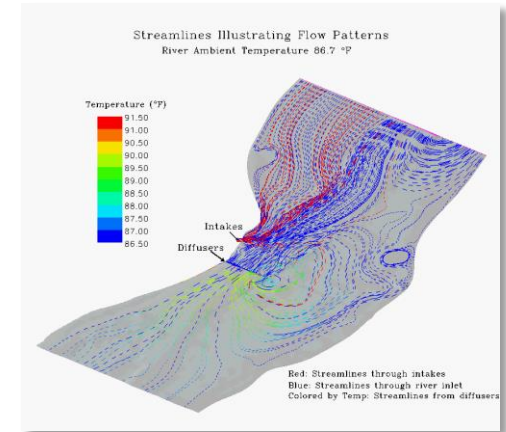
- The Tennessee Valley Authority (TVA) is a corporate agency of the United States of America (formed in 1933) that manages the Tennessee River and provides electricity to the Tennessee Valley.
- At TVA the hydrothermal team is responsible for helping the power plants maintain river temperature environmental compliance
 - In-house development of computational models (cold state) that simulate river flow (1D hydraulics), power plant functions (condenser, cooling towers), and mixing zone (2D plume)
 - Issue daily river temperature forecasts (end of mixing zone)
 - Near real-time forecasts and advisements during critical periods
 - Provide recommendations for cooling tower operations
 - Coordinate special river flows (steady flow, flow bumps)
- TVA has integrated Delft3D-FLOW into its hydrothermal forecasting system (FEWS-HTMS) for daily, operational forecasts
 - Delft3D-FLOW models developed (Deltares) for three baseload power plants
 - Presentation will focus on Browns Ferry on Wheeler Reservoir, Alabama, USA



TVA electricity service area in the southeast United States

Project Motivation and Goals

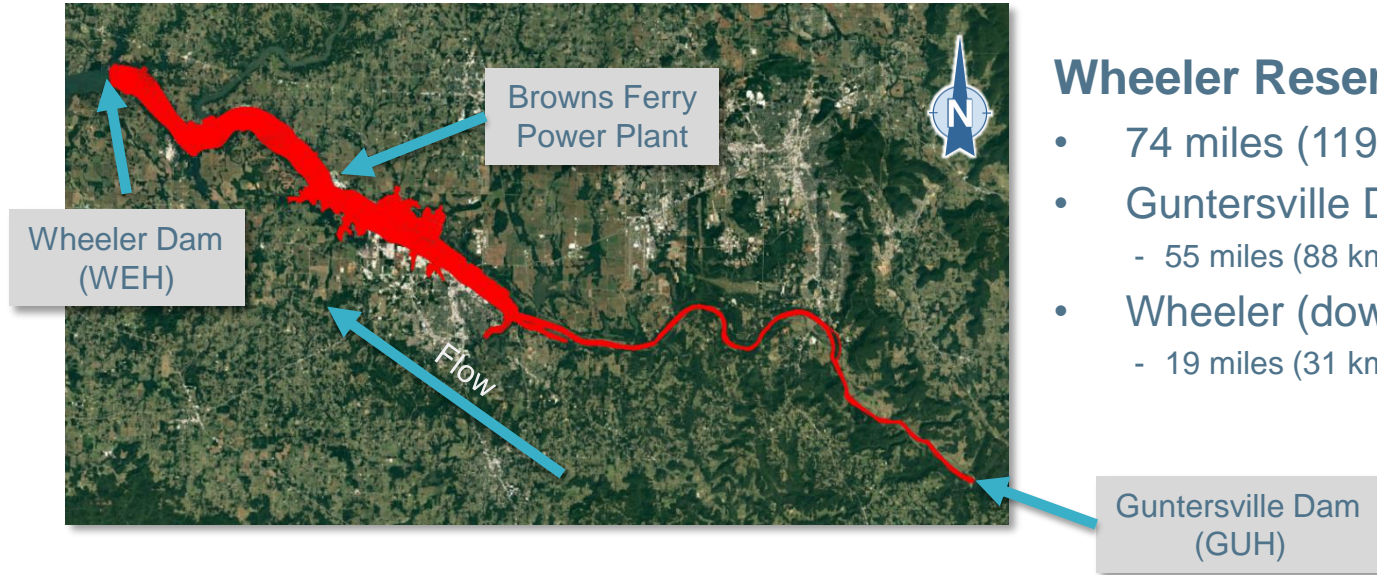
- Complex flow patterns occur in the vicinity of the power plants (withdrawal of cooling water, wave reflection off of downstream dams, bathymetry, etc.)
 - 1D hydraulics in TVA models cannot accurately represent localized 3D flow (recirculation)
- To ensure environmental compliance, TVA operates the river and cooling tower equipment conservatively during summer months
 - Steady flows (reduce reservoir sloshing and reverse flows; forego income from hydro peaking)
 - Forecast uncertainty can result in extended operation of cooling towers
- **Business Justification:** An improved representation of river processes (decrease forecast uncertainty) will allow for increased hydro peaking (increased revenue), further optimization of cooling equipment (reduced costs), and reduced compliance risk
- **Goal:** generate a 48-hour river temperature forecast in 30-minutes with an accuracy of 1.0°F (0.55°C) on the 24-hr rolling average using a 3D hydrodynamic model



Fluent model results on Wheeler Reservoir, Alabama, United States

Field Campaign

- Field campaign conducted in 2016 (May 2–6)
 - Collect flow, velocity, and water temperature data near Browns Ferry
 - Assist in the development of a Delft3D-FLOW model for Wheeler Reservoir



Wheeler Reservoir

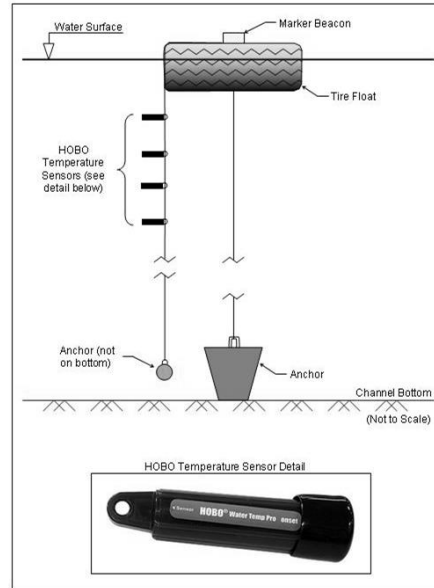
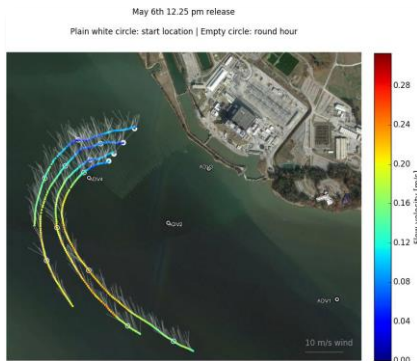
- 74 miles (119 km) long
- Guntersville Dam (upstream)
 - 55 miles (88 km) from Browns Ferry
- Wheeler (downstream)
 - 19 miles (31 km) from Browns Ferry

Field Campaign

Instrumentation

- Hobos (29 stations, 430 sensors)
- ADV (9 bottom mounted)
- ADCP tracks
- Telogs across reservoir (6 WSE)
- Drogues (6 units, GPS enabled)
- Thermal camera (aerial)
- Meteorology station at power plant
- Plant permanent temperature stations (6 stations)

Droge
tracks



Tire float Hobo
temperature station

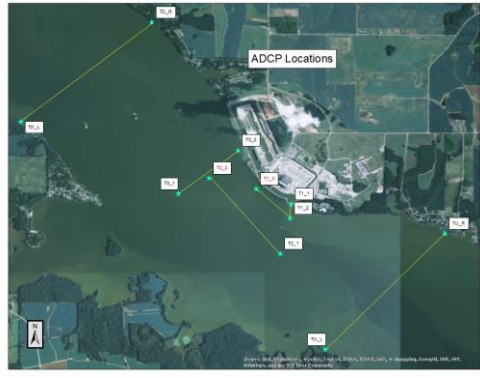


Location of Hobo stations



Location of ADVs

Field Campaign



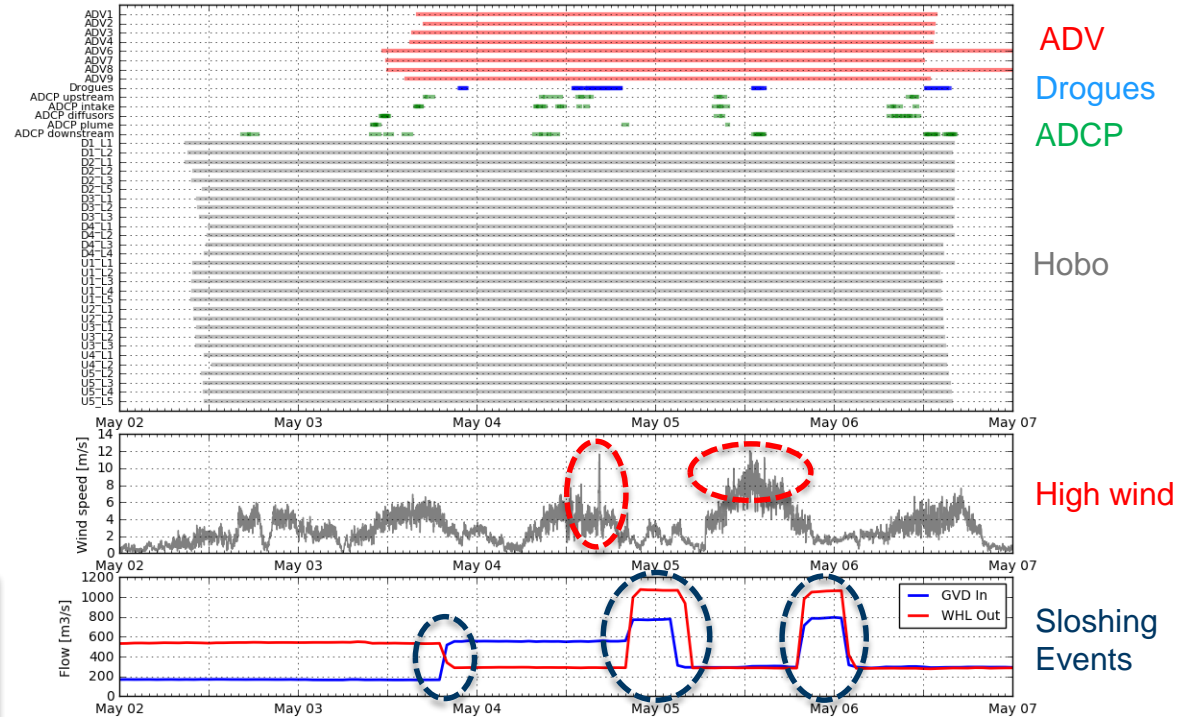
ADCP transects



ADCP



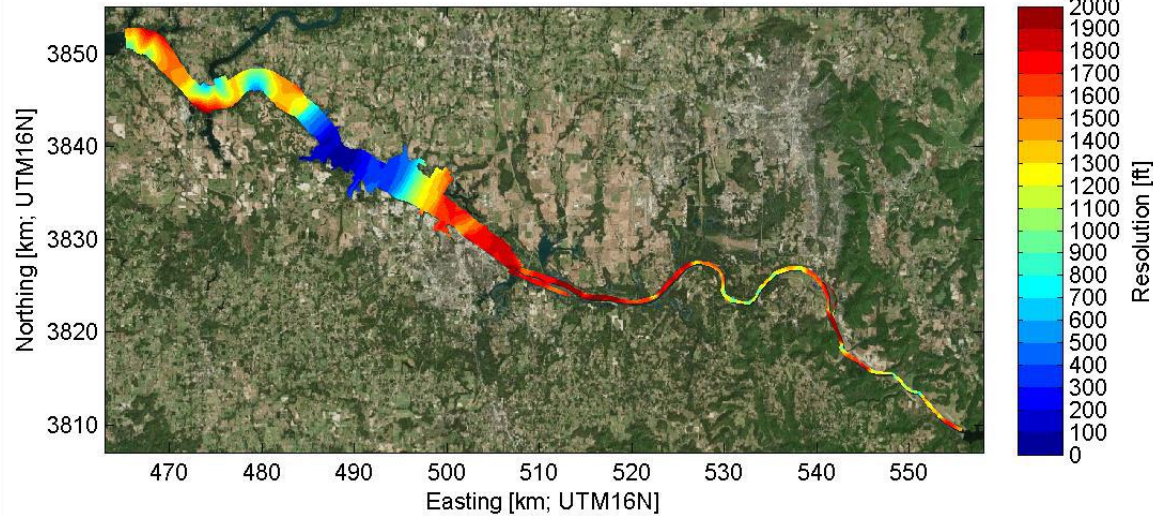
TVA Sideview



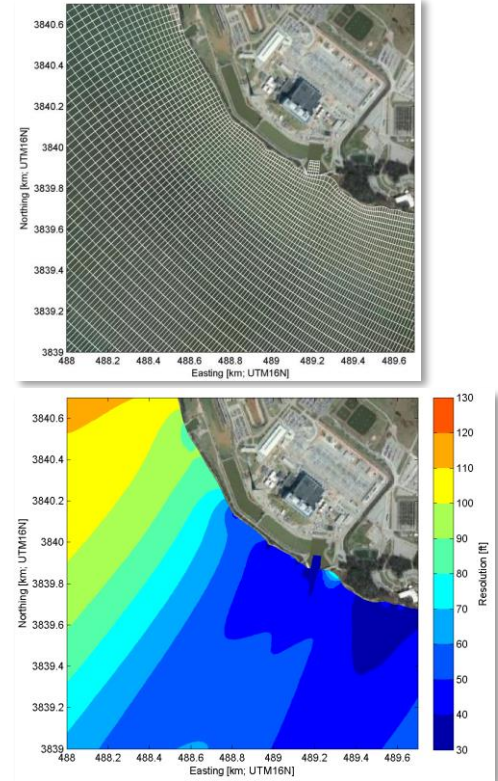
River flows were scheduled to capture steady periods, peaking operations, and reservoir sloshing

Model Setup

Grid size: 300,000 active cells (516x116x30)

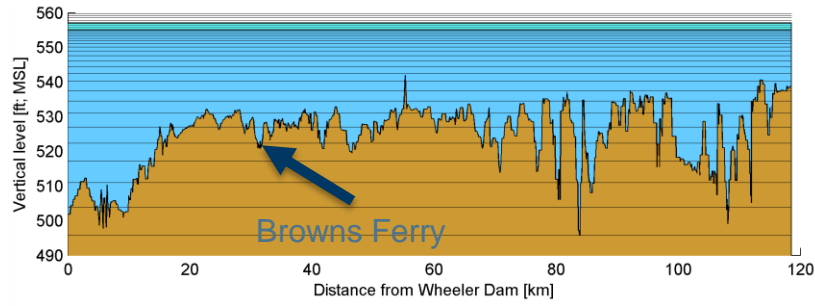


Model grid cell resolution ranges from 30–60 feet (9–18 meters) near the diffusers up to 2,000 feet (600 meters)



Model Setup

- Z-layer (30 vertical layers)
 - 0.65 feet (0.2 meter) at water surface
 - 48 feet (14 meter) at bed
- Roughness
 - Manning: 0.028
- Turbulence Model
 - K-Epsilon & Buoyancy Flux (density stratification)

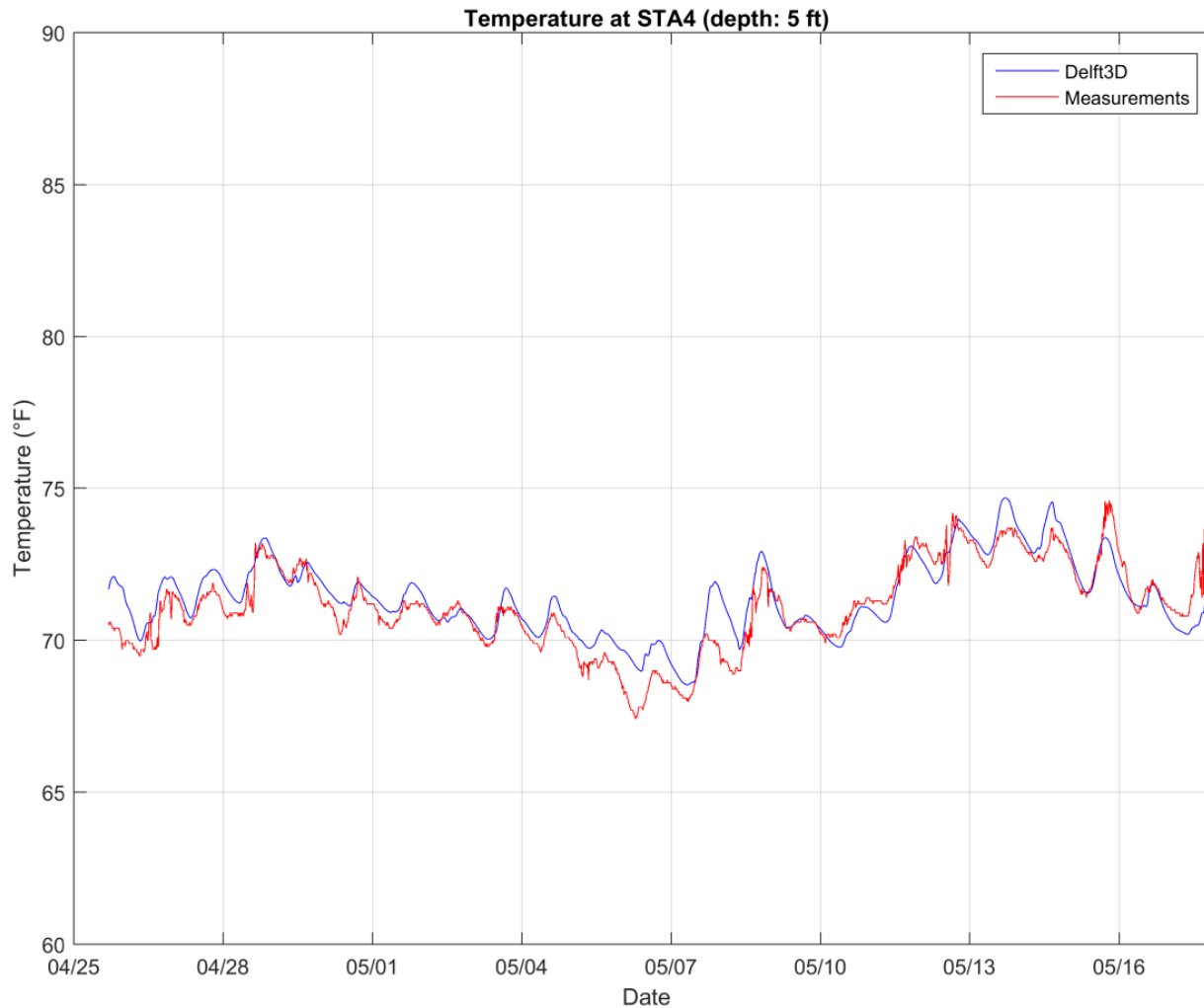


Bathymetric cross-section of Wheeler Reservoir and Z-layers



Location of local inflows to Wheeler Reservoir

- Wind forcing high temporal resolution (10 minute)
- Air temperature and solar radiation at hourly interval
- Local inflows calculated daily by TVA River Forecast Center (RFC)

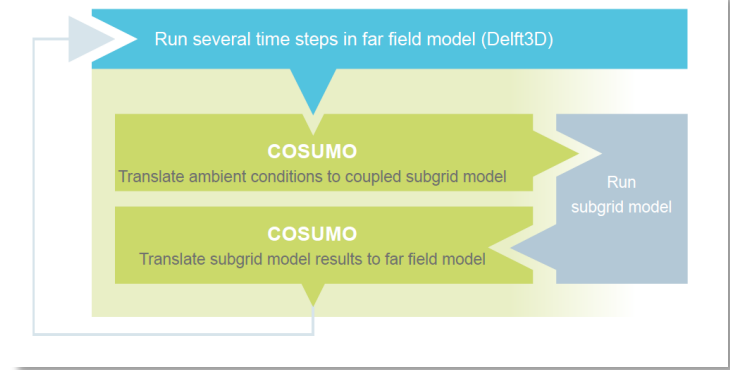


Station 4

- Upstream ambient temperatures
- Approximately 4 miles (6.5 km) upstream of plant
- Compliance point
- Permanent installation

Coupled Modeling Framework

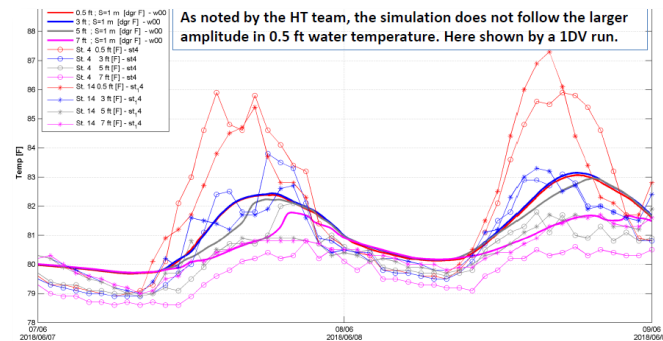
- Separate subgrid model needed to simulate the diffuser plume
- Iterative nature of the problem requires a coupled model framework to simulate recirculation while meeting run-time constraint
 - Plant equipment (TVA)
 - Plume (TVA, updated by Deltares)
 - Reservoir (Deltares Delft3D-FLOW)
- Model interaction coordinated COSUMO
 - COupled SUBgrid MOdels
 - Developed by Deltares in MATLAB
 - Not yet available with Delft3D-FM
- COSUMO converts plume geometry to diluted sources and entrainment sinks for Delft3D-FLOW



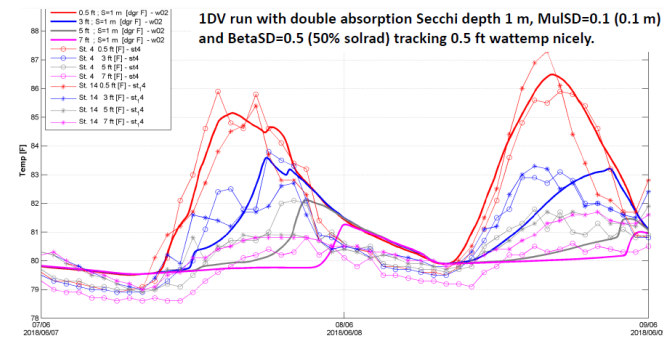
Delft3D-Flow Enhancements

- Simulation did not follow the near-surface (0.5 feet) diurnal heating
 - Absorption of solar radiation in the near-infrared 700-2500 nm range in the top layer of Wheeler Reservoir was not well represented
 - Compliance depth is 3-5-7 foot average
- Updated with new “double absorption” functionality
 - Blend of two Lambert-Beer Law profiles with user-defined ratio (β_{SD}) of incoming solar radiation associated with Secchi depth and the rest of the radiation absorbed with fraction of the Secchi depth

$$I(z) / I_{inc} = \beta_{SD} \exp(-k_{SD} z) + (1 - \beta_{SD}) \exp(-k_{shallow} z)$$



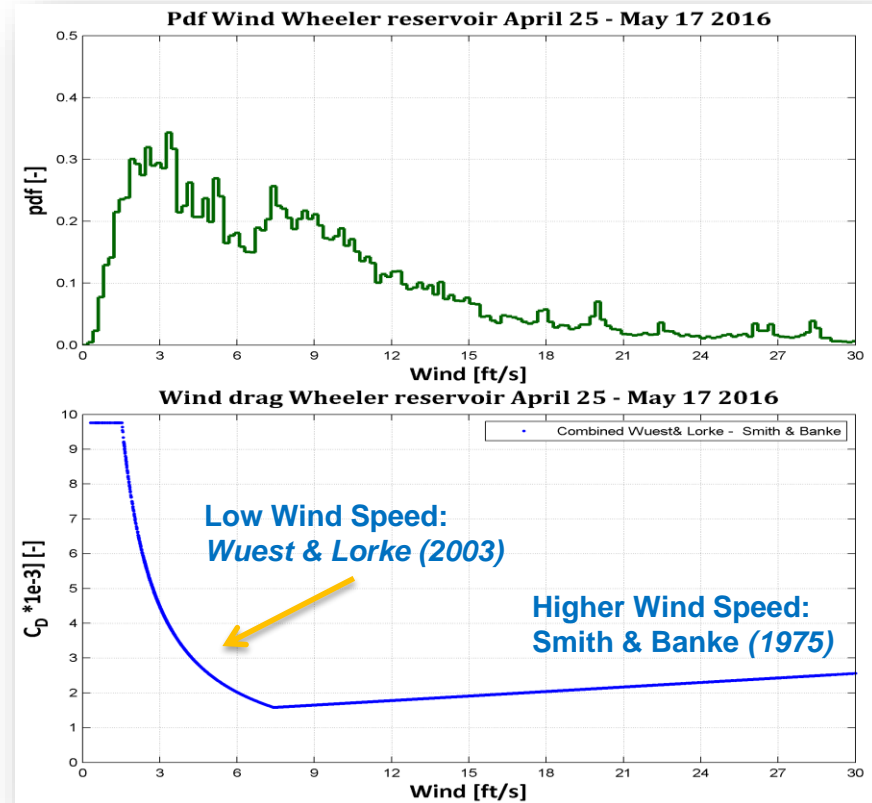
Without “double absorption”



With “double absorption”

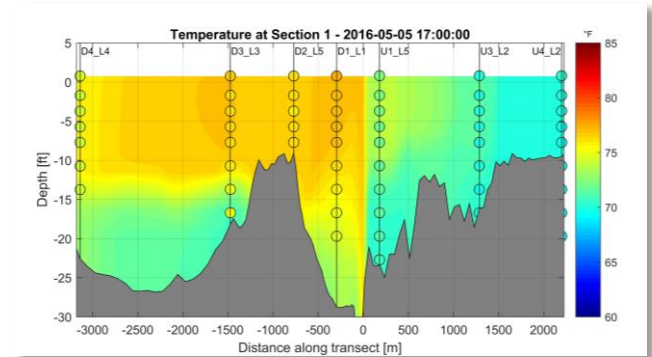
Delft3D-Flow Enhancements

- Wind related
 - Increased wind drag coefficient (C_d) at low ($U_{10} < 4$ m/s) wind speed
 - $C_d = \text{Stanton} = \text{Dalton}$ (coef. sensible & latent heat)
- Enhancements currently in model branch (not in release version but available)



Additional Enhancements

- SlotJet (TVA)
 - Current plume model does not accurately distribute heat from diffusers in the water column
 - Upgrade using Jirka (2006)
 - > Add flow drag force components
 - > Elongates plume path
 - Target completion is Spring 2019
- FEWS
 - “Modifier copy” enhancement in 2018.02



Temperature cross-section at diffusers

*Jirka, G. H., 2006. Integral Model for Turbulent Buoyant Jets in Unbounded Stratified Flows Part 2: Plane Jet Dynamics Resulting from Multiport Diffuser Jets. Environmental Fluid Mechanics (2006) 6: 43-100.

Hardware

- Ability to run 9 river temperature forecasts concurrently
 - Analyze multiple hydro generation schedules during daily scheduling of river (generated by RiverWare)
 - Support 3 power plants during critical periods
 - Able to quickly reconfigure processor allocation
 - Computing cluster accessible for special studies (outside of FEWS)
- Tech specs
 - 9 FEWS forecasting shells (Virtual machines)
 - Supermicro Servers (Physical servers, child nodes)
 - > 54 blades / nodes total
 - > 6 per model scenario
 - Intel Xeon Processor E3-1285 v6 @ 4.1 Ghz
 - > 4 core / partitions
 - > 216 cores / partitions total
 - > 18 per model scenario (3 nodes for Delft3D, 1 for OS)
 - Cisco Nexus 93108TC-EX
 - > 10 Gigabit (necessary because of MPI)

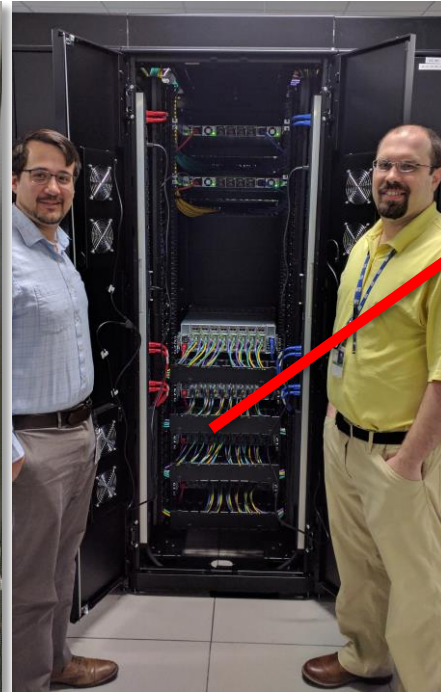


TVA Delft3D-FLOW
computing cluster

Hardware

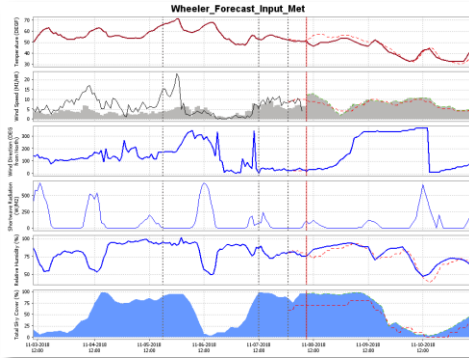


Network Switch

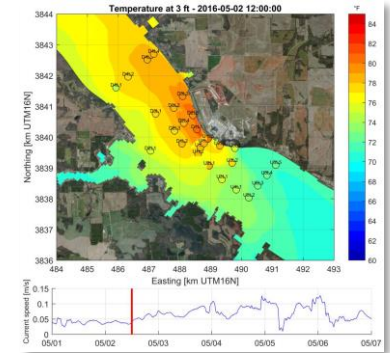
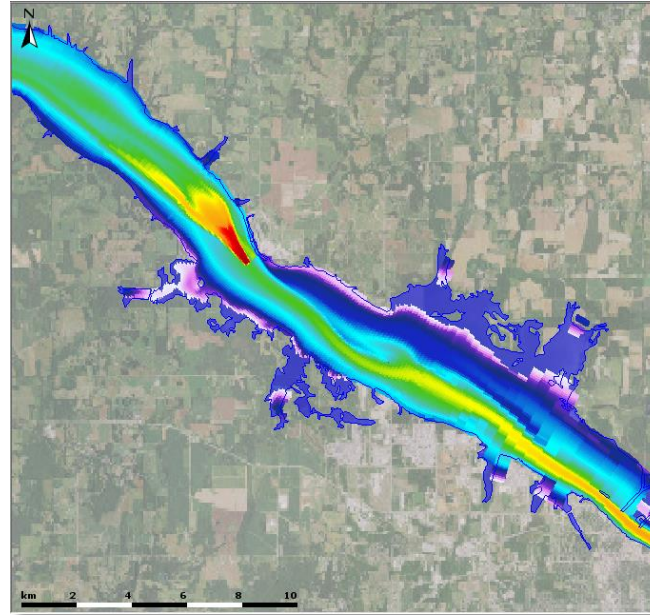
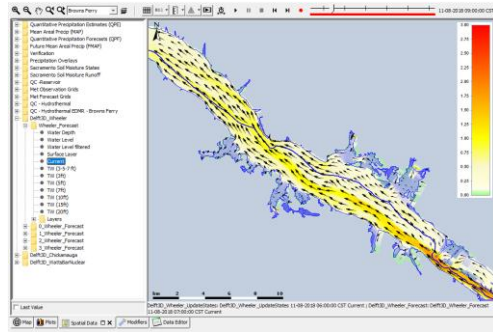


Server / Node

Data Products



FEWS plots



MATLAB images and animations

	A	B	C	D	E	
	TW24 (DEG)	TW24 (DEG)	TW24 (DEG)	TW24 (DEG)	TW24 (DEG)	T
	St 4 or 14, 3-5-7	St 4 or 14, 3-5-7	St 4 or 14, 3-5-7	St 4 or 14, 3-5-7	St 4 or 14, 3-5-7	S
CST/COT	BFN-(S3) Delft3D_Wheeler	BFN-(S3) Delft3D_Wheeler	BFN-(S3) Delft3D_Wheeler	BFN-(S3) Delft3D_Wheeler	BFN-(S3) Delft3D_Wheeler	B
	[1]	[1]	[1]	[1]	[1]	[
Date	11-03-2018	11-04-2018	11-05-2018	11-06-2018	11-07-2018	1
Day	Sat	Sun	Mon	Tue	Wed	Th
Mean	63.6	63.0	62.7	62.8	62.7	
Sum	1526.7	1574.4	1505.9	1506.3	1504.8	
Min	63.2	62.9	62.6	62.6	62.2	
Max	64.3	63.1	62.9	63.0	63.0	
01	64.3	63.1	62.9	62.6	63.0	
02		63.1				
03	64.2	63.1	62.9	62.6	63.0	
04	64.1	63.0	62.9	62.6	63.0	
05	64.0	63.0	62.9	62.6	63.0	
06	63.9	63.0	62.9	62.6	62.9	
07	63.9	63.0	62.9	62.6	62.9	
08	63.8	63.0	62.8	62.7	62.9	
09	63.7	63.0	62.8	62.7	62.9	
10	63.7	63.0	62.8	62.7	62.9	
11	63.6	63.0	62.8	62.7	62.9	
12	63.5	63.0	62.8	62.7	62.8	
13	63.5	63.0	62.8	62.7	62.8	
14	63.5	63.0	62.7	62.8	62.7	
15	63.4	63.0	62.7	62.8	62.7	
16	63.4	62.9	62.7	62.8	62.6	
17	63.4	62.9	62.7	62.9	62.6	
18	63.3	62.9	62.6	62.9	62.5	
19	63.3	62.9	62.6	62.9	62.4	

Tabular reports (FEWS)

Summary

- TVA and Deltares, in partnership, have implemented an operational river temperature forecasting system using a 3D hydrodynamic model (Delft3D-FLOW) for the Tennessee River
- Delft3D double absorption, and wind drag functions; and FEWS modifier copy feature available to Deltares community
- Production forecasting in summer 2019
- Project benefits:
 - Increased hydro generation during critical summer months
 - Further optimization of cooling tower use
 - Reduced compliance risk and impact



Mural of Tennessee Valley Watershed Dam (painted 1956)



Questions?